Advancing the Fundamental Sciences

Proceedings of the Forest Service National Earth Sciences Conference, San Diego, CA, 18-22 October 2004

Volume 1

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Editors

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Cover:
Backprint–A creek in the Tushar Mountains, Fishlake National Forest, central Utah. Photo by Bert Lowry.

Top left–Waterfall on Fridley Run, near Harrisonburg, Virginia, on the George Washington and Jefferson National Forest. Photo by Mike Land.

Bottom left–The Dolores River just outside the Grand Mesa, Uncompahgre, and Gunnison National Forests, western Colorado. Photo by Jerry Freeouf.

Top right–Island Lake and Fremont Peak, Wind River Range, Bridger-Teton National Forest, Wyoming. Photo by Scott Clemons.

Middle right–Terminus of Hubbard Glacier, Tongass National Forest, southeast Alaska. Photo by J. Lott.

Bottom right–Quartz Creek, North Fork Clearwater River, Clearwater National Forest, Idaho. Photo by Richard Jones.

Title page: Powder River, Wallowa-Whitman National Forest, northeast Oregon. Photo by Bruce McCammon.

Preface

Bruce McCammon and Bonnie Ilhardt

It is a great pleasure for us to present the proceedings of the Advancing Fundamental Sciences conference held in San Diego, California, in October 2004. This conference was attended by nearly 450 Forest Service earth scientists representing hydrology, soil science, geology, and air. In addition to active members of the earth science professions, many retired scientists also attended and participated in the week's events. Even though it rained much of the week, attendees maintained a high level of enthusiasm and participated actively.

The week was filled with memorable, but transient, events. A variety of keynote speakers reminded us of our history, challenged us with new thoughts, and reaffirmed our responsibility for proper stewardship of the unique physical resources on Forest Service lands. Panel discussions allowed the pioneers of the physical science disciplines to be recognized for their careers and acknowledged for their contributions. Speakers took the opportunity to present new work and interact with their peers. Poster displays gave many people an opportunity to present their work and explain its importance. Everyone who attended will remember the three-part play "The Life and Times of Forrest Stump." The play presented a snapshot of a hypothetical physical scientist's career beginning when physical scientists were new to the agency and ending when he retired after a long and distinguished career. The skit struck close to home for many and left the crowd howling with laughter and asking for more. Conference critiques showed clearly that the variety of events during the week led to the success of the conference.

These proceedings are the durable product of the conference and come to you only as the result of hard work by authors, reviewers, and editors. These proceedings include 60 technical papers that have been through a series of peer and editorial reviews. Fifty-six people participated as reviewers of the technical papers. Each paper was improved through incorporation of two sets of peer-review comments. Our thanks go to each of the people who volunteered to be a reviewer. Special thanks go to Michael Furniss, Caty Clifton and Kathryn Ronnenberg for coordinating the reviews, providing a high level of editorial consistency, and for preparing this proceedings.

We hope that these proceedings will serve as a valuable reference for your work in the future.

Bruce McCammon
Retired, Pacific Northwest Region
Conference Chair

Bonnie Ilhardt
Eastern Region
Conference Co-chair

Editors' Note

Michael J. Furniss, Catherine F. Clifton, and Kathryn L. Ronnenberg

Most earth scientists like rain. We know it is the source of much we hold dear, sustaining the systems we study and love, necessary for flowers to grow and flourish and bloom. But… rain for a week? In San Diego? It was an unusual deluge that greeted us in southern California, but fitting. It accompanied an unprecedented gathering of more than 400 Forest Service earth scientists for a first-ever national conference. It was a landmark event. Good times, along with the precipitation, were in abundance. The weather lifted rather than dampened the mood as we ran through downpours, arriving soaked and excited for the next encounter.

Many attendees expressed surprise that "there are so many of us." We have a lot in common through our work, but until that week, we'd never seen so many soil scientists, geologists, hydrologists, and air specialists together in one place. There was a strong sense of a "community of practice": of shared goals, common experience and participation that reached across the Nation.

We were, perhaps, the largest such collection of public lands earth scientists on Earth. The conference was a celebration and expansion of our collective knowledge, experience, identity, history, and a glimpse of our future potential. We commend the conference organizers for this extraordinary, multidisciplinary conference, for their recognition that knowledge from one branch is unable to advance without knowledge from another, and that together we are a stronger, more sustainable community.

Two thousand four was also the year of the Forest Service Centennial celebration. The sense of history was in the air, as retirees mixed with newer hires. We took stock of the five or six decades that earth scientists have contributed to the Forest Service, the ways times have changed, and the many ways we have advanced the agency and the conservation of earth resources.

The conference program offered a broad diversity of plenary and themed sessions, workshops, and field trips, and received rave reviews throughout the week. The book you hold contains submitted technical papers from the themed sessions. These 60 peer-reviewed papers represent a wide spectrum of earth science investigation, experience, research, and innovation in the Forest Service. Take the time to read and enjoy them, but don't stop there. You are encouraged to give an author a call or email to discuss what you read and how it relates to your work. Load up the CD in the back and review the keynote talks. Check the intranet web site for more memories and resources.

Let this collection be a portal into the rich pool of expertise, engagement, and collaboration that is our community of practice. The bonds formed and strengthened in San Diego can help sustain us in the decades to come. Our community was in full bloom that week, but it exists between conferences. Just as flora (and maybe conferences) need rain, communities of practice need cultivation to flourish. We have many ways to connect across forests, regions, and stations, to inform and support each other. In so doing, each of us can help nurture our community of practice.

We encourage you to call or email someone from another region. Email someone you know but haven't seen since San Diego. Create and participate in informal events that connect people. Convene discussions on common challenges, both remote and in person. Share experiences, successes, and failures. We each have the ability to cultivate and sustain our community of practice. Everything works when we participate and contribute. There is no better time than now.

Advancing the Fundamental Sciences: Proceedings of the Forest Service National Earth Sciences Conference, San Diego, CA, 18-22 October 2004

Contents, Volume 1

Page

Preface i
Bruce McCammon and Bonnie Ilhardt

Editors' Note iii
Michael Furniss, Catherine Clifton, and Kathryn Ronnenberg

I. Concurrent Session Papers 1

Section 1. Applied Science and Technology
Part 1. Fire and Smoke 1

Erosion Risk Management Tool (ERMiT)–A Probability-Based Erosion Prediction Model 3
Peter R. Robichaud

Hillslope Erosion Rates in Areas With Volcanic Parent Materials and the Effects of Prescribed Fires in the Blue Mountains of Eastern Oregon and Washington, USA 7
Robin M. Harris, Catherine F. Clifton, and Steven M. Wondzell

Long-Term Ecological Changes With Postfire Emergency Seeding 20
Jeff Bruggink

NcNally Postfire Discharge and the Relationship of Sierra Nevada-Wide Flood Frequency Curves and Local Kern River Discharge Curves 27
Terry A. Kaplan-Henry

The Effects of Selected Postfire Emergency Rehabilitation Techniques on Small Watershed Sediment Yields in Southern California 36
Peter M. Wohlgemuth and Peter R. Robichaud

Detecting Smoke Plumes and Analyzing Smoke Impacts Using Remote Sensing and GIS for the McNalley Fire Incident 43
Ricardo Cisneros, Andrzej Bytnerowicz, Brad Quayle, and Trent Procter

Sierra Nevada Framework Smoke Monitoring: Testing Implementation Through a Pilot Program 50
Trent Procter

Air Quality and Prescribed Fire Management–Moving Toward a Solution Space 53
Tom Robison

Advances in Fire Convection Dynamics 60
Brian E. Potter, Joseph J. Charney, Warren E. Heilman, and Xindi Bian

Contents Page

Part 2. Watershed Management 67

Using Stream Channel Reference Data to Guide Land Management Decisions 69
Pete Bengeyfield

Sediment From a Small Ephemeral Gully in South Carolina 76
William F. Hansen and Dennis L. Law

Quantifying the Effects of Livestock Grazing on Suspended Sediment and Stream Morphology 85
Pete Bengeyfield

Using Multiple Fine-Sediment Size Classes to Evaluate the Condition of Trout Spawning Habitat 94
Pamela J. Edwards, Thomas C. Cain, and Charles J. Gagen

Water Quality Effects of Blue-Green Algal Blooms in Diamond Lake, Oregon 102
Mikeal Jones, Joseph Eilers, and Jacob Kann

Delineation of a Karst Watershed on Prince of Wales Island, Southeast Alaska 111
Katherine M. Prussian and J.F. Baichtal

An Examination of References for Ecosysems in a Watershed Context: Results of a Scientific Pulse in Redwood National and State Parks, California 118
Tom Lisle, Ken Cummins, and Mary Ann Madej

Part 3. Surface and Groundwater 131

Chronic Misapplication of the Relationship Between Magnitude and Frequency in Geomorphic Process as Illustrated in *Fluvial Processes in Geomorphology* by Leopold, Wolman, and Miller 133
Tim Sullivan and Walt Lucas

The Evolution of Channel Maintenance Science in the Forest Service 136
John Potyondy

Forest Service Channel Maintenance Flows in the Klamath Basin 145
Michael L. McNamara and Tim Sullivan

Keeping Our Streams Flowing: Tonto National Forest Groundwater Policy 157
Richard Martin and Grant Loomis

USDA Forest Service Policy on Managing Groundwater Resources 166
Stephen P. Glasser

Section 2. Experimental and Research Watersheds 171

The Forest Service Barometer Watershed Management Program, a Historic Viewpoint 173
Larry J. Schmidt and Byron Beattie

Contents Page

Development of Watershed Hydrologic Research at Santee Experimental Forest, Coastal South Carolina 180
Devendra Amatya and Carl Trettin

Understanding the Hydrologic Consequences of Timber Harvest and Roading: Four Decades of Streamflow and Sediment Results From the Caspar Creek Experimental Watersheds 191
Elizabeth Keppeler and Jack Lewis

Forest Road Erosion Research at the Coweeta Hydrologic Laboratory 197
Mark S. Riedel, Lloyd W. Swift, Jr., James M. Vose, and Barton D. Clinton

The Entiat Experimental Forest: A Unique Opportunity to Examine Hydrologic Response to Wildfire 205
Richard D. Woodsmith, Kellie B. Vache, Jeffrey J. McDonnell, Jan Seibert, and J. David Helvey

Discharge and Sediment Loads at the Kings River Experimental Watershed in the Southern Sierra Nevada of California. 217
Sean M. Eagan, Carolyn T. Hunsaker, Christopher R. Dolanc, Marie E. Lynch, and Chad R. Johnson

Section 3. Watershed Protection and Restoration
Part 1. Monitoring and Restoration 225

The Role of BMPs in 303(d)-Listed Waters: A New Alternative to TMDLs 227
Bruce Sims and Chris Knopp

Best Management Practices (BMP) Implementation Monitoring: Keys to Success and Pitfalls to Avoid 232
Julianne Thompson and Jenny Fryxell

A Regional Protocol for Monitoring Best Management Practices Implementation and Effectiveness on Timber Harvest Operations 237
Karen Sykes, Dave Welsch, Roger Ryder, and Tim Post

Monitoring Exposed! WARM: A Database Tool to Share and Query Watershed Resources Monitoring Information 244
Sherry Hazelhurst and Ken Heffner

Aquatic Restoration Through Hydropower Licensing, Bond Falls Project, Michigan
Mark A. Fedora 255

TRTR Funds–Successes in Watershed Restoration in the Eastern Region
Bonnie Ilhardt and Kristine Smith 261

Contents Page

The Alkali Creek Story: 40 Years of Gully Control 271
Mark Weinhold

The Once and Future Streams: Re-creating Bailey and Karnowsky Creeks, Central Oregon Coast Range, USA 279
Johan Hogervorst and Barbara Ellis-Sugai

Contents, Volume 2

Part 2. Roads 289

Lessons Learned From Management Response to Flood-Damaged Roads in the Western Washington Cascades 291
James Doyle and Gary Ketcheson

Erosion and Channel Adjustments Following Forest Road Decommissioning, Six Rivers National Forest 297
Carolyn Cook and Adam Dresser

Roads in the River: Encroachment, Implications, and Solutions 310
Bill Shelmerdine

Road Decommissioning Effectiveness Monitoring Techniques 318
Carolyn Napper

Section 4. Valuing the Earth Sciences
Part 1. Soil 329

Ten-Year Results From the North American Long-Term Soil Productivity Study in the Western Gulf Coastal Plain 331
D. Andrew Scott, John Novosad, and Gala Goldsmith

Soil Compaction Study of 20 Timber-Harvest Units on the Ouachita National Forest 341
Kenneth R. Luckow and James M. Guldin

Monitoring to Improve the Understanding of Herbicide Fate and Transport in the Southern Sierra Nevada, California 352
Jerome V. DeGraff , Brent Roath, and Earle Franks

Part 2. Geology 361

Jökulhlaup in the Wind River Mountains, Shoshone National Forest, Wyoming 363
Liz Oswald and Ellen Wohl

Contents Page

Reclamation, Remediation, and Hydrologic Monitoring of the Minnie Mine and Mill Site, Okanogan County, Washington 368
Rodney T. Lentz

The Role of Geology in Sediment Supply and Bedload Transport Patterns in Coarse-Grained Streams 383
Sandra E. Ryan

A River Runs Underneath It: Geological Control of Spring and Channel Systems and Management Implications, Cascade Range, Oregon 391
Anne Jefferson, Gordon E. Grant, and Sarah L. Lewis

Hubbard Glacier, Russell Fiord, and Situk River: A Landscape in Motion 401
Robert Gubernick and Steven Paustian

Part 3. Air 419

Using the Critical Load Concept to Protect Ecosystems from Acidification 421
Deborah Ulinski Potter and Cindy Mitchell Huber

The Potential Effects of Acid Deposition: What's a National Forest To Do? 428
Stephanie J. Connolly, Thomas C. Cain, Jeremy S. Vestal, and Pamela J. Edwards

Methylmercury Contamination: Impacts to Aquatic Systems and Terrestrial Species, and Insights for Abatement 438
Charles E. Sams

Part 4. Water 449

A Short History of Watershed Management in the Forest Service: 1897 to 2100 451
Stephen P. Glasser

The Marginal Economic Value of Streamflow From National Forests: Evidence From Western Water Markets 458
Thomas C. Brown

An Army of Watershed Specialists: Good Working Relationships Encourage Everyone to Value Watersheds 467
Scott Tangenberg

Section 5. Partnership and Collaboration 473

Forest Sustainability Criteria and Indicators: A Common Language for the 20 States Served by the Northeastern Area 475
Constance A. Carpenter and Sherri Wormstead

Contents Page

Beyond Boundaries: Resource Stewardship in the Skagit River Basin–Communities and National Forests in Partnership 478
Greta Movassaghi and Mary A. Carr

Ecological Management Decision-Support Model of the Applegate River Basin 507
Mike Mathews

Klamath Adjudication–Lesssons Learned 513
Holly R. McLean

The Coastal Initiative–Innovative Partnerships to Restore Watersheds 516
Karen Bennett

The Pathfinder Project: A Collaborative Effort to Provide for Instream Flow Management 522
John M. Almy and Gary Shellhorn

Cooperative Forest Watershed Management in Maryland: Watershed Restoration Across Land Ownerships 537
Anne Hairston-Strang

II. Poster Abstracts 543

Excavator Subsoiling Applications: Integration of Subsoiling With Grapple Piling and Road Obliteration 545
J. Archuleta and M. Karr

Application of Water and Sediment Models in Hydropower Relicensing 545
Margaret Beilharz

Detecting Water Yield Increase in a Downstream Direction 546
Gregory S. Bevenger

Land Type Associations of Weber County, Utah 546
Jeff Bruggink, DeVon Nelson

Forest Practice Changes in Response to Soil Protection Guidelines on the Umatilla National Forest 546
Craig R. Busskohl

Low-Water Crossings and Channel Functions: What Works and What Doesn't 546
Kim Clarkin, Suzan Hixson, Gordon Keller, Terry Warhol

Hemlock Dam Removal–The Issues and the Story So Far 547
Bengt Coffin

Contents Page

Protecting and Restoring Riparian Area Structure and Function Along Forest Highways and Low-Volume Roads 547
James E. Doyle and Roy Jemison

Movement of Sediment Associated With Lowered Reservoir Levels in the Rio La Venta Arm of the Presa Netzahualcoyotl, Chiapas, Mexico 547
Juan de la Fuente, Bonnie Allison, Saul Bezares, Sue Hilton, Tom Lisle, Alisha Miller, Brenda Olson, Rebecca Quinones, Jose Velasquez

Turbidity Threshold Sampling in Watershed Research 548
Rand Eads, Elizabeth Keppeler, Jack Lewis

Monitoring of Stream Channel Cross Sections on the Chequamegon-Nicolet NF 548
Sara Eckardt and Dale Higgins

The 1997 Flood in Northern California: Applications to Refining Landslide Hazard Assessments in the Klamath Mountains, North-Central California 548
Don Elder, Juan de la Fuente, Polly Haessig

Monitoring in the Upper South Platte Watershed, Colorado: Before and After Wildfire 549
Deborah Entwistle, Lee MacDonald, Kevin Bayer, Ken Kanaan, Jennifer Hall

Improving Project-Level Soil Interpretations With Geospatial Technologies 549
Don Fallon, Eric Winthers, Haans Fisk

A Simplified Nitrogen Deposition Collector: A Tool for Evaluating Ecological Impacts 549
Mark E. Fenn

Fishxing 3.0: Software and Learning Systems for Fish Passage Through Culverts 550
Michael Furniss, Susan Firor, Antonio Llanos, Kathleen Moynan, Michel Love, Jeff Guntle, and Robert Gubernick

Managing Low-Water Crossings on Roads 550
Leslie S. Gonyer

Abandoned Mine Inventory, Assessment, and Restoration: Case Studies on the Klamath National Forest, California 550
Polly A Haessig, Edward K Rose, Don Elder, and William Snavely

Applying Hydrology to Forest Management–Examples Over a Career 550
William F. Hansen

Guidance for Intermountain Region Hydrology Specialist Reports–Field Review Notes, Technical Assessments, and NEPA Specialists Reports 551
Ronnie-Sue Helzner and Sherry Hazelhurst

Contents Page

The Rebirth of a Stream–the Enchanted Valley Stream Restoration Project 551
Johan B. Hogervorst and Barbara Ellis-Sugai

Mapping Air and Natural Gas Resources–the Management Value of Integrating Disparate Information 551
Melody R. Holm, Jeff Sorkin, and Janice Wilson

The Effectiveness of Aerial Hydromulch on the Cedar Fire in Controlling Water Movement and Erosion 552
Ken Hubbert, Pete Wohlgemuth, and Pete Robichaud

Energy Development in the Eastern United States and Air Pollution Impacts on Aquatic and Terrestrial Resources 552
Cindy Huber, Chuck Sams, and Andrea Stacy

Using BARC for Fire Disturbance Analysis 552
Kevin Hyde

Lichen Air Quality Biomonitoring Partnership on the Salmon-Challis National Forest 553
Gary L. Jackson and Larry St. Clair

Restoration of Bluewater Creek Riparian Rangeland Meadow in the Zuni Mountains of Western New Mexico 553
Roy Jemison

Relationships Between Hydrology, Exotic Plants, and Woody Fuel Loads in the Middle Rio Grande of New Mexico 553
Roy Jemison

Beyond Statistics: Landscape Controls That Mask Apparent Effects of Harvest Activities on Soil Saturation 554
Adelaide Johnson, Kellie Vache, and Rick Edwards

Modern Stromatolites and Benthic Phototrophs in Ultra-Oligotrophic Waldo Lake, Oregon 554
Al Johnson

Low-Volume Roads Engineering Best Management Practices Field Guide 554
Gordon Keller and James Sherar

Lessons Learned Between BAER Assessment and Implementation on 2003 Southern California Fires 555
Allen King

Modeling the Role of Evapotranspiration in the Unsteady State of the Groundwater Regime in Watershed-Scale Projects 555
Tom Koler

Contents Page

Influence of Prescribed Fire on Fish and Streamwater Mercury Concentrations 555
Randy Kolka, Jason Butcher, and Trent Wickman

Influence of the Intensity of Silviculture on Soil Carbon 555
Randy Kolka, Rachel Tarpley, Marty Jurgenson, and Brian Palik

Application of a LIDAR-Generated Digital Elevation Model to Active Landslide and Geomorphic Process Mapping and Interpretation. 556
Benjamin R. Kozlowicz and Mark E. Smith

Native Plants and Fertilization Help to Improve Sites and Stabilize Gullies on the Sumter National Forest 556
Dennis L. Law and William F. Hansen

Coordinated Interagency Response to the Aspen Fire 556
Robert E. Lefevre, Salek Shafiqullah

Ecological Classification, Organic Layer, and Large-Scale Prescribed Fire Monitoring on the Superior National Forest 556
Barb Leuelling and Jeff Tepp

Effects of Forest Management in the Caspar Creek Experimental Watersheds 557
Jack Lewis, Elizabeth Keppeler, and Tom Lisle,

Restoration of Cherry Creek–Lessons From a Southwestern Stream 557
Grant Loomis and Tom Moody

Characteristics of Peak Flow Return Intervals for Small-Drainage-Area Watersheds of the Southern Cascades of Eastern Oregon: Implications for Culvert Sizing 557
Walt Lucas

Effects of Pine-Bluestem Restoration on Soil Quality on the Ouachita National Forest and Implications for Improved Air Quality and Watershed Condition 558
Ken Luckow and Hal Leichty

How to Lighten Your NEPA Workload 558
Tom Mainwaring and Carl Leland

Quantifying Measurement Error for Accurate Testing of Channel Cross-Sectional Change 558
Daniel A. Marion

Ecosystem Mapping and Soil Survey in the Western Upper Peninsula of Michigan 558
Sarah E. Mase

Geomorphic and Hydrologic Effects of High-Elevation Summer Storm Events 559
Alisha Miller, Tuli Tannaci, Juan de la Fuente, Abel Jasso, and Steve Bachmann

Contents Page

A Comparison of Northern California Sediment TMDLs 559
Alisha Miller and Juan de la Fuente

Stream Restoration at Road Crossings in Wisconsin 559
Jim Mineau and Dale Higgins

The 1997 Flooding in Two Northern California Klamath National Forest Streams: Geomorphic Effectiveness and Sediment and Large-Wood Budgets 560
Zackary J. Mondry

Drought, Storms, and Streamflow and Stream Temperature Monitoring on the Coconino and Prescott National Forests, Northern Arizona 560
Zackary Mondry

Evaluation of Habitat Variability, Channel Changes, and the Effectiveness of Restoration Projects in an Eastern Washington Stream 561
Mark Muir, Susan Bolton, Robert Wissmar, and Pete Bisson

Tools to Evaluate the Effect of ATVs on Soil Physical Properties 561
Carolyn Napper

Impacts of an Historical Wildfire on Hydrologic Processes: A Case Study in Arizona 561
Dan Neary

Regulatory Tools for Watershed Management 561
Karen Nelson

Spatial Data Analysis of Soils Within the Kisatchie National Forest Using Geographical Information Systems 562
John C. Novosad, Wayne H. Hudnall, and Jacqueline A. Prudente

Streamflow Analysis of the Little Popo Agie River Near Lander, Wyoming 562
Liz Oswald, Greg Bevenger, and Laurie Porth

Ground-Penetrating Radar and Seismic Refraction as Tools for Characterizing Aquifer Properties in Recently Active Glacial Moraine Settings, Tongass National Forest, Alaska 562
Noel S. Philip, Steven D. Sheriff, and Robert A. Gubernick

The Stream Systems Technology Center 562
John Potyondy

Monitoring Soil Erosion Following Wildfires in North-Central Washington State 563
Kenneth J. Radek

Climate Variability and Change in the Southern Appalachians 563
Mark S. Riedel

Contents Page

Estimating Impacts of Cattle Grazing on Stream Sediment Budgets 563
Mark S. Riedel, Kenneth N. Brooks, and Elon S. Verry

Gradient Analysis of Soil, Vegetation, and Climate on the Tonto National Forest 564
George T. Robertson and W.H. Moir

Rehabilitation of the Left Hand Canyon Dispersed Recreation Area 564
Theresa Stevens Savery

Long-Term Soil Productivity of Western Gulf Coast Loblolly Pine Stands 564
D. Andrew Scott, John Novosad, and Rodney Peters

The Dosewallips Washout: A Reach Analysis Case Study to Evaluate Road Management Solutions and Consistency With the Aquatic Conservation Strategy 565
Bill Shelmerdine and Dan Cenderelli

The Olympic National Forest Road Management Strategy–Aquatic Risk Assesment 565
Bill Shelmerdine, Robert Metzger, Scott Hagerty, and Robin Stoddard

Keeping Water on the Land Longer 565
Janice Staats

Forests on the Edge: Projecting Housing Development on Private Forests Across America's Watersheds 566
Susan Stein, Mark D. Nelson, Dave Theobald, Ronald E. McRoberts, and Mike Eley

Automated Water Quality Monitoring in the Clackamas River Watershed, Mount Hood National Forest 566
Ivars Steinblums

Soil Moisture Monitoring at SNOTEL Climate Stations on National Forest Lands in Oregon and Washington 566
Sheila Strachan

An Application of the Hillslope Erosion Model (HEM) to Determine Erosion Predictions and Interpretations for Terrestrial Ecosystem Survey (TES) 566
Steven Strenger, Steve Sebring, and Wayne A. Robbie

A Comparison and Evaluation of Stream Substrate Embeddedness Techniques 567
Traci L. Sylte

Dunham Creek Rehabilitation: Early-Day Riparian Harvest Gone Bad–the Consequences, the Remedy, and Highlight for Riparian Health Management First and Foremost 567
Traci L. Sylte

Contents Page

Analysis of Relationships of Stream Shading vs. Vegetation Density and Spectral Radiance 567
Bárbara Gutiérrez-Teira, Charles H. Luce, and David Nagel

Sediment Transport and Production From Two Small Watersheds in Central Idaho 568
Robert Thomas, John King, Robert Kenworthy, and Nick Gerhardt

Integrated Forest Plan Monitoring Program: Tongass National Forest Riparian and Aquatic Synthesis 568
Julianne Thompson and Emil Tucker

Real-Time Smoke Monitoring–Current Instrument Evaluation and Telemetry Systems 568
Andy Trent

Effects of Prescribed Fire on Mercury Concentrations in Water and Fish in the Larch Lake Watershed, Superior National Forest, Minnesota 569
Trent R. Wickman

State Water Quality Exceedence: Fecal Coliform and *E. coli* 569
Kirk Wolff

Development of ELTP Layer for the Hoosier National Forest, Southern Indiana 569
Andrey V. Zhalnin, George R. Parker, and Patrick C. Merchant

III. Author Index 571

IV. Conference Organizers and Producers 573

V. Manuscript Reviewers 575

VI. Contents of Multimedia CD-ROM 577

About the Advancing the Fundamental Sciences Portable Electronic Presentation CD

The CD in the inside back cover is an interactive learning resource that presents many of the conference plenary talks and two of the workshops in an electronic format. The format provides for interactive access: you may watch them start to finish, or just the parts that most interest you.

A help screen is available from the home page to assist you with navigating the presentations.

The CD runs on both Windows and Macintosh-compatible machines. This CD content can also be found online at *http://www.stream.fs.fed.us/afsc*

See page 577 for a preview of the introductory screen.

1. Concurrent Session Papers

Section 1. Applied Science and Technology

Part 1. Fire and Smoke

Overleaf:
The view northwestward across Lake Pend Oreille towards Blacktail and Grouse Mountains on the Idaho Panhandle National Forests, northern Idaho, summer 2004. Photo by Preston Hiatt.

Erosion Risk Management Tool (ERMiT)–A Probability-Based Erosion Prediction Model

Peter R. Robichaud
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After wildfires, land managers must assess the potential for increased flooding, erosion, and sedimentation, and the increased threat these effects may pose to people, structures, and valued resources. A Web-based Erosion Risk Management Tool (ERMiT) has been developed to predict surface erosion from postfire hillslopes, and to evaluate the potential effectiveness of various erosion mitigation practices. The model uses a probabilistic approach that incorporates temporal and spatial variability in weather, soil properties, and burn severity for forests, rangeland, and chaparral hillslopes. Using multiple runs of the Water Erosion Prediction Project (WEPP) model, ERMiT provides event-based erosion rate probabilities-with and without treatments-for five post-fire years.

Keywords: *post-fire modeling, erosion prediction, resource management, erosion control, BAER treatments, straw mulch, contour-felled logs, seeding*

Post-fire rehabilitation efforts continue to be a major land management activity due to the increase in the number, size, and intensity of wildfires in the western United States during the past decade. The threat of future wildfire damage to resources and property is creating a demand for effective erosion mitigation strategies as well as improved modeling tools on which to base treatment decisions. Post-fire rehabilitation treatments cannot prevent erosion, but they can reduce overland flow amounts, site soil loss, and sedimentation for some rainfall events. Thus the risk of postfire damage to water quality, habitat, roads, and other structures cannot be eliminated, but it can be reduced. It is useful to do risk assessments-balancing the increased risk of erosion, flooding, and other hazards against the risk reduction expected from specific treatments-when making postfire treatment decisions. The Erosion Risk Management Tool (ERMiT) (Robichaud et al. 2006, 2007; Robichaud et al. [in press]) has been developed to provide a risk assessment (i.e., probability-based) approach to post-disturbance erosion modeling and rehabilitation treatment effectiveness.

ERMiT provides probabilistic estimates of single-storm postfire hillslope erosion by incorporating variability in rainfall characteristics, soil burn severity, and soil characteristics into each prediction. ERMiT uses WEPP technology as the runoff and erosion calculation engine. WEPP simulates both inter-rill and rill erosion processes and incorporates the processes of evapo-transpiration, infiltration, runoff, soil detachment, sediment transport, and sediment deposition to predict runoff and erosion at the hillslope scale (Flanagan and Livingston 1995). Through the ERMiT interface, stochastic weather files generated by CLImate GENerator (CLIGEN) (Nicks et al. 1995) are selected for use in WEPP. Users may customize climate parameter files using the integrated Rock:Clime web interface (Scheele et al. 2001).

ERMiT users specify: 1. climate parameters based on location with adjustments made through Rock:Clime (Elliot 2004); 2. vegetation type – forest, range, chaparral; 3. soil type – clay loam, silt loam, sandy loam, loam-and rock content; 4. topography – slope length and gradient; and 5. soil burn severity class – low, moderate, high. These input choices are similar to other WEPP-based interfaces (Elliot 2004) (Figure 1). However, the incorporation of variability in these parameters and the probability-based output are unique to ERMiT.

The general process by which ERMiT incorporates parameter variability is to: 1) determine the range of possible parameter values; 2) select representative values from the range; and 3) assign an "occurrence probability" to each selected value such that the sum of assigned occurrence probabilities adds to 100 percent. Thus, all possible parameter values are represented in the model by the four to five selected values. The specific processes are:

Climate variability: Using a 100-year climate record generated by CLIGEN, WEPP is run for 100 years and the rain events with the greatest runoff from each year are rank ordered by runoff amount. The years and rain events with the 5th, 10th, 20th, 50th, and 75th ranked runoff amounts are selected for further analysis (Figure 2). Occurrence probabilities for the five rain events associated with the selected runoff events are 7.5, 7.5, 20, 27.5, and 37.5 percent, respectively.

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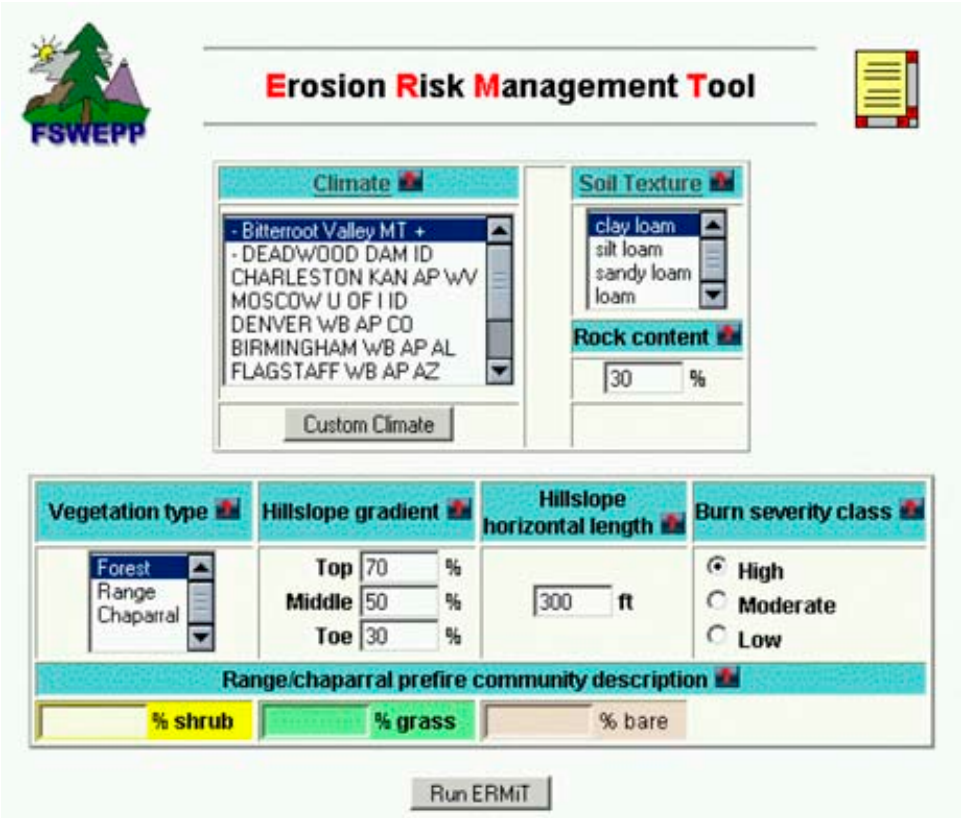

Figure 1. Example Erosion Risk Management Tool (ERMiT) user input screen accessed at http://forest.moscowfsl.wsu.edu/fswepp/.

Soil parameter variability: The variable effects of postfire ground cover, soil water repellency, and soil erodibility are modeled by variability in inter-rill erodibility, rill erodibility, effective hydraulic conductivity, and critical shear. Selected values, which vary by soil texture and soil burn severity, are grouped in five soil parameter sets from least erodible to most erodible. Thus, there are ten soil parameter sets for each soil texture-five for high soil burn severity and five for low soil burn severity. The five soil parameter sets (Soil 1, Soil 2, Soil 3, Soil 4, and Soil 5) are assigned occurrence probabilities of 10, 20, 40, 20, and 10 percent, respectively.

Soil burn severity spatial variability: WEPP models each hillslope in three sections, and in ERMiT each hillslope section can be either High or Low. Based on the user-designated soil burn severity input (high, moderate, or low), four spatial arrangements of High (H) and Low (L) sections, each with an assigned occurrence probability, are used. For example, a user designation of high soil burn severity will use four spatial arrangements of H and L for the three sections of hillslope (HHH, LHH, HLH, and HHL), which are assigned occurrence probabilities of 10, 30, 30, and 30 percent respectively.

Temporal variability: The changes in soil parameter values over time, due to recovery, are modeled by increasing the assigned occurrence probabilities of the lower erosion soil parameter sets and decreasing the occurrence probabilities of the higher erosion soil parameter sets. Also, the four spatial arrangements of hillslope sections are adjusted to include fewer high soil burn severity soil sets and more low soil burn severity soil sets with each year of recovery.

Through ERMiT, WEPP is run for each permutation of input parameters. Thus, every combination of the five selected rainfall events, five soil parameter sets, and four soil burn severity spatial arrangements is run to produce 100 event sediment delivery predictions. For each permutation, the product of the three component occurrence probabilities is the occurrence probability attached to the sediment delivery prediction. The probable erosion prediction output can be viewed in graphical (Figure 3) or tabular (Figure 4) form, with output data available for import into spreadsheets.

The interactive box in the tabular output screen allows users to delineate the level of risk (probability of exceedence) for potential erosion and then compare the relative effectiveness of various treatments to non-treatment as well as to one another (Figure 4).

ERMiT can also provide probabilistic estimates of the erosion reduction to be expected for three treatments-seeding, straw mulching, and contour-felled log or straw wattle erosion barriers. Data from rain simulation, sediment fence, and paired catchment studies are being used to calibrate the erosion reduction and sediment trapping

Figure 2. Example ERMiT climate output screens. (a) Generated precipitation and runoff information for input parameters. (b) Selected rainfall events used for the ERMiT erosion predictions.

a

Erosion Risk Management Tool

Bitterroot Valley MT +

Modified by RockClime on January 10, 2003 from STEVENSVILLE MT 247894 0

T MAX 20.7 1 27 .48 36.30 47 .41 56.81 63.12 72.63 71.19 59.76 47 .01 31.26 22.44 deg F

T MIN 4.64 9.19 14 .45 20.59 27 .27 33.85 36.59 35.13 28.06 20.44 13.08 6.94 deg F

MEAN P 4.58 3.54 3.75 2.86 3.54 2.87 1.26 1.91 1.80 2.00 3.03 3.67 in

WET 9.34 7.09 7 .36 7 .33 8.86 9.58 5.71 5.96 6.43 6.44 8.18 8.7 4

clay loam soil texture, **30%** rock fragment

70% top, 50% average, 30% toe hillslope gradient

300 ft hillslope horizontal length

high fire severity on **forest**

100 - YEAR MEAN ANNUAL AVERAGES

35	**in**	annual precipitation from	9182	storms
2.2	**in**	annual runoff from rainfall from	1242	events
4.2	**in**	annual runoff from snowmelt or winter rainstorm from	1812	events

b

Ranking of event (return interval)	Storm Runoff (in)	Storm Precipitation (in)	Storm Duration (h)	tp (fraction)	ip (ratio)	10-min peak intensity (in h^{-1})	30-min peak intensity (in h^{-1})	Storm date
1	2.50	0.29	2.06	0.07	8.77	0.89	0.51	April 5 year 46
5 (20-year)	1.81	1.26	7.05	0.03	29.96	3.84	2.22	March 27 year 44
10 (10-year)	1.38	0.00	0.00	0.01	0.00	N/A	N/A	April 5 year 42
20 (5-year)	1.13	1.37	1.98	0.07	3.55	2.14	1.65	June 21 year 4
50 (2-year)	0.81	1.06	1.91	0.03	1.01	0.56	0.56	October 18 year 43

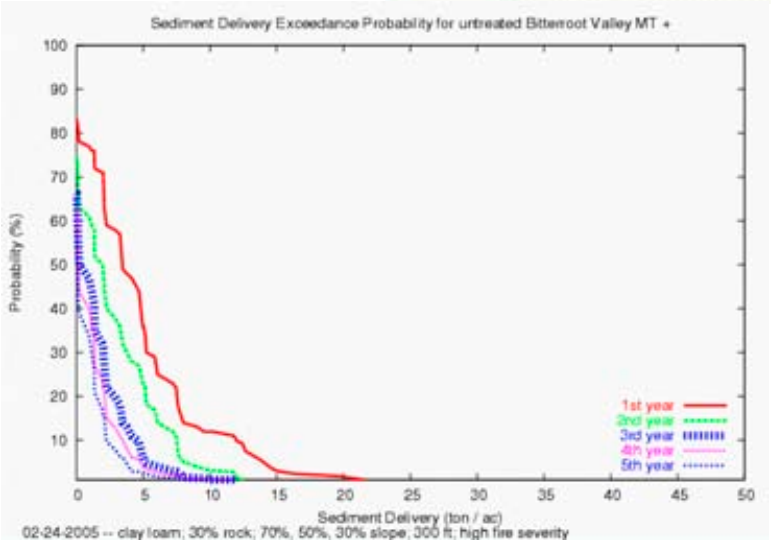

Figure 3. Example ERMiT graphical output for sediment delivery exceedence probability for five postfire years in the area being modeled.

Target chance event sediment delivery will be exceeded 10 % go	Event sediment delivery (ton ac^{-1})				
	Year following fire				
	1st year	2nd year	3rd year	4th year	5th year
Untreated	11.98	7.51	4.51	3.45	2.25
Seeding	11.98	4.51	3.45	2.25	2.25
Mulch rate 0.2 ton ac^{-1}	5.9	4.93	4.51	3.45	2.25
Mulch rate 0.4 ton ac^{-1}	3.27	3.78	4.51	3.45	2.25
Mulch rate 0.7 ton ac^{-1}	2.24	3.66	4.51	3.45	2.25
Mulch rate 0.9 ton ac^{-1}	1.7	3.27	4.51	3.45	2.25
Logs & Wattles go Dia. 1 Sp. 10	xxx	xxx	xxx	xxx	xxx

Figure 4. Example ERMiT tabular output with predicted sediment delivery (ton ac^{-1}) for untreated, as well as seed, mulch (four rates provided), and erosion barrier (barrier specifications are determined by the user) treated hillslopes. Predictions for five postfire years are included.

efficiency (sediment stored by a contour-felled log divided by the sediment leaving the hillslope) of these treatments. Based on these data, straw mulch lowers predicted first-year erosion rates due to increased ground cover, more than the other treatments. Predicted erosion rates for erosion barriers vary by rainfall intensity (less erosion reduction occurs with high-intensity rainfall events) as well as estimated sediment storage capacity already filled.

Validation of ERMiT predictions by various users is ongoing. New data from treatment effectiveness studies and postfire erosion measurements will expand and refine the number of postfire rehabilitation treatments that can be modeled in ERMiT. Land managers who have used the model find the probability-based erosion predictions particularly useful when applied to risk-based management decisions, such as where to apply postfire rehabilitation treatments to get the most benefit for the cost.

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Hillslope Erosion Rates in Areas With Volcanic Parent Materials and the Effects of Prescribed Fires in the Blue Mountains of Eastern Oregon and Washington, USA

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Prescribed fire is often proposed as a treatment for restoring forest health and reducing long-term risk of wildfires. It is generally assumed that wildfires and wildfire-related erosion pose greater threats to water quality and fish habitat than prescribed fires. However, limited empirical data are available for quantifying background erosion rates and the influence of prescribed fire on those rates. This study in the Blue Mountains of northeastern Oregon and southeastern Washington was designed to quantify background erosion rates and to examine the effects of prescribed fire on hillslope erosion and stream sedimentation. Two study areas were selected on the Umatilla National Forest. The first was a paired-watershed study at Skookum Creek in Oregon where stream discharge and sediment yield have been recorded continuously since the watersheds were gaged in 1992. Measurements within the watersheds were augmented with hillslope erosion plots in 2002. Hillslope erosion plots were also established in 2002 in the Red Fir prescribed burn project in Washington. Preliminary results from the Skookum paired-watershed study showed large differences between hillslope erosion rates measured from plots and watershed sediment yields, suggesting that episodic processes dominated sediment production and transport and therefore controlled watershed-scale sediment budgets. Preliminary analyses of all hillslope erosion data combined indicated that erosion rates were significantly related to aspect and amount of bare ground, but were not influenced by prescribed fire.

Keywords: *fuel treatment, prescribed fire, sediment yield, silt fence, streamflow, surface erosion, water quality*

Introduction

Changes in forest composition and the mortality of forests in the interior West over the last century are often characterized as forest health problems (Everett et al. 1994; Hessburg et al. 1994; Quigley and Arbelbide 1997). Forest health has been targeted by recent legislation, administrative procedures, and management strategies with the aim of reducing long-term risks to forests from wildfire, drought, insects and disease (USDA FS and USDI 2001; USDA FS 2002, 2003). These management strategies emphasize using prescribed fire and other fuel reduction techniques to reduce wildfire risk, and are often motivated by concerns for protecting water supplies and species listed as threatened or endangered. Implied in the widespread use of prescribed fire as a management tool to reduce the risk of stand-replacing wildfires is the assumption that the direct effects of wildfires, as well as wildfire-related erosion and sedimentation of streams, are greater threats to water quality and fish habitat than are the effects of fuels treatments.

Most previous watershed studies of the impact of fire were focused on the effects of stand-replacing wildfires, salvage logging after fire, or prescribed fire associated with timber harvesting and slash control (McIver and Starr 2000). Despite the existing body of literature that describes the effects of fire and other land-management activities on erosion, sediment, and water quality, there remain significant knowledge gaps specific to effects of prescribed fire and fuels treatments. Few published studies have been conducted in areas with volcanic parent materials or volcanic-ash-derived soils – the soil types most common in central and eastern Oregon and southeastern Washington. Data are lacking on hillslope transport and redistribution of eroded sediment and the delivery of sediment to streams. At the local level, limited data are available to validate planning and assessment tools currently being used. Consequently, analyses rely on results from studies

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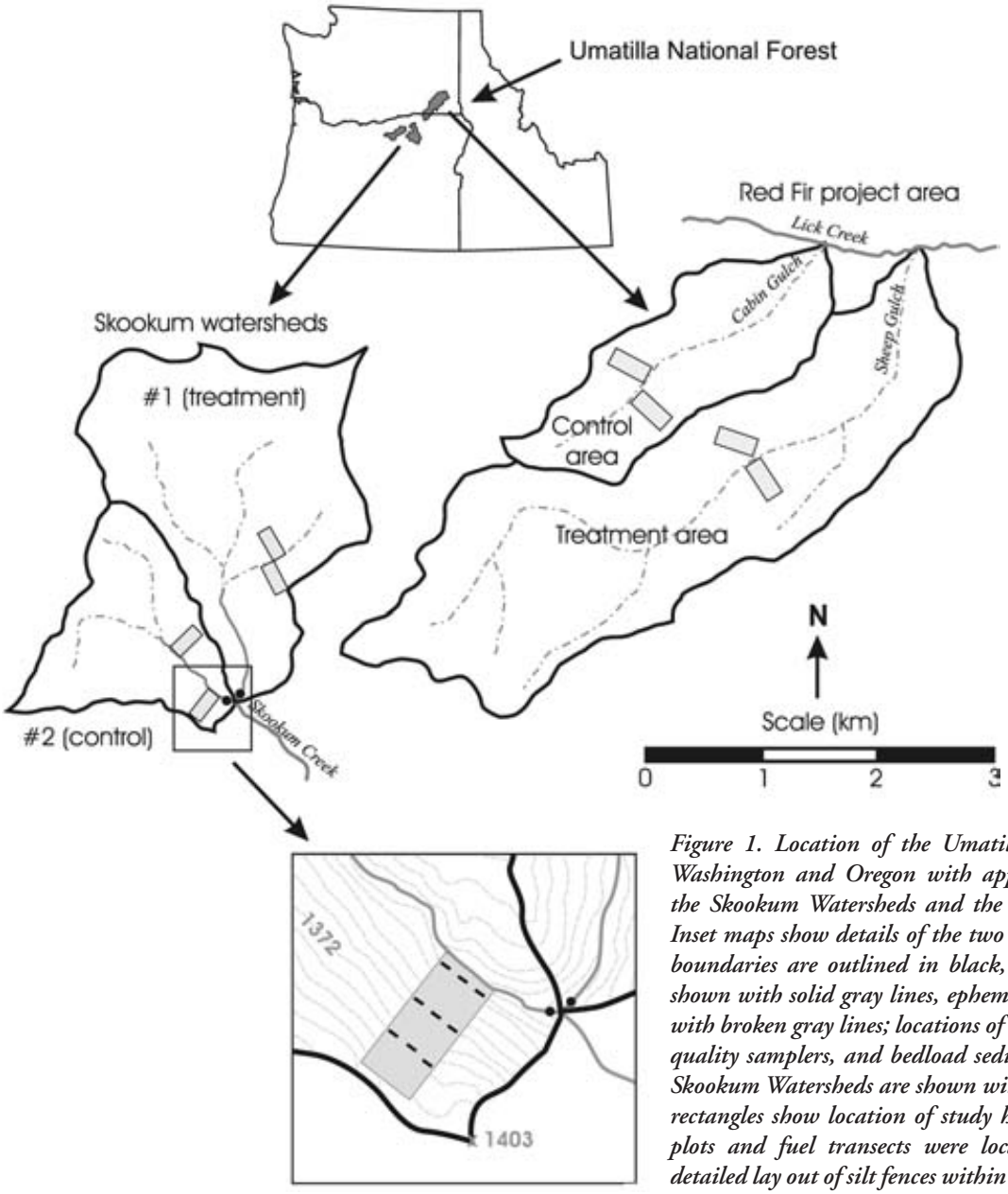

Figure 1. Location of the Umatilla National Forest in Washington and Oregon with approximate locations of the Skookum Watersheds and the Red Fir project areas. Inset maps show details of the two study areas: watershed boundaries are outlined in black, perennial streams are shown with solid gray lines, ephemeral streams are shown with broken gray lines; locations of the gaging weirs, water quality samplers, and bedload sediment boxes within the Skookum Watersheds are shown with filled circles. Shaded rectangles show location of study hillslopes where erosion plots and fuel transects were located. Inset box shows detailed lay out of silt fences within a single study hillslope, dashed lines are topographic contours (contour interval 12 m), dark lines within the study plot denote locations of silt fences. There are three fences each, at upper-, mid-, and toe-slope positions.

conducted in other regions, and from studies of wildfire, logging, and road building practices. Empirically derived data are needed to support revision of National Forest management plans and to plan fuels reduction treatments, particularly in the wildland-urban interface and in watersheds with Endangered Species Act-listed salmon.

This study is designed to collect data on background erosion rates and to examine the effects of prescribed fire on hillslope soil erosion and stream sedimentation. We report 11 years of background discharge and sediment yield data, and two years of background hillslope erosion data, from the Skookum paired-watershed study. We also present preliminary results from two years of post-treatment data from the Red Fir prescribed burn project.

Study Area

The project areas are located in the northern Blue Mountains of the interior Columbia River basin in a region characterized by uplifted, dissected volcanic plateaus. The Skookum paired watersheds are located in the John Day River basin in northeast Oregon. The Red Fir prescribed

Table 1. Skookum, Red Fir, and Lick Creek study area descriptions.

	Skookum Project	Red Fir Project	Lick Creek Project
Area (km²)	8	6.8	6.3
Elevation range (m)	1,220 - 1,730	915 - 1,370	1,250 - 1,555
Average precipitation (cm)	56	38	89
Aspect	north and south	north and south	north
Treatment date	Deferred	October 2002	October 2004

burn project is located on a tributary of the Asotin River in the Lower Snake River basin in southeast Washington (Figure 1, Table 1). Forest conditions are similar at both project areas. Dry south- and west-facing slopes are characterized by open stands of ponderosa pine (*Pinus ponderosa*) and Douglas-fir (*Pseudotsuga menziesii*). Hillslope hollows with deeper soils typically have mixed dominance, with abundant western larch (*Larix occidentalis*) and lodgepole pine (*Pinus contorta*). Ridge-tops, north, and east slopes have denser, mixed stands of larch, lodgepole pine, and grand fir (*Abies grandis*). Historically, fire regimes were mixed, with areas of low, moderate, and high-severity fires (Arno 2000), but none of the project areas have experienced a stand-replacing fire in recent times. Fuel loadings on dry south-facing slopes appear to have changed little from historical conditions. In contrast, fuel loadings have changed dramatically in wetter and cooler sites where fire exclusion led to increased density of shade tolerant conifers (Franklin and Agee 2003). In the Skookum watershed, ridge tops and north-facing slopes that previously supported dense stands suffered high mortality in the most recent (1990) spruce budworm (*Choristoneura* spp.) outbreak. Since then, many dead trees have fallen, and loadings of downed woody fuels have reached 224 tonnes/ha in some areas. Grasses and forbs now grow densely within stands of dead timber, especially on north-facing slopes, and a variety of coniferous species are establishing in these areas.

The Skookum project area, about 8 km² in size, is located in the headwaters of Skookum Creek (lat 45°5'N, long 119°28'W), a tributary to the North Fork John Day River near the town of Monument, Oregon (Figure 1). Elevations in the project area range from 1220 to 1730 meters. The watershed is within a designated roadless area and is relatively unaffected by past timber management. Two adjacent tributaries (control and planned treatment) were instrumented for a paired catchment study in 1992. The watersheds were fenced to exclude domestic livestock at that time. The larger watershed, Skookum #1 (5 km²) was designated as the planned treatment watershed and the smaller watershed, Skookum #2 (3 km²) was designated as the control. In 2002, monitoring in both watersheds was expanded with the installation of erosion plots to measure rates of hillslope erosion, down slope transport, and delivery of sediment to stream channels. A 1998 prescribed burn plan called for controlled burning in the treatment watershed and adjoining areas, leaving the control watershed untreated. By spring of 2004, planned treatments had not been implemented in large part because of weather and fuel conditions, and the existing plan was deemed out of date.

The Red Fir prescribed burn project is located in southeast Washington in tributaries to the North Fork Asotin River (lat 46°15'N, long 117°25'W) in the lower Snake River drainage, near the town of Pomeroy, Washington (Figure 1). Elevations range from 915 to 1555 meters. Treatment hillslopes include both south and north-facing slopes. Control plots were established on hillslopes with similar aspects in an adjacent drainage approximately 1 km away. These control hillslopes had been treated with prescribed fire in 1999 but the effects of this earlier prescribed burn are unlikely to influence erosion rates measured in this study because ground cover vegetation appeared to have recovered completely by 2002. The Red Fir project, implemented in 2002, was a Forest Service district prescribed burn designed to reduce fuel loading.

Methods

The study was designed to take advantage of the existing Skookum paired-watershed study and fuels reductions treatments already planned by the USFS. The Skookum watersheds, with 11 years of pre-treatment data, provided a rare opportunity to examine erosion budgets at multiple scales and within the context of longer-term water and sediment yield. Thus we augmented existing measurements with silt-fence erosion plots to measure hillsope erosion rates within both of the Skookum watersheds. We recognized the possibility that the watersheds would not be treated as planned due to their large size, lack of roads, heavy fuel accumulations, and the fact that they are contiguous with a large roadless area. The risks and consequences of an escaped prescribed fire would be substantial. Therefore we considered other planned

prescribed fire projects within the Blue Mountains. The Red Fir prescribed burn project, which had a high probability of taking place as planned, had relatively easy access, and contained planar hillslopes with nearby controls, was selected to measure hillslope erosion and down-slope transport of sediment. This site was not located within gaged, experimental watersheds and therefore lacks the long period of pre-treatment monitoring available at the Skookum watersheds. Also, because of the timing of the treatments, no pre-treatment data could be collected and analyses focus on comparison between treatment and control sites only, without reference to background conditions.

Hillslope Erosion Plots

Variable-area erosion plots were used to measure hillslope erosion rate in both project areas. In the Skookum project area, plots were established at both the control and proposed treatment watersheds in July 2002. At the Red Fir site, erosion plots were established in the control in July 2002, and one week after the sites were burned in October 2002. Erosion plots on the treated hillslopes at the Red Fir site were located and staked with steel fence posts at the time that the control plots were established to avoid unintentionally biasing plot placement to sample areas of greater (or lesser) burn intensity.

Sediment fences were located on planar hillslopes (neither concave nor convex across the contour) so that calculated erosion rates would not be confounded by convergent or divergent patterns of overland flow. Fences were laid out in transects consisting of three replicates, spaced 30 m apart, with transects located at upper-, mid-, and toe-slope positions along the length of the hillslope. Sediment fences were designed following the methods described by Robichaud and Brown (2002), and were made from black silt-fence fabric supported with light-weight metal fence posts (Figure 2). Each fence is 5 m wide and oriented perpendicular to the hillslope (or parallel to the contour). Two features of our design differ from the design described by Robichaud and Brown (2002). First, we used 1.83-m-wide fabric, using the excess width to form a contiguous apron, covering the soil surface and extending 0.5 to 0.8 m upslope of the actual sediment fence, to allow collection of small amounts of sediment without accidentally collecting any of the underlying soil. Secondly, all plots are "unbounded" so the contributing area of each plot is defined by a variable area of hillslope that contributes runoff, surface erosion and dry ravel over the period of measurement. We used unbounded plots because they provided an estimate of cumulative erosion rates along the length of the hillslope so that differences between transects can be used to calculate net erosion and deposition rates along the length of the hillslope. If net downslope transport of eroded sediment occurred, it should be evident in a downslope increase in the amount of sediment collected. The amount of sediment collected in the toe-slope transects, alone, measured the gross delivery of sediment to the valley floor.

Sediment in the fences was collected in late spring (after snowmelt) and again in the fall. Additional collections were planned following all intense summer rainstorms that generated significant overland flow; however, such storms have not occurred in the study areas to date. To collect the accumulated sediment, all large branches, sticks and cones were first removed and discarded. Large accumulations of dirt were collected with a trowel, and the fence apron was then swept with a whisk-broom and fine sediment was collected with a dust pan. Collected materials were labeled, bagged, and transported to the laboratory. In the laboratory, larger organic debris was separated by hand and discarded. The remaining sample was sieved into size-fractions, oven dried (96 hr at 55°C), and weighed. The oven-dried samples were combusted in a muffle furnace (10 hr at 600°C) to burn off residual organic matter and

Figure 2. Example of a sediment fence. The fence is 5 meters wide, 0.5 m tall, with a 0.8 m long apron. The upslope edge of the apron is buried in a shallow trench. See Robichaud and Brown (2002) for installation details.

then re-weighed. The weight of the remaining sample was corrected for the residual mineral content from the combusted organic materials, assuming that the mineral content of organic matter averaged 5.05 percent (Wondzell, unpublished data).

A variety of additional measurements were collected to characterize conditions at each erosion plot. These measurements were taken in a plot measuring 10 m wide, starting at the sediment fence and extending upslope for 10 m. Slope and aspect of the plot were recorded. Duff thickness was measured at 0.5-m intervals along the length of the upslope, vertical face of the 0.1-m-wide trench into which the upslope end of the silt-fence material was buried. Visual estimates of the percent cover of ash, charcoal, bare ground, gravel, rock, duff, wood, and vegetation were made. These estimates focused on the ground surface exposed to direct raindrop impact so that the sum cannot exceed 100%. Further visual estimates of vegetation cover were made to break total canopy cover into the following growth forms: grasses, forbs, sub-shrubs, shrubs, and trees. These measurements were collected from both control and treatment plots during the summer prior to the prescribed burn, directly after the burn, and every summer after treatment. Photographs of the plots were taken from the plot perimeters: from the mid-point of the silt fence and from the mid-points of the upper and side boundary lines of each plot (Figure 3 and 4). Fuel load transects were established at each hillslope in the Skookum project area. Four, 15.24-m fuel load transects were spaced across each hillslope position, alternating with the silt fences, for a total of 12 fuel load transects per hillslope. Data were collected following methods described by Brown (1974).

Paired, Small-Watershed Study

The Skookum Experimental Watershed Study was established 1992. Measurements collected within the Skookum study area include stream discharge, suspended sediment, annual bedload sediment yields, water and air temperatures, and precipitation. Annual summaries of total yields are made on a water-year basis – from 1 October through 30 September of the following year. The control and treatment watersheds are instrumented with 120 degree V-notch weirs. Stream stage is measured at the gaging stations by float sensors in stilling wells. From 1992 to 2001, stage was recorded on punch tapes at 15-minute intervals using a Fisher-Porter[1] analog to digital recorder. Stage data were converted to discharge using the program HYDRA and the rating equation for a 120-degree V-notch weir (Rantz et al. 1982). In 2001, the Fisher-Porters were upgraded to Design Analysis H-510 digital recorders.

Figure 3. Red Fir project area, Sheep Gulch South, plot #3, a south-facing plot in an upper slope position. The photograph was taken looking across the erosion plot on 14 August 2002, before the prescribed fire.

Figure 4. Red Fir project area, Sheep Gulch south, plot #3 photographed on 28 October 2002, immediately after the prescribed fire from almost the same location as Figure 3. Much of the large log visible in the foreground of Figure 3 was consumed by the fire. Loss of some shrub cover exposed logs not visible in Figure 3.

Stream water samples were collected using battery-operated pumping samplers with intakes positioned in the deepest part of the channel, approximately 15 cm above the streambed. Samplers were programmed to collect a daily composite sample consisting of four samples drawn at six hour intervals (midnight, 6:00 AM, noon, 6:00 PM). The samples were analyzed for total suspended solids at the Umatilla National Forest water laboratory in Pendleton, Oregon.

Bedload was collected using in-channel bedload boxes, measuring approximately 1.5 m long, 0.7 m wide, and

[1]The use of trade or firm names in this publication is for reader information and does not imply endorsement by the U.S. Department of Agriculture of any product or service.

0.7 m deep, with plywood sides and bottom, set into the stream channel with the upstream lip set flush with the streambed. The bedload boxes spanned the full width of the active stream channel. Boxes were emptied once a year by diverting the stream, draining the box, and shoveling the collected sediment into a bucket. The total volume of collected sediment was measured in "buckets" and later converted to a dry weight. In both 2002 and 2004 a sub-sample of the bedload sediment was collected from Skookum #1; only small amounts of sediment had accumulated in the bedload box of Skookum #2 in these years so the entire amount was collected. Wet volumes of the collected sediment were measured in a graduated beaker and then oven dried at 55°C until successive weighings had stabilized, indicating that all water was evaporated from the sample. Samples were sieved into particle-size fractions and weighed. In all cases, samples contained large but variable amounts of water, which had a substantial effect on estimated conversion factors from wet volume to dry weight (mean = 0.55 kg dry sediment per liter wet bedload sample; SD = 0.25). We combined data from both watersheds, weighted by the wet volume of each sample, to estimate a conversion factor, 0.60 kg dry sediment per liter wet bedload sample, that most closely approximated the volumes measured as the bedload traps were emptied.

Water and air temperatures were recorded at hourly intervals using an Onset HOBO[1] temperature logger. From 1992 to 2003, precipitation was measured using a Fisher-Porter punch tape weighing precipitation gage equipped with an antifreeze and methanol reservoir to capture snow precipitation. Measurements were logged at 15-minute intervals. In 2003, a tipping bucket raingauge equipped with a snow conversion kit was installed to replace the Fisher-Porter raingauge.

Data Analysis

A hierarchically nested sampling design was used to study erosion across scales, from the plot scale up to the whole watershed scale. Individual plots provided point estimates of erosion rates, differences between transects in different hillslope positions traced the transport and redistribution of sediment along hillslopes, the toe-slope transect of sediment fences measured the amount of sediment delivered to valley floors. At the Skookum Watersheds, the automated water samplers and bedload boxes quantified the amount of sediment leaving the watershed.

Hillslope Erosion Plots: Erosion rates among blocks of erosion plots were examined for significant differences ($\alpha = 0.05$) using analysis of variance (ANOVA). Data were first natural-log transformed because raw erosion data were highly skewed (many small values and few large values). Because this project is in progress, analyses of the sediment collections completed to date are complicated by an unbalanced number of sampling periods – with three sample collections completed (spring 2003, fall 2003, and spring 2004). Preliminary analyses showed that erosion rates were not significantly different between season (spring 2003, fall 2003) or year (spring 2003, spring 2004), consequently, the amounts of sediment collected from each plot were summed across all measurement dates and divided by the 1.66 years for which the sediment fences have been in place, thereby converting mass of sediment collected to an annual erosion rate. Separate analyses were conducted for each project area. The Skookum project has not been treated, but allows investigation of background erosion rates and the influence of aspect and slope position on these rates. The Red Fir project was treated with prescribed fire and thereby allows investigation of prescribed fire effects on erosion rates.

The first step in the analyses for each project area was to examine the effect of slope position against the hypothesized relation that would be expected if eroded sediment was transported the length of the hillslope resulting in a net, down-slope accumulation of eroded sediment. Separate ANOVA analyses were conducted for each project area. ANOVA analyses showing a significant affect of slope position ($\alpha = 0.05$) were further examined using Tukey means comparisons tests to identify hillslope positions with significant differences. These analyses were conducted by combining plots from all hillslopes within a project area (aspect and treatment combined); by examining plots divided into analysis blocks by aspect (proposed treatments combined); and finally, by examining plots divided into analysis blocks for each individual hillslope. The relatively small number of erosion plots (three within a single transect at a given slope position) and the high variability between plots suggested that this test would have little power to detect small differences. Consequently, we also examined the data looking for non-significant differences that followed the hypothesized trend. If there was no evidence that erosion rates measured within a single hillslope were dependent upon slope position (i.e., lack of significant differences in the means comparison tests; lack of hypothesized trend) we dropped slope position as a categorical variable and treated each plot as an independent replicate in all subsequent analyses.

To examine the effect of aspect on annual erosion rates, all nine erosion plots on a single hillslope were treated as independent replicates, grouped into a single block within the ANOVA. As before, project areas were analyzed separately. Data from treated hillslopes within the Red

Fir project area were not used in this analysis because the results could have been confounded by unbalanced treatment effects. ANOVA analyses showing a significant effect of aspect ($\alpha = 0.05$) were further examined using a Tukey means comparison test to further identify specific differences in annual erosion rates related to aspect.

Erosion rates measured on the Red Fir erosion plots were examined for significant differences ($\alpha = 0.05$) resulting from the prescribed fire treatment using ANOVA. Separate analyses were conducted for north-facing and south-facing hillslopes. These analyses were confounded by an unbalanced treatment effect (despite a balanced experimental design). The prescribed fires were set at ridge top and upper slope positions and allowed to spread downhill, but failed to reach toe-slope transects on the south facing slopes and both toe-slope and mid-slope transects on the north facing slope. Because erosion plots were treated as independent replicates, unburned plots were grouped with control plots, resulting in 6 burned plots and 12 control plots with southerly aspect and 3 burned plots and 15 control plots with northerly aspect. Treatment sample sizes were very small so the data need to be interpreted with caution.

To further clarify the relation between hillslope erosion rates and the factors typically related to surface erosion, a regression analysis was conducted using the continuously distributed variables: slope, average duff thickness, and the natural-log transformed average of bare ground plus ash. A backward, stepwise procedure was used to eliminate non-significant variables ($\alpha = 0.05$). Relating the average annual rate of observed hillslope erosion to the amount of bare ground plus ash was complicated by the fact that ground cover estimates were repeated each summer. Relatively little change was observed, through time, on control plots, but large changes in the amount of bare ground and ash were apparent on the treated plots. Consequently, use of the time-averaged bare ground plus ash in the regression analysis might obscure results. Therefore, the regression analysis used the data from each collection date, expressed as an annualized rate (rather than the average of all three collections). We assumed that ground cover would change little over the winter, so that the bare ground estimates from summer 2002 were regressed against spring 2003 erosion rate; bare ground estimates from summer 2003 were regressed against fall 2003 and spring 2004 erosion rates.

Watershed-scale Sediment Budgets: Data collected from the Skookum Experimental Watersheds provides a time-series of precipitation inputs and water and sediment yield over the 11 pre-treatment years of study. Runoff ratios (total annual precipitation divided by total annual water yield) were calculated from these data. Annual runoff ratios and yields from the two watersheds were analyzed to see if differences between watershed means (the 11-year mean annual unit-area runoff ratios and yields of water, suspended sediment, and bedload sediment) were significantly different than zero ($\alpha = 0.05$). Finally, average annual yields were calculated by averaging total annual yield over the 11 complete years of measurement data currently available (1993 through 2003, inclusive).

Results

Skookum Experimental Watersheds

Precipitation and water yield in the Skookum watershed during the pre-treatment period showed high inter-annual variability with large differences in unit area water yields between catchments (Figure 5). The 20-year average precipitation measured at Madison Butte Lookout, a Natural Resource Conservation Service SNOTEL site located at the headwaters of the Skookum watersheds was about 56 cm per year. Of pre-treatment years sampled, six had below average precipitation, while four years were above average. Unit area water yields from Skookum #1 (proposed treatment watershed) were significantly higher than yields from Skookum #2 (control watershed) ($p = 0.013$). Runoff ratios were also significantly higher in Skookum #1, where annual runoff was 19 percent of precipitation inputs compared to 14 percent of precipitation inputs in Skookum #2 ($p = 0.006$).

Suspended and bedload sediment yields showed high inter-annual variability in both watersheds (Figure 5). Unit area suspended sediment yields were significantly higher in Skookum #1 than in Skookum #2 ($p = 0.037$), even though the two catchments have similar geology, soils and vegetation. Suspended sediment yields from Skookum #1 peaked in 1995 and 1996, and decreased dramatically the following year, 1997, the year with the highest water yield observed over the period of record. Similarly, unit area bedload yields are significantly higher in Skookum #1 than in Skookum #2 ($p = 0.006$). Bedload yields from Skookum #1 peaked in 1995 and decreased gradually thereafter. Suspended sediment comprises more than 99% of the total sediment yield from both watersheds.

There were no significant differences in hillslope erosion rates within the Skookum watersheds among upper-, mid-, and toe-slope positions when the data from all plots was combined or when analyzing north-and south-facing plots separately. Examining the four hillslopes individually resulted in one case where erosion rate varied significantly with slope position ($p = 0.009$). The means comparison test, however, showed that the rate measured at mid slope (50.18 g/m hillslope width) was significantly higher than

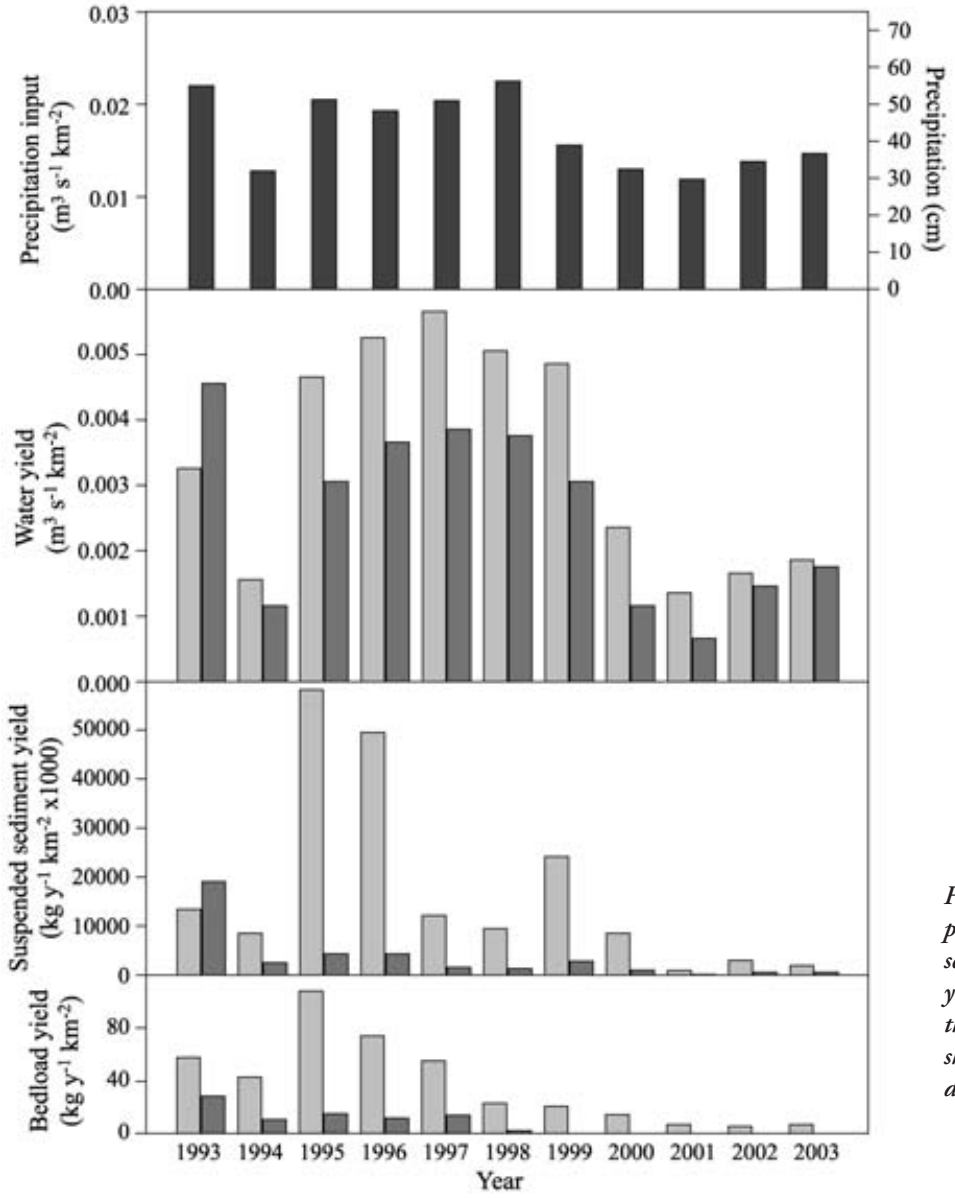

Figure 5. Skookum project area annual precipitation, water yield, suspended sediment yield, and bedload sediment yield from 1993 through 2003. In the lower three panels, Skookum #1 is shown in light gray, Skookum #2 in dark gray.

at either the upper slope (9.04 g/m) or the toe slope (8.08 g/m). In no case did the observed trends support our hypothesized relation of a net, down-slope accumulation of eroded sediment at the sediment fences caused by sediment erosion and subsequent transport along the length of the hillslope.

Annual hillslope erosion rates were strongly influenced by aspect, with significantly higher rates on south-facing hillslopes than north-facing hillslopes (Figure 6). Soils on south-facing slopes were more exposed, with less cover of litter and duff than on north-facing slopes. We observed frequent signs that animal burrowing activity on the south-facing aspects was contributing local sediment to the sediment fences. We did not observe signs of burrowing activity and sediment loading of the fences on the north-facing aspects.

Treatment Effects

At the Red Fir site, there was no significant difference between the burned and unburned plots in the annual hillslope erosion rate averaged from the three collection dates (Figure 7). On the north-facing treatment hillslope, the prescribed fire burned only the upper three plots, leaving six of the plots (middle and lower) unburned. On the south-facing treatment hillslope, the prescribed fire burned the upper and middle plots, leaving the three lower plots unburned. In our analysis, the unburned erosion plots in the planned treatment block were grouped with the control plots. The resulting data structure was highly unbalanced, and had little statistical power to resolve the small differences observed between the burned and unburned plots (Figure 7). At the Red Fir site, elk are

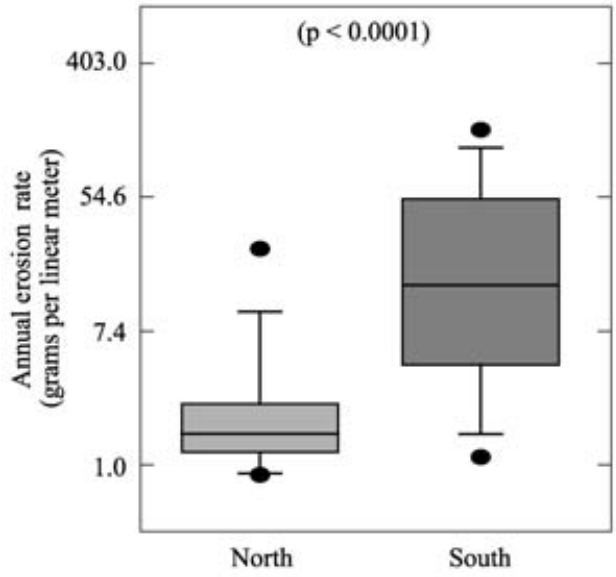

Figure 6. Comparisons of annual erosion rates between north- and south-facing hillslopes in the Skookum project area during the pre-treatment phase of the project (n = 18 for each box). Box and whisker diagrams show median values (fine line in the filled box), 25th and 75th percentiles (box), 10th and 90th percentiles (whiskers) and individual observations beyond the 10th and 90th percentiles.

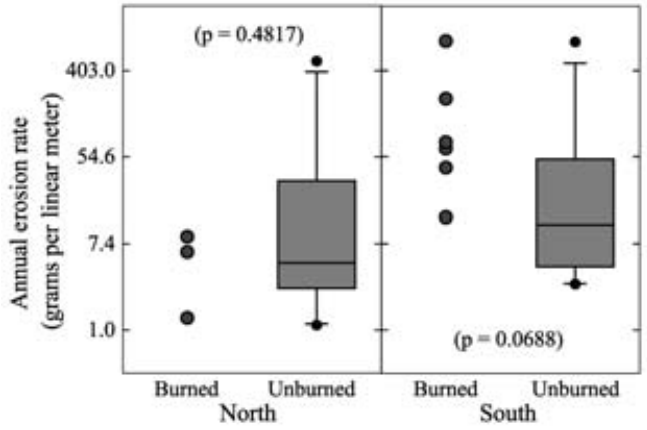

Figure 7. Comparison of annual erosion rates between burned and unburned plots on north and south aspects at the Red Fir project area (north, unburned, n = 15; south, unburned, n = 12). Box and whisker diagrams show median values (fine line in the filled box), 25th and 75th percentiles (box), 10th and 90th percentiles (whiskers) and individual observations beyond the 10th and 90th percentiles.

Figure 8. Red Fir project area, Cabin Gulch south, plot #6, a south-facing mid slope plot. Note the obvious bioturbation caused by elk walking above the sediment fence when the ground was wet, accumulation of sediment, short delivery distances, and damage to the sediment fence.

attracted to the erosion plot silt fences, and there is evidence of damage to the plots, especially on the south-facing control hillslope (Figure 8). Much of the erosion measured in these locations appears to be caused by elk trampling above the silt fence.

Exploratory data analysis suggested that the amount of bare ground was positively correlated with the observed annual erosion rates. Backwards, stepwise regression analyses showed that natural-log transformed sum of bare ground plus ash was more highly correlated to erosion than were either slope angle or duff thickness. The relation between the area of bare ground and erosion also appears to vary with aspect, with an equivalent bare ground area supporting higher erosion rates on south-facing aspects than on north-facing aspects (Figure 9). The amount of bare ground plus ash was usually higher in burned plots than in unburned plots, and on south-facing aspects, burned plots had among the highest observed erosion rates. Burning leads to substantially reduced ground cover and increased areas of the soil surface covered by ash in the time immediately after the fire. However, this cannot be linked to the treatment effects in the statistical analysis

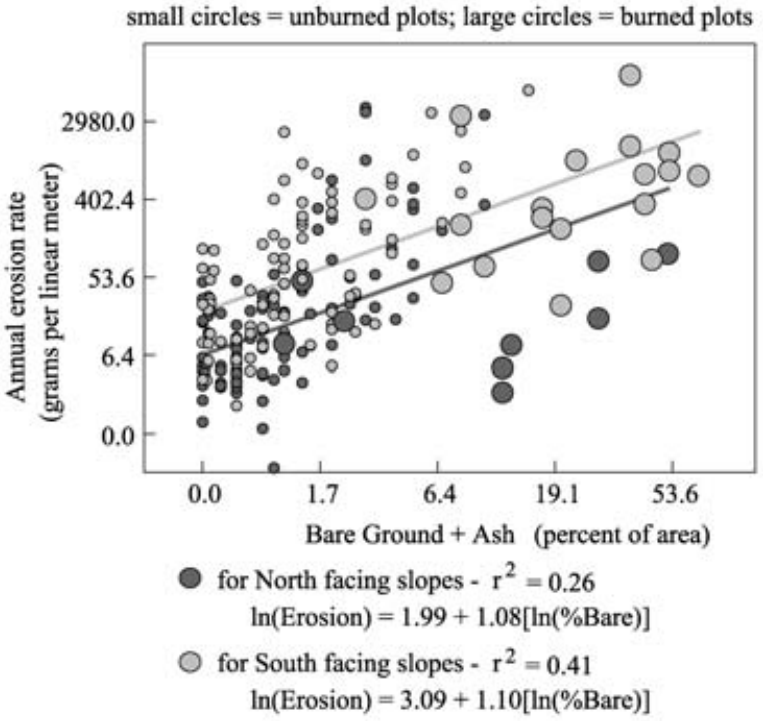

Figure 9. Skookum and Red Fir project areas bare ground plus ash percent of plot area vs. annual erosion rate. Burned plots are denoted with large filled circles; unburned plots with small filled circles.

because of the small number of burned plots and the highly unbalanced sample design.

Discussion

Background Natural Disturbance – The Spruce Budworm Outbreak

The Skookum Experimental Watersheds are a paired watershed study with 11 years of pre-treatment data on discharge, suspended sediment, bedload sediment, and water temperature. Our study design called for establishing erosion plots one full year before implementing the prescribed burn which would allow a "Before-After/Treatment-Control" study design to examine changes in sediment budgets at scales ranging from the plot, to the hillslope, to the whole watershed. For a variety of reasons, however, the Skookum watersheds were not treated, turning this into a study of background erosion rates. The study remains valuable because it provides information on baseline erosion rates from watersheds with volcanic parent materials within the Blue Mountain physiographic province. These results will be useful in the design and evaluation of future projects for purposes of improving erosion estimates, understanding the range of natural variability, and calibrating predictive models.

The degree to which the extensive forest mortality resulting from the spruce budworm outbreak in the early 1990s contributed to the changes in water and sediment yields observed over the period of record is an intriguing question. Suspended sediment yield peaks in 1995 and 1996 may be related to the forest mortality from the spruce budworm outbreak. Loss of the forest canopy would have exposed the soil surface to direct impact of raindrops and decreased transpirational losses might have led to increased runoff, both of which could contribute increased amounts of sediment to channels and help transport this sediment out of the watersheds. Residual live trees remaining in areas where most trees had died would have been more exposed to wind, and were probably more likely to be toppled during windstorms in the years immediately following the catastrophic die off of the canopy. Root wads from toppled trees provided exposed, easily detached soil that was available for erosion. Eroded sediment from root wads in toe-slope, riparian, and stream-bank positions may have contributed to the peak yields of suspended and bedload sediment observed in 1995 and 1996.

Understory vegetation is now dense, especially on northwesterly through easterly aspects because loss of the forest canopy has increased the amount of light available to forest floor vegetation. Further, as root systems and boles of insect-killed trees began to rot away, the trees would have been much less wind-firm, falling under the forces of gravity, snow loading, and wind. Dense vegetative cover now protects the soil from erosion and increased downed logs now provide an abundance of sediment storage locations on the hillslopes. Further, transpiration from the dense understory has probably reduced water yields from the watersheds. A combination of all these processes could explain the reduced water and sediment

yield since 2000. However, annual precipitation has also been below average since 1999, which may also contribute to decreased sediment yields in recent years. Without pre-budworm outbreak data, however, the identification of causal mechanism is speculative. Overall, large differences in sediment yields between watersheds, high inter-annual variability, and confounding affects from extensive forest mortality would likely make it difficult to discern prescribed fire effects on watershed-scale sediment yields unless these were very large.

Hillslope-scale Erosion and Sediment Transport

Infiltration-excess overland flow is a major driver of erosion in the intermountain west, especially following fire [see reviews by Wondzell and King (2003)]. While there is little direct research on the influence of prescribed fire on erosion, research following wildfire suggests that the potential to increase erosion rates is correlated to fire severity. Large, stand-replacing wildfires have the greatest impact on soil properties that influence erosion. Most prescribed fires are set when weather and fuel conditions make large, high severity fires unlikely. Even if prescribed fires did increase potential hillslope erosion rates, without large storms to generate overland flow in the year or two after the burn, significant erosion is unlikely.

We never observed evidence of overland flow that would have driven surface erosion and downslope transport of eroded sediment at any of our study sites over the course of this study. Without major storm events to drive extensive overland flow, the physical mechanism that would drive erosion and down-slope sediment transport is lacking. Under these conditions it is not surprising that observed patterns of erosion did not support the hypothesized relation of a net, down-slope accumulation of eroded sediment at the sediment fences. Rather, observations made while emptying the erosion fences suggested that the hillslope area contributing sediment to the erosion fences was very small, perhaps extending no more than a meter upslope of the fence apron. In the most part, erosion resulted from bioturbation. Clods of dirt appeared to have been kicked onto the fence aprons, judging from the deep footprints elk left in wet soil immediately above the fences in several locations. Similarly, small mammals digging immediately above the plots send small amounts of dirt into the fences. All these facts combined suggest that each sediment fence functioned as an independent sample unit under the conditions during which these study was conducted.

Watershed-scale Sediment Budgets

The design of this study allowed estimation of both total sediment delivery to the stream channel and net sediment yield from the watershed. The difference between these two values was the net channel erosion rate, where positive values represented channel aggradation and negative values represented bank erosion or channel incision.

Preliminary estimates of background hillslope erosion rates suggested that low amounts of sediment are delivered to valley floors within each catchment, as measured with the silt fences located in toe-slope positions. A simple, watershed-scale budget of sediment delivery was made by estimating the length of mainstem channel, and clearly defined tributary channels within each watershed and multiplying by a sediment delivery rate. We assumed that the sediment delivery to each meter of valley-floor length equaled two-times the overall average hillslope erosion rate measured from all 32 hillslope erosion plots within the Skookum watersheds (i.e., one side of the valley floor receiving sediment inputs at the rate measured on south-aspect hillslopes; the other side receiving sediment inputs at the rate measured on north-aspect hillslopes). Skookum #1 had 3.40 km of mainstem channel and 5.33 km of tributary channel; Skookum #2 had 2.29 km of mainstem channel and 1.96 km of tributary channel. The calculations showed that, on average, 52 kg of sediment were delivered to the valley floor of Skookum #1, while valley floors in Skookum #2 received an average of 25 kg/y.

Watershed-scale estimates of sediment yield derived from water samples collected at the outlet streams suggest sediment losses hundreds of times greater than sediment delivery rates to the valley floors (12,000 kg/y from Skookum #1 and 3,000 kg/y from Skookum #2). Assuming that the dry bulk density of suspended sediment is 1.7 g cm^{-3} and assuming an average wetted perimeter of 0.70 m for mainstem channels and 0.35 m for tributary channels, and assuming that sediment is eroded evenly from the entire channel network, annual sediment yields could be accounted for by 3 to 12 mm of streambed and streambank erosion. Most of the annual sediment yield is comprised of suspended sediment, and most of this is removed from the watershed by peak flows during spring snowmelt. Our calculations probably overestimate the degree of stream erosion needed to supply annual sediment yields because the calculations do not include sediment eroded from hillslope hollows lacking obvious channels that are connected to the stream network during snowmelt. Because sediment may be stored on valley floors for long periods of time, continued erosion of stored sediment may maintain elevated sediment loads in streams, even when little erosion is occurring on upland sites. The results of

both the hillslope- and watershed-scale erosion patterns highlight the influence of episodic hillslope erosion events, sediment storage on floodplains, and minor amounts channel erosion on watershed-scale sediment budgets.

Concerns and Issues for Management

Requirements for species protection under the Endangered Species Act have caused many changes in project design. In general, riparian protection requirements limit the scope of management activities in these areas. To date, prescribed fire treatments are generally designed to have no measurable effect on streams and riparian areas for consultation purposes under the Endangered Species Act. Design criteria include not burning within the riparian conservation area (riparian and buffer zone) and limiting total area in bare soil in the project area. Results presented in this paper validate the design of treatments for no effect to aquatics under "normal" weather conditions. Avoiding active treatment within riparian areas may, over the short term, prevent direct effects of sedimentation to streams but riparian conditions, including fuel loading, may or may not be at desired levels in a project area. Further, at the landscape scale, effective fuels treatments to reduce uncharacteristic wildfire risk may in some cases conflict with riparian protection management standards (generally interpreted as no active treatment). Active riparian treatment using prescribed fire may be desired in certain circumstances for purposes of improving riparian conditions and reducing landscape-scale wildfire severity.

Future Work

Sampling of erosion plots will begin at a third fuels treatment project, the Lick Creek site, in June 2005. Fuel conditions forest wide are increasingly complex, and managers are turning to combined treatments of mechanical thinning and burning to reduce fuel loads. These types of treatments will be more common in the future, and the Lick Creek project will provide data on combined treatment effects on hillslope erosion rates. Additional study plans include: 1) analyzing Skookum fuel load measurements; 2) comparing hillslope erosion to changes in channel morphology using stream reference reaches; 3) comparing pre- and post-burn fuel load measurements for Lick Creek; 4) comparing results with FSWEPP modeled results; 5) sharing data with FSWEPP developers for local model calibration; 6) sharing study results with local managers for use in developing project effects analysis; and 7) archiving data in the Pacific Northwest Forest Science Databank.

Summary

Challenges faced in this study include the uncertainty of treatments being implemented and short timeframes during which measurable effects were likely. Successful implementation of planned prescribed fire projects was often uncertain because of stringent requirements for burning, availability of resource personnel, and competing priorities. Once implemented, timeframes in which to measure potential effects were limited by relatively rapid recovery of understory vegetation and the likelihood of significant storms occurring during this period was relatively low. As a result, responses under more extreme weather conditions such as winter rain-on-snow events or intense summer convective storms were difficult to capture.

The preliminary data reported here showed that background hillslope erosion rates varied significantly by aspect and were generally higher on south-facing slopes. At the watershed scale, annual sediment yields were highly variable. Watershed sediment budgets showed that episodic erosion events most likely control sediment delivery to streams but that sediment storage in valley floors and subsequent removal via bank erosion influences annual sediment yields over the long term. Without large storm events in the first two years after prescribed fire, there was no significant difference in hillslope erosion between burned and unburned plots. The significant relationship between bare ground and erosion rates demonstrated the role of soil cover in controlling surface erosion.

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Long-Term Ecological Changes With Postfire Emergency Seeding

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Post-fire emergency response treatments are developed to immediately protect life, property and watershed related values. However, many treatments have long-term effects on the soil and vegetation of the ecosystem. This study compares treated and non-treated vegetative composition eight years following post-fire emergency restoration efforts. The long term effects of seeding native grasses with two types of soil disturbances were evaluated. The use of native grass species for emergency rehabilitation was shown to decrease overall species diversity and prohibit the establishment of several native plant species following fire. Seeding of native grass species was shown to be successful only with treatments that included surface soil disturbance. The long-term implications of emergency restoration seeding and recommendations for its use are discussed.

Keywords: *soil, fire, vegetation, succession, rehabilitation, seeding, native*

Introduction

The Burned Area Emergency Response (BAER) program has been with the Forest Service since 1975 (USDA FS 2001). The program has evolved from watershed emergency stabilization to a program of emergency protection of identified values at risk. The values at risk under today's BAER program can range from the original watershed emphasis to listed species habitat, cultural resources, and infrastructure (USDA FS 2001). The objectives of the Forest Service BAER program are found in the Forest Service Manual (FSM) 2523 (USDA FS 2004). The objectives are: "To determine the need for and to prescribe and implement emergency treatments to minimize threats to life or property or to stabilize and prevent unacceptable degradation to natural and cultural resources resulting from the effects of a fire". Many types of treatments are prescribed and implemented to reduce the threats to the identified values at risk. The use and necessity of emergency treatments have been questioned as to the success and ecological consequences of treatments (Dellasala et al. 2004). Various monitoring efforts are being conducted to determine the applicability of many treatments to meeting the intended objectives.

One of the most common treatments for the past 30 years has been the use of grass seed to provide a vegetative cover on burned lands to reduce the rain drop impact and runoff energy associated with post-fire rain events. More recently, native grass seeding has been used to reduce the potential for invasive plants. The effectiveness of seeding burned areas, particularly by broadcast aerial or ground methods has been reviewed by Robichaud et al. (2000) and Byers (2004). Reviews of past monitoring information has showed that there is very little quantified data on the effectiveness of seeding burned areas to meet emergency restoration objectives. There is also very little data on long term (5+ years) effects of BAER seeding treatments on the ecological succession of burned areas.

Recently there has been an emphasis on the use of native species for all restoration and rehabilitation treatments. Executive Order 13112, Forest Service policy FSM 2081 (USDA FS 2004), and several Forest Service Regional policies direct the agencies land managers to use native species for any planting or seeding operations whenever possible. The direction to use native species is firm and BAER teams often use native species mixes when seeding treatments are prescribed for post-fire emergency protection. The Forest Service BAER program (FSM 2523) emphasizes natural recovery first and second the use of native species that originate from genetically local sources. Further down in preference is the use of non-native species that are non-persistent and not likely to spread beyond the treatment area.

The effectiveness and ecological effects of seeding are often not quantified during BAER implementation nor post BAER operations. The BAER program provides for funding to determine qualitatively if treatments are installed properly and/or if they are effective at meeting emergency objectives. However, the BAER program cannot fund the validation of treatment types, quantified measurements, nor the effects of treatments beyond the emergency period (FSM 2523). The effects of native species seeding to the post fire ecosystem processes may be much longer than the initial emergency period. There is very little information available on the long term (5+ years) effects of emergency

Furniss, M.J., Clifton, C.F., Ronnenberg, K.L., eds., 2007. *Advancing the fundamental sciences: proceedings of the forest service national earth sciences conference, San Diego, CA, 18-22 October 2004*. PNW-GTR-689. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station.

seeding of native species in wildfire areas. This study quantitatively looks at the long term effects of native grass seeding as part of a BAER program.

Study Area

The study was conducted in August 2004 within the 12,000-acre (4860-ha) Buffalo Creek Fire that occurred in May 1996. The fire area is located adjacent to the town of Buffalo Creek, CO and is approximately 50 miles (80 km) southwest of Denver, CO. The pre-fire vegetation was predominantly continuous canopies of Douglas-fir (*Pseudotsuga menziesii*) and ponderosa pine (*Pinus ponderosa*). A depauperate understory existed under the closed canopies of the conifer species. Soils of the area are derived from the Pikes Peak Batholith (USDA NRCS 1992). The soils are referred to as decomposed granite (DG) soils. The soils are coarse textured with very little soil structure. The clay content is low and the water holding capacity is low. The soils are easily eroded when surface cover is removed. They also have a high potential to produce hydrophobic conditions following fire due to the high amount of coniferous litter and high volume of macro pore space. The elevation of the area is 2300 to 2600 m. Precipitation averages 40-46 cm per year. Severe thunderstorms are common during the summer months.

The human-caused Buffalo Creek Fire was a very complete fire, leaving very few unburned islands of vegetation within the fire area. Approximately 3038 ha of the 4860 ha burn area was mapped as high fire severity (USDA FS 1996a). Hydrophobic soil conditions were reported in the fire area for several years. Infiltration rates were significantly reduced due to the hydrophobic soil conditions (Moody and Martin 2001a). Natural regeneration in the first few years following the fire was poor. There were very few pre-fire herbaceous understory plants or shrubs, and many seeds were consumed during the fire event.

Several major runoff events occurred in the first two years following the fire. These events caused losses to homes, lives, roads, water supply to the city of Denver, and other natural resources. The events removed surface horizons and moved sediment stored in drainages throughout the fire area. (Moody and Martin 2001b)

BAER Treatments

Emergency BAER treatments were installed in 1996, 1997, and 1998. Treatments varied as to type and location. Restoration measures were prescribed and implemented to protect lives and property, protect water quality, and protect long-term soil productivity. Some of the treatments implemented were grass seeding (aerial and ground), contour felling, contour trenching, dozer ripping, Rotoclear[1] mulching, bank stabilization, channel modification, and water source protective barriers. Grass seeding treatments included broadcast aerial and ground seeding. Species used in the treatments ranged from mixes of non-persistent grains to native grass species. A summary of the grass seeding operations is shown in Table 1.

Ground seeding was done on ground disturbing treatments including dozer ripping and Rotoclear chipping. The dozer ripping treatment included the use of shallow ripper teeth pulled behind a small dozer perpendicular to the slope. A broadcast seeder was mounted on the back of the dozer and seed was spread on the ripped path and outside of the ripped path more than twice the width of the ripped path. The ripped paths were spaced 12-15 m apart. The Rotoclear treatment included the use of a rotating, toothed drum that mulched materials passing beneath it (Figures 1 and 2). The Rotoclear was pulled behind a large Caterpillar D8 dozer. The dozer would

Figure 1. Rotoclear machine showing rotating drum.

Figure 2. Rotoclear machine with dozer.

[1]The use of trade or firm names in this publication is for reader information and does not imply endorsement by the U.S. Department of Agriculture of any product or service.

Table 1. Summary of seeding treatments for the Buffalo Creek Fire restoration.

Treatment	Species in Mix	Percent of Species in Mix by Weight	Estimated Total Pure Live Seeds per square meter	Hectares Seeded	Dates of Seeding
Aerial Seeding	white oats (*Avena sativa*)	100	110	2,025	June 1996
Aerial Seeding	white oats	50 estimated	210	2,025	March 1997
	slender wheatgrass (*Elymus trachycaulus*)	25 estimated			
	Canby bluegrass (*Poa canbyi*)	25 estimated			
Rotoclear	slender wheatgrass	23.41	430-530	405	August - December 1996
	thickspike wheatgrass (*E. macrourus*)	25.65			
	streambank wheatgrass (*E. lanceolatus*)	14.05			
	green needlegrass (*Nassella viridula*)	14.49			
	mountain brome (*Bromus marginatus*)	9.87			
	Canby bluegrass	5.05			
	Idaho fescue (*Festuca idahoensis*)	3.75			
	Arizona fescue (*F. arizonica*)	1.01			
Dozer Ripping	slender wheatgrass	23.41	430-530	608	April - May 1997
	thickspike wheatgrass	25.65			
	streambank wheatgrass	14.05			
	green needlegrass	14.49			
	mountain brome	9.87			
	Canby bluegrass	5.05			
	Idaho fescue	3.75			
	Arizona fescue	1.01			

push burned trees over and the Rotoclear mulched the tree into 8- to 13-cm chips and incorporated some of the woody material into the soil surface. The Rotoclear was pulled along the contour perpendicular to the slope. Two 4-meter-wide Rotoclear paths were created, spaced 12 to 15m apart. Grass seed was broadcast over the paths and outside the paths to more than twice the width of the path.

In general, the two aerial seedings did not provide adequate plant establishment. Neither were effective in controlling surface runoff and erosion (Bruggink et al 1998). Most of the seed did not germinate, was lost to overland flow, or was consumed by animals. The Rotoclear and dozer ripping treatments did show some effectiveness in controlling runoff and erosion (Bruggink et al. 1998), however, the effectiveness appeared to be related to the soil disturbance and addition of organic matter that allowed increased infiltration. The native seeding that was included in the treatments did germinate successfully in the areas with some soil disturbance within the first two years of seeding, but the contribution to reducing runoff was not evident (Bruggink et al. 1998). Ground based broadcast seed that fell adjacent to the disturbed soils had similar results to the aerial seeding.

In summer 2003 (seven years after the burn), the burn area was visited by the author. At that time there were visual differences in the type and amount of vegetative species on both the dozer ripped and Rotoclear treatment areas compared to areas that were seeded without soil disturbance and areas that were not treated. There was a noticeable difference in species composition, species cover, and the amount of bare ground between areas treated with ground disturbance treatments and those with no soil disturbance. The areas that received broadcast seeding without any soil disturbance appeared similar in species composition and diversity to areas that were not treated.

Table 2. Cover class mid-points used in calculations.

Data Sheet Code	Canopy Cover Range (percent foliar cover)	Canopy Cover Midpoint used in calculations (percent foliar cover)
T	0-1.0	0.5
1	1.1-5.0	3.0
2	5.1-25.0	15.0
3	25.1-50.0	37.5
4	50.1-75.0	62.5
5	75.1-95.0	85.0
6	95.1-100.0	97.5

In summer 2004, the vegetation was sampled on the Rotoclear, dozer ripped, aerial seeded, ground seeded without soil disturbance, untreated, and unburned sites. The sampling was intended to determine the long term successional effects of seeding burn areas, to determine the difference in seeding with soil disturbance compared to seeding without soil disturbance, and to determine the long term effects of BAER treatments in reducing erosion.

Methods

Sampling sites were stratified by the type of treatment. The aerial seeding was dropped from the list of treatments due to the following reasons.

1. The first aerial seeding included only a non-persistent cereal grain (white oats, *Avena sativa*) that was not successful according to the 1998 monitoring report.
2. The second aerial seeding was also reported as having very poor success in the 1998 monitoring report. This mix did include two native species; however these species were also included in the dozer ripping and Rotoclear treatments where seed was spread both on disturbed and non-disturbed soils. An assumption was made that the ground broadcast seeding between the dozer ripped and Rotoclear paths would represent all broadcast seeding (aerial and ground) where no soil disturbance was used. These areas became the controls for the soil disturbance and seeded applications.
3. Very little to no visual difference could be detected between non-seeded areas and areas that received broadcast seeding with no soil disturbance.

A total of four sites were sampled. Vegetation data at each of the sites were collected. The vegetation sampling method followed USDA Forest Service Region 2 Rangeland Handbook (USDA FS 1996b) protocols for cover-frequency transects. The transects included 30.48 m transects with 20 Daubenmire (Daubenmire 1959) 20-cm x 50-cm frames (subplots) along each transect to determine percent cover by species. Six cover classes were used plus a trace class. The class midpoints shown in Table 2 were used in calculations for cover data. Data for each frame included life form, species, and cover class. Ground cover type and it's cover class were also collected for each frame. Species frequency was determined for each species by transect and average species canopy cover. Three transects were completed for each treatment type as well as for each control. The only exception was the control for the dozer ripping, where only two transects were completed (Table 3). The Rotoclear and dozer ripped sites had both transects along the soil disturbance paths that were seeded, and also between the paths that were seeded but had no soil disturbance.

Analysis

General averages of vegetation and ground cover by treatment typ, and Student's t-tests (Steel and Torrie 1980) (two-tailed, unequal variances) for significant ($p < 0.05$ and $p < 0.01$) species differences within treatment types were calculated. Sample size for treatments was $n = 60$ except for the dozer ripping treatment where $n = 40$. The general summaries by treatment type included total species richness (total species counts), cover percents of seeded species (mean percent cover), total number of unique species (total species counts unique to treatment type), and percent effective ground cover (mean percent ground cover). Selected species were compared between soil disturbed seeding and non-soil disturbance seeding for

Table 3. Summary of sites and replications.

	Site 1 - Dozer Ripping		Site 2 - Rotoclear		Site 3 - Control	Site 4
	Soil Disturbance	No Soil Disturbance (control)	Soil Disturbance	No Soil Disturbance (control)	Untreated	Unburned
Number of Transects	3	2	3	3	3	3
Average Slope Percent	20	20	10	8	25	10
Average Aspect (degrees)	275	275	30	35	276	280
Date Sampled	16 Aug. 2004	16 Aug. 2004	17 Aug. 2004	17 Aug. 2004	16 Aug. 2004	17 Aug. 2004

Table 4. Average effective ground cover eight years post-treatment.

	Average Percent Effective Ground Cover
Rotoclear Seeded	76 bd
Non-Rotoclear Control, Seeded	52 be
Dozer Ripping Seeded	84 a
Non-Dozer-Ripping Control, Seeded	88 c
Burn Control, Unseeded	65 acde
Unburned Control	96 abc

a, b, c, e, f - significant difference at p < 0.01 level
d - significant difference at p < 0.05 level

*Table 5. Average foliar cover eight years post-treatment. *The unburned control includes only foliar cover from vegetation less than 3.7 m in height.*

	Average Percent Foliar Cover
Rotoclear Seeded	65 a
Non-Rotoclear Control, Seeded	44 a
Dozer Ripping Seeded	41 c
Non-Dozer-Ripping Control, Seeded	51 b
Burn Control, Unseeded	39 ab
Unburned Control	24* abc

a, b, c - significant difference at p < 0.01 level

significant ($p < 0.05$ and $p < 0.01$) differences of foliar cover. All summary statistics and t-test of significance were performed using Microsoft Excel (2002) software.

Results

Effective Ground Cover

One of the objectives of the study was to determine the long-term soil protection and stability of the dozer ripping and Rotoclear treatments. Total effective ground cover was used as an indicator to determine long-term soil protection from erosion and to determine long-term maintenance of soil productivity. Ground cover has beenshown to be a reliable, quantifiable and repeatable indicator for measuring soil health and stability (Beasley 1974; O'Brien et al. 2003; Pannkuk and Robichaud 2003). Ground cover in the form of coarse woody debris is also essential to maintaining long-term soil productivity (Graham et al. 1994). Effective ground cover for the study included living and dead vegetation on the soil surface, as well as rock greater than 1.9 cm in diameter (USDA FS 2003). There were significant differences in effective ground cover 8 years following treatment application both within and between treatments (Table 4). The Rotoclear seeded treatment had significantly higher ($p < 0.01$) effective ground cover than the area that was seeded but had no Rotoclear treatment. The dozer ripping and seeded treatment showed no difference in effective ground cover compared to the area that was seeded but received no dozer ripping. Only the Rotoclear seeded showed average differences within a site location compared to its control. This indicates that the Rotoclear seeded treatment 8 years post-fire has a significantly higher amount of effective ground cover compared to its control. However, much of the ground cover consisted of wood chips created from the mulching of trees by the Rotoclear. The dozer ripping and seeding treatment showed no difference compared to its control.

Foliar Cover

Foliar cover is often used as a surrogate to determine production and to give an estimate of soil health and stability (Dadkhah and Gifford 1980; Meyer et al. 2001); however, foliar cover can vary significantly from year to year or by season, especially with grass and forb species, and it is not a good predictor of soil loss (Hardy 2002). In this study, foliar cover was used to verify the ground cover estimates and to determine productivity differences between treatments and their controls (Table 5). The results show a similar trend to effective ground cover when

Table 6. Plant species richness across treatments and controls.

	Total Species	Total Forbs	Total Grasses	Total Shrubs	Total Trees	Unique Species
Rotoclear Seeded	33	23	9	1	0	8, compared to control seeded
Non-Rotoclear Control, Seeded	43	27	14	2	0	18, compared to Rotoclear seeded
Dozer Ripping Seeded	32	18	13	1	0	9, compared to non-dozer ripping seeded
Non-Dozer-Ripping Control, Seeded	36	24	10	1	0	13, compared to dozer ripping seeded
Burn Control, Unseeded	38	28	7	3	0	
Unburned Control	25	15	5	3	2	

comparing the treatments to their controls. However, there was a jump in foliar cover for the Rotoclear treated transects. This indicates that the Rotoclear treated sites had a much higher plant production during the 2004 growing season. The increase in plant production may be due to the increase in soil carbon with the woody material, the increase in soil moisture due to the surface cover from the wood chips that may have reduced evaporation and drying the of the soil, or to both mechanisms.

Species Richness

The total number of vegetative species found, grouped by each life form class, was determined for the treatments studied and their controls (Table 6). Based on total counts, the controls that had no soil disturbance had higher total number of plant species. The burned non-seeded control also had a higher total species richness than the seeded treatments with soil disturbance. The greatest differences by life form showed that more forbs were present in the controls without soil disturbance and more grasses in the soil disturbance treatments. The higher richness of grasses in the soil disturbance is due to the success of the native species that were seeded. The total number of unique species was higher in the treatment controls. The summary results point to a long term reduction in total species richness when native grass species are used for emergency fire restoration and successful establishment occurs.

Species and Genera Differences

The Rotoclear seeded treatment was compared to its seeded control, and the dozer ripped and seeded treatment was compared to its control (Table 7 and Table 8). Some plants could be identified only to genus, while others displayed enough identifying characteristics to be classified to species level. The species and genera that showed significantly higher ($p < 0.01$) canopy cover in the non-Rotoclear control included three native forb species and genera, and one native *Carex* species (Table 7). The Rotoclear and seeded plots had significantly higher ($p < 0.05$ and $p < 0.01$) canopy cover for two seeded native grasses and one non-seeded native grass. There was also a higher ($p < 0.05$) canopy cover for an unidentified *Poa* species that is believed to be one of the seeded grasses, *Poa canbyi*. The Rotoclear treatment created conditions that provided favorable conditions for seeded native grasses. These grasses and the soil conditions created by the treatment prohibited the establishment of several native species that would likely have been present without the Rotoclear and seeding treatment.

Several species and genera showed significantly higher canopy cover for the dozer ripped and seeded treatment compared to the control (Table 8). The control had higher canopy cover for one native forb species ($p < 0.05$), one native family (Asteraceae) ($p < 0.05$), one native *Carex* species ($p < 0.05$), and one native grass species ($p < 0.01$). The dozer ripped and seeded showed significantly higher canopy cover for two of the native grasses ($p < 0.01$) that were seeded, and for one native forb species ($p < 0.05$). These results are similar to the Rotoclear treatment in that the soil disturbance with native seeding prohibited the establishment of several native species. The successional pathways and species composition eight years following the emergency rehabilitation treatments is dissimilar to the natural fire recovery of the area.

Conclusions

This study has shown that soil disturbance was required for successful immediate establishment of native grass species following fire on decomposed granitic soils. Areas that were broadcast seeded without soil preparation showed no evidence of successful grass seed establishment. The total amount of effective ground cover only increased with the Rotoclear treatment or the treatment where woody material was distributed on the soil surface. Seeded native grasses competed with the native flora. Species diversity

Table 7. Canopy cover differences by species and genera for Rotoclear seeded and non-Rotoclear control.

Control	Rotoclear Seeded
Carex species ** (*Carex* spp.)	Slender Wheatgrass ** (*Elymus trachycaulus*)
Dogbane ** (*Apocynum cannabinum*)	Arizona Fescue * (*Festuca arizonica*)
Penstemon species ** (*Penstemon angustifolius*)	Bluebunch Wheatgrass * (*Pseudoroegneria spicata* ssp. *spicata*)
Potentilla species ** (*Potentilla* spp.)	*Poa* species * (*Poa* sp.)

**** Significance level p < 0.05; ** Significance level p < 0.01***

Table 8. Canopy cover differences by species and genera for dozer ripped and seeded and non-dozer ripped control.

Control	Rotoclear Seeded
Carex species * (*Carex* sp.)	Slender Wheatgrass ** (*Elymus trachycaulus*)
Poa species ** (*Poa* sp.)	Idaho fescue ** (*Festuca idahoensis*)
Aster species * (Asteraceae Family)	Little Goldenrod * (*Solidago nana*)
Potentilla species * (*Potentilla* sp.)	

**** Significance level p < 0.05; ** Significance level p < 0.01***

was reduced in areas where the native seeded grasses were established following emergency post-fire restoration activities. Where the native grass seed was successful, the emergency restoration activities have created a long term successional pattern that differs from the natural fire recovery successional pattern.

Recommendations

Recommendations for future use of native grass species for emergency fire restoration on similar soil and pre fire vegetation types include:

1. Consider non-persistent or sterile species for immediate post-fire protection needs.
2. The use of native species for emergency protection post-fire must consider the long-term vegetation objectives. If there are no defined desired conditions for future vegetation composition, then it may be better to use only non-persistent species.
3. Soil preparation may be required for establishment of native grass species following fire on soil and pre-fire vegetation types similar to those in this study.

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McNally Postfire Discharge and the Relationship of Sierra Nevada-Wide Flood Frequency Curves and Local Kern River Discharge Curves

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The analysis tool recommended to USDA Forest Service Burned Area Emergency Rehabilitation (BAER) team hydrologists to determine design flow in ungaged systems is defined in *Magnitude and frequency of floods in California* by Waananen and Crippen (1977). These authors provide discharge equations for the 2-year, 5-year, 10-year, 25-year, 50-year, and 100-year recurrence interval storms for six regions in California based on 703 streamflow stations. Stream channel discharge relationships were developed from tributaries and USGS gage stations in the Kern River basin in response to the need to develop local hydro-physiographic discharge relationships for BAER assessment. Kern River hydro-physiographic channel geometry and discharge relationships versus drainage area were developed from this effort. This information was used to determine pre-fire stream design flow for the 2002 McNally fire. Comparison of discharge using local Kern River hydro-physiographic relationships and those derived from Waananen and Crippen (1977) yielded interesting results. With the exception of the 5-year recurrence interval, discharges derived from field measurements and local data are at least a magnitude of order higher for most of the recurrence intervals studied than those derived from Waananen and Crippen. Discharge relationships for the 5-year recurrence interval have the closest relationship using these two methods. Since the 2002 McNally fire, the response of fire-affected watersheds to winter and summer thunderstorm events has been studied. Rattlesnake Creek and Tobias Creek watersheds were surveyed in 2002 either prior to or immediately after the fire, and again in 2003 and 2004. Parameters measured include cross-sections, longitudinal profiles, bank stability, and particle distribution. Discharge estimates were calculated using resistance equations, which base discharge on bankfull depth, bankfull cross-sectional area, wetted perimeter, hydraulic radius bed material, and slope. The results of this study suggest that post-fire runoff may provide the means to estimate actual post-fire discharge by a watershed and thus be useful in validating adjusted design flows calculated during BAER assessment.

Keywords: *hydrology/water, watershed, hydrologic processes, hydrologic modeling, physiographic processes, streamflow*

Introduction

Wildfires result in increased runoff commensurate with burn severity. Burned Area Emergency Rehabilitation (BAER) teams use burn severity to estimate runoff increases resulting from fires. This increase is calculated as adjusted design flow – the flow increase expected to occur as a result of decreased infiltration and interception following a wildfire. This discharge value is used to evaluate the need to increase the capacity of drainage structures such as culverts and bridges, and provides an estimate of flooding potential to nearby communities.

Before an adjusted design flow can be determined, the pre-fire design flow must be calculated. This is the flow expected to occur prior to the fire, responsible for forming present day channel conditions, and used to estimate proper performance of culverts and other drainage structures. BAER teams are directed to determine design flow from related storm duration and magnitude (design storm) estimates from U.S. Geological Survey data, or to calculate it from a regional analysis for an equivalent design recurrence interval (Forest Service Handbook 2509.13,40 [USDA FS 1993]). These estimates assume pre-fire ground infiltration and ground cover conditions. The analysis tool recommended to BAER team hydrologists to determine design flow in ungaged systems is defined in *Magnitude and frequency of floods in California* by Waananen and Crippen (1977).

Adjusted design flow is calculated using the same relationships as design flow; however, runoff response is estimated by assuming increased runoff commensurate with burn severity, in terms of recurrence interval. This recurrence interval estimates the response of the newly burnt landscape to an average annual storm. For example, a pre-fire landscape would respond with a discharge associated with a 1.5- to 2-year storm given an average rainfall event, while post-fire, the same landscape may

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respond as if the discharge were associated with a 5- or 10-year event. The increased discharge associated with predicted recurrence interval is then prorated across the watershed by burn severity level to yield the post-fire discharge or the adjusted design flow. Watershed area above infrastructure and communities at risk from post-fire erosion-related damage (flooding, debris flows, culvert failures and washouts) often determines the size of watershed chosen for analysis.

This paper will demonstrate how *Magnitude and frequency of floods in California*, Waananen and Crippen (1977), the recommended method used to analyze both design and adjusted design flows, underestimates discharge for most rainfall response conditions when compared to discharge relationships determined from gaged and ungaged sites in the vicinity of the Kern River, in the southern Sierra Nevada. In addition, post-fire discharge calculations based on channel characteristics may provide hydrologists with a process to measure actual post-fire adjusted design flow and monitor BAER design flow predictions.

Calculation Methods for Emergency Runoff Response

The most widely used publication for calculation of design flow in California is U.S. Geological Survey Water-Resources Investigation Report 77-21, *Magnitude and frequency of floods in California*, by A.O. Waananen and J.R. Crippen (1977). This investigation provides analysis of 703 stream flow stations across California, with records ranging in length from 5 to 85 years and provides a method for evaluating magnitude and frequency of floods at gaged and ungaged sites. Because climatic and topographic conditions create a variety of watershed responses to precipitation events, these authors have divided California into six regions: North Coast, Northeast, Sierra, Central Coast, South Coast, and South Lahontan-Colorado Desert regions. Each region has a set of discharge equations developed for the flows from a 2-year, 5-year, 10-year, 25-year, 50-year, and 100-year storm event. Equations for the Sierra Region are as follows:

$$Q_2 = 0.24(A^{0.88})(P^{1.58})(H^{-0.80}) \quad (1)$$

$$Q_5 = 1.20(A^{0.82})(P^{1.37})(H^{-0.64}) \quad (2)$$

$$Q_{10} = 2.63(A^{0.80})(P^{1.25})(H^{-0.58}) \quad (3)$$

$$Q_{25} = 6.55(A^{0.79})(P^{1.12})(H^{-0.52}) \quad (4)$$

$$Q_{50} = 10.4(A^{0.78})(P^{1.06})(H^{-0.48}) \quad (5)$$

$$Q_{100} = 15.7(A^{0.77})(P^{1.02})(H^{-0.43}) \quad (6)$$

where Q = discharge, subscript indicates recurrence interval in years; A = drainage area in square miles; P = mean precipitation in inches; H = altitude index in thousands of feet. (Altitude index is computed as the average of the altitudes at points along the main channel of the stream 10 and 85 percent of the distance from the site to the basin divide as outlined on a topographic map.) These authors also provide references to water resource investigations for other areas within the United States.

The method set forth in Waananen and Crippen (1977) was initially applied to the 2002 McNally fire to determine design flow and adjusted design flow. The McNally fire affected roughly 150,000 acres (60,750 ha) on the Sequoia National Forest in the North Fork Kern River basin, which is located in the Sierra Region as defined by Waananen and Crippen (1977). Figure 1 shows the relationship of flows by recurrence interval to drainage area using the equations for the Sierra Region defined by these authors. The equations used drainage area, mean annual precipitation, and altitude values for the North Fork Kern watershed.

The North Fork Kern River is roughly an 1100-square mile (2820-km^2) watershed, as measured from north of Mount Whitney to Lake Isabella. The North Fork Kern River is located within the Kern River basin. The area defined as the Sierra Region by Waananen and Crippen (1977) ranges from Mt. Shasta to Bakersfield and encompasses roughly 47,000 square miles (122,000 km^2). Figure 2 shows the contrast in size between North Fork Kern and Sierra Region as well as gage stations located in the Kern River vicinity. The Sierra Region crosses numerous hydro-physiographic areas and is significantly larger than the North Fork Kern River watershed, which is located within a single hydro-physiographic area.

Design flows (pre-fire flows) for watersheds in the North Fork Kern River were calculated using the equation for the 2-year recurrence discharge from Waananen and Crippen (1977). Adjusted design flows (post-fire flows) were based on expected runoff response by burn severity. The McNally burn severity map was used to determine relative percentages of high, moderate, and low burn severity, and unburned areas in each watershed. Runoff response calculations used the 2-year recurrence discharge equation for unburned and low severity areas, the 20-year recurrence discharge equation for moderate severity areas, and the 50-year recurrence discharge equation for high severity burn areas (Figure 1).

Development of Discharge Curves for the Kern River

During the summers of 2000, 2001, 2002, and 2003, stream channel geometry and flow relationships were developed using Kern River tributary streams and USGS

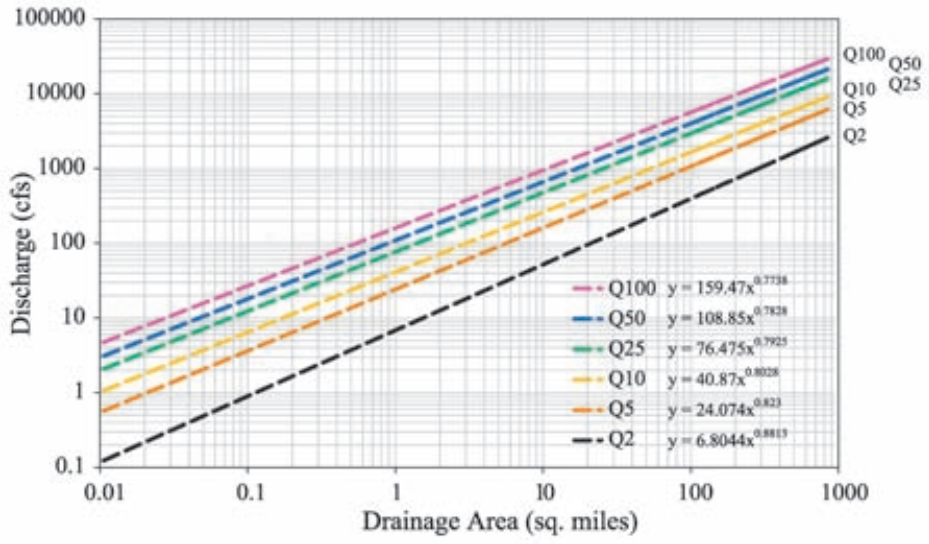
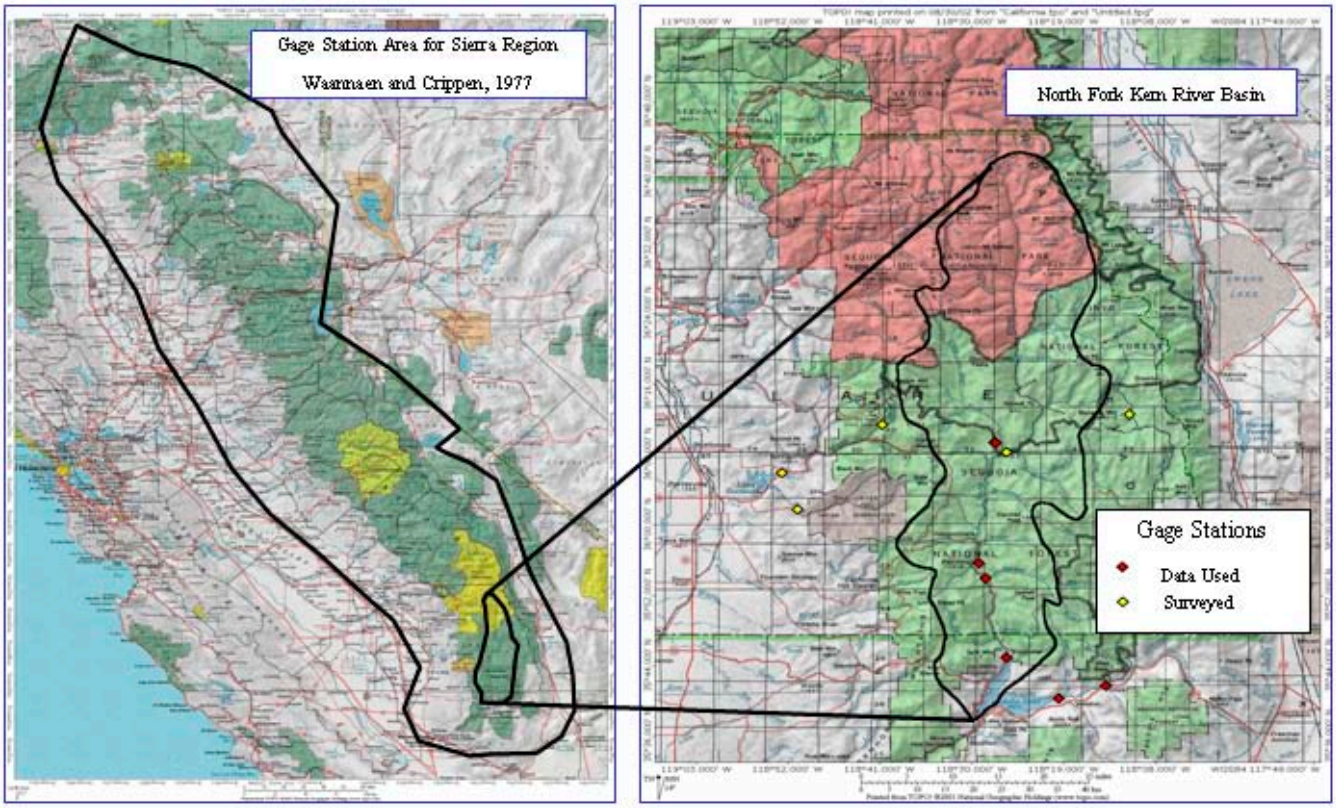


Figure 1. Sierra Nevada Region flood frequency curves from Waananen and Crippen (1977) using drainage area, mean annual precipitation and altitude index values from the North Fork Kern River.

Figure 2. Contrast and location of the Sierra Region and the North Fork Kern River basin. (below)



gage stations. Field crews collected data from cross sections, longitudinal profiles, and pebble counts following the protocol from Harrelson et al. (1994). Staff plate readings were taken at gage sites for bankfull discharge. Bankfull discharges were determined from station rating curves or USGS flow records. A protocol modified by McCandless and Everett (2002) was used for field surveys at gage stations. Modification of the protocol involved surveying only riffle habitats, and bed and bank material for most sites was characterized from reach-averaged pebble counts and riffle pebble counts. Stream bank material was not analyzed in this study.

Flow from most tributary streams was calculated using the Darcy-Weisbach with friction factor method after Hey (1979). Darcy-Weisbach uses hydraulic slope, cross-sectional area, mean depth, and the specific gravity of water in the following relationship:

$$U = \left(\frac{8gdS}{f}\right)^{1/2} \qquad (7)$$

where U = velocity, g = specific gravity of water, d = mean depth, S = hydraulic slope, and f is the friction factor defined by Hey (1979).

The friction factor, after Hey (1979), employs maximum depth, hydraulic radius and D_{84} of the bed material as follows:

$$\frac{1}{\sqrt{f}} = 2.03\log\left(\frac{aR}{3.5D_{84}}\right) \quad (8)$$

where f = friction factor, D_{84} is the fraction of the bed material that 84% is finer than, R = hydraulic radius, and a is a function of channel cross section shape that varies between 11.1 and 13.46 and can be approximated as:

$$a = 1.11\left(\frac{R}{d_{max}}\right)^{-0.314} \quad (9)$$

Manning's equation was used to calculate flow for channels with extremely low gradients and sand-size bottom material. Cross-sectional area, wetted perimeter, and slope were used to solve Manning's equation:

$$Q = \left(\frac{1.486}{n}\right)(A)(R^{2/3})(S^{1/2}) \quad (10)$$

where: Q = discharge in cubic feet/second, A = cross-section area in square feet, R = hydrologic radius in feet (area/wetted perimeter), S = water surface slope, n = Manning's roughness coefficient.

For those tributary streams with low gradient (slope between 0.001 and 0.02) and sand-size bed material Jarrett's resistance equation (1984) was used to calculate Manning's 'n'. Manning's 'n' is calculated as a function of slope and hydraulic radius (area divided by wetted perimeter). Jarrett's equation for Manning's 'n' is:

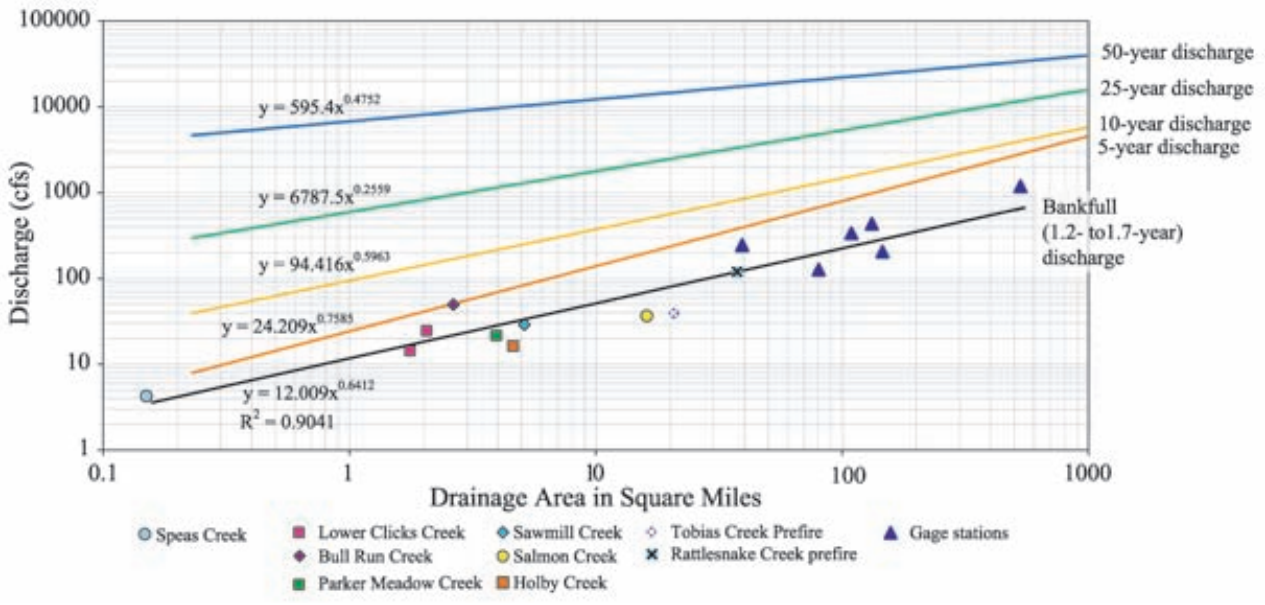
$$n = 0.39S^{0.38}R^{-0.16} \quad (11)$$

where: n = Manning's n value, S = hydraulic gradient, and R = hydraulic radius.

Field surveys and discharge measurements within the Kern River provided data to develop discharge versus drainage area relationships with a 1.2 to 1.7-year flood frequency (the lower-most [black] line in Figure 3). Actual data points for surveyed stations are also shown. The recurrence interval of 1.2 to 1.7 years is derived from discharge measurements either calculated as described above, or measured at gage stations then compared to annual peak flow frequency analysis at gage stations. Frequency analysis for gage stations determined the 2-year, 5-year, 10-year, 25-year, and 50-year return interval curves (Figure 3).

Comparison of Sierra Region discharge curves using the relationships defined by Waananen and Crippen (1977) to local Kern River hydro-physiographic curves derived from field measurements provided surprising results. There is a large discrepancy between the sets of curves, even though many of the same gage stations evaluated in the Kern River were also used by Waananen and Crippen (1977). This is especially interesting since there is a very strong correlation between gage station sites and discharge data from non-gaged sites within the Kern River area, with an R^2 value of 0.9. Figure 4 displays the relationship of Sierra Region flood frequency curves to local Kern River hydro-physiographic discharge curves by recurrence calculated using Waananen and Crippen (1977). It is interesting

Figure 3. Local Kern River hydrologic physiographic discharge relationships for bankfull, 5-year, 10-year, 25-year and 50-year recurrence interval. The 1.2- to 1.7-year discharge data were derived from field surveys; 5-, 10-, 25-, and 50-year discharges were acquired from USGS gage station discharge records.



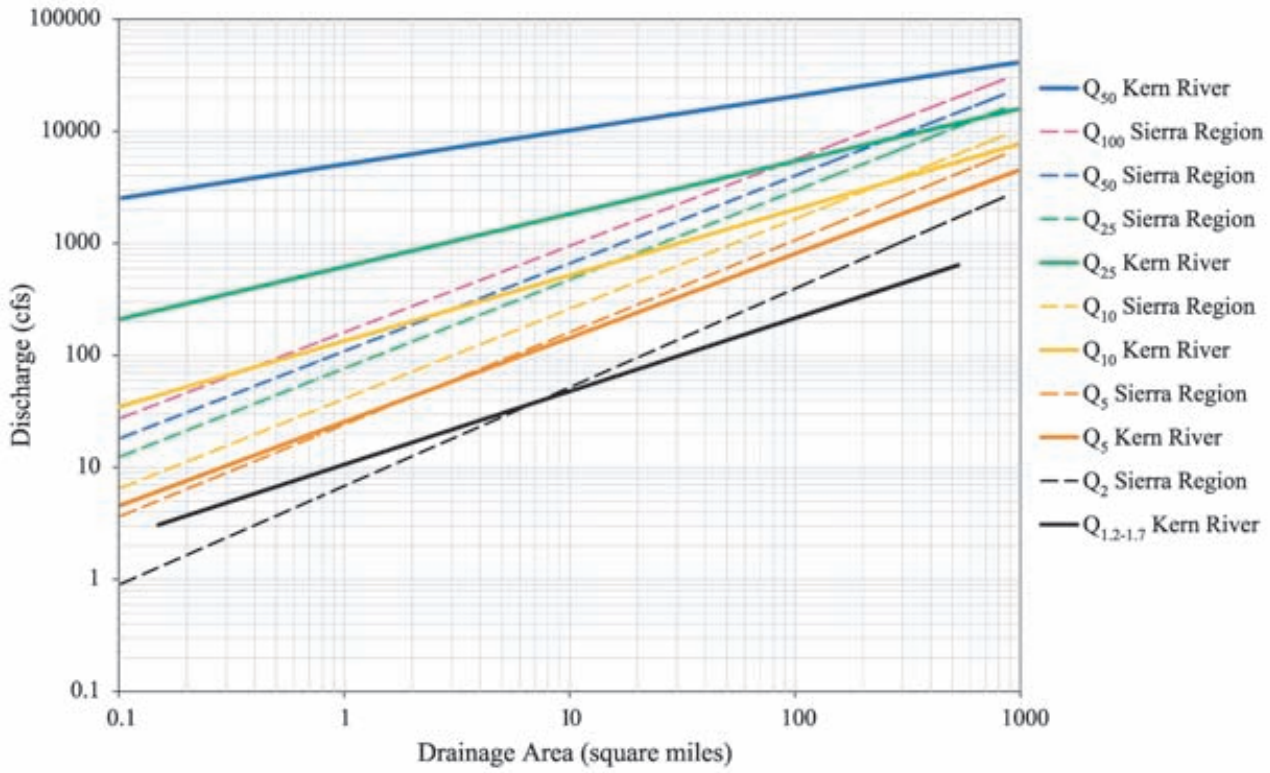


Figure 4. Relationship of Sierra Region flood frequency curves after Waananen and Crippen (1977) to local Kern River hydrologic physiographic flood frequency curves.

to note that for all frequency curves except the 5-year flood frequency curve there is an order of magnitude difference between locally calculated discharge and that calculated using Waananen and Crippen (1977). Discharge calculations using Waananen and Crippen (1977), for recurrence intervals greater than 5 years, are substantially lower than the measured discharge from the Kern River area. The 5-year flood frequency curve is reasonably similar to Kern River discharge relationships, while the 2-year flood frequency curve from Waananen and Crippen is lower for watersheds of roughly less than 5 square miles (13 km^2) and greater for watersheds greater than 10 square miles (26 km^2). This suggests that the Sierra Region equations provided by Waananen and Crippen (1977) provide reasonable estimates of discharge for 5-year recurrence interval estimates for any size watershed, and 2-year recurrence interval estimates for watersheds of roughly 5 to 10 square miles (13 to 26 km^2) within the Kern River area.

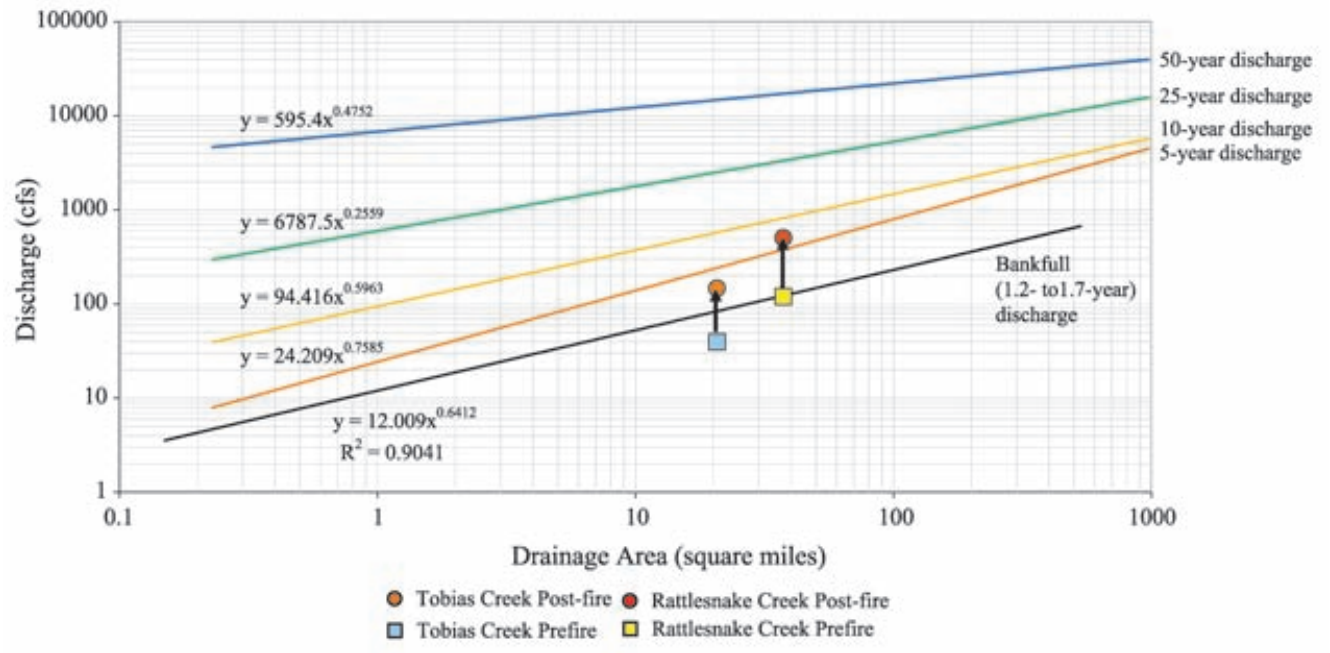
Just why this occurs could be related to application of state-wide gage station data across the Sierra Region to develop equations which were then applied to much smaller watersheds. The large variation in climate from north to south would be expected to account for some of the differences. Discharge relationships determined from local data (Figure 4) suggest that the equations from Waananen and Crippen grossly underestimate discharge for the North Fork Kern River, and it is clear that using data outside the immediate area provides substantially lower discharge for adjusted design flows. This could have serious implications in the case of BAER runoff determinations, which have the potential to affect life, property, and resources.

The data used to develop the Kern River hydro-physiographic discharge relationships (Figures 3, 4 and 5) are displayed in three groups (Appendix 1). The first group of figures represents field data collected at non-gaged sites along with discharge, velocity, and friction or n values used for resistance calculations. The second group is field data collected at gage stations and discharge information from station rating curves or USGS records. The third group is information used to develop discharge at the various recurrence intervals by watershed size derived from frequency analysis of peak flow data from the identified USGS gage stations.

Monitoring of Predicted Adjusted Design Flows in the McNally Fire Area

The author is responsible for the selection of recurrence interval relative to burn severity and runoff rate estimates used in the McNally fire. Monitoring results suggest that

Figure 5. Shift in post-fire discharge for Rattlesnake and Tobias Creeks as compared to local Kern River hydrologic physiographic discharge.



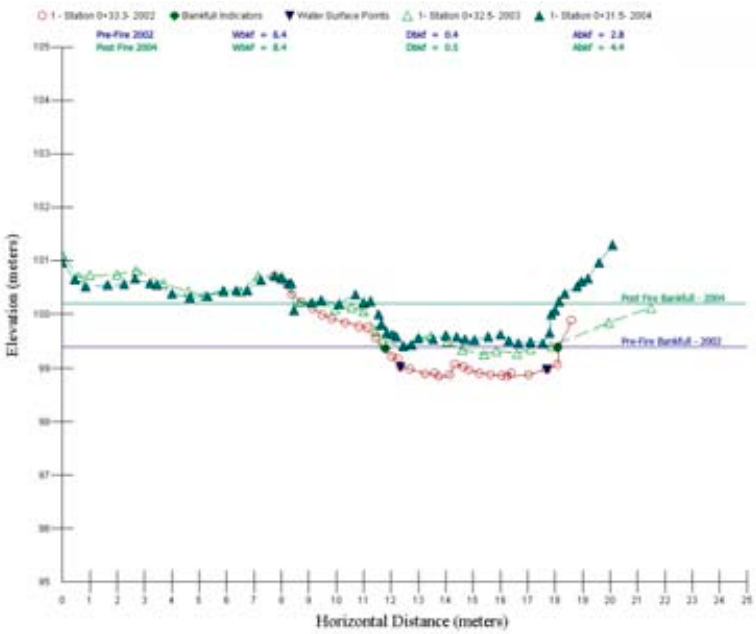


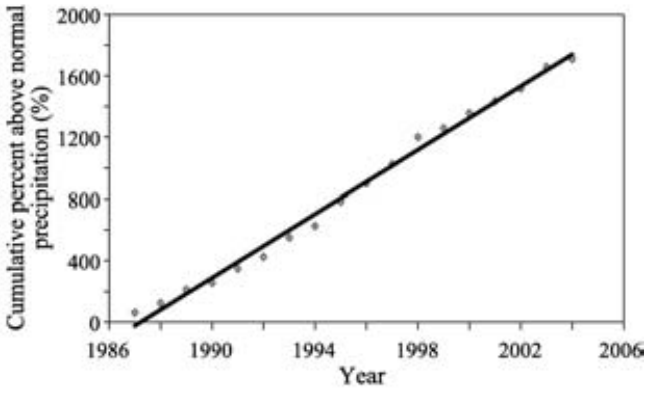
Figure 6. Rattlesnake Creek cross section 0+31.5 (2000-2004).

selected recurrence interval and discharge response for burn severity was grossly over-estimated, with the exception of those lands burned at low severity. This does not alleviate concern surrounding variance between Sierra Regional Flood Frequency curves versus local Kern River hydro-physiographic discharge curves. It only suggests that monitoring and follow up investigations of post-fire runoff rates is important so hydrologists can better estimate adjusted design flows in an emergency.

Monitoring of ungaged stream channels within the McNally fire area continued following the fire. And, serendipitously, the Tobias Creek watershed was surveyed just days prior to the fire. Rattlesnake Creek watershed was surveyed immediately after the fire prior to seasonal rains. These surveys were used in the creation of the bankfull hydro-physiographic discharge curves (Figure 3). Continued post-fire surveys have provided information on channel geometry following the wildfire.

Following the fire, channels of Tobias Creek and Rattlesnake Creek developed a new floodplain in response to increased runoff. Cross-sections and longitudinal profiles surveyed in 2003 and 2004 provided data on the channel geometry response to rainfall events. One of the cross sections taken on Rattlesnake Creek provides a good

Figure 7. Cumulative percent above average precipitation in the vicinity of the McNally fire at KR3 Intake, 1986-2004. (below)



example of floodplain development after the fire (Figure 6). Three years of data are overlaid in this figure. The newly formed floodplain provides bed and geometry information that was used to estimate discharge as previously discussed. When discharge values were plotted on Kern River hydro-physiographic discharge curves, they occurred between 5-year and 10-year recurrence curves. Rattlesnake Creek sustained higher burn severity and showed a higher recurrence than Tobias Creek. The post-fire discharge values have been plotted as circular points immediately above their square pre-fire points (Figure 5).

Rainfall events included the winter storm of November 2002 and numerous average annual thunderstorm events of July and August 2003. However, a study of 1987 to 2004 cumulative annual percent-above-normal rainfall by year did not show anomalous or unusually intense rainfall post-fire (Figure 7). This suggests that the increased runoff after the fire rather than an unusually high runoff season is responsible for the change in channel geometry. Furthermore, field investigations at Osa Meadow between August 2003 thunderstorms provide visual support that post-fire runoff is responsible for the creation of new floodplain in Rattlesnake and Tobias Creeks. Osa Meadow is located at the eastern edge of the McNally fire. The upstream section of the meadow was not affected by the fire; however the lower section of the meadow received increased runoff generated by a low severity burn in the headwaters of a tributary channel. The series of summer thunderstorms responsible for development of a new floodplain in Rattlesnake and Tobias Creeks was responsible for flooding in the lower portion of Osa Meadow. The portion of the meadow upstream where burning did not occur in tributary streams was unaffected by the storm. Figures 8a and 8b show Osa Meadow above and below the flooding caused by the McNally fire. The distribution of organic material defining the high water in upper Osa Creek meadow has a width of roughly three feet

Figure 8. (a) Osa Meadow upstream of fire effects. (b) Osa Meadow downstream of fire effects.

(0.9 m) commensurate with bankfull width, suggesting a storm responsible for a discharge of 1.2 to 1.7 years. The lower meadow had an accumulated flood width of roughly thirty-three feet (10 m) resulting from the same storm event. As evidenced in these two photos, the two sections of creek responded differently to the same event. These two areas are no more than 200 feet (61 m) apart.

Summary

The results of this study suggest that local flow relationships provide the basis for design and adjusted design flow for emergency evaluations. However, when local information is unavailable the use of the 5-year flood frequency equation from Waananen and Crippen (1977) provides reasonably good estimates for watersheds of all sizes, while the 2-year flood frequency curves provide reasonable estimates of discharge for watersheds of roughly two to ten square miles (5 to 26 km^2) within the Kern

River area. Other recurrence interval discharge equations from Waananen and Crippen (1977) grossly underestimate discharge for the North Fork Kern River area. This could have serious consequences in the case of BAER runoff determinations which have the potential to affect life, property, and resources.

Comparison of post-fire effects to predicted adjusted design flow may provide managers with a way to predict discharge following fire, based on channel geometry. Currently there are only two locations with data available, so the concept is based on professional judgment and limited data. With additional study it may be possible to develop a dataset based on local fires and their effect on post-fire channel discharge. This study suggests that post-fire channel geometry may provide information on runoff rates following wildfires when compared to a set of recurrence interval discharge curves developed for the physiographic region associated with the wildfire event.

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I would also like to thank the Pacific Northwest Region of the Forest Service who supported the funding of Channel Geometry and Discharge curve development in the Southern Sierra Nevada. Without this funding this study would never have taken place. Very special thanks go to Dr. Dave Rosgen whose intensive review improved the quality of this document and Dr. Dan Tormey who spent many hours asking the right questions and providing sound suggestions. Additional thanks go to the two reviewers provided by the conference review team, Valdon Hancock and Mike McNamara.

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Appendix 1. Data used for development of local hydrologic physiographic relationships.

Ungaged Creeks	Drainage Area (mi^2)	X-Sectional Area (ft^2)	Discharge (cfs)	Velocity ($ft\ s^{-1}$)	Friction factor *or "n" value	Resistance Equation Used
Speas	0.15	1.20	4.24	2.97	0.39	Darcy-Weisbach
Lower Clicks Creek	1.76	8.60	14.32	1.53	0.07*	Jarrett
Lower Clicks Creek	2.06	11.80	24.49	2.21	0.06*	Jarrett
Bull Run Creek	2.64	10.66	49.63	4.44	0.03	Darcy-Weisbach
Parker Meadow Creek	3.95	7.21	21.7	2.04	0.16	Darcy-Weisbach
Holby Creek	4.62	10.76	16.25	1.15	0.02*	Jarrett
Sawmill Creek	5.13	8.50	29.02	2.87	0.08	Darcy-Weisbach
Salmon Creek	16.10	13.99	36.62	3.73	0.12	Darcy-Weisbach
Tobias Creek 2002 Pre-fire	20.70	26.91	39.5	1.46	3.50	Darcy-Weisbach
Tobias 2003 Post-fire	20.70	39.83	146.34	3.75	0.44	Darcy-Weisbach
Rattlesnake 2002 Pre-fire	37.42	23.36	119.5	5.99	0.24	Darcy-Weisbach
Rattlesnake 2003 Post-fire	37.42	77.50	503	6.55	0.22	Darcy-Weisbach

Gage Stations		Drainage	X-Sectional	Bankfull	Bankfull Return
Name	Number	Area (mi^2)	Area (ft^2)	Discharge	Interval in Years
Wishon Fork Tule River	11202000	39	37	243.7	1.69
Tule River Near Springville	11204000	80	60.7	127.15	1.2
South Fork Tule River	11204500	109	63.2	337	1.31
Little Kern River Near Quaking Aspen Camp	11185400	132	74.00	435.00	1.53
SF Kern River Near Olancha	11188200	146	50.00	205.00	1.55
Kern River Near Quaking Aspen Camp	11185350	530	230.00	1186.00	1.21

Gage Stations		Drainage	Discharge Values at Associated Return Intervals from Gage Records			
Name	Number	Area (mi^2)	5-Year	10-Year	25-Year	50-Year
Salmon Creek	11186380	0.23	7.00	50	300	3000
Salmon Creek	11186360	0.30	12.00	90	700	7000
Salmon Creek	11186340	0.45	10.00	40	175	1000
Wishon Fork Tule River	11202000	39	1548	5333	11530	15049
Tule River Near Springville	11204000	80	1360	2280	not available	not available
South Fork Tule River	11204500	109	3084	4466	6857	12075
Little Kern River Near Quaking Aspen Camp	11185400	132	2010	7370	14000	57200
SF Kern River Near Olancha	11188200	146	1000	1314	3500	20000
Kern River Near Quaking Aspen Camp	11185350	530	4053	7867	15000	30000
Kern River Near Onyx	11189500	530	2389	3576	6784	17196
Kern River near Kernville river only	11186000	846	5241	10533	27076	46510
Kern River at Isabella	11190000	982	1788	3612	10000	40000

The Effects of Selected Postfire Emergency Rehabilitation Techniques on Small Watershed Sediment Yields in Southern California

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Forest Service Research has quantified the effects of selected Burned Area Emergency Response (BAER) treatments on sediment yields from small watershed by constructing dams to impound runoff and measure debris from several burn sites in southern California. In this paper, we cite examples from three studies to demonstrate the effectiveness of these treatments. In 1999 the Mixing Fire burned over 1200 hectares of mixed pine/oak forest with a brush understory on granitic terrain in the San Bernardino National Forest. A 1-hectare watershed treated with log erosion barriers (LEBs) was compared to a nearby untreated burned catchment. Results indicate that, although the LEBs retained considerable sediment, unforeseen differences in site characteristics masked any differences in treatment effectiveness. The 2002 Williams Fire burned over 15,000 hectares of chaparral on largely metamorphic terrain on the Angeles National Forest. Seven different 1- to 2-hectare watersheds were used to compare the effects of the soil flocculent polyacrylamide (PAM) or prefabricated small-diameter log structures as channel check dams against nearby untreated watersheds. Results indicate that PAM had no effect but that the channel check dams significantly reduced sediment yield. In 2003, the Cedar Fire burned about 117,000 hectares of brush on granitic terrain in the Cleveland National Forest. Three 2- to 3-hectare watersheds were used to compare two levels of an aerial hydromulch treatment (100 percent treated and 50 percent contour strips) to a nearby untreated watershed. Preliminary results indicate that the 50 percent treatment produced more sediment than the untreated but the 100 percent treatment generated less than half the sediment of the untreated watershed. Rigorous testing needs to continue before these erosion control treatments become standard practice.

Keywords: *fire, post-fire erosion, erosion control, monitoring, debris basins, sediment yield, BAER treatments*

Introduction

In fire-prone ecosystems of the southwestern United States, it has been well documented that wildfire can dramatically alter the erosion response of upland landscapes (Kraebel 1934; Wells 1981; Heede et al. 1988), primarily by removing the protective vegetation canopy and ground surface organic material. In addition, the combustion of soil organic matter can create a subsurface water-repellent layer that restricts infiltration and promotes overland flow (DeBano 1981), thereby enhancing sediment production (Hamilton et al. 1954; Hibbert 1985). In southern California, first-year post-fire sediment yield is 35 times greater on average than annual levels in comparable unburned areas (Rowe et al. 1954).

Accelerated post-fire erosion and sedimentation can threaten life, property, and infrastructure at the southern California wildland/urban interface, where growing population centers meet the adjacent steep mountain fronts. Moreover, post-fire environmental degradation can adversely affect habitat and populations of endangered species along sensitive riparian corridors. To mitigate these undesirable post-fire consequences, federal land managers have developed a Burned Area Emergency Response (BAER) program of hillslope and stream channel rehabilitation treatments for the purpose of erosion control. The goal of these treatments is to cost-effectively protect both the onsite and downstream values at risk until the native vegetation community can recover to the point that the watershed functions normally again.

Furniss, M.J., Clifton, C.F., Ronnenberg, K.L., eds., 2007. *Advancing the fundamental sciences: proceedings of the forest service national earth sciences conference, San Diego, CA, 18-22 October 2004*. PNW-GTR-689. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station.

Landscape level post-fire erosion control treatments attempt to reduce and delay the accelerated erosion and sedimentation that typically follows wildfires. Although many types of treatments have been used over the years, they can be grouped into three different classes: 1) ground covers (mulch, seeding) to reduce the erosive power of rainsplash and overland flow; 2) mechanical barriers (log erosion barriers, straw wattles) to retain debris; and 3) chemical sprays (wetting or flocculating agents) to promote infiltration, thereby reducing overland flow. Unfortunately, the benefits of many of these erosion control measures have yet to be quantitatively demonstrated in rigorous field studies (Robichaud et al. 2000).

Forest Service Research has quantified the effects of selected BAER treatments on small watershed sediment yields from several burn sites in southern California. The purpose of this research is to evaluate the effectiveness of these rehabilitation efforts as erosion control practices, as well as to document the post-fire sediment yield response from a variety of different field locations. Eventually, the results will be incorporated into models for planning and risk assessment.

Study Sites and Treatment Descriptions

The study sites are located on Forest Service lands in the mountains of southern California (Figure 1). Although the study areas have differing site characteristics (Table 1), they were all burned in wildfires during the late summer or early fall. Fires in southern California are especially intense at this time of year, occurring at the end of the summer drought and often fanned by strong Santa Ana winds. For this study, we chose small burned watersheds, 1 to 3 hectares in size, which were treated operationally with various rehabilitation measures. Sediment yield from these treated watersheds was then compared with similar nearby burned but untreated control watersheds.

Figure 1. Study locations in southern California.

Table 1. Selected study site characteristics

Attribute	Mixing Fire	Williams Fire	CedarFire
Elevation	1500 m	900 m	700 m
Bedrock	Granitic	Metamorphic	Granitic
Soil Texture	Loamy sand	Loamy sand	Sand
Watershed Area	1 ha	1-2 ha	2-3 ha
Aspect	N to NW	SW to SE	W to S
Hillslope Angle	37%	68%	21%
Channel Gradient	27%	34%	14%

The Mixing Fire

In September 1999, the Mixing Fire burned over 1200 ha on the San Jacinto Ranger District of the San Bernardino National Forest. The fire occurred in an area of granitic terrain at an elevation of 1500 m in the San Jacinto Mountains. The general area receives annual average precipitation of 550 mm, including snow in the winter and occasional thunderstorms in the summer. The specific study site supported a mixed forest of pine (*Pinus coulteri*), black oak (*Quercus kelloggii*), and canyon live oak (*Quercus chrysolepis*) with an understory of buckbrush (*Ceanothus leucodermis*) and manzanita (*Arctostaphylos* spp.) (Wohlgemuth et al. 2001).

Much of the area burned by the Mixing Fire was treated with log erosion barriers (LEBs). LEBs are built by felling and placing fire-killed trees along the hillside contours (Figure 2). They are designed to retard the overland flow of water and sediment on hillside slopes, reducing post-fire hillslope erosion and sediment delivery to stream channels (Robichaud et al. 2000). LEBs are placed in an overlapping arrangement that maximizes ponding (fostering infiltration and sediment deposition) and minimizes potential barrier failure.

The Williams Fire

In September 2002, the Williams Fire burned over 15,000 ha on the San Gabriel River Ranger District of the Angeles National Forest. The fire occurred in an

Figure 2. Overlapping network of log erosion barriers (LEBs) on the Mixing Fire site.

area of metamorphic terrain at an elevation of 900 m in the San Gabriel Mountains. The general area receives annual average precipitation of 700 mm generated almost exclusively by winter cyclonic storms. The specific study site supported brushfields of mixed chaparral dominated by buckbrush, chamise (*Adenostoma fasciculatum*), and scrub oak (*Quercus berberidifolia*) (Wohlgemuth 2003).

A portion of the Williams Fire area was treated with polyacrylamide (PAM), a proprietary soil-flocculating agent. The intent of this helicopter-applied treatment is to aggregate the fine soil particles, thus promoting infiltration and thereby reducing overland flow (Flanagan and Chandhari 1999), especially in areas of suspected water repellent soils. Other sections of the Williams Fire were treated with prefabricated small-diameter log structures placed perpendicular to the flow, roughly 5-10 m apart along the stream courses. These barriers were intended to serve as sediment storage sites and grade control structures to prevent the scouring of the channel bed and banks by accelerated post-fire runoff (Wohlgemuth 2003).

The Cedar Fire

In October 2003, the Cedar Fire burned over 117,000 ha on the Descanso Ranger District of the Cleveland National Forest. The fire occurred in an area of granitic terrain at an elevation of 700 m in the foothills of the Laguna Mountains. The area receives annual average precipitation of 415 mm, primarily generated by winter cyclonic storms with rare summer thunderstorms. The specific study site supported chaparral brushfields composed almost exclusively of chamise (Kirsten Winter, Cleveland National Forest, personal communication).

Approximately 350 ha of the Cedar Fire were treated with aerial hydromulch. A wood and paper fiber matrix with a non water-soluble binder, the mulch was mixed as a slurry and applied by helicopter. It was delivered at two application rates: 100 percent cover, and 50 percent cover in 30 m contour strips. The intent of the mulch treatment was to bind the loose surface soil together, reducing detachment and transport by rainsplash and overland flow, while still allowing infiltration across the landscape.

Methods

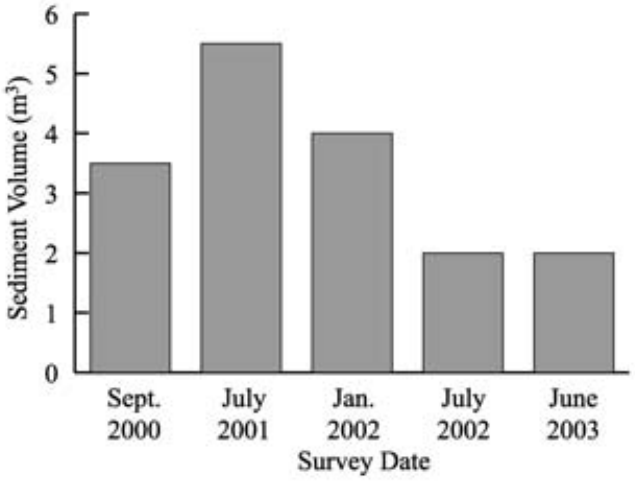
Monitoring facilities and equipment were installed at the Mixing Fire site within two months after the wildfire. One watershed was instrumented in an area treated with LEBs and a nearby catchment was instrumented as an untreated control. The monitoring installations consisted of wood and sheet metal debris dams constructed across the stream channels to impound sediment; raingages; and a weather station (temperature, relative humidity, solar radiation, wind speed, and wind direction). Initial LEB sediment storage capacities were estimated by measuring two or three ground surface profiles across the storage area perpendicular to the log, obtaining an average, and multiplying by the length of the log. LEB accumulations were determined by periodically re-surveying the profiles and calculating the difference in storage volumes. Sediment yield from the watershed was measured by collecting the trapped debris from behind the dam in buckets and weighing it on a portable scale. Subsamples of the sediment were taken back to the laboratory to correct the field weights for moisture content. Results were normalized by watershed area as megagrams per hectare, Mg/ha (metric tons), to facilitate comparison.

The Williams Fire burned over existing small watershed monitoring facilities on the San Dimas Experimental Forest. Two watersheds were selected for a PAM application and two nearby catchments were chosen as untreated controls; PAM application occurred two months after the fire. Two other watersheds had 25 to 35 log structures

placed in the channels and were compared against a single nearby control catchment. The monitoring facilities consisted of earth-fill dams with concrete outflow structures (Rice et al. 1965), raingages, and a weather station (temperature, relative humidity, solar radiation, wind speed, and wind direction). Sediment yields were calculated as volumes using an engineering end-area formula (Eakin 1939) based on repeated sag tape surveys of permanent cross sections (Ray and Megahan 1978). The volumes were converted to weights using measured debris densities, and the results were normalized by watershed area as Mg/ha to facilitate comparison.

Monitoring facilities and equipment were installed at the Cedar Fire site within three months after the wildfire. One watershed was instrumented in an area treated with 100 percent aerial hydromulch cover, a second nearby catchment was instrumented in an area with 50 percent contour strips, and a third catchment was instrumented as an untreated control. The monitoring installations were configured as for the Mixing Fire, above. Small sediment accumulations were also handled in the same way as those from the Mixing Fire. However, large sediment accumulations were handled differently. As with the Williams Fire sites, volumes were calculated from sag-tape surveys and converted to weights using measured debris densities. The sediment was then removed with a mechanical excavator and the surveys were repeated to obtain the new baseline geometry. Regardless of the measurement technique, results were normalized by watershed area as Mg/ha to facilitate comparison.

Figure 3. Sediment accumulation behind the log erosion barriers (LEBs) on the Mixing Fire site by survey date. Initial survey – January 2000.



Results and Discussion

Mixing Fire

The 1.2-ha treated watershed at the Mixing Fire site contained 157 LEBs with an initial total sediment storage capacity of 72 m^3. Overall, the LEBs performed as designed. Only about 6 percent of the LEBs failed due to undermining and another 6 percent had a significant flow of water around the ends of the logs (Wohlgemuth et al. 2001). At present, less than 4 percent of the LEBs have had their storage area filled with sediment, while about 5 percent have been rendered useless after being struck by wind-toppled fire-killed trees. The LEB accumulations for the first four years of the study are shown in Figure 3. Cumulatively, a total of 17 m^3 of sediment has been trapped by the LEBs, less than 25 percent of their capacity. Note that the vast majority (over 75 percent) of the material accumulated during the first two years of the study (Figure 3).

Sediment yield for the Mixing Fire, separated by winter cyclonic storm and summer thunderstorm seasons, is shown in Table 2. These values are small compared to the Williams Fire and Cedar Fire sites, as well as to other published rates of southern California post-fire sediment yield (Rowe et al. 1954; Loomis et al. 2003). However, there are spectacular differences in sediment yield between the treated and untreated watersheds.

Initially, the treated catchment on the Mixing Fire site produced an order of magnitude more sediment than the untreated. This can be explained in part by the fact that the soil depths on the treated watershed are only half those of the untreated (Wohlgemuth et al. 2001). With the fire in late summer, the soils must have been nearly de-watered. With the low precipitation in the first post-fire winter (see

Table 2. Precipitation amounts and sediment yield results for the Mixing Fire by rain season.

	2000		2001		2002		2003	
	Winter	Summer	Winter	Summer	Winter	Summer	Winter	Summer
Precipitation (mm)[a]	254	47	301	68	167	8	550	49
Watershed Treatment	Sediment yield (Mg/ha)							
Log erosion barriers	0.20	0.20	0.04	0.06	0.10	Trace	0.05	Trace
Untreated	0.01	0.02	0.01	1.70	1.10	Trace	0.05	Trace

[a] *Average annual precipitation is 550 mm.*

Table 3. Precipitation amounts and sediment yield results for the Williams Fire by year.

	Watershed	2003	2004
Precipitation (mm)[a]		525	435
Watershed Treatment	Sediment Yield (Mg/ha)		
Polyacrylamide (PAM)	Treated 1	33.7	0
	Control 1	24.6	1.5
	Treated 2	53.9	0
	Control 2	59.8	0
Log structures	Treated 1	10.0	1.3
	Treated 2	8.4	0
	Control	34.7	0

[a] *Average annual precipitation is 700 mm.*

Table 2), water storage in the shallow soils was presumably exceeded on the treated watershed but not on the untreated catchment. The saturated soils in the treated catchment generated sediment delivery from the hillslopes to the streams by overland flow, and the routing of this sediment to the debris basin by channel runoff.

The pattern of watershed response on the Mixing Fire then reversed itself, starting with the second summer after the fire (see Table 2). A high-intensity thunderstorm produced a large sediment pulse in the untreated watershed, but had little effect on the treated catchment. Site inspection revealed that the source of the sediment in the untreated watershed was a large area of bare ground directly adjacent to the stream channel. The massive overland flow off this bare patch extensively rilled the hillside, and channelized flow scoured the channel bed and banks. Erosion from this section of bare ground continued to generate high levels of sediment yield into the winter of 2002 (Table 2).

It is unfortunate that sediment yield on the Mixing Fire site was governed more by the inherent site characteristics than by the presence or absence of the LEBs. This demonstrates the need to carefully choose comparable study watersheds. It also points out the problem with lack of replication in the study design. Because of the differences in soil depths and vegetation cover, any watershed response that would relate to the efficacy of the LEBs as a post-fire rehabilitation treatment has been effectively masked.

Williams Fire

The sediment yield results of the post-fire treatment comparisons for the Williams Fire (Table 3) indicate that, for this study site, PAM does little to reduce small watershed sediment yields. Although site differences may once again be a factor, with multiple treated and untreated catchments [with Treated 1 paired with Control 1 (untreated), and Treated 2 paired with Control 2 (untreated)], minimum replication was achieved. Observations over the course of the first post-fire winter revealed pervasive rilling on all watersheds, suggesting substantial overland flow. Although infiltration tests were not performed on the different watersheds, presumably the PAM did not work as intended. Alternatively, it is possible that these coarse-textured upland soils had too few fines to allow the PAM to be effective.

Table 4. Precipitation amount and sediment yield results for the Cedar Fire.

		2004
Precipitation (mm)[a]		170
		Sediment Yield (Mg/ha)
Watershed Treatment	100 percent cover	6.7
Aerial hydromulch	50 percent cover	20.5
	Untreated	14.9

[a] *Average annual precipitation is 415 mm.*

In contrast, the results indicate that, on the Williams Fire, the log structures in the two treated watersheds reduced the sediment yield by two-thirds compared to the single untreated control (Table 3). Although the untreated catchment is unreplicated, previous work (Rice et al. 1965) suggests that the sediment yield in the untreated watershed was actually lower than the two treated catchments prior to the Williams Fire. Virtually all of the storage space created by the log structures filled with sediment, and only a few of the structures failed by undercutting or side cutting. Debris retention and the protection against downstream channel incision could easily account for the observed difference in watershed sediment yield (Wohlgemuth 2003). There was also a rapid sediment yield decline in all watersheds during the second post-fire year (Table 3). This presumably attests to rapid watershed recovery in the fire area, although low precipitation values were undoubtedly partially responsible.

Cedar Fire

The first-year post-fire sediment yield results for the aerial hydromulch treatment comparisons on the Cedar Fire indicate that the 100 percent coverage produced less than half the sediment of the untreated control (Table 4). Paradoxically, the 50 percent coverage watershed generated half again as much material as the untreated watershed. This suggests that perhaps the hydromulch treatment is effective only at full coverage. Alternatively, with no replication, there is a distinct possibility that inherent site characteristics may again be obscuring treatment effects.

However, tests of water repellency, infiltration, soil depths, and landscape morphometry have thus far revealed no differences between the watersheds.

Curiously, there is little evidence across the Cedar Fire study area of hillslope overland flow, as observed on the Williams Fire. In contrast, there is a dramatic hydrologic response in the ephemeral stream channels to even comparably small rainstorms of moderate intensity (less than 10 mm of rain in an hour). In the absence of overland flow, it is unclear how the water reaches the channels so quickly after a burst of rain. Observations in the stream courses also reveal substantial erosion of the channel bed and banks. This suggests that the majority of the material captured in the debris basins consists of remobilized channel sediments. Thus, the whole premise of treating hillslopes to reduce watershed sediment yields may be unfounded in this environment. However, the catchment with the 100 percent aerial hydromulch treatment produced fewer runoff events with smaller stormflow peaks than the other two watersheds under very similar rainfall patterns. This indicates that perhaps the value of this rehabilitation treatment is not to reduce hillslope erosion but rather to control water on the hillsides before it can reach the stream channels.

Conclusions

Accelerated erosion following fire is inevitable, magnifying the risk of sedimentation-related damage to biological and human communities at the wildland/urban interface. Land managers will continue to seek out post-fire erosion control measures that are both effective and environmentally benign. The methods of erosion control employed in this study show some promise, but were not an unqualified success. The studies presented here suggest that LEBs were successful in retaining some sediment on the Mixing Fire, but that a test of treatment effectiveness was inconclusive because differences in site characteristics may have masked LEB performance. Results from the Williams Fire were likewise inconclusive, but suggest that for coarse-textured upland soils, PAM may be ineffective. However, log structures placed in the stream channels soon after burning showed great promise as a means of reducing sediment yield downstream. Aerial hydromulch at high percent coverage rates may have been an effective treatment on the Cedar Fire, but exactly how it worked remains unclear. The foregoing uncertainties illustrate the need for continued testing on these and other BAER treatments before they become standard practices. Furthermore, robust economic analyses are necessary to determine whether the various treatments are a cost-effective means of reducing erosion from hillslopes and sediment yields from burned watersheds.

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Detecting Smoke Plumes and Analyzing Smoke Impacts Using Remote Sensing and GIS for the McNally Fire Incident

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Remote sensing and GIS techniques were developed and evaluated to retrospectively analyze the impacts of the McNally Fire on air quality. The McNally Fire was a large wildfire over 54,700 ha (150,000 acres) in size that occurred in the Sequoia National Forest, California, 21 July through 26 August 2002. MODIS satellite images and NOAA pictures were used to digitize smoke plumes. Smoke plumes were analyzed using ESRI ArcGIS Spatial Analyst. Air monitoring data was acquired from 23 locations for PM_{10}. Ozone data was acquired from 40 locations. ArcGIS Geostatistical Analyst was used to analyze and produce prediction maps using Kriging as an interpolation method. A strong positive correlation between PM_{10} maximums and number of smoke plumes was observed. The correlation between PM_{10} averages and number of smoke plumes observed was not as strong. Very high ozone concentrations generated by the the McNally fire were observed northeast of the fire, and affected mainly mountain sites. Ozone impacts due to the fire were not observed at valley sites. Remote sensing and GIS techniques were useful in assisting with the evaluation of fire smoke impacts on air quality.

Keywords: *wildfire, air quality, smoke, remote sensing, GIS, PM_{10}, ozone*

Introduction

Wildland fires are a complex combustion source that involve several categories of fuels, and are characterized by fire behavior that changes over time with fuel and weather conditions. Smoke from wildfires is composed of hundreds of chemicals in gaseous, liquid, and solid forms (Ottmar and Reinhardt 2000). Some of the main concerns for land managers are the production of particulate matter and ozone from prescribed burns and wildfires. Managing fire to comply with national ambient air quality standards (NAAQS) requires an increasingly detailed base of scientific knowledge and information systems. Wildfire smoke is transported across state and land management agencies. Smoke impacts during these episodic events can threaten public health and may be the dominant cause of visibility reduction. Particulate matter (PM), the direct product of smoke is one of the greatest concerns due to its impacts on public health and visibility (Billington et al. 2000). Burning of forests can generate the precursors for substantial ozone concentrations downwind of the fire (Cheng et al. 1998). But, there is little research that links fire emissions with ground-level ozone concentrations. Also, there is uncertainty about the effects of ozone formation caused by mixing of fire emissions with urban sources (Sandberg et al. 2002).

The McNally fire was a large-scale wildfire, over 54,700 ha (150,000 acres). It occurred in the Sequoia National Forest, in the Sierra Nevada of California, during the period of 21 July through 26 August 2002. Smoke from this fire was transported over hundreds of kilometers across the California state boundary, degrading air quality and reducing scenic values. Characterization of effects of wildland fires on ambient air quality is incomplete due to the deficiency of air quality monitoring sites in rural areas. Knowledge about fire's effects on air is needed to meet regulatory and management requirements. New methods

Furniss, M.J., Clifton, C.F., Ronnenberg, K.L., eds., 2007. *Advancing the fundamental sciences: proceedings of the forest service national earth sciences conference, San Diego, CA, 18-22 October 2004*. PNW-GTR-689. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station.

and information are needed to assess, monitor and predict smoke plumes.

This report evaluates the use of remote sensing and GIS techniques as a decision support tool to retrospectively analyze the McNally fire impacts on air quality. Also, the report evaluates the extent and duration of wildfire smoke on communities and provides insight to the magnitude of smoke impact from the fire on PM_{10} (particulate matter, 10 microns or less) and ozone.

Methods

Aerial Data Acquisition

The MODIS images came from the TERRA satellite. MODIS or Moderate Resolution Imaging Spectro-radiometer is an instrument aboard NASA's TERRA and AQUA satellites. The daytime pass of TERRA goes over California at approximately 12:00 pm (1900 UTC). MODIS images were compiled and processed over the duration of the McNally Fire by the Remote Sensing Application Center (RSAC). The bounding coordinates of the image subset were: (west) 119.95° W, (east) 116.96°W, (north) 37.41°N, and (south) 34.41°N. The images were set to a spatial resolution of 250 meters, and georeferenced using the Lambert Azimuthal projection parameters. MODIS data were input into NASA processing software application for reflectance correction. The images were then imported into ERDAS Imagine[1] and saved in IMG (.img) format. Twenty-five images were collected.

Pictures were also collected from National Oceanic & Atmospheric Administration (NOAA) in JPG format. NOAA pictures helped us digitize plumes that went across state boundaries, as NOAA pictures covered a larger area than MODIS images. There were a total of 15 NOAA pictures collected for the whole incident.

Plume Analysis Procedures

To view smoke plumes, the best band combination to use is the natural color composite. The bands are 1 (red), 4 (green), and 3 (blue). Imagine files have seven bands (Table 1).

MODIS images were screen digitized in ArcGIS, as shown in Figure 1, and further processed in ArcInfo Workstation. ArcInfo Workstation was used to clean and build the topology of the polygons created in ArcGIS.

NOAA pictures were used to help digitize smoke plumes that went across state boundaries, because they covered a larger area than MODIS images. It was complicated to differentiate between clouds and smoke using NOAA pictures, but these pictures were good for depicting the overall direction and distance of the plume.

Table 1. The seven bands and wavelengths of MODIS imagery.

MODIS Band	Wavelength (nm)	Name
1	620-670	red
2	841-876	near IR
3	459-479	blue
4	545-565	green
5	1230-1250	mid IR
6	1628-1652	mid IR
7	2105-2155	mid IR

Figure 1. MODIS images were screen digitized.

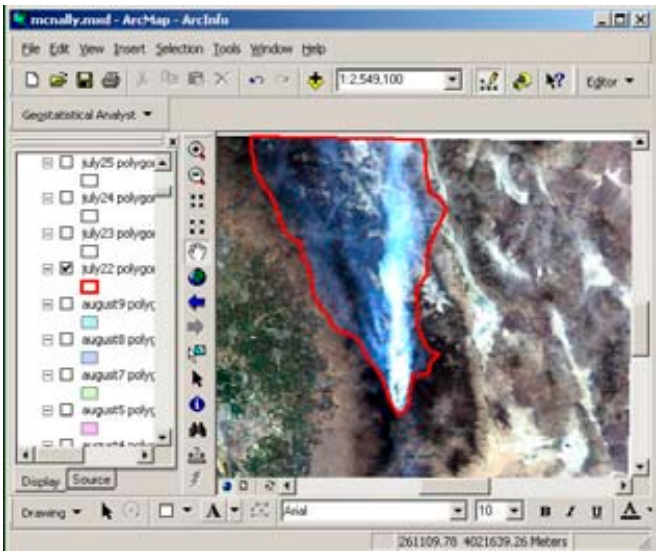
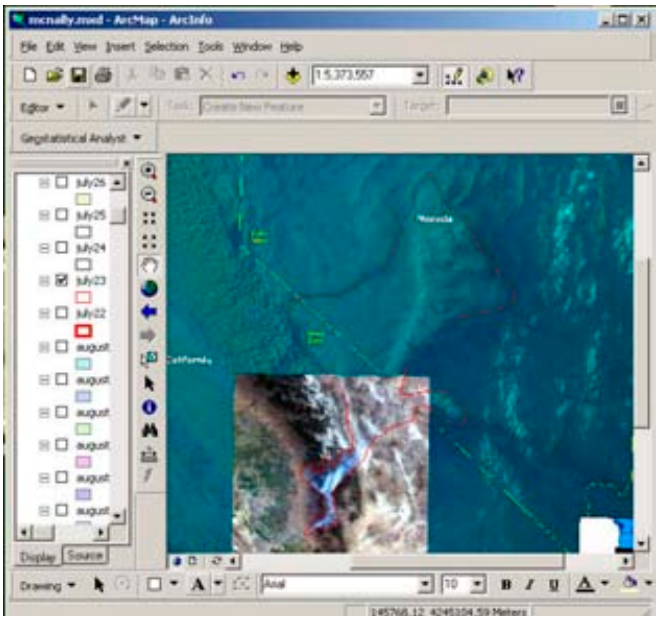


Figure 2. NOAA pictures were used in conjunction with MODIS images to digitize plumes that went past MODIS extent.



[1]The use of trade or firm names in this publication is for reader information and does not imply endorsement by the U.S. Department of Agriculture of any product or service.

Figure 3. Twenty-five smoke plume polygons were digitized over the entire duration of the fire.

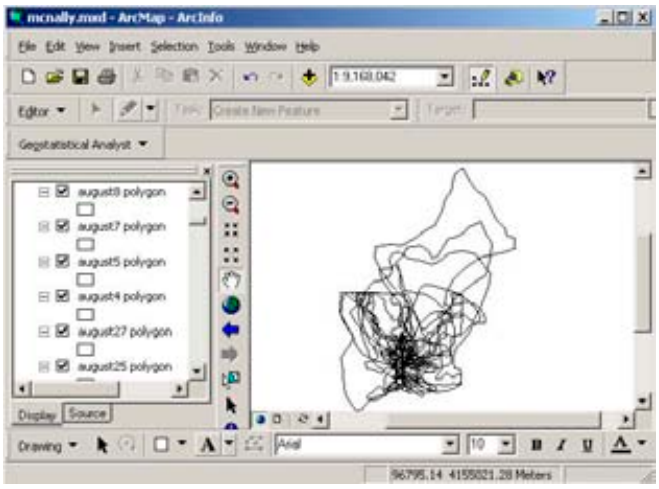


Figure 4. A single smoke plume polygon.

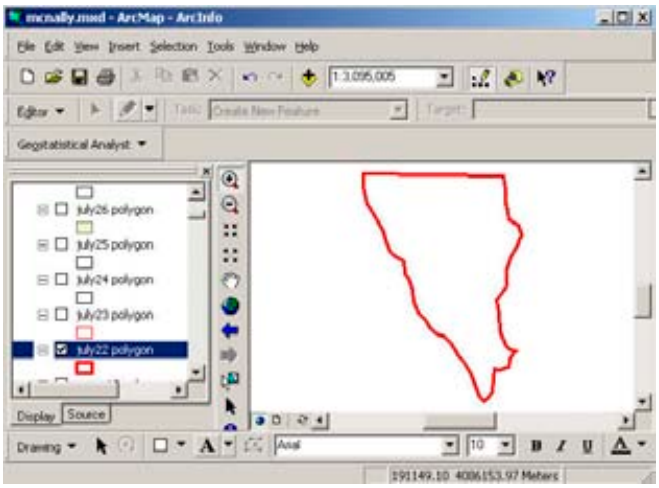


Figure 5. The polygon in figure 4 is converted to raster format.

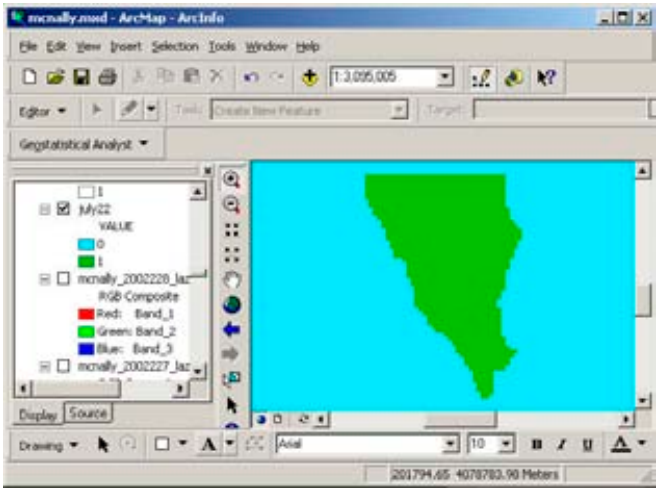
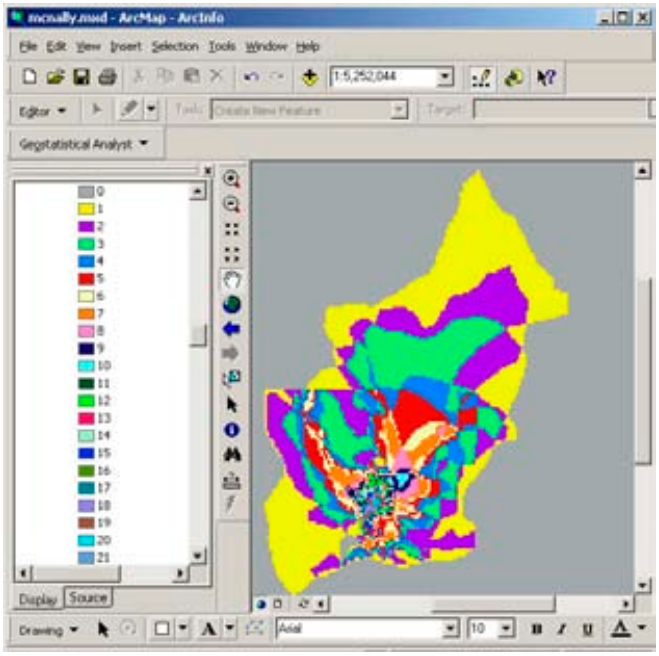


Figure 6. Map produced by the Raster Calculator.



A total of 25 smoke plume polygons were created (Figure 3), each representing a smoke plume observed one time per day. The MODIS satellite takes a snapshot once per day around noon. The fire lasted for 35 days. Plumes were digitized for 25 days out of a total of 35 days possible days of the fire, because on some days the images weren't available, or the image wasn't clear. All polygon coverages created were projected in NAD 1927, UTM Zone 11N. The Geographical Coordinate System used was GCS North American 1927.

All polygons were converted to raster format (Figure 4, Figure 5). The area inside the polygon was given a band value of 1, and a band value of 0 was assigned for the area outside of the polygon.

Raster datasets were created from each polygon and became thematic data. The Spatial Analyst extension in ArcGIS was used to describe the raster created from polygons. The cells created had a size of 3108 m with a total of 250 rows and 266 columns, and one band. This output resolution was determined by the Spatial Analyst. The optimum cell size to capture the appropriate detail varies from study to study. The smaller the cells, the greater the resolution and accuracy, but coding, database storage, and processing speed are more costly.

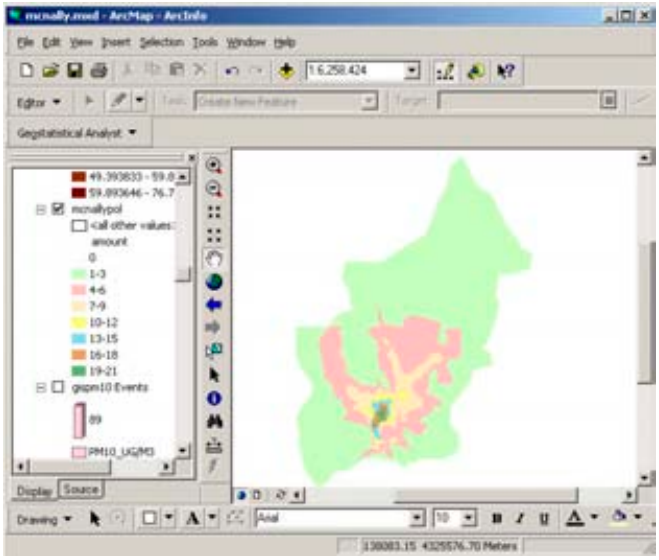
A zonal function was chosen to continue with the processing of all 25 raster datasets. Zonal functions compute an output raster dataset. The output value for each location depends on the value of the cell at that location and the association that the location has within a cartographic zone. All raster datasets must share the same coordinate system and the same projection.

The Raster Calculator provides the tools to perform mathematical calculations such as arithmetic operations. All 25 raster datasets were added together to produce the final raster. Each single input raster had a band value of 0 and 1, which represents the times that a plume was

observed. The final raster has a band value of 0-21; the value describes the number of times or days a plume was observed over a given location. The highest value was 21, which indicates that when overlaying all of the 25 plumes (raster) together only 21 overlapped. In other words, 21 out of the 25 plumes was the highest frequency observed over the same location (Figure 6).

The final raster was converted into a polygon coverage and classified by the number of plumes observed in a given location, grouped in threes. There were a total of seven groups (1-3, 4-6, 7-9, 10-12, 13-15, 16-18, and 19-21). The coverage was classified into seven groups because it is easier to interpret output images with seven colors than with twenty-one colors (Figure 7).

Figure 7. Frequency of plume occurrence classified into seven groups. The numbers refer to the frequency of plumes observed.



Air Quality Data Acquisition for Particulate Matter

Air monitoring data for particulate matter was acquired from 23 locations. The air monitoring data collected hourly concentrations of PM_{10}, which were converted into 24-hour averages. The data included air quality data from the Air Resources Board network, IMPROVE (Interagency Monitoring of Protected Visual Environments), the Great Basin Air Pollution Control District in Bishop, CA (north and east of the fire), and the Forest Service's Kernville Work Center (just south of the fire). IMPROVE data is part of the long term monitoring program establish to monitor visibility trends. The monitoring data from Bishop is part of the Great Basin Air Pollution Control District monitoring network. The data from the Kernville Work Center came from a monitoring station set up by the Forest Service at the beginning of the fire.

Air Quality Data Acquisition for Ozone

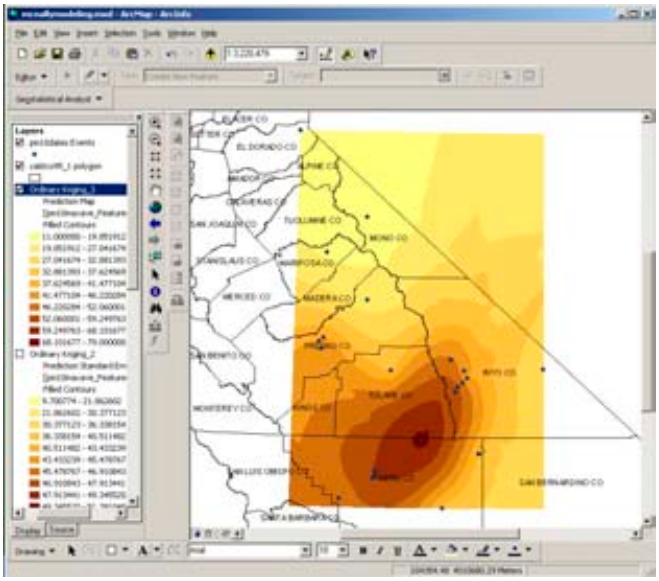
Air monitoring data for ozone was acquired from 40 locations. Twenty-four locations used ozone passive samplers and 16 used active monitors. The ozone passive concentrations were provided in two-week averages, thus hourly data from the active monitors was converted to two-week averages as well. The ozone passive data were provided by the USDA Forest Service Riverside Fire Lab. The active monitor data were provided by the Sequoia National Park, San Joaquin Air Pollution District and Air Resources Board network.

Air Quality Data Analysis Procedures

Interpolation methodologies were used to create a prediction map (Figure 8 and 9) in Geostatistical Analyst to showcase what could be done using GIS. Ordinary Kriging is a quick interpolator that is very flexible, allowing investigation of spatial autocorrelation. Inverse Distance Weighting (IDW), the simplest of all interpolators, could also be used, but it does not provide a standard error map. IDW is a quick, exact deterministic interpolator. It allows a few choices regarding model parameters, and there are no assumptions required for the data. For the purpose of this project Ordinary Kriging was used because it allows the creation of a prediction standard error map, although no manipulations were done. Geostatistical Analyst was used to create a prediction map and a standard error map.

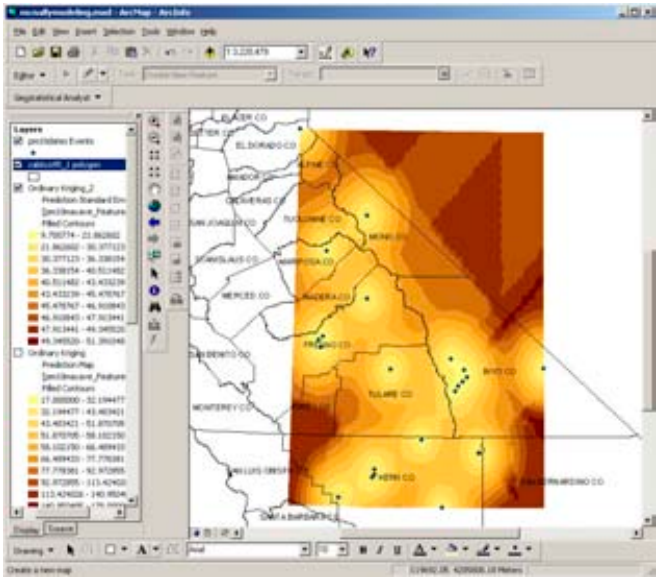
Air quality data from monitoring stations were transferred into ArcGIS, and a point coverage was created.

Figure 8. Prediction map created using ordinary Kriging. Blue dots symbolize monitoring station locations. The map displays the PM_{10} 24-hour average concentrations in $\mu g/m^3$ averaged over the duration of the fire.



The PM_{10} 24-hour averaged data covered the duration of the fire from 21 July through 27 August. Ozone data was collected in two week averages and covered the following dates: 2 - 16 July, 16 - 30 July, 30 July - 13 August, and 13 - 28 August 2002.

Figure 9. Standard error map. The blue dots represent the monitoring sites. Predictions are more reliable closer to the monitoring sites.



Results and Discussion

The following discussion used the satellite plume data, PM_{10}, and ozone air quality data processes outlined in the methodology to analyze the impacts of the McNally fire.

Data Analysis Using Remote Sensing and GIS for PM_{10}

Looking at Figure 10, it is evident that the locations with the highest frequency of smoke plume occurrences also had the highest PM_{10} 24-hour Maximum concentrations. This finding indicates a positive correlation between frequencies of plume observed over the general fire area and production of particulate pollution measured as PM_{10}.

The correlation between plumes and the average of the PM_{10} 24-hour concentrations was not as strong (Figure 11).

When looking at the correlation coefficient r^2 for PM_{10} 24-hour averages and PM_{10} 24-hour maximum, the interpretation is the same as the observations made before using GIS and remote sensing. A strong positive correlation between the frequency of smoke plumes and the concentrations of PM_{10} 24-hour maximums for the duration of the fire was observed (with $r^2 = 0.820$ and alpha = 0.05). For the duration of the fire, the correlation between frequency of smoke plumes and PM_{10} 24-hour

Figure 10. The PM_{10} 24-hour maximum concentrations ($\mu g/m^3$) bar graph overlay over the plume layer.

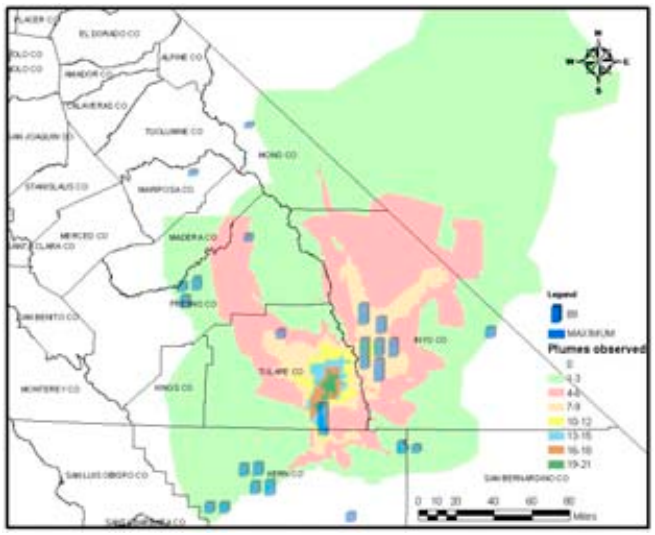


Figure 11. The average of the PM_{10} 24-hour concentrations ($\mu g/m^3$) bar graph overlay over the plume layer.

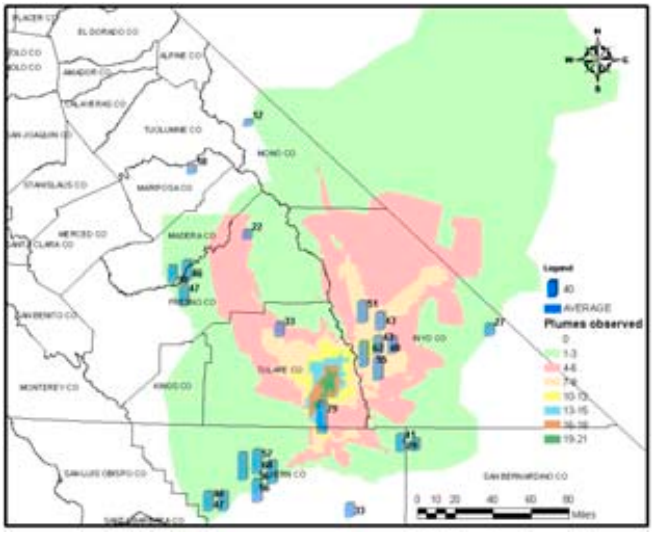


Figure 12. Two-week averages of ozone concentration (ppb) overlaid over the plume layer.

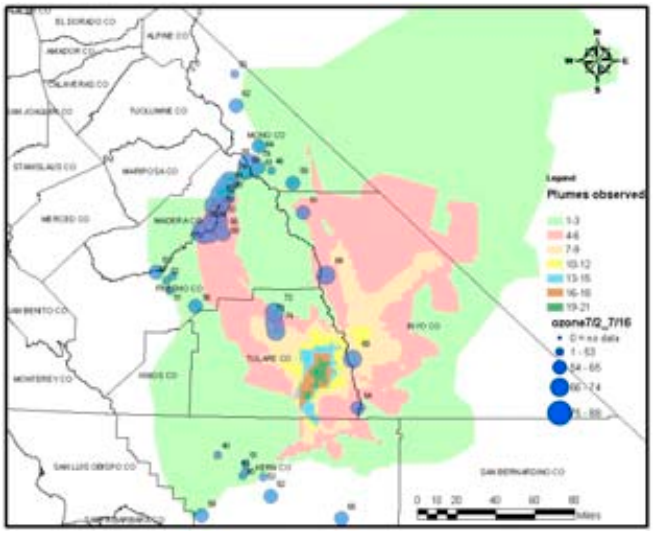


Figure 13. Ozone concentrations (ppb) and ozone monitoring locations, before the McNally fire.

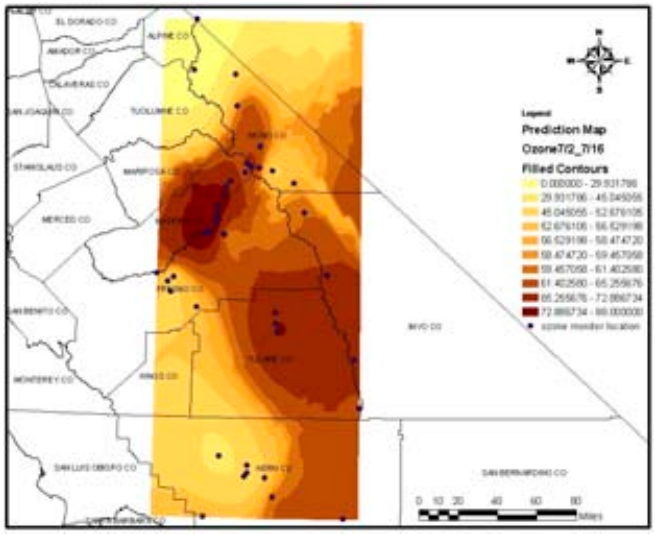
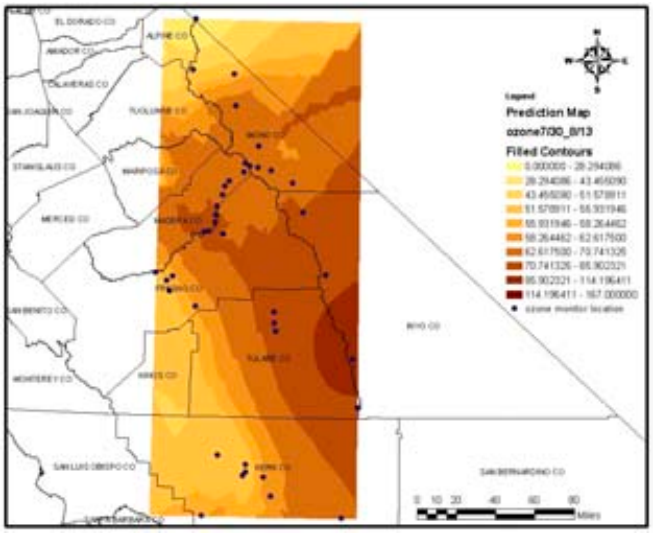


Figure 14. Ozone concentrations (ppb) and ozone monitor locations, on 30 July 2002, during the McNally fire.



averages was also positive, but not as strong (with r^2 = 0.492 and alpha = 0.05). It is clear that a large area of the Sierra Nevada experienced very high levels of PM_{10} concentrations during the fire.

Data Analysis Using Remote Sensing and GIS for Ozone

There is no observational evidence of correlation between frequency of smoke plumes and ozone concentrations (Figure 12).

Before the McNally fire started, the highest ozone two week concentration averages occurred in the mountain sites. Figure 13 illustrates a typical ozone distribution in the area before the fire started. During that period (2 - 16 July 2002), the maximum two week average did not exceeded 90 ppb.

During the fire (30 July - 13 August), the distribution of ozone concentrations is completely different. The highest concentrations occurred in the eastern part of the Sierra Nevada, downwind of the fire, with the maximum two week averages over 160 ppb. Figure 14 provides evidence of correlation between ozone generation and catastrophic forest fires. In the Sierra Nevada, due to the proximity of the urban-related California Central Valley plume, which is rich in nitrogen oxides (NO_x), there is a strong potential for generation of very high ozone concentrations when elevated concentrations of volatile organic compounds (VOCs) are present as a result of forest fires.

Ozone monitoring locations located in the San Joaquin Valley or in urban locations apparently were not affected by the McNally fire. Descriptive statistics are about the same before and during the fire for monitoring sites located in cities. Monitoring sites located in the mountains did show differences in ozone concentrations before and during the fire (Table 2).

Conclusions

In this paper, we outline a method for relating fire emissions to particulate matter and ozone concentrations using remote sensing and GIS. Locations that had the highest frequency of plume impacts also had the highest PM_{10} 24-hour maximums concentrations. There is clear observational evidence of positive correlation between frequencies of plumes observed over a site with particulate

Table 2. Descriptive statistics of two-week ozone averages (ppb) for 40 ozone monitoring stations before and during the fire. The monitoring sites were classified as city (urban location), or mountain location.

	2 - 16 July		16 - 30 July		30 July - 13 Aug.		13 - 28 Aug.	
Ozone Concentration (ppb)	**city**	**mtn.**	**city**	**mtn.**	**city**	**mtn.**	**city**	**mtn.**
Mean	52.95	67.79	52.5	71.47	53.89	76.19	55.32	87.8
Maximum	65	88	65	90	68	167	73	186
Minimum	40	46	44	51	42	41	44	59
Average	24	42	21	39	25	126	29	127
Standard Deviation	7.4	10.8	6.4	11.2	9.2	24.1	9.7	24

matter air pollution. The highest PM_{10} maxima occurred in the eastern part of the Sierra Nevada closer to the fire and downwind of the fire. The McNally fire produced very high two-week average ozone concentrations in mountain sites, but there is no evidence that the fire affected sites in urban locations. During the fire, the highest ozone episodes occurred in the eastern part of the Sierra Nevada downwind of the fire.

Remote sensing and GIS approaches used in this paper could be beneficial for other air quality concerns such as for $PM_{2.5}$, and could be applied to analyze other wildfires. We conclude that GIS techniques and remote sensing could be extremely useful in evaluating wildfire impacts on air quality.

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Sierra Nevada Framework Smoke Monitoring: Testing Implementation Through a Pilot Program

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An increasing need to treat hazardous fuel conditions in the Sierra Nevada combined with a geographic relationship to surrounding air basins with very serious air quality issues has resulted in challenges for land management and air regulatory agencies. A series of policies, plans and regulations at federal, state, and local levels addresses issues that require attention in order to increase treatment with prescribed fire while protecting public health. Monitoring fine particles (PM_{10}) produced by smoke provides land management and regulatory agencies with information necessary to avoid significant community impacts. Recently, new filter-based monitoring systems have been developed. Met One's BAM-1020 beta attenuation mass monitor is a federal reference method that meets the EPA requirements for monitoring PM_{10} compliance, but can be limited in use by land management agencies due to a lack of portability and reliance on line power. Met One's E-BAM is a portable real-time beta gauge. While not a federal reference method, the EBAM has shown strong correlation with BAM data and is highly portable. A pilot program has been developed to test the utility, accuracy, reliability, and data management requirements of these instruments in a comprehensive network. The test network will include three fixed-site BAMs in sensitive communities and approximately 10 portable EBAMs that will be deployed in communities as needed to characterize the impacts of smoke from prescribed fire and wildland fire.

Keywords: *air quality, air pollution, smoke, monitoring, regulations, hazardous fuels*

Introduction

California has a significant number of sources that emit fine particles (defined as particles with an aerometric diameter of 10 µm (PM_{10}) and 2.5 µm ($PM_{2.5}$) and smaller, respectively). The climatic, meteorological, and geographic features in many parts of the state provide suitable conditions for these pollutants to accumulate and reach serious levels. Fine particle concentrations in much of the state are at levels that cause respiratory illness and premature human mortality. About half of the state, primarily central and southern California, does not attain the federal PM_{10} and $PM_{2.5}$ standards. Virtually all of the state, with the exception of Siskiyou and Lake counties, is non-attainment or unclassified for the more stringent California PM_{10} standard.

California is divided into 35 regulatory air pollution control districts with oversight provided by the California Air Resources Board (CARB) and the US Environmental Protection Agency (EPA). This regulatory framework is considered effective at developing local accountability and control strategies tailored to local issues. However, it also presents a very challenging and complex environment to land management agencies attempting to manage an increasing fuels issue. California leads the nation in aggressive strategies to reduce air emissions, and with major emitting industrial sources largely controlled, the focus is now on smaller sources.

Generally there is good public support both for air quality and for the need to reduce hazardous fuels. However, when the two issues are seen to conflict, the urban population is often more air quality sensitive, and is pitted against more fire-sensitive rural communities. In this setting of air quality and fuels issues the public increasingly expects agencies charged with the stewardship of these resources to resolve conflicts and negotiate a path that protects public health, maintains public safety, and protects forest resources. High quality information, including monitoring of fine particles, is necessary to help define the operational area that can accomplish fuels reduction while minimizing the impacts of smoke on air quality.

Issues Leading to the Investment

A successful smoke monitoring program can lead to a wealth of information adding more certainty to issues related to public health, and a better understanding

Furniss, M.J., Clifton, C.F., Ronnenberg, K.L., eds., 2007. *Advancing the fundamental sciences: proceedings of the forest service national earth sciences conference, San Diego, CA, 18-22 October 2004*. PNW-GTR-689. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station.

of spatial and temporal trends that effect community exposure.

Irrespective of regulatory requirements, Forest Service managers require smoke monitoring information to assist in better fire management, air quality stewardship, and maintaining good community relationships. Some of the management questions that a monitoring program can help answer include:

What are the tradeoffs between prescribed fire and wildfire impacts? A better understanding of emission production and exposure of wildfire and prescribed fire is necessary to fully understand the role of prescribed fire in eventually reducing emissions generated from wildfire.

How does urban air pollution and smoke contribute to visibility impairment? Visibility in national forests, especially in Class I wilderness areas, is an important resource and wilderness value. Understanding the entire mixture of pollutants and sources will be critical in working with states to improve visibility.

What is the natural and current background of smoke? Comparing current background of smoke and PM concentrations with pre-European estimates will be important in defining natural background. Natural background may be used to determine regulatory allocations.

What is the impact on communities and public health? This is the essence of regulatory pressure on public land agencies, and monitoring is necessary for informed decisions to protect public health.

What is the public tolerance? In addition to regulations for prescribed fire California regulates actions that create public nuisances. More monitoring data will help understand thresholds of public tolerance that differ from health thresholds.

How can monitoring contribute to the testing and validation of models? Models being developed to predict smoke dispersion, such as the Blue Sky smoke model, can be validated if the modeling domain is characterized with monitoring.

What mitigation and contingencies are the most successful in minimizing smoke and public exposure? The Forest Service has developed guidelines and training to institute measures that can be effective in reducing emissions. Monitoring in conjunction with these mitigations can validate their effectiveness.

In addition to management needs, regulatory requirements and policy in California dictate or strongly recommend monitoring in some situations. California's Title 17 (Smoke Management Guidelines for Agricultural and Prescribed Burning) has provided the template for local regulations and requires smoke management plans to include appropriate monitoring, which may include visual monitoring, ambient particulate matter monitoring or other monitoring approved by the district for:

(1) projects greater than 250 acres (101 ha);

(2) projects that will continue burning or producing smoke overnight;

(3) projects conducted near smoke sensitive areas; or

(4) as otherwise required by the district (CARB 2001).

Monitoring data also contributes to more informed regulatory decisions. Serious air quality issues in California require action with or without data and often daily regulatory decisions, such as burn-day allocations, are supported by meteorology data, but not air quality data. Air quality monitoring data can also be used to test, validate, and adjust PM_{10} reduction strategies.

Pilot Study Design

The Forest Service has experimented with a number of particulate samplers over the last 20 years with varying success. Nephelometer based optical monitors have been used with some success, but California has expressed more support for filter-based monitoring systems such as MetOne Instruments BAM 1020 and E-BAM samplers. These systems measure a radioactive isotope passing through filter paper before and after particles are deposited on the filter (Trent 2003).

The southern Sierra Nevada National Forests have steadily emerged as a candidate to test monitoring equipment due to serious fuels issues and the proximity to the San Joaquin Valley Air Basin, which is one of the most severely polluted air basins in the United States. An approach to characterizing smoke in the Sierra Nevada was developed during the Sierra Nevada Framework project and suggested different approaches for regional scale characterization and project level / community characterization. The Sierra Nevada Framework smoke monitoring study plan recommends using the Interagency Monitoring for Protected Visual Environments (IMPROVE) monitoring network in coordination with the state network to examine regional scale trends. The study plan recommends using BAM 1020 and E-BAM technology to evaluate community impacts. The Sierra Nevada Smoke Monitoring Pilot (SNSMP)) was designed to test the study plan recommendations.

BAM 1020 instruments were installed where the objective was to monitor year-round background, and where a secure site with line power was available. These instruments are located on the Sequoia National Forest in the communities of Pinehurst, Springville, and Kernville. The BAM 1020 is an EPA approved equivalent method

for PM_{10}. Seven additional tripod mounted E-BAMs were deployed on the Sequoia, Sierra, Stanislaus, and Inyo National Forests. E-BAMs, although not an EPA approved "equivalent monitoring method", provide quality data and portability, allowing good flexibility in deployment for short-term smoke events. These tripod mounted instruments also require line power. In addition three portable solar powered E-BAMs mounted on trailers are available for events where line power is not available. Some of the E-BAMs are equipped with basic meteorological instrumentation, including wind speed and direction, air temperature, relative humidity, barometric pressure, solar radiation, and precipitation.

Data Delivery

Particle data related to monitoring smoke is most useful in near real-time. Data that can be returned to land management and air regulatory agencies in near real-time allows for fire management strategies that can reduce smoke production or alter the transport. It also provides information to air regulatory agencies that can be used to better manage allocations and more information for burn day designations.

The SNSMP is testing the use of satellite modems via ORBCOMM combined with data delivery to a Web page that satisfies the real-time needs. The Website can be accessed at *http://www.satguard.com/usfs4*. Graphics of one, eight, and twenty-four hour averages are displayed along with tabular data details. Air Resource Specialists, Inc., in Fort Collins, Colorado provides data quality assurance reviews, monthly and annual data reports, and equipment support for the project.

Pilot Review

The SNSMP is planned to continue through March 2006. At that time the Region 5 Forest Service Air Program will review the durability, portability, maintenance, and data delivery of the network. In addition, we will review how well the instrumentation was used by air regulatory agencies and the Forest Service to improve coordination and make more informed decisions.

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Air Quality and Prescribed Fire Management–Moving Toward a Solution Space

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Smoke issues have come to the forefront as National Forests increase prescribed fire management treatments to implement the Healthy Forests Initiative and the Healthy Forests Restoration Act. Increases in the population living within the wildland-urban interface have resulted in a larger population exposed to prescribed fire smoke. The combination of increased burning and public smoke exposure has created a need for detailed public involvement plans; planning and prioritization of areas for treatment; interagency coordination between regulatory agencies, smoke managers, and public health officials; better predictive tools for weather forecasting, smoke production and dispersion; real-time air quality monitoring; creative methods of responding to legitimate health conditions; and derivation of realistic, quantifiable air quality objectives. The Okanogan-Wenatchee National Forests (OWNFs) in north-central Washington are a focal point for implementing a prescribed fire program of landscape-scale burns. Local objective levels of air quality particulate have been defined, and are monitored using an air quality instrumentation network. An extensive program of public information has been developed. Collaborative forest health treatments have been initiated with private property landowners and homeowner associations. The forests and the Washington State Department of Ecology (DOE) have entered an agreement whereby the Forest Service operates a network of nephelometers that are incorporated into a DOE air quality website. The desired outcome is the successful completion of an accelerated prescribed fire program with minimal exposure of the public to unhealthy levels of smoke concentration. This paper focuses on OWNFs' efforts since the wildfires of 1994 to develop quantifiable air quality objectives and incorporate them into an interagency prescribed fire management regulatory framework for an expanding burn program.

Keywords: *air pollution, air quality, smoke, prescribed fire, fire management*

Introduction

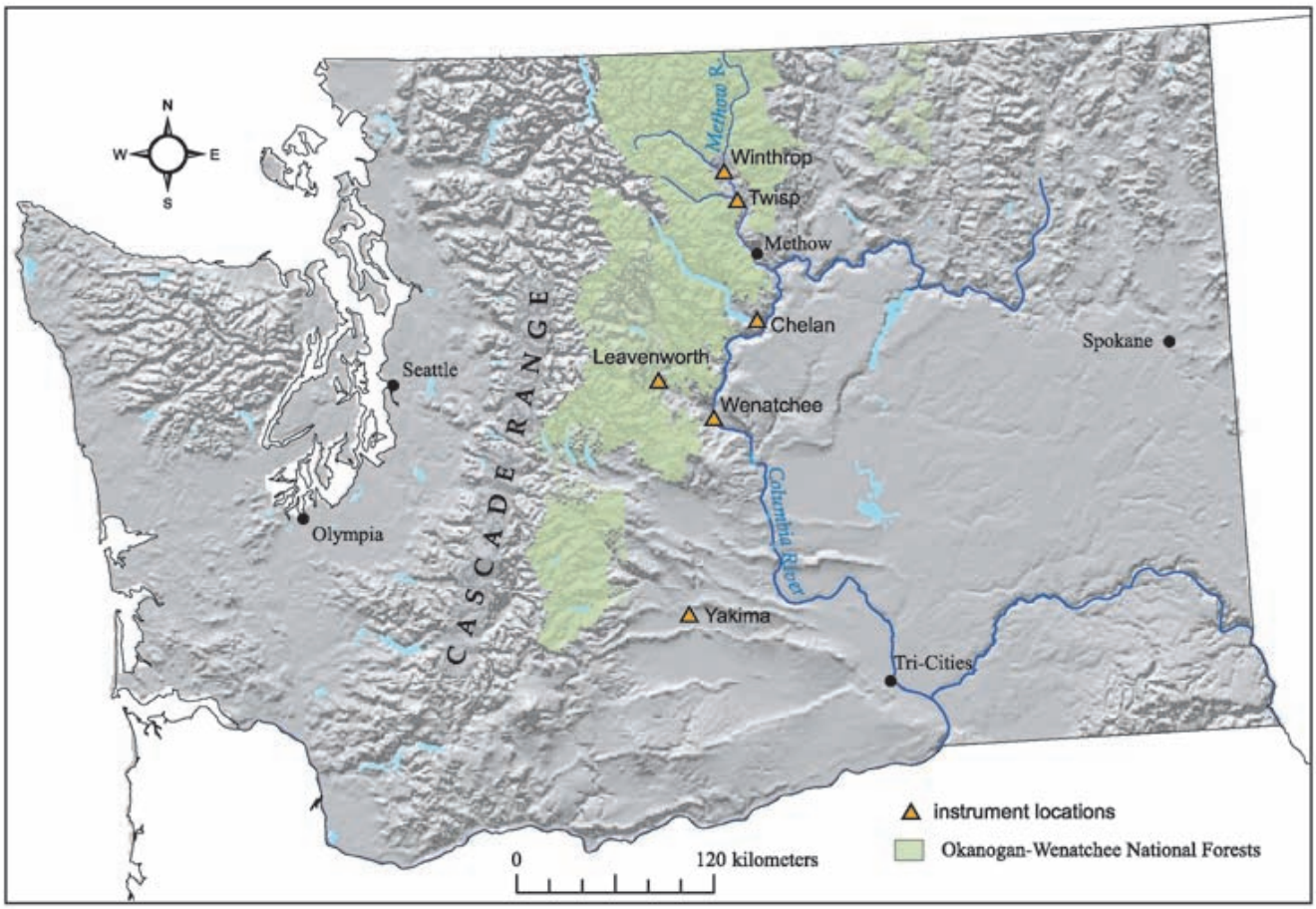
On 28 July 1994, dry-lightning storms started multiple wildfires across the Eastern Cascades of central Washington State. Conditions were extremely dry in the national forests. The 1994 water year was the third in a row in which annual streamflow had been well below average at various long-term gaging stations (USGS 2004; Robison 2004). Water years 1993 and 1994 were more than one standard deviation below period of record average values for the Wenatchee, Stehekin and Methow Rivers. The largest of the fires burned 185,000 acres (74,867 ha) on the Wenatchee National Forest. At that time, it was the largest wildfire complex within a single national forest in the history of the Forest Service (FS). The fires caused many weeks of impaired air quality in all five cities of Chelan County. This paper discusses the evolution of two resource management programs, the Healthy Forests Initiative, relying heavily on prescribed fire, and the Air Quality Management Program, both of which have evolved since the fires of 1994. The subject area is the Okanogan-Wenatchee National Forests (Forests) of central Washington State (Figure 1).

Following the 1994 wildfires, emergency fire restoration efforts began immediately with a detailed assessment of the burn area. Burn intensity mapping showed that sixth-field subwatersheds had as much as 50-75% of total drainage area in a condition of moderate to high burn severity. This fact as well as the large area burned increased the emphasis on quickly accomplishing emergency fire restoration. Various efforts to seed, fertilize, contour-fell burned snags across steep slopes, remove road culverts and improve road drainage were completed in what became the largest and most expensive emergency fire restoration effort in agency history.

In addition to the emergency restoration efforts, the forest supervisor chartered a science team to review the fires and make specific recommendations as to actions that could be taken to reduce the risk of recurrence of such large and intense wildfires. The team was charged with finding answers to three specific questions: Why were the

Furniss, M.J., Clifton, C.F., Ronnenberg, K.L., eds., 2007. *Advancing the fundamental sciences: proceedings of the forest service national earth sciences conference, San Diego, CA, 18-22 October 2004*. PNW-GTR-689. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station.

Figure 1. Location of air quality instruments within the Okanogan-Wenatchee National Forests of central Washington state.



fires so large? Why did they burn with such intensity? Were they within an expected range of natural variability?

Scientific Review Findings

The science team effort produced a number of key findings regarding changes in fire ecology, and the composition and structure of vegetative stands across the Eastern Cascades, especially on sites in the lower elevational range of coniferous vegetation. This broad area was labeled "dry site forest". It parallels but is east of the crest of the Cascades. These observations were packaged into a "Dry Site Initiative" which became one of a number of resource discussions that have led to the "Healthy Forests Initiative" (HFI) on a national scale (Office of the President 2002; Townsley 2004). The initiative focuses on identifying areas of "dry site forest", reducing fuel loadings, removing understory vegetation, reducing potential for insect and disease infestation across large landscapes, and creating a vegetative mosaic less prone to catastrophic fires on the scale of the 1994 fires. The amount of silvicultural burning, and especially the use of large-scale prescribed fire, has increased as a result of the initiative.

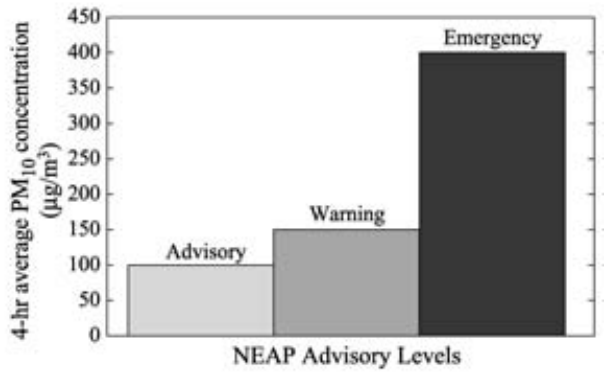
Chelan County Natural Events Action Plan

A second outcome of the fires of 1994 was the preparation of a Natural Events Action Plan (NEAP) for Chelan County. The Washington State Department of Ecology (DOE) led an interagency effort to prepare this contingency plan for wildfire. The NEAP was published in June 1997 and contained three goals: educate the public about wildfire, mitigate health impacts, and institute best available control measures (Greef 1997).

The NEAP defined three threshold levels of air particulate concentration: advisory, warning and emergency, and prepared a public health news release for each. The levels were based on a 4-hour average concentration of fine particulate less than 10 microns in diameter (PM_{10}) as measured in micrograms per cubic meter ($\mu g/m^3$) (Figure 2). This was the first NEAP in the country prepared as a contingency plan for wildfire and a subsequent adverse air quality situation.

Agency roles and responsibilities were defined. The Forests' role is to provide information about weather and wildfire conditions, and alert state and local agencies whenever a wildfire could potentially grow to such size

Figure 2. Natural Event Action Plan (NEAP) advisory levels of particulate.



as to generate a smoke incident. The DOE will review nephelometer data both from permanent DOE operated instrument sites and from any temporary sites established for the fire emergency, release public health information, and provide advice and counsel to the local public health agencies. Local public health officials issue public service news releases as needed. The NEAP has been implemented in Chelan County for wildfire situations almost every year since publication in 1997.

Air Quality Management During Prescribed Fire Operations

The emphasis on prescribed burning as a result of the local "Dry Site Initiative" and the national-scale HFI has increased attention on refining working relationships, roles and responsibilities of all agencies involved in fire management. The Washington State Department of Natural Resources (DNR) administers the Smoke Management Plan for the State of Washington via statute. DNR reviews each silvicultural burn request and makes daily approval decisions based on meteorological forecasts and projections of smoke production and dispersion (Washington Department of Natural Resources 1993). DOE operates air quality monitoring instrumentation, posts air quality information, and issues approvals for agricultural burning for the State. The FS is the prescribed fire manager for fires occurring on the national forests.

Prior to 1994, DOE's air quality focus was monitoring air quality in major population centers; it operated only two air samplers in the Eastern Cascades. In 2002 the Forest Service and DOE signed an agreement for the operation of five additional instruments, to provide better definition of background air quality, define impacts from all particulate sources including prescribed burning, and identify acceptable windows for burning. The Forest Service purchased and operates Radiance Research Nephelometers, but pays DOE for quality control oversight and posting of data on a state-wide DOE website. Figure 1 shows the location of instruments in the Eastern Cascades.

The collective knowledge and experience of the agencies involved in wildland fire management and public health since the 1994 fires has led to some consensus as to how to successfully operate these programs. It has become clear that wildfires occur on an almost annual basis, causing negative air quality impacts across a broad geographic area of the Eastern Cascades. Smoke becomes an air quality issue when trapped in local valley bottoms. Upper Columbia River valley communities, and often other states and Canada, are affected by adverse air quality conditions when major wildfire events occur. The causative events of air quality incidents can be a considerable distance away, but still may result in impacts on valley communities. Fires as far away as western Washington, Canada, and Alaska, and at least on one occasion, a dust storm in China, have resulted in noticeable air quality impacts. Agencies have concluded that the public should be given as much advance notice as possible when adverse air quality conditions are anticipated.

Forest fire management specialists have concluded, based on local experience and observation, that fuel reduction treatments have made a difference in control of wildfires (Harrod 2004). Wildfires have different burn behavior in stands where site treatments have reduced stocking of standing trees, minimized fuel ladder structure, and reduced volume of fuels. Agencies further concluded that strategic placement of these treatments has been effective in protecting areas of urban interface from fast-moving wildfires. Although these treatments have shown to be effective, they are limited in number. It will take many more treatments across a broader landscape to accomplish HFI objectives.

2003 Issuance of a Notice of Violation

The 2003 burning program in the Methow Valley began on 15 May and continued until 10 June. The Methow Valley Ranger District (MVRD) burned over 2,000 acres (809 ha) of prescribed fires. On 18 June, as a result of air quality conditions in the Methow Valley, DOE issued a Notice of Violation (NOV) to the Regional Forester, Pacific Northwest Region, "for causing and/or allowing air pollution from prescribed silvicultural burning in violation of the Washington Clean Air Act…that caused a nuisance, obscured visibility on roads, and presented a risk to the health of people who were residing in the area of the fires". The peak hourly $PM_{2.5}$ particulate value was 129 $\mu g/cm^3$ at the Twisp nephelometer on 5 June. Figure 3 shows daily maximum hourly nephelometer readings converted to $PM_{2.5}$ particulate in units of micrograms per cubic

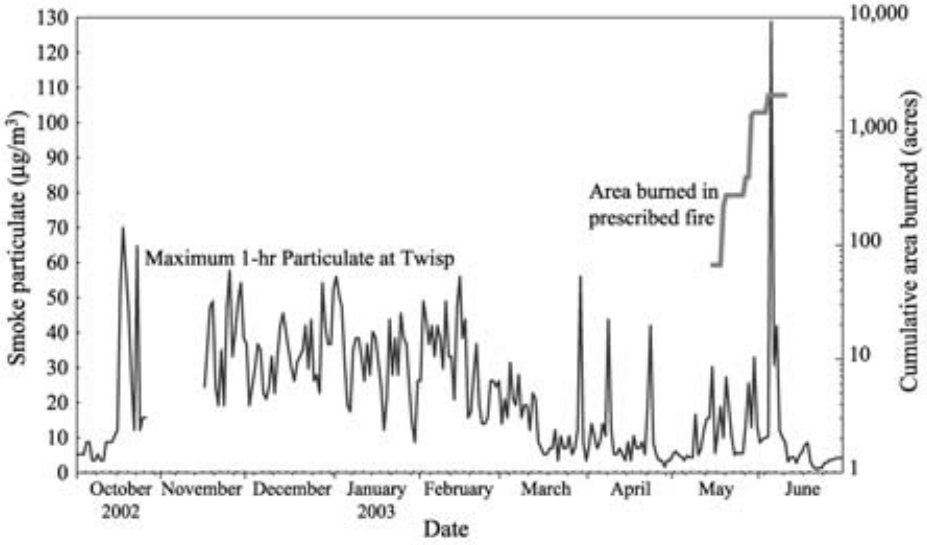


Figure 3. Twisp nephelometer daily 1-hour maximum $PM_{2.5}$ values for October 2002 to June 2003, with burn acreage.

meter (µg/m³). The monitor at Twisp was the only air quality instrument in the Methow Valley at the time. Observations of local conditions at Winthrop, eight miles further up valley and closer to the burns, were reported to be considerably worse.

The legal basis for this NOV is still debatable given that the burns had been ignited following daily dialogue between the Forests and DNR, and approval had been given by DNR. However the incident did highlight the fact that further dialogue was needed between the three agencies involved, especially given the increase in the prescribed fire program and the use of landscape scale burns. Because of the magnitude of air quality impacts, the forest conducted an internal review and initiated a number of corrective actions. These actions were incorporated into a settlement agreement between the three agencies and became the basis for further refinement of working relationships.

Settlement Agreement Action Items. A number of action items were implemented immediately as part of the settlement agreement.

- A Forest Service nephelometer was moved to Winthrop in the Methow Valley and added to the DOE state network, supplementing the existing DOE instrument at located at Twisp.
- A camera was installed at the Forest Service IMPROVE monitoring site overlooking the lower Methow Valley to provide live images of air quality conditions in the lower valley on the FS website. The live camera image can be viewed at *http://www.fsvisimages.com/pasa1/pasa1.html*.
- The MVRD started routinely requesting an on-site meteorologist for landscape-scale fires when conditions warranted.
- The forests began identifying landscape burns when requesting burn approval from DNR.
- This allowed DNR to issue three-day, instead of one-day, approval windows when warranted for these multiple day burns.
- DOE was given a daily listing of approved burns.

Longer-term improvements were also implemented. The MVRD improved and expanded the district public involvement plan (USDA FS 2004). A Forest Service complaint tracking system was developed and implemented so the District could document every inquiry from the public about burn activity and record agency responses. Coordination meetings and field reviews were scheduled for the three agencies. Attention was focused on coordinating public information messages issued through the news media regarding burning. Collaborative work continued with the Pacific Northwest Research Station and University of Washington research scientists to refine smoke dispersion computer models (Ferguson 2004). A resolution to settle the NOV was signed by DOE, DNR, and the Forest Service Pacific Northwest Region in September 2003.

2004 Refinements to the Air Quality Management Program

Action items were implemented in 2004 with good results. Between 29 March and 1 June over 7,600 acres (3,075 ha) were burned on the Forests. The MVRD burned 3,200 acres (1,295 ha), including several multiple-day landscape burns. Ranger district personnel implemented an expanded public involvement plan, while recording and responding to all public contacts (USDA FS 2004). DOE monitored complaints, coordinated responses with the MVRD, and monitored air quality data. The Forests continued to submit landscape burn requests as a special category, and DNR reviewed these for multiple day burn approval. DNR agreed that in the event a three-day approval was given for a landscape burn, approval would

not be rescinded, even if conditions deteriorated on day 2 or 3. In that case the prescribed fire manager and forest staff would make the decision whether to proceed on each subsequent day.

The forests began tracking data from the network of nephelometers to show daily conditions, seasonal variability and trends, downloading data each morning from the DOE website. Data were converted to $PM_{2.5}$ particulate concentration in units of micrograms per cubic meter using relationships established by Trent et al. (2001). Daily concentrations were graphed as daily 24-hour average, daily maximum hourly average, and daily maximum 4-hour average values. The daily trend lines for these three indices were compared graphically to the U.S. Environmental Protection Agency (EPA) 24 hour Air Quality Index (AQI), the EPA 1-hour AQI, and the Chelan County NEAP advisory levels, respectively. These graphical presentations were reviewed daily to view background conditions prior to ignition of a new prescribed burn, and to monitor conditions during and following a burn, in an attempt to better define the contribution of each prescribed burn to local particulate air quality levels. The forests selected the daily maximum hourly average value of particulate as the key indicator of background air particulate because experience showed considerable variation in daily conditions during a burning event that was not registered with either the 24-hour average or 4-hour-average values. The Forest defined an air quality objective of maintaining particulate levels resulting from prescribed burning between 41 and 80 μg/m^3, within the "Moderate" level EPA 1-hour AQI category (Hardy 2001). EPA defines six condition categories: Good, Moderate, Unhealthy for Sensitive Groups, Unhealthy, Very Unhealthy and Hazardous. The Forests' procedure was to monitor air quality particulate levels and avoid new prescribed fire ignitions when particulate measurements approached the lower end of the Moderate range.

On 28 March, early in the 2004 prescribed burning season, an approved multiple-day landscape-scale fire was burning in the Methow Valley. The maximum hourly reading for the Twisp nephelometer the previous day was 39 μg/m^3. The forest elected not to ignite a second portion of the prescribed burn area scheduled for 28 March because of potential adverse smoke impacts in Methow Valley. The same situation occurred on 26 April when the prior day maximum particulate reading was 37 μg/m^3. In both cases, though approval had been given for ignition of an adjacent unit within the project perimeter, ignition was postponed, and within one day, air quality conditions improved enough so that burning could be resumed.

By defining an air quality objective, the Forests attempted to incorporate ambient air quality conditions into the daily prescribed burning decision-making process, in order to avoid new ignitions when background air quality conditions are poor, to postpone additional ignitions for ongoing multiple-day burns when conditions are marginal, and to better monitor the contribution of particulate from a burn to local air quality conditions. A number of factors were considered in selecting the 41 to 80 μg/m^3 particulate level as the numeric objective. This particulate level is comparable to local air quality conditions during winter months, based on a two-year period of air quality data collection. The "Moderate" level EPA 1-hour AQI category is an established index. Particulate concentration is monitored by local real-time instruments. Data can be accessed essentially real-time via web sites and are available for daily prescribed fire decision-making. And finally, experience has taught us that when local conditions

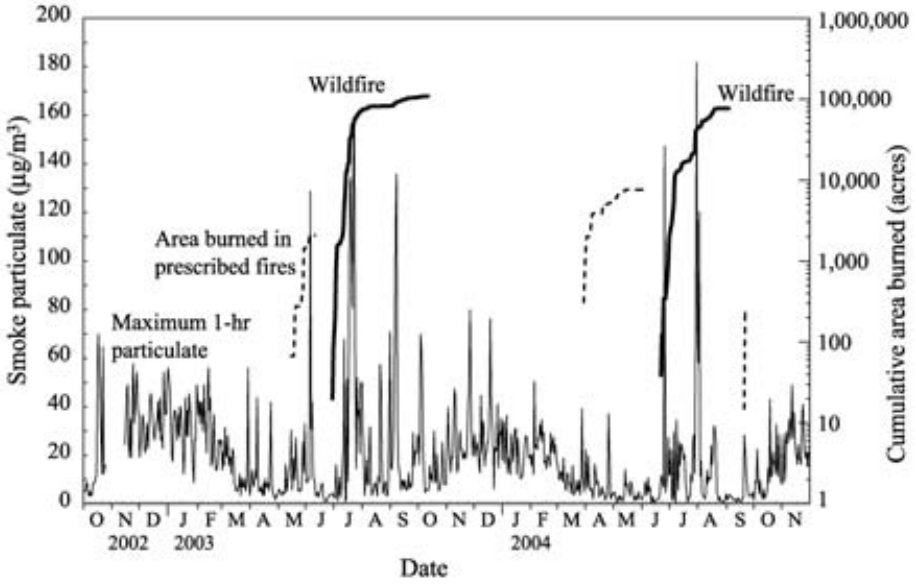


Figure 4. Twisp nephelometer daily 1-hour maximum $PM_{2.5}$ values for October 2002 to November 2004 with burn acreage.

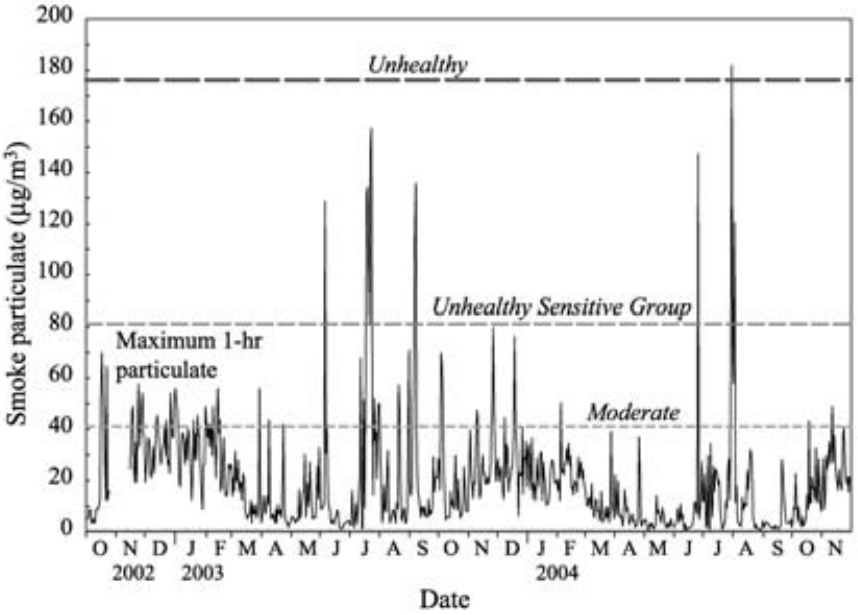


Figure 5. Twisp nephelometer daily 1-Hour maximum $PM_{2.5}$ values, EPA 1-Hour AQI for October 2002 to November 2004.

reach the objective level the general public starts to express concern. With the guidelines in place, particulate values did not exceed 41 µg/m³ for the 2004 prescribed burn season at any nephelometer site. However hourly values reached 182 µg/m³ later in the year, during the 2004 wildfire season (Figure 4).

Summary

Experience gained from increased use of prescribed fire in an area where wildfire is an annual occurrence, urban interface issues are escalating, and air quality can suffer significant impacts, has led to a better understanding of how to protect air quality while implementing the HFI.

A local public involvement plan is an essential component of a HFI strategy. Reliable sources of information and opportunities for public involvement and comment are needed at both the program and project planning stages. There should be multiple opportunities for agency contact with local residents. The general public has a wide range of opinions about HFI prescribed fire treatments. Most of the public is supportive where treatments have been applied, reviewed on the ground, and obviously been effective in wildfire control and protection of urban interface developments. But there are those who feel that prescribed fire should not be used as a treatment because smoke intrusions are invasive, harmful, and unnecessary. We have found that public misinformation abounds regarding the relevant pollutants in smoke, possible health effects, and how to interpret monitoring values. The public feels that the FS has an obligation to study health impacts of smoke and inform them of both negative impacts and benefits of burning; to provide air quality and public health information; and to find, explore, analyze and fund alternative treatments. Individuals who wish to burn agricultural residues on private land off-forest continue to express confusion and frustration because of the two state regulatory agencies involved and duplicate processes for approval of agricultural versus silvicultural burn requests.

Smoke can be life threatening to those predisposed to respiratory ailments. Smoke impacts are real, and include a range of health conditions ranging from eye and respiratory tract irritation to asthma, bronchitis, and reduced lung function, to significant respiratory and cardiovascular-related effects (USEPA 2003; Hardy 2001; Therriault et al. 2001). Even with limited period-of-record data, annual patterns are becoming apparent. Average daily particulate concentrations are higher during winter months, and lower in spring and fall (Figure 5). One-hour and 4-hour maximum spikes can occur from prescribed fire but are of short duration. The maximum hourly values over the period of record are the result of wildfire events. These latter air quality incidents last for a considerably longer period of time.

Air quality objectives need to be developed for prescribed burns. It is apparent that 24-hour $PM_{2.5}$ air particulate standards are not an appropriate measure for determining accomplishment of air quality objectives, given that significant peak values can occur for much shorter periods of time. A 1-hour daily maximum value provides a better identifier of significant particulate events on a local scale. It is important to have local real-time monitoring data to assess ambient conditions and to monitor attainment of air quality objectives. This allows management decisions regarding a day's burn activities to be based on the prior day's values, and even the current day's early morning conditions.

Opportunities

There are a number of opportunities for refinement of air quality objectives for use in prescribed fire management. There should be further discussion of the use of a specific air quality numeric value of 41 $\mu g/m^3$ as a project scale objective. It should be understood that this air quality objective is not proposed as a regulatory standard, requirement, or threshold, but as an objective that incorporates a quantitative air quality measurement into a decision making process that includes many factors including legal requirements, regulatory procedures, public and fire fighter safety, costs, resource management objectives and local public health.

The ability to project the impact of a particular landscape burn relative to an air quality objective needs improvement. Spatial models that project particulate production and dispersion, given site-specific fuel loading, topographic features, and meteorological forecasts, do not currently have the resolution to accurately project particulate dispersion at a local scale. Research scientists are refining the BlueSkyRAINS computer model to incorporate a finer resolution of detail for project-scale landscape burns in Eastern Cascade valleys (Ferguson 2004). This predictive tool would allow fire managers to design prescribed burn projects, and select areas to be burned that optimize natural smoke dispersion and minimize local public exposure to adverse smoke conditions.

Conclusion

The Healthy Forests Initiative is a forest management priority on a national scale because of the extensive wildfires that occurred in the Eastern Cascades in 1994, and those that occurred on an even larger scale elsewhere. The forests are implementing this initiative with a variety of treatments including more frequent use of landscape-scale prescribed fire. Landscape burns will be conducted by the forests within a State Smoke Management Plan regulatory framework administered by DNR. The forests will respond to air quality issues by implementing a comprehensive local public involvement plan and by establishing local site-specific air quality objectives that will be used as one criterion in reviewing daily burn approvals and in making a final decision to burn. Following two years of air quality monitoring, we conclude that these air quality objectives have value on the OWNFs because they allow immediate assessment of local conditions and input to a daily go, no-go decision-making process. Data now available allow an immediate read on whether objectives have been attained for the previous day. The forests will collaborate with DOE in monitoring air quality conditions, reviewing air quality data and in responding to public comments.

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Advances in Fire Convection Dynamics

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The convective column created by a fire has a strong impact on the behavior of the fire. This paper examines three aspects of fire-atmosphere interaction that influence the development of the convective column. The stratification of temperature, humidity and wind near the ground influences the early formation of the fire and its convective column, and can lead to unexpected variability in the fire's behavior. Moisture produced by combustion of woody fuels has the potential to enhance the convective column's vigor, but research is needed to determine whether this happens in actual fires. The structure of the atmosphere over large regions (the synoptic structure) can bring dry, high-momentum air down from heights of 10 or more km, affecting the convective column and fire behavior. Each of these topics represents an aspect of convective behavior around fires that is the subject of current research and has implications for fire behavior and firefighter safety.

Keywords: *fire, weather*

Introduction

For almost 100 years, the paradigm of fire behavior taught and employed in the United States has held that three main factors dictate fire behavior (Graves 1910). These factors are fuels, weather, and terrain. Historically, research and management have ranked the importance of the three factors for funding, time, and manpower in the aforementioned order. The fastest changing component of the behavior triad is the weather, and while it is not directly manageable or predictable over the long term, it is also one of the major causes of fire-fighter fatalities and fire escapes. (Whether human error or weather is the greater cause is not clear, especially in cases where human actions compromise the quality of the weather information available during fire management.)

A further common division of fire behavior is separation into "plume dominated" and "wind-driven" (sometimes called "wind dominated") fires. These categories seem reasonable and somewhat intuitive, but in reality it is quite difficult to decide whether a fire belongs in one or the other class. A particular fire may alternate between plume and wind dominated repeatedly during its existence. All fires are dangerous, but because a wind dominated fire spreads primarily in the direction of the prevailing winds, the danger is more predictable than for a plume dominated fire. Conditions above the ground play a major role in determining the behavior of plume dominated fires, and can lead to abrupt changes in direction or rate of spread. A strong updraft, whether tilted over due to strong winds or vertical in their absence, generates a stronger inflow of air at the ground and more vigorous fire development in general, so that updraft strength is directly related to many aspects of fire behavior that are important for firefighter safety.

Researchers and analysts have used two parameters, Byram's convection number (Nelson 1993) and the convective Froude number (Clark et al. 1996) to classify fires in the past. In practice, it is rare to have the data necessary to make such a classification. Even when data are available, these numbers change values over time and space, so that one part of a column may qualify as "plume dominated" for a time, while the remainder of the column at times is "wind driven." Because of this, the most common criterion used to determine a plume or wind dominated fire is purely subjective observation.

It is possible there is some discrete, definite boundary between plume and wind dominated fire behavior. It is more likely that while some fires are quite visibly in one class or the other at a particular time, most fires at most times fall in a grey area where it is unclear which process dominates. Because of this it is important to understand

Furniss, M.J., Clifton, C.F., Ronnenberg, K.L., eds., 2007. *Advancing the fundamental sciences: proceedings of the forest service national earth sciences conference, San Diego, CA, 18-22 October 2004*. PNW-GTR-689. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station.

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the physics of how fires interact with the atmosphere. Decades, if not centuries, of observations and anecdotes provide some understanding. In the last fifty years, that understanding has gone from statistical or qualitative in nature to more analytical and quantitative. The complexity of the situation has limited the utility of all of these types of understanding, however. To develop an analytical understanding of a complex system starting with a simplified model often allows progress that would otherwise be impossible. In the case of fire, starting with the "no wind" case, unrealistic though it is, does just that.

In this paper, we describe three aspects of fire convection and the interaction of fire with the atmosphere: layering of air near the ground, potential impacts of moisture, and synoptic influences on convection. We ignore wind in our discussions in order first to better understand the nature of the convection. Eventually, a complete theory of fire convection must include the influence of wind profiles. For now, however, the "simple" case of no wind presents enough unanswered questions.

Describing the Environment

The basic properties of the atmosphere that influence convective development during fires are the temperature and wind profiles. Generally speaking, fires of significant size develop under conditions of high atmospheric pressure. High pressure usually means clear skies and dry conditions, while low pressure indicates clouds and often rain. For this reason, the following discussion emphasizes high pressure situations.

The daytime temperature profile for an idealized atmosphere has four basic parts, depicted in Figure 1. At the bottom is the surface layer. Strong solar heating, especially when there is little available moisture, creates a region where the ground is very hot and the air temperature drops rapidly with height. This is generally an unstable layer, where vertical movement of air releases stored energy and adds to the turbulent energy. Above this, where air flow is unobstructed by the ground and surface structures, is the mixed layer. In this region, turbulence and heating from below churn the air so that moisture, momentum, and thermal energy are fairly uniform. This layer has neutral stability, meaning that when a bubble of air rises or falls it neither releases nor requires any energy. Above the mixed layer is, by definition, a relatively unmixed region. This layer is generally stable, often a thermal inversion, where vertical motion requires some energy input. Finally, in the situation typical for many large fires, a region of neutrally stable subsiding air tops the stable layer.

Generally, the mixed layer deepens from sunrise through midafternoon. As the sun heats the ground, which in turn heats the air near it, the increasingly buoyant air can rise and mix upward to greater heights. At night, the surface and mixed layers are often absent. Under high pressure, the clear skies lead to enhanced cooling at the ground so that a surface inversion forms. Above this, there may be a remnant mixed layer from the daytime, and another inversion above this. The lowest inversion has the greatest influence on fire behavior.

Moisture plays an important role in the short-term processes of fire convection and fire behavior, but less so than stability. Moisture in the surface layer can be low or high, compared to the mixed layer. For example, air from the Gulf of Mexico blowing northward into Missouri would be relatively moist. Air moving into the same area from the northwest, perhaps behind a cold front, would be relatively dry. For this reason, one cannot generally describe surface layer moisture in the same way as stability, even when focusing on conditions typical of large fires.

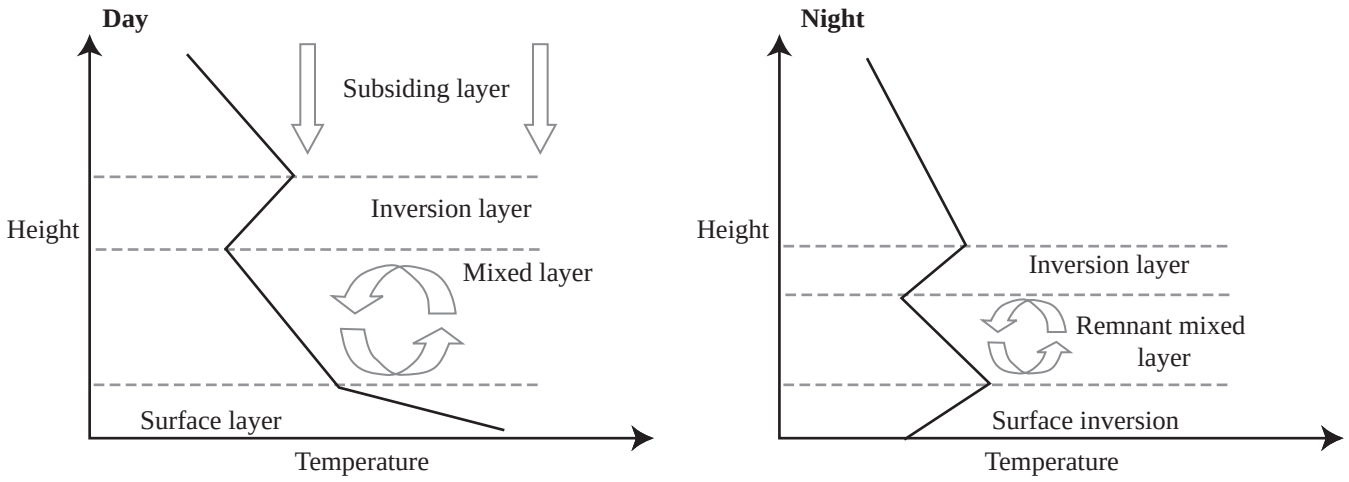

Figure 1. Idealized model of the vertical structure of the troposphere.

Table 1. Stages of fire-atmosphere interaction, based on the three-layer model. Air Layer is the layer of the atmosphere interacting with the fire during the given stage, while Stability, Plume Growth, Winds, and Moisture describe the qualities of the air properties typical of the layer involved in that stage.

Stage	Air Layer	Stability	Plume Growth	Winds	Moisture
Surface	Surface	Unstable	Rapid, energy added	Light and variable	Moist
Deepening	Mixed layer	Neutral	Moderate, no change	Stronger, variable	Dry
Penetration	Inversion and Subsiding	Stable	Slow, requires energy	Strongest, more steady	Drier

Above the mixed layer, the atmosphere is typically dryer than it is in the mixed layer. Subsidence above the inversion generally represents the driest part of the atmospheric profile.

Three Layer Model for Fire-Atmosphere Interaction

There are several ways to describe the stages, phases, or regions of fire. These include simple frameworks such as ground/surface/canopy or smoldering/creeping/running, and more complex concepts like Countryman's (1969) six zone framework describing stationary mass fires. These all have legitimate, valuable uses. The ground/surface/canopy distinction is useful for understanding behavior and fuel consumption patterns. The smoldering/creeping/running distinction tells a fire manager how quickly the fire is moving and what sorts of management actions are most appropriate. Countryman's (1969) zones divide a mass fire into six zones, based on a combination of visual properties and the apportionment of energy. None of these models, however, provides insight into the relationship between the fire and the atmosphere in a way that clarifies the influence of the atmosphere.

Potter (2002) proposed a three stage model for describing fire that emphasizes the relationship between the fire and the layers of the atmosphere described above. The stages of the model are the surface stage, the deepening stage, and the penetration stage. These stages are tied to fire's interactions with, and influence on, air in the surface layer, the mixed layer, and the inversion and subsidence layers, respectively. (In the penetration stage, the fire may interact with the inversion and then the subsidence layers, depending on the strength of the fire and the inversion.) Table 1 summarizes atmospheric properties during these three stages. In addition to the wind and stability aspects shown in the table, the moisture of the layers influences both fuel moisture (and therefore fire rate of spread and energy release) and plume development.

In this model, a fire does not necessarily go through all stages, and it can exist in a given stage more than once. All natural and prescribed fires begin in the surface stage. If there is a surface inversion, this is also a penetration stage – the surface air is stable, and any plume development requires the fire to do work. If a fire burns through a day and into a night, it may go from the deepening stage during the day back to a surface or penetration stage at night. In general, fires in the eastern U.S. tend to burn for one day, and would go through the stages in the listed order, before they return to the surface stage and die out. In the western U.S., fires are more likely to shift back and forth among the stages over multiple days. Because smoke can block sunlight and outgoing longwave radiation, it can affect stability so that yesterday's smoke influences the stages of today's fire.

The atmospheric three stage model has proven useful for some applications beyond research. In case studies of prescribed burns in Missouri and Michigan, we found that looking at the temperature, humidity, and wind of the layers involved in the stages and their contribution to BEHAVEPlus (Andrews et al. 2003) estimates of rate of spread and flame length, could explain some otherwise unexpected variations in these fire properties during prescribed burns. As a result, the Eastern Area Modeling Consortium (Heilman et al. 2003; USDA Forest Service 2004) now provides estimated values for temperature, humidity, and wind for the surface, mixed, and above-mixed layer air up to 48 hours in the future for use in BEHAVEPlus calculations. If the three sets of weather values yield widely varying fire property estimates, this suggests the potential for real-world variations in fire behavior.

Released Moisture

The main difference between small, scattered fair weather cumulus clouds and a towering, destructive cumulonimbus

cloud is the amount of water available in the atmosphere. Water and the energy released when it changes from vapor to liquid and from liquid to solid drive large storms, including tornadoes, downbursts, and strong straight-line winds.

Byram (1959) and Johnson and Miyanishi (2001) present a chemical equation for the combustion of woody material. The latter authors state that complete combustion of 1 kg of woody material yields 0.56 kg of water substance and 20 MJ[1] of energy. Potter (2003) proposes that during the combustion process, and after turbulent mixing of air near the ground, this moisture adds from 1 g to 5 g of water to each 1 kg of air rising in the fire's convective plume. (Moisture in air is often stated in terms of grams per kilogram (g/kg), with the understanding that this means "grams of water per kilogram of air". We follow this convention here.) The following discussion assumes that the air in the updraft from a large fire has been moistened by 2 g/kg. Potter (2003) presents a detailed discussion of the implications of this moisture, so we present a much abbreviated discussion here.

When air remains at a constant pressure and temperature, and water is added, one of the effects is a decrease in the average density. This is simply a result of the fact that the molecular weight of water is 16, while the average molecular weight of air is slightly less than 29 (Wallace and Hobbs 1977). The change is very small, but it can be important in calculations involving similarly small differences in density as air rises or descends. For example, at Mack Lake, MI on 5 May 1980 – the date of the Mack Lake fire (Simard et al. 1983) – calculations of the density of air without and with background moisture differ by only 0.004 kg/m^3. Using density without accounting for moisture, calculations indicate this air will freely rise to a height of 3000 m, and will not reach a height where the moisture in it condenses. When moisture is considered, the slight decrease in density is sufficient to allow the air to rise to the condensation level. The subsequent release of latent heat as the water condenses keeps the air warm enough that it can freely rise to 8800 m. If the fire had added 2 g/kg to the air, this height would increase to 9600 m.

The basic force behind thunderstorms is buoyancy, driven by the density differences between a parcel of air and the air around it. Consider, as an analogy, an ice cube in a glass of water. If the cube were pushed to the bottom of the glass, it would bob to the surface when released. If the ice cube were in peanut oil instead of water, the density of the cube would be greater than that of the oil, and the ice cube would sink. In the atmosphere, density differences are primarily due to temperature and moisture differences. Relatively hot or moist air is less dense than its environment, and will rise more energetically. If the moisture in the air condenses as the air rises, the condensation process releases energy that heats the air, further increasing its buoyancy and allowing higher, more vigorous ascent. One can calculate the energy released during this ascent and estimate the effect of increased temperature or moisture on that energy. For the Mack Lake Fire, warming the surface air by 2 K would have doubled the buoyant energy. Adding 2 g/kg of moisture to the surface air, instead, would have increased the buoyant energy by a factor of 2.9, almost tripling it. Raising temperature by 2 K and moisture by 2

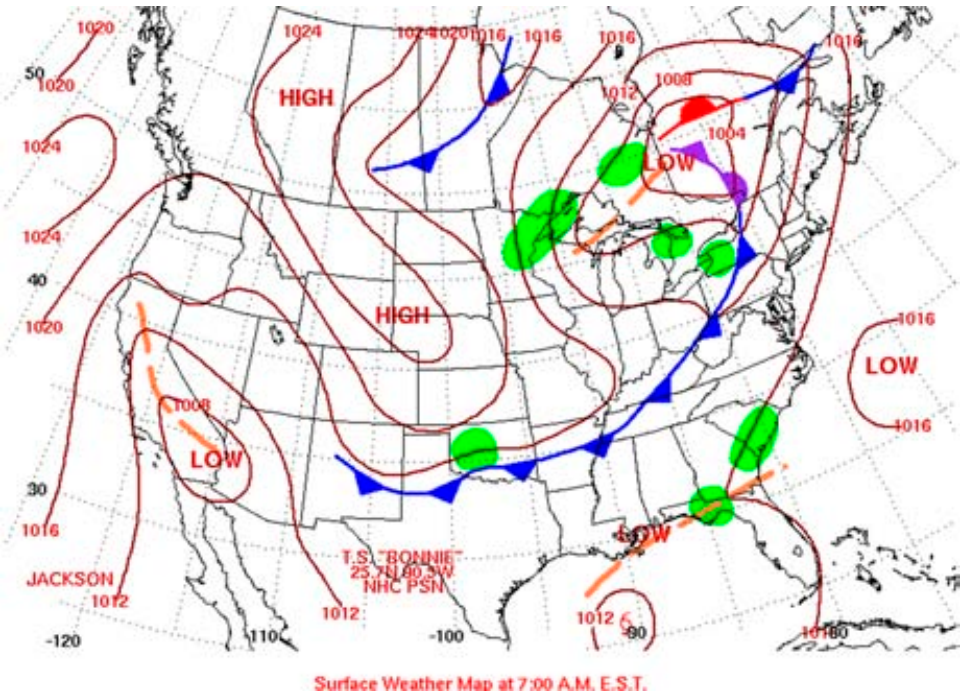

Figure 2. An example of a synoptic-scale low pressure system, with associated cold (blue) and warm (red) fronts. This map shows the pressure pattern for 1200 UTC (0800 EDT) on 11 August 2004.

[1]MJ = Megajoules

g/kg at the same time would have increased the buoyant energy of the surface air four-fold. Any of these increases in buoyant energy would have been sufficient to produce a vigorous updraft with strong inflow near the ground and strong near-fire horizontal winds.

Moisture in a fire plume has potential implications for downdrafts, as well. Downbursts, macrobursts, and microbursts are all types of downdrafts, varying in their spatial extent, duration and intensity - we will refer to them all simply as "downdrafts" here. Downdrafts develop through a combination of evaporative cooling and frictional drag from falling raindrops, snow, and hail. Without moisture to form rain, snow and/or hail, strong downdrafts would not form. More moisture means a greater potential for downdraft formation, though the manifestation of that potential depends on a variety of other factors. The connection between moisture and downdraft development is generally accepted and understood by meteorologists, and at least one fire study cited a downdraft as a cause of firefighter fatalities (Goens and Andrews 1998). Presently, however, the role released moisture could play in the formation of downdrafts is not known.

Synoptic Influence

In meteorology, "synoptic structure" refers to patterns that cover an area roughly one-half to two-thirds the size of the United States. The most common example of a synoptic structure is a low pressure system with cold and warm fronts (Figure 2). Synoptic weather systems can be thought of as the broad-scale organizing mechanism behind local weather. For instance, when a front passes over a given location, an observer on the ground might note a shift in wind speed and direction, a temperature drop or rise, rapid variations in humidity, or some combination of these changes. But observations at a single point seldom reveal the overlying synoptic system ultimately responsible for the formation of the front, the timing of its passage, the environmental changes that occur as it passes, and its lifespan.

Synoptic weather systems change throughout their lifetime. The fronts associated with low pressure systems can have varying intensities, which lead to different horizontal and vertical temperature and wind structures, so that one should not expect all fronts or other types of weather systems to affect fires equally. Furthermore, synoptic structures have varying effects on fires developing in different locations within them (Schroeder et al. 1964). As discussed above, information about atmospheric conditions in near-ground atmospheric layers can offer insight into the potential for unusual fire behavior. Synoptic weather patterns can, in turn, offer weather forecasters insight into how the near-ground atmospheric layers might vary. For this discussion we focus on how synoptic-scale weather systems can enhance or inhibit dry, windy conditions at the surface.

Earlier, we described how the mixed layer deepens throughout the day. If the top of the mixed layer rises

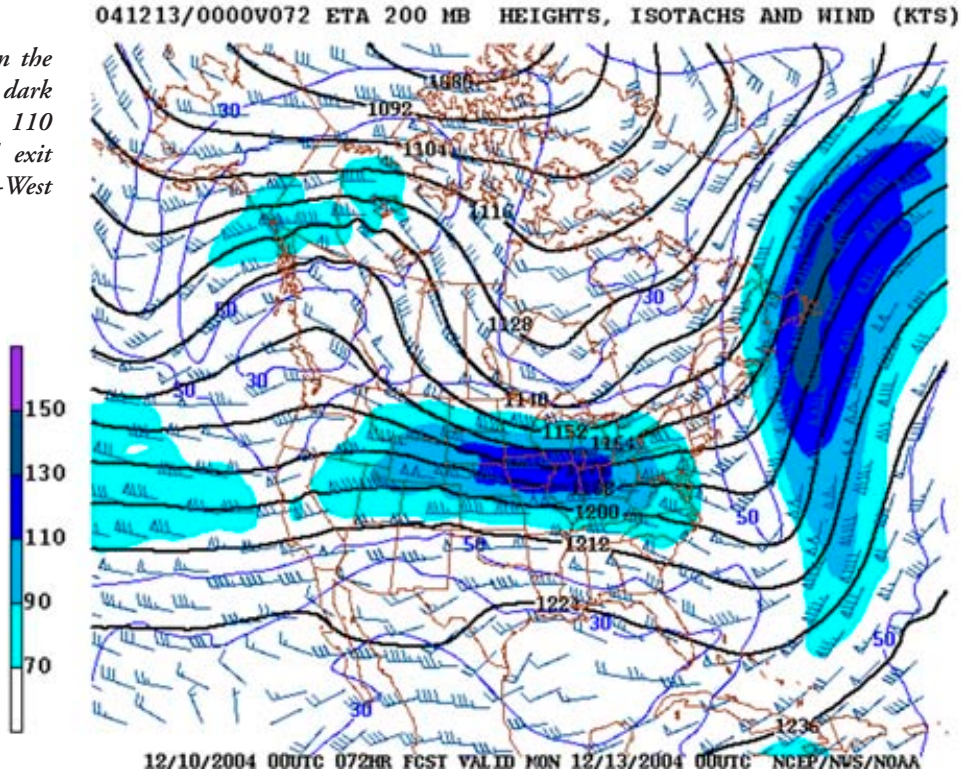

Figure 3. Example of a jet streak in the upper troposphere (250 mb). The dark blue area indicates winds between 110 and 130 knots. The equatorward exit region would be over the Kentucky-West Virginia area.

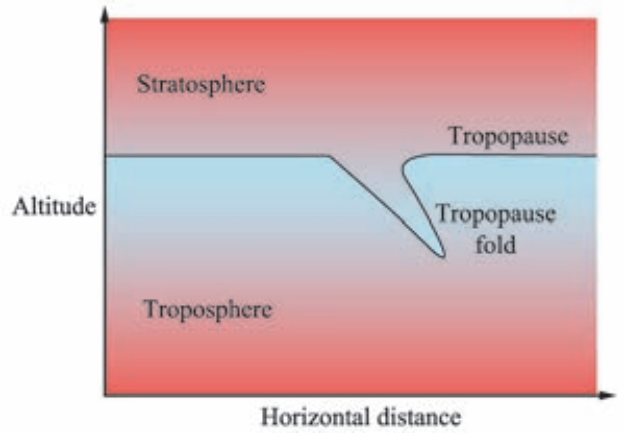

Figure 4. Illustration of a tropopause fold (not to scale).

upward at a time and place where dry, windy air sits above but close to the top of the mixed layer, that dry and windy air may be drawn into the mixed layer. It may then descend to the surface, where it may influence fire behavior. Since the mixed layer can reach depths of 3 to 4 km, this type of interaction can draw down air that is substantially different from surface air.

Presently, two mechanisms have been identified as potential sources of descending, dry, windy air. One involves descent associated with regions 3 to 5 km above the ground where bands of high speed winds, known as "jet streaks", decelerate (Figure 3) These regions, known as jet exit regions, can span thousands of square kilometers. They typically have dry, fast moving air descending on the equator-ward side. Kaplan et al. (personal communication, manuscripts in preparation[2]) have found jet exit regions over several historically notable wildland fires.

The second potential source of descending, dry and windy air is known as a tropopause fold (Charney et al. 2003). The tropopause is the boundary, roughly 7 to 12 km above the ground, between the part of the atmosphere known as the troposphere (where temperature generally decreases with height) and the stratosphere above it (where temperature is constant or increases with height). Air in the stratosphere is much drier than air in the troposphere, so the tropopause marks a transition not only in temperature gradient, but also in moisture. Tropopause folds (Figure 4) are long, narrow intrusions of dry air that form in association with cold fronts, bringing air from the stratosphere down towards the ground. They do not typically reach the ground, except at high elevation locations, but it is possible for the mixing layer to rise upward to meet them, or for the energy from a fire to allow local mixing to reach a tropopause fold.

[2]Kaplan, ML, C Huang, YL Lin, and JJ Charney. [N.d.] A Multi-Scale Paradigm for Rapid Vertical Airmass Coupling Resulting in High Fire Weather Potential. Part I: Observations of the Double-Trouble Case Study. and Part II: Numerical simulations of the Double-Trouble Case Study. Manuscripts in preparation. On file with J. Charney, USDA Forest Service, 1407 S. Harrison Road, Suite 220, East Lansing, MI 48823.

Conclusions

While thinking of fires in terms of the character of their convective columns is not new, recent work is connecting on-the-ground fire behavior more directly with the atmospheric processes within the convective column. These connections tie together the vertical temperature, moisture, and wind structures of the atmosphere, from the ground up to ten or more kilometers in altitude, with fuels, combustion, and subsequent fire behavior. This recent work brings many years of research in meteorology that was not originally associated with fire into the conversations and mental models now being used to understand fire behavior, especially extreme or erratic fire behavior.

The three topics (the three-layer model of fire-atmosphere interactions, the question of moisture's importance, and synoptic influences on fire behavior) discussed here provide examples of these new developments in the study of fire-atmosphere interaction and fire-driven convection. The three-layer paradigm is a simplistic framework that illustrates the potential for even small fires to behave in unexpected ways, and has potential as a planning tool. Questions about fire-released moisture indicate that there are potential ties between fuel load and fuel moisture, and the intensity and development of the fire's convective column, that go beyond simple heating of the air. The synoptic studies in progress now can provide insight into regional weather conditions that could influence fire behavior in previously unexpected ways. Each of these – and many topics that are sure to come to light as research proceeds over the next decade – has implications for fire fighter safety and resource management.

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Section 1. Applied Science and Technology

Part 2. Watershed Management

Overleaf:
Twin Falls, Richland Creek, Ozark Plateaus. Photo by A.C. Haralson, Arkansas Department of Parks & Tourism, Little Rock, Arkansas.

Using Stream Channel Reference Data to Guide Land Management Decisions

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In order to make informed land management decisions, managers concerned with aquatic resources need information at a variety of scales. "Project level" decisions require fine-scale information relating to specific small watersheds or stream reaches, while planning level decisions require a characterization of broad scale patterns that will influence allocation and scheduling of activities. Quantified reference data can provide a basis for decisions at both scales by defining conditions that would exist in stream channels under the present climate and tectonic regimes in the absence of land management. At smaller scales, data from undisturbed reaches can be directly compared with similar managed reaches to determine departures from reference conditions, while at larger scales reference data from a number of reaches can be use to define desired conditions across a region.

Keywords: *reference reach, TMDL, forest planning, sediment, channel morphology*

Physical Setting

Most of the data for this study were collected on the Beaverhead-Deerlodge National Forest (B-D), covering approximately 3.4 million acres (1.4 million hectares) in southwest Montana. The region is bordered by the continental divide on the west, and contains the headwaters of four major river systems (Big Hole, Beaverhead, Madison and Ruby). Wide valley bottoms are separated by isolated mountain ranges. The valley bottoms of the major rivers are mostly in private ownership, with public land located at higher elevations.

The dominant physical realities of this region are high elevation and low precipitation. Valley bottoms are semi-arid, averaging about 5800 feet (1769 m) in elevation and receiving an average of 13.6 inches (34.5 cm) of precipitation a year. The mountains receive more precipitation (27.2 inches [69.1 cm] per year), with most of that in the form of snow. Overall, annual precipitation has averaged 20.4 inches (51.8 cm) since 1980.

Livestock grazing is the land use that most affects aquatic values on the Beaverhead-Deerlodge National Forest. Seventy-eight percent of the forest is located in grazing allotments. Roadless and wilderness areas account for 62% of the forest, so some of the more common effects to aquatics from roads, timber harvest, and mining are either isolated or minimal. There is a wide range of suitable rangeland contained within the allotments. Some allotments, mainly on the eastern portion of the forest, are predominately suitable, while others are heavily timbered with little suitable range.

Additional data were collected throughout the Greater Yellowstone Ecosystem, which stretches south and west of the Beaverhead-Deerlodge into Wyoming and Idaho. Some of the Ecosystem mimics conditions on the B-D, although precipitation levels are often somewhat higher.

Methods

A comprehensive stream channel survey was initiated on the Beaverhead-Deerlodge National Forest in 1991. The survey was designed to collect stream channel data that would characterize physical channel attributes at the reach scale. Survey sites were chosen to: 1) identify reference conditions; 2) identify problem areas for restoration; and 3) portray the range of stream conditions throughout the forest. The following parameters were measured as part of the standard survey:

1. A monumented cross-section depicting floodplain, bankfull elevation, water surface, and thalweg. The cross section is used to compute entrenchment and width-to-depth ratio. (Rod and level)
2. Sinuosity (Pacing)
3. Gradient (Rod and level)
4. Stream substrate (Wolman pebble count, Wolman 1954)
5. Fifty bankfull widths and depths (measuring rod)
6. Channel Stability Evaluation (Pfankuch 1975)
7. Bank Erosion Hazard Index (Rosgen 1996)
8. Valley Bottom Width (pacing)
9. Reach photographs
10. Notes describing overall conditions with respect to previous and current management effects.

Furniss, M.J., Clifton, C.F., Ronnenberg, K.L., eds., 2007. *Advancing the fundamental sciences: proceedings of the forest service national earth sciences conference, San Diego, CA, 18-22 October 2004*. PNW-GTR-689. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station.

The sites are permanently established with painted rebar and surveyed to local benchmarks, usually a nail in a tree. Where applicable, measurement protocols given in Harrelson et al. (1994) were used.

By 2002, a total of 682 stream reaches had been measured throughout the forest. Forty-four percent of the total streams on the forest have at least one survey, with many streams having multiple sites. On average, 3.3 survey sites were measured per 6th-code HUC (Hydrologic Unit, or watershed). Measured sites were considered to be a "representative reach" (Gordon et al. 1992), and depict conditions along a greater length of stream channel. The survey sites depict conditions on 3.7% of the stream length on the forest. Of the 682 sites, 137 were determined to be in reference condition. These have been combined with an additional 78 reference sites measured throughout the Greater Yellowstone Area (GYA) in the summer of 2002 to create a reference dataset of 215 reaches. The dataset includes stream reaches that represent watersheds of a variety of sizes, geologies, and precipitation ranges.

The Use of Reference Reach Data in Project Planning (NEPA Analysis)

Under the National Environmental Policy Act (NEPA), federal agencies initiating land management activities must complete an analysis to determine the effect of the project on the natural environment. The Affected Environment section of the NEPA analysis requires a determination of the existing condition before the effect of the proposed project is evaluated. One way to evaluate existing condition is to compare current conditions with reference data for similar sites (Frissell et al. 1986). The stream surveys enabled us to do this for the Beaverhead-Deerlodge National Forest.

The concept of using minimally disturbed sites as references has appeared in the literature in recent years (Dissmeyer 1994; Minshall 1994; Maxwell et al. 1995). Recent methodologies for analyzing watershed conditions (USDA et al. 1994, 1995; McCammon et al. 1998) recommend the use of reference watersheds as a means of determining the effects of land management

Reference reaches are matched with project reaches on the basis of the similarity of their valley bottom widths, valley bottom gradient, and the drainage area above the reach. Rosgen (1996) demonstrated that valley types provide an indication of stream channel morphology. Bengeyfield (1999) showed the relationship between valley features and drainage area to stream types for southwest Montana. Using a Classification and Regression Tree procedure (Brieman et al. 1984) and an earlier version of this data set, he used valley bottom width, valley bottom gradient, and drainage area to predict Level One stream types. A cross-validation procedure showed that E stream types, for example, were correctly predicted 89% of the time. Analyzing the data from the reference data set and project reach stream surveys produces a comparison table (Table 1).

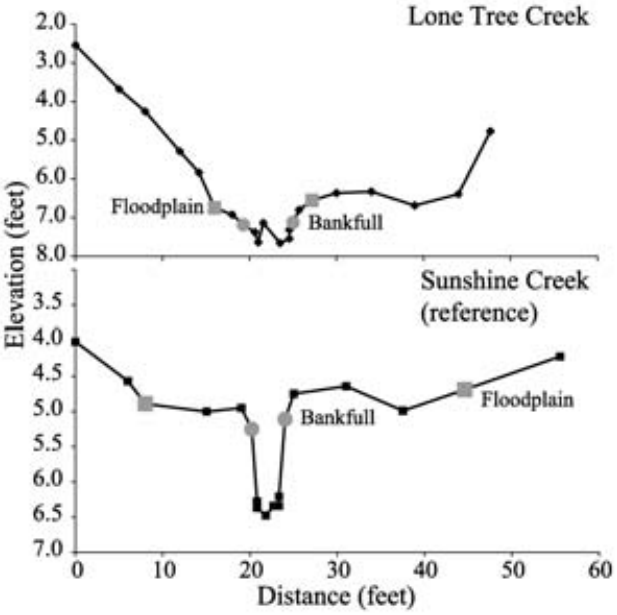
Table 1. Comparison of stream survey parameters between project reach (Lone Tree Creek) and reference reach (Sunshine Creek). * indicates data not collected.

Parameter	Lone Tree Creek	Sunshine Creek
Valley Bottom Width (VBW) (ft)	25	75
Valley Bottom Gradient (VBG) (%)	2.53	2.75
Area (acres)	1500	704
Stream Type	B4	E4
Entrenchment	1.96	9.63
Width/Depth Ratio	28.5	3.3
Sinuosity	1.05	1.8
Gradient (%)	2.41	1.53
D_{50} (mm)	30	13
W_{50} (ft)	3.7	5.9
Channel Stability	64 - Fair	48 - Good
BEHI	*	24.8

A comparison of the data for Lone Tree Creek (project) and Sunshine Creek (reference) shows that both valley bottoms are narrow and moderately steep, and their watersheds are small (Table 1). However, they contain different stream types (B4 vs. E4). Lone Tree Creek is more entrenched (1.96 vs. 9.63), wider and shallower (width-to-depth ratio = 28.5 vs. 3.3), straighter (sinuosity = 1.1 vs. 1.8), and steeper (gradient = 2.4 vs. 1.5) than the reference. It is not only wider at the cross section, but along the entire reach (W_{50} = 5.9 vs. 3.7). Lone Tree Creek is not as stable as Sunshine Creek. (Channel Stability = 64 vs. 48), and is more susceptible to streambank erosion (Bank Erosion Hazard Index [BEHI] = 30.5 vs. 24.8). The relationships between the project and reference reaches can be displayed graphically as shown in Figures 1 and 2.

An analysis of the data and graphs shows Lone Tree Creek differing from the reference for most of the stream parameters measured. The largest differences are in channel dimension, with somewhat smaller differences in pattern and profile. Lone Tree Creek is wider, straighter, and steeper than Sunshine Creek. Channel Stability and Bank Erosion Hazard reflect similar patterns. Notes taken onsite at the time of the survey indicate heavy trampling by livestock, willows that are in poor condition, and a species of sedge that increases with grazing pressure.

Figure 1. Cross-sections of Sunshine Creek (reference) and Lone Tree Creek (project).



By comparing onsite data from Lone Tree Creek to reference conditions, the departure from expected channel dimensions can be quantified and displayed graphically. In this case, the notes describe a disturbance (livestock grazing) that would logically produce the channel conditions measured, suggesting a cause/effect relationship for the existing condition. Similar effects due to grazing have been documented by Clifton (1989), Clary and Webster (1990), and Kovalchik and Elmore (1992). The data and analysis suggest there is considerable difference between the existing and desired conditions in Lone Tree Creek, necessitating a change in grazing management in order to restore reference conditions.

Lone Tree Creek is one of five reaches surveyed for the Antelope Creek Grazing Allotment. Employing reference data, site specific conditions were described for individual reaches and then compared to the reference data. This allowed departure from desired conditions to be displayed. By including these data in Chapter 3 of the NEPA document, the need for change was established, and an alternative was generated that prescribed more stringent standards for livestock management.

The Use of Reference Reach Data in a Regulatory Framework (TMDL Analysis)

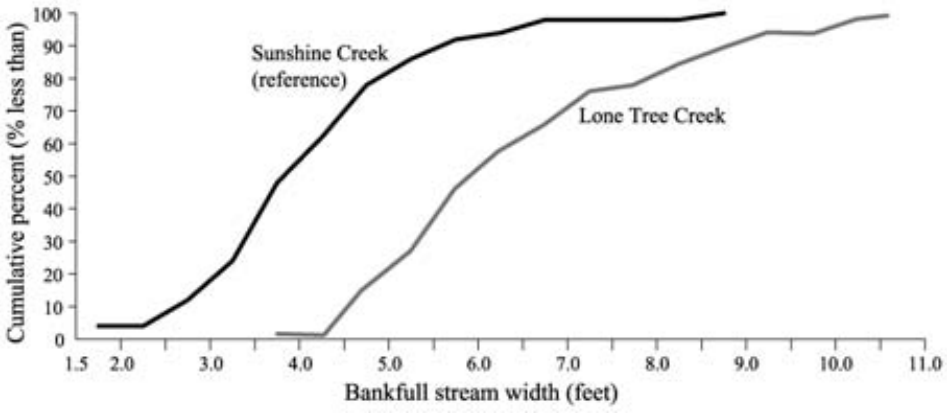
In recent years, states have identified Water Quality Limited Segments (WQLS) as impaired water bodies that are in need of restoration in order to meet the requirements of the Clean Water Act. This process is designed to be quantitative, and specific levels of a pollutant are required to be met before the stream can be removed from the impaired list. The use of reference conditions is considered to be an acceptable concept for determining target levels of pollutants (EPA 1999). Furthermore, it is recommended that reference conditions be measured across a region to define variability (Frissel et al. 1986; Minshall 1994).

Data from the measurement of 215 reference reaches throughout southwest Montana and the Greater Yellowstone Ecosystem provides information that can be used to establish acceptable target levels for specific Rosgen stream types (Rosgen 1996). Figures 3 through 5 display cumulative distribution curves for substrate size and width/depth ratio derived from the reference data set for stream types B, C, and E.

For example, if a stream were placed on a state's 303(d) list as being impaired for sediment, and the impaired reach were a B4 stream type, then Figure 3 could be used to establish target levels for substrate distribution. If fine sediment were a concern, the target might be that only 16% of the substrate could be below 6 mm in size. If bedload transport were a concern, the D_{84} of the impaired reach might be targeted at 160 mm. Confidence intervals define acceptable range of variability for monitoring purposes.

If an E stream were placed on the 303(d) list for habitat alteration as a result of streambank alteration due

Figure 2. Cumulative distribution curve for bankfull stream widths for Sunshine Creek (reference) and Lone Tree Creek (project).



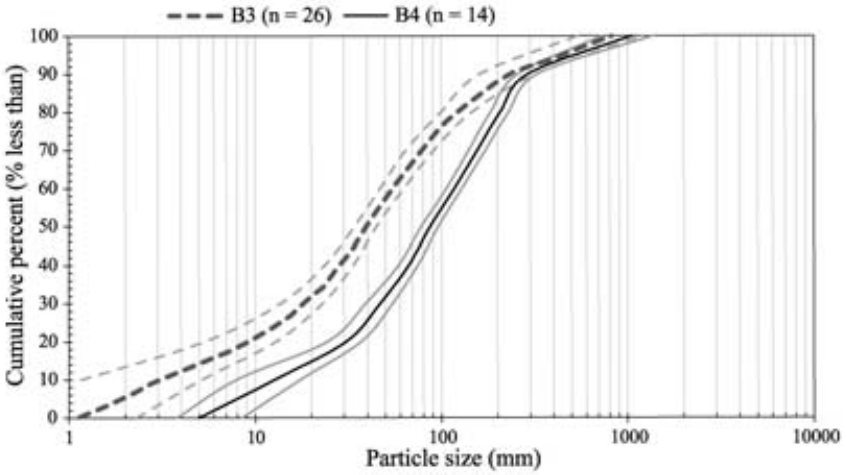


Figure 3. Particle size distribution, B stream types, with 95% confidence limits.

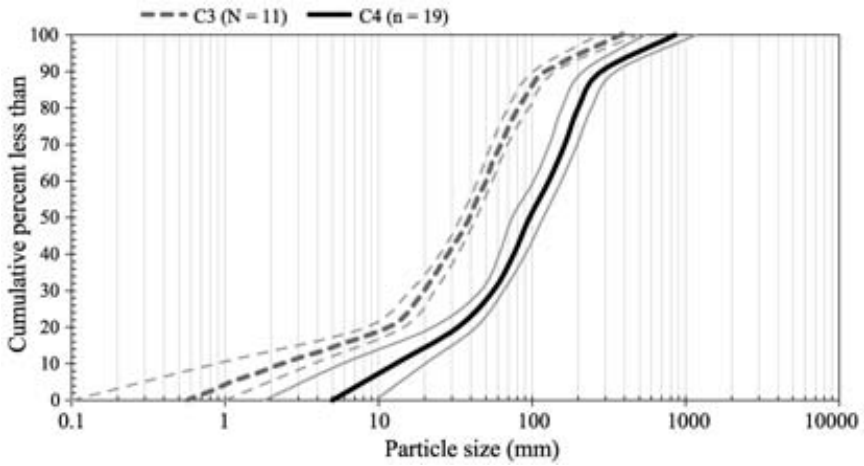


Figure 4. Particle size distribution, C stream types, with 95% confidence limits.

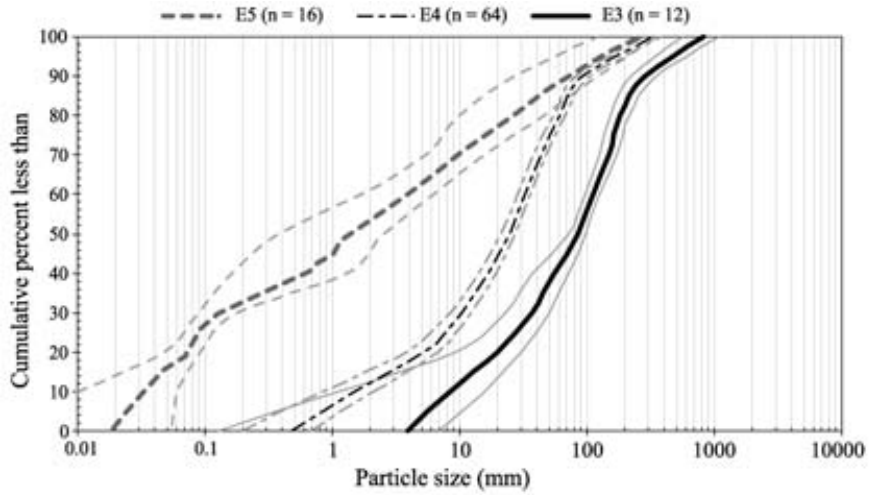


Figure 5. Particle size distribution, E stream types, with 95% confidence limits.

Table 2. Distribution of stream types in Beaverhead/Greater Yellowstone Area dataset.

Level 2 Stream Type	B Streams	C Streams	E Streams
2	1		
3	26	12	10
4	16	22	65
5		2	18
Ea			25

to livestock grazing, then a target might be established for width/depth ratio in order to restore overhanging banks. The distribution throughout the reach should be such that the average width/depth ratio should be about 3 to 3.5.

The Use of Reference Reach Data at the Landscape Scale (Forest Planning)

National Forests throughout the country are presently going through a revision of Forest Plans that were first completed in the 1980s. As part of that process, the Desired Future Condition (DFC) for individual resources must be described (CFR 219). For stream channels, a logical DFC would be to maintain the dimension, pattern, and profile that have been developed by natural flow regimes under the present climate and tectonic regimes. Reference reach data can help in describing these conditions and establishing goals for management.

The reference reach dataset for the Beaverhead-Deerlodge and Greater Yellowstone Ecosystem contains 215 reaches. These were stratified by stream type, with results summarized in Table 2. The B2 and C5 strata were dropped from further analysis because their sample size was too small. This left a reference dataset of 213 reaches. The remaining strata were subject to statistical analysis for mean, standard deviation, and 90% confidence interval (Table 3).

These data localize the Rosgen classification and can form the basis for describing DFC for each of the stream types. For example, for E stream types to maintain stable channels given the natural flow regime, they should have a width/depth ratio close to the mean for E stream types, in this case, 6. If the width/depth ratio of a given reach fell between 5.5 and 6.5, a manager could be 90%

Table 3. Statistics for reference reach strata representing various stream types. Confidence Intervals are all $\alpha = 0.1$. *W/D ratio is width to depth ratio; % < 6mm is the percent of the substrate smaller than 6 mm in diameter;* D_{50} *is median particle size;* D_{84} *is the particle size 84% of the substrate is smaller than;* W_{50} *is average channel width; CS is the channel stability rating (Pfankuch 1975) ; BEHI is the Bank Erosion Hazard Index (Rosgen 1996).*

Stream Type	Statistic	Entrenchment	W/D ratio	Sinuosity	Gradient	% < 6mm	D_{50}	D_{84}	W_{50}	CS	BEHI
B3	Mean					6	107	306			
N=26	SD						41	195			
	90% CI					3 - 8	120-94	369-243			
B4	Mean					17	41	148			
N=16	SD						18	70			
	90% CI					12 - 22	48-34	177-119			
Total B	Mean	1.7	13.3	1.22	0.039				13.4	64.7	25.5
N=42	SD	0.3	5.9	0.14	0.026				6.5	16.1	7.4
	90% CI	1.78 - 1.62	14.8 - 11.8	1.26 - 1.18	0.049-0.029				15.5-11.3	69.6-59.8	27.9-24.1
C3	Mean					5	91	206			
N=12	SD						29	84			
	90% CI					0 - 10	104-78	244-168			
C4	Mean					16	39	104			
N=22	SD						14	53			
	90% CI					13 - 18	44 - 34	133 - 85			
Total C	Mean	18.2	23	1.48	0.013				29.4	71.1	24.3
N=34	SD	16.6	11.9	0.35	0.014				19.5	18.8	6.8
	90% CI	22.8 - 13.6	26.2 - 19.8	1.57 - 1.39	0.017-0.009				41.4-17.4	82.5-59.7	28.5-20.1
E3	Mean					8	82	201			
N=10	SD						22	79			
	90% CI					0 - 18	93 - 71	160			
E4	Mean					22	25	70			
N=65	SD						16	45			
	90% CI					19 - 25	28 - 22	79 - 61			
E5	Mean					64		38.5			
N=18	SD						0.48	73.8			
	90% CI					60 - 71	0.54	67.1- 9.9			
Ea	Mean			1.25	0.062		0.69-0.27				
N=25	SD			0.21	0.022						
	90% CI			1.32 - 1.18	0.069-0.055						
Total E	Mean	11.1	6	1.6	0.017				6.6	62.5	20.9
N=118	SD	14.4	3.4	0.4	0.01				6.1	15.3	4.9
	90% CI	13.3 - 8.9	6.5 - 5.5	1.66 - 1.54	0.019-0.015				8.6-4.6	67.6-57.4	22.7-19.1

certain it was representing that mean. By describing each of the parameters in these terms, the DFC for that particular stream type can be described. How these data are eventually displayed in the Forest Plan will be determined in an interdisciplinary mode. For example, in the Rosgen classification, reaches that are slightly entrenched really have no upper limit on entrenchment ratio. Therefore, establishing a range of 13.6 to 22.8 for C reach entrenchment would be unrealistic and unnecessarily constraining. In this case, the DFC for C reach entrenchment might be better expressed as > 13.6.

Discussion

The measurement of a variety of physical parameters in watersheds that are undisturbed or minimally disturbed can be used to define physical stream conditions that reflect the present climate and tectonic regime of a region. If these measurements are used as references, land managers can estimate the dimension, pattern, and profile that would be the result of natural processes for stream channels within their area. By measuring the parameters that are used as delineative criteria in the Rosgen classification, stream types can be locally defined. For example, E stream types are defined in the classification system as having a width/depth ratio of less than 12. In the Greater Yellowstone Ecosystem/southwest Montana area, measurements of 118 E stream reaches show an average width/depth ratio of 6. Consequently, if a given E reach had a width/depth ratio of 10, and the stream banks were trampled by livestock, that reach might be determined to be trending away from stability as a result of getting wider and shallower.

These data can be used at various scales depending on the situation. For NEPA documents, where very site specific data is required to characterize stream conditions, reference and project reaches may be matched based on valley bottom characteristics. Demonstrating the difference between reference and project conditions will give the manager an idea of the status and trend of streams in the project area and how they may respond to a proposed action. On the Beaverhead-Deerlodge National Forest, NEPA documents have incorporated this approach since 1997.

In the TMDL arena, targets for parameters that define the condition of a stream with respect to beneficial uses must be established. Reference data, sampled throughout the area, can help define the conditions whereby beneficial uses can be expected to be self-maintaining. In Montana, the Ruby River and Yaak River TMDLs are presently using reference data to help establish targets for sediment and channel dimensions. At the Forest Planning scale, Desired Future Conditions define the hoped for end result of a suite of management operations over the entire forest. In past planning efforts, the DFCs for streams were often simple narratives that were neither quantitative nor measurable. The ability to gather reference data over a wide geographic area and a variety of stream types allows the DFC for each stream type to be described in a manner that provides the land manager a picture of the conditions that should exist regardless of the suite of management activities applied to the land. In the Forest Plan Revision process, the Beaverhead-Deerlodge National Forest is basing its DFCs for aquatics on local reference data. Across all scales, the ability to quantify standards, targets, and DFCs, makes any subsequent monitoring program more effective.

Reference data can provide land managers timely and excellent information with which to make decisions. However, they are not a panacea, and should not be applied in a vacuum. The need for professional interpretation at all levels of analysis is paramount. Choosing individual reference reaches, setting confidence limits, establishing acceptable risk, and determining the relative importance of different types of reference data, all require field-based knowledge of the watersheds in question. Rather than dogmatically establishing limits to management, reference data should be looked on as a tool that enables specialists to make better recommendations, and allows managers to gain a better understanding of how aquatic systems work.

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Sediment From a Small Ephemeral Gully in South Carolina

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Since acquired in the 1930s, the Sumter National Forest, South Carolina, U.S.A., has emphasized land stabilization and restoration of eroded landscapes. Public concern over ground disturbance associated with some gully treatments suggested the need to verify sediment contributions, since many ephemeral gullies remain barren. We answered the questions, "Can a gully be barren, actively eroding, and not contribute sediment?" This paper summarizes the sediment measured from a discontinuous valley-side gully approximately 0.10 hectares (0.25 acres) in size. Measurement began in July 1994 with the installation of a filter fabric fence. In August 1994, runoff from Tropical Storm Beryl delivered 4.5 tonnes (5 tons) of sediment. By February 1999, a total to 40 tonnes (44 tons) of sediment accumulated. Remeasurement in March 2004 indicated a total of 48 tonnes (53 tons) with an average annual sediment delivery rate of 51 tonnes/hectare. Soil erosion occurred during intense rainfall events and freeze-thaw cycles; however, only severe storms produced enough stormflow to deliver sediment. During inactive periods, leaf-fall effectively hid the sediment transport path, giving an appearance of stability. Results suggest that small ephemeral gullies can be sources of sediment and should not necessarily be neglected. Carefully selected indicators may help determine if sediment delivery is a concern from ephemeral gullies.

Keywords: *ephemeral gully, filter fence, survey laser, erosion, sediment yield, storms, stream order, stormflow*

Introduction

The Sumter National Forest (SNF) was acquired in the 1930s within the authority granted in the Weeks Law of 1911 to obtain and improve denuded and eroding lands within navigable watersheds to help produce sustained water and timber resources. Historic agriculture, logging and road practices contributed to the severe erosion and declining watershed conditions within the piedmont of South Carolina. National Forest emphasis on controlling erosion began with the Civilian Conservation Corps reforesting denuded lands and stabilizing gully networks. Ongoing efforts continue to address control and improvement of severely eroded lands through reforestation and treatment of actively eroding sites (Hansen 1991; Hansen and Law 1996). Many others have studied or discussed various aspects of gullies (Hoover 1949; Heede 1976, 1982; Singer et al. 1978; Yoho 1980; Schumm et al. 1984; Hansen 1995), reporting a wide range in conditions and sediment delivery. In most cases, sediment delivery was estimated from large ephemeral gully systems as a result of significant runoff or by calculating the volume lost from the gully dimensions.

This study began in an effort to help address a public concern relative to proposals to treat gullies that are barren, eroding, but with limited apparent effects downstream. A barren, ephemeral gully in Chester County, South Carolina, with unknown downstream sediment delivery was selected in 1994 for measurement of sediment. At that time, leaves covered the downstream channel, and the gully did not appear to be actively delivering sediment. Treatment was not being proposed or contemplated at that time.

Area Description

The study site is in Chester County, east of Union, South Carolina, on formerly farmed land acquired by the SNF in 1992. The ephemeral gully forms a Strahler order 1 channel within the Little Turkey Creek drainage (Figure 1) (Strahler 1957). The gully to be scrutinized is a discontinuous valley-side gully, with a drainage area of about 0.1 ha (0.25 acres). Adjacent to the site are several other barren, ephemeral gullies somewhat smaller in size. Based on examination of aerial photos, the gullies were formed prior to the 1940 aerial photo, but some noticeable headcut migration was visually detected in the measured gully until the 1969 photo. Aerial photos in 1974 (Figure 2) and 1990 (Figure 3) suggested that gully expansion had reached its limit with no major changes in the gully shape or extent during that period. So logically, there was uncertainty in whether the ongoing surface erosion

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Figure 1. Gully vicinity LEEDS, S.C. Quadrangle - USGS Topographic Contour Map, Lat. 34°44′N, Long. 81°25′W. Distance from the gully southeast to the sharp bend in the road is about 0.57 km (0.36 miles). Contour interval is 3 meters (10 feet).

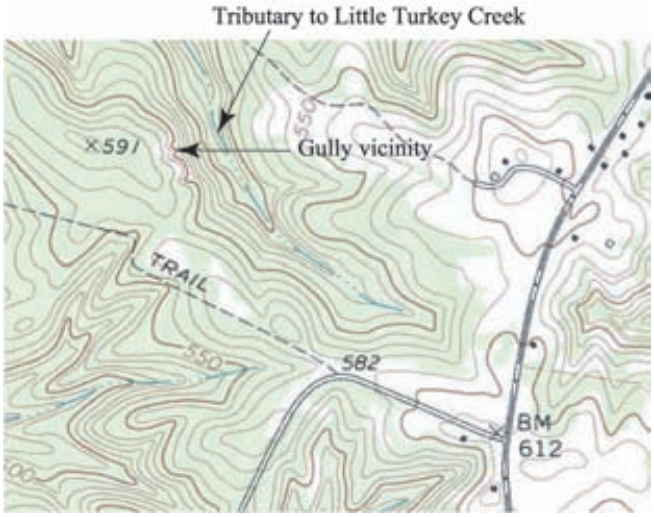

Figure 2. Aerial photo taken in April 1974, with gully marked. Note the 6-meter width of the gravel road at photo bottom.

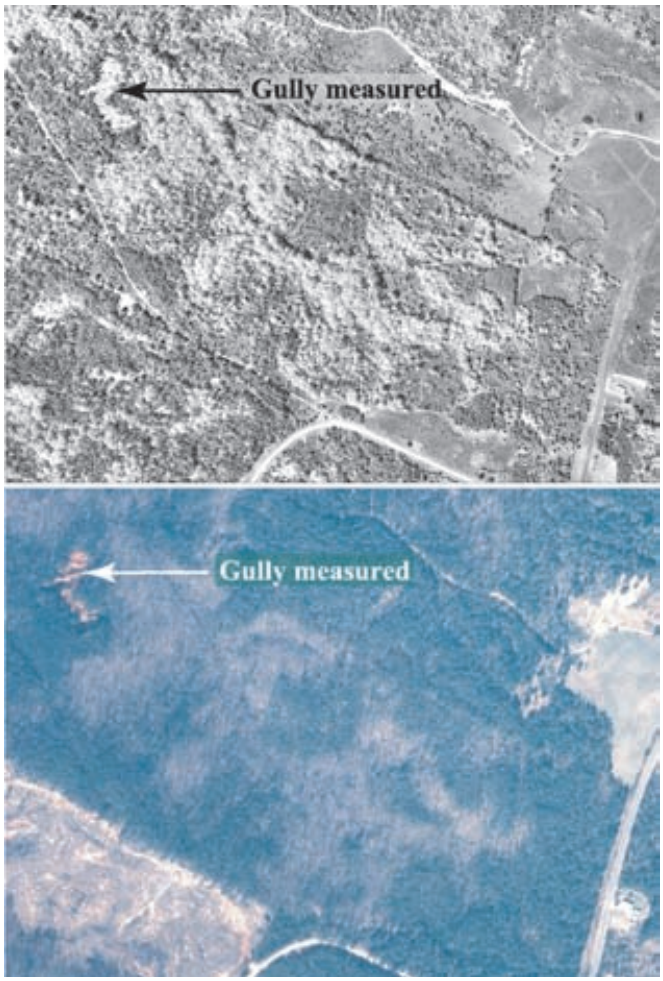

Figure 3. Aerial photo taken in February 1990. No major changes in gully size were noted in comparison to 1974 photo.

associated with the barren soils could be delivered as sediment sufficient to justify treatments. The downstream channel appeared stable and well covered in leaves suggesting limited or no sediment delivery.

Portions of the study area were probably farmed about a century ago. Eventually much of the farmed area on sloping terrain became depleted of nutrients, resulting in poor crop yields, abandonment, severe sheet erosion, and continued exposure to the elements, with gullies forming in areas where flow concentrated (Figure 4). Portions of the landscape were either planted to loblolly pine (*Pinus taeda*), or naturally recovered to mixed pine and hardwood forest after farming ceased. However, the severely eroded soils within the measured gully and adjacent gully barrens have been unable to support significant vegetative cover for many decades (verified at least 65 years). Many of the bottomland trees adjacent to the area are mature timber probably over 80 years old. The skid or temporary roads in the 1940 aerial photo suggested that logging likely occurred in the 1930s. Concentrated flow from skid roads or skidding practices onto heavily eroded soils may have contributed to the localized gully expansion or enlargement noted between 1940 and 1969. However, this is speculation and has not been substantiated beyond observing that a logging road contouring the hillslope, ends abruptly near the gully barrens. The sparse trees within the gully exhibit characteristics of low site conditions such as fusiform disease, chloritic needles, rank branching, rough bark, exposed roots and poor form.

Figure 4. General view of gullied area within tract. Sharp pinnacle-like boundaries separated the individual gully channels.

Rainfall averages about 114 cm (45 inches) per year in this area of the South Carolina piedmont, and is variable, but typically well dispersed through the year with average monthly rainfall between 7 and 13 cm (3 and 5 inches) (NOAA 2004). Water yield averages about 43 cm (17 inches) per year based on the gaged larger streams (Cooney

et al. 2003). The less eroded hillslopes were typically Pacolet soil series that have thin A and B-horizons. Inclusions of Catuala soil series exist locally and have a fragipan-like B-horizon that is noticeable on the exposed upper margins of the gully. Soils within the gully are severely eroded and entrenched about 10 meters at the deepest into the saprolite materials of the C-horizon. Most of the gully has no remaining A-horizon or B-horizon, except for moderately eroded remnants along the gully upper margins near the ridge.

Methods and Materials

In July 1994, filter fabric dams were constructed to capture sediment within an ephemeral channel. Materials included steel T posts, wire fencing, filter fabric, and wire C clamps and post ties. Methods were derived from Dissmeyer (1982) but differed from the construction materials and hillslope location described (Figure 5). Steel fence posts (1.8 m or 6 feet long) were initially installed at 0.9 - 1.5 m (3 - 5 ft) spacing, but more posts were added later to handle the weight of the sediment and water. The 1.2 m-high (4 ft) wire fence and filter fabric were buried about 0.15 m (6 inches) beneath the soil surface and oriented across the ephemeral channel to assure that the sediment would be retained and the water filtered through the fabric. The filter fabric was attached to the wire fence with C clamps using hognose pliers. During installation, care was taken to align the designed overflow dip in the fabric with the center of the channel so overflow could occur if needed without going around the edges and damaging the integrity of the structure. Since the initial fabric dam was nearly full within the first year, two other sediment dams were added in 1995 downstream of the initial site to maintain filtering and sediment capacity. The weight of sediment bent some steel posts and pulled the fence from the slope, leaving a gap for water and sediment to escape. The structures were reinforced with more posts and any gaps were filled with cloth bags containing soil, sand, concrete, or a combination of these.

Measurements were made in 1994, 1999 and 2004. Sediment deposits behind the dams were taken by measuring the elevation changes as sediment accumulated at 0.3 - 0.6 m (1 to 2 ft) spacing intervals for cross sections every 0.9 m (3 ft) up the channel. Elevation differences were measured with a Nikon Laser Level[1] with rod sensor, and cross sections were marked with rebar pins. Measurements were located with an expandable 7.6-m (25-ft) survey rod adjusted to fit between the rebar pins at either end. Soil samples were taken to determine bulk densities at each measurement time to be sure that any settling was taken into account. In March 2004, a total station survey instrument (Topcon Model GTS-605) was used to survey the area and establish more benchmarks for future needs.

[1]The use of trade or firm names in this publication is for reader information and does not imply endorsement by the U.S. Department of Agriculture of any product or service.

Figure 5. The fabric dam was installed in July 1994 below the 0.1-hectare ephemeral gully. The filter fabric was supported with steel posts, wire fencing and C clamps.

The fine detail of the drainage boundary was surveyed using a Criterion 400 Survey Laser (Griswold 1993) (Figure 6). Traverse (PC) software was used to map station locations by distance, angle and slope from base locations. The survey laser was used to determine the gully boundary including a narrow, pinnacle-like section.

Results and Analysis

In August 1994, about 13 cm (5 in) of rain from Tropical Storm Beryl delivered over 4.5 tonnes (5 tons)

Figure 6. A Criterion 400 survey laser provided quality measurements to determine gully drainage extent. Laser has selective filter that can detect prism through vegetative cover, or can shoot directly to any solid surface, measuring distance, azimuth, slope and elevation change.

Figure 7. About 4.5 tonnes (5 tons) of sediment were deposited from Tropical Storm Beryl in August 1994. Sediment surface elevations and bulk density measurements were taken to estimate sediment amount.

Figure 8. Additional dams were added to capture sediment. After 4.5 years (February 1999), a total of 40 tonnes of sediment were captured for an average sediment yield of 89 tonne ha^{-1} y^{-1} (36 tons ac^{-1} y^{-1}). Most of the sediment was delivered during three major tropical storm events.

of sediment (Figure 7) (NOAA 2004). The amount of sediment captured from one storm event in such a small drainage area was a surprise. The filter fence was nearly half full of sediment and the steel fence posts were bent from the weight of the sediment and water. Some of the sediment was lost due to overflow. By February 1999, a total of 40 tonnes (44 tons) of sediment accumulated behind the sediment fences indicating an average sediment delivery rate of 89 tonnes ha^{-1} yr^{-1} (39 tons ac^{-1} yr^{-1}) (Figure 8). Tropical Storms Jerry (1995) and Danny (1997) each contributed about 15 cm (6 inches) of rainfall, which produced enough flow to deliver sediment (NOAA 2004). The delivery of sediment was relatively dormant during the period 1997 to 2002 due to extended drought conditions. During the spring and summer of 2003, much higher than normal rainfall reactivated the delivery of sediment within the gully. The March 2004 measurement indicated an additional 8 tonnes (9 tons) of sediment had accumulated since 1999. After 9.5 years, total sediment accumulation was 48 tonnes (53 tons), resulting in an average annual sediment delivery rate of 51 tonnes/ha (22 tons/ac). This amount is probably conservative due to the amount lost in the initial overflow, and the extended drought between 1997 and 2002. During the study, ten storms produced flows in the nearby Enoree River at or above the flows associated with Tropical Storm Beryl, with Tropical Storm Jerry (1995) producing the 30-year flow of record (Cooney et al. 2003). It is likely that most if not all of these storm events, and perhaps a few others, contributed to the sediment captured.

Measurements and site visits after some of the major storms led to our curiosity to find other indicators of gully activity. Erosion of the bare gully surfaces occurred regularly in response to intense rainstorms, freezing rain and freeze-thaw events that dislodged soil particles. During most events of any significance, particles were moved by gravity or water, relocated on-site with moderate events with most accumulating at the toe of the slope or in the ephemeral channel for storage. Much of the gully remained sparsely vegetated or barren during the decade due to continuing erosion of the saprolite materials of the C-horizon. The highly weathered saprolite also has low available nutrients. Without treatment, most gullies and galled barrens in saprolite materials remain exposed for decades. Although erosion events are fairly common, sediment delivery downstream is episodic. Two distinct, buried organic layers were found in the sediment deposits delivered between August 1994 and February 1999 (probably Tropical Storms Jerry in 1995 and Danny in 1997). These layers as well as site visits after major events testify to the episodic nature of sediment delivery. Downstream reconnaissance following severe storm events led to identifying the historic sediment path of the gully onto a nearby stream terrace. Areas were found with recent sediment deposits, buried organic layers, clay stained trees and buried tree trunks in the flow path. It was apparent that the sediment path on the low gradient terrace had changed with time due to the accumulation of materials and occasional woody debris falling, accumulating sediment and diverting the path. The red clay stains on lower tree trunks and the lack of the buttressed root collars in older hardwoods due to their burial were persistent indicators of accumulated sediment in the delivery path.

A summary of the sediment measurements for the study is provided in Table 1. During the March 2004 sampling of the sediments, the bulk densities varied from 1.38 to 2.3 g/cm^3. When comparing the densities with

Table 1. Summary of sediment volume, density and weight measurements with total volume and accumulated weight adjusted for sediment density changes. Data from Wade Tract gully sediment measurements taken from July 1994 to March 2004.

	July - Sept. 1994		Sept. 1994 -Feb. 1999	July 1994 - Feb. 1999	Feb. 1999 - Mar. 2004	July 1994 - March 2004	
Fence	Added Volume (m^3)	Added Weight (metric tons)	Added Volume (m^3)	Added Weight (metric tons)	Added Volume (m^3)	Added Volume (m^3)	Added Weight (metric tons)
1	4.16	4.50	11.40	21.09	1.95	17.51	4.29
2			6.92	12.80	0.53	7.45	1.17
3			0.00	0.00	0.00	0.00	0.00
Total Volume (m^3)	4.16		18.32		2.48	24.96	
Accumulated Weight (metric tons)*		4.50		39.92			48.34

** Accumulated metric tons are based on weighted soil densities of sediments resampled for each measurement.*
Sept. 1994 – Density of material averaged 1.08 g/cm³ for the August 1994 storm.
Feb. 1999 – Density averaged 1.45 g/cm³ for August 1994 storm, and 1.85 g/cm³ for Sept. 1994 - Feb. 1999 sediment.
Mar. 2004 – Density averaged 1.5 g/cm³ for August 1994 sediment, 2.0 g/cm³ for 1994 - 1999 sediment, and 2.2 g/cm³ for 1999 - 2004 sediment.

the location and depths of the accumulated sediment, it became apparent that the sediment from the August 1994 event (derived from Tropical Storm Beryl) continued to be substantially lower in bulk density than the rest of the sediments. High winds from unstable air masses documented elsewhere during Tropical Storm Beryl may have caused an unusual amount of tree sway, twist, lean or blowdown, exposing finer soil materials to erosion. The August 1994 sediments initially had bulk densities averaging about 1.08 g/cm³, and these materials settled to 1.45 g/cm³ in 1999 and to 1.5 g/cm³ in 2004. Sediments deposited between August 1994 and February 1999 filled the upstream fabric dam (fence number 1 in Table 1) and part of the second, with bulk densities averaging 1.85 g/cm³ in 1999 and 2.0 g/cm³ in 2004. Sediments added since 1999 and measured in 2004 accumulated primarily at the upper end of the upper fabric dam (fence 1) with a lesser amount added to the second dam, with bulk densities averaging 2.2 g/cm³. With time, the materials captured have increased in their density and the more recent sediments are also denser. Over the study, 70 percent of the captured materials were retained in the upper structure, 30 percent in the middle structure and no measurable quantity in the lower structure.

Sediment accumulated from 1999 to 2004 primarily in the upper reaches of the first dam, suggesting that the coarse or the heavier particles may be settling out before they reach the first fabric dam. It is not known if this is due to storm differences in effective runoff or due channel changes from the fabric dam. The fabric dam and resulting sediment accumulation have changed the channel gradient, width and depth upstream. Perhaps larger storms would be needed to move materials into the second and third fabric dams. But the subtle changes associated with the filling of the first fabric dam may be enough to alter the delivery and lead to the current trend in upstream channel sediment storage.

Besides the sediment measured in the fabric dams, many observations were made over the extended study that provide useful information for assessing small ephemeral gully erosion and sediment delivery. On-site erosion was evident within the exposed gully area basically anytime, but especially following intense rainfall events and freeze-thaw cycles. Rainfall events left areas where soil pedestals were protected by small rocks and roots from raindrop impact and erosion. Freeze events expanded ice crystals that heaved soil and small plants above the surface. During thaw events, particles lifted from the surface were heard and seen tumbling down the slope as their ice support weakened upon melting. Many of the processes eventually undermined the fine surface roots and left them exposed after surface erosion (Figure 9). These processes help to perpetuate the soil exposure that has been maintained for decades without recovery. Only the large magnitude, severe rainfall events generated enough flow energy to transport sediments downstream in the small ephemeral channel to accumulate in the sediment dams. During inactive periods, the seasonal leaf-fall and wind-blown leaves hide much of the sediment accumulation within the channels, giving an appearance of low activity, with no apparent sediment being delivered (Figure 10).

Figure 9. Soil erosion was evident on low to moderate sloping areas with exposure of fine roots and pedestaling of soils are indicators of the raindrop energy and poor infiltration on these barren soils.

Figure 10. Following autumn leaf fall, indicators of gully activity with respect to sediment delivery disregarding the filter fabric fence are masked to the casual observer.

Other indicators of erosion within the gully and adjacent gully areas included headcuts (primary or uppermost nickpoint), cavitation, slope failure, root exposure, tree decline or mortality along gully margins, areas of sediment aggradation and in some instances secondary nickpoints (Figure 11). These indicators obviously helped verify erosion processes, but did little to actually confirm that sediment was being delivered downstream. Indicators of sediment delivery became more obvious after major events, when fresh sediments covered the channel and the sediment path was dominated by the red clay color.

We noted that the red clay stains at the base of trees in the channel persist and appear to be a reliable indicator of sediment delivery (Figure 12). The stains are a result of red piedmont clay materials in sediment laden runoff or rainfall splash from fresh sediment deposits onto trees. Stain depth was sometimes higher and brighter on the portion of the tree facing the flow delivered from the

Figure 11. Surface erosion along the upper edges of the gully was enough to remove almost all the soil supporting this pine tree during its lifetime.

Figure 12. Sediment marks within the flow path are especially evident from the reddish clay soils onto the base of trees.

gully channel. Within the sediment path on an alluvial terrace, the trunks of mature bottomland hardwood trees showed no enlargement at their base, another indicator that the sediment had buried their trunks some time ago. The sediment track and stained trees continued to a small perennial stream, several hundred feet away. Red clay deposits along the channel margins continued downstream. Soil cores in the sediment track revealed brighter soil colors of fine alluvial materials, while areas outside of the sediment path had darkened red alluvial soils from historic

gully erosion that has had more time to incorporate organic materials and change colors during weathering processes. Buried organic layers are more likely to be present where flow velocity is low, and less likely where flow has a defined path, velocity and depth sufficient to move organic materials.

Discussion and Conclusions

Our study was a result of public concerns associated with having clear reasons for stabilizing and restoring ephemeral gullies. Upon visiting the site and reviewing the findings, individuals concerned about past gully control measures have a much better appreciation of how ephemeral gullies function. Even small gullies can remain barren and continue to erode and deliver sediment for decades, affecting soil, water and aquatic resources. During the study, we identified many storms and events that produced erosion from a small ephemeral gully and associated gullies and other barren areas nearby. More importantly, we identified that severe tropical storms were necessary to deliver sediments from extremely small ephemeral gullies. Until we evaluated the storm and flow frequency of these type events over the study period, it was not apparent that they recur so frequently. Water quality and aquatic habitat are much more likely to be affected by sediment delivery downstream from small ephemeral gullies than we had thought. Since funding to treat gullies is limited, we can use this information to help prioritize treatments. Gullies that are not only eroding, but also actively and frequently delivering sediments to streams would get a higher priority for treatment.

Gullies have many characteristics that make them difficult to understand. Sometimes a relatively simple study as this can help answer public concerns and be beneficial in forming responsible recommendations and decisions. Although this study was intended to only characterize sedimentation associated with a specific gully, it has provided information on how ephemeral gullies function in the piedmont of South Carolina. Following the gully activity for nearly 10 years demonstrated that ephemeral gullies may have their own timing and activity level, and effects are not always obvious. Ephemeral gullies can erode and not produce measurable sediment. However, as evidenced in this study, severe storms can generate the flow needed to deliver sediment from very small gullies.

Other information of the study is interesting, but in some instances would need more verification. The information collected on differences in sediment density seemed to support the idea that the low-density sediments delivered in the August 1994 storm were unusual, even after almost a decade. Perhaps this could be linked to the severe winds and many localized tornadoes experienced outside of the study area during Tropical Storm Beryl. However, the increase in material density with time should be expected and considered when measuring sediment accumulations over time. The increase in coarse materials settling in the upper reaches of the upper fabric dam may be due to channel changes associated with the accumulating sediments. Changes in channel gradient, width and depth occur with aggradation. In addition, sediments captured by the fabric dam may absorb stormflow and filter particles or organics before they can be delivered as sediment. Although interesting with potential implications to the results, the study was not set up to determine the specific processes that may be associated with sediment deposits, as they may vary with channel changes, storm intensities and time.

This study provides an example of simple but effective sediment observations and measurements that helped address a public issue of concern. The approach has been effective in describing and communicating some of the erosion and sediment delivery processes that may occur in small ephemeral gullies. Even without detailed measurements, the fabric dams with accumulated sediment effectively illustrate these results to varied audiences that visited the site or were shown pictures of the results.

The reader should be aware of some precautions and limitations before applying these methods. Under normal circumstances and construction methods, silt fences and concentrated surface waters in channel systems are incompatible. Careful design and installation are needed to contain concentrated flow and accumulating sediment.

We believe that filter fabric dams may have many potential uses in addressing erosion, sediment and water quality issues. As suggested by Dissmeyer (1982), they are very useful in storing sediments derived from hillslope surface erosion. Under most circumstances, hillslope erosion in forests is very low because ground disturbance and concentrated flow is generally limited. The fabric dams have been used to help determine effects from more severe ground disturbances such as wildfire, bladed fireline and temporary road construction. Ground disturbances may contribute concentrated flow from compacted or exposed surfaces. The fabric dams have been used to determine effectiveness of mitigation measures such as drainage dips and erosion control methods. Sediment effects become more likely to be measurable in affected ephemeral channels than on hillslopes because the drainage area increases. Until this gully study, a turbid watermark to light sediment accumulation would commonly be left across the fabric with little or no accumulation at the base of the fence. In those instances, these observations indicate that a flow event occurred, but little sediment was produced. This is

still valuable information in monitoring the effectiveness of methods.

We have some advice or considerations for those attempting to use fabric dams to measure sediment. Consider low gradient channel sections that offer some reduced stream velocity, more channel storage and stable banks. Tall sediment retention structures are unstable. The effective height of the structures used for this study was about a meter. Reducing the height of the structure will limit the amount of sediment captured, but improve its stability under the force and pressure of the flow and sediment. As sediment fills the structure, detention of flow and filtering capability of the exposed filter cloth is reduced. Adding another filter dam downstream can help maintain the filtering capacity and prevent loss of data during overflow. Do not forget that the accumulated sediments within the structure may alter the channel gradient and dimensions and improve the channel's ability to detain or accumulate sediments upstream. Measure the channel dimensions substantially beyond the elevation of the effective dam height. Under the circumstances of this study, the longevity of the filter fabric dams is at least a decade.

We feel that the fabric dams would be well suited to many other conditions. This study area has some of the most severe land use and erosion history in the piedmont of South Carolina. The severity of conditions is also evident when a 0.1 ha ephemeral gully repeatedly delivers sediment downstream over a decade. The severity is also suggested by the Universal Soil Loss Equation average annual rainfall/runoff index (R-factor) for the area: a relatively high rating at 4,600 (megajoules/ha) (mm/hour) [i.e., 275 in units of 100 (foot tons/ac) (inches/hour)] (Wischmeier and Smith 1978). The R-factors in the southeastern U.S. are substantially higher than most of the rest of the country. We have used the fabric dams in ephemeral drainages in the Blue Ridge Mountains with areas of about 1 ha (2-3 ac), and they withstood severe to record events associated with Tropical Storms Jeanne and Ivan in 2004.

Advantages of the filter fabric dams include low to moderate cost, flexibility of scheduling measurements to fit study details desired, and their ability to provide a visual indicator of the accumulated sediment captured. The study costs over the decade were not closely tracked, but expenditures are estimated at $10 000, which included $1000 to install the three fabric fences, $500 for the boundary survey, $500 for deposition and stream sediment measures, $3000 for the three measurements and data compilation of sediment accumulations and probably about $5000 in analysis, documentation and reporting. The flexibility of scheduling measurements to fit individual schedules and having a visible field demonstration are important considerations. Whether seen in a picture or on a site visit, the filter fences are effective communication tools. Disadvantages may be the time needed to measure the elevation changes in the sediments, sample the sediment density during each measurement, and compile the data. The fabric dams are not permanent structures, and failure may eventually occur. The deposits may need to be stabilized or removed when the study is complete.

Assessment of ephemeral gullies and downstream areas after major disturbance events may be a realistic approach in the southeastern U.S. due to the frequency of events. However, for many other areas, the frequency of disturbance events would make the fences difficult to rely on. Even without field assessment, analyzing gully history using aerial photos can be a viable tool in identifying changes in land use, gully shape, size and extent through time. This approach is more difficult where gullies expand into forested terrain. We recommend the fabric dams as a useful tool if the other erosion and sediment indicators are inconclusive. They provide a low technology approach to monitoring sediment under certain conditions that could be adjusted to produce higher levels of accuracy or detail if required.

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Quantifying the Effects of Livestock Grazing on Suspended Sediment and Stream Morphology

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Suspended sediment measurements, physical channel measurements, and allotment inspection notes are combined to describe the effects of livestock grazing on a 12-square-mile (31 km^2) watershed in southwest Montana. In years when streamflow reached bankfull stage, suspended sediment produced during the grazing period (post-1 July) was 4.3 times greater when livestock were present. In absolute terms, livestock are responsible for about 5.6 tons (5.1 metric tons) of suspended sediment per day during the grazing period. Stream channels within the watershed became wider and shallower, and had increased fines as a result of streambank trampling by livestock. Although a rest-rotation grazing system was implemented in 1974, stream surveys indicate continued shifts in channel morphology away from the most probable stable form of channel. Allotment inspection notes provide support for cause/effect suspended sediment relationships.

Keywords: *stream morphology, livestock grazing, sediment*

Introduction

Livestock trampling on streambanks leads to two major adverse effects on the functioning of the channel. First, streams become wider and shallower as trampling leads to channel widening (Braun 1986). The same disturbance mechanism often leads to increased suspended sediment concentrations either through direct introduction of particles, or by creating raw areas on streambanks that are susceptible to erosion by subsequent high flows (Skovlin 1984; Clifton 1989; Clary and Webster 1990). Overton et al. (1994) compared reference and grazed conditions to show effects on physical channel attributes. Because of its effects on spawning gravels, the amount of fine sediment in a stream channel has been used as an indicator of the quality of salmonid habitat (Duncan and Ward 1985). However, because of the difficulty in spatially and temporally measuring suspended sediment, combined with the difficulty of isolating the effects of livestock, there has been little quantification of sediment loading solely as a result of livestock use. On the South Fork of Blacktail Creek, measured suspended sediment data, quantified channel surveys, and allotment records combined to provide an opportunity to determine suspended sediment concentrations and loading for a watershed in which the only land uses were livestock grazing and occasional dispersed recreation.

Furniss, M.J., Clifton, C.F., Ronnenberg, K.L., eds., 2007. *Advancing the fundamental sciences: proceedings of the forest service national earth sciences conference, San Diego, CA, 18-22 October 2004*. PNW-GTR-689. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station.

Background and Physical Setting

The South Fork of Blacktail Creek is located in the Southwest Corner Allotment on the Madison Ranger District of the Beaverhead-Deerlodge National Forest, Montana. The mainstem and tributaries generally have the potential to be E stream types (narrow, deep channels that are sinuous and relatively flat with ready floodplain access) (Rosgen 1996) throughout their lengths, as shown by reference reaches in similar nearby valley bottoms. Table 1 displays important physical and land use characteristics of the S.F. Blacktail Creek watershed. The allotment was converted from sheep to cattle in 1974. Livestock were managed on a three-pasture rest-rotation grazing system, and thus were present in the watershed only during certain times in any given year. July 1 was the "on date" for the allotment, so livestock were not present during the peak flow period for Blacktail Creek. Pasture moves were scheduled in the permit for 11 August, but in practice that date could vary a few days either way depending on annual conditions. The pasture was rested during 1986, 1989, and 1992.

Methods

In the fall of 1985 a series of monitoring stations were established on the Beaverhead National Forest for the purpose of quantifying suspended sediment from various land uses. The South Fork of Blacktail Creek was chosen because it represented a watershed where livestock grazing was virtually the only land use taking place.

[1] Retired

Table 1. Summary of physical characteristics and land use for South Fork Blacktail Creek.

Area	12 mi^2
Annual precipitation	35 inches
Slope	30-65%
Mean elevation	8500 ft
Geology	Tertiary sediment/shale
Road density	0.4 mi/mi^2
Stream crossing density	0.1 crossings per stream mile
% watershed grazed	100%
AUM density	$109/mi^2$
Timber harvest	0
Number of mines	0

Monitoring operations began in April 1986. A stilling well and water level recorder, in conjunction with a rating curve constructed from approximately 15 streamflow measurements per year, were used to determine hourly discharge. An ISCO sediment sampler[1] collected four samples per day at six-hour intervals for an integrated daily sample. The station generally operated from early May through mid September from 1986 -1992. The area immediately around the stilling well and ISCO intake was fenced to exclude livestock.

Stream surveys were initiated on the Beaverhead National Forest in 1991 to determine the effects of land uses on channel morphology (Bengeyfield, this volume). Standard channel measuring techniques were employed (Harrelson et al. 1994). Additionally, at each survey site, fifty bankfull widths were measured to display in a cumulative distribution curve, to show the change in width along a reach of stream. In 1995 and 1999, a total of eight stream surveys were undertaken in the South Fork Blacktail watershed. Three were on the mainstem of South Fork Blacktail Creek, three were on the Bonita Fork tributary, and one each on the Greys Fork and Dukes Fork tributaries. Physical stream attributes from these surveys were compared to reference data from similar channel segments to determine the condition of the reach (Bengeyfield, this volume).

Streamflows were stratified by whether they were above or below bankfull stage. The bankfull flow is important because it is instrumental in maintaining channel dimensions and sediment transport (Dunne and Leopold 1978).

Livestock entered the allotment on 1 July each year, and their direct effect on sediment production is limited to the time they are present in the pasture in which the stream gage is located. Consequently, this analysis is focused on comparing post-grazing sediment production between years when livestock are present versus when they are absent, and between those years when bankfull flow was attained versus sub-bankfull years.

The combination of water column data (suspended sediment), physical channel data (channel morphology, cumulative width distribution), and allotment inspection notes allow a cause and effect picture to be drawn for the effects of livestock grazing on suspended sediment production.

Results

Suspended Sediment Production During Grazing Period

Stream discharge varied considerably throughout the study period (Figure 1). There were three years when bankfull flow was attained (1986, 1991, 1993), two years of extremely low flow conditions (1987, 1989), and three years of moderate flow (1988, 1990, 1992).

Table 2 displays the results of sediment monitoring stratified by time of year and streamflow regime.

Post-grazing sediment loading data (measured as cubic feet per second [cfs] x mg/L x 0.0028) indicate that livestock increase post-grazing sediment loading during bankfull years by 430% (15.5 tons per day with livestock vs. 3.6 tons per day without livestock), and by 157% during low/moderate flow years (4.1 tons per day with livestock vs. 2.6 tons per day without livestock) (Table 3). It is likely that bankfull years produce greater post-grazing sediment totals because higher discharges from the peak flow period extend into the summer, providing more energy for streambank erosion and sediment transport, while at the same time, the presence of livestock on streambanks provides a source of sediment.

Figures 2, 3 and 4 are examples of bankfull years showing the dependency of suspended sediment concentrations corresponding to both streamflow and livestock presence.

The three graphs demonstrate the relationship between stream flow and suspended sediment concentration (mg/L). During the peak flow period, flow and sediment are highly correlated, especially in 1986 and 1991. In 1986, the rest year (Figure 4), and 1991, when livestock were not present until 11 August (Figure 2), sediment remains streamflow dependent. As streamflow drops, sediment remains low. In 1993, when livestock enter the pasture on 1 July (Figure 3), sediment begins to rise as stream flow declines and remains independent of stream flow throughout the time livestock are present. In 1991, suspended sediment appears to increase about the time livestock enter the pasture, but data after 11 August are lacking. During 1991 and

[1]The use of trade or firm names in this publication is for reader information and does not imply endorsement by the U.S. Department of Agriculture of any product or service.

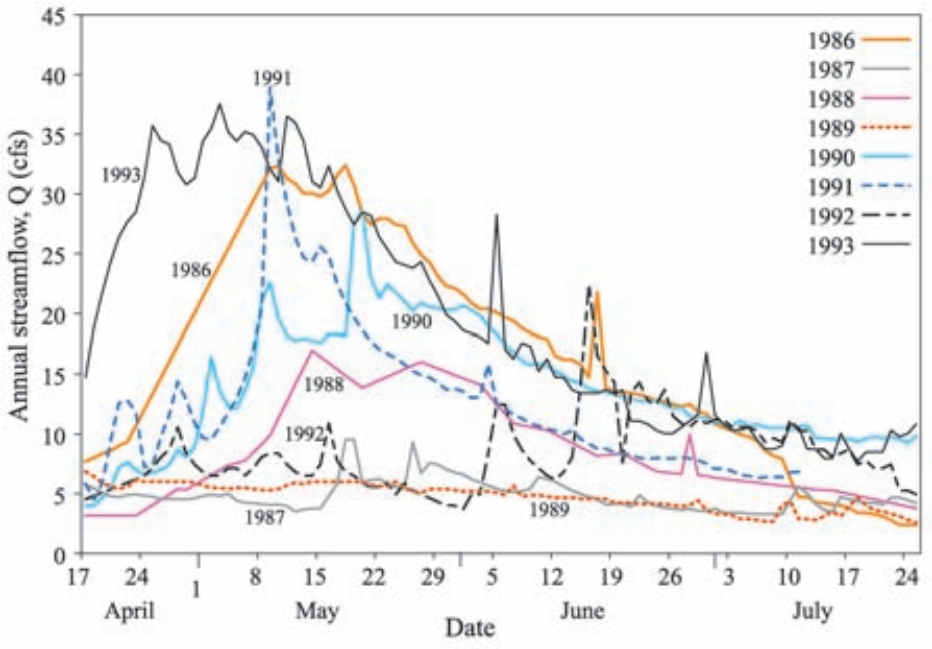


Figure 1. Annual streamflow, South Fork Blacktail Creek, 1986 - 1993.

Table 2. Suspended sediment loading, South Fork Blacktail Creek.

Flow Regime	Year	Streamflow (acre-feet per year)	Sediment pre-grazing (tons/ day)	Sediment post-grazing (tons/day)	Total Sediment (tons/day)	Streamflow (cfs)	Sediment pre-grazing (%)	Sediment post-grazing (%)	Livestock Present
Bankfull	1986	3289	24.8	3.6	28.4	8.29	87	13	No
	1991	2165	15.3	5.4	20.7	8.51	74	26	11 Aug.
	1993	4288	41.8	25.5	67.3	9.64	62	38	1 July
Mean		*3247*	*27.3*	*11.5*	*38.8*	*8.81*	*74*	*26*	
Low	1987	1183	3.8	2.6	6.4	4.09	59	41	1 July
	1989	1042	1.8	1.2	3.0	3.44	60	40	No
Mean		*1112*	*2.8*	*1.9*	*4.7*	*3.76*	*59.5*	*40.5*	
Moderate	1988	1756	36.6	8.1	44.7	4.59	82	18	11 Aug.
	1990	3518	7.4	1.6	9	9.83	82	18	1 July
	1992	2032	3.6	3.9	7.5	6.7	48	52	No
Mean		*2435*	*15.8*	*4.5*	*20.4*	*7.04*	*71*	*29*	

Table 3. Post-grazing sediment loading.

Flow Regime	Year	Livestock Present	Sediment (tons/day)
Bankfull	1991	Y	5.4
	1993	Y	25.5
	Avg.		*15.5*
	1986	**N**	**3.6**
Low/Moderate	1987	Y	2.6
	1988	Y	8.1
	1990	Y	1.6
	Avg.		*4.1*
	1989	N	1.2
	1992	N	3.9
	Avg.		*2.6*

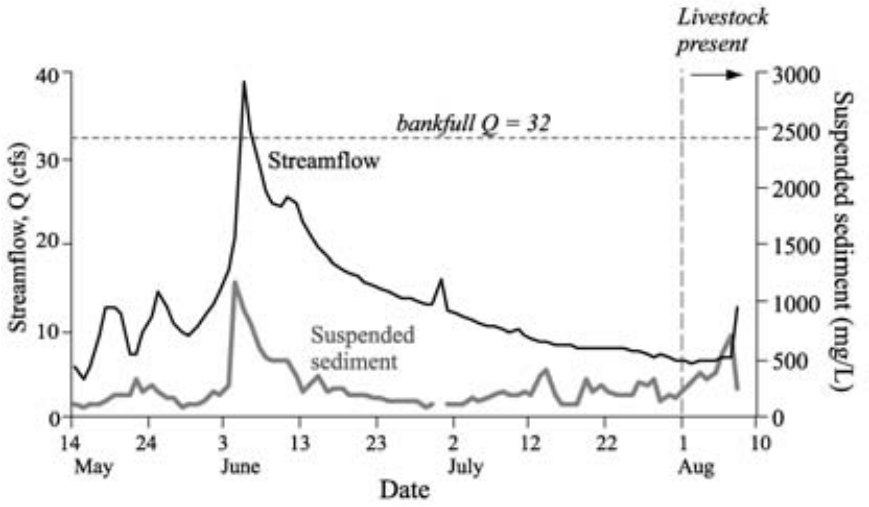


Figure 2. Streamflow and suspended sediment, 1991. Livestock present after 11 August.

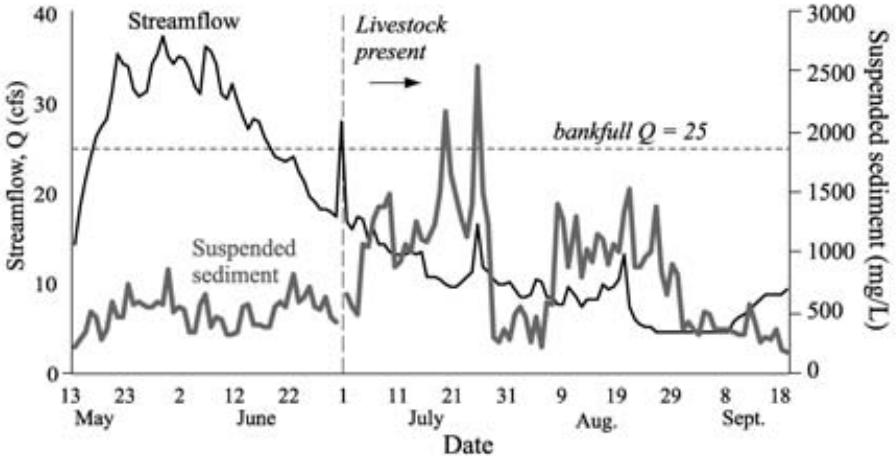


Figure 3. Streamflow and suspended sediment, 1993. Livestock present after 1 July.

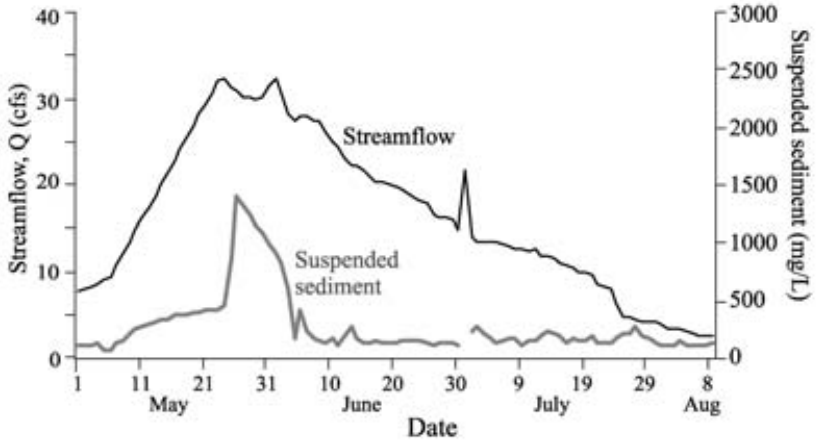


Figure 4. Streamflow and suspended sediment, 1986. Pasture rested.

1993, streamflow was about the same during the post grazing period (1991 = 8.51 cfs [0.24 cms or m^3/s]; 1993 = 9.54 cfs [0.27 cms]) but the sediment concentrations are considerably higher when livestock are present (mean post-grazing concentration in 1991 = 241 mg/L; in 1993 = 878 mg/L). During the rest year, post-1 July streamflow approximates the other years (8.29 cfs [0.23 cms]), but sediment concentration is considerably less (154 mg/L).

Figure 5 displays the difference in suspended sediment production when livestock are present after 1 July during bankfull flow years.

When livestock are absent from the pasture (all of 1986, prior to 11 August in 1991), sediment concentrations are generally less than 500 mg/L. When livestock are present (post-1 July 1993), sediment concentrations are considerably elevated. During bankfull years, the falling

Figure 5. Suspended sediment production (mg/L) for post-1 July during bankfull years.

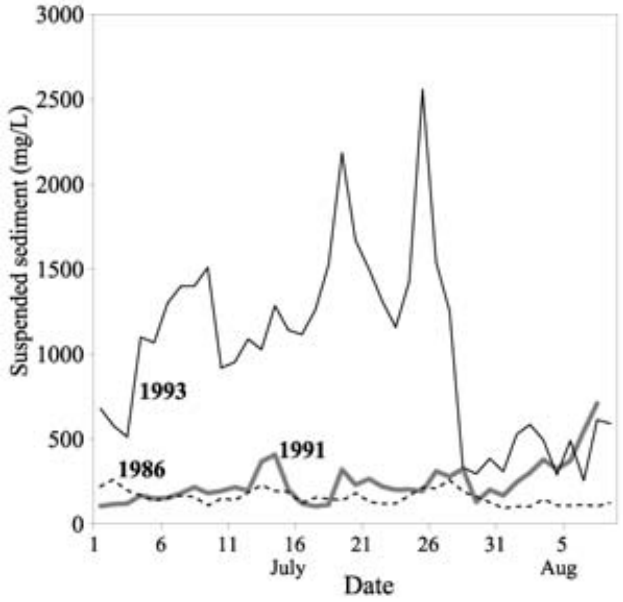


Figure 6. Streamflow and suspended sediment, 1987. Livestock present after 1 July.

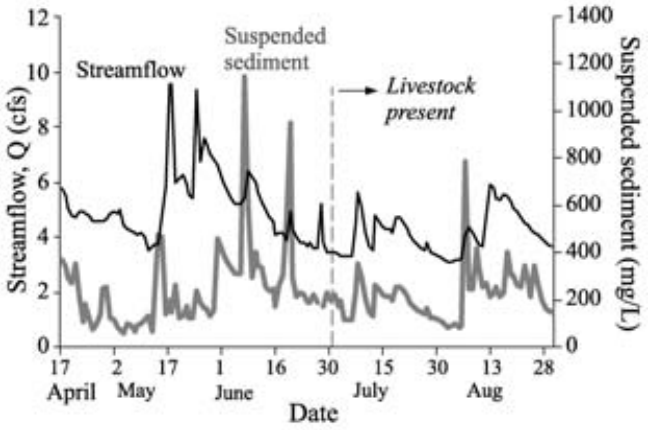
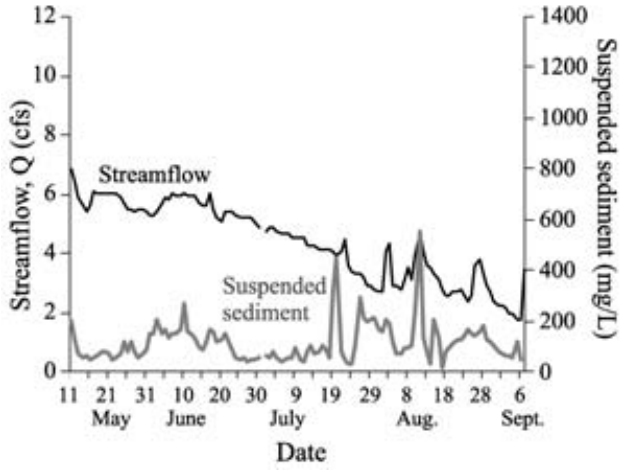


Figure 7. Streamflow and suspended sediment, 1989. Pasture rested.



limb of the hydrograph maintains higher flows into the summer. The presence of livestock on streambanks causes soil particles to be directly introduced to the stream, and trampling exposes streambanks to erosion. This combination of effects leads to higher sediment concentrations.

Low flow years show the same trend of similar streamflow levels producing higher sediment concentrations when livestock are present (Figures 6 and 7). During low flow years (1987 and 1989), sediment concentrations mimic streamflow quite well. Streamflows for this period are much the same for both years (1987 = 4.1 cfs [0.12 cms]; 1989 = 3.4 cfs [0.096 cms]), yet suspended sediment concentrations almost doubled when livestock were present (1987 = 216 mg/L; 1989 = 122 mg/L).

Comparing the average sediment production between grazed and ungrazed years (Table 4), we can see that the presence of livestock contributes to a dramatic increase in suspended sediment loading and concentration. Although sediment is clearly flow dependent, with more being produced during the years when bankfull stage was attained, the increase in both concentration and loading during the time that livestock are present shows the influence of grazing as well.

The average sediment concentration for the period after 1 July during rest years is 152.5 mg/L. This can be assumed to be a background concentration for the stream in its current condition. By subtracting this value from the total concentration when livestock are present, it is possible to determine the effect of livestock on sediment concentration, and to then calculate the sediment loading as a result of livestock. Livestock alone produce approximately 5.6 tons (5.1 metric tons) of sediment daily during the post-1 July period (Table 5).

The 5.56 tons per day (5.0 metric tons) that livestock increased sediment during the July through mid-September period from 1986-1993 equates to a total of 2085 tons (1891 metric tons) of suspended sediment for the period of record. The average May through September sediment loading for that period was 12.1 tons per day (11.0 metric tons), or 13,552 tons (12,292 metric tons) for the period

Table 4. Suspended sediment production for South Fork Blacktail Creek, 1986-1993.

	Suspended Sediment	
Suspended Sediment with:	**Sediment loading (tons/day)**	**Sediment concentration (mg/L)**
Livestock present (5 yrs.)	8.62	391.6
Livestock absent (3 yrs.)	2.94	152.5

Table 5. Post-grazing sediment production as a result of livestock presence.

Year	Flow Level	Post-1 July Accelerated Sediment Concentration (mg/L)	Post-1 July Streamflow (cfs)	Post-1 July Accelerated Sediment Loading (tons/day)
1987	low	63.5	4.09	0.73
1988	moderate	418	4.59	5.37
1990	low	0	9.83	0
1991	bankfull	88.6	8.51	2.11
1993	bankfull	726.1	9.64	19.59
Mean		*259.2*	*7.33*	*5.56*

Entrenchment, as defined by Rosgen (1996), is flood prone width divided by bankfull width, and indicates the degree of channel incision. A large entrenchment value describes a narrow, deeply incised stream channel; a small value describes a wide, shallow stream channel.

of record. The sediment produced by livestock during the summer months in five years was 15.4% of the total suspended sediment produced over an eight-year span.

Stream Survey Data , 1995 - 1999

The stream survey data do not directly measure sediment in the water column as was done in the above analysis, but instead give a picture of various channel components that directly contribute to sediment production. These data indicate that at the majority of the sites measured in the South Fork Blacktail Creek, channel morphology has been altered by livestock trampling of stream banks, and sources of in-channel sediment have been created and perpetuated.

The stream survey data (Table 6) indicate that the main reason for the impairment of these streams was a change in the entrenchment ratios as a result of livestock trampling [see text box, above right]. For example, the most probable stable form for all the reaches should be E stream types (Rosgen 1996), but trampling along the banks has altered the interface between the top of the bank and the floodplain so the channel has become more entrenched, and shifted to a B stream type. The average entrenchment for E stream types in southwest Montana is 11.0 (Bengeyfield, this volume), while the average entrenchment for the South Fork Blacktail Creek sites is 1.8.

The presence of a reference reach in a tributary to South Fork Blacktail Creek that is adjacent to the Southwest Corner Allotment provides an opportunity for comparison of a number of parameters between reaches. The reference reach is in a neighboring allotment, and appears to be seldom grazed. All reaches have similar valley characteristics (valley bottom width, valley slope, and drainage area, Table 7).

An example of the increase in entrenchment at these reaches is demonstrated in Figure 8 by comparing the cross-section of the Bonita Up reach with that of the reference reach. It can be seen from the bankfull and floodplain indicators that streamflows at Bonita Up are less likely to reach their floodplain than those of the reference, South Fork Blacktail Trib Down. Hence, more stream energy is contained at high flows, leading to accelerated bank erosion and sediment entrainment.

An effect of excessive trampling of streambanks is an increase in overall stream width. By comparing the cumulative width distribution of Bonita Up, Bonita Down, and Greys Creek with South Fork Blacktail Trib Down, the reference reach, we can see that this effect has occurred on the tributaries of South Fork Blacktail Creek (Figure 9). All of the tributary reaches are considerably wider than the reference reach throughout their length. For example, the mean width of the reference reach is between 1.5 and 2.0 feet (0.46 to 0.61 m), while the mean width of Bonita Up is between 4.5 and 5.0 feet (1.4 and 1.5 m).

Table 6. Entrenchment, stream type and functionality of survey sites, South Fork Blacktail Creek

Stream	Entrenchment	Stream Type	Function
SF Up	8.9	E	FAR
SF Mid	2.0	B	FAR
SF Down	5.3	E	F
Bonita Up	2.0	B	NF
Bonita Mid	2.5	E	FAR
Bonita Down	1.8	B	NF
Dukes	1.3	G	NF
Greys	11.2	E	F

Table 7. Valley bottom characteristics of South Fork Blacktail tributaries.

Stream	Valley Bottom Width (ft)	Valley Slope (%)	Drainage Area (acres)
Reference	235	3.2	546
Bonita Up	110	4.6	288
Bonita Down	150	3.8	300
Greys	140	1.3	648

Figure 8. Cross sections of Bonita Up and South Fork Blacktail Trib Down.

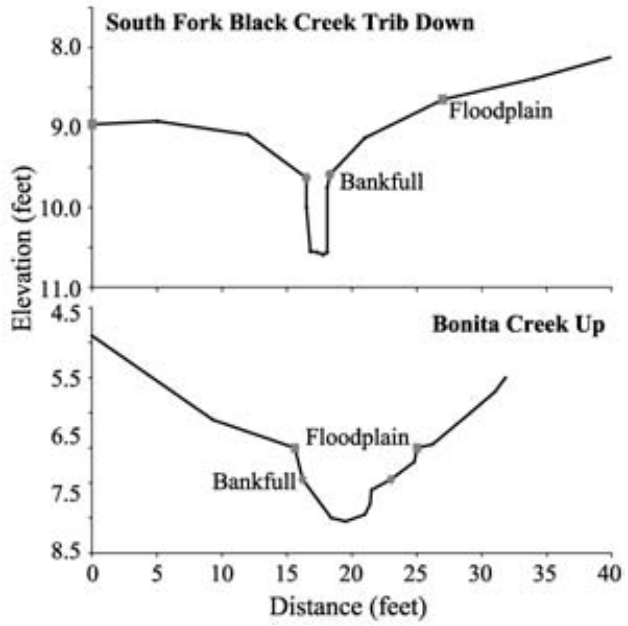


Figure 9. Cumulative width distribution for tributaries to South Fork Blacktail Creek.

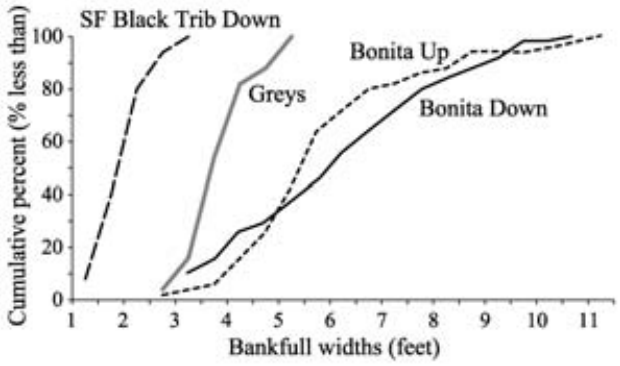
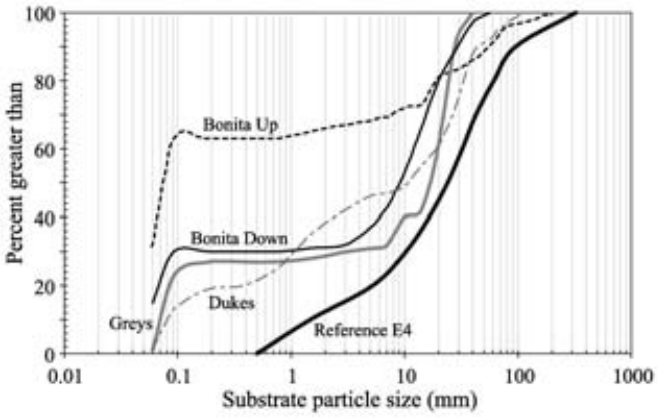


Figure 10. Substrate distribution for survey sites in South Fork Blacktail Creek.



Another effect of livestock trampling is to increase sediment in the stream channel. As fine sediment is deposited in the channel, it causes the substrate distribution to be more heavily weighted to smaller sizes. The survey sites in South Fork Blacktail Creek, as compared to a reference distribution for E4 stream types in southwest Montana, show a pattern that supports this change in substrate size (Figure 10) (Bengeyfield, this volume). All reaches show a shift to a finer substrate when compared to reference conditions. For example, about 12% of the reference reaches have fines under 2 mm in size, while about 30% of Dukes and Bonita Down are less than 2 mm.

Allotment Notes

The Southwest Corner Allotment was grazed by sheep until 1974, when it was converted to cattle. Notes in the allotment file indicate heavy sheep grazing had an adverse effect on vegetation along ridge tops, and that the channel stability of Blacktail Creek was rated as Poor. It was speculated however, that cattle were likely to cause more damage to stream banks than sheep, and that observations of utilization should be taken in the riparian area to determine the allowable AUMs (W. Page, personal communication, 1974). Cattle were managed under a rest-rotation system from the outset, but annual inspection notes indicate that their distribution across the allotment was often poor. A 50% utilization standard was most often employed as a trigger to move livestock to the next pasture. It appears that the allotment was generally inspected once a year, towards the end of the grazing season. Inspection notes reveal that the utilization standard was seldom reached in the uplands, but often exceeded in the stream bottoms. Some excerpts from the notes underscore this point:

- "Cattle concentrated in bottom of Greys Fork. Light use on upper slopes and ridges. Utilization 24%. (14 August 1974)
- "Still cows in bottoms." (4 September 1974)
- "Cattle pretty well used bottoms. Most of use is where cattle were dropped in drainages." (12 October 1975)
- "95% of cattle were between forest boundary and Dukes Fork. All of these cattle were in the stream bottom." (16 July 1981)
- "Need to keep rider to move cows out of bottoms." "The creek bottoms are used enough for this year, however cattle are scheduled to stay for one more month." (14 August 1987).
- "Inspected utilization in riparian areas and adjacent benches. The cattle should be removed from the allotment." (26 September 1988)

- "Bottoms averaged 60-70% use. 31% average streambank disturbance." (11 October 1991)
- "Dukes Fork and Greys Fork are at or beyond riparian guidelines with very little use in the uplands." (1994)

Discussion and Conclusions

Livestock grazing has been shown to adversely affect stream channels through the alteration of physical dimensions of the channel and by adding sediment (Kaufman and Krueger 1984; Clary and Webster 1990). This effect has been demonstrated in a number of case studies (Platts 1983; Clifton 1989), and literature reviews (Skovlin 1984). Overton (1994) compared reference and grazed conditions to show effects on physical channel attributes. Because of its effects on spawning gravels, the amount of fine sediment in a stream channel has been used as an indicator the quality of salmonid habitat (Duncan and Ward 1985).

A major factor that contributes to sediment loading is the condition of the channel and riparian area. Channels in poor condition will have more sediment sources, and annual disturbance by livestock is more likely to make that sediment available for erosion and transport, both during the low flow and high flow periods. Data from around the South Fork Blacktail watershed indicate that much of the riparian area/stream channel network in the watershed is in poor condition with high levels of fine material in the channel. Of the eight stream surveys located on the South Fork Blacktail Creek and its tributaries above the stream gage, six are either non-functioning or functioning-at-risk, and seven were judged to be in a downward trend (Beaverhead-Deerlodge National Forest, unpublished data).

The percentage of fine sediment is consistently much higher than for reference levels for E4 stream types. The average values for all survey sites in the watershed yield a Bank Erosion Hazard Index (Rosgen 1996) of Moderate, and a Channel Stability Evaluation (Pfankuch 1975) of Poor. Reference conditions for the same protocols rate Low and Good respectively. Streambank alteration by livestock was measured at three of these sites, and averaged 73%. All of the ten reference E reaches in the Gravelly Mountains of Montana in geologies similar to those at South Fork Blacktail Creek are E3 and E4 stream types (Rosgen 1996). In reference E4 stream types the amount of material less than 6 mm in size is 22%. For the eight sites in South Fork Blacktail Creek the average is 49% of the substrate less than 6 mm. The only management activities in the watershed are livestock grazing (109 AUMs per square mile) and dispersed recreation, which has a negligible effect on sediment production. There is one road in the watershed, with two stream crossings. In reviewing these data describing existing conditions and land use, it can be concluded that livestock grazing has created unstable stream channels that contain excessive fine sediment. It seems that conditions exist on the ground that would support the above analysis of suspended sediment concentrations and loadings.

It is the presence of livestock in the riparian area that leads to both changes in channel morphology and increases in sediment production. Trampling of stream banks increases width/depth ratios, while at the same time weakening stream banks, making them more susceptible to erosion. Additionally, hoof action on stream banks directly introduces sediment to the channel, and livestock walking in the channel disturb and entrain already deposited sediment. The analysis concerning the post-grazing time period demonstrates that the combination of these activities appreciably increases both concentration and loading of suspended sediment. During that period, sediment concentration is more livestock dependent than flow dependent (Figures 2-4). However, when livestock are present and flows are bankfull or greater, increased shear stress leads to particle detachment and higher loadings. It is likely that during the post-grazing period in low flow years, most of the sediment being entrained is generated by livestock moving in the channel and disturbing the bed and banks. When stream power increases with higher flows, more of the available sediment is entrained by erosion throughout the channel area.

Although most of the annual sediment load (68%) is created when livestock are not present, the stream bank alteration and bed disturbance by livestock during the grazing season create nearly continuous sediment sources that are available when stream flows rise in the spring. That these sources do indeed exist is evidenced by a comparison of physical channel parameters with reference conditions in similar valley bottoms. Increases in entrenchment, stream width, stream bank erosion hazard, and fine substrate material, coupled with a decrease in channel stability, all indicate changes in stream bank composition and sediment supply. Consequently, a high percentage of the 16.8 tons (15.2 metric tons) of sediment produced daily during the pre-grazing time period is attributable to livestock. These data enable us to assess the effectiveness of management on the allotment in terms of maintaining riparian condition and reducing sediment.

Notes taken prior to and during the period of measurement support the sediment data collected in the 1980s, and the stream surveys conducted in the 1990s. It is apparent that even with a rest-rotation system employed from the inception of cattle grazing, distribution of livestock was poor and use in the riparian area was

excessive. In this case, simply implementing a rest-rotation system was not enough to protect riparian areas and stream channels from experiencing accelerated stream bank alteration and its associated sedimentation.

Combining the management history of the watershed with the suspended sediment data collected from 1986-1993, and with the stream survey data collected in 1995-1999, provides a comprehensive picture of the effect of livestock grazing on sediment production. The following conclusions can be drawn.

1. The presence of livestock during the summer months increases suspended sediment concentrations and loading. The increases are greater during years when bankfull flow is attained because more sediment sources are available and the increase in shear stress caused by higher flows leads to particle detachment. During bankfull years, post-grazing suspended sediment was increased by 430% during years when livestock were present. During low-flow years, post-grazing suspended sediment increased 157% over livestock-free periods. Livestock are responsible for about 5.6 tons per day of additional sediment during the post-grazing period.

2. Livestock trampling of streambanks has led to an increase in both channel entrenchment and the percent of fines in the channel. Comparing measurements of these parameters with reference data from within the South Fork Blacktail watershed shows large discrepancies between reference conditions and those surveyed reaches on the Southwest Corner Allotment. High levels of streambank alteration by livestock were measured at each of the surveyed reaches, suggesting a cause-effect relationship for the changes in entrenchment and fine sediment

3. The instability along streambanks created by livestock trampling provides sources of sediment available for in-channel erosion during periods of high flows. Because of the variability of peak flows, and the general flow dependency of sediment loading, this situation could well produce more sediment than the direct effect of livestock during low-flow periods.

4. The rest-rotation grazing system is not adequate by itself to prevent livestock damage to stream banks and the resulting increases in sediment. The Southwest Corner Allotment has been managed under a rest-rotation system since 1974, but has had relatively little successful livestock management within the pastures when cows are present. To maintain acceptable sediment levels in streams, effective herding is needed when livestock are present.

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Using Multiple Fine-Sediment Size Classes to Evaluate the Condition of Trout Spawning Habitat

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Trout biomass and substrate samples from potential spawning areas were analyzed from 36 streams throughout the Monongahela National Forest, West Virginia to determine if trout biomass and sediment relationships on the forest were consistent with what is reported in scientific literature, and whether the data could provide additional insights into those relationships. Graphs of trout biomass plotted against various size fractions of substrate sediment show fairly large variability in the data, suggesting that fine sediment is only one of many factors that controls trout populations. Trout biomass did not change significantly as the percent of fine sediment < 4 mm diameter increased, showing that this more traditional metric is not applicable for the small sized trout found in this forest's streams. By contrast, trout biomass decreased significantly as the percentage of sediment < 1 mm diameter increased. The most important size class for predicting trout biomass was the < 1 mm fraction. Once sediment < 1 mm diameter comprised 45 percent of the < 4 mm fraction, trout biomass was almost always less than 20 kg/ha. Analyses of other individual particle sizes indicate that "good" spawning materials contain a mix of particle size classes. Consequently, we propose that the traditional single-size classification approach be replaced by an evaluation of multiple particle sizes. This approach, particularly when combined with data about other factors that could affect trout productivity, would provide a more thorough understanding of how management activities could affect trout or whether mitigations could improve stream conditions for trout.

Keywords: *sedimentation, stream substrate, trout, monitoring*

Introduction

A wealth of literature supports the effects of sediment on salmonids in the North America. Unfortunately, much of that research has been performed in the laboratory or in controlled environments, such as flume experiments. There is a need to examine sediment relationships using field data, to determine how well results under controlled conditions compare with those in the field.

The Monongahela National Forest in West Virginia has conducted aquatic monitoring for more than two decades, including the routine collection of substrate sediment and fish data. The forest traditionally has evaluated stream conditions by classifying fine sediment as those < 4 mm diameter (Chapman 1988), as this size class is widely accepted as the critical one for salmonids. However, the < 4 mm diameter class was established primarily based on studies of western salmonids larger than those typically found in the eastern U.S., especially the salmonids of the inland East. Regional and local studies in the East have suggested that smaller particles are more important in affecting smaller fishes and their habitats. For example, Hausle and Coble (1976) and Argent and Flebbe (1999) reported a negative relationship between brook trout (*Salvelinus fontinalis*) egg and fry survival when fine sediments comprised 20-25 percent of the bed substrate. Hausle and Coble (1976) defined fine sediment as < 2 mm diameter, while Argent and Flebbe (1999) defined them as 0.43 to 0.85 mm. Peterson and Metcalfe (1981) showed that Atlantic salmon (*Salmo salar*) eggs had poorer survival in fine sediment defined as 0.06 to 0.5 mm diameter, when compared to fine sediment defined as 0.5 to 2.2 mm

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diameter. Hakala (2000) showed that sediment between 0.063 mm and 1 mm diameter had a negative effect on spawning substrate quality and brook trout populations in West Virginia.

Consequently, we wanted to examine data collected from the Monongahela National Forest's routine monitoring procedures to determine: 1) if they show relationships between trout biomass and sediment that are consistent with the literature; and 2) if the data already available from the monitoring program can provide additional useful insights. These questions are of more than just academic interest. For years the forest has used the literature to make statements about relationships between trout and sediment in a variety of documents, but it has not substantiated that those relationships apply to streams in the Monongahela National Forest. Being able to confirm some of the most basic relationships would strengthen the validity of statements in those documents. In terms of the second point, too often monitoring simply is done to fulfill a legal or institutional requirement without consideration of the long-term value for land management decisions. With the limited resources available for monitoring, it is critical to ensure that monitoring actually provides useful information.

Methods

Sites and Field Procedures

Forty-one streams across twelve land type associations on the Monongahela National Forest (Figure 1) were selected for fish sampling in 1999 because: 1) few data existed for these streams, 2) there was interest in examining the productivity of these streams, or 3) projects were planned in the watersheds in which they exist. While some data were available for several years since 1990, only the data from 1999 were used in this analysis; this data set was large enough for analysis without interjecting variability from multiple years of data collection with potentially greatly different streamflow conditions. In each stream, a 91.4-m representative reach was electrofished. Two passes were made moving upstream and two crewmembers netted shocked fish. Each fish was identified to species and weighed prior to returning them to the stream. Biomass was expressed as kg/ha of stream surface area.

Five streams (Beaver Creek of the Greenbrier River, Fox Run, Ken's Creek, Little Laurel Creek, and Mill Run, a tributary to Taylor Run) had either no fish in the sampled reaches or only non-game species of fish. The other 36 streams contained either native brook trout only or mixes of brook trout and non-native rainbow trout (*Oncorhynchus mykiss*), brown trout (*Salmo trutta*) or both. In this paper we report only on the trout (both native and non-native) that were captured, though the relationships for all trout mirrored those of only brook trout. None of the sampled streams are stocked with fish, so the rainbow and brown trout originated from migrating individuals from off-site stocking.

During the same site visit, spawning gravel substrate were sampled from the same reach using shovel sampling (Grost et al. 1991). Shovel sampling entails pushing the blade into the desired location in the streambed to about half way up the length of the blade. The handle of the shovel then is pushed downward to lever the blade out of the bed. The shovel blade then is slowly lifted from the stream, and water is allowed to drain from the sample before storing it in a zipper-lock plastic bag. During extraction and transference to the bag, care is taken to avoid losing the smallest fraction of the sample.

Six shovel samples were collected from six separate sites considered by the forest's fisheries biologist to have suitable characteristics for spawning. Suitable spawning materials were defined in terms of adequate substrate size (predominantly gravel to small gravel) and position in the channel (typically, but not exclusively, pool tails). Each shovel sample was placed in a separate zipper-lock plastic bag and processed individually. Samples were oven-dried at 100°C until they reached a constant weight. Each oven-dried sample was mechanically shaken through a nest of sieves [mesh sizes: 53.8 mm, 38.1 mm, 8 mm, 6.3 mm, 4 mm, 2 mm, 1 mm, and < 1 mm (i.e., pan)] for 7 minutes. The sample weight in each sieve was determined gravimetrically to the nearest gram.

Percent fine sediment of each sample was defined in two ways: < 4 mm diameter (cumulative weights of the materials in the pan, 1-mm, and 2-mm sieves), which is the procedure that the forest traditionally has used to define fine sediments, and < 1 mm diameter (the pan fraction). The latter was considered because a recent study by Hakala (2000) showed sediment between 0.063 mm and 1 mm diameter was most detrimental to brook trout in Monongahela National Forest streams. For the purposes of percentage computations, total sample weight was determined from the cumulative sample weights in only the 8-mm and smaller sieves, because the fisheries staff on the Monongahela has defined spawning materials as particles < 38.1 mm.

Data Analysis

Mean fine sediment weights were determined for each stream reach based on the six samples. Mean percentages then were determined and are used in the analyses in this paper.

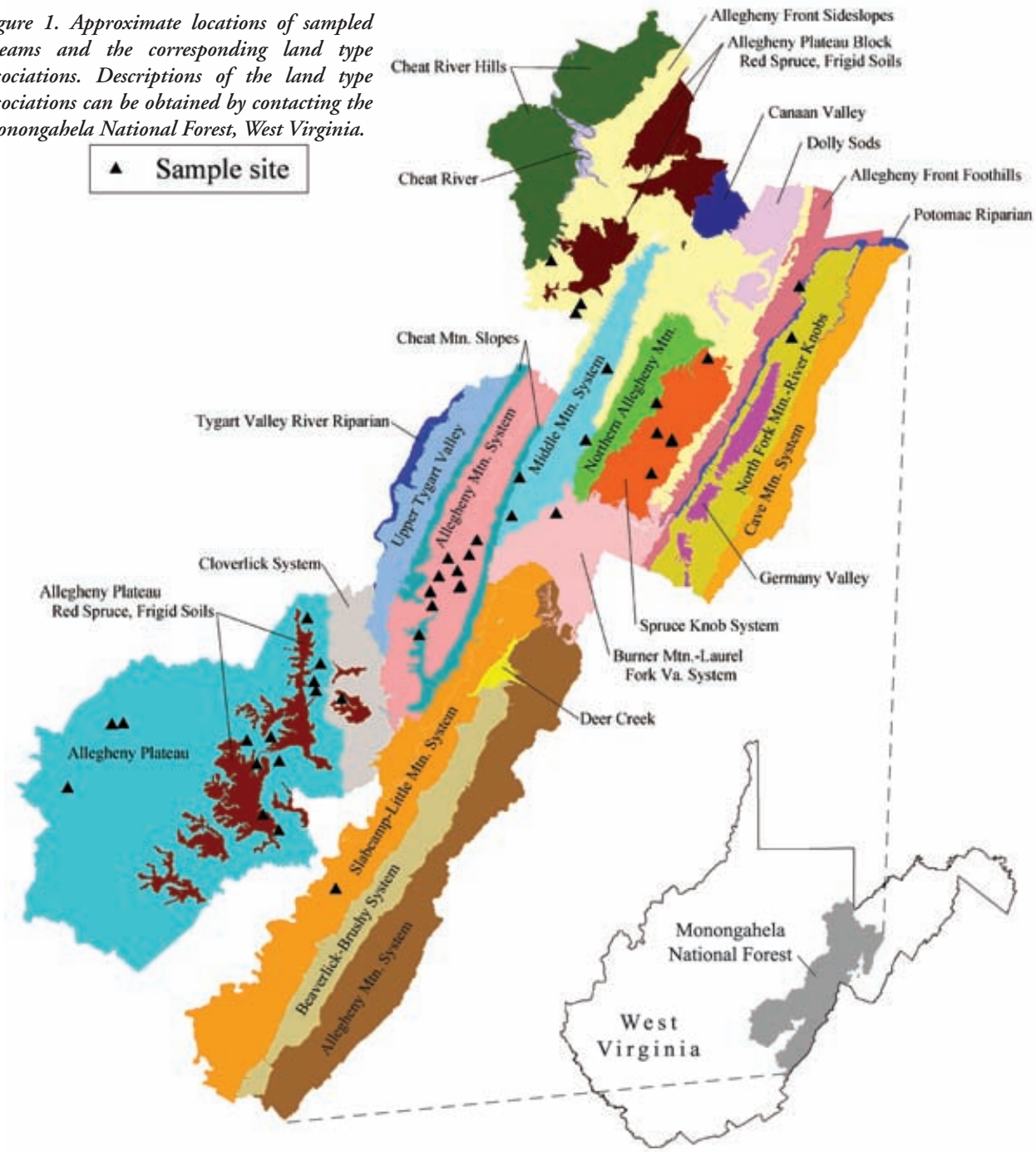


Figure 1. Approximate locations of sampled streams and the corresponding land type associations. Descriptions of the land type associations can be obtained by contacting the Monongahela National Forest, West Virginia.

To describe the general relationships between trout biomass and mean fine sediment values for all the sampled sites, trend lines were developed using locally weighted regression with Locfit software (Loader 1998). Locally weighted regression was used because this approach does not assume an a priori defined form of the fitted equation, such as linear, quadratic, etc. Thus, it can be used to provide a trend line that better describes the overall pattern of the data than one that has a more stringent user-defined form, particularly for trends that are difficult to determine visually. The degree value of the local polynomial and smoothing parameter for the locally weighted regressions were selected using procedures outlined by Cleveland (1994), in which the residual pattern was examined to assure the values of both parameters were appropriate and not over-fitted.

Because locally-weighted trend lines do not have associated slope and intercept coefficients, tests of significance were performed on the data, not on the trend lines. Mann-Kendall tests (Mann 1945) were run to determine whether the increases or decreases in the data were statistically significant. Because the data were

relatively widely spread and there are other factors that can affect productivity, statistical significance was defined at $p \leq 0.10$. Where trend lines showed a change in direction in trout biomass from increasing to decreasing or from increasing to leveling off, the data set was separated into two data sets at the inflection point and both were analyzed for significance.

Stepwise regression was used to determine the size classes that were most important to controlling trout biomass levels (SAS Institute Inc. 1988). Nonparametric correlation analysis (Spearman correlation analysis) was performed (SAS Institute Inc. 1988) to verify if the size classes that were identified as important were directly or indirectly related to trout biomass.

Results

Trout biomass from all the sampled streams except one, Strader Run, fell within a wide, but well-defined range of 4.48 kg/ha to 99.7 kg/ha (Figure 2). The broad range of trout biomass found across the forest suggests, not surprisingly, that fine sediment is only one factor controlling fish productivity. For unknown reasons, Strader Run appears to be an anomaly for streams on the Monongahela, with a biomass of 168.1 kg/ha. Because of its atypical, extraordinarily high biomass and the potential for that single stream to bias the trend and statistical results, Strader Run was removed from the data set for all subsequent analyses.

Trout biomass relationships for the < 1 mm and < 4 mm fine sediment fractions are similar (Figures 2a and 2b, respectively). Most data are clustered and bounded by the dashed lines we inserted to better illustrate the common range of the data. If these streams are representative of streams throughout the forest, the lower and upper boundaries in Figures 2a and 2b suggest that few streams in the Monongahela have less than 4 percent of spawning materials composed of < 1 mm diameter fractions or less than 12 percent composed of < 4 mm particles, and greater than 18 percent composed of < 1 mm diameter fractions or greater than 45 percent composed of < 4 mm particles.

The general relationships between trout biomass and the percentages of sediment < 1 mm and < 4 mm diameters are illustrated by the trend lines fitted to the data (Figure 3a

Figure 2. Relationships between trout biomass and fine sediment in potential spawning materials for fine sediment defined as (a) particles < 1 mm diameter and (b) particles < 4 mm diameter.

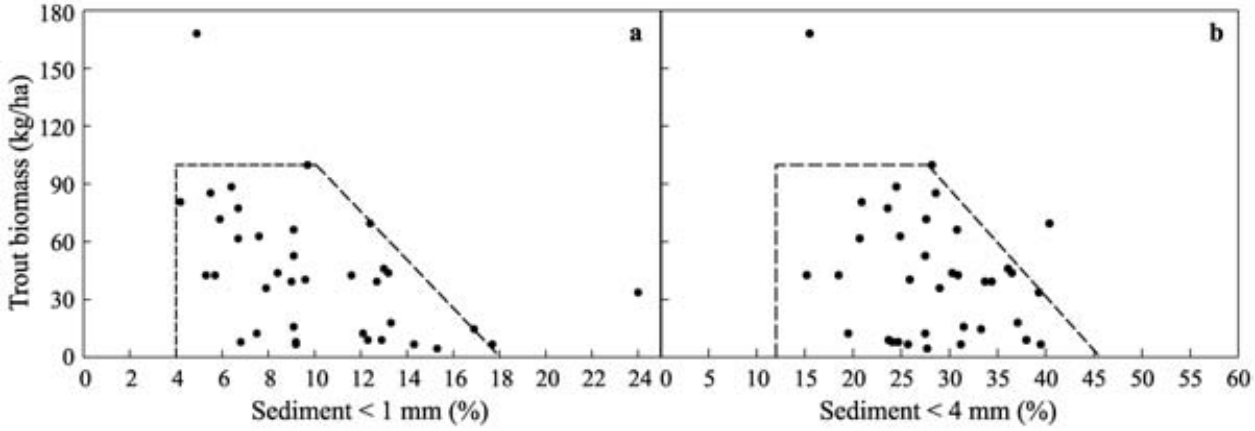
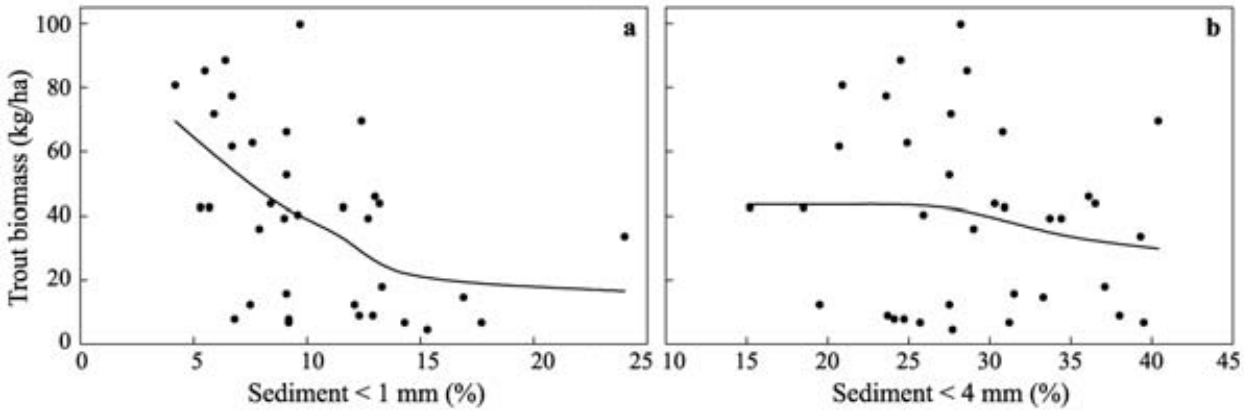
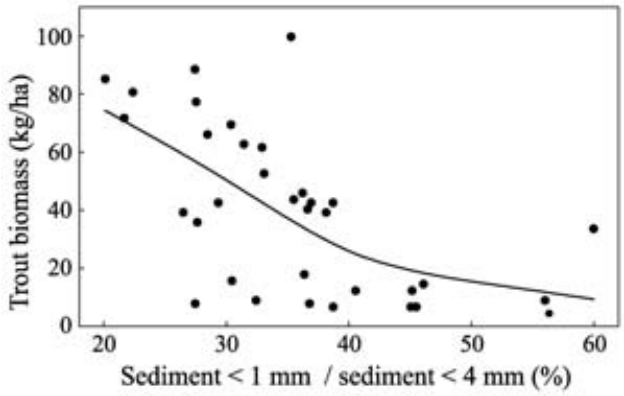


Figure 3. Locally-weighted regression lines show trout biomass responses to increasing fine sediment in potential spawning materials for fine sediment defined as (a) particles < 1 mm diameter and (b) particles < 4 mm diameter.



and 3b). Trout biomass decreased significantly (p = 0.002) as the percentage of < 1 mm sediment increased (Figure 3a). By contrast, trout biomass showed a much less distinct and not statistically significant response (p = 0.378) in relation to particles < 4 mm diameter (Figure 3b). Not surprisingly given the relationships in Figures 3a and 3b, as the percentage of < 1 mm particles increased relative to total fine sediment (i.e., < 4 mm) there was a corresponding significant (p = 0.000) reduction in trout biomass (Figure 4). When approximately 45 percent of total fine sediment was made up of < 1 mm materials, trout biomass was almost always less than 20 kg/ha.

Figure 4. Trout biomass responses as < 1 mm particles in potential spawning materials become an increasing larger percentage of the < 4 mm fraction. The trend line was determined using locally-weighted regression.



The distinct differences in trout biomass patterns between the individual < 1 mm size class compared to the cumulative < 4 mm size class illustrates the potential importance of considering size classes individually rather than cumulatively. Consequently, to obtain a clearer understanding of how individual sediment size classes are related to trout biomass, we examined trout biomass relative to the percentage of materials in each individual sieved particle size class (except for the < 1 mm size, which is presented in Figure 3a).

The trend line for the 1 to < 2 mm size fraction indicates that trout biomass increased and then decreased with increasing percentages of particles in that fraction (Figure 5a); however, the data are widely distributed and the probabilities of significance on both sides of the inflection point were not significant (p = 0.239 increasing trend line side; p = 0.779 decreasing trend line side). For the next two larger size fractions (2 to < 4 mm and 4 to < 6.3 mm), the trend lines for trout biomass increased with increasing percentages of these particles, and then reached a plateau (Figures 5b and 5c, respectively). The probabilities for the increasing portions of the 2 to < 4 mm and the 4 to < 6.3 mm fractions were significant (p = 0.008 and p = 0.092, respectively), but as the trend lines suggested, the data on the plateaus did not change significantly (p = 0.806 and p = 0.721, respectively). The point at which the trend lines leveled off occurred at a greater percentage than where the inflection point occurred for the 1 to < 2 mm fraction. This shift suggests these slightly larger particles are less deleterious to trout than the smaller ones. While the trend line for the 6.3 to < 8 mm fraction shows similar leveling off after increasing, it is difficult to say how trout are affected when the percentage of particles in the 6.3 to < 8 mm size class becomes large, because there was only one mean value that exceeded 12 percent. Consequently, the data were not separated into different sets for analysis of significance, and the data did not show any significant increase (p = 0.221). Trout biomass for the largest size spawning materials (8 to < 38.1 mm) returned to the same pattern as that exhibited by smaller sized particles, first increasing slightly then decreasing in response to increasing sediment (Figure 5e). The pattern of the trend line was not strong, and the analyses of the data indicate no significant changes in biomass on either side of the inflection point of the trend line, though the probability was approaching significance for the data on the increasing portion of the trend line (p = 0.127). Data on the decreasing portion had a significance of p = 0.272.

Obviously, these trend lines represent only the overall responses of the available data; they do not represent predictions of fish biomass for a specific sediment level in an individual stream. Indeed, one reason for using locally-weighted regression was to focus on the trends rather than inappropriately predicting biomass responses from sediment values based on a small data set. The shape of the trend lines is the important feature here, and the points of inflection should not be used as thresholds for defining the ideal allowable percentage of sediment in any size class. There simply is too much variation in biomass data because of the myriad limiting factors to use an inflection point derived from analysis of a single variable as a threshold.

The trend lines and statistical results do provide some useful preliminary information and insights, which should be validated further as more monitoring data become available. First, the < 1 mm particle size data are consistent with the general findings in the literature that fine sediment is detrimental to trout (Argent and Flebbe 1999; Hausle and Coble 1976; Phillips et al. 1975; Tappel and Bjornn 1983; van den Berghe and Gross 1989), and the more specific findings from a small set of streams in the Monongahela National Forest that particles of < 1 mm diameter have the most demonstrable negative effect on trout biomass (Hakala 2000). Second, defining fine

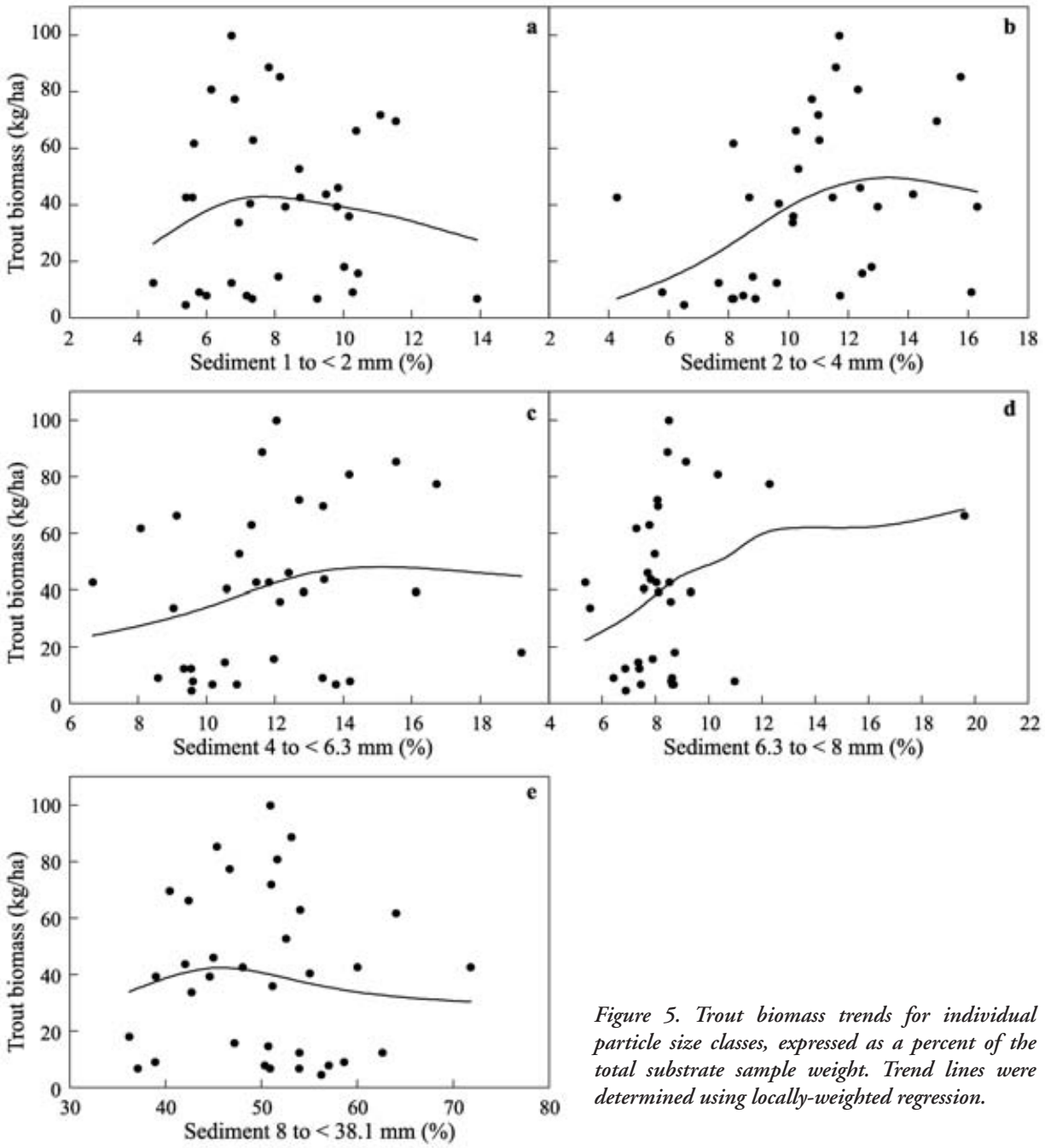


Figure 5. Trout biomass trends for individual particle size classes, expressed as a percent of the total substrate sample weight. Trend lines were determined using locally-weighted regression.

sediment as materials < 4 mm in diameter does not seem to be a useful metric for determining the suitability of spawning materials for the relatively small-sized trout found in the Monongahela National Forest. And third, the increasing and then decreasing or flattening patterns of the data and/or trend lines for particle sizes ≥ 1 mm suggest that the best spawning materials are ones that contain a mixture of particle sizes and are not dominated by a single size. Again, this is a general trend, and other conditions, such as water chemistry, habitat availability, and fishing pressure, will influence how well trout succeed in any individual stream.

As a result of these three findings, we propose that the traditional single-size classification approach be replaced with a multiple particle size analysis approach to evaluate the condition of spawning habitat or the extent to which sediment may be a limiting factor in a stream. Without knowing much else about a stream (which often is the case for many streams on public lands), simply determining the mix of particle sizes may indicate if sediment is a limiting factor for trout. A good mix of particle sizes seems to be one in which the intermediate class sizes (2 to < 4 mm, 4 to < 6 mm, 6 to < 8 mm) have percentages similar to each other and greater percentages than the smaller size classes,

the < 1 mm size class is only a small percentage of the total spawning material, and the 8 to 38 mm diameter particles make up about half of the spawning material by weight.

Results from stepwise regression support the idea that a mixture of substrate size classes is important for trout success. This procedure is parametric and assumes each of the individual sediment size classes is independent of the others, which is not wholly true, but the results are illustrative nonetheless. In the model, the most important size class for predicting trout biomass was the < 1 mm fraction ($p = 0.0039$); this is not surprising based on the fairly strong (i.e., less variability in the data around the trend line than for other size classes) inverse relationships in Figures 3a and 4. The only other variable that was statistically significant in the stepwise regression was the 2 to < 4 mm fraction ($p = 0.0396$). Nonparametric correlation analysis showed trout biomass to be positively and significantly correlated with this fraction ($r = 0.42$, $p = 0.0114$), meaning that trout biomass generally increases with increasing percentages of 2 to < 4 mm materials, consistent with Figure 5b. The other intermediate size fractions (4 to < 6.3 mm and 6.3 to < 8 mm) and the 1 to < 2 mm fraction each were positively and significantly correlated to the 2 to < 4 mm size fraction ($r = 0.76$, 0.49, and 0.52, respectively, and $p \leq 0.0001$, 0.0026, and 0.0011, respectively). The high degrees of correlation explain why these other fractions were not significant in the stepwise regression; i.e., the contributions of each fraction to predicting trout biomass would have been duplicative with the 2 to < 4 mm class. The high degrees of correlation also support the idea that balanced percentages of these size classes provide the mixes of particle sizes that are conducive to trout success.

Discussion

As stated earlier, our findings are only empirical, so we only can speculate about the mechanisms driving the responses. Since the samples were collected in potential spawning materials, it is perhaps most intuitive to make conclusions related directly to sediment effects on spawning, redd conditions, and egg development. Thus, the interpretation would be that very small particles hinder oxygen diffusion to eggs laid in redds and fry emergence (Chapman 1988). More-intermediate sized particles provide better conditions in terms of oxygen supply, better substrate for spawning use and success, or both.

However, the composition of spawning material in any reach is an index of the overall sediment composition throughout the reach, not just the spawning areas. Thus, one could reasonably assume that if very small sized sediment dominates spawning materials, other habitats in the reach also are affected by high percentages of very fine sediments. This parity simply could mean that poor physical conditions are ubiquitous in the stream reach and contribute to a lack of habitat variability, which would affect trout during all portions of their life cycle, as well food sources for the fish (Suttle et al. 2004).

The empirical relationships between trout biomass and the very smallest sized mineral materials also have implications relating to current on-the-ground activities-for example, selection of road-surfacing materials. Research by Kochenderfer and Helvey (1987) in the Monongahela National Forest found that 38.1-76.2 mm clean limestone gravel provided a stronger roadbed and less surface erosion than crusher run limestone gravel (0-76.2 mm). Finer materials, including crusher run types of gravel, are usually recommended on older, well-established roads because they create a smoother riding surface, but they are more apt to experience washing (Kochenderfer and Helvey 1987) and "kicking" off of the driving surface by vehicles. Consequently, the combination of our findings and this road research suggest that fine-sized road surfacing particles should be avoided on new road construction, particularly around stream crossings and their approaches, and around water diversion features, such as cross drain culverts and broad-based dips. In addition, on established roads, small-sized, angular stone (to improve packing) composed of stable material (e.g., limestone rather than friable sandstone) would be less detrimental to streams than stone that grades down to very fine-sized particles.

The deleterious effects of even low levels of the finest-sized sediment also may mean that sediment delivery to streams needs to be controlled much more vigorously than is often done. Implementation of sediment control practices that extend beyond those routinely recommended in forestry best management practices may be needed to control the introduction of very fine sediments, as these can be dislodged and transported by even small amounts of water, such as those encountered during small storm events. Installation of silt fences, straw bales, geotextiles, or other sediment retention methods immediately around stream crossings or other sensitive areas may be required in all cases, not just in some cases or at the equipment operator's discretion.

We believe the general relationships we observed between trout biomass and the very small sediment particle sizes, and between trout biomass and the mixture of more intermediate particle sizes probably apply to other streams in the Appalachians that hold similar communities of similarly sized fish. Of course, given the broad range of biomass occurring with the various sediment size classes, it is important to re-emphasize what may be obvious.

Sediment may not be, and probably is not, the only limiting factor in many stream systems, but sediment should be one of the variables that is evaluated when reviewing overall stream conditions. A thorough understanding of stream conditions and potential limiting factors is necessary to determine if a proposed project or a routine activity will significantly affect stream health, or if dollars spent on mitigation to improve conditions will target important factors or be wasted because other factors are equally or more important in controlling fisheries health.

Conclusion

Trout biomass and associated particle size data from likely spawning materials in reaches from streams across the Monongahela National Forest were examined. The results indicated that the traditional classification of fine sediment as materials < 4 mm in diameter is not a useful metric by which to evaluate spawning materials conditions for small-sized trout on the forest. Instead, we recommend a simultaneous analysis of all available size fractions, paying particular attention to the percentage of materials in the < 1 mm fraction and the percentages of more intermediate particle sizes. The best spawning materials likely are ones that contain a mixture of particle sizes and are not dominated by a single size. Of course, combining information about other stream conditions or limiting factors in the assessment of spawning conditions should further improve any conclusions made, help identify the need for and types of mitigation strategies used during forest management activities, or suggest how routine on-the-ground procedures can be modified to positively affect stream health.

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Water Quality Effects of Blue-Green Algal Blooms in Diamond Lake, Oregon

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In 2001, a serious bloom of potentially toxic cyanobacteria (blue-green algae) developed in Diamond Lake, a popular recreational lake in the Umpqua National Forest (UNF), Oregon. Toxins produced by cyanobacteria have been implicated in human health problems ranging from skin irritation and gastrointestinal upset, to death from liver or respiratory failure. Blooms have continued at Diamond Lake since 2001 and prompted a call for action to control the problem. In the interim, a strategy was developed to deal with the public health threat posed by cyanobacteria. UNF staff, working with private and government organizations, developed a plan to monitor the lake. Results from the monitoring program were interpreted in light of the World Health Organization (WHO) guidelines for toxic cyanobacteria species. We describe this effort and offer lessons learned to other lake managers faced with similar issues.

Keywords: *aquatic ecosystems, paleoecology, history, water quality, lakes, recreation, public health, cyanobacteria, blue-green algae, aquatic/riparian habitat*

Introduction

Diamond Lake is a 1300 ha lake located at an elevation of about 1600 m in the central Oregon Cascade Range (Figure 1). This relatively shallow lake (maximum depth 15 m) is located immediately north of Crater Lake National Park in the Umpqua National Forest. The lake watershed is wholly contained within the national forest and national park. Diamond Lake was probably fishless before 1910 when rainbow trout (*Oncorhynchus mykiss*) stocking began. In a typical year, the Oregon Department of Fish and Wildlife (ODFW) stocked as many as 1,000,000 trout fry from a hatchery at the lake. A lodge, 100 summer homes, and three Forest Service campgrounds were built from 1920 to the 1960s. A successful trout fishery was interrupted when tui chub (*Gila bicolor*) were introduced, likely as bait fish, and caused the sport fishery to collapse in the 1940s.

In 1954 the lake was treated with rotenone and rainbow trout were restocked the following spring. The trout fishery was successful and remained so until the 1990s when tui chub were discovered in the lake once again. Efforts began to respond to the tui chub and the decline in the trout fishery, but no one was prepared for the apparent effect of the chub on water quality in Diamond Lake. In 2001, following a routine sampling of the lake, we discovered that the lake contained a high density of *Anabaena flos-aquae*, a potentially toxic species of cyanobacteria.

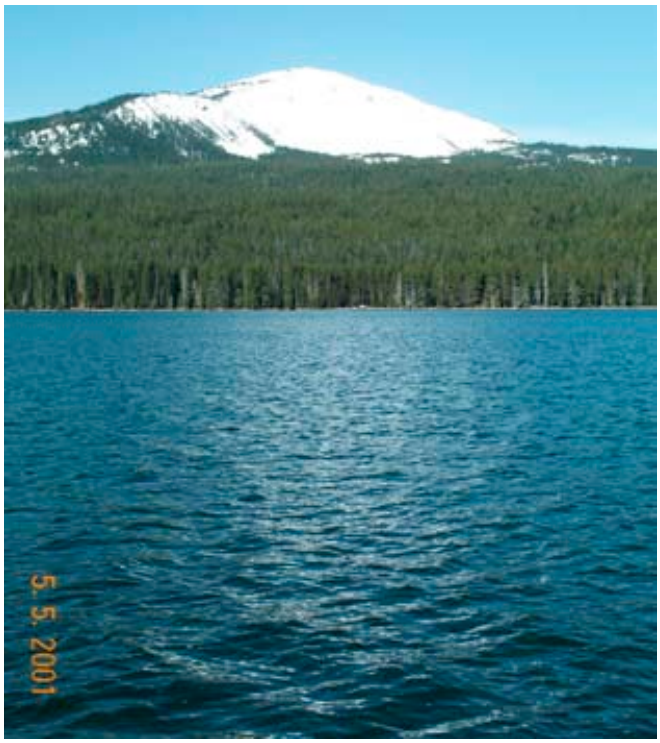
This paper describes Diamond Lake, Oregon, and potentially harmful blue-green algae blooms. We recount the public health actions taken during dense blooms of the blue-green alga *Anabaena flos-aquae* during the summers of 2001-2004, and the role water quality monitoring played in recognizing and responding to the public health risk. Finally, we list some lessons learned by the UNF that may apply to other water bodies.

Diamond Lake Description and History

Diamond Lake is a popular recreational site in the Umpqua National Forest (Figure 2). The primary attraction in summer has always been the abundant trout fishery, although the proximity to Crater Lake, the spectacular scenery, and hiking opportunities draw many other visitors. At the height of its use in the late 1970s, Diamond Lake drew over 780,000 visitors per year. With the collapse of the trout fishery, that use is now a fraction of its peak.

Furniss, M.J., Clifton, C.F., Ronnenberg, K.L., eds., 2007. *Advancing the fundamental sciences: proceedings of the forest service national earth sciences conference, San Diego, CA, 18-22 October 2004*. PNW-GTR-689. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station.

Figure 1. Diamond Lake, Oregon (photo by Joseph Eilers).



Efforts have been made to expand other uses, including water skiing.

The lake experienced algal blooms during the 1960s, and in 1998 Diamond Lake was placed on the Oregon 303(d) list of water bodies not meeting water quality standards for pH and nuisance algae. Earlier investigations indicated that the lake was productive either from natural inputs of phosphorus (Lauer et al. 1979), or from human development of the shoreline (Meyerhoff et al. 1977). Subsequent investigations also reinforced the notion that the lake was becoming culturally eutrophic (Salinas and Larson 1995). A sediment core collected in 1996 (Eilers et al. 2001) indicated that there might be a link between the fish populations and water quality in the lake, but no one was prepared for the rapid change in 2001 (USDA Forest Service 2004a, 2004b).

History of Diamond Lake, Oregon, 1910-2001

1910s - Fish stocking begins and fishery is highly successful
1920 - 1950 - Lodge, campgrounds and 100 summer homes built
1950s - Tui chub population explodes
1954 - Lake is treated with rotenone
1990s - Tui chub return and recreational fishery crashes
2001- Severe *Anabaena flos-aquae* blooms begin

The UNF routinely sampled Diamond Lake monthly each summer, beginning in 1992. The sampling included in-situ measurements of pH, dissolved oxygen and collection of zooplankton and phytoplankton samples (Table 1). During June 2001, the lake water appeared noticeably chalky and blue-green, but no attempt was made to expedite the analyses of the biological samples. An ad hoc sample collected in July was analyzed privately and the results revealed the presence of a dense population of *Anabaena flos-aquae* (JM Eilers, MaxDepth Aquatics, Inc., Bend, Oregon, personal communication, 2001). As of 25 July 2001 the bloom had a density of about 100,000 cells/mL and by early August the density reached 575,000 cells/mL. Samples analyzed by Wright State University, Dayton, Ohio, confirmed the presence of the algal toxins anatoxin-a and microcystin from 6 August through 28 August. Maximum anatoxin-a concentration was reported as 310 µg/L and represented a risk to human health from water contact and accidental ingestion (Eilers and Kann 2002). The 2001 peak anatoxin-a concentration was determined from a phytoplankton sample obtained by towing an 80-micron mesh net. The value was later revised to an estimate of 15.0 µg/L (Kann 2005). In previous sampling from 1992 to 2000, the highest estimated density of *Anabaena flos-aquae* was 8,540 cells/mL. The summer

Table 1 - Water quality and lake morphometry for Diamond Lake, Oregon (Eilers et al. 2001; Johnson et al. 1985; Salinas and Larson 1995).

Parameter	Median	1992-1995	1967-1995
pH	8.6	7.16-9.23	7.1-9.8
Chlorophyll a (µg/L)	6.8	2.6-8.3	1.0-39.8
Total phosphorus (µg/L)	45	17-62	17-62[a]
Total inorganic N (µg/L)	64	<16-88	<16-322[b]
Silica (mg/L)	3.8	1.9-3.7	1.9-6.5
Conductivity (µS/cm)	39.8	38.3-40.9	
Alkalinity (µeq/L)	412	396-421	
Morphometry			
Lake area (ha)	1,300		
Watershed area (ha)	13,600		
Maximum depth (m)	15.8		
Mean depth (m)	7.3		
Lake volume(hm)	95.1		
Hydraulic residence time (yr)	0.6[c]-1.6[d]		
Lake elevation (m)	1,580		
Max. watershed elevation (m)	2,799		

[a] excluding one observation of 140 µg/L 1976.
[b] excluding one observation of 385 µg/L 1967.
[c] estimate based on precipitation volume inputs for the topographic watershed.
[d] estimate based on surface discharge from the lake outlet (Johnson et al. 1985).

Figure 2.. Diamond Lake, Oregon map.

of 2001 was the first time since the UNF began systematic sampling of Diamond Lake, that potentially harmful blue-green algae made up 80 percent of the biomass of any given sample (Eilers and Kann 2002).

Public Health Issues

The chalky, aqua-green appearance of the lake provided a visual clue that something was amiss with the lake, making it easier to communicate with the public and professionals alike (Figure 3). The UNF had to address several issues. These included:

1. What was the significance of the phytoplankton data, with respect to the public health threat of *Anabaena flos-aquae*?
2. If the blooms did present a public health concern, what action should be taken by the Forest Service and other agencies?
3. How should the UNF communicate with the public?
4. How should the UNF determine when the public health concern has abated?

First we needed to interpret the data. Forest Service hydrologists are not usually familiar with toxic cyanobacteria. At the time this issue arose, neither the State of Oregon nor the U.S. Environmental Protection Agency provided criteria or guidelines dealing with water pollution threats from cyanobacteria. To understand the problem, we turned to experts in the field of cyanobacteria (Dr. Jacob Kann) and cyanobacteria toxins (Dr. Wayne Carmichael). Their advice was to use the guidelines provided by the World Health Organization (WHO) regarding public health risks associated with cyanobacteria and their toxins.

The World Health Organization and American Water Works Association (Chorus and Bartram 1999; Yoo et al. 1995) recommend that blue-green algae densities exceeding 500 cells/mL should be monitored closely. This is Alert Level 1, where greater sampling frequency and

Figure 3. Diamond Lake, Oregon cyanobacteria bloom. Photo by Joseph Eilers.

spatial coverage may begin. Alert Level 2 occurs when cell densities reach 2,000 cells/mL and warnings are posted for the general public. Alert Level 3 occurs when density reaches 15,000 cells/mL and people are warned to avoid contact with lake water. Alert Level 4 is reached when blue-green algae density exceeds 100,000 cells/mL. At Alert Level 4 lakes all uses should be curtailed, including boating and fishing (Table 2). These human health guidelines are relatively conservative with respect to toxin concentrations expected at the above alert levels. However, because dense wind-driven shoreline accumulations can occur as these buoyant algal cells rapidly rise to the water surface, a sample of toxigenic algae may have a cell density from 100 to 1,000 times higher an hour later or a even few hundred yards away (Eilers and Kann 2002). Thus, these guidelines provide discrete levels of response to minimize the risk of exposure to toxic cyanobacteria.

During this investigation period we learned that there are multiple toxins produced by various species and strains of cyanobacteria, and that other countries are also coping with this threat (Chorus and Bartram 1999). The science of blue-green algae is complicated and evolving. Some species never produce harmful toxins, and some species produce toxin only at certain times. Sunlight, calm water, and warm temperatures often produce high densities of algae near the surface. Blue-green algae are most likely to produce toxin when cell density is high. The species dominant in Diamond Lake, *Anabaena flos-aquae*, most commonly produces anatoxin-a, a neurotoxin with a toxicity rivaling that of cobra venom on a mass basis (Table 3). However, *A. flos-aquae* is also capable of producing microcystin, a hepatotoxin with cumulative long-term effects. Symptoms of neurotoxin exposure include skin irritation or rash, diarrhea, nausea, cramps or general tiredness, sensations of numbness, dizziness, tingling and fainting, dermatitis and gastroenteritis (Douglas County 2004).

Occasional human illness and deaths occur around the world from cyanobacteria toxins in water. In Oregon, several dogs have died along the John Day River since 2001, and a young man died in Wisconsin in 2002 after swimming in a golf course pond (Wisconsin State Journal 2003). Toxins produced by blue-green algae can have acute and chronic effects. Mammals are vulnerable

Table 2. Guidelines for water contact and monitoring during cyanobacterial blooms (Chorus and Bartram 1999; Yoo et al.1995).

Alert Level	Cyanobacteria (cells/mL)	Advisory	Monitoring
1	500	None	Weekly phytoplankton only, increase shoreline sites
2	2,000	Avoid scums	Weekly phytoplankton and toxin at one site of maximum phytoplankton density
3	15,000	No swimming, waterskiing, or pets in water	Weekly phytoplankton and toxin at all sites with phytoplankton density greater than 15,000 cells/mL
4	100,000	Lake closed to all uses	Weekly phytoplankton and toxin at all sites with phytoplankton density greater than 15,000 cells/mL

Table 3. Comparison of toxins. Cyanobacteria toxins are in bold. From Skulberg et al.(1984).

Toxin	Source	LD_{50} (µg/kg)
Muscarine	Amanita mushroom	1,100
Anatoxin	**Anabaena**	250
Microcystin	**Microcystis**	60
Neurotoxin	Cobra snake venom	20
Aphantoxin	**Aphanizomenon**	10

to toxins, but less is known about immediate effects and bioaccumulation in fish. In 2004, the Oregon Department of Human Services advised people not to consume fish from Paulina Lake when *Anabaena flos-aquae* density was greater than 1,000,000 cells/mL (Oregon Department of Human Services 2004).

Response to the 2001 Bloom

At Diamond Lake, it became clear that a real public health threat was present. The Forest Service asked for help from the Douglas County and State of Oregon health departments, the Oregon Department of Environmental Quality (ODEQ), and other scientists who had experience with blue-green algal blooms. The UNF established an incident management team with public communications, lake management, water quality and public health specialists. A plan was quickly developed and implemented based on the WHO guidelines. Water contact warnings were posted at the lake.

In order to increase the likelihood that the public response would comply with warnings, the team developed a public communications strategy. Communications involved the Diamond Lake Ranger District, Diamond Lake homeowners, and the Diamond Lake Lodge. The Forest Service and Douglas County posted signs at boat ramps, campgrounds, and entrance roads around the lake. Press releases were distributed to local and regional newspapers, television and radio. The blue-green algae bloom and the potential public health risk at Diamond Lake became well known.

The Umpqua National Forest and Douglas County Department of Health and Social Services closed two swimming beaches on 10 August. All swimming, water skiing and boating were prohibited from 17 August until 27 August, when *Anabaena flos-aquae*, anatoxin-a, and microcystin tests results showed that lake water was safe (Figure 4).

Once the public was warned, we focused our attention on monitoring cyanobacteria, in order to determine when the threat had diminished sufficiently to allow full use of the lake. Fortunately, Diamond Lake is not a public drinking water supply and monitoring only needed to address recreational contact. A monitoring program was designed (M. Jones, Umpqua National Forest, Roseburg, Oregon, personal communication, 2004) that linked the intensity and frequency of sampling to the density of the cyanobacteria. Although *Anabaena flos-aquae* density fell below 1,000 cells/mL by mid-August, water contact was restricted for 10 more days because toxins produced by cyanobacteria remain harmful after the cells have died and lysed. This additional period of safety is required during the post-bloom period. The incident management team met throughout the summer to manage water quality monitoring, public health measures, recreation activities and public information. No documented cases of human health effects from blue-green algae at Diamond Lake are known. Public health measures limited human exposure to blue-green algae during part of the bloom in 2001.

Beyond 2001

Although the end of the bloom in 2001 provided a welcome relief from the work of responding to the

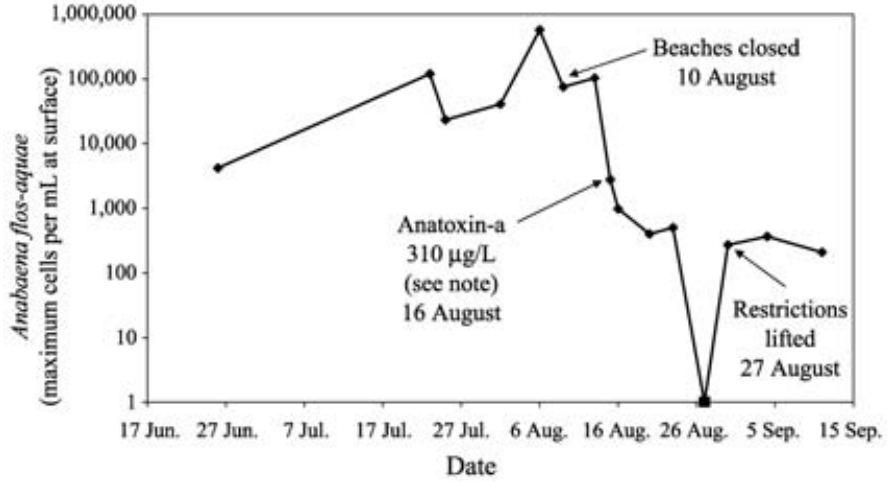


Figure 4. Cyanobacteria bloom, Diamond Lake, Oregon 2001. Anatoxin-a peak later revised to 15.0 ug/L (see text).

Table 4. History of management actions at Diamond Lake, Oregon, 2001-2004.

Alert Level	Action	Cyanobacteria (cells/mL)	Date Alert Level Reached in Each Year			
			2001	2002	2003	2004
Level 1	Begin sampling	500	26 June[a]	6 May	28 May	10 May
Level 2	Warning	2,000	10 Aug.	27 June	27 June[b]	16 July
Level 3	Water contact restriction	15,000	10 Aug.	23 July (to 7 Aug.)	1 July (to 8 Aug.)	None
Level 4	All uses (boat) restricted	100,000	17 Aug. (to 25 Aug.)	None	None	None
All Alerts Lifted			27 Aug.	31 Aug.[b]	28 Aug.[b]	27 Aug.[b]

[a] Sampling began after Alert Level 1 (500 cells/mL) blue-green algae density was reached.
[b] Date is approximate, based on blue-green algae density records.

cyanobacteria bloom, a number of questions needed to be answered before the summer of 2002. These included:

1. What was the cause of the cyanobacteria bloom in 2001?
2. Was this an isolated event or could another bloom be expected?
3. How should we monitor for blooms in the future?
4. What was the level of risk to the public?

To answer these and other questions, we needed a systematic way to organize the data collected in 2001 and earlier years. From 1992 to 2001, the UNF contracted to sample the lake about three times per summer. During 2001, the lake was sampled much more frequently and additional short-term investigations were conducted to evaluate spatial and temporal aspects of the cyanobacteria and associated water quality. These efforts by the Forest Service staff, ODFW, ODEQ, and contract scientists produced a tremendous amount of data that had not been organized. These data and others were arranged into a Microsoft Access®[1] database and interpreted in light of the questions listed above (Eilers and Kann 2002). The Access® database made it possible to both review the conditions associated with the bloom in 2001 and provide a framework for organizing data in the future. The data could then be easily shared among interested parties and researchers studying Diamond Lake.

One conclusion from the analysis of the 2001 data was that lake monitoring needed to begin earlier in the spring during rapidly changing conditions. We sampled more frequently in 2002, using pre-assigned stations for shoreline sampling when the bloom occurred. We made arrangements with phycologists for rapid analysis of the phytoplankton samples. We searched for information on cyanobacteria and prepared information sheets to answer frequently asked questions. Paleolimnological analysis of a sediment core collected in October 2000 (in a study funded by ODFW related to the effect of the tui chub) showed a strong linkage between fish populations and the abundance of cyanobacteria in Diamond Lake (Eilers et al. 2001). The serious cyanobacteria bloom in 2001 made it possible to accelerate several research projects on the lake. The result was a new bathymetric map of the lake, a map of the macrophyte beds, the discovery of ebullition zones (depressions with bubbles emerging), a substrate map of the lake, and a hydroacoustic analysis of fish abundance (Eilers and Gubala 2003).

By the time of ice-out in April 2002, new monitoring and communications plans were ready. Research was underway to better understand the relationship between fish populations and cyanobacteria blooms at Diamond Lake. The Diamond Lake Lodge cooperated by conducting daily measurements of lake transparency with a Secchi disk This low-cost information helped track phytoplankton population trends with immediate results (Figure 5).

Dense blue-green algae blooms have occurred on Diamond Lake every summer since 2001. Three of four summers, *Anabaena flos-aquae* densities were higher than 15,000 cells/mL, and water contact by people and pets was prohibited for two to five weeks (Table 4).

Current Protocol for Toxic Algae Monitoring and Alerts

From May through September Diamond Lake Ranger District collects phytoplankton samples from the center of the lake on Monday of each week. These samples are sent overnight to Aquatic Analysts laboratory for analysis of species composition and density. The results arrive the following Thursday. If *Anabaena flos-aquae* densities exceed 500 cells/mL, two additional shoreline sites are sampled the following week. If densities exceed 2,000 cells/mL, one sample is sent to Wright State University for toxin analysis.

[1]The use of trade or firm names in this publication is for reader information and does not imply endorsement by the U.S. Department of Agriculture of any product or service.

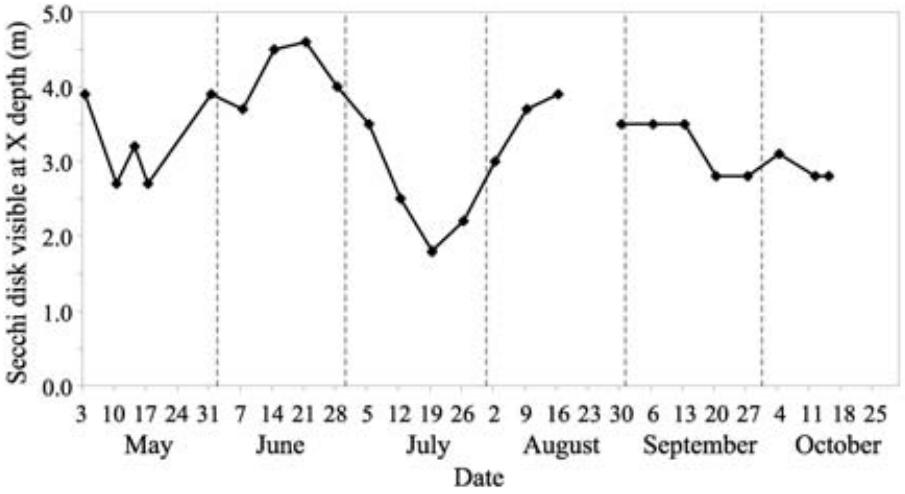


Figure 5. Secchi depth visibility, Diamond Lake, Oregon, 2004.

Toxin samples are collected from all sites with densities greater than 15,000 cells/mL (Table 2). Together, the Umpqua National Forest and Douglas County Department of Health and Social Services decide whether to change alert levels for the upcoming weekend.

The marina manager at Diamond Lake Lodge measures Secchi depth, water temperature and wind speed weekly, so we know quickly if algae density is increasing or decreasing.

All lake management decisions are based on blue-green algae densities, rather than specific toxin levels, because tests for phytoplankton identification and density cost about $100-250 per sample and results are available the same week. Toxin results can take as long as six weeks, and cost about $500. These samples are used to document whether toxin was present when swimmers were in the water. Cyanobacteria do not always produce toxin, even during a dense bloom. Lake managers can err by keeping people out of the water when no toxin is present, or by failing to issue warnings when toxin is present. Both errors have consequences. In the first case, people will be disappointed and business will suffer when there is little risk. In the second, people or pets may be harmed if they're exposed to algae toxin. Toxin tests are used to document whether water contact was restricted appropriately.

In order to avoid sending conflicting or complicated messages to the public, it's important not to change alert levels often. Health alerts and restrictions are the most useful when they are clear and consistent. At Diamond Lake, Level 2 advisories are usually posted June to August each summer, and a Level 3 water contact restriction issued once during the peak blue-green algae bloom. A Level 4 restriction on all lake uses, including boating, was used only once after *Anabaena flos-aquae* cell densities reached several hundred thousand cells/mL in the summer of 2001.

Water Quality Monitoring

Water quality monitoring can help recognize changes in lake ecology. In 1992, there was no reason to expect algae or water quality problems, but not much was known about Diamond Lake. The Umpqua National Forest and Rogue Community College, Grants Pass, Oregon, sampled Diamond Lake in June, July and August every summer from 1992 to 2002. Occasional March, April, May and September profiles in the deep lake center and other, shallower locations (including under-the-ice spring sample dates) were sampled in some years. Similar monitoring continues to the present.

Measurements taken in the middle of Diamond Lake in July 2004 are typical of the summer blue-green algae bloom. A Secchi disk was visible to only 1.8 meters, the surface water temperature was 20°C, and pH was 8.9. Dissolved oxygen at the surface was almost saturated at 9 mg/L (Raymond 2004). Lake pH is increasing, the lake bottom is increasingly anoxic, and algal blooms are changing nitrogen and phosphorus levels in the lake (Table 5). Algae consume the high natural phosphorus, and nitrogen fixation by blue-green algae adds organic nitrogen.

Lake biology is changing too. Introduced rainbow trout, and millions of tui chub, are feeding on invertebrates and zooplankton. Large benthic amphipods are declining, with a shift to smaller invertebrates. The lake is experiencing a loss of the large zooplankton taxa. Large cladocerans that fish prefer have disappeared. Fewer than 10 percent of the individual zooplankton in Diamond Lake in the 2003 summer were edible by planktivorous fish. The lake is now dominated by very small rotifers that are not effective phytoplankton grazers and provide little food for fish (Table 6). Phytoplankton samples also show that *Anabaena flos-aquae* are dominating the July and August algae bloom for the first time since 1992.

Table 5. Diamond Lake chemical changes.

Parameter	1900[a]	1975	2003
Lake PO_4 phosphorus	~30 µg/L	15 µg/L	0-5 µg/L
Lake TKN organic nitrogen	low	moderate	high
Surface pH	8.0	9.0	9.5
Anoxic hypolimnion	probably rare	50% of years	annual

[a] *Speculation based on paleolimnological data.*

Table 6. Diamond Lake biological changes.

Parameter	1900[a]	1975	2003
Benthos	amphipods	chironomids + amphipods	chironomids
Zooplankton	copepods	cladocerans	rotifers
Phytoplankton	chrysophytes + centric diatoms	mixed	cyanobacteria + pinnate diatoms
Macrophyte depth	~ 9 m	8 m	6 m
Fish	none	trout	tui chub

[a] *Speculation based on paleolimnological data.*

The experience acquired from 1992 to 2000 helped the Umpqua National Forest expand monitoring activities at Diamond Lake. We had already consulted knowledgeable limnologists, hydrologists and laboratories. We knew how to collect samples for physical and biological analyses, preserve the samples and interpret the results. When it was obvious that *Anabaena flos-aquae* presented a health risk to swimmers, we were able to collect algae and toxin samples and get results quicker.

Lessons Learned

Dense blue-green algae blooms have occurred on the Diamond Lake every summer since 2001. In three of four summers, *Anabaena flos-aquae* densities were higher than 15,000 cells/mL, and water contact by people and pets was restricted. Visitors to Diamond Lake Lodge and Forest Service campgrounds, and 100 summer home owners accommodate these restrictions by avoiding water contact, fishing from docks and boats, and following press releases to decide what activities are safe. The Umpqua National Forest and the Douglas County and Oregon health departments work together each summer to keep Diamond Lake open for all uses except when there is a risk to public health. Together, the agencies restricted swimming for up to five weeks during the summer since 2001 and no human health effects were documented.

The Umpqua National Forest now has a clear monitoring scheme and guidelines for swimming restrictions, so we can tell visitors quickly when there is a potential risk from cyanobacteria toxins. In 2001, we learned the value of recognizing a problem quickly, working with health officials, and using clear guidelines to tell the public what we knew.

Blue-green algae blooms can appear suddenly, and can be a serious health risk. We offer the following advice to others with potentially harmful blue-green algae blooms:

- Give lake managers the information they need to make good decisions in the midst of controversy. Blue-green algae blooms in water bodies that are used for drinking water may present the highest risk of exposure to toxins.
- Get help from experts, and work together with state and local health departments. Use the incident command system in emergency situations.
- Use clear guidelines. Health departments are trained to handle public health situations. Develop standard signs, warnings, and press releases.
- Increase sample frequency and sample locations as risk increases. If you have a routine monitoring program, you'll know where to send samples and what the results mean. Write a monitoring plan and document the research you used.
- Develop monitoring protocols, use quality control procedures, and manage your data. That includes keeping a record of when warnings were issued and when they were lifted.

Our experience at Diamond Lake is one example of how water quality monitoring can help recognize water quality problems and protect public health on National Forests.

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John Wallig, Diamond Lake Ranger District, Toketee, Oregon; Randy Webb, Diamond Lake Lodge, Diamond Lake, Oregon; Al Johnson, Willamette National Forest, Eugene, Oregon; and Scott Tangenberg, Lassen National Forest, Susanville, California.

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Delineation of a Karst Watershed on Prince of Wales Island, Southeast Alaska

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Karst systems have developed in the extensive areas of carbonate bedrock underlying portions of the Tongass National Forest, southeast Alaska. Karst development includes losing streams, sinks, caves, grikes, and resurgence streams. Many of the resurgence streams maintain productive salmon populations important to local culture and economics. Identifying source areas of resurgence streams is crucial to protecting water quality and watershed planning in karst ecosystems. Historically, watershed assessments have only considered topographic boundaries when defining various watersheds. This method is difficult in karst areas where surface waters are rare. Two projects on northern Prince of Wales Island, part of the Thorne Bay Ranger District, have employed tracer dye studies to illustrate the complexity of karst systems, and help redefine watershed boundaries to assist in watershed planning efforts. Through dye trace tests we were able to identify subsurface flow pathways, identify downstream effects, and better assess cumulative effects on a watershed scale. Success of groundwater tracing efforts hinged on locating the springs that feed coastal streams. This required careful inventory of shorelines and margins of the carbonate outcrops. Activated charcoal packets were anchored within these streams and springs to absorb dye. Tracer dye injection points were generally discrete karst features where surface waters enter the systems. The charcoal packets were recovered at intervals to allow time for the dye to move through the systems. Tracking the locations of dye injection and recovery helped identify specific subsurface water flow pathways and measure minimum flow velocities. Identification of these subsurface pathways enabled us to delineate karst watershed boundaries, understand the downstream effects of proposed management, and better manage karst areas.

Keywords: *karst, insurgence, resurgence, dye trace, watershed delineation*

Introduction

Karst is a geomorphologic term describing the topography resulting from the chemical dissolution of carbonate bedrock. In southeast Alaska, karst refers to areas where this distinct geomorphology has developed from the dissolution of limestone or marble bedrock. Karst characterization includes grikes, caves, insurgence and resurgence streams, and extensive areas where runoff does not exist on the land surface. Instead, these waters infiltrate into the subsurface environment (insurgence) and may re-appear many miles away (resurgence). This process of surface waters appearing and disappearing is just one of the distinct features of karst watersheds.

Furniss, M.J., Clifton, C.F., Ronnenberg, K.L., eds., 2007. *Advancing the fundamental sciences: proceedings of the forest service national earth sciences conference, San Diego, CA, 18-22 October 2004*. PNW-GTR-689. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station.

Southeast Alaska has over 869 square miles (2,228 km^2) of known karst (Figure 1). Of this area, 731 square miles (1,874 km^2) are on national forest land as part of the Tongass National Forest. Within the Thorne Bay Ranger District, 283 square miles (725 km^2) of karst are located on northern Prince of Wales and surrounding islands (Baichtal and Swanston 1996) (Figure 1). The development of karst is dependent upon many influences such as volume of precipitation, water temperatures, water chemistry, vegetation, soils, and in the case of southeast Alaska, elevation relative to past glaciations.

The coastal temperate rainforest environment of southeast Alaska is essential to the development of karst. With annual precipitation ranging from 100 to 200 inches (254 to 508 cm), and average annual air temperatures of around 45°F (7.2°C), the climate is ideal for carbonate dissolution. In addition, the role of glaciers in modifying existing karst features and depositing glacial till has a significant effect on karst development. Where glacial till was deposited, infiltration is limited, peatlands have

Figure 1. Project area locations in the Prince of Wales Island area, southeast Alaska.

developed and hence acidic soils are present. With the development of the peatlands on poorly drained areas and the acidic waters that flow from them, a system of vadose caves and vertical shafts have developed. These have combined with pre-existing subsurface conduits and cave systems to form the current drainage networks.

The carbonate that underlies the study areas consist of Upper Silurian aged (419-423 million years old) Heceta Limestone of the Alexander Terrane. This unit consists of light gray, massive, sublithographic limestone, with abundant amphiporoid corals, dasycladacean algae, oncoids, and brachiopods. Limestone also contains subordinate stromatoporoids, gastropods, pelecypods, bryozoans, trilobites, graptolites, conodonts, and aphrosalpingid sponges. Algal, coralline, and microbial buildups are interpreted to represent platform margin reefs, with carbonate turbidites, debris flows, and slump deposits that accumulated in deeper water off the shelf margin (Soja 1991). Contact with underlying Ordovician to Silurian aged Descon and Luck Creek Breccia Formations is generally conformable, but limestone detritus resembling the Heceta in polymictic conglomerate that conformably underlies Heceta in several places indicates that carbonate sediments were deposited, lithified, and eroded in the Early Silurian prior to the main period of Heceta Limestone deposition. The Heceta Limestone is overlain by the Early Devonian aged Karheen Formation, composed of sandstone, shale, and pebble, cobble, and boulder conglomerate, characterized by redbeds, calcareous cement, and crossbedding (S. Karl, USGS, personal communication).

Structural features within the Alexander Terrane are complex. These structures consist primarily of northwest-to-southeasterly strike slip faults and shear zones and secondary faulting and shearing in a east-to-westerly direction. These formations have been further modified by extensive thrust faulting and localized folding. Dissolution in limestone is accelerated along fault and shear zones, therefore solution channels and lineaments are common along the major and secondary fault zones.

The project areas (located on northern Prince of Wales Island [NPOW] and Tuxekon Island) were last glaciated during the Wisconsin glacial advance from the north and northeast 21,000 to 14,000 years ago. Karst existed on Prince of Wales and surrounding islands prior to the last glacial advance. Recent phreatic passages in two pre-Wisconsinan caves have dissolved through Tertiary paleokarst breccias (Aley et al. 1993). Older passages have been plugged or collapsed by debris from past glacial episodes. Most caves predate the most recent glaciation, based on the presence of glacial clays, glacial sediments, wood, Pleistocene vertebrate remains, and possibly ancient ice. Such evidence clearly suggests that glaciation modified a pre-existing karst landscape, collapsing some passages and systems, gouging into others, and filling some with sediments. The epikarst (surficial karst), which is exceptionally well developed at higher elevations, has been destroyed at lower elevations by the scouring of the most recent glaciation.

Methods

The methods used to delineate watersheds in karst are drastically different from those methods used in non-carbonate environments. Surface water runoff in non-carbonate environments flows across the ground surface and is ultimately controlled by topography. However, in carbonate environments where surface waters are rare, insurgences and resurgences must be located on the ground, and where possible, these waters must be traced through the subsurface environment, to identify flow paths, and hence watershed boundaries. Although runoff in both carbonate and non-carbonate areas generally flows down gradient, those waters in carbonate environments don't necessarily flow downhill relative to surface topography. The following methods describe ways to determine flow paths using both geomorphic and dye trace methods.

Mapping of Hydrogeologic Features

Success of tracer projects in karst areas hinges on the ability to identify and map all features that influence runoff. These mapped features include streams, significant sinkholes (those that are open to the subsurface), insurgences, resurgence caves and springs, and any other features where runoff flows into or out of the subsurface environment. Aerial photo interpretation, contour maps, field reconnaissance, and a general understanding of the bedrock geology, are essential in successful identification and mapping of features. All features identified on the ground or through map or photo interpretation were mapped, labeled, and characterized regarding feature type and characteristics (Figures 2 and 3). In some cases, water quality parameters, such as pH, temperature, and conductivity, were collected and used in planning the dye trace.

Aerial photographs were used in this study to identify runoff features and track runoff patterns. Streams, sinkholes, lineaments, geologic contacts, and large closed basins can be identified through aerial photo interpretation. Depending upon the scale and degree of forest canopy, karst features can be more or less evident through a stereoscope. In some cases sinkholes and karst lineaments can be very obvious from aerial photos.

Contour maps were also used to determine where surface drainage features were located on the landscape. Closed depressions, or large internally drained basins, can be identified as areas that contain no drainage outlet. In some cases, digital imagery such as LIDAR can be used to color-code negative contours for identifying sinkholes and closed depressions (Baichtal and Langendoen 2001; Langendoen and Baichtal 2004)

Extensive field reconnaissance was performed to confirm features identified from map or photo work, and to explore for additional drainage features. Surface water streams were walked to determine contributing area, or source at the headwaters, and to determine if the waters dissipated or disappeared into the subsurface. Karst lineaments and geologic structural boundaries were investigated in the field for potential insurgence or resurgence features. Bedrock contacts are logical locations for water to appear or disappear, depending upon the bedrock and the nature of surface runoff. Features identified along these contacts were characterized and mapped. All wetland boundaries proximal to carbonate bedrock were also scouted to determine drainage and to identify additional karst features.

Planning Dye Traces

Dye trace methods used in this project followed those outlined in Aley and Fletcher's Water Tracers Handbook (1976). These methods use several different fluorescent dyes for tracing. The methods also describe the use of activated charcoal packets for adsorption and the laboratory analysis process for detection.

Planning is a crucial element in a successful dye trace, and in delineating watershed boundaries. Both the NPOW and Tuxekan project areas were separated into five distinct sets of insurgence locations that were chosen for dye introduction. For NPOW, the introduction points were determined according to their location relative to each other and proximity to a proposed road project. Points were far enough separated that two of the five traces could be done simultaneously using the same dyes. On Tuxekan, the five distinct areas were structurally separated, and were capable of handling five sets of four dye introductions all at once. Generally, the dye trace plan must separate out insurgences according to the number of dye tracers available, and the geologic, or structural boundaries between areas, to limit contamination between traces. Where clusters of insurgences are in close proximity, one or several of the more significant features were chosen for dye injection.

Collection of Background Data

To ensure that no prior trace of the proposed dyes existed in the drainage system scheduled for tracing, background water chemistry information was collected. A set of charcoal packets was placed in all resurgence locations for seven to ten days to collect baseline water chemistry. Packets were placed under rocks within the normal flow section of stream, were bound by a cord, and tied to the stream bank. All packets were placed for easy access during all flow levels, and placed to ensure packets would remain underwater during low flows, yet not be moved, or carried away, during high flows.

Dye Introduction

After all background packets had been replaced with fresh packets, dyes were introduced into designated insurgences. Transport and introduction were undertaken with care to prevent contamination of the injector's body or clothing by the dye materials. There was no handling of charcoal packets following dye injection without full cleansing of hands and a change of clothing. The dyes used in this study were purchased from Ozark Underground Laboratories Inc. , and included Rodamine

WT, Fluorescein, Eosine, and Sulferodamine dyes. Each of these dyes is characterized by a distinct wavelength when placed in a fluorophotospectrometer; therefore each can be chemically distinguished. The packets contain activated charcoal enclosed in a mesh pouch and anchored to the streambed of a resurgence stream. As runoff in the resurgence zone flows through the dye packet, the charcoal adsorbs the dye and retains the chemical trace for analysis. These tracer packets were recovered from the resurgence area and sent to Ozark Underground Laboratories for analysis. Laboratory reports state the concentration of each dye that is recovered for each site.

The time provided between dye trace introductions is dependent upon the volume of water that is available to flush the dyes. When a dye is introduced into a system, it must be fully flushed before introducing that same dye into the same drainage network. In this study, dye traces were performed between August and November when large storms are generally back-to-back, soils are saturated, and flushing of the drainage networks is rapid. Times between dye tracer introductions ranged from one to three weeks, depending upon flow volumes and access opportunities. The process of packet replacement for the NPOW project generally took a day with two groups of two people, and an additional day for dye introduction. The Tuxekan project required several days for packet replacement and several days for dye introductions.

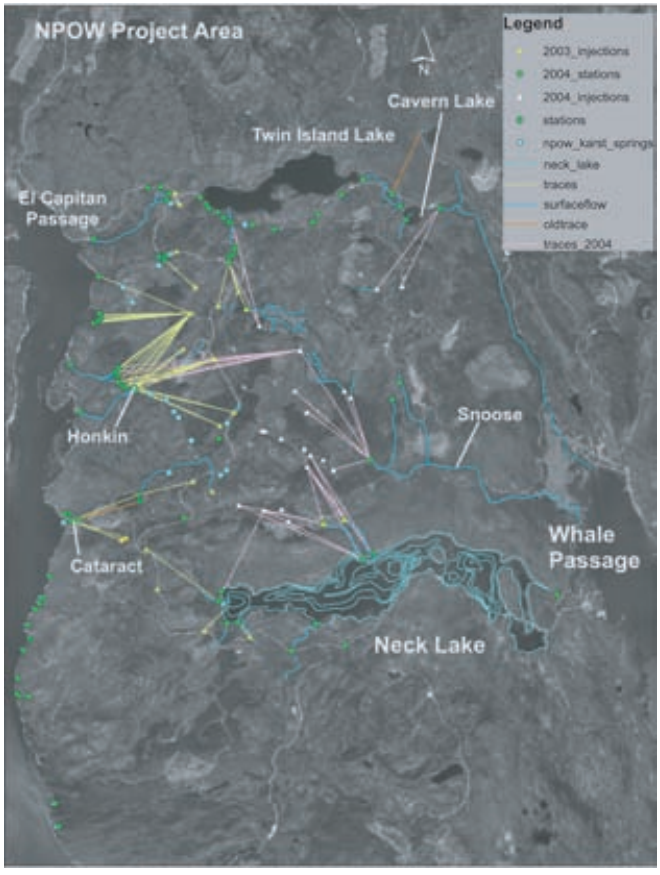


Figure 2. North Prince of Wales Island project area, insurgence and resurgence locations, and dye trace results.

Plotting Dye Trace Results and Modifying Remaining Traces

When performing a multi-year dye trace, there is opportunity to adjust dye traces according to results of previous work. In the case of the NPOW project, the results of the work performed in 2003 led to increased investigation and an expanded project area for 2004. Because there were no east-west watershed divides identified in the 2003 work, additional field work was done prior to the 2004 work to identify insurgences that might lend information to this question. Trace results in 2004 provided insight to the watershed divide, which better defined the watershed boundary.

Results

Ozark Underground Laboratories performed charcoal packet analysis for both of these studies. The results of the analysis included type and concentration of each dye recovered. The NPOW project area covered approximately 36 square miles (93 km^2). Over a two-year sampling period, 38 dye traces were introduced. Thirty-six of these traces were recovered at 65 springs (Figure 2). In the smaller Tuxekan project area, covering approximately 28 square miles (72 km^2), 14 dyes were introduced during one sampling season. Thirteen of these dyes were recovered at 20 springs (Figure 3).

North Prince of Wales Island

Dye was recovered at resurgence areas near Neck Lake and Snoose Creek in the southern portion of the project area, Honkin Spring and Cataract Spring in the western portion of the project area, and Twin and Cavern Lakes in the northern portion of the project area (Figure 2). All source areas, where dye was introduced, were located along the high karst plateau of the project area. Resulting dye paths trended northeast, northwest, southeast, and southwest, with no dominant trend direction.

The 2003 dye introduction points were largely along the mainline road system (National Forest System Roads 15 and 20). This road is located along the western flank of the high plateau, trending north-south. The 2004 dye introduction locations were concentrated along the eastern flank of the high plateau and dispersed in a northern, central, and southern trend, focusing on key insurgence features.

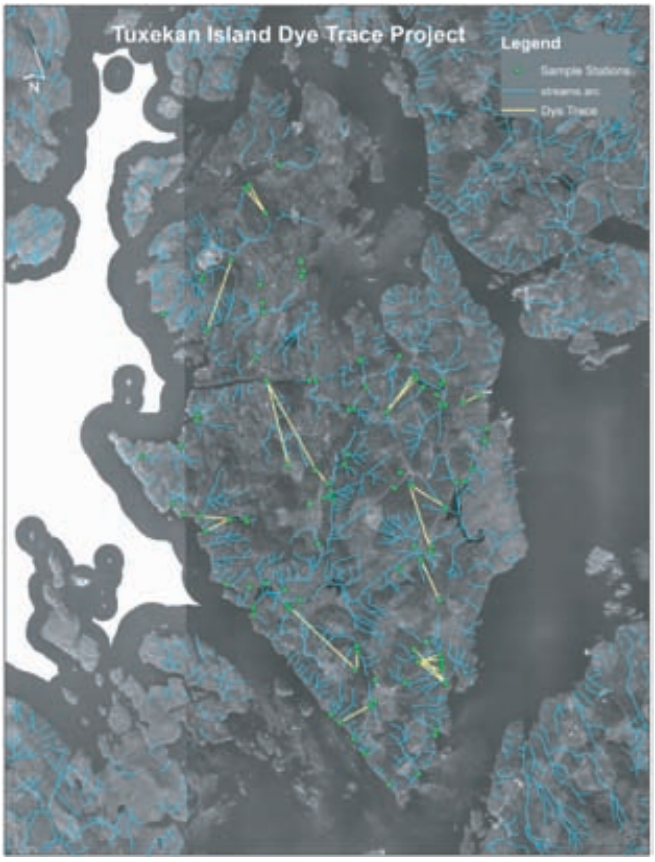


Figure 3. Tuxekan Island project area, insurgence and resurgence locations, and dye trace results.

All but three of the 2003 dye introductions eventually entered El Capitan Passage. Most of the 2004 dye introductions eventually entered Whale Passage. The few dyes that crossed this trend were used to delineate the east-west boundary along the high karst plateau. All springs in the western portion of the project area, including Cataract and Honkin, flow into El Capitan Passage, along the western shoreline of Prince of Wales Island. Twin Island Lake flows into Cavern Lake, which flows into 108 Creek, and eventually out into the estuary of Whale Passage. Snoose Creek, a significant drainage in the central portion of the project area, also flows into Whale Passage. Snoose Creek enters Whale Passage slightly south of 108 Creek and within the estuary. Neck Lake outfalls into Neck Creek, which flows a short distance before entering Whale Passage.

A large percentage of the 2003 dye was recovered at Honkin Spring, centrally located along the western portion of the project area. The Honkin Spring Cluster, a series of springs proximal to Honkin Spring, gained source waters from four different insurgences in 2003, and an additional insurgence in 2004. All these source waters are located along the western flank of the high Plateau in 2003, and with the exception of a small sink located in the northern portion of the eastern flank of the project area in 2004. Dye from this small sink (84) was the only dye recovered along the eastern resurgences in 2004. Neck Lake received dye from the southern portion of the eastern flank of the project area in 2004 and received one hit of dye from along the road in 2003. Snoose Creek collected dye from the central portion of the eastern flank of the project area in 2004. Dye recovery was not monitored in the Snoose Creek area in 2003. Twin Island Lakes received dye from the Beaver Falls area, in the northern portion of the eastern flank of the project area. Cavern Lake is downstream of Twin Island Lake and received dye from upslope within its topographic watershed, insurgences 91 and 92.

Several significant resurgences did not receive dye in either year of sampling. For example, resurgences 86 and 87 located in the central portion of the project area, which flow into Snoose Creek, were monitored during the 2004 season and received no dye. The resurgences in the southwestern portion of the project area, 35 to 38, were monitored during the 2003 season and received no dye.

Tuxekan Island

The Tuxekan Island project area was more linear in shape than the North Prince of Wales project area and a greater number of significant structural features separated the areas of delineation. This allowed a single dye to be introduced in numerous locations within the project area without contaminating adjacent watersheds. Of the 14 dyes that were introduced, 13 were recovered in 20 springs (Figure 3). Similar to the North Prince of Wales project area, Tuxekan resulted in no significant trend for dye recovery. Dye traces follow northwest, northeast, southwest, and southeast flow paths.

Most dyes were recovered less than a mile (1.6 km) away from and within topographic boundaries of, the introduction points. The few exceptions include I-2, which was recovered southwest at 87; I-5, which was recovered northwest at 60; and I-12, which was recovered northwest at 12; all greater than a mile in distance from introduction points. Topographic boundaries were crossed at introduction point I-12, where dye was recovered in two separate watersheds; I-6, where dye was recovered across a topographic boundary to the southeast; and I-2, where dye was recovered across a topographic boundary to the southwest.

Discussion

Results of these dye traces revealed underlying flow paths. These subsurface flow paths are combined with surface water flow paths to delineate watershed boundaries. The complexity of delineating watersheds is confirmed in

the results of these two projects. This complexity lies in the inter-relationship and processes controlling topography, structural geology, and runoff, or flow volume.

Topography

Topography played a large role in the runoff patterns of both project areas. Many of the topographic watershed boundaries remained unchanged. Those boundaries that did change resulted from dye trace information. Delineation of watershed boundaries must be an iterative process in karst areas because of the influence of subsurface flow paths, and hence dye trace results. Prior to dye tracing, karst watershed boundaries followed topographic divides. With each additional dye trace, the boundary can change to reflect source area. In some cases, the source area of the introduction point became the watershed boundary. In other cases, the watershed boundary was altered, just slightly, to reflect additional source areas.

Structural Geology

Outcrop pattern, bedrock contacts, structure, and glacial deposits and scouring control landform development and the subsurface flow paths. Spring locations are associated with fault and shear zones, bedrock contacts, and sea-level stance associated with isostatic adjustment after the last glacial advance. In both study areas, the large northwest-southeast faults control the individual drainage basins and the associated east-west shear zones tend to control groundwater flow pathways. Bedrock geology and generalized fault patterns are shown in Figures 4 and 5.

High and Low Flows

The volume of runoff affected the direction of flow in at least one location on both project areas. On NPOW, dye from insurgence location 87 was recovered at the Honkin Spring cluster and at Headwaters resurgence (Figure 2). Honkin Spring flows west into El Capitan Passage, while Headwaters Cave flows east into Snoose Creek, and eventually Whale Passage (Figure 2). This evidence indicates a watershed that extends the entire width of Prince of Wales Island. On Tuxekan Island, I-5 flows north to Scott Lagoon and south to Karheen Lake (Figure 3). The geology and dye trace results suggest that normal flow in these cases would be in one direction. Overflow during larger storm events would then flood the

Figure 4. Bedrock geology, structure, and dye trace results, North Prince of Wales Island project area.

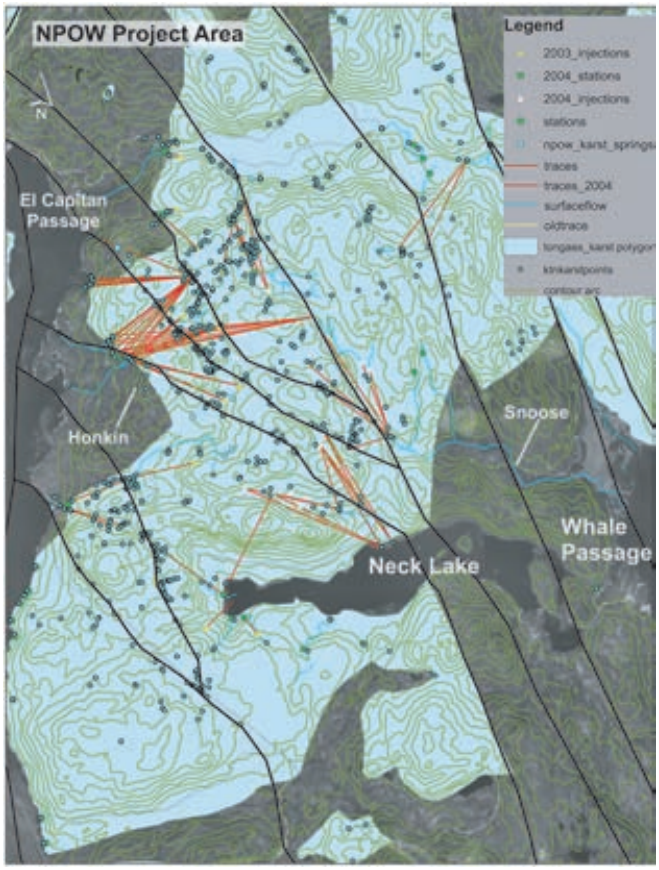
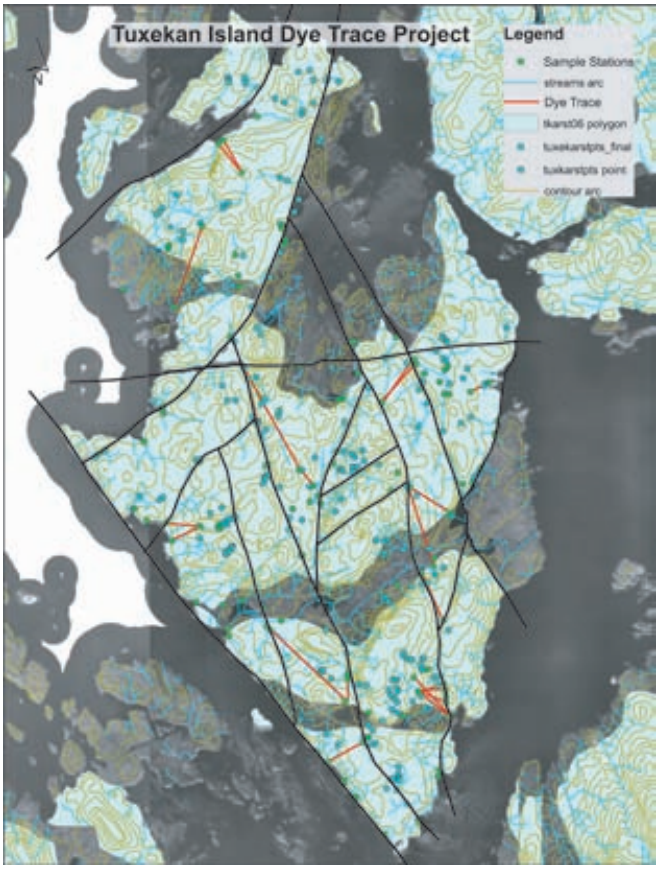


Figure 5. Bedrock geology, structure, and dye trace results, Tuxekan Island project area.



dominant passages and spill over into a secondary set of flow passages. Additional dye traces aimed to measure flow velocity may suggest dominant flow paths, and at what flow volume the dominant flow paths are exceeded.

Conclusions

Tuxekan and NPOW project area watershed boundaries were delineated using the usual tools available for surface topographic watershed boundaries, while also incorporating dye trace results. Topography was the dominant characteristic in the delineation of the boundaries; however, structural geology and flow volume played a large role. Studies with dye tracers revealed subsurface flow paths and helped account for the majority of runoff in the study watersheds. Dye tracers are valuable in delineating karst watersheds and identifying subsurface flow paths in complex geologic structures. Now that the primary karst groundwater basins have been established for these areas, more in-depth studies are planned to determine high and low flow velocities and dominant flow paths.

Acknowledgements. Many thanks to Tom Aley and the staff at Ozark Underground Laboratories for their extensive laboratory analysis that enabled the high level of detail attained in the dye trace results. And huge thanks to the hard working field crew including Dustin Walters, Marika Gertz, Brandy Prefontaine, Adam Cross, Brian Raper, Marsha Gillis, Dan Nolfi, Johanna Kovarik, and many others that endured wet, cold, windy, and seldom sunny, weather conditions to access dye trace packets throughout the project.

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An Examination of References for Ecosystems in a Watershed Context: Results of a Scientific Pulse in Redwood National and State Parks, California

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Characteristics of reference sites for stream and riparian ecosystems were examined and discussed during a 'pulse' (a short, interdisciplinary field-based inquiry) that visited three pristine streams in old-growth redwood forests in northern California. We concluded that useful reference sites need not be pristine, but must be rich in data linking physical and biological processes, and must frame conditions in a watershed context. Not requiring pristine conditions allows data-rich watersheds with a spectrum of conditions to be incorporated into a regional reference framework. We describe and exemplify three types of references: 1) Reference sites (e.g., watersheds) offer real-world examples of how ecosystems function over time; 2) Reference parameters measured in a region offer first-cut comparisons that can lead to deeper, more contextual analyses; 3) Analytical references can reveal disturbance-related departures from conditions predicted with simple assumptions about some aspects of system behavior. Each type has strengths and weaknesses, and used in combination they can effectively inform management decisions.

Keywords: *environmental references, stream ecology, fluvial geomorphology, watersheds*

Introduction

Ecosystem management requires interdisciplinary problem solving and an expanded scale and scope of analysis, particularly in lotic and riparian ecosystems that are integrated by the flux of water, sediment, organic material, organisms, heat, and dissolved constituents through watersheds. The need to address interactions between physical and biological processes over the landscape is perhaps greatest at the scale and organization of a watershed, where each point responds to cascading influences from upstream, upslope, and upwind over a range of time scales. Now, with the growing appreciation that biological functions are embedded in physically dynamic landforms (e.g., Minshall 1988; Fausch et al. 2002; Benda et al. 2004), the underlying problem for land managers is, how do physical and biological processes interact in a watershed, or, how does a living watershed function? With incomplete information about these complex systems, resource professionals commonly seek references to serve as benchmarks of functioning systems, asking 'What does a properly functioning watershed look like?'

Managers, regulators, and scientists commonly use relatively pristine systems as references against which to compare other sites of the same type or region that have comparable management issues (USGS 2004). Conditions are evaluated by comparing data for a set of quantitative parameters from pristine and managed systems. The assumption is that human effects account for significant departures from reference conditions and can be analytically separated from variations due to climatic events (e.g., hurricanes) or state variables (e.g., geology, topography), which are assumed to affect the site independently of human influence.

References other than pristine systems are available in the land-management arena, as suggested by Webster's broad definition of reference, '…taken or laid down as standard for measuring, reckoning, or constructing'. Nevertheless, reference conditions are usually associated with pristine or desired states – the "best" sites a region has to offer. In some

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cases "reference condition" is defined based on a specific reference site and becomes the target for restoration efforts, and later, for the evaluation of restoration effectiveness (Jungwirth et al. 2002; SER 2002). For example, a 'desired future condition' can be based on some perceived pristine or near-pristine condition that enhances a valued resource, e.g., productive fish habitat, without being tied to specific reference sites (Salwasser et al. 1996).

Any use of reference conditions should include an analysis of spatial and temporal variability. 'Historic range of variability' (Landres et al. 1999) describes the variability of ecological conditions particularly in the period before and after European settlement in North America. The concept that ecosystems are disturbed and recover from natural occurrences such as floods (Wolman and Gerson 1978), volcanic eruptions (Franklin et al. 1995) and wildfire (Minshall et al. 1997) emphasizes that all systems are in some stage of evolution from major events (Reeves et al. 1995).

Scale is a primary consideration in spatial variation. In some areas of the United States, ecoregions (Omernik 1987) have been divided into sub-regions as a framework for establishing ecological expectations – reference conditions – that are based on the sampling of many minimally impaired reference sites within the sub-region (Ohio EPA 1987). Physical, chemical, and biological data have been used to establish a database of reference conditions for the sub-region. In some cases, a reference framework is based on statistical analysis of a set of sites interpreted to represent reference conditions (e.g., Clarke et al. 2003). Ordination and principal component analyses have also been used to establish reference sites from large regional data sets. However, qualitative "best professional judgment" criteria are still used to select from the array of data the sites that should serve as references (e.g., McIninch and Garman 2002). Comparisons of such reference sites with those judged to be impaired encounter statistical problems of pseudo-replication (Stewart-Oaten et al. 1986) and fail to account for the inherent succession of ecosystems (Loehle and Smith 1990)

These considerations lead to the question, 'Is there something inherent in the reference sites, perhaps complexity or diversity, that sets them apart from others across regions regardless of temporal variability?' To examine this problem, a pulse study conducted by multi-disciplinary teams was held in the old-growth redwood forests of Redwood National and State Parks (RNSP) in north coastal California in June, 2003. Discussions during and following the Redwood Pulse resulted in a re-evaluation of, and some new proposals for, the use of various forms of references in the management of watershed ecosystems.

The Redwood Pulse

The Redwood Pulse was modeled after the procedure established by Dr. Jerry Franklin (USDA Forest Service, Pacific Northwest Research Station, now at University of Washington), whereby multi-disciplinary teams of scientists focus their collective wisdom and insights on ecosystem functions at a specific site during short, field-based inquiries (Franklin 1982). Hence the term pulse.

The goal was to arrive at new insights about linked aquatic-terrestrial ecosystems. In the leadup to the Redwood Pulse, a framework for inquiry was developed concerning the notion of 'reference condition' as applied in watershed studies. The discussions centered on the importance of natural variability in the parameters selected to characterize a site, whether at the reach or the watershed scale. A collective interpretation was that this variability gives those sites less modified by human activities much of their resilience to natural disturbance. In this view, parameters in pristine sites could exhibit high variance at any point in time, and human disturbance could lead to a reduction in variance. As a consequence, reference sites might actually be more variable than disturbed ones. Thus, the motivating question for the Redwood Pulse was, 'Would reference sites, here defined as most-pristine, exhibit more variation in selected parameters than would be expected in disturbed sites in the same region?' This relative variability was anticipated to be distinguishable to the attendees who collectively had wide-ranging field experience in the Redwood and similar regions.

The pulse participants represented a range of disciplines, including geomorphology, hydrology, fisheries biology, aquatic ecology, plant ecology, entomology, social science, soil science, and natural resources management. (A list of participants is available on request from the corresponding author.) We did not visit disturbed sites nor collect data with the intention of testing an hypothesis. Instead, we used the question of ecosystem variability as a springboard to discuss reference concepts in a field setting. During the pulse, teams from the larger group of twenty-one participants worked side by side, focusing their particular expertise on each site in turn and continuously exchanging perspectives as they made observations and some measurements. During the evening, these separate insights were discussed, integrated, and recorded around the campfire in the Franklin tradition.

In this paper, we report the results of the discussions and propose that the richness of data on influential abiotic and biotic processes can qualify a site as an ecosystem reference, in addition to its condition. Our initial focus on variability led to a conclusion that data richness is an important criterion for selecting reference sites. We also

Table 1. Characteristics of pulse sites.

	Site 1: Upper Prairie Creek	Site 2: Godwood Creek	Site 3: Little Lost Man Creek
Watershed area (km²)	10.5	4.0	9.9
Stream gradient (%)	1.0	1.6	2.6
Bedrock geology	Coastal plain sediments	Coastal plain sediments	Sandstone and mudstone
Dominant riparian overstory	Old-growth redwood on floodplain	Old-growth redwood on banks	Old-growth redwood high on banks
Sub-dominant riparian composition	Red alder and big leaf maple[1]	Hemlock, spruce, vine maple, alder[3]	Red alder near edge of stream, big leaf maple
Percent canopy cover	80	85	80
Bankfull width (m)	7	5	8
Valley width (m)	130	83	40
Bed surface grain size: D_{50} (mm), *S.D.* (phi scale)	67 (*1.1*)	18 (*1.3*)	54 (*2.1*)
Dissolved oxygen	94.7%	97.1%	97.3%
pH	6.65	7.36	7.37
Conductivity (μs/cm)	61.7	90.3	52.6
Trophic status	Highly autotrophic	Slightly autotrophic	Highly heterotrophic
Salmonids	coho, Chinook, steelhead, cutthroat[2]	Same	Same

[1] **Red alder, *Alnus rubra*; big leaf maple, *Acer macrophyllum*.**

[2] **Coho salmon, *Oncorhynchus kisutch*; Chinook salmon, *O. tshawytscha*; steelhead, anadromous *O. mykiss*; cutthroat trout, *O. clarkii***

[3] **Vine maple, *Acer circinatum***

compare the utility of reference sites with two other types of reference: reference parameters and analytical references.

Observations and Discussions

Table 1 lists some characteristics of the three stream reaches visited during the pulse, all within the Prairie Creek basin and judged to be "pristine" by Park personnel and scientists from local agencies and universities. Their basins are uncut except for Little Lost Man Creek, which contains a 35-year-old, 40-acre patch cut, and Upper Prairie Creek, which is crossed by a paved road. The Yurok people located their villages outside these deep woods and the occasional understory fires that they would light did not harm the large redwood trees (*Sequoia sempervirens*) (Sawyer et al. 2000) Although all three streams flow through old-growth redwood forests with an understory dominated by ferns and salmonberry (*Rubus spectabilis*), the influence of the redwood trees on the stream differed according to the height and width of the floodplain and the proximity of the trees to the channel (Figures 1, 2 and 3). Godwood and Upper Prairie Creeks are underlain by poorly indurated gravel and sand considered to be deposits of an ancestral Klamath River of Plio-Pleistocene age (Kelsey and Trexler 1989). As a consequence, some of the modern bed particles may have been transported and sorted under very different hydraulic conditions than are present today, but the modern channels are apparently adjusted to transport this imposed particle-size distribution. Little Lost Man Creek is underlain by a more competent sandstone unit of the Francisican Assemblage (Cretaceous age) including coherent sandstone with some interbedded sandstones and mudstones. This stream reach was steeper and more confined than the other two.

Although all three sites were considered pristine, participants observed strong differences between them, including species composition of the riparian zone, proximity of old-growth redwoods to the stream channel, abundance of fine sediment, patchiness of light reaching the stream bed, distribution of riffles and pools, and location and size of large wood within the channel and on the streambanks and floodplains. Most notably, the riparian stand characteristics were very different. The pristine site in Little Lost Man Creek exhibited sediment effects that are usually attributed to human disturbance, such as unstable banks, high bed mobility, and a drape of silt over the gravel armor.

The instream biology was correspondingly variable. For example, invertebrate samples indicated that the Upper Prairie and Godwood Creek sites were autotrophic (food sources produced instream), with the former much more so than the latter, while Little Lost Man Creek was strongly heterotrophic (food sources contributed by the riparian area) (e.g., Merritt et al. 2002). All three stream sites exhibited algal development, including some filamentous forms, associated with light gaps. The ratio of invertebrates

*Figure 1. (Above) Site 1 is Upper Prairie Creek (photographed March 2004). At Upper Prairie Creek, alders (***Alnus rubra***) grow close to the channel (foreground), maples (***Acer** *spp.) are found on a 1- to 2-m-high floodplain, and old-growth redwoods grow on a higher terrace about 2 m high (in background). Although the stream drains an old-growth redwood forest, hardwoods and shrubs rather than redwoods influence the channel directly in terms of litterfall, shade and wood. This led to a high 'patchiness' of sunlight reaching the stream channel, and low levels of large in-channel wood (although numerous redwood snags and large down wood exist on the floodplain). The wide floodplain in this area supported an abundance of small back channels, high flow channels and alcoves. Banks were composed of coarse cobbles and boulders derived from ancient Klamath River deposits, so the streambed particles were, in a sense, pre-washed, pre-rounded and deposited under different hydraulic conditions. The channel has well developed gravel bars.*

that use periphyton (scrapers) relative to those that use detritus (shredders + collectors) as a food source was used to evaluate autotrophy versus heterotrophy at the stream ecosystem level. The discrepancy between the high penetration of light to the stream bed in Little Lost Man Creek and the very low density of periphyton scrapers was likely due to dense growths of filamentous algae on coarse substrate surfaces. Scrapers are not able to feed efficiently on filamentous algae (Cummins and Klug 1979).

The three sites also differed significantly in abundance of invertebrates that filter fine particulate organic matter (FPOM) in transport (organic portion of suspended load) as their food source and require abundant stable substrates for attachment. Upper Prairie and Godwood Creeks apparently had plenty of stable substrates (large cobbles) but a poor supply of appropriate FPOM for filtering collector food supply. Water clarity at all three sites indicates little suspended load, and the lack of filtering collectors likely further reflects a poor supply of FPOM in suspension. Little Lost Man invertebrates indicate a lack of sufficient stable substrates as well as a poor FPOM supply. Much of the cobble substrate was covered with filamentous algae, which likely rendered their surfaces unsuitable for attachment by filtering collectors or grazing by algal scrapers.

*Figure 2. Site 2 is Godwood Creek. (photographed March 2004). Godwood Creek has more cohesive banks than the other sites, so undercut banks and overhangs are common. At this site, redwoods grow on the edge of the banks and channel, most commonly on terraces 2 to 3 m high. Spruce (***Picea sitchensis***) and hemlock (***Tsuga heterophylla***) are also components of the conifer overstory at this site. Vine maples (***Acer circinatum***) overhang the channel in many areas, but alders are not prevalent. This site is the shadiest of the three, with little algae in the stream. Large in-channel wood is abundant, and many point bars and log jam deposits are present in this reach. The channel substrate consists of loosely packed pebbles and small cobbles.*

Figure 3. Site 3 is Little Lost Man Creek (photographed March 2004). Little Lost Man Creek has the coarsest substrate of the three sites, with some 1-m diameter boulders in mid-channel. The floodplain is narrow and point bars are infrequent. Several instances of recent bank failures were noted. Fern-covered streambanks are steep and are devoid of large trees on the lower 7 to 8 m (perhaps indicative of a past debris torrent disturbing the channel banks). However, when trees fall, they commonly reach the stream and large in-channel wood was more abundant here than in Upper Prairie Creek. Alders grow at the channel's edge. Filamentous algae were present during the July visit.

Our data collection exercises motivated discussions of stream reach variability and reference conditions. A related and recurring question that arose while visiting the sites was, 'How did the site get this way?' (again, in the Franklin tradition). We agreed that a knowledge of the legacy of a site, in terms of long-term state variables (e.g., climate and geology) and the disturbance history (e.g., floods, fires, and landslides), was critical to understanding current conditions and ecosystem processes. This reinforces the conclusion that a key requirement of a reference site is the extent of available data, regardless of where the site might lie along a spectrum from pristine to disturbed.

Types of Reference

The original question of the characteristics of pristine reference sites evolved into an examination of the types of references (Table 2) and their usefulness in evaluating the condition of aquatic and riparian ecosystems in the context of their watersheds.

Reference parameters. Perhaps the most widely used referencing approach is to directly compare the value of a parameter measured at a site of interest to a reference value, range, or distribution, without considering influencing processes. References can be derived from sites judged to be pristine or representative, or from sites sampled randomly in a region. A single-valued reference parameter can take the form of a sample statistic (e.g., mean, maximum or minimum), a scientifically determined or regulatory threshold leading to a degraded condition, or a desired state. A single-valued reference leaves no ambiguity as to whether a criterion is met, but the variability of natural systems suggests that such a comparison is too simplistic.

Table 2. Reference types; their expressions as values, models or locations; and examples.

Reference Type	Expression	Example
Parameter:		
Single value	Average	Pools per mile
	Minimum, maximum	Water temperature
	Threshold	Total Maximum Daily Load (USEPA)
	Presence /absence	EPT [Ephemeroptera (mayflies), Plecoptera (stoneflies), Coleoptera (caddisflies)]
Distribution	Range	Flow regime?
	Cumulative percent	Wood volume/channel area
Process	Value or distribution	Litter input/area-year
Analytical reference		
	Budget	Water, sediment, sediment, dissolved constituents, temperature
	Distributed models	SHALSTAB (Dietrich and Montgomery 1998).
Site:		
Watershed	Reference watershed	H.J. Andrews (LTER), Caspar Creek Experimental Watersheds
	Reference framework	National Ecological Observatory Network (proposed)

Even if used merely as a benchmark, it does not provide an interpretation of a deviation from the reference value unless, as a threshold, it triggers some regulatory action.

A comparison against the full distribution of values from a set of data offers a broader use of reference parameters. Here, the distribution of values from a set of reference sites is presented as a range, standard deviation, or cumulative frequency distribution. Comparison of values against the reference distribution provides information on the deviation from the central tendencies of the reference sites. This broader approach is more informative and can reveal the uncertainty in making management decisions. Distributions of environmental parameters (e.g., wood loading, sediment concentrations) measured in managed and pristine systems in the same region commonly overlap (Lisle 2002). Commonly the 'best' reference sites exhibit wide variation in the parameters selected as measures of their condition, making it difficult to define a target for restoration.

A reference can represent a level of achievement of acceptable conditions on a scale that runs from 'not properly functioning' or 'at risk', to 'properly functioning' (NMFS 1996, 1999). However, a reference condition does not need to represent a pristine system or a target, but can be a benchmark for comparison without a predetermined value or decision context. Application of the Webster definition is still appropriate – a standard to compare with a system in order to help guide analyses to better understand how it got this way and what its trajectory is. Nevertheless, a useful reference must contain some meaning in order to allow an interpretation. In this view, a reference can be used to expose extraordinary conditions and be used in the analysis of cause and effect (e.g., stream cleaning, recent debris flow, influences on riparian communities).

However, any reference parameter is limited in its usefulness to understanding causal linkages, and expanding the scale and context of a reference demands new strategies. One strategy is to quantify relations between terrestrial riparian and aquatic conditions by focusing on processes that transfer watershed products between parts of the watershed ecosystem. Because physical and ecological processes occur at a variety of time scales, a meaningful reference for a parameter like wood loading could be the annual or decadal inputs of wood that are governed by rates of mortality from disease, windthrow, bank erosion and landslides and, ultimately, tree growth (Van Sickle and Gregory 1990; Benda et al. 2002). Also, reference processes could include seasonal or annual rates of primary production or nutrient cycling or fluxes of sediment, nutrients, or organisms. A reference could be used to track trends in processes over time at the same site in the same watershed, or to compare processes among different sites or watersheds in a region. Concentrating on rates of movement from one state to another provides insight into the mechanisms resulting in variability in space over time. For example, with regard to invertebrate life cycles, all three of the sites examined in the Redwood Pulse were dominated by those taxa with annual or shorter generation times. These would be populations with the potential for quick response to changes in the physical environment, and their presence is not very compatible with a view of pristine systems as being relatively stable.

Analytical references. Expanding the use of references from reaches to watersheds requires more than just expanding the same site-scale measurements to more places. One strategy is to employ an analytical reference such as a budget, that is, a statement of spatial and temporal variations in inputs and outputs and changes in storage of a watershed product such as sediment (Reid and Dunne 1996), wood (Benda and Sias 2003; Hassan et al. in press), or particulate organic matter.

As an example, inputs of particulate organic matter (POM) were generally in balance with outputs for a small first-order woodland stream in Michigan (Figure 4) as well as for twenty-three reaches in four different watersheds (Figure 5). The amount of detritus in storage in a reach of stream is the result of biological activity (microbial respiration, invertebrate assimilation) and flow-related loading and unloading of storage in the sediments. The majority of the POM is stored in fine particles, which account for the majority of microbial respiration and 80% of the invertebrate assimilation (Petersen et al. 1989).

In the case of large woody debris (LWD), although historic values for volumes lost or gained usually cannot be determined precisely, enough can be learned of past events and conditions to roughly evaluate departures from natural loadings. This allows some basic questions to be addressed:

- What accounts for present wood loading, and more specifically, how much has land use affected riparian sources and input and output mechanisms?
- What is the trajectory in wood loading given the present and future potential of the riparian forest to contribute wood to the stream?
- Which management alternatives are consistent with the desired trajectory?

Another form of analytical reference is the output of a numerical model relating an environmental or ecological variable to a simplified representation of one or more watershed processes that is applied to the conditions and state variables of a target watershed (Power et al. 1998). Thus, the primary purpose of an analytical reference is not to accurately predict actual conditions, but to project what

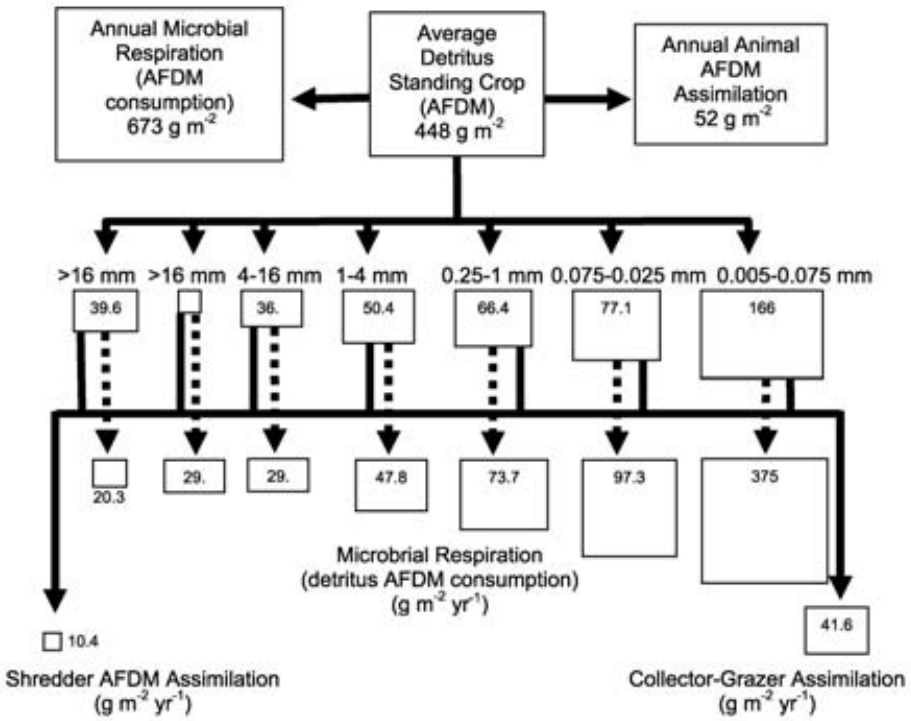

Figure 4. Summary of annual average ash free dry mass (AFDM) in the benthic detritus (bedload) standing crop and consumption by microbial respiration and animal assimilation. Microbial respiration (hatched arrows) and invertebrate (shredders, collectors, and scrapers) assimilation (open arrows) apportioned by mm particle size categories (16 mm W = wood, bark, twigs – a very resistant fraction; 16 mm L = leaf litter). All particle sizes > 1 mm are defined as coarse particulate organic matter (CPOM) and < 1 mm defined as fine particulate organic matter (FPOM). Data from a first order tributary of Augusta Creek in southern Michigan. Modified from Petersen et al. (1989).

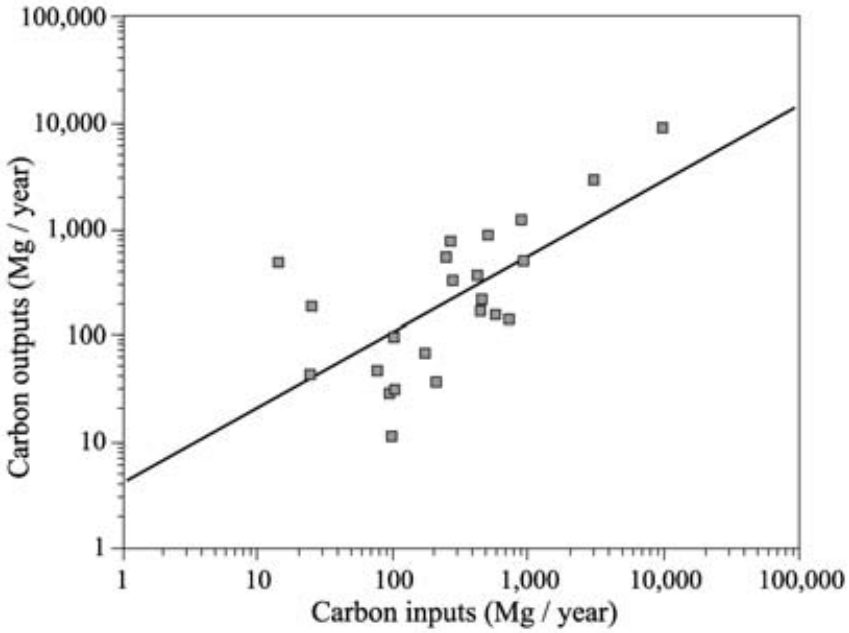

Figure 5. Generally balanced relationship between annual carbon inputs and outputs for 23 stream locations in four watersheds. Modified from Petersen et al. (1989) and based on data in Cummins et al. (1983).

would be found if certain assumptions or conditions were met. Deviations from the analytical reference can reveal the relative strength of other influences.

For example, reference particle sizes of sediment on streambed surfaces in a watershed can be computed from drainage area and channel slope of each reach by assuming that a gravel bed should be at the threshold of movement under bankfull discharge conditions (Power et al. 1998). This is a characteristic of active gravel-bed channels that maintain equilibrium with modest sediment loads. A streambed that is much coarser than the reference particle size could indicate sediment starvation or inputs of large material by debris flows or landslides; a much finer bed could indicate large channel-routed sediment loads, particularly of fine material.

Similar theoretically based models are available for referencing stream temperature based on shade (Bartholow 2002), woody debris loading based on topography and riparian stand structure (Van Sickle and Gregory 1990), the occurrence of shallow landslides based on drainage area and slope [SHALSTAB (Dietrich and Montgomery 1998)], and invertebrate communities dependent on the predictable nature of riparian litter inputs (Grubbs and Cummins 1996).

Numerical models provide a site-specific, theoretical framework to examine relations between environmental conditions and controlling processes. They also enable simulations based on a wide range of scenarios and tests of ecosystem sensitivity to stressors. However, the power of numerical models is limited by the very strategy that makes them computationally possible-simplification of the whole suite of processes that determine the functions of ecosystems in the context of their watersheds. In fact, every model can do no more than produce a reference, because none can incorporate all of the conditions and processes that govern the behavior of a natural system.

Reference watersheds. There is a commonly held view that human influences on watershed conditions transcend those due to climatic events or state variables, thus significant departures from reference values within the same region must be due to human activities. Our observations in the Redwood Pulse led us to doubt that view. We found, for example, that geology in a pristine site we examined produced channel conditions that are commonly attributed to human disturbance. It was clear that establishing a local context – 'how it got that way' – is essential to applying a reference approach.

To this end, we conclude that expanding both the context and scale of references would require a database linking processes in an integrated system – a reference watershed. We envision reference watersheds as real-world examples of the full suite of processes that govern the functioning of a living watershed. Watersheds could qualify as references by having comprehensive, long-term data bases. Our vision of reference watersheds is most closely represented in Long Term Ecological Research (LTER) sites and experimental watersheds that are devoted to research and protected from endemic land use, except for controlled experimental treatments. Many, but not all, LTER sites are essentially pristine. Thus our view that data richness, rather than condition, is a primary requirement conforms to an existing system of reference watersheds. Insofar as pristine watersheds in many regions are rare, this expands the number of watersheds that could be used as references.

A reference watershed should be large enough (say, 10^0-10^1 km^2) to incorporate important processes linking terrestrial, riparian, and aquatic ecosystems in a network of low-order tributaries. They should be rich enough in data and information to explain the variability in observed environmental parameters and their relation to causal factors (again, "how it got this way"). Although it is important to know how pristine systems work, it is also important to know how cumulative effects occur in disturbed systems and what impacts to monitor. Moreover, both pristine and anthropogenically disturbed watersheds are subject to infrequent large disturbances such as wildfire and floods, and thus a variety of states can exist within and among any number of reference watersheds. Examples of data-rich reference watersheds include LTER sites [including H.J. Andrews, in Oregon (*www.fsl.orst.edu/lterhome.html*); Hubbard Brook, in New Hampshire (*www.hubbardbrook.org*); Coweeta, in North Carolina (*coweeta.ecology.uga.edu/webdocs/1/index.htm*)], many of which were once treated experimentally but are now off-limits to major treatments. Others include watersheds associated with Biological Field Stations. For example, Augusta Creek at the Michigan State University Kellogg Biological Station (Mahan and Cummins 1978) or Linesville Creek at the University of Pittsburgh Pymatuning Laboratory of Ecology (Coffman et al. 1971), and experimental watersheds [e.g., Caspar Creek, northern California (*www.fs.fed.us/psw/topics/water/caspar/*)] that still undergo periodic large-scale treatments.

Ideally, the number of reference watersheds could be expanded to include a wider range of conditions. This would allow conditions in a targeted watershed to be compared to those resulting from a range of disturbance intensities (natural or anthropogenic) and state variables. With extensive data, the causal linkages would be relatively well known in the reference watersheds. Comparisons between watersheds would reveal not only the departure of environmental variables from desirable states, but also the linkages that would suggest how more desirable conditions could be achieved. Moreover, reference watersheds could aid analyses of target watersheds by revealing the strong pathways between watershed condition and environmental variables. Depending on the condition of the target watershed, some reference watersheds may be more useful than others. Reference watersheds in a similar condition could indicate how the target watershed functions now, whereas more pristine references could indicate how it might function in an improved condition, and therefore suggest the most plausible approach to restoration. A broader reference framework would evolve as watersheds that host research or administrative studies accumulate enough data to assume the role of a reference watershed. This could occur naturally as analyses prompted by initial comparisons with the 'founding' reference watersheds expand the information base for other watersheds. Recently developed remote sensing and analytical techniques (LIDAR, GIS) enable rapid accumulation of large-scale data sets for new areas.

Relative utility of reference types. The three types of references vary in the degree to which they address a number of issues important to analysis of watershed ecosystems (Figure 6):

- **Linkages** – A reference should incorporate linkages between processes that determine ecological conditions in order to enable analyses of cause and effect. The complexity of natural systems characterized by cascading fluxes of watershed products through various landforms requires a broad scope of analysis. The capacity to link aquatic biota to the stochasticity of the physical system (such as matching critical life history stages with hydrology and temperature) is a valuable attribute of a reference.
- **Scale** – For many problems, the spatial scale of analysis needs to embrace geographic areas (watersheds) that influence a reach of river, and time periods, that cover major climatic fluctuations (e.g., ENSO).
- **Temporal variability** – Sequences of events and contingencies create a wide range of possible outcomes in natural systems that are conditioned by past events and climatic change.
- **Diversity** – To separate anthropogenic effects on ecosystems, references must address the wide diversity in underlying controls, such as landforms, climate, and geology, that affect ecological conditions and processes in a region.
- **Efficiency** – All of the preceding present complications for arriving at an assessment of the effects and risks of ecosystem management. Nevertheless, references must be understandable and practical for use by managers.
- **Reality** – The real world is the ultimate reference, and references must represent it as accurately as possible.
- **History** – Conditions in watershed ecosystems are the culmination of environmental events and processes played out over time and space. Knowledge of history at local and regional scales provides the background to project reference conditions backward and forward, so that contemporary conditions can be interpreted in the context of environmental trajectories.

Reference sites, such as LTER sites or experimental watersheds, ground us in the functioning of real watershed ecosystems over time. The linkages are there to discover and quantify, although there are technological and institutional limitations on the scope and scale of information that can be gathered. The value of reference sites increases exponentially as records lengthen and the systems become more completely understood. Analyses that employ this information can become more powerful by using data from reference watersheds in other areas that have different controlling conditions, or from less data-rich watersheds in the same region, as described earlier as a reference framework. However, reference sites are limited in their capacity to reveal variability, because they represent one history of an infinite number of possibilities created by climatic variability and disturbance events.

Reference parameters provide real-world information at a regional scale and are often readily available. They provide straightforward comparisons with monitoring data, revealing anomalies and prompting more in-depth analyses. However, without further analysis, interpretations are severely limited because of lack of context with other conditions and processes that lead to cause and effect.

Analytical references are becoming more attractive as references because they can address a wide range of scales,

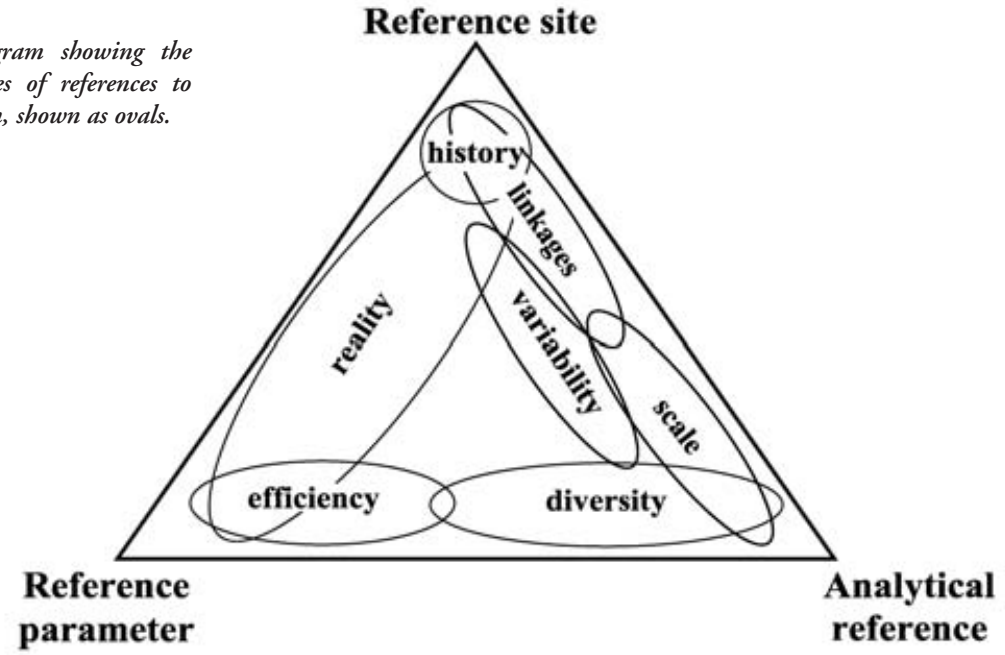

Figure 6. Triangle field diagram showing the relative capacity of three types of references to provide qualities of information, shown as ovals.

stochastic processes, and levels of risk. They explicitly make linkages between various processes and conditions, and can simulate events that have not been observed. In the final analysis, however, they are only as good as their representation of reality, which must be confirmed by examination of real places in real time.

Conclusions

Redwood Pulse participants examined the nature of conditions of three pristine channel reaches that would commonly serve as references. The resulting discussions led to a reappraisal of what constitutes a valuable reference and an appreciation of the utility and shortcomings of a broad range of reference types.

We concluded that a reference site should be a well-studied system, not necessarily pristine, but rich in data linking watershed and ecological processes. For managers, the great benefit of this approach is that pristine watersheds may not be required to establish workable management goals. A greater emphasis on gathering and integrating significant data sets through time would expand the number of watersheds that could be used to establish references. This opens the possibility of formulating a regional referencing framework whereby data-rich watersheds with a spectrum of conditions provide a context for investigating cumulative effects.

A referencing framework provides a means to determine the causal linkages between underlying conditions, environmental variation, and the functioning of the watershed and its ecosystems. In comparison, stand-alone reference parameters taken out of context of the variety of settings where they are measured or applied offer limited interpretive power. Nevertheless, such parameters are easily available and allow initial comparisons that should motivate deeper analyses. Moreover, the full set of values of a particular parameter in a region offers a wider context for interpretation than a single value, such as a threshold or average. Reference parameters that express process or function, that is, rates rather than state variables, are more likely to capture linkages influencing ecosystem condition.

Analytical models provide formal, explicit organization of our understanding of these interactions and a means to sort out strong influences from weak ones, and anthropogenic effects from natural ones. As analytical tools are developed with new knowledge and techniques, analytical references will provide a new wave of approaches for addressing cumulative watershed effects. However, models are ultimately based on knowledge and data from real systems, and their development should motivate new, interdisciplinary field studies.

Finally, Pulse participants concluded that references are essential tools in management-driven analyses of watershed ecosystems, where biological and physical processes interact in a complex structure of linkages activated by stochastic disturbances. Our discussions revealed a variety of reference types, each with strengths and weaknesses, which can be integrated to support more effective, full-scale analyses. Science-based management decisions will always rely on incomplete understanding of watershed ecosystems, but analyses using data-rich reference sites and valid analytical models, combined with the best professional judgment, will help to achieve the competing goals of the public's interest in resource management.

Acknowledgments. This contribution is a distillation of the collective thoughts of the participants of the Redwood Pulse. Paula Yoon of the Redwood Regional Watershed Center was instrumental in arranging logistical support for the Pulse. Redwood National and State Parks provided the use of an environmental school lodge, kitchen, and cabins for the pulse participants. Thomas Dunklin and Betsy Watson recorded and transcribed notes of summary discussions. Mike Furniss facilitated communication among participants through the establishment of an interactive web site. Insightful comments by Bret Harvey on earlier drafts are much appreciated. All photos by the authors.

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Section 1. Applied Science and Technology

Part 3. Surface and Groundwater

Overleaf:
Photo: Torrent sedge (*Carex nudata*) on the North Fork John Day River, Umatilla National Forest, Oregon. Photo by Bruce McCammon.

Chronic Misapplication of the Relationship Between Magnitude and Frequency in Geomorphic Processes, as Illustrated in *Fluvial Processes in Geomorphology* by Leopold, Wolman, and Miller (1964)

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M.G. Wolman and J.P. Miller's paper, *Magnitude and frequency of forces in geomorphic processes* (1960), examined the long-term work done by erosion. They showed that for processes like sediment transport, where movement of materials is driven by shear stress, a large proportion of the work is performed by relatively frequent events of moderate magnitude. Erosional work as indexed by the product of the rate of movement of an event and its frequency of occurrence reaches a maximum at a relatively frequent event. The relationship between magnitude and frequency as charted in Figure 3-23 in *Fluvial Processes in Geomorphology* (Leopold et al. 1964) is frequently referenced. Through time the abscissa in this chart has often appeared as "discharge" rather than "applied stress" as originally published. This transposition reasonably defines sediment transport in a channel only for flows up to bankfull depth. However, once flows overtop the bank, the rate of increase for in-channel bed shear (γRS) must show an inflection. This relationship is not shown in the incorrect representations of the magnitude/frequency relation and has implications for methodologies that attempt to calculate total sediment transport at flows in excess of bankfull.

Keywords: *channel geomorphology, bankfull discharge, sediment transport*

Introduction

In their 1960 Journal of Geology paper, *Magnitude and frequency of forces in geomorphic processes*, M. Gordon Wolman and John P. Miller examined the relative importance in geomorphic processes of extreme, so-called catastrophic events and more ordinary events of smaller magnitude. They evaluated the relative amounts of "work" done on the landscape over the long-term by events of all magnitudes. They concluded that a large part of sediment transport by various media is performed by events of moderate magnitude that recur relatively frequently, rather than by rare events of unusual magnitude. Many features of the landscape are formed by frequent events with relatively small applied stress. Notably, and with lasting impact, they found that stream channel dimensions in alluvial channels seem to be molded by flows at or near the bankfull stage.

A conceptual depiction of the relationships discussed in their paper was presented as Figure 1 of the 1960 paper (see our Figure 1). Leopold, Wolman and Miller duplicate that chart as Figure 3-23 in *Fluvial Processes in Geomorphology* (1964). The form of the chart has been frequently duplicated in subsequent papers that purport to reference either that book or the earlier paper.

In many of the subsequent papers, the abscissa of this chart has often been depicted as "discharge," rather than "applied stress" as originally published. We will show a couple of examples, drawn from a target-rich environment, where this has occurred. The fact that discharge and applied stress are not synonymous is obvious and will not be elaborated upon here. Overlooking this distinction has consequences, especially in the estimate of bedload sediment transport at stages above bankfull.

Shear Moves Bedload Sediment

Gravity is the bus that drives sediment to the sea.

There are multiple modes of sediment transport in streams. Bedload is pushed along by shear stress, while suspended and washload sediment must be maintained in suspension by turbulence and upward velocities that equal or exceed settling velocities of particles.

Figure 2 shows the basic vectors of sediment transport in rivers: gravity, shear stress, normal stress, and friction.

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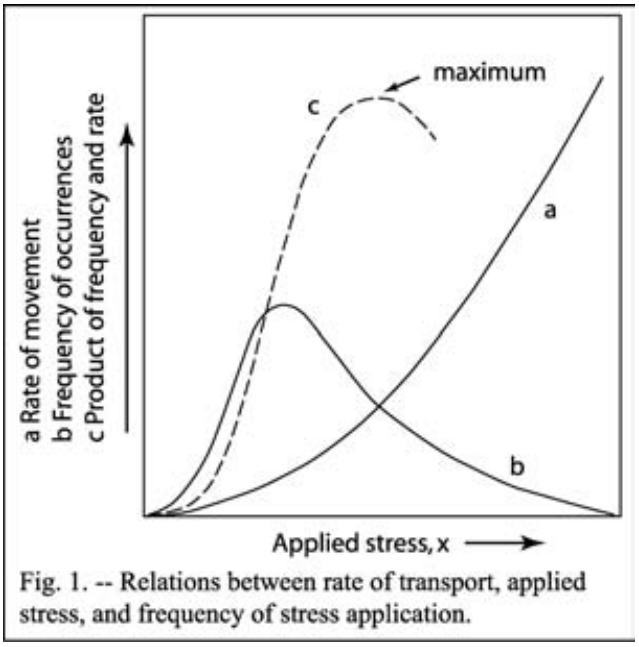

Fig. 1. -- Relations between rate of transport, applied stress, and frequency of stress application.

Figure 1. From **Magnitude and frequency of forces in geomorphic processes***, Wolman and Miller (1960).*

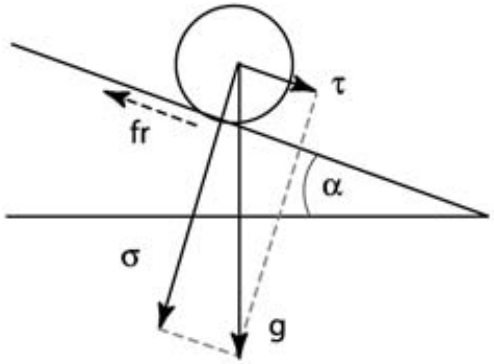

Figure 2. Forces on a particle; bedload sediment transport. Original figure from a no longer available Internet instruction module from the University of Exeter, Department of Geography, Module 1202/2- "Stream Form and Process".

Shear is an applied stress. Commonly denoted by the Greek letter Tau, τ, shear is the force applied tangentially to the sediment surface. It is useful to remember that stress and pressure have the same units: force per unit area, lb/in^2 or N/m^2 .

In *Fluvial Processes*, Leopold, Wolman and Miller describe the relationship between shear and sediment movement in the following terms:

> "To the extent that the movement of sediment by water or air is dependent upon shear stress, the rate of movement can be described by the equation
>
> $$\mathbf{q = k(\tau - \tau^c)^n},$$
>
> where q is the rate of transport, k [is] a constant related to the characteristics of the material transported, τ [is] the shear stress per unit area, τ^c [is] the critical or threshold shear required to move the material, and n [is] an exponent.", p. 79

It is important to remember that shear stress, not discharge, is being described in this equation. The authors' use of the term "q", standard nomenclature for describing discharge, has probably led to some of the later confusion.

This transport relationship is a power function illustrated by the "a" line (Figure 1 in *Magnitude and frequency of forces in geomorphic processes*, also our Figure 1). Applied stress is the independent variable. Figure 3-23 in *Fluvial Processes* is identical. In the text of the 1960 paper and in the subsequent book, Wolman and Miller emphasized that stress must exceed critical threshold values before particles move. Unfortunately, the charts show movement beginning at an implied applied stress just past zero. This, too, has probably led to subsequent confusion.

The Relationship Shown in Wolman and Miller (1960) Has Often Been Misrepresented

Figure 1, the cornerstone chart from *Magnitude and frequency of forces in geomorphic processes*, has been referenced many times. In many instances, the abscissa has been transformed from applied stress to flow. Figures 3 and 4 are two examples.

Flow Increases Faster Than Does Shear at Stages Above Bankfull

All erosional processes are driven by gravity. The gravitational force acting on water drives the flow downslope in a confined channel, where the slope of the water surface represents the balance between the energy gradient and frictional resistance from the channel bed and banks.

Shear and flow are partially products of water depth, both increasing as water stage increases. As water levels exceed bankfull stage, water flows out on the floodplain and flow increases considerably faster than does channel shear. Shear, not flow, is moving bedload sediment.

The transport relationship charted in line "a" of Wolman's Figure 1 remains correct above bankfull stage. Transforming the independent variable from applied stress to flow, as in (our) Figures 3 and 4, leads to an incorrect view of the bedload transport rate at stages above bankfull. Bedload transport continues to increase when flows exceed bankfull, but only as shear increases.

It follows that extrapolation of flow/bedload sediment transport rates determined at less than full channel flows,

Figure 3. Transformation of the abscissa from applied stress to discharge. From Andrews (1980).

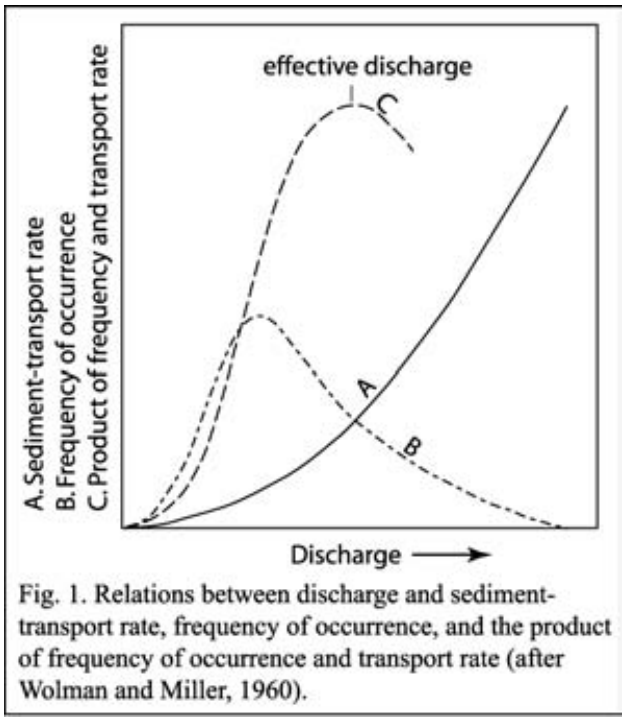

Fig. 1. Relations between discharge and sediment-transport rate, frequency of occurrence, and the product of frequency of occurrence and transport rate (after Wolman and Miller, 1960).

Figure 4. Transformation of the abscissa from applied stress to discharge: A recent example of the same mistake. From Schmidt and Potyondy (2004).

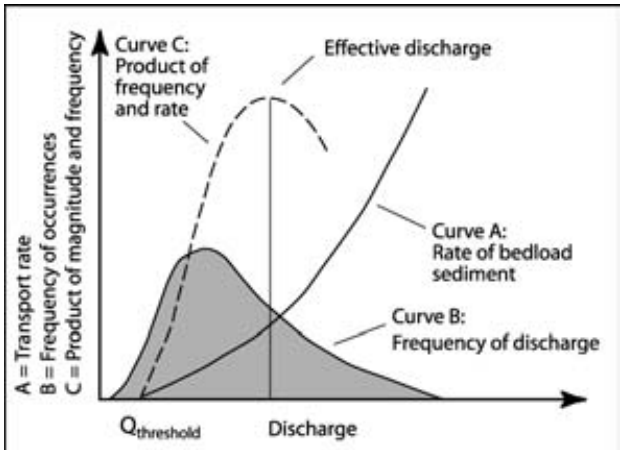

Figure 1 -- The magnitued-frequency concept applied to bed-load transport and disch]arge adapted from Wolman and Miller 1960. The concept suggests that a range of inter-mediate flows transports more sediment over the long-term than either high or low discharges. $Q_{threshold}$ refers to a threshold discharge at which bedload transport begins.

to flows in excess of bankfull, can lead to an overestimation of total bedload transport.

Conclusion

Wolman and Miller's 1960 paper opened innovative lines of inquiry for geomorphology. Figure 1 in that publication has been widely, and often incorrectly, reproduced. The abscissa of that figure is often incorrectly portrayed as "flow" rather than "applied stress" as originally published. Of physical necessity a depiction of bedload sediment as a function of flow needs to show a diminished slope beginning at the stage of bankfull flow.

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The Evolution of Channel Maintenance Science in the Forest Service

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Channel maintenance instream flows consist of a specified range and duration of flows designed to provide for the self-maintenance of alluvial stream channels. Channel maintenance flows provide for processes that determine the form of the physical channel. Agency scientists placed emphasis on physical channel form to satisfy constraints imposed by litigation in Forest Service reserved water rights claims. The original channel maintenance flow methodology was developed by Forest Service hydrologists in 1982 and the technical basis for channel maintenance flows and quantification approaches has evolved significantly over the last 20 years. Under the original approach, the channel maintenance hydrograph consisted of a rigid stepped hydrograph fixed in time and capped at bankfull discharge. Under current approaches, the flows necessary to maintain channels are seen as a naturally variable range of flows typically beginning at intermediate flows below bankfull discharge and including high flows that inundate the floodplain. While the original approach focused primarily on the need to transport sediment through the stream system, more recent approaches recognize that the required flows must also provide sufficient low and high flows to sustain streamside vegetation. As understanding of gravel-bed streams processes and the linkages between streamside vegetation and streamflows increases, additional improvements and refinements to quantification approaches are likely.

Keywords: *channel maintenance, instream flows, favorable conditions of water flows*

Introduction

The Forest Service attempted to acquire channel maintenance instream flows in many adjudications throughout the western United States during the 1980s and 1990s. These instream flows claims have generally failed, their failure attributed to hostile state court forums, the stringent test established by the U.S. Supreme Court for implied reserved water rights, and the difficulty of quantifying instream flow water rights for dynamic hydrologic stream systems (Witte 2001). This paper concentrates on the scientific aspects of channel maintenance flows and the extraordinary change in scientific thinking pertaining to channel maintenance that has occurred within the Forest Service and the scientific community between the origination of the first channel maintenance methodology in the 1980s and the present. A brief discussion of the legal framework surrounding the development of channel maintenance instream flow concepts and pertinent court decisions is provided to establish context.

Furniss, M.J., Clifton, C.F., Ronnenberg, K.L., eds., 2007. *Advancing the fundamental sciences: proceedings of the forest service national earth sciences conference, San Diego, CA, 18-22 October 2004*. PNW-GTR-689. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station.

The Legal Context of Channel Maintenance Instream Flows

The genesis of the doctrine of federal implied reserved water rights occurred in 1899, but it was not until 1963 that the doctrine was expanded by the United States Supreme Court in Arizona v. California to include national forests, parks, and recreation areas. Prior to the court's decision in 1963, the application of the doctrine (which holds that when Congress reserves land it impliedly reserves water in a quantity sufficient to meet the purposes for the reserve) was widely believed to be restricted to Indian reservations.

Following the expansion of the doctrine to other federal reserves, the Forest Service began filing for instream flows on National Forest System lands. These efforts occurred in state water courts throughout the West pursuant to the limited waiver of federal sovereign immunity provided by the McCarren Amendment (passed by Congress in 1952). This amendment gave state water courts jurisdiction to hear federal water right claims.

Litigation of one of the first claims filed under the federal implied reserved water rights doctrine for National Forest System lands occurred during the adjudication for the water rights of the Rio Mimbres on the Gila National Forest in New Mexico. Instream flow claims for the benefit of fish, recreation, and aesthetics were filed under the

authority of the Creative Act of 1891 and the Organic Administration Act of 1897.

These claims were denied in 1978 by the United States Supreme Court in United States v. New Mexico by a narrowly split (5 to 4) decision. The majority ruled that the Forest Service could not claim federal reserved water rights for Multiple-Use Sustained-Yield Act purposes and strictly construed the purpose for which water could be claimed under the doctrine on National Forest System lands to two purposes, "securing favorable conditions of water flows and to furnish a continuous supply of timber."

In an effort to protect stream flows for these narrow purposes on National Forest System lands, the Forest Service defined favorable conditions of water flows to include healthy stream channels. Under the constraints imposed by the Supreme Court, the Forest Service devised a methodology to determine the amounts of water necessary to maintain stream channels in a condition suitable for "securing favorable conditions of water flows." The flows quantified under this approach came to be known as channel maintenance instream flows. Due to the constraints of the federal impliedly reserved water rights doctrine, only the minimum amount necessary to secure favorable conditions of water flows could be claimed (Witte 2001).

Channel maintenance flows are non-consumptive instream flows specifically designed to maintain the physical characteristics of the stream channel (Schmidt and Potyondy 2004). Providing for channel maintenance requires that stream channels support healthy streamside vegetation and have flows of sufficient magnitude, duration, frequency, and timing to maintain channel morphology so that the capacity of the channel to convey natural flows is unimpaired over the long term.

The Original Channel Maintenance Methodology

The original channel maintenance methodology was primarily developed by Forest Service hydrologists David Rosgen and Hilton Silvey (Rosgen 1982) and are based to a large extent on concepts contained in the classic geomorphology textbook, "*Fluvial Processes in Geomorphology*" by Leopold, Wolman, and Miller (1964). Subsequent personal involvement in Colorado's Water Division One litigation by Luna Leopold, Emeritus Professor of Geology at the University of California, Berkeley, former Chief Hydrologist of the U.S. Geological Survey, and one of the world's leading authorities on river hydraulics and geomorphology, gave credibility to these ideas.

The Forest Service's original channel maintenance procedure was documented in the Forest Service directives system, Forest Service Handbook 2509.17, Chapter 30, "Procedure for Quantifying Channel Maintenance Flows" (USDA Forest Service 1985). In it, channel maintenance flows are defined as, "A range and duration of in-channel flows necessary to maintain the stability and effective function of the stream channel. This includes those flows which are necessary to provide for the self-maintenance of the stream channel network so as to retain its capacity for passing flood discharges and minimize channel erosion and/or sediment deposition associated with instability or disequilibrium conditions. The consequences of not maintaining channel stability include channel aggradation, channel erosion, floodplain encroachment, vegetation encroachment, changes in hydraulic geometry, and reduced channel capacity with resultant increased risk of flooding and associated resource damage."

The channel maintenance procedure was intended for application to snowmelt dominated, perennial, alluvial channels capable of adjusting their dimension, shape, pattern, or gradient, or several of these characteristics, in response to changes in streamflow (Rosgen et al. 1986). Generally accepted concepts used by engineers, hydrologists, and geomorphologists formed the basis for the channel maintenance procedure.

Three basic flow components were considered essential for a channel maintenance flow regime: (1) a peak flow (bankfull discharge); (2) a low flow (baseflow discharge); and (3) snowmelt rise and recession discharges (Figure 1). Bankfull discharges were considered essential because flows near bankfull have been shown to move the most sediment over the long term (Wolman and Miller 1960) and are frequently referred to as channel-forming flows. Baseflows were considered necessary to maintain the "thread of the stream" (the thalweg channel) by migrating sediment from riffles to pools and preventing vegetation encroachment and seedling establishment in the active channel by maintaining high water tables. Gradual rise and recession flows were included to avoid rapid changes in stage which might cause accelerated bank erosion and to allow for a duration of flows that mimics the natural hydrograph. This was accomplished by beginning the claim when average annual flow was first attained during the spring snowmelt hydrograph. Flows were then gradually increased in 10 percent increments between the average annual and bankfull discharges resulting in a stair-stepped hydrograph up to and including bankfull discharge. The recession limb of the hydrograph was constructed in a similar manner except that the duration of recession flows was constrained to one day under the concept of the existence of a hysteresis effect, allowing for a rapid recession. Hysteresis assumes

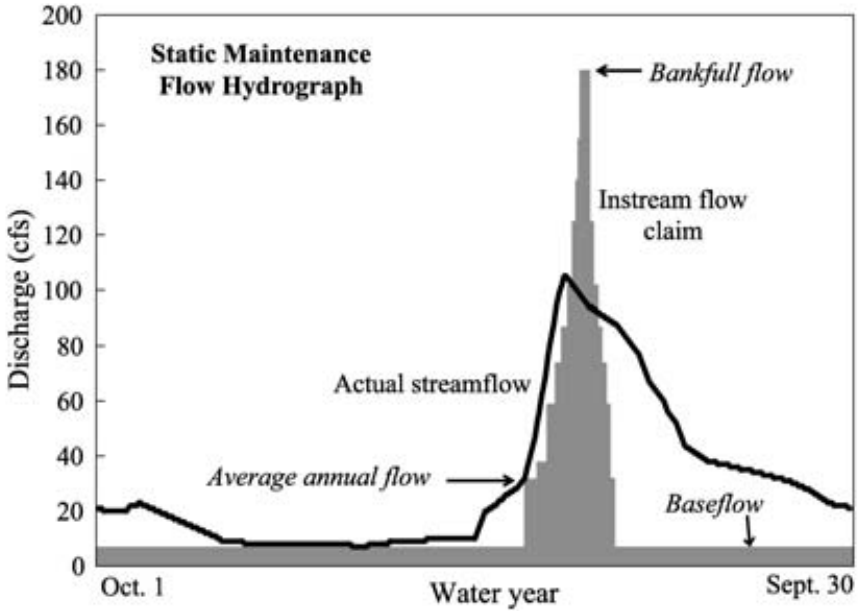

Figure 1. The original form and elements of the static maintenance flow hydrograph consisting of gradual rising steps, a cap at bankfull discharge, a recession limb, and year-round baseflows.

that the majority of the sediment is transported during the rising limb and therefore flows during the recession portion of the hydrograph are not as critical for sediment movement and channel maintenance. Therefore, flows after the peak were allowed to decrease rapidly relative to the rise.

A typical static channel maintenance flow hydrograph is constructed using this procedure (Figure 1). The term static is used because the shape of the hydrograph was fixed in quantity and time once it was initiated by the occurrence of average annual flow. A static form was required because the procedure was developed under the assumption that the instream flow claim must meet the basic requirements of State water rights law, that is, in order to provide for certainty in water administration the amounts claimed needed to be precisely stated with respect to time and amount. Details of the procedure for constructing maintenance flow hydrographs can be found in Forest Service Handbook 2509.17, Chapter 30 (USDA Forest Service 1985).

Significant technical points of contention included questions of whether average annual flow was the appropriate required discharge for the beginning of channel-maintaining sediment transport, whether peak flows constrained to no more than bankfull discharge were adequate to maintain stream channels, and whether baseflows played any important role in maintaining physical channel characteristics.

Development of the Dynamic Hydrograph

Technical problems with the static nature of the channel maintenance flow hydrograph first surfaced during the 1991 trial of an adjudication encompassing the South Platte River and its tributaries, hereafter referred to as Water Division 1. During the trial, experts for the State of Colorado analyzed the entire period of daily flow records for 19 USGS gaging stations and superimposed the static hydrograph to determine how often the claim would actually be met. The analysis showed that actual hydrographs varied from year to year to such an extent that the static claimed hydrograph frequently misaligned with the occurrence of peak flows (e.g., Figure 2). Note that in this example bankfull discharge occurs in the stream, but at the time of its occurrence, significantly lower amounts of water are claimed due to the fixed, static nature of the claim process. Likewise, when bankfull discharge is claimed, natural stream flow for that year has already receded so that water equal to bankfull is unavailable. The net result is that in this high flow year scenario, the bankfull discharge required to maintain the channel would fail to be claimed by the Forest Service.

The pattern from the 19 streams examined showed that the channel maintenance flows claimed would only reached bankfull discharge 15 to 19 percent of the years of record (Gordon 1995). This low occurrence of bankfull discharge was significantly less than the 67 percent of the years (every two out of three years) that Forest Service technical testimony had argued was necessary for the channel to be maintained. The State concluded its testimony by pointing out that even if the claim was granted, the Forest Service would fail to achieve the desired maintenance objective. Conceding, but never refuting the analysis, the Forest Service proceeded to develop the dynamic hydrograph in a span of several weeks to overcome the deficiencies of the static approach.

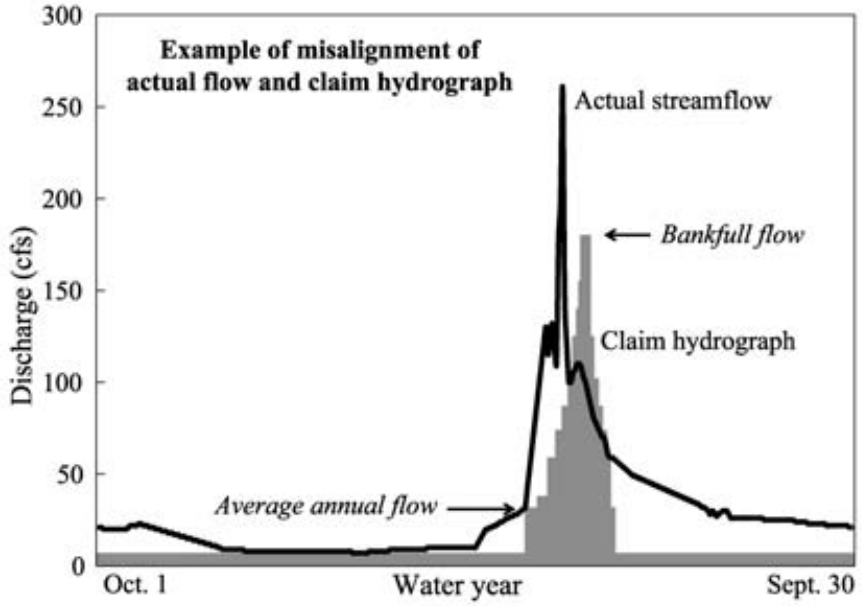

Figure 2. A typical example of misalignment between actual streamflow and the static maintenance flow hydrograph.

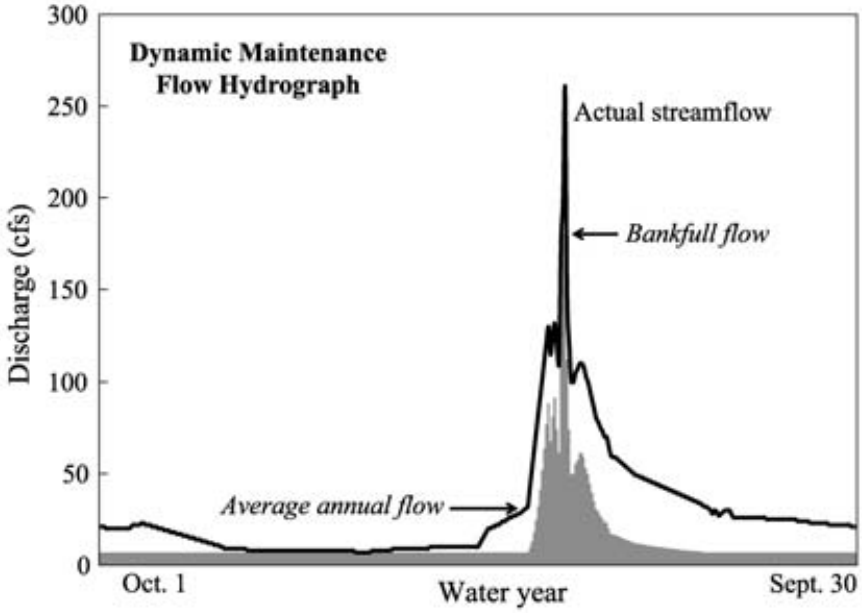

Figure 3. The form and elements of the dynamic maintenance flow hydrograph structured so that the claim is only made when water is in the channel and claimed flows are proportionally distributed so that more water is claimed at flows approaching bankfull discharge.

The "dynamic" hydrograph was so named because it rises and falls with natural stream flows. To achieve this, the dynamic claim hydrograph was structured and positioned so that it only claimed flows when water was actually in the stream channel (Figure 3). The dynamic form retains most of the essential features of the static form: claim initiation beginning with attainment of average annual flow, a maximum peak set at bankfull discharge, and a baseflow component. However, instead of the "stairstep" appearance of the static claim, the dynamic form claimed a sliding percentage of the streamflow such that more water was claimed at flows closer to bankfull. Amounts were calculated according to the following formula:

$$\text{Claimed flow} = Ql + \left((Qs - Ql) \times \left(\frac{Qs - Q\,a}{Qb - Q\,a} \right) \right)$$

where: Qs = actual streamflow, Ql = baseflow, Qa = average annual flow, and Qb = bankfull flow.

Positioning the claim under actual stream flows eliminated a primary deficiency of the static hydrograph by assuring that the claim was active only when flows up to the channel forming bankfull discharge occurred. Scientifically this provided an improved solution of the channel maintenance flow problem. Administratively however, the dynamic solution was complex and problematic because it might not meet fundamental requirements of a water right with respect to time and amount and it would be difficult to administer in practice. In addition, other technical points of contention pertaining to bankfull discharge, the initiation of sediment movement at average annual flow, and the need for baseflow remained.

In the final decision in the Water Division 1 litigation in 1993, Judge Behrman denied both the static hydrograph and dynamic hydrograph based channel maintenance claims. The judge observed that the technical challenges to quantify channel maintenance claims had not been adequately met and noted that it might be impossible to do so (Gillilan and Brown 1997). He further commented that the hurried time constraint imposed on the development of the dynamic hydrograph in particular was not the ideal environment for careful scientific study and suggested that a proposal developed under calmer and more scholarly circumstances would be appropriate (Gordon 1995).

Current Approaches

The USDA Forest Service Stream Systems Technology Center was established in 1992, in part, to improve the scientific understanding of channel maintenance flows. Since that time, they have consulted with a wide array of scientists in the Forest Service, other agencies, universities, and consultants, with the aim of arriving at a consensus on the best science available to address this issue.

While there is still diversity of opinion on many technical aspects of channel maintenance, initial consultation with the scientific community identified four technical areas that were at odds with then existing Forest Service approaches:

1. Channel maintenance requires a range of flows, including peak flows exceeding bankfull discharge;
2. In alluvial gravel-bed streams, required channel maintenance flows need to periodically move the caliber of sediment making up the bed of the channel (Phase 2 transport);
3. Baseflows, while perhaps necessary for other important ecological functions, play an insignificant role in maintaining the physical form of the channel; and
4. Streamside vegetation plays an important role in maintaining stream channels.

Sediment Transport

A major change in scientific thinking beginning in the late 1980s and through the 1990s is the concept that channel maintenance in gravel-bed streams centers around a range of intermediate flows rather than bankfull discharge alone. While Emmett (1976) was the first to propose two distinct phases of transport in armored channels as early as 1976, it was not until the 1980s that others expanded the concept to describe phases of bedload transport in gravel-bed streams (Jackson 1981; Jackson and Beschta 1982; Beschta 1987; Ashworth and Ferguson 1989; Warburton 1992). During the 1990s, numerous other scientists confirmed that intermediate discharges transport mainly sand (Phase 1 transport) whereas discharges near or above bankfull transport coarser bedload (Phase 2 transport) (Church et al. 1991; Komar and Shih 1992; Kuhnle 1993; Carling 1995; Lisle 1995; Wathen et al. 1995; Petts and Maddock 1996; Wilcock and McArdell 1997; Whiting et al. 1999; Ryan and Emmett 2002; Church and Hassan 2002). While there is widespread agreement that movement of coarse gravels beginning at discharges associated with Phase 2 transport and continuing on to higher discharges is important for channel maintenance, considerable uncertainty exists regarding the best manner to identify this initiation discharge and numerous approaches have been proposed (Emmett 1999; McNamara et al. 2000, Ryan et al. 2002, Whiting and King 2003, Schmidt

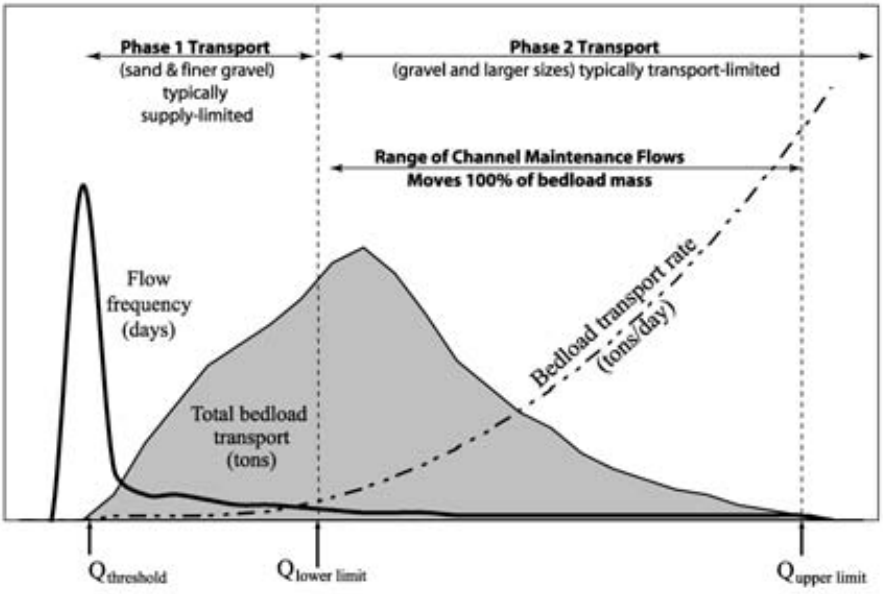

Figure 4. A conceptual model of total bedload transport that forms the basis for the current proposed approach for quantifying channel maintenance instream flows in gravel-bed streams in the western United States.

and Potyondy 2004). Regardless of methodology used to identify initiation, investigators generally have found that Phase 2 transport begins at discharges ranging between 60 to 100 percent of bankfull discharge (Jackson 1981; Pitlick 1994; Carling 1995; Petts and Maddock 1996; Ryan and Troendle 1996; Whitaker 1997; Ryan et al. 2002, 2005; Trush et al. 2000).

Schmidt and Potyondy (2004) summarize the current science and develop a conceptual gravel-bed river total bedload transport model (Figure 4) which forms the basis for a proposed approach for quantifying channel maintenance instream flows in gravel-bed streams in the western United States. The approach is appropriate for quantifying channel maintenance flows on perennial, unregulated, snowmelt-dominated, gravel-bed streams with alluvial reaches. Under this approach essential channel maintenance flows begin at a lower limit of discharge associated with the onset of Phase 2 bedload transport (80% of bankfull is used as an example in the diagram) and includes all flows up to an upper limit set at the 25-year flood stage (Figure 5). All flows from the lower limit to the upper limit are claimed as necessary for channel maintenance whenever these flows occur assuring that claims are made only when water actually exists in the stream channel. While all high flows contribute to sediment transport and channel morphology, flows exceeding the 25-year event are excluded as unnecessary for channel maintenance because they are thought to play a role primarily in valley maintenance (Hill et al. 1991). In addition, because extreme high flood flows may cause property damage, they are excluded for practical purposes because it is difficult to characterize these high flows as a "favorable condition of water flow." The current hydrograph structure claims considerably less water than either the static or dynamic approaches because it places greater reliance on short duration flows approaching and exceeding bankfull to accomplish the necessary sediment transport.

A remarkable shift in our understanding of the range of sediment transporting flows needed for channel maintenance has occurred (see Figure 6). The original peak flow structure began with a conservative estimate of when bedload may begin to move in some channels, typically a value of around 20% of bankfull discharge, and was limited to flows no higher than the bankfull discharge contained within the main channel, excluding flows that would spill onto the floodplain. The current peak flow approach begins with the initiation of coarse sediment transport making up the bed of the channel, commonly a value ranging from 60 to 100% of bankfull discharge and having an average of about 80% of bankfull discharge. The flows exceed bankfull to a significant degree and include flows that spill onto the floodplain, recognizing that the floodplain is an extension of the channel that needs to be periodically disturbed in order to maintain floodplain processes and streamside vegetation.

Streamside Vegetation

A parallel shift in thinking has also occurred regarding the role of vegetation in channel maintenance flow processes. Under the original approach, vegetation was essentially considered an "enemy" of channel maintenance and the original approach argued that baseflows were necessary to prevent vegetation encroachment within the channel while failing to acknowledge the role streamside

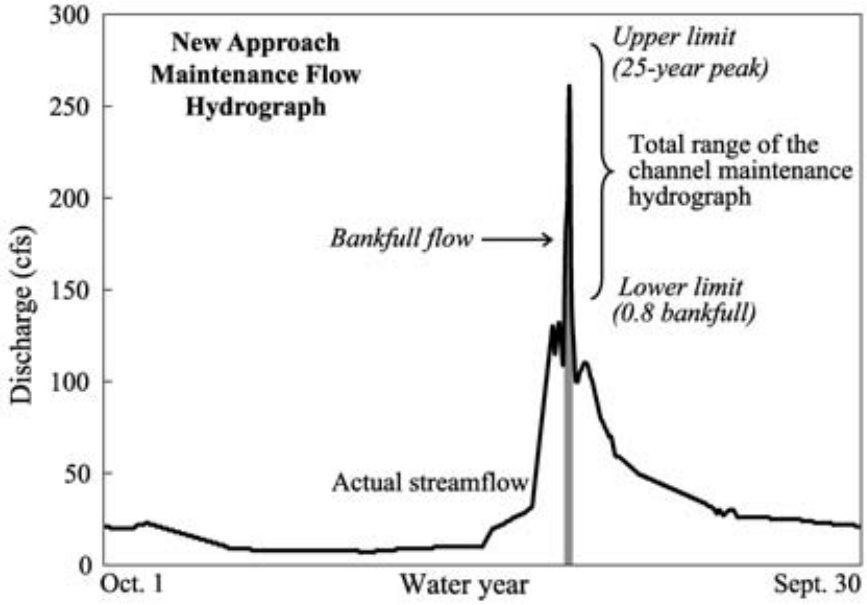

Figure 5. The form and elements of the maintenance flow hydrograph under the current approach. Channel maintaining flows begin at a lower limit with the initiation of coarse gravel (Phase 2 transport) and include flows up to an upper limit, the 25-year peak flow.

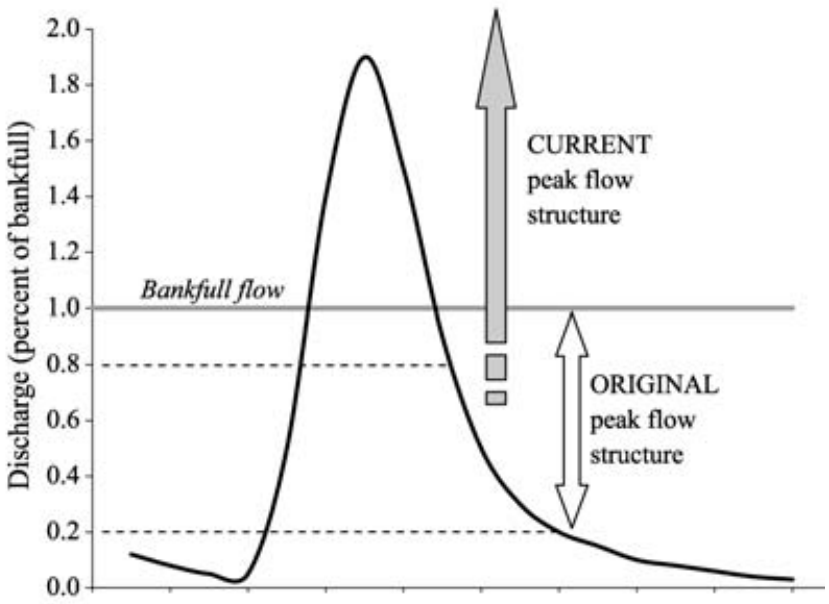

Figure 6. An illustration of the remarkable shift in the range of flows considered necessary for channel maintenance between the original static hydrograph approach of the 1980s and the range of flows considered to necessary today.

vegetation plays in providing for streambank stability. The primary concern centered on possible detrimental effects to the channel that might result from in-channel vegetation blocking orderly sediment transport through the system.

The current approach treats streamside vegetation as an essential part of a well-maintained channel by recognizing that a properly functioning channel requires a flow regime that not only conveys water and sediment, but also maintains adequate streamside vegetation to protect the integrity of channel banks and floodplain while at the same time keeping the channel proper free of perennial vegetation (Schmidt and Potyondy 2004). Toward that end, high flows exceeding bankfull stage are needed to provide for periodic disturbance to assure regeneration and to scour vegetation from the channel. These high flows can substantially influence channel dynamics, encourage floodplain scour and sediment deposition, provide for water storage and nutrient cycling and the periodic disturbance required by streamside and floodplain plant communities (Jackson et al. 1987; Gebhardt et al. 1989; Gregory et al. 1991; Stromberg et al. 1991; Jackson and Beschta 1992; Mahoney and Rood 1993).

The association between riparian vegetation and streamflow is particularly evident in arid environments and year-round baseflow may also be needed to sustain protective streambank vegetation in losing reaches in arid and semi-arid regions (Stromberg and Patten 1996). However, in many temperate mountainous environments, adequate soil moisture during the growing season is available to sustain streamside and floodplain vegetation because subsurface flows contribute moisture to riparian soils and mountainous sideslopes contribute water to maintain soil moisture and baseflow making instream baseflows unnecessary (Schmidt and Potyondy 2004).

Conclusion

The goal of this paper is to describe the differing approaches to channel maintenance that the Forest Service has employed over the years. Science by its very nature is dynamic and continually expanding in its understanding. Furthermore, disciplines, especially relatively young sciences such as fluvial geomorphology, operate under accepted paradigms until new paradigms are adopted and this is part of the process that has been especially evident over the last decade (Kuhn 1962). The change implemented by the Forest Service in its channel maintenance technology in response to challenges to its science in legal proceedings and other forums is a positive, rather than a negative attribute.

More hydrologists and geomorphologists work in the field of fluvial geomorphology today than at any time in the past. Numerous papers are being published, research is in progress, and understanding of geomorphic processes is expanding and changing as interest in the disciple continues. By discussing and understanding the strengths, weaknesses, and appropriateness of past methodologies, it may be possible to encourage the development of improved ideas and approaches.

Two specific areas need further research with respect to current channel maintenance science: First, much remains to be learned about sediment transport science in coarse-grained gravel bed channels typically found in the mountainous watersheds of the national forests; Second,

much remains to be learned about streamside vegetation and species specific linkages between streamside vegetation and streamflows in mountain streams. As work in these areas continues, we can be certain that the science of channel maintenance will once again evolve in response to this new knowledge and the approach employed today may again need to be refined to reflect the new science.

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Forest Service Channel Maintenance Flows in the Klamath Basin

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The Fremont-Winema National Forest has filed channel maintenance in-stream flow water rights claims within the Upper Klamath River basin, Oregon. Claims were filed at 31 sites under the 1897 Organic Act, and represent an estimate of the minimum flows necessary to maintain stream channels over time. Data were collected on stream hydrology, the composition of bed-material, bedload transport over a range of flows, and channel characteristics. These data were used to formulate an instream flow claim based on the ability of the stream to move the larger particle sizes composing the streambed and banks, and thereby maintain the channel. Channel maintenance flows were determined to begin when the framework component of the bed-material as determined by the Parker-Klingeman bedload transport model began to be mobilized by the stream. Streambed framework materials consist of gravel-sized particles, and make up the major morphological features of the streambed. Channel maintenance flows are relatively high flow events, and include the range of high but not extreme discharges that are most effective at transporting bedload sediment and thereby maintaining channel capacity. Because this method for quantification of channel maintenance flow claims is calibrated to individual stream characteristics, it can be easily adapted for use in a wide variety of streams and conditions.

Keywords: *channel maintenance flows, Upper Klamath River basin, Fremont-Winema National Forest, Organic Act, bedload*

Introduction

Favorable Conditions of Flow and Reserved Water Rights

The Forest Service has filed Favorable Conditions of Flow (FCF) claims at 31 sites under the 1897 Organic Administration Act, 16 U.S.C. § 475, which defined the purposes for which National Forests were originally created. In 1978, the United States Supreme Court (United States vs. New Mexico, 438 U.S. 696, 706-707) reaffirmed the idea that that one of the reasons the National Forests were established was for the purpose of "securing favorable conditions of water flows." Water rights claims for instream flows were prepared by the Fremont-Winema National Forest, and were initially submitted to the Oregon Department of Water Resources in April 1997. The purpose of this paper is to provide detailed information on the concepts and procedures used in developing Favorable Conditions of Flow (FCF) channel maintenance instream flow water rights claims by United States Department of Agriculture, Forest Service, on national forest lands within the Upper Klamath River basin, Oregon. These claims prescribe the minimum amount of streamflow necessary to maintain stream channels over time and thereby ensure the delivery of water to downstream users.

Since the passage of the Organic Act, engineers and natural scientists have become more knowledgeable about the hydrologic cycle and have gained a better understanding of the effect of forested lands on incoming precipitation, runoff patterns, evaporation, and transpiration. The phrase "favorable conditions of flows" has been interpreted to apply to forest management and the hydrologic cycle in the following two ways. First, the forest was thought of as a moderator of runoff and streamflow, where flood flows such as spring runoff were stored. It was generally recognized that forest cover might increase infiltration of precipitation into the ground, reducing runoff and flood peaks and eventually increasing low flow in streams. Secondly, it was important to protect forests and the integrity of stream channels for the conveyance of streamflow so that forest lands could contribute to a sustainable water supply to downstream users.

Furniss, M.J., Clifton, C.F., Ronnenberg, K.L., eds., 2007. *Advancing the fundamental sciences: proceedings of the forest service national earth sciences conference, San Diego, CA, 18-22 October 2004*. PNW-GTR-689. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station.

If a stream channel has reduced capacity to convey water, flows are impeded, the risk of flooding is increased, and the efficiency of water delivery to downstream users is impaired. The FCF instream flow claims are intended to maintain the physical characteristics of the channel so that the ability of the channel to convey streamflow and sediment is maintained. These non-consumptive claims do not reduce the amount of streamflow available for downstream appropriators and other uses. They are initiated only during periods of high streamflow, and require the minimum amount of streamflow necessary to maintain proper functioning condition of streams by maintaining channel capacity and channel features so that the ability to pass natural flows is ensured.

Channel Maintenance

Channel maintenance and the morphology of channels depend on a complex set of watershed physical processes and factors related to stream hydrology and the transport of sediment. A certain quantity of streamflow is necessary to transport the sediment entering the channel and thereby maintain channel form. As well as removing sediments supplied to the channel, higher flows prevent the encroachment of vegetative growth in the channel (Reiser et al. 1989). The amount of streamflow needed to maintain the channel depends on the quantity and sizes of sediment entering the channel. A stream will adjust to streamflow and sediment inputs to maintain a mean equilibrium that reflects the prevailing flow and sediment regimes (Lane 1955; Rosgen et al. 1986).

To maintain a channel's shape, the volume of material transported into the channel reach must be conveyed through the reach over time. Failure to convey the sediment load delivered to a stream reach over time will result in sediment accumulations in the reach and reduction in the capacity to convey flood flows. Channel maintenance flows must account for fluctuations in flow and the quantity and characteristics of the sediment and other debris supplied to the channel. Channel maintenance processes act over time. While sediment may accumulate during one period of time, accumulated sediments are eventually removed. For example, erosion of streambanks or sediment influx from tributaries may locally increase bed elevations, leading to small-scale flooding and flow diversion, with sediments eventually transported and redistributed to downstream areas.

The frequency and duration of moderately higher streamflows, especially flows around bankfull and larger, are particularly important for controlling channel morphology (Hill et al. 1991). Bankfull flows are those flows that fill the channel up to the stage where the stream just begins to overflow into its floodplain. In gravel-bed streams, these relatively high flows result in significant rates of bedload transport (Beschta 1987), because bedload transport rates generally increase rapidly with increasing streamflow. Large floods are very effective at altering channel form as they are able to transport significant amounts of sediment. However, over longer periods of time large events transport a far smaller total volume of bedload (Leopold 1992). In contrast, flows that fill the channel to the level of the floodplain (bankfull flows) are most effective at moving sediment over time, and are the dominant channel-forming flows (Wolman and Miller 1960; Andrews 1984; Leopold 1992) in mobile, alluvial bed channels. The mean recurrence interval of bankfull flows (on an annual flood frequency series) for a large variety of rivers has been found to be about 1.5 years (Dunne and Leopold 1978), but can also vary considerably from the 1.5-year flood (Hey 1994).

Sediment Transport

The movement of sediment involves its entrainment, transport, and ultimate deposition. Bedload and suspended load are the two major modes of sediment transport (Graf 1971; Richards 1982). Suspended sediment consists mainly of finer particles such as silts and clays, which are completely supported by the turbulence of flowing water. Bedload usually consists of particles of sand, gravel, cobbles, and boulders that are transported by traction, or roll, slide, and bounce along the streambed.

In flowing water, the smallest particles such as silt, clay, and colloids are held in suspension within the water column. Suspended sediment concentrations typically show considerable variation over time, and respond in a non-linear and highly sensitive manner to changes in flow and sediment availability. Particle settling velocities and fluid forces in turbulent flow work to maintain larger particles such as sand in suspension. As a result, the distribution of sand of 0.01- to 1-mm diameter in the water column is not uniform, and often results in transport alternately as bedload and in suspension (Beschta 1987). The spatial concentrations of these larger particle sizes may continuously shift as flows encounter different channel geometries and hydraulic conditions in downstream transport.

Bedload transport rates in streams vary spatially and temporally, even during constant flow conditions. Generally, bedload transport increases rapidly with increasing discharge. That is, as discharge increases, bedload transport rates increase at an exponentially greater rate than the flow (Gomez 1991).

Importance of Bedload and Suspended Sediment to Channel Maintenance. Bedload is important in the formation of channels. Gomez (1991) points out that a significant portion of river-deposited sedimentary rocks in the geologic column are composed of particles coarser than the maximum sand size transported in suspension in contemporary river systems. Further, he states:

'If river morphology is viewed as the result of interplay between hydraulic conditions and the resistance of materials in the channel perimeter, bedload transport provides the major process linkage between these factors, and virtually all aspects of morphologic change in a river, including bank erosion, are governed by bedload transport.'

Movement of the coarser or larger bedload has been found to be more important in the formation of channel geomorphic features than the finer fraction of the bedload (Leopold 1992). The coarser fraction of the material transported by the stream annually, although it makes up a smaller fraction of the total bedload, determines and comprises the major features of the channel's morphology.

Suspended sediment may be important in channel-forming processes where it is a dominant component of the sediment supplied to the stream. In high energy gravel-bed streams, suspended sediment likely plays less of a role in channel maintenance than bedload. The finer fraction of suspended sediment (silts and clays) can often be transported very long distances within a river system [Fisk (1947), as cited in Chorley et al. (1984)], and may be transported through a reach without significant deposition.

In light of the dominant role of bedload in channel formation and maintenance, the methodology for determining FCF water rights claims should be based on bedload transport rates over a range of flows for a particular stream and the properties of the bed-material sediments to determine the appropriate flows needed to maintain channels. By determining the quantity and size of bedload transported with increasing discharge, a FCF instream flow claim can be established that asks for the smallest amount of streamflow necessary to accomplish the objectives of channel maintenance.

Estimation of Bedload Transport. Physical bedload prediction models are widely used to estimate bedload transport rates where extensive bedload samples and long-term flow information may not exist. These physically-based models rely on the premise that a unique relation exists between hydraulic variables, sedimentological parameters, and the rate at which bedload is transported. They use information including channel dimensions and profile, the size distribution and characteristics of bed-material, stream hydraulics, and energy slope, and bed shear stress (Vanoni 1978; Parker and Klingeman 1982; Dawdy and Vanoni 1986). Bedload transport equations generally assume equilibrium between bedload inflow and outflow. When applying a bedload transport equation, more accurate predictions can be obtained when the model is calibrated against field data from the particular site where it is to be applied (Dawdy and Vanoni 1986).

Bedload transport in the Upper Klamath basin was estimated by the Forest Service using the model developed by Parker and Klingeman (1982). This bedload transport model utilizes bed shear stress to estimate transport. Bed shear stress is measured as the force of flowing water against the bed, and is calculated based on the specific weight, depth and energy slope of the water. The Parker-Klingeman (PK) bedload transport model can be calibrated to the individual hydraulic, morphologic, and bedload transport characteristics of streams.

The subpavement particle size distribution was used as the basis for bedload transport modeling, because over time, the bedload composition more closely resembles the subpavement particle size distribution. Calibration of the model using locally derived hydraulic and bed-material characteristics should greatly enhance the predictive power of a bedload transport formula (Dietrich and Smith 1984). A more detailed description of the application of the PK model is described in Bakke et al. (1999).

Streambed Characteristics: The Nature of Bed Sediments

Adequate characterization of bed-material is a fundamental part of establishing Favorable Conditions of Flow instream flow claims, using the approach taken in the Klamath River basin by the Forest Service. Bed-material distributions are used in the bedload sediment transport modeling process, to characterize channel roughness, and to determine initiation of transport of bedload. Bedload initiation information obtained from bed-material sampling is important in the development of water rights claims for channel maintenance.

Bed-material in alluvial, gravel-bed rivers is often observed to be poorly sorted and spatially heterogeneous, and can include a large variety of size classes. This spatial heterogeneity is often more pronounced in streams and rivers in mountain environments. Differences in material sizes on the bed of a stream can be caused by a variety of processes including mass wasting inputs, glacial lag deposits, logs or other debris, tributary inflow, and the migration of channel bedforms. The specific geomorphic and geologic context of a stream will influence the patterns of sediment delivered to the stream, and ultimately its bed-material size distribution.

Bed-material is characterized by a bed surface layer that is often more coarse than the underlying material, especially in heterogeneous sediments (Chin et al. 1994). Below dams or in other areas of diminished sediment supply, this layer has been called a static armor layer (Gessler 1967; Little and Mayer 1976; Bray and Church 1980) and is relatively immobile at ordinary discharges. Mobile armor, in contrast, exists where an upstream sediment supply is present (Andrews and Parker 1987), and is mobile under frequently occurring high flows (Leopold and Rosgen 1991).

The mobile armour layer may also be described as pavement (Parker et al. 1982; Parker and Klingeman 1982), and is approximately equal in thickness to the depth of the larger exposed particles (Andrews and Parker 1987; Andrews and Erman 1986). The layer of generally finer bed-material lying below the pavement layer is called the subpavement layer (Parker and Klingeman 1982), or the sub-armour layer. This layer may act a source of sediment to replenish the surface layer as it erodes (Parker and Sutherland 1990). An understanding of the various processes by which the bed of the stream and the pavement and subpavement layers change with increasing flow is important for the application of bedload transport equations used to predict amounts and size classes of bedload at various flows (Dawdy and Vanoni 1986).

The pavement layer of the stream (Figure 1) has been described as being inherently mobile and dynamic, and interchanges with the bedload. It forms readily on streambeds, and has been found to be present even during floods capable of moving all available grain sizes (Parker and Klingeman 1982). It has also been described by Parker and Klingeman (1982) as being a regulator that forms "just so as to render all available grain sizes of nearly equal mobility." The pavement layer acts to hide the smaller sized bed-material from the flow, and limit its entrainment into the bedload. In turn, larger particles exposed on the bed surface are more exposed to flow, and as a result are nearly as mobile as the finer material (Parker and Klingeman 1982; Andrews and Parker 1987).

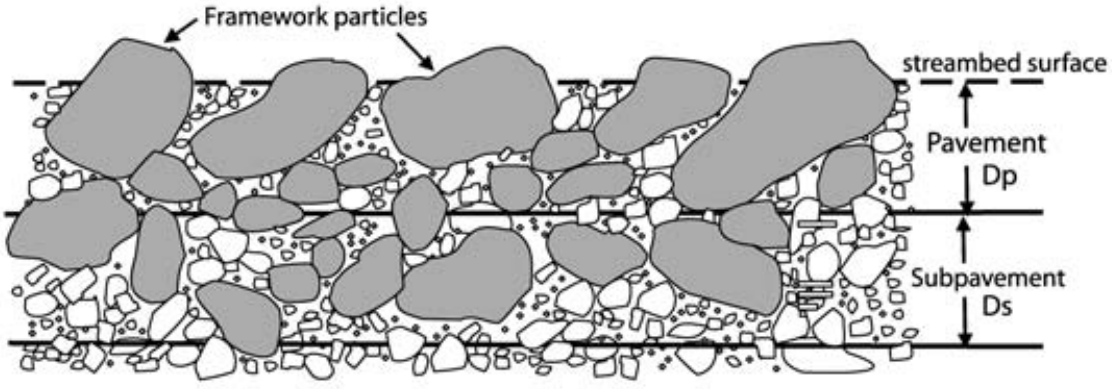
Gravel-bed, alluvial channels are composed of materials deposited by flowing water. In many alluvial rivers gravels deposited by the river consist of a framework of coarse particles or clasts, the voids of which are filled to some degree with finer sediments, which are termed the matrix materials (Miall 1996; Church et al. 1987; Carling and Reader 1982). Framework particles are usually in tangential contact with each other and form a stable, self-supporting structure (Pettijohn 1975). Deposits in which finer material such as sand and silt exceeds 30 percent of the total volume of sediment are called 'matrix supported' gravels. Large framework clasts in these deposits are not necessarily in contact with each other, and the spaces between large particles are filled with finer material.

Study Area, Channel Maintenance Sites and Data Collected

Physiogeographic Setting

The Upper Klamath River basin is located in south-central Oregon and northern California. It is bordered on the west by the summit of the Cascade Range, on the north by the Deschutes River basin, on the south by the Pitt River watershed, and on the east by the northwestern margin of the Great Basin. The geology is mostly volcanic, with minor accumulations of alluvium and other sedimentary strata. Precipitation varies from over 70 inches (178 cm) annually in the higher areas of the Cascades, to less than 20 inches (51 cm) annually in lower, more arid areas. The portion of the basin above Upper Klamath Lake is over 3000 mi^2 (7680 km^2) in area.

Figure 1. Alluvial gravel deposit, with pavement (Dp), and subpavement layer (Ds). Framework is shown by the darker particles. Matrix is composed of finer material between larger grains, and may consist of small gravel, sand, or finer material.



The Klamath River flows about three hundred miles (482 km) from its headwaters to the Pacific Ocean. Three major tributaries contribute to the flow of the Klamath River. These are the Sprague, the Sycan, and the Williamson, all of which arise in a mountainous region of south-central Oregon and drain into Upper Klamath Lake. The Klamath River itself begins where the river flows out of Upper Klamath Lake.

Sites and Data Collected

Thirty-one USDA Forest Service claim sites were included in the analysis of channel maintenance flows. These channel maintenance sites were located on alluvial channels within the boundaries of the Winema, Fremont, and Klamath National Forests, and were usually located near the national forest boundary. All flow and bedload information was collected at a claim site consisting of a specifically designated cross section, termed the channel maintenance cross section. Selection of the location of this cross-section followed guidelines outlined in Rantz (1982). Information on bedload transport, bed-material, stream discharge, and water surface slope data were collected at all claim sites.

More intensive bedload sampling and discharge measurements were done at ten fluvial process study claim sites (Table 1) to help further understand fluvial processes in the Upper Klamath River basin. These sites were selected because they were located in diverse geomorphic settings, which were thought to represent a variety of hydrologic and geomorphic conditions typically encountered in the Upper Klamath River basin. Information on sediment transport and discharge at these sites increased our understanding of fluvial process in the Upper Klamath River basin. The number of bedload samples at these locations varied from 5 to 26, however all but one fluvial site had more than 11 samples collected. Forest Service personnel collected all bedload samples with the single exception of the Sprague River at Chiloquin, Oregon site, where the US Geological Survey (USGS) collected the bed-material. Two of the streamflow gages were run by other agencies, and had substantially longer periods of record than the Forest Service gages, which ran for 5 to 7 years. All streamflow gages at these sites were recording gages.

Bedload transport samples were collected at 21 miscellaneous sites. Real time stream gages were operated at 10 of these sites. Discharge was measured approximately monthly during the spring, summer, and fall months at the remaining 11 ungaged sites. From two to four bedload samples were collected at each of these sites.

Methods

Discharge Measurements and Rating Curves. Discharge measurements were performed and discharge rating curves developed for each site using methods established by the Water Resources Division of the USGS, as outlined in Rantz (1982). Discharge records were adjusted to accommodate shifts in channel controls and bed elevations, and to accommodate ice blockage in the channels during the winter and spring months. Flow duration curves were generated from processed stream data. At sites with data recorders, pressure transducers were used to record hourly water stage. Transducers were housed in a stilling well located near the cross section used for discharge measurements.

Bed-material Sampling. Given the broad spectrum of particle size classes often encountered in gravel-bed rivers, it is difficult to design and implement a sampling program that adequately represents all or most of the material present. Changes in substrate size and condition can vary longitudinally, laterally, and over time. The volume and area of the bed that was sampled must represent the bed-materials well enough to be used in the bedload

Table 1. Fluvial Process Sites, number of bedload samples collected, and period of record for discharge records used for claims.

Fluvial Process Site	Bedload samples collected	Flow data period of record	Number of years of flow record
Annie Creek	20	1991-1999	9
Cherry Creek	26	1993-1999	7
Fivemile Creek	12	1993-1999	7
N. Fk. Sprague River Sandhill	13	1993-1999	7
Paradise Creek	12	1993-1999	7
S. Fk. Sprague River Brownsworth	13	1993-1999	7
Sprague River Chiloquin	5	1921-1999	59
Spencer Creek	21	1993-1999	7
Sycan River above marsh	16	1993-1999	7
Williamson River Sheep Creek	11	1978-1999	22

transport model and in the calculation of framework bed particles. Our objective was to determine bed-material characteristics in the vicinity of the cross-section used for bedload transport estimates and flow measurements.

A fundamental aspect of accounting for the spatial and temporal variability of bed-material samples is the selection of a sample site. Bed-material samples generally were taken a short distance upstream or downstream of the bedload sampling cross section within the same hydraulic control as the cross-section. If this was impractical, samples were taken in a location with thalweg bed-material characteristics similar to the channel maintenance cross section. For most sites several bed-material samples were collected.

Volumetric samples of bed-material were collected after the methods of Milhous et al. (1995) using a barrel sampler, consisting of an open-ended and shortened steel drum. For most streams a 55-gallon (208-L) barrel sampler was used (diameter 58 cm). However, for streams with bed-material consisting of cobbles, pebbles, and sand sized particles, a 10-gallon (37.8-L) barrel sampler was used (diameter 27 cm). Since most of our streams were relatively shallow, the barrel sampler was generally effective. However, there were concerns regarding the adequate capture of fine material while using the sampler. Polyethylene tarp skirting was used as a flow barrier around the base of the barrel while sampling to prevent currents from washing fine material out of the sample.

The pavement layer depth was defined by the vertically oriented embedded depth of the largest particle exposed within the area of the streambed contained within the barrel sampler. Embedded depth was equal to the distance in the vertical direction of the most deeply embedded exposed particle to the surface of the matrix material (Figure 2). After the pavement layer was removed, subpavement samples were taken to a depth equal to the embedded depth of the pavement layer.

It was common for unequal total volumes of pavement and subpavement to be collected at each site, due to the fact that the pavement depth was measured into the channel bed from the plane of embeddedness. Larger particles embedded in the pavement layer protrude past the plane of embeddedness a short distance, and this increases the volume of the sample collected by an amount equal to the volume of the pavement particles that extend beyond the plane of embeddedness. Thus, in order to compare pavement with subpavement in each size class, proportions by weight were determined for each particle size class.

Bedload Sampling. Bedload sampling must account for spatial and temporal variation in bedload transport rates in order to adequately characterize mean bedload transport rates across a channel cross section at a given flow. Samples were taken at all sites with a 3-inch (7.62-cm) Helley-Smith sampler (Helley and Smith 1971) using methods outlined in Emmett (1981), Klingeman and Emmett (1982), and Edwards and Glysson (1988). The Helley-Smith sampler is a pressure difference bedload sampler developed specifically for use in gravel bed rivers. The hydraulic efficiency of the Helley-Smith sampler is 1.54. This sampler gives adequate information on the amount and sizes of bedload in transport, however since the sampler has a 3 x 3 inch (7.62 x 7.62 cm) opening, there is an upper limit to the sizes of material that it will collect. Sampling at all sites was done at ten equally-spaced points across the channel maintenance cross section, and the sampler was in place for 1 minute at each sampling point. For most samples four passes were made across the stream, thus giving total sample time of 40 minutes. This sampling time was thought to adequately account for temporal variability in bedload transport. Sampling was occasionally done near the upper limits of applicability of a handheld Helley-Smith sampler because of deep water and high flows. At some sites because of high flows and high bedload transport rates, the sampling times were reduced to 15-30 seconds at each vertical point. Sample times were altered because adequate sample volume was collected by the sampler in the shorter amount of time. When at-a-point sample times were reduced, total sample times were reduced correspondingly, since only four passes were made across the stream. Thus total sample times for a single bedload sample ranged from 10 to 40 minutes.

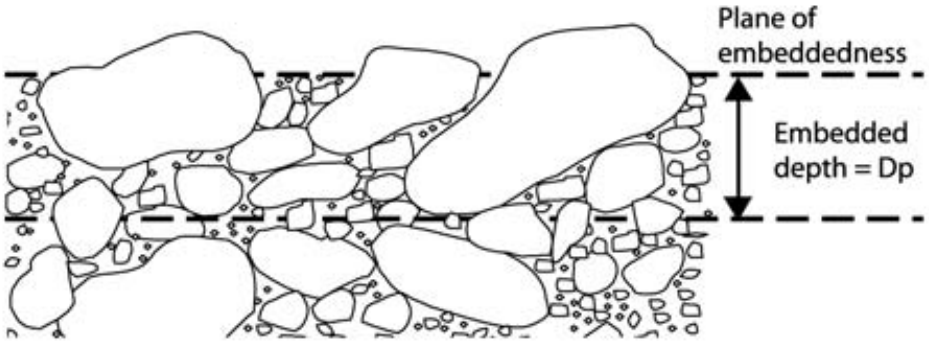


Figure 2. Pavement depth (Dp) is equivalent to the vertically oriented embedded depth of the largest exposed particle contained within the barrel sampler. Finer material between larger grains is matrix material.

Laboratory Analysis. Bed-material and bedload samples were dry sieved and weighed in the laboratory. Particles with a median diameter, or b-axis larger than 63 mm were weighed individually and their median diameter determined in the field. The sieve sizes used for bed-material analysis ranged from 0.063 to 64 mm. Sieve sizes used for bedload analysis ranged from 0.25 to 64 mm. Sizes below 0.25 were assumed to consist predominantly of particles transported in suspension.

Water Surface Slope and Cross-Sections. Longitudinal profiles of water surface slope and detailed surveys of the channel cross-sectional profile at the sampling cross section were needed to adequately characterize energy conditions and channel shape at the sampling location. To facilitate this, a permanent benchmark was established at each site, and this was used to determine relative water surface elevations up-and downstream of the sampling cross-section.

A tripod-mounted level was used to determine water surface elevation and bed surface longitudinal profiles and cross-sections at each bedload sampling site. Water surface slope is a good surrogate for energy slope, which is important for estimating the stream power available for bedload transport. Surveys were done adjacent to the streambank upstream and downstream of the bedload sampling cross-section. The elevation of the water surface was determined at closely spaced intervals. Interval length was dependent on the size of the stream and the complexity of the channel. Generally, elevation intervals were more closely spaced for smaller, higher gradient streams, and wider for larger, less steep streams and rivers. Longitudinal profiles were used to determine water surface slope in the immediate vicinity of the sampling cross-section, usually from the upstream to downstream channel controls. A linear regression was applied to the slope survey points, and the median surveyed slope was selected as the representative slope. Several detailed surveys were done of each channel maintenance cross section. Survey points were spaced at relatively close intervals. Particular attention was paid to documenting breaks in slope or high and low points in the channel cross section.

Determining the Claim Initiation Discharge

The Forest Service claims were initiated when the framework component of the bed-material particle sizes began to be mobilized, as determined by the Parker and Klingeman (1982) bedload transport model. The process for determination of each FCF claim involves several steps:

1. Develop site stage/discharge rating curve and hydrograph
2. Determine stream bed-material and channel characteristics
3. Model and predict bedload transport over a range of flows
4. Develop framework bed-material size distribution
5. Determine lower and upper limits of flow

This procedure was used at all FCF claim sites. The following is an example of the process and data used for determining the minimum flow needed to begin mobilizing the framework material for a fluvial process site.

Develop Site Stage/Discharge Rating Curve and Hydrograph

The South Fork of the Sprague River fluvial process site is located at the outlet of a 62.1 square miles (161 km^2) mostly forested watershed at an elevation of 4540 ft (1384 m), just upstream of the confluence with Brownsworth Creek. The geology is almost exclusively volcanic, with minor accumulations of alluvium near streams. Normal precipitation in the watershed ranges from about 40 inches (~102 cm) per year at the highest elevations to about 20 inches (~51 cm) per year near the gage (Oregon Climate Service 1992).

The South Fork of the Sprague River gage has operated from water year 1993 to the present. Discharge records from 1993-1998 were used for developing the FCF claims. A data logger instrumented with a pressure transducer was used to record stage, and observations of stage were made at 30-minute intervals. A stage vs. discharge rating curve was developed (Rantz 1982), and this was used to generate a mean daily hydrograph for the period of record. The hydrograph was inspected for periods of ice blockage of the channel, and mean daily hydrographs from nearby ice-free gages from the same period were used to adjust the hydrograph. Flow records were used to generate a flow duration curve (Dunne and Leopold 1978) representing the water years 1993-98.

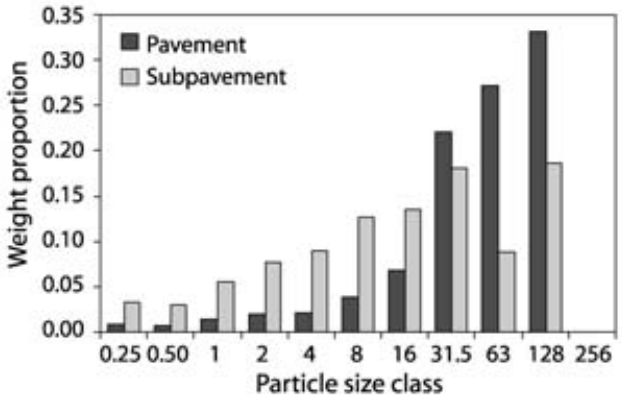
Determine Stream Bed-material and Channel Characteristics

Bed-material data were used to generate size distributions for both the pavement and subpavement layers. Cumulative distributions were used to generate median particle diameters (D_{50}) and the 84th percentile (D_{84}) for the bed-material (Figure 3).

Weight proportions of bed-material in each particle size class were then determined. Usually several samples

of both pavement and subpavement were collected. To calculate the proportions of material in each particle size class, weights of different samples in each size class were added and the proportions calculated from the weight totals in each size class.

Figure 3. Bed-material distribution of pavement and subpavement, S. Fork Sprague River.



Model and Predict Bedload Transport over a Range of Flows

The Parker-Klingeman (PK) model uses bed shear stress to estimate bedload transport. A more detailed description of the application of the PK model is described in Bakke et al. (1999). The procedure consists of calibrating two empirical constants (an exponent and a reference Shield's stress) using site-specific information, including two or more bedload measurements, bed-material and channel cross-section characteristics, and water surface slope. The PK equation can be calibrated for a wide set of conditions. A program called SEDCOMP (Dawdy 1997) was used to optimize the bedload transport equation, and calibrate it to site specific information on bedload transport at each claim site. A separate program FLOWDUR (Dawdy 1997) uses the calibrated parameters and optimized PK equation developed in SEDCOMP combined with an estimated flow duration curve and bedload rating curves to compute thresholds for bedload transport of different size classes of material.

Develop Framework Bed-material Size Distribution

Mobilization of particle size classes consisting of framework particles is essential for maintaining channel morphology. These particle size classes represent the size fractions which, when mobilized, maintain channel form over time. These materials consist of gravel-sized particles, and make up the major morphological features of the streambed (Leopold 1992). The bed-material framework particles for this study were determined through analysis of bed-material samples that were collected at each bedload sampling location.

As was mentioned earlier in this paper, the pavement layer of the stream-bed is generally coarser than the underlying subpavement layer. The first step in identifying the framework particles is to calculate the weight proportions in each particle size within the pavement and subpavement layers. The framework gravels are determined by subtracting the weight proportion in each size class of subpavement from the respective proportion in each size class in the pavement. This procedure determines the bed-material size classes of the pavement layer that generally have a higher proportion by weight than the material found within those size classes in the subpavement layer. These materials are the framework gravels.

Table 2 provides an example of the calculations used to determine this distribution. The weight proportions of subpavement are subtracted from the corresponding proportions of pavement. Weight proportions were used

Figure 4. Application of the Parker-Klingeman bedload transport model.

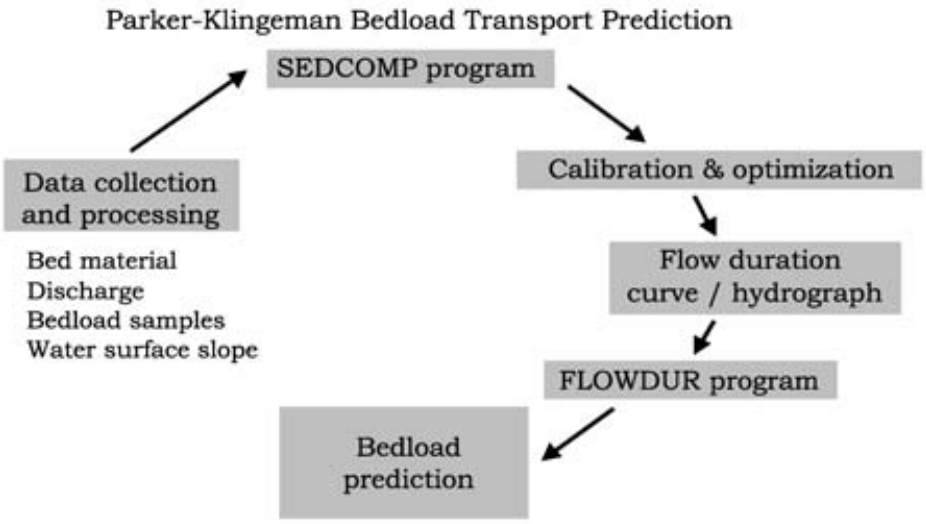


Table 2. Weight proportions of bed material and determining the framework particle size distribution, S. Fork Sprague River. Proportions of subpavement are subtracted from the pavement to obtain the framework distribution. In this example the framework is from 32 to 126 mm.

	Particle Size (greater than, mm)										
Layer	0.25	0.50	1	2	4	8	16	31.5	63	126	253
Pavement	0.008	0.008	0.014	0.019	0.022	0.038	0.068	0.220	0.271	0.331	0
Subpavement	0.032	0.029	0.055	0.077	0.089	0.127	0.136	0.180	0.088	0.187	0
Framework (pavement - subpavement)	< 0	< 0	< 0	< 0	< 0	< 0	< 0	0.040	0.184	0.144	0

because unequal volumes of material were collected in each layer of bed-material. The volume is different between the layers because the pavement depth is determined by the embedded depth of the largest exposed particle. The framework size distribution was determined for the South Fork Sprague River, and is combined with the pavement and subpavement distributions in Figure 5.

The calculated framework distribution for this example ranges from 31.5 to 126 mm in size. The lower limit of the FCF claim begins when the framework distribution of the bed material begins to be mobilized.

Determine Lower and Upper Limits of Flow

Bedload transport model results can be used to determine the lowest discharge at which a particular particle size class shows appreciable movement. The bedload transport quantities and sizes per unit discharge are quantified by discharge increment, and the relative amount of transport for each particle size class is determined.

Moving framework particles is essential for channel maintenance. The instream flow claim initiates at the flow where 2% of the total bedload by weight is composed of framework particles. This percentage was selected based on comparative observational analysis of bedload transport rates at all claim sites. On average at all the claim sites, these claim initiation flows, based on the mobilization of framework particles, corresponded to about 60% of bankfull flow.

The 25-year flood event calculated using regional flood frequency estimates (Harris et al. 1982) was selected as the upper limit for the claim, because it represented a reasonable upper limit for the channel maintenance claims. These estimates were customized to conditions in the Klamath River basin by EA Engineering (unpublished report 1987).

Final Claim Structure

South Fork Sprague River Example

An example of the application of a Favorable Condition of Flow water rights claim for the period 1993-98 is shown in Figure 6. The claim is shown by the shaded region of a mean daily hydrograph for this location. At South Fork Sprague River the instream flow initiates at the claim initiation water flow (140 cfs [3.96 cubic meters per second {cms}]), and is capped at the 25-year event at 926 cfs (26.2 cms). For most years, water is claimed predominantly during higher flows during the late winter and spring months. Water year 1994 was the driest year

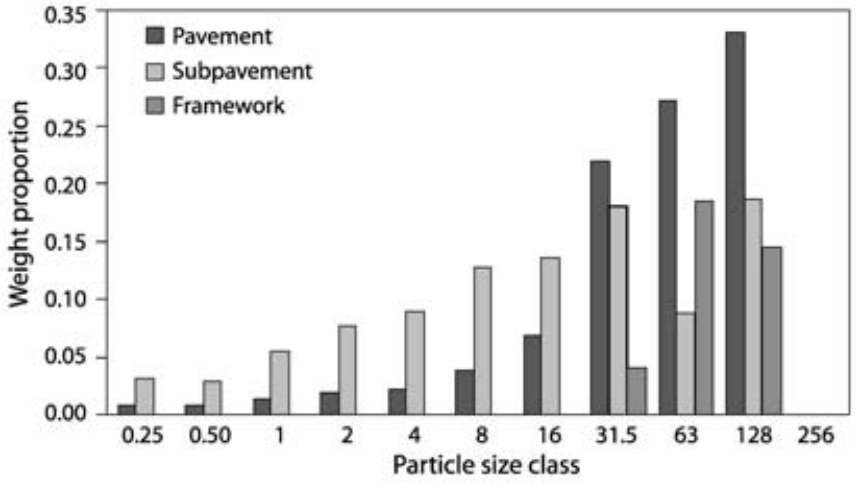


Figure 5. Framework distribution with pavement and subpavement, South Fork Sprague River.

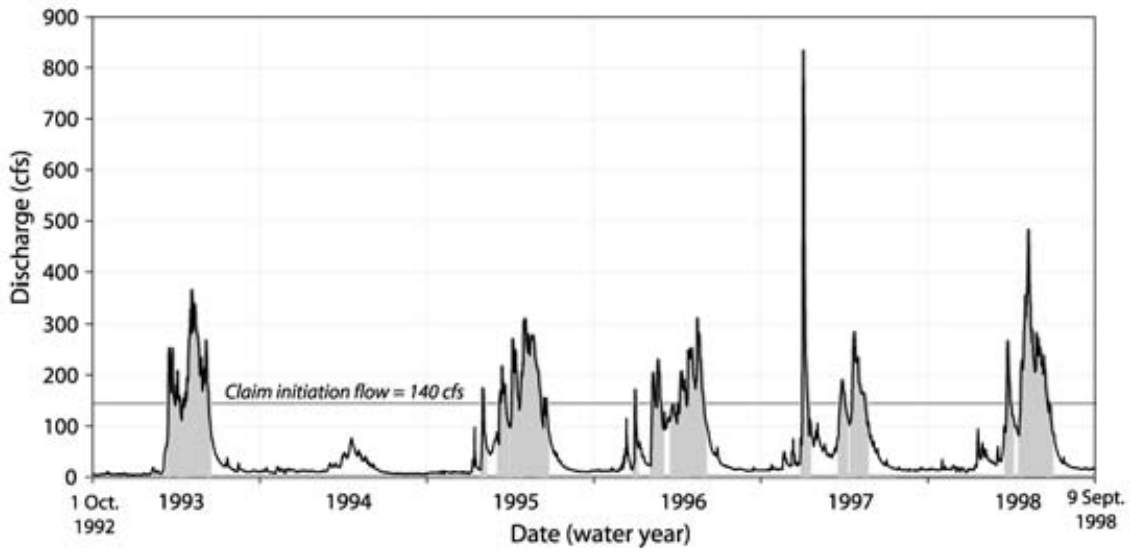


Figure 6. Mean daily hydrographs from South Fork Sprague River for water years 1993-1998. Favorable conditions of flow claims are the shaded areas of the hydrograph.

since this site has been gaged, and streamflow remained below the claim initiation flow for the entire water year.

Discussion

An examination of the hydrographs in Figure 6 reveals that the FCF instream flow claims consist of a series of peak flows with the bulk of the discharge occurring during spring snowmelt runoff. The runoff increases in December and January of 1995 and 1996 are probably early season rain-on-snow peak flows. April through July runoff in water years 1993-1996 for an Upper Klamath River basin gage as percent of average is summarized in Table 3. These data were compiled for the USGS-operated gage on the Sprague River at Chiloquin. The driest year on record was 1994, with runoff predicted at 32% of average. In contrast, 1993 was a very wet year, with runoff predicted at 129% of average. In 1995-96, runoff was at near normal levels. To the extent that the estimate of streamflow at the USGS gage represents conditions at the South Fork Sprague gage, the hydrographs for the years 1995 and 1996 probably are typical of the percent of water claimed during near average projected runoff years. However, the timing of spring runoff and the resulting claim may vary from year to year, despite any similarities in runoff volume.

Inspection of the hydrographs (Figure 6) also reveals that most of the water volume claimed for FCF in-stream claims occurs during the spring months when potential and existing agricultural irrigation withdrawals are at a minimum. During the period July through September, no water would have been claimed for FCF claims. Exercise of FCF in 1993 and 1994 would have ended in mid-June, and in May of the 1996 water year. It is also important to note that this claim site is located on Forest Service managed public lands in an area where no agricultural activities exist or are likely to occur. However, diversions from the South Fork of the Sprague occur several miles below this location in the upper Sprague River valley.

Table 3. Percent of average runoff, Klamath River basin, Sprague River at Chiloquin gage.

Year	Percent of Average Runoff
1993	129
1994	32
1995	90
1996	99

Summary and Conclusions

Favorable Conditions of Flow (FCF) in-stream flow claims were developed using extensive knowledge of site hydrology, geomorphology, the sizes and character of streambed-materials, combined with information about the transport of bedload by the stream. They are based on the premise that a certain quantity of streamflow is necessary to transport inputs of sediment to the channel and thereby maintain the channel's form and its ability to convey streamflow and sediment. The claims were developed in five steps. These were:

1. Develop site rating curve and hydrograph
2. Determine stream bed-material and channel characteristics

3. Model and predict bedload transport over a range of flows
4. Develop framework bed-material size distribution
5. Determine lower and upper limits of flow

The FCF instream claims are initiated during relatively high flow events. The lower limit of these claims is determined by the characteristics of the material composing the streambed and the results of bedload sediment modeling. Instream flows are capped by the 25-year flood. The frequency and duration of these higher streamflows are important for controlling channel form and dimensions. The resulting instream flow encompasses the range of discharges that are most effective at conveying bedload sediment and thereby maintaining channel capacity. In light of the dominant role of bedload in channel formation and maintenance, this method uses bedload transport rates over the range of flows observed at a particular stream and the properties of the bed-material sediments to determine appropriate FCF streamflows needed to maintain channels. Further, because bedload transport rates increase rapidly with increasing discharge, and because higher discharges occur relatively infrequently, a high percentage of the bedload can be moved by a relatively small volume of streamflow-the minimum amount of flow necessary to maintain the channel.

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Keeping Our Streams Flowing: Tonto National Forest Groundwater Policy

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Rapid population growth in central Arizona has increased the demand for water supplies. As surface water sources are fully appropriated, current development efforts are focused on groundwater. The Tonto National Forest has been the recipient of an increasing number of requests to develop groundwater resources from a variety of entities including communities and subdivisions, copper mines, Native American tribes and state agencies. Because groundwater pumping could have an impact on national forest resources, the Tonto National Forest has required development proponents to conduct aquifer tests prior to authorizing long-term pumping. Several of these tests indicated that groundwater removal would have a significant impact on stream flows and associated water-dependent resources. As a result, the forest developed a groundwater policy aimed primarily at protecting National Forest resources. The policy identifies the objectives for managing groundwater and specifies the steps that groundwater development proponents must follow before use of groundwater will be authorized. This paper describes the current groundwater situation relative to the Tonto National Forest. It also illustrates, through a series of case studies, the interdependence between ground and surface water and the dramatic impacts that groundwater withdrawals can have on surface waters. Finally, the primary elements of the forest groundwater policy are discussed. This policy provides managers with an additional tool to protect valuable streams, springs and riparian areas on the forest.

Keywords: *groundwater, water policy, stream flow, riparian, water dependent resources, surface/groundwater interaction*

Existing Groundwater Situation

Demand for development of forest groundwater resources is increasing. Most of this demand involves the development of water for transport and use off-forest. The increase in requests to use groundwater can be attributed primarily to:

Rapid Population Growth. The population of central Arizona is growing very rapidly. This increase in growth translates into a growing demand for water resources.

Fully Appropriated Surface Water Resources. Most surface waters are fully appropriated by existing users. As a result, groundwater is often the only source of water available for future needs.

Arizona Water Law. Arizona water law is somewhat unique in that there are few regulations governing groundwater resources (outside of several specially designated areas including Phoenix and Tucson). In most areas of the state, the right to develop groundwater rests with the overlying landowner and no water right is required. Thus, all that is required to obtain National Forest groundwater resources is a Special-Use Authorization for well drilling and water conveyance.

Cost. The Forest Service charges nothing for the water it provides, only for the land use authorization.

Case Studies

The Tonto National Forest's groundwater policy evolved from our experiences with proposed groundwater development projects. Three of these projects include: The proposed Carlota Copper Mine, a medium sized copper mine partially located on the forest; the Sunflower Well, a well on private land that was proposed to provide water for widening and relocating a highway located on the forest; and the Chaparral Pines pipeline, a water supply pipeline that conveys water from a wellfield on private land across the forest to a subdivision near Payson, Arizona, also on private land (Figure 1). The discussion that follows provides brief descriptions of each of these projects.

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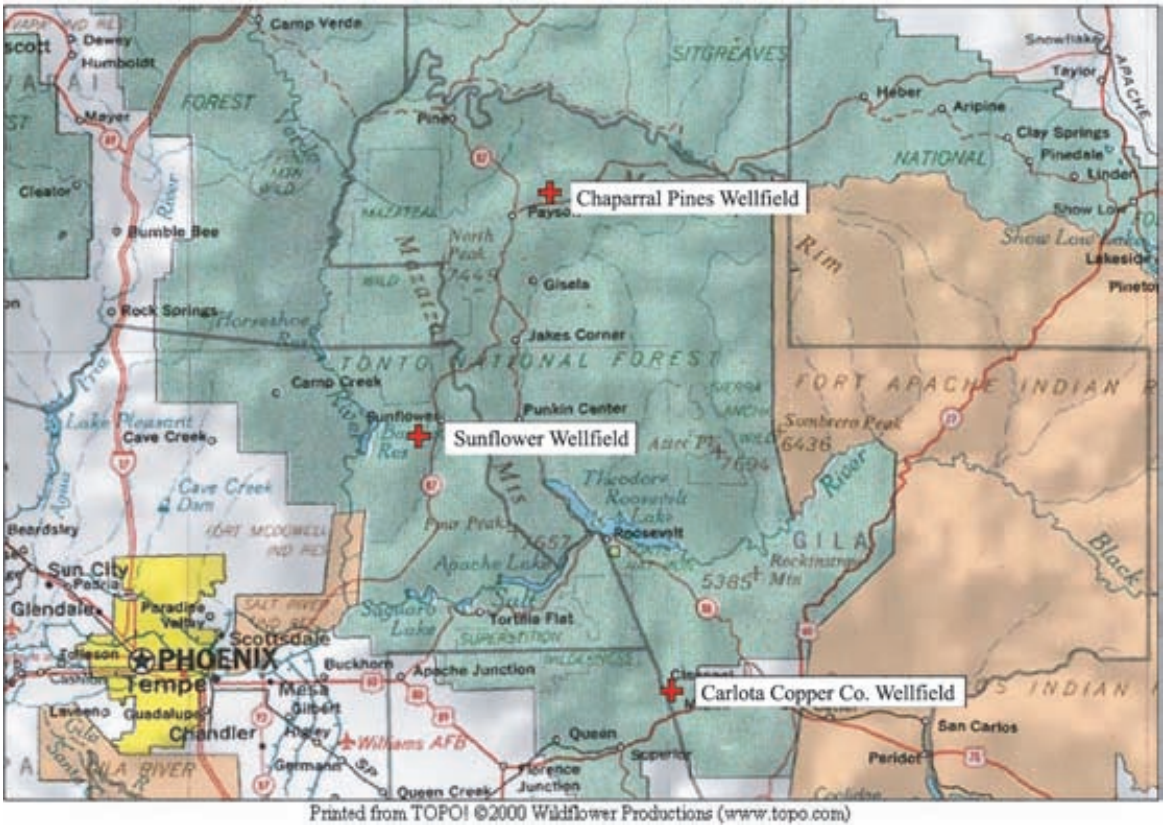
Figure 1. Groundwater development project locations.



Carlota Copper Company Wellfield

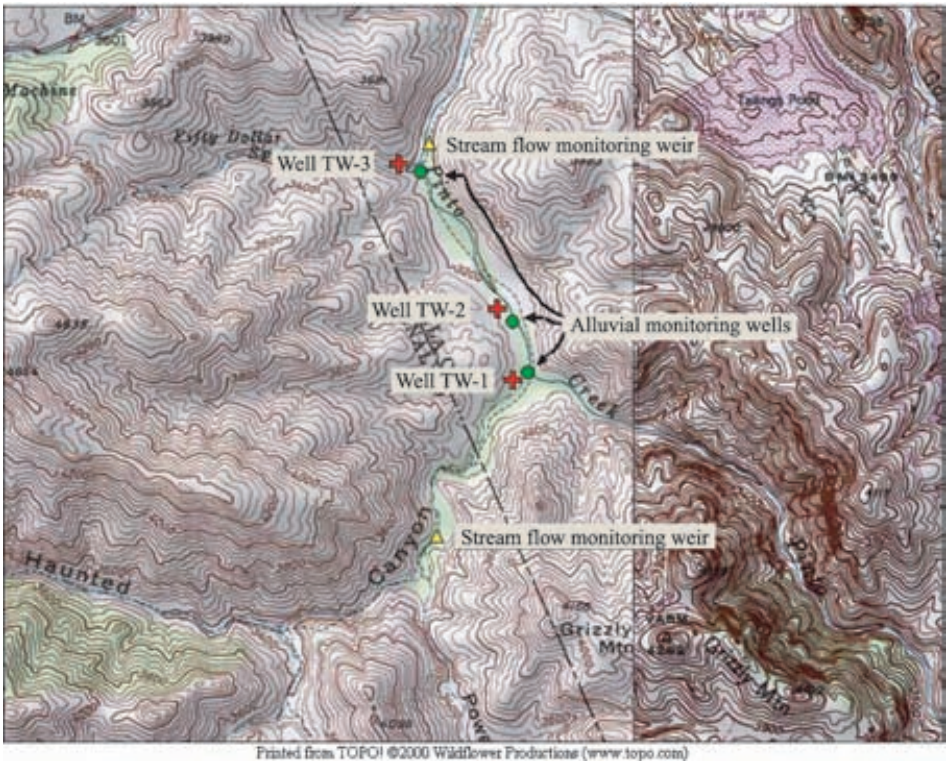
The proposed Carlota Copper Mine is located six miles (9.6 km) west of Miami, Arizona, at an elevation of approximately 3,700 feet (1128 m) in a rugged mountainous semiarid region. Vegetation is composed predominately of chaparral, desert brush and juniper-grassland. The Carlota Copper Company proposes to mine 100 million tons (90.7 million metric tons) of ore from open pits over a twenty-year period to produce 900 million pounds (409 million kg) of copper. The ore would be leached with a sulfuric acid solution in a heap leach process. Water requirements for the mine average 590 gallons per minute (gpm) [1,926 liters per minute (Lpm)] with peak water requirements of 850 gpm [3,217 Lpm] during dry months.

The mine is located in the Pinto Creek watershed, which drains into Roosevelt Lake, a major water supply reservoir for the Phoenix metropolitan area. Pinto Creek, which becomes perennial below the project area, is a valuable resource on the forest, and is a rare perennial stream in the Sonoran desert (Figure 2). Pinto Creek has been designated as an Aquatic Resource of National Importance (ARNI) by the EPA, has been studied for eligibility for inclusion in the nation's Wild and Scenic River System, has been nominated for unique waters status, has been named as one of the ten most endangered rivers in the nation by the American Rivers environmental group, and has been called a "jewel in the desert" by Barry Goldwater. To protect the stream, the forest applied for and received an instream flow water right from the state that seeks to maintain median monthly flows along a nine mile reach of the stream located approximately four miles below the Carlota project area. These flows range from 1 to 2.7 cubic feet per second (cfs) [0.03 to 0.08 cubic meters per second (cms)].

The mining company conducted an extensive search for water that included: acquisition of Central Arizona Project

Figure 2. Pinto Creek.

Figure 3. Carlota Wellfield.



water from Roosevelt Lake, five surface water reservoir sites on Pinto Creek and Powers Gulch, water purchased from nearby municipalities or other commercial sources, low quality water from adjacent mining operations, and groundwater from a variety of locations. For various reasons, many of these water supply sources could not meet mine requirements, and the source ultimately selected included groundwater from a wellfield located approximately two miles (3.2 km) downstream of the main project area near the confluence of Pinto Creek and Haunted Canyon (Figure 3).

Three test wells were drilled at this site from June to September 1993, ranging in depth from 755 feet to 1220 feet (230 m to 372 m) below ground surface. All three wells experienced artesian flows with artesian discharge from the middle well (TW-2) flowing at 250 gpm (946 Lpm). Test pumping of these wells was conducted to evaluate the long-term yield potential of the aquifer, and the impact of pumping on surface water resources and on alluvial groundwater elevations. Well TW-2 was pumped for 25 days at a rate of 600 gpm (2,271 Lpm). A monitoring network was installed to detect potential impacts. The network included three shallow alluvial monitoring wells, four bedrock complex monitoring wells, weirs at two springs, and a weir or Parshall flume at two locations in Haunted Canyon and Pinto Creek.

During the 25-day pump test of TW-2, stream flow at a weir in Haunted Canyon (located approximately 2,300 feet [701 m] south of the TW-2 well) declined from approximately 45 gpm at the start of the test to 5 gpm at the end of the test (170 to 19 Lpm). Flow increased progressively to approximately 27 gpm (102 Lpm) within a few days of shutting off the pump. The water level in an alluvial monitoring well in Haunted Canyon located approximately 1,550 feet (472 m) south of TW-2, declined approximately one foot during the 25-day test and recovered slowly following the test (Figure 4).

Based on these test results, the forest sent a letter to the Arizona Department of Water Resources (ADWR) requesting an appropriability determination. In Arizona, water pumped from a well is considered to be appropriable if withdrawing that water tends to directly and appreciably reduce flow in a surface water source. ADWR reviewed the aquifer test results and concluded that the well was withdrawing appropriable water and would need a water right if it was to be used. The Carlota Copper Company subsequently submitted a water right application. The forest protested the application based on its instream flow water right downstream on Pinto Creek. The forest negotiated a wellfield mitigation program with the mine that seeks to maintain median monthly flows in Haunted Canyon and Pinto Creek in exchange for the forest's withdrawal of its protest.

Sunflower Well

The second groundwater withdrawal project influencing the development of the forest's groundwater policy was

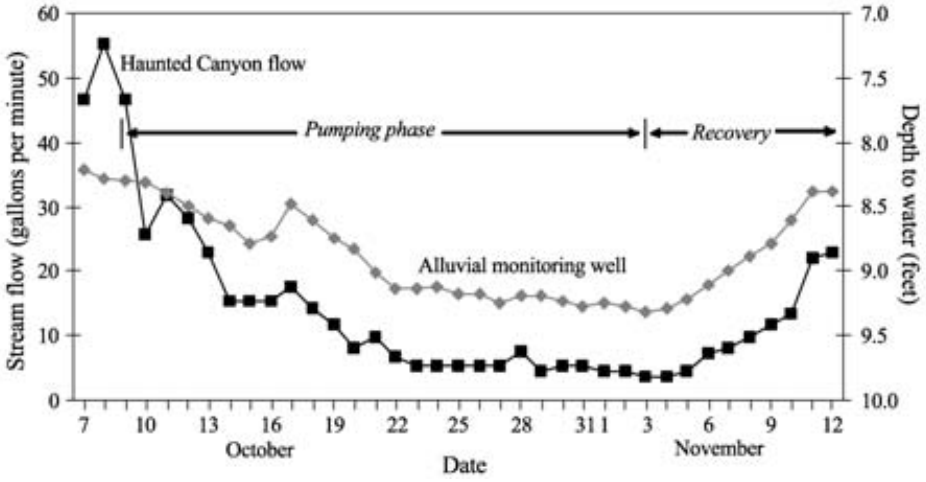


Figure 4. Carlota Project pump test results.

the Sunflower Well. This well was proposed as a water supply source for upgrading a portion of Arizona State Highway 87 that carries heavy traffic from the Phoenix metropolitan area to summer recreation areas in the high country along the Mogollon Rim in north-central Arizona. Water requirements for highway construction were estimated to be about 200 gpm (757 L per minute) for compaction of fills and for dust control.

The Sunflower Well is located on private land near Sycamore Creek, which has reaches of both intermittent and perennial flow near the well. Sycamore Creek, like Pinto Creek, is a stream with reaches of perennial flow in the Sonoran Desert. It supports valuable riparian vegetation, provides habitat for native fish, and is a popular recreation area.

The Record of Decision (ROD) for the Environmental Impact Statement (EIS) prepared for the highway upgrading project stated that construction water would not be withdrawn from Sycamore Creek. To evaluate the effects of the well on Sycamore Creek, an aquifer test with observation wells and a streamflow monitoring flume was conducted.

The proposed production well was completed to a depth of 240 feet (73 m) in fractured basalt. Water rose under artesian pressure to a depth of approximately 20 feet (6.1 m) below ground surface. The monitoring network consisted of four shallow observation wells in the alluvium bordering the creek, two deep observation wells in the bedrock basalt aquifer and a Parshall flume in a perennial reach of Sycamore Creek just downstream of the well (Figure 5). The aquifer test was originally scheduled for three days with the production well pumping at an average rate of 250 gpm (946 Lpm).

Water levels in the shallow monitoring wells declined before, during and after the test. Water levels declined at a slightly greater rate during the test. The majority of the decline was believed to be attributable to natural conditions. The impact of pumping on stream flow through the flume was dramatically different than the impact to the shallow observation wells. Prior to beginning the test the flow rate through the flume was about 90 gpm (90 Lpm). About six minutes after the pump in the production well was turned on, flow through the flume started to decline. Approximately six hours into the test, flow in Sycamore Creek declined to zero. One hour and 20 minutes after the pump was turned off, Sycamore Creek started flowing through the flume again. Two hours after the pump was turned off, flow through the flume was 37 gpm (140 Lpm), and 10 hours after turning the pump off, flow through the flume was 61 gpm (230 Lpm) (Figure 6).

Based on the results of this test the contractor was not allowed to use the well for the highway upgrade project.

Mayfield Canyon Wellfield

The purpose of this project was to provide water for a subdivision and golf course near the community of Payson, Arizona. The wellfield was located on a parcel of private land, known as Calhoun Ranch, that is entirely surrounded by National Forest System lands. The proponents intended to construct a pipeline that would transport water from the wellfield across the forest and back onto private lands where the subdivision and golf course were located. Mayfield Canyon flows through the private lands where the wellfield is located, enters the forest for approximately one-half mile, then flows back onto private lands in the community of Star Valley (Figure 7). The stream becomes perennial on the Calhoun Ranch private lands due to groundwater discharge that seeps into the bed and banks of the channel and from a significant spring (estimated to discharge at approximately 30-40 gpm [113-151 Lpm]). Perennial flow continues downstream of the private land onto the forest for approximately 200 yards (183 m) until it seeps into

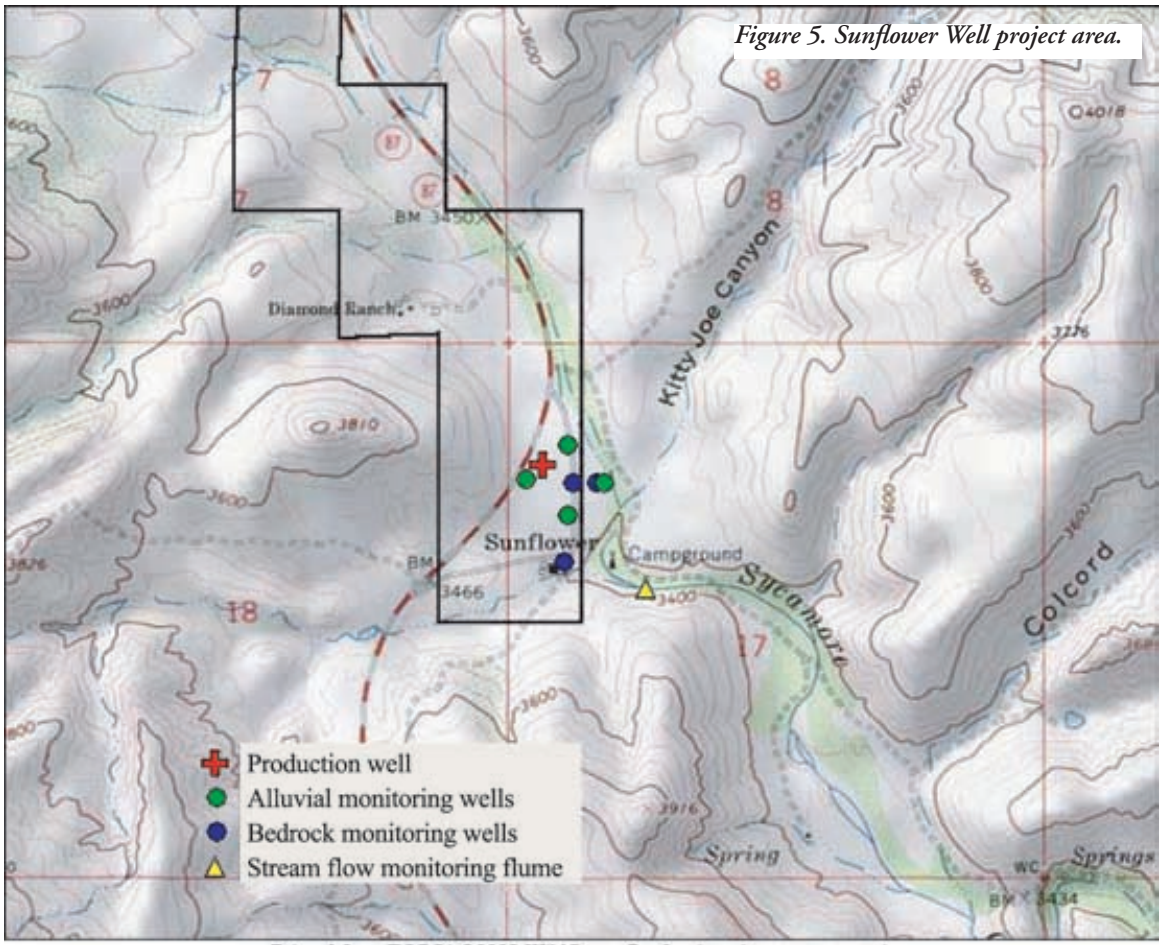


Figure 5. Sunflower Well project area.

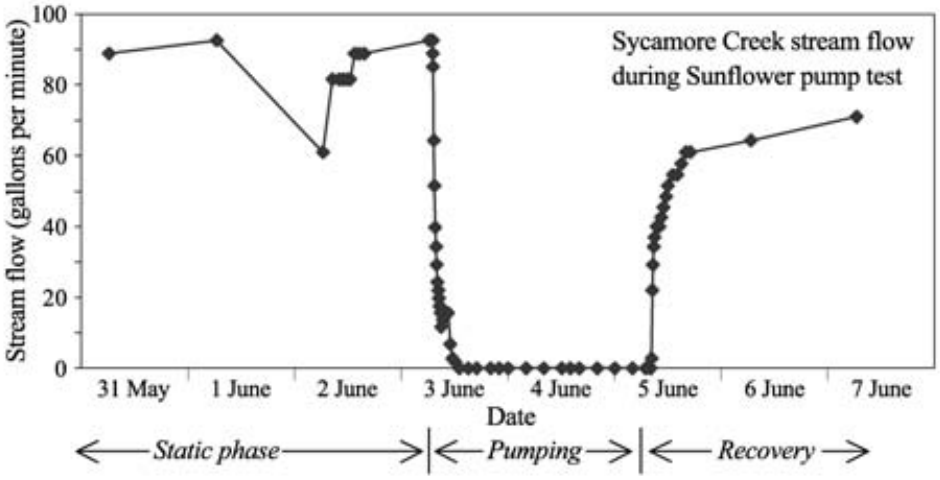


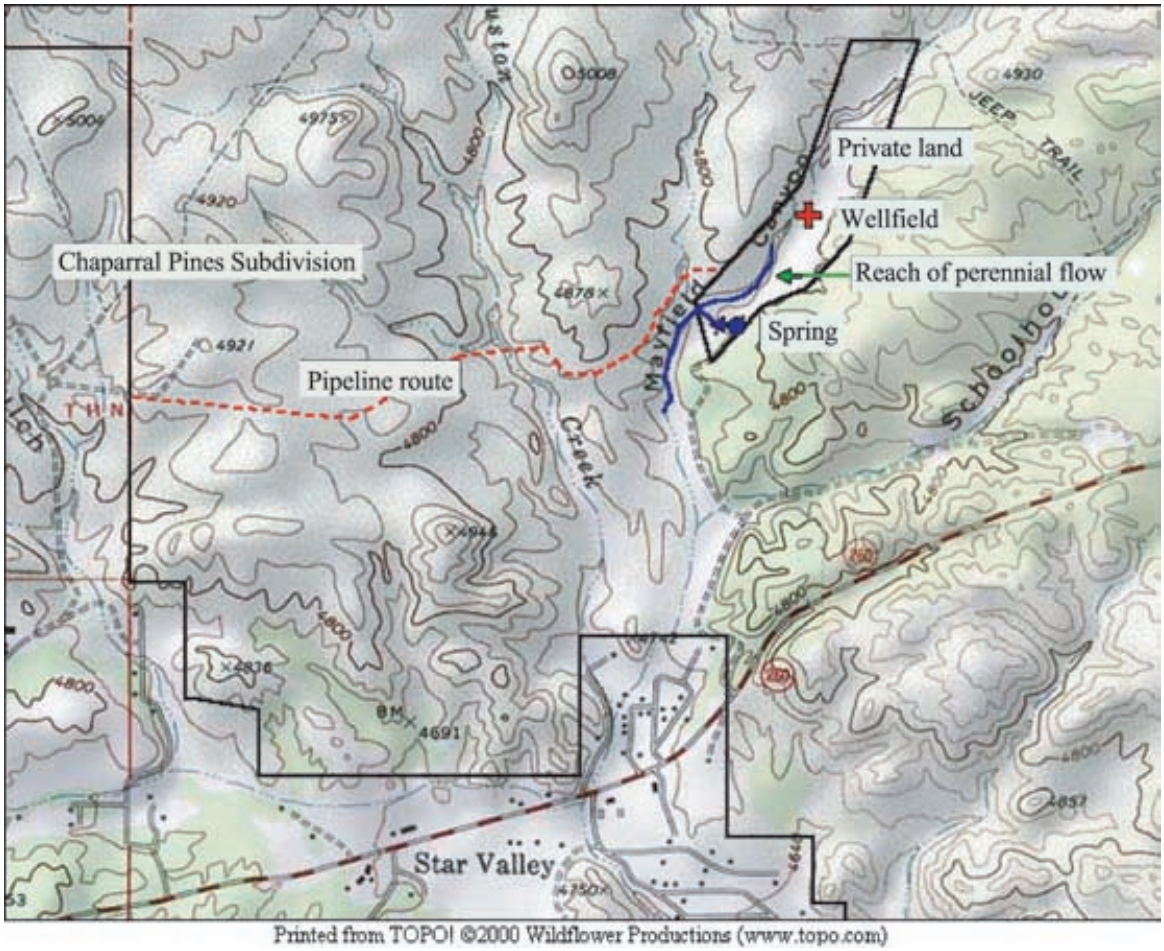
Figure 6. Sunflower pump test, Sycamore Creek streamflow.

the sands and gravels of the stream bottom alluvium. The reach of perennial flow on the forest supports a lush riparian zone of cottonwood and willow trees. Peak water requirements for the golf course and subdivision were estimated at approximately 360 gpm (1,362 Lpm). The residents of Star Valley who are dependent on wells for the majority of their water needs were concerned that development of the wellfield on Mayfield Canyon (which is up gradient of Star Valley) would reduce groundwater availability to their wells.

The subdivision developer needed a Special-Use Permit from the forest for the pipeline from Calhoun Ranch to the subdivision at Chaparral Pines. The forest, as part of its compliance with the National Environmental Policy Act (NEPA) evaluated the actions connected with the project proposal. In this instance, it meant looking at the impacts of pumping the groundwater as well as the impacts of the pipeline itself.

Eight wells were drilled at the Calhoun Ranch site ranging in depth from 200 to 500 feet (61 to 152 m)

Figure 7. Chaparral Pines Wellfield and Pipeline.



and completed in fractured granite. Prior to submitting an application for a Special-Use Permit, the developer completed a number of aquifer tests including a 33-day test on the most productive well, which was pumped at a constant rate of 300 gpm (1,135 Lpm) during the test. Drawdown in five observation wells ranged from 20 to 30 feet (6.1 to 9.2 m) during the test. Streamflow in Mayfield Canyon was not monitored during this test. The developer's consultant concluded that impacts on surface water flows from operation of the wellfield would be negligible because flow in Mayfield Canyon is intermittent and the result of precipitation events.

Once the developer submitted a Special-Use Permit application, the forest requested a second 30-day aquifer test with flow measurements in Mayfield Canyon to directly assess impacts to stream flows. The developer refused, stating that a long-term aquifer test had already been completed and that the consultants who conducted the test had reached their conclusions about groundwater-surface water impacts. As an alternative, the forest asked the developer to conduct a water budget analysis that would assess the impacts of groundwater withdrawals on inputs and outputs of water resources in the watershed. The developer agreed to this request and subsequently concluded that groundwater pumping would not reduce the surface runoff component of the water budget, but could affect baseflow in the reach of Mayfield Canyon above the cone of influence of the groundwater wells. A Special-Use Permit was subsequently issued and the photos in Figure 8 display the impacts of wellfield operation on the reach of Mayfield Canyon within the national forest.

Groundwater Pumping Concerns

Effect On National Forest Resources

Groundwater and surface water form an interconnected hydrologic system. Recharge to groundwater supplies originates from precipitation and surface waters. Conversely, groundwater discharge is the reason that perennial streams, springs and seeps flow throughout the year. Groundwater pumping from wells can result in lower water tables and reduced stream flows. Because surface water and shallow groundwater sustain riparian and aquatic ecosystems, groundwater removal can have negative impacts on these resources.

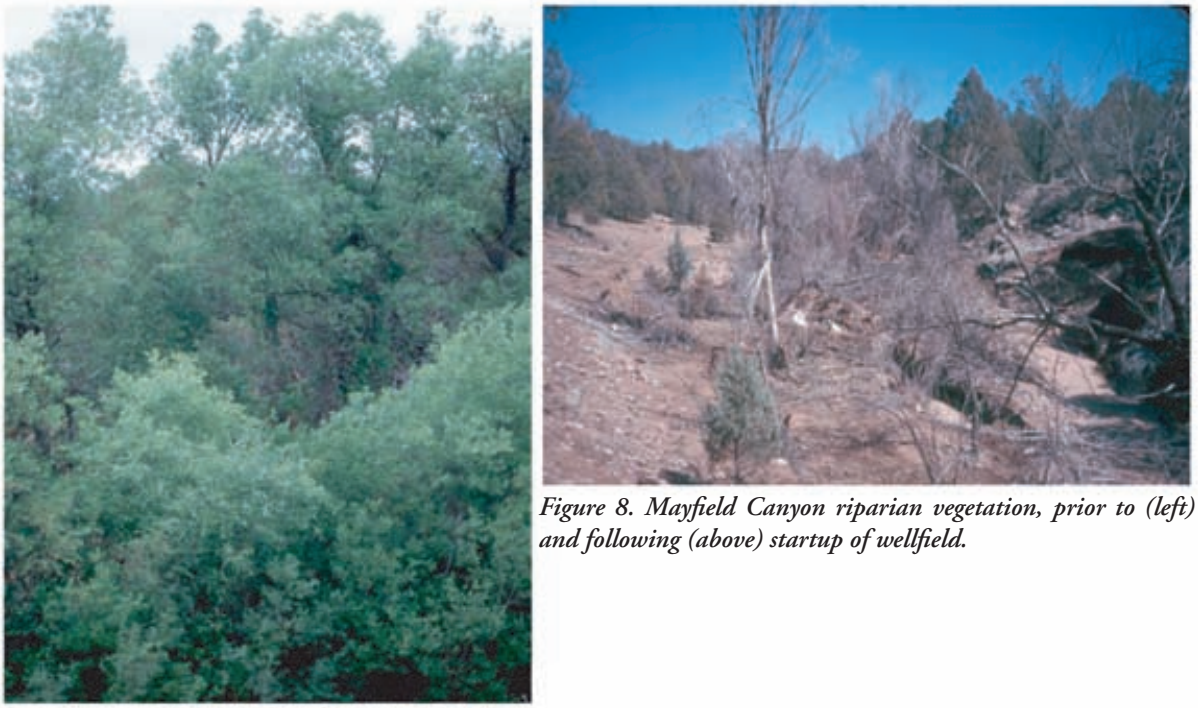


Figure 8. Mayfield Canyon riparian vegetation, prior to (left) and following (above) startup of wellfield.

Effect on Adjacent Water Supplies

Many public and private entities within and adjacent to the forest currently rely on groundwater for a variety of purposes. Authorization of additional wells and removal of groundwater from the forest can lower water levels and affect these existing groundwater users.

Limited NEPA Analysis

Historically, NEPA analyses of proposals to develop forest groundwater resources have focused on the impacts of drilling and the construction of infrastructure such as wells, pumping facilities, roads and power lines. Little attention has been paid to the potential impact on forest water resources, associated riparian areas, and adjacent water supplies. Continuation of our historic methods for evaluating impacts could result in the authorization of new water developments that adversely affect important forest resources and activities. The potentially serious degree of resource damage also implies that the forest should evaluate any new requests for groundwater carefully prior to authorization.

Special-Use Permits Are Long-Term Commitments

Special-Use Permits for the conveyance of water across the forest are issued for a specific number of years. Although the Forest Service has the legal right to deny reissuance of such permits, it is often difficult to do so. In essence, most Special-Use Permits for water are permanent commitments. This makes it very difficult to correct existing resource problems that can be attributed to such developments.

Lack Of Consistency

Historically, the forest responded with a variety of approaches to requests for the development and use of groundwater. In some instances we immediately denied such requests, while in others we encouraged such development and use. Such inconsistency without a sound rationale usually leads to problems.

Groundwater Policy

Policy: Groundwater shall be managed for the long-term protection and enhancement of the Forest's streams, springs and seeps, and associated riparian and aquatic ecosystems. Development and use of groundwater for consumptive purposes shall be permitted only if it can be demonstrated that such proposals will adequately protect Forest resources.

Criteria For Development And Use Of Groundwater

Proposals to develop and use groundwater derived from National Forest System (NFS) lands must meet the following conditions:

A. The proposal to use water must be consistent with applicable laws, regulations, polices, rules, and forest land and resource management plans (Forest Service

Manual [FSM] 2702 & 2703).

B. The proposal to use water must adequately protect National Forest resources (FSM 2702.1 & 2541.34).

C. If the proposed place of use of water will be located on non-NFS lands, the proponent must demonstrate that alternative water sources do not exist off-forest (FSM 2703.2).

Consistency With Existing Policies And Management Direction

The forest policy for the development and use of groundwater is consistent with National and Regional policy and direction. For instance, the Forest Service Manual (FSM) 2541.34 indicates that if projected water requirements of uses not directly related to Forest Service programs "will adversely affect national forest resources, the potential permittee must seek alternative water sources or develop mitigation plans acceptable to the Forest Service." Similarly, the manual indicates that Special-use authorizations should be denied if they are in conflict with other forest management objectives, or can reasonably be accommodated on non-NFS lands (FSM 2703.2).

Procedures - Methods to Implement Policy

The evaluation of water development proposals has three phases.

1. Preliminary Analysis

This phase initiates the evaluation process. If water is to be used off-forest, the proponent must demonstrate that alternative water sources do not exist off-forest. For all proposals, the following information is assembled and evaluated.

Description of Proposal
Quantity of water needed
Infrastructure requirements

Inventory of Key Resources
The location of potentially affected surface water resources.
The location and description of riparian vegetation.
Any known Threatened and Endangered species.
Pertinent geologic information.
Pertinent hydrologic information.

Inventory of Existing Water Developments

2. Exploration And Testing

This phase involves drilling for a suitable water supply, and testing for impacts on forest resources and adjacent water supplies. The Exploration and Testing phase would be initiated only if the proposal satisfies the requirements of the screening process in the preliminary analysis phase.

Temporary Permit Issued. If the Preliminary Analysis indicates a reasonable likelihood of developing water without adverse impacts on forest resources or adjacent water users, a Temporary Permit may be issued for the Exploration and Testing phase of the proposal. This Temporary Permit shall contain the conditions necessary to minimize impacts to forest resources.

If sufficient water is found in the exploration phase to meet the needs of the proponent, testing is then conducted.

Testing Conducted. Prior to testing, a monitoring plan must be submitted to the Forest Service for approval. After approval of the monitoring plan, long-term pump testing, modeling, or both, are conducted, and effects of pumping are observed or predicted.

3. Construction And Production

This phase involves the permitting of all infrastructure, the conveyance of water, and long-term monitoring and mitigation. This phase occurs only if testing indicates that forest resources will not be adversely affected or can be mitigated, and nearby water developments can be adequately protected.

Permit Issued. Infrastructure needed to produce and convey water is constructed.

Monitoring And Mitigation. Any monitoring or mitigation measures necessary to ensure protection of forest resources during the construction of water storage and conveyance facilities, and during the long-term removal of groundwater will be included as a Plan of Operations attached to and made part of the Special-Use Permit. If long-term monitoring detects additional or unforeseen adverse impacts to forest resources that were not discovered during the exploration and testing phase, or if mitigation measures do not adequately protect forest resources, the Permit shall not be reissued.

Other Considerations

NEPA Analysis and Documentation

The scope of any analysis needed to comply with NEPA will depend largely on potential resource impacts, and on the level of public concern.

For NEPA purposes, groundwater exploration and development can often most logically be addressed in two distinct phases. The first NEPA analysis can address the impacts associated with the exploration and testing phase. This phase can be separated from the development and production phase because the availability of groundwater and the impacts from pumping are often unknown during the exploration phase. A second NEPA analysis can be conducted if a suitable supply of groundwater is found and if test pumping does not result in impacts that would constitute a reason for denial of a Special-Use Permit for the production phase. The second NEPA analysis would address impacts identified during the exploration and testing phase, from the construction of infrastructure, and from the operation of the proposed facilities.

Water Rights

Applicable laws and regulations governing wells and water rights will be adhered to for all proposals.

Conclusions

A rapidly growing population in the Southwest is causing increasing demands on scarce groundwater. Requests for Special Use Permits to withdraw groundwater on the national forests are now common and increasing as well. Case studies and hydrologic theory confirm that groundwater and surface water are usually strongly interconnected and form a single hydrologic system: groundwater withdrawals typically directly result in lower streamflows. Policies and procedures for considering groundwater development proposals are needed that work within the NEPA process to ensure that permits are granted only when consistent with our stewardship responsibilities to protect surface-water dependent values.

USDA Forest Service Policy on Managing Groundwater Resources

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Until now, the USDA Forest Service lacked a national policy on managing groundwater resources of the national forests and grasslands. There are many problems and missed opportunities for resolving groundwater caused issues and concerns that the agency can best tackle with a nationally consistent and comprehensive groundwater policy. The policy proposed in this paper fulfills all of those needs: it covers water quantity and quality issues, clean-up of contaminated groundwater, commercial bottling operations, inventory and investigation procedures, and special use permitting of new wells.

Keywords: *groundwater resources, policies, permitting, aquifers*

Background

In the past, the USDA Forest Service personnel responsible for managing the national forests and grasslands too often ignored the groundwater below their feet, tried hard to do so, or assumed that the same agency policies for managing surface water applied equally to groundwater. There were exceptions, of course, if some kind of sub-surface activity was proposed, such as mining, oil, gas or water well drilling, or clean-up at an abandoned mine site. The laissez-faire strategy worked pretty well in many cases, but over time there has been a steady increase in the number of cases where those strategies failed and caused adverse impacts to the lands or the natural resources located on those lands. By the late 1980s, hydrologists and geologists in the agency's national headquarters were working together to develop a national policy for groundwater management.

Bureaucratic turf wars between the two staff directors involved in this joint effort prevented the draft groundwater policy from being issued in 1989 as it could have been. When I arrived in the Washington Office late in 1989, I pursued tackling the bureaucratic issues for a year or so without success, then gave up on it. By the late 1990s with new directors in place, I again pursued bringing the draft policy to fruition by sending it out to the Regions for review and comment. I also formed an ad hoc team to revise the earlier draft based on the comments received and new information that had become available.

It occurred to me that field personnel would need two companion documents to this new policy to be able to use it successfully. One would be a user-friendly handbook or desk guide on techniques and methods proven useful for investigating, managing or mitigating groundwater underlying National Forest System (NFS) lands. The second document would be a compilation of federal and state laws, rules, regulations, and case law pertaining to groundwater in each of the 43 states that have NFS lands. Both of these documents have been completed.

Current Groundwater Issues and Concerns

Freshwater aquifers currently supply 37 percent of the drinking water that Americans depend upon annually. A total of 83.3 billion gallons per day (bgd) (315 million cubic meters per day [Mm^3d])was withdrawn from the groundwater resource in 2000, up 14 percent from 1985, according to the U.S. Geological Survey (USGS 2003). Some 56.6 bgd (214 Mm^3d) was used for irrigation, 16 bgd (60.6 Mm^3d) for public water supply, 4.4 bgd (16.6 Mm^3d) for mining and 3.5 bgd (13.2 Mm^3d) for individual domestic water needs.

The U.S. Geological Survey identified 21 groundwater provinces in the United States (Meinzer 1923). Most aquifers within these provinces are found in valleys, on the Great Plains, and in relatively flat terrain along the East and Gulf coasts or the Great Lakes. Since NFS lands often are located in mountainous areas of the West and

Furniss, M.J., Clifton, C.F., Ronnenberg, K.L., eds., 2007. *Advancing the fundamental sciences: proceedings of the forest service national earth sciences conference, San Diego, CA, 18-22 October 2004*. PNW-GTR-689. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station.

along the Appalachian chain in the East, they are not usually overlying the major aquifers. There are some exceptions: some national forests and grasslands from Texas through Nebraska overlie the Ogallala and Edwards aquifers; portions of the Osceola and Ocala National Forests in Florida overlie the Floridian aquifer; several forests in North and South Carolina overlie coastal aquifers; some national forests in the Great Lakes basin overlie aquifers there; portions of the Custer National Forest in Montana, the Humboldt-Toiyabe National Forest in Nevada, and several national grasslands in Wyoming, North and South Dakota, Colorado, Kansas, Oklahoma, Oregon and New Mexico overlie important aquifers. Some of these aquifers are being heavily pumped with increasing risk of severe depletion that may cause many unintended consequences to both people and ecological values of those places.

Almost all national forest lands, wherever located, also serve as groundwater recharge areas because they typically receive more annual precipitation than nearby valley areas. This is a very important function they serve in the water cycle or water budget that hydrologists and water supply engineers plan on. It is very important to ensure that groundwater recharge areas do not serve as points of contamination of the aquifers. Yet, there is no national or even regional inventory of groundwater resources underneath NFS lands in this country. We must start to work on one soon; this paper supports that undertaking.

Based upon many experiences that the U.S. Environmental Protection Agency (EPA) has had since 1970 with clean-up of contaminated groundwater, it has become obvious that preventing contamination of groundwater is by far the least costly and most environmentally sound way to ensure the usability of that resource in the future. The Forest Service intends to follow such an approach, especially in the near future. This agency has only very limited hydro-geological expertise - only about six employees out of a professional workforce of about 8,000 currently have such a background.

The state laws that regulate groundwater resources too often ignore the real connections between groundwater and surface water that exist in nature. Many states completely separate the two kinds of water in their laws, or encourage maximum development of groundwater, sometimes with devastating consequences such as land subsidence, loss of wetlands, salt-water intrusion, loss of surface water flows, and other effects. California does not even have a state groundwater law. Some state laws were written in the 18th or 19th centuries and need to be modernized, in the opinion of many water experts and this author. The Forest Service respects the authority of states to allocate water and control water quality as delegated by the Congress through federal laws. The agency adheres to state water rights laws to the extent they are not incompatible with federal laws that govern the proper administration of NFS lands and resources. To ensure that Forest Service employees are familiar with state groundwater laws, a document that includes a short summary of the laws and includes Internet hot-links to the actual text of all of these state laws and regulations in the 43 states that contain NFS lands has been drafted (Glasser and Chapman 2006). That document will be posted on a Forest Service website in 2005.

Groundwater Policy Components

There are a number of component parts to the proposed agency policy for groundwater (USDA Forest Service, In press) which will be briefly discussed in this paper. They include: objectives, responsibilities, definitions, assessments, uses, clean-up of contaminated groundwater, source water, permitting, monitoring, fees, legal aspects, and sustainability strategies.

Objectives

The Forest Service will manage groundwater underlying NFS lands to ensure the long-term protection and enhancement of these aquifers and other groundwater systems, surface streams, springs, lakes, ponds and their associated riparian and aquatic ecosystems.

Further, authorization of consumptive water uses by other parties will occur only if such authorized uses can adequately conserve, restore, or protect dependent resources and values over the long run.

Both of these objectives are based upon a number of federal statutes and their implementing regulations governing the National Forest System from 1897 to the present.

Responsibilities

The new policy includes a number of specific responsibilities of certain Staff Directors in the Washington Office, Regional Foresters, Station Directors and the Area Director; Forest Supervisors and Research Project leaders; and Project, Program or Team Leaders in the Research and Development Branch.

Definitions

Some 17 technical terms used in the new policy are clearly defined to ensure understanding and common usage in the future.

Assessments

The use of appropriate methods, models, tools, techniques to investigate, inventory, assess or quantify the quality and the volume of groundwater resources underlying NFS lands is very important in achieving success in such endeavors. Temporal and three-dimensional spatial scales are also critical elements in these processes. The new policy and its related Technical Guide for Managing Ground Water are intended to be used in tandem by field practitioners. Some cautions on the use of these methods and tools are also noted in both documents.

Groundwater Uses and Impacts

The Forest Service has authorized many water wells that pump groundwater from underneath NFS lands, and it also has hundreds of its own water wells that serve administrative sites, recreational facilities and other uses. These uses will continue and new ones will undoubtedly be added in the future. The Forest Service needs to begin to quantify the amount of groundwater being withdrawn from beneath its lands by all water users if we are to work toward sustaining groundwater as a natural resource in perpetuity.

A provision of the new policy is a requirement to install water meters on all pipes four inches or larger in diameter used to withdraw groundwater for any purpose. This requirement will apply to both authorized pipelines and to agency owned pipelines. Annual withdrawals in cubic feet of water will be reported to the Director of Watershed, Fish and Wildlife in the Washington Office.

The new policy addresses impacts on groundwater related to mining, oil, gas and coal bed methane operations, geothermal facilities, tunneling projects, sand and gravel removal, and landfill operations that need to be recognized and appropriately addressed at the local, state or regional levels. Readers are referred to appropriate portions of Forest Service Manual (FSM) chapters 2810, 2820, and 2880.

Clean-up of Contaminated Groundwater

Direction is provided to prevent future contamination from agency authorized or conducted activities, and where contamination has already happened, to be pro-active in remediation. There is abundant existing direction and technical guidance on planning and implementing clean-up operations in FSM chapter 2160, the National Contingency Plan, USDA Manual DM 5600-1 Chapter V, and requirements of the Comprehensive Environmental Response Compensation and Liability Act of 1980 which need to be followed by anyone contemplating a groundwater clean-up operation.

Conjunctive Use of Surface and Groundwaters

The new policy states that one should always presume there are hydrologic connections between surface water and groundwater on NFS lands unless it can be clearly proven that there are none in the local setting. This is a reasonable, conservative assumption that we think is very important to achieving long-term sustainability of the groundwater resource at a minimum of cost. There are many real world cases where contamination of water occurred because it was wrongly believed there were no connections between ground and surface waters; in other cases, too much pumping of groundwater has dried up surface waters in streams, ponds, lakes, and wetlands. Also, removal of surface waters by diversion or pumping has caused declines in groundwater levels because the groundwater recharge mechanism has been shut off.

The Forest Service recognizes the growing trend toward conjunctive water management by many water utilities, districts, and planners. The agency needs to assure that its employees are also aware of this trend and are equipped to deal with it if such proposals to make use of surface water, groundwater or both, that originates under, on, or from NFS lands, arrive on their desks. Specific direction on evaluating these applications is given in the next section of FSM chapter 2543 - Permitting.

Permitting

A two-phase process for evaluating applications for new ground water resource developments of any kind on NFS lands is provided in this section of the policy. The reader should also see the paper by Martin and Loomis in this publication. In fact, much of the national policy on permitting water wells included in FSM 2543.5 originated from the process used by the Tonto National Forest (New Mexico) and was then codified by the Southwestern Region of the Forest Service.

Assuming there are no alternate water supplies outside the national forest, the first or exploratory phase of permitting is the information gathering and screening phase where, after National Environmental Policy Act (NEPA) analysis is completed, the project proponent may be authorized to drill one or more test wells and perform a 72-hour continuous pump test while measuring effects on the water table and surface waters nearby. Often computer modeling, additional drilling of wells, and surface water monitoring sites may be required. If it appears there is a large enough water supply of sufficient quality that can

be developed in an environmentally safe and economically feasible manner, then plans for development are evaluated and documented in accordance with NEPA requirements.

The next phase is the issuance of permits for the construction of the water production facilities and associated infrastructure if located on NFS lands, once a NEPA decision and all applicable state authorizations are in place. FSM 2711 provides additional guidance about the permitting process. Monitoring and mitigation measures should be included in the permit and the annual plan of operations by the permittee.

Laws, Rules and Regulations on Groundwater

There is no single federal law that addresses groundwater in a comprehensive manner. The Safe Drinking Water Act delegated primary responsibility for protecting drinking water to the states, whether from surface water or groundwater. The Clean Water Act implies that groundwater is to be managed like surface waters, but it does not set clear goals for managing groundwater.

State laws, rules and regulations for the allocation of groundwater among competing water users exist in almost all states. They are based upon one or more basic legal theories: absolute ownership, correlative rights, prior appropriation, and reasonable use. Many states artificially separated their surface water right laws from their groundwater laws, which has led to some damage to groundwater resources.

The Forest Service policy is to follow state water laws substantially and procedurally as long as they do not conflict with federal laws applicable to management of NFS lands and resources. In an effort to increase Forest Service personnel's awareness of state water laws and as an aid to water attorneys in the USDA Office of the General Counsel, an 86-page compendium of these laws, their regulations, and pertinent case law in the 43 states with NFS lands has been completed as a separate document. Contact the Forest Service Washington Office, Fish and Wildlife staff about how to access this document.

Strategies for Sustaining Groundwater

The new policy contains five strategies designed by the U.S. Geological Survey (Alley et al. 1999) to sustain the availability and usability of groundwater resources in the United States. These strategies should work on NFS lands. There may be additional strategies that would work in local areas as well; the point is to try to use some strategy for many years or decades to ensure that the groundwater resource is not totally depleted, contaminated to a point where it becomes unusable by people or by dependent animal or plant life.

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Section 2. Experimental and Research Watersheds

Overleaf:
Maybeso Creek, Maybeso Experimental Forest, Tongass National Forest, southeast Alaska. Photo by Michael J. Furniss.

The Forest Service Barometer Watershed Management Program, a Historic Viewpoint

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During the 1960s, Byron Beattie, Director Division of Watershed Management and Edward Dortignac, Branch Chief of Water Resources of the USDA Forest Service National Office, Washington, DC, conceived a program to bridge the gap between watershed research results and management scale application of science-based principles. The proposal was to select, instrument and calibrate National Forest System watersheds in the range of 50,000 to 150,000 acres (20,200 to 60,700 ha) in each of several hydrologic provinces. Teams of watershed scientists including hydrologists, soil scientists, geologists, and natural resource managers would apply and evaluate science-based management prescriptions. This initiative was the impetus that brought an influx of scientifically trained hydrologists and soil scientists into the Forest Service. This effort included the establishment of a Watershed Systems Development Unit (WSDU) in Berkeley, CA, led by Clyde Shumway. WSDU provided technical support in acquiring state-of-the-art instrumentation and data management programs. An essential part of their effort was the development of computer programs to predict the effects of management activities on water yield and sediment. These were to be applied on the selected "barometer watersheds" as well as in support of the Pacific Southwest Water Plan initiative. Barometer watersheds varied in their success due, in part, to the difficulty of operating sophisticated technology in remote environments. Also, in many cases, coordinating the application of management prescriptions with calibration proved challenging. Regardless of the success of an individual barometer watershed, these efforts on the whole provided the platform for developing critical skills that formed the career foundation for many hydrologists and other earth scientists in the Forest Service.

Keywords: *representative watersheds, barometer watersheds, water yield, history, watershed management*

Introduction

The U.S. Forest Service Barometer Watershed program was envisioned by Byron Beattie, Director, Division of Watershed Management and Edward J. Dortignac, Chief, Water Resources Branch, USDA Forest Service National Office, Washington, DC. Beattie and Dortignac described the broad goals and objectives of the program in their paper entitled "Using representative watersheds to manage forest and range lands for improved water yield" (Dortignac and Beattie 1965). The essence of the concept was to prototype science developed at plot and small watershed scale and pilot test these findings at a management scale and integrate them with ongoing multiple use practices. The outcomes of watershed prescriptions would be predicted in advance. The post-prescription outcomes would be evaluated and modified as necessary before being more broadly applied in the climatic-physiographic region, referred to as a hydrologic province, represented by the barometer watershed. Dortignac and Beattie (1965) describe the concept as follows:

> The knowledge gained from experimental watersheds of the Forest Service and the data accumulated on other representative watersheds establishes a broad base of knowledge for scientific management of forest and range lands. These findings make it possible to predict hydrologic behavior on a selected watershed for given climatic events, provided the watershed is intensively inventoried and appraised. A reasonably accurate prediction of results is essential

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[1] Retired

to management decisions on whether or not to expend the energy and funds needed to implement a watershed prescription.

The Forest Service uses a system of "Representative Watersheds", 50,000 to 150,000 acres [20,200 - 60,700 ha] in size to bridge the gap between research findings and operational management of drainage basins for improving the timing, quantity and quality of water yield from the National Forests. These watersheds register the changes in water yield occasioned by a wide variety of activities in the watershed. From this, the term "Barometer Watersheds" was derived.

The timing for this program seemed opportune in its coincidence with the International Hydrologic Decade and the increased public interest in water yield opportunities (Barr 1956). Also, the Multiple Use Sustained Yield Act of 1960 created a new operating environment that required coordination among activities on the land. The Pacific Southwest Water Plan added additional impetus for water yield studies in watersheds tributary to the Colorado River and in California.

As envisioned by Beattie and Dortignac, a hydrologic province with broadly similar characteristics would be identified, and a representative watershed ranging from 50,000 to 150,000 acres (20,234 to 60,703 hectares) would be selected within this region. For example, the Wasatch Plateaus Province of central Utah was represented by the Straight Canyon Barometer Watershed. After careful survey and characterization of soils, geology, vegetation, climate and hydrology, these watersheds would have integrated multiple use prescriptions developed and applied. The Barometer Watersheds were to have state-of-the-art hydro-meteorological instrumentation installed to evaluate the effects of these integrated prescriptions on water yield characteristics. In addition to the stream gaging stations and recording precipitation gages, a central weather station was included that logged net radiation, dew point, wind at two levels, and temperature. These measurements were supplemented with storage precipitation gages, snow pillows and snow courses.

Beattie and Dortignac prepared a number of additional papers that described the program, as well as describing watershed management concepts that could be applied (Beattie 1962, 1967a, 1967b; Dortignac 1966, 1967). The Glazebrook (1969) paper described progress to that point and indicated that the number of watersheds would not be increased beyond those already established. Glazebrook also stressed that barometer watershed prescriptions would be evaluated in the context of ongoing forest planning efforts. Prescriptions would be considered as alternatives in the plans and implemented if selected in the planning process.

Operations

Essential to this effort was the prediction in advance of the expected outcomes and effects of proposed watershed and other resource prescriptions. Some of the conceptual considerations the watershed scientist needed to evaluate are described in the water balance flow chart in Figure 1. The Watershed Systems Development Unit (WSDU) was established in 1966 to provide support to the field units in installing and maintaining the equipment and to provide the necessary computer programs to translate and manage the data. Of equal importance was the development of computer models to predict the water yield outcomes associated with various prescriptions. A program called "BURP" predicted the water yield outcomes from application of vegetation management prescriptions. The WSDU unit was led by Clyde Shumway and housed at the Pacific Southwest Research Station in Berkeley, CA. Cliff Mansfield provided instrumentation support. By the time the unit was established and operating, a backlog of untranslated data tapes had accumulated at many of the barometer watersheds. A key part of the data management process was a machine to read the punch paper tapes and convert them into computer cards for processing by the computer. This machine was acquired in the late 1960s and experienced considerable down time due to mechanical problems. The machine was housed in Ogden, UT, and all the data from the various watersheds was processed through this machine. Getting the data in proper format and correcting for time errors and missing data required a considerable amount of the barometer hydrologist's time. The computer program development took place on the highly capable computers at the University of California at Berkeley. After development and testing these programs had to be adapted to the less capable computer systems available at the regional office level. Barometer hydrologists pioneered in the use of some of the earliest remote terminal systems available for accessing the central computer systems over phone lines from ranger stations.

The predicted outcomes of the applied prescriptions were to be compared to the measured outcomes. The intent was to refine and adjust the data acquisition and the model until it produced predictions with a reasonable accuracy. Once validated, the model and prescriptions could be applied throughout the hydrologic province, providing managers with predictable outcomes of their planned activities.

These barometer watersheds and the data management and predictions were to be managed on the ground by a

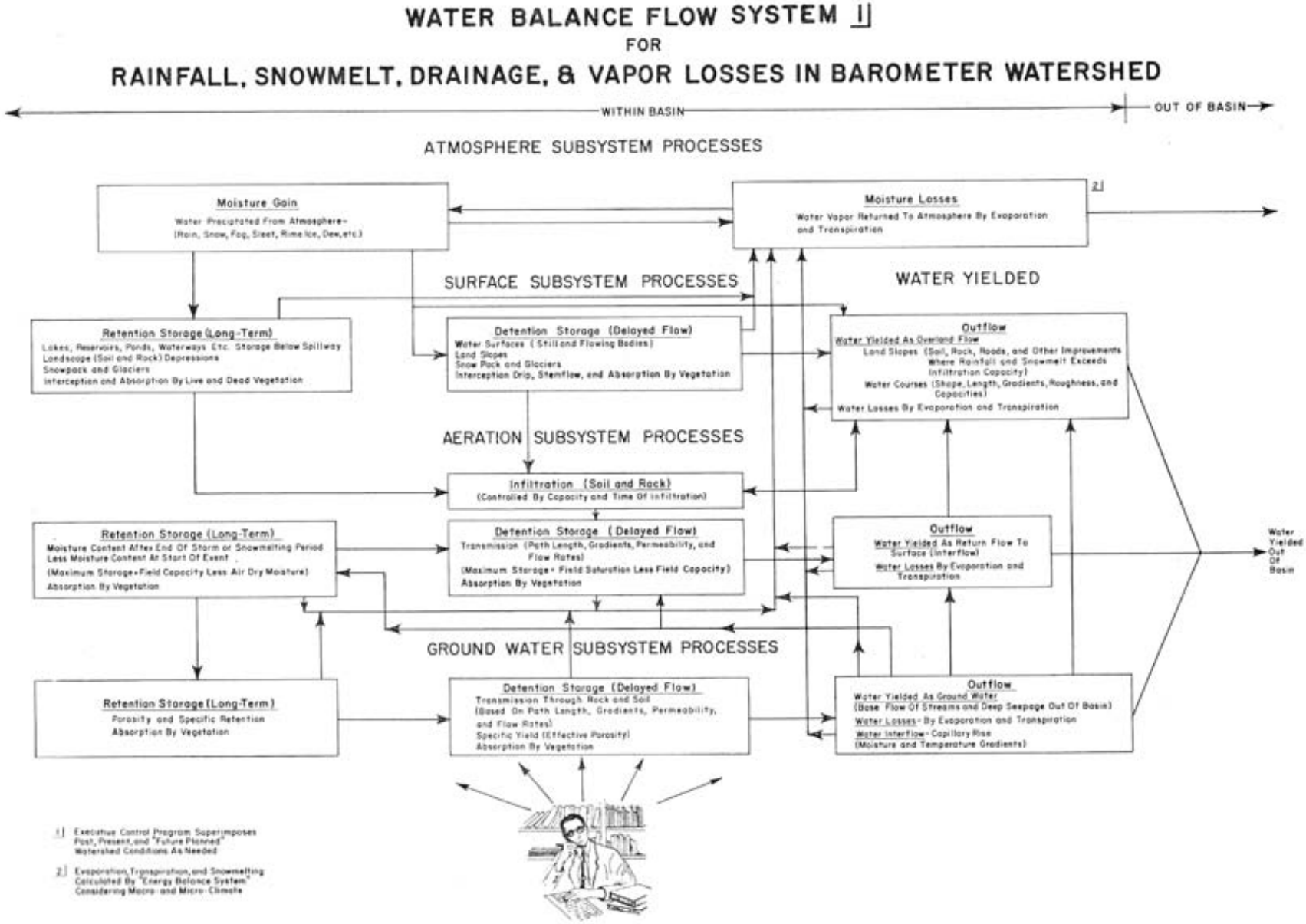

Figure 1. System for Evaluating Water Yield

After Dortignac and Beattie 1965

corps of watershed scientists that included hydrologists, soil scientists and geologists. Large numbers of these specialists were hired beginning in the mid 1960s and extending into the early 1970s. Glazebrook (1969) indicates, for example, that the number of watershed scientists employed by the Forest Service went from 4 in 1961 to 112 in 1969. These people were well trained academically but faced a steep learning curve on the job to cope with myriad daily challenges.

At the outset, 50 provinces were identified that involved National Forest System lands and 50 barometer watersheds were planned. (Delk 1979). By 1969, 23 of the anticipated 50 had been established (Glazebrook 1969). The established barometer watersheds, as of March 1970, are listed in Table 1.

There was wide variation in the level of investment and activity involved in establishing hydro-meteorological instrumentation. This was also true of efforts to characterize the vegetation, soil, climate and geology. For example some watersheds like Lake Fork, East Fork Smiths Fork, Straight Canyon, Encampment River, Black River, Entiat River and Umatilla River were projects where most of the anticipated instrumentation was installed and operating. Other watersheds achieved varying levels of characterization and instrumentation. By 1979, the Delk report identified only 12 watersheds as still operating at some level (Delk 1979). The operating barometer watersheds are identified in bold in Table 1.

Assessment

Based on the analysis and findings of the Delk (1979) report, the National Program emphasis was discontinued. Regions and forests were left to determine what level of emphasis and priority should be given to continuing the Barometer Watershed Program on a local basis. The challenges imposed by the National Environmental Policy Act (NEPA), National Forest Management Act (NFMA), and other acts usually resulted in a choice to shift personnel and funding to these more urgent demands. By the mid

Table 1. Established Barometer Watersheds. These are the 24 barometer watersheds that were established by 1970. **The watersheds identified in bold type are the ones that remained active at the time of the Delk Report in 1979.** *R-1 is the USDA Forest Service Northern Region, R-2 is Rocky Mountain Region, R-3 is Southwestern Region, R-4 is Intermountain Region, R-5 is Pacific Southwest Region, R-6 is Pacific Northwest Region, (R-7 was merged with R-9), R-8 is Southern Region, R-9 is Eastern Region, R-10 is Alaska Region.*

Barometer Name	State	Region	Hydrologic Province
1. Meadow Creek (Horse Cr)	**ID**	**R-1**	**Northern Rocky Mountains (Selway R.)**
2. West Fork Madison River	MT	R-1	Western Rocky Mountains (Madison R.)
3. Lake Creek	**CO**	**R-2**	**Central Rocky Mountains (Arkansas R.)**
4. Encampment River	**WY**	**R-2**	**Sierra Madre (North Platte R.)**
5. Salome	AZ	R-3	Central Arizona (Salt R.)
6. Black River	**AZ**	**R-3**	**Mogollon Rim (Salt R.)**
7. Straight Canyon	**UT**	**R-4**	**Central Utah Plateau (San Rafael R.)**
8. Antimony Creek	**UT**	**R-4**	**Southern Utah Plateau (Colorado R.)**
9. East Fork Smiths Fork	**UT**	**R-4**	**Uinta Mountains (Green R.)**
10. Big Creek	CA	R-5	Southern Sierra Mountains (Kings R.)
11. Upper Santa Ynez River	CA	R-5	South Coastal (Santa Ynez R.)
12. Green River	**WA**	**R-6**	**Northwest Middle Cascades (Puyallup R.)**
13. Entiat River	**WA**	**R-6**	**North East Cascades (Columbia R.)**
14. Umatilla River	**OR**	**R-6**	**Northern Blue Mountains (Columbia R.)**
15. Upper Clackamas River	OR	R-6	West Slope Middle Cascades (Willamette R.)
16. Upper Sauk River	WA	R-6	North West Cascades (Skagit R.)
17. Davidson River	**NC**	**R-8**	**S. Appalachian Mtns. (French Broad R.)**
18. Upper North River	VA	R-8	Valley & Ridge (Potomac R.)
19. Cranberry River	WV	R-9	Appalachian Plateau (Kanawha R.)
20. Hurricane Creek	AR	R-9	Ozark Plateau (White R.)
21. Kawishiwi River	MN	R-9	Laurentian Upland (St. Louis R.)
22. Wild River	NH	R-9	New England (Androscoggin R.)
23. Pine River	MI	R-9	Lower Michigan (Manistee R.)
24. Kadaskan River	**AK**	**R-10**	**Island Southeast (Coastal SE Alaska)**

1980s only a few barometer watersheds struggled on. Most of these had a research study underway making the continued investment more attractive. The program is described in the Forest Service Manual (USDA Forest Service 1965) and the progression in direction can be seen in the revision (USDA Forest Service 1979). The 1965 direction focuses heavily on the technical application of scientific principles and watershed management concepts. By contrast the 1979 direction focuses more on coordination with research efforts and forest planning processes.

The Delk (1979) report provided an insightful assessment of the status of the program. It also described what had been achieved as compared with the original concepts described by Dortignac and Beattie (1965). Delk also provided some views regarding how the program might be adapted to be more relevant and useful in light of current programs and emphasis in the Forest Service. He noted that the barometer program was very successful as a training ground for many of the cadre of hydrologists who currently served the national forests. However, this program was less successful in accomplishing the representative watershed role for a variety of reasons. Drawing on Delk and personal experience the following points may provide useful insights to those charged with developing similar efforts in the future.

Technology. The desired outcomes of the barometer watershed effort relied on cutting edge and yet-to-be-perfected technology. Watershed characterization included stream gaging, precipitation, and climatic measurements. The belief was that current chart recorder technology would produce a backlog of undigested data. To overcome this, punched paper tape technology was selected. This equipment offered the possibility of rapid reduction and compilation of data. The actual situation proved more problematic and the equipment was subject to more mechanical wear and tear, required electrical energy, and thus had a higher maintenance requirement in remote locations. The equipment frequently failed and data was lost until parts could be obtained and installed.

The data tapes required specialized technology to translate the punch paper tapes to computer cards and then to process them through computer programs to produce data records. A considerable quantity of data tapes had been produced before the tape translator reader was acquired. The tape translator was also subject to frequent breakdowns and delays in receiving replacement parts. This added to a further backlog of unresolved data and an accumulation of undetected instrument calibration problems.

The computer programs to compile the data were under development concurrently with the initial data acquisition. These factors all combined to produce a data analysis backlog that was difficult to overcome. Hindsight suggests that using existing proven data recording technology might have produced better results. At least providing the proven technology as a redundant backup to the punched paper tape systems, as was done by the US Geological Survey, would have provided more reliable and continuous data sets. As reliable improved technology becomes available it can be brought on-line.

Coordination. The outcomes of the barometer watershed effort depended on predicting the results of an integrated prescription, then implementing the prescription and testing the actual outcome with the predicted outcome. The time horizon to accomplish this would likely require at least ten years using the paired watershed approach. This would involve five years of calibration followed by five years of post-activity evaluation. The reality was that coordinating timber harvest and other activities with barometer watershed objectives was not achieved for a variety of reasons. These included inability to delay ongoing timber harvest activities, failure of timber markets to develop as planned, fires, and changing environmental requirements.

Scale Issues. Study strategies for dealing with watersheds of 50,000 to 150,000 acres (20,200 to 60,700 ha) were inadequate. While perhaps a realistic management scale, they represent a huge departure from small research watersheds and plot studies. The relative amount of change possible from an activity is limited by scheduling, timing, duration and extent of the treatment relative to the size of the watershed as a whole. In addition, a range of environmental constraints and limitations required by consideration for other resource values effectively reduced the magnitude of the prescribed treatment on runoff. A further consideration is the inherent limitation on the accuracy of stream gages on larger flowing rivers. Taken together, these factors made it unlikely that any anticipated resource use or activity would progress at a rate and magnitude to produce a detectable change over the larger watershed area. The lack of detectable change would make it difficult to validate predictions. Hindsight suggests more focused evaluation of smaller management scale watersheds might have been more effective. Perhaps scaling up from one square mile (2.6 km^2) research watershed results to a ten square mile (26 km^2) watershed application with replication within the larger 50,000 to 150,000-acre (20,200 to 60,700-ha) watershed might have produced measurable changes to evaluate. Another possibility would be the use of nested watersheds. For example, some successful studies at Horse Creek, a tributary of the Meadow Creek Barometer on the Clearwater National Forest, Idaho, and Coon Creek, a tributary of the

Encampment River Barometer on the Medicine Bow National Forest, Wyoming (sub-watersheds within larger barometer watersheds), could provide useful information regarding the type of results that could be achieved when applied in a larger watershed. A study at Battle Flat on the Prescott National Forest, Arizona, did rely on the development of extensive networks of nested stream gages. Unfortunately the studies did not get beyond the calibration stage before being discontinued.

Scientific Skills and Experience. Those few barometers that had higher degrees of success benefited from involvement of experienced forest service research scientists. These, for example, included studies at Horse Creek, Coon Creek, and Entiat, and other locations. Other joint efforts involving pilot demonstration watersheds between National Forest Systems and Research at Beaver Creek on the Coconino National Forest in Arizona are good models of the cooperation needed to have a greater likelihood of successful outcomes.

Adaptability. As Delk (1979) points out, the legal, institutional and external requirements imposed on land managers had changed considerably in the years since the program started. Priorities had shifted. The funding process had changed as well, and the amount of funding available was diminished. The barometer program required a sustained effort over a period exceeding a decade to be successful. Even if the technology and trained personnel had been available at the outset, it is unlikely that the effort could have responded to the changes in funding and priority at the scale that was undertaken. Perhaps a greater emphasis on a few prototypes to demonstrate the concept might have proven more effective. A tangible proof of concept is a powerful advocate for the value of a program. Prototyping also allows discovery of flaws and the opportunity for adjustments to be made before broader applications are implemented. Future programs of this nature must consider how they will adapt to rapidly changing priorities, requirements and funding.

Accomplishments

As Glazebrook (1979) pointed out, even though the original planned effort was blunted, there were a number of successes. For example, the barometer watershed program has provided insight into the hydrologic functioning of large watersheds under different conditions of geology, soils, climate, landforms and vegetation. These areas provided excellent training grounds for forest land managers, soil scientists and hydrologists. They have also provided valuable insights to the public regarding watershed management through show-me trips, media articles and interpretative signs. These areas, in some cases, provided venues for scientific study both by internal research scientists and by external cooperators. Meeting the challenges of managing data and developing predictive programs were the forerunners of current planning and assessment tools used in watershed management and land management planning. The barometer watershed effort also produced new analytical methods for dealing with wildland hydrology issues and improved the ability of the Forest Service to deal with watershed issues. A significant part of this improvement is due to the increase in the number of trained scientific professionals in soils and hydrology fostered by the barometer watershed program.

Summary

As we look to the future, it is clear that land management planning and decision making are advantaged by having facts about the climatic and hydrologic situation. Knowledge of the vegetation, soils and geology, coupled with these data, provides an opportunity to improve our ability to evaluate proposed actions in advance of implementation. This predictive ability offers the opportunity to modify actions or incorporate mitigation as was attempted in "An approach to water resources evaluation of non-point silvicultural sources" (WRENSS) (USDA FS 1980). These water facts are vital to the effectiveness of scientifically trained hydrologists and soil scientists in providing advice to managers. Programs such as the barometer watershed management effort have provided additional insights into how wildlands operate. Continuing to emphasize gathering data at strategic sites and pilot testing research findings on a management scale remain valuable tools in closing the gaps between scientific knowledge and management applications. Closing this gap remains one of the key challenges facing land management agencies in the future. Efforts are continuing to improve the speed with which we bring science to bear on management problems. Care needs to be taken, however, in how we deal with new abilities to acquire data. Technology is improving in its ability to gather data effectively at less cost in remote areas. This improved ability to acquire data places a greater burden on the analyst to wisely choose how to strategically set up the data acquisition network to meet objectives. The data acquisition effort must be operated effectively so that data becomes useful information to help guide management. We must avoid the temptation to acquire data merely because it is easy to do so. Data is of little value if it is just collecting dust in an archive.

Overall, while the barometer watershed program failed to achieve all that it set out to accomplish, the program did provide some valuable insights into the operation of wildland watersheds. Approaches similar to

the barometer program can lead to improved modeling of watershed processes, predicting effects of management prescriptions, and identifying critical variables to be measured. Cooperative efforts between the National Forest System and Research and Development are a key factor in attaining successful outcomes in future efforts of this nature.

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Development of Watershed Hydrologic Research at Santee Experimental Forest, Coastal South Carolina

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Managing forested wetland landscapes for water quality improvement and productivity requires a detailed understanding of functional linkages between ecohydrological processes and management practices. Watershed studies are being conducted at USDA Forest Service Santee Experimental Forest, South Carolina, to understand the fundamental hydrologic and biogeochemical processes and their linkages with soils, vegetation, topography, climate, and management practices in the low gradient forested landscapes of the South Carolina Coastal Plain. This study presents an overview of and builds on the long-term watershed hydrologic research begun in 1964 by our predecessors at this experimental forest. Monitoring and modeling studies using a paired watershed approach are being conducted to describe the effects of management practices on two first-order, forested watersheds. Long-term flow data from two 160-ha first-order, one 500-ha second-order, and one 4,500-ha third-order watersheds, provide an opportunity to evaluate the flow dynamics and hydrologic effects of scale, land use distribution, and climate on these coastal watersheds. DRAINMOD-based models are being tested with these data for their applicability as a water management tool on these poorly drained natural forested watersheds. The long-term information on hydro-meteorology, water quality and water table levels from these watersheds has also provided baseline data on the eco-hydrologic processes that are useful to researchers, planners, land owners and industries for the assessment of land management and climatic impacts. Such information for poorly drained low gradient coastal watersheds is becoming increasingly important for sustainable development as population pressure and timber demand continue to rise in the southeastern United States.

Keywords: *poorly drained soils, forested wetlands, forest management, outflow (runoff), water budget, water quality, hydrologic modeling, DRAINMOD*

Introduction

Historical Development Before Hurricane Hugo (1989)

In the early 1960s, limited information on hydrologic processes, flooding patterns, and water balance components was available for the low gradient, forested wetlands of the humid coastal plain of South Carolina, though similar information and data were continuously becoming available for upland forests through the US Forest Service Coweeta Experimental Forest in North Carolina. With continuing growth in the timber industry, the public and landowners started to become concerned about impacts of forest management (harvesting, thinning, etc.) on runoff, soil moisture, and flooding on these low gradient poorly drained coastal plains in the southeastern United States. In order to address these issues, a first-order experimental watershed (WS 77) with a drainage area of 160 ha (~400 acres) was created in 1963 within the US Forest Service's 2468-ha Santee Experimental Forest (SEF), under the leadership of Dr. Cortland E. Young, Jr., and Dr. Ralph A. Klaiwitter at the US Forest Service Southeastern Forest Experiment Station in Charleston, South Carolina. The SEF was established in 1938, some 55 km northwest of Charleston (Figure 1; Appendix A) for scientific studies (Table 1). The main objectives of the first study were to quantify the evapotranspiration (ET) of a typical coastal plain pine forest, and evaluate the excess soil moisture status using detailed measurements of water budget components. In 1964 another, much larger, watershed (WS 78, 5000 ha [~ 12000 acres]) was added to study the precipitation-runoff relationships of two different-sized watersheds in coastal forest systems (Figure 1). Forest Service scientists, assisted by hydrologists at the U.S. Geological Survey in

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Figure 1. Location of experimental watersheds 77, 78, 79, and 80 within Francis-Marion National Forest, South Carolina (from 1964 map). Note that watersheds 77, 79, and 80 are within the 2468-ha Santee Experimental Forest, established in 1938.

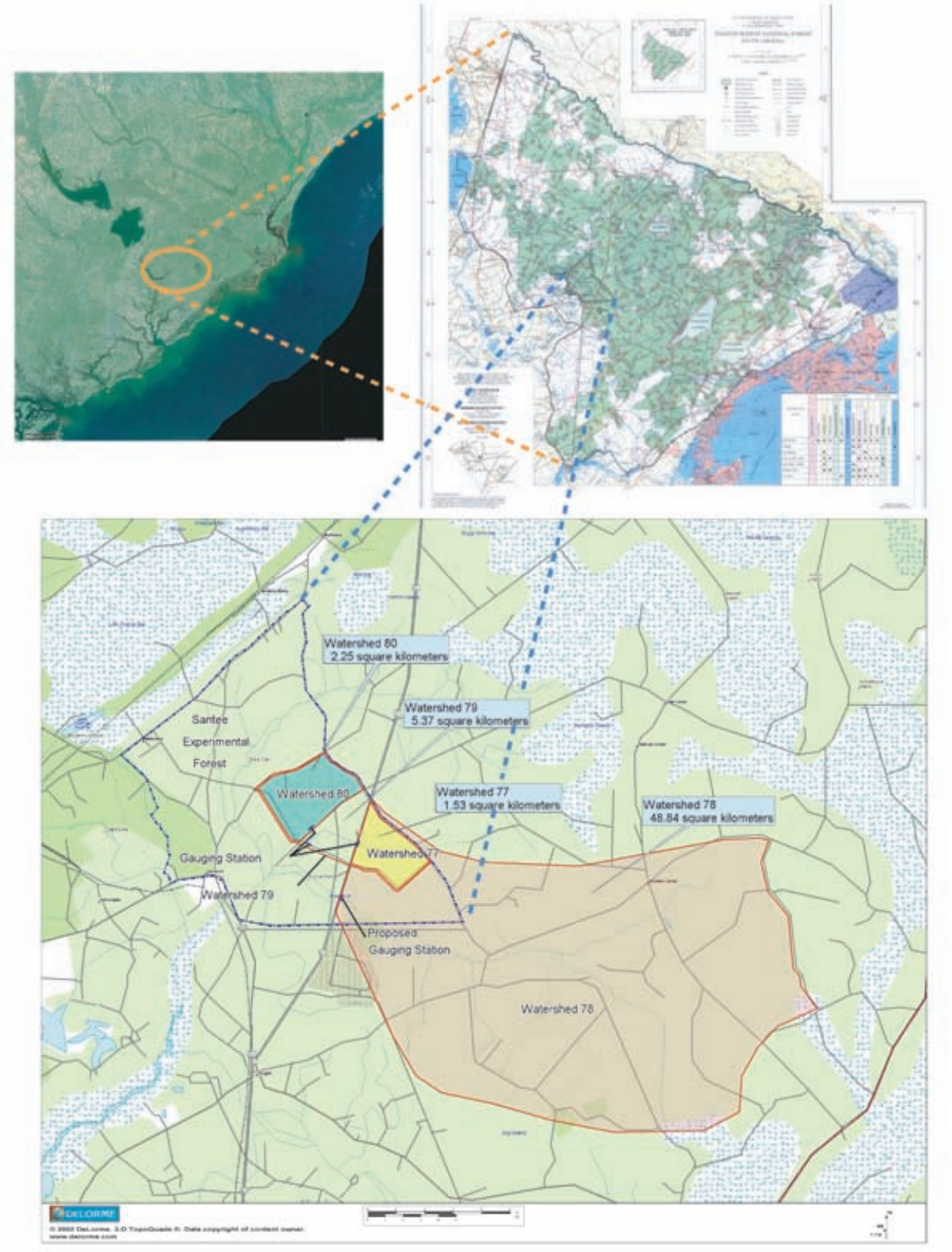

Table 1. Types and descriptions of infrastructure for each of the four watersheds at the Santee Experimental Forest, South Carolina.

Watershed No.	Drainage Area	Period of Record	Design of the Outlet	Associated Data	Condition	Needs
77 (Treatment) (First order, Fox Gully)	160 ha	1963-81; 1989 - present	Compound V-weir	Stage, Soil moisture, Water quality, GW levels, Met station	Good, monitoring continuing (No data 1981- 1989)	Analysis and publications of old data. Some ongoing.
78 (Turkey Creek)	5000 ha	1964-84; 2005 - present	Outlet in a dam	Stage, Velocity, Flow rates	Discontinued in 1984	Analysis and publications; Monitoring water quantity and quality is starting soon.
79 (Second order, Fox Gully)	500 ha	1966-73; 1989-90; 2003 - present	V-weir and 3-box culvert	Stage, Water quality	Good, monitoring continuing	Processing data analysis, Publications
80 (Control)	206 ha 155 ha since November 2001	1968-81; 1989- present	Compound weir	Stage, Water quality, GW levels, Met station, Throughfall	Good, monitoring continuing (No data 1981-1989)	Analysis of old data and publications ongoing.

Columbia, SC, installed a stream gaging station on WS 78 and collected data from 1964 to 1984 (Table 1).

Building upon the excellent cooperation between National Forest and Experimental Station, in 1965 Young and Klaiwitter added an additional gaging station on a 500-ha (~1200-acre) second-order watershed (WS 79) (Table 1, Figure 1, Appendix A). This provided an opportunity for Forest Service scientists and researchers to compare the effect of watershed size on precipitation-runoff relationships for these coastal forested wetlands, which would have been very difficult with only the original two watersheds (WS 77 and WS 78). While these studies were still ongoing, Young and Klaiwitter capitalized on the opportunity provided by the construction of Yellow Jacket Road by the Francis-Marion National Forest in 1968, by adding another 200-ha (~500-acre) experimental watershed (WS 80) draining to Fox Gully Branch (Figure 1; Appendix A). With the establishment of a flow gaging station in 1968 (Table 1), these four watersheds of varying sizes could be used to study not only the soil moisture and runoff processes, but also the effects of different types of treatments such as eradication of understory, clearcut, thinnings, drainage, and impoundments. A paired watershed approach was suggested with the fourth watershed (WS 80) as a control and the first watershed (WS 77) as a treatment for studying the effects of various silvicultural management treatments. The outlet systems on these watersheds were designed with compound v-notch weirs to accommodate high floods, as well as to hold sufficient water to support other management objectives such as timber, wildlife, forage and aquatic biota (Klaiwitter 1970). Some of the main objectives of these proposed studies on forested wetlands and their water resource and water management issues were outlined in the Southern Research Station (SRS) report (USDA FS 1963). All of these experimental watersheds were included in the inventory prepared by the American Geophysical Union (AGU 1965).

Monitoring was discontinued on the first-order, paired watersheds WS 77 and WS 80 in November 1982, and on the large watershed, WS 78, in November 1984. Data recording on the second-order watershed (WS 79) was not available after 1978. No further monitoring except for the weather station at the Santee Headquarters was conducted until October 1989, when Hurricane Hugo struck these experimental watersheds and forests. The chronology of activities on these watersheds is given in Table 2.

Developments after Hurricane Hugo (1989)

After Hurricane Hugo hit the experimental watersheds in late September 1989, the treatment watershed (WS 77) was salvage harvested. The control (WS 80) was not salvaged, with most of the trees, stumps, and branches left undisturbed in the forest. At the same time, recognizing a need to understand the hydrologic and water quality

Table 2. Chronology of watershed activities at Santee Experimental Forest.

Year	Description
1937	Santee Experimental Forest established
1946	Weather station for rain and temperature measurements established at Santee Headquarters
1963	Watershed WS 77 established as a treatment watershed
1964	Watershed WS 78 established as a large fourth-order watershed
1966	Watershed WS 79 established as a second-order watershed
1968	Watershed WS 80 established as a control watershed
1968	Flow monitoring initiated in November
1963 - 1968	Young and Klaiwitter studies
1974 - 1977	Binstock (1978) Study on WS 77 and WS 80
1976	Water quality monitoring initiated
1980	Richter (1980) and Richter et al. studies on WS 77 and WS 80
1981	Flow and water quality monitoring discontinued on all but WS 78
1984	Flow monitoring discontinued on watershed WS 78
1989	Hurricane Hugo damages the forest in September
1989	Both flow and water quality monitoring reactivated in November on watersheds WS 77, 79 and WS 80
1990	WS80 is non-salvage harvested (all roots, stumps, branches left intact on the watershed)
1990	Rain and temperature measurements established at Met25
1992	Manual wells established on WS 80 and WS 77
1994	Plots established for growth study (Hook et al. 1991)
1996	Automatic recording WL40 wells established on WS 80 and WS 77
1996	Electronic data loggers installed at Met25 (rain and temperature), CR10 Campbell Scientific data logger installed at Santee Headquarters weather station
1999	Long-term study of vegetation dynamics initiated (Burke 1998)
2000	Sun et al. study on WS 77 and WS 80
2001	Binkley (2001) study; Secondary outlet unplugged, reducing WS80 drainage area to 160 ha
2003	Miwa et al. study; Amatya et al. studies; WS 77 undergoes prescribed burning on 10 May; Throughfall monitoring on WS 80 begins; Backup flow meter installed on WS 79 and 80; Harder study begins on WS 80.
2004	A collaborative project to reinitiate monitoring of WS 78 on Turkey Creek and its hydrological study begins; Harder study completed with 2003-04 data.
2005	Streamflow monitoring on Turkey Creek begins in January; A collaborative study with Florida A&M University begins on this watershed; A new study on biomass removal by prescribed fire begins on WS 77, 79, and WS 80.

impacts of hurricanes and other natural disturbances, monitoring of both the water quantity (outflow) and quality were resumed.

Streamflow gaging stations on both the first-order (WS 77 and WS 80) and second-order (WS 79) watersheds were upgraded with automatic GL3150 (Global Water)[1] sensors with pressure transducers for recording stage height to estimate flow rates. Flow monitoring at the large fourth-order watershed (WS 78) was not resumed. A fully automatic CR10 (Campbell Scientific) weather station was installed in 1996 at the Santee Headquarters to monitor air temperature, humidity, wind speed and solar radiation needed for the estimates of evapotranspiration (ET). An additional sensor to measure net radiation was added in 2003. Watersheds WS 77 and WS 80 were also equipped with automatic stations – precipitation recorders in 1990, additional sensors to measure air and soil temperature in 1995. Several manual monitoring wells were installed on both of the first-order watersheds in 1990. Two shallow automatic recording wells were installed on WS 77 and one on WS 80 in 1992 (Appendix A). One additional deep automatic well was installed on WS 80 in 2003. Throughfall gages were also installed across watershed WS 80 in July-August 2003. A chronology of various activities that took place on these watersheds is shown in Table 2.

[1]The use of trade or firm names in this publication is for reader information and does not imply endorsement by the U.S. Department of Agriculture of any product or service.

Other Planned Monitoring

- To re-install the evaporation pan and monitoring device to measure pan evaporation at the weather station at Santee Headquarters.

- To install backup data loggers at WS 77 and WS 79 to insure against loss of flow data.
- To install piezometers on the control watershed (WS 80) to examine the deep groundwater fluxes in this system.
- To measure leaf area index (LAI) and stomatal conductance of the pine-hardwood stand on the control watershed (WS 80).
- To install the Eddy Flux tower to quantify the carbon and water fluxes on WS 80 with mixed pine-hardwood stands.

Data Analysis and Management

Most of the strip chart and magnetic tape data from the rain gages and flow recorders used on the watersheds before the Hurricane Hugo were sent to Coweeta Hydrologic Laboratory in North Carolina for digitizing into electronic formats. Precipitation, weather, flow (for WS 77, WS 79, and WS 80) and water table data were converted to digital formats. Accordingly, all data from 1964 through July 1999 have been checked for appropriate QA/QC (Gartner and Burke 2001) and then archived in a single Microsoft Access database. Efforts are underway to append the database with data from August 1999 to date. These data are currently being stored at the Center for Forested Wetlands Research in Charleston, South Carolina. Also based on a recent Memorandum of Understanding with Atlanta-based Tetra-Tech, Inc., flow data from watershed WS 78 for the period of 1964 to 1973 has been converted into digital formats. Data from 1974 to 1976, processed at Coweeta Hydrologic Laboratory, were already in digital formats, and no data have yet been found for 1977 to 1984. Only the field service records on paper formats are available through May 1984. The recorded stage heights taken every two to four weeks of the service period may be used to derive the discharges using the stage discharge relationship created in 1964.

The Center for Forested Wetlands Research (CFWR) at Southern Research Station Unit 4103 has recently participated in an Internet-based hydrologic data sharing program (HYDRODB 2004) developed by Oregon State University under the sponsorship of the US Forest Service and the National Science Foundation's Long Term Ecological Research (LTER) program (*http://www.fsl.orst.edu/climhy/hydrodb/harvest.htm*). CFWR has also posted hydrologic and metadata from Santee Experimental Forest watersheds WS 77 and WS 80 on HYDRODB for internet based data sharing where researchers and users can download data for inter-site comparisons and various other research and study purposes.

Results To Date

Only a limited amount of information was published from data measured between 1964 to 1982 on these experimental watersheds. Young and Henderson (1965, 1966) published the procedures for measurement of soil moisture and pan evaporation, respectively, at the study site. Young (1966) reported a two-year water budget for the treatment watershed (WS 77), concluding that excess water in the form of runoff could be problematic in downstream flooding, and that there was no dependable base flow generated from this natural watershed. Young (1967) also described the flooding pattern, flashiness, and effects of storage on these forested lands in controlling the outflow processes. The limited records then showed that the Santee watershed (WS 77) tended to release rainfall more quickly than do other forested areas in the Southeast. Young and Klaiwitter (1968) found the total runoff varying between 427 to 869 mm for three above-average rainfall years, yielding 38% on average of the total rainfall lost to runoff from WS 77. Young et al. (1972) also presented an analog version of a hydrologic model for a wetland forest at this site. Significant works evaluating the hydrologic and water quality effects of prescribed burning using the paired watershed approach on WS 77 and WS 80 were published by Binstock (1978), Richter (1980) and Richter et al. (1983a, 1983b). Binstock (1978) found no significant effects on the water quality or the soil chemistry of the experimental watershed following a prescribed winter burn. Richter (1980) found an average annual outflow to precipitation ratio of 27% (with a range of 15% to 43%) for 1965 to 1978 for WS 77, while an average ratio of 20% (with a range of 12% to 30%) was found on the control, WS 80, from 1970 to 1978. No published information has yet been found on the fourth-order Turkey Creek watershed (WS 78) and the second-order Fox Gully Creek watershed (WS 79) (Figure 1).

Hook et al. (1991) published some information on the impacts of Hurricane Hugo. Sun et al. (2000) evaluated the water budgets and water table pattern of the two experimental watersheds, finding average annual outflow to precipitation ratios of 30% for WS 80 and 23% for WS 77. Later, Binkley et al. (NCASI 2001) published water chemistry data from these two watersheds in their study of the nutrient concentrations of over 300 streams in small, forested watersheds across the continental United States. Miwa et al. (2003) studied the stream flow dynamics and hydrograph characterization of these watersheds. They demonstrated that headwater stream flow was highly responsive to rain events and that the stream processes are regulated by rainfall intervals, antecedent soil moisture, vegetation, soil types, and physical characteristics of

the watershed including topography and surface water storage.

More recently, Amatya et al. (2003a) compared the six-year hydrology of the control watershed (WS 80) with that of an artificially drained watershed in eastern North Carolina. Results showed that WS 80 had much shallower water table depths with higher frequency outflows as compared to the North Carolina watershed, even though WS 80 had lower average annual rainfall. Amatya et al. (2003b) also tested a DRAINMOD hydrology model developed for poorly drained soils to evaluate the hydrology and water budget of WS 80, and demonstrated the potential of the model to accurately describe the hydrology of natural forested wetland given reliable inputs of soils and weather data. Most recently, Harder (2004) completed a study characterizing the detailed water budget of the control watershed (WS 80).

Because of the extended period of near-surface water table elevations caused by large storm events in 2003, with the highest annual rainfall (1671 mm) in 14 years (1990-2003), the stream runoff for the control watershed accounted for as much as 48% of the total rainfall. The results of the study served both to characterize hydrologic processes (runoff, water table response to rainfall, ET and soil moisture dynamics), and to quantify the water budget for a wet year (2003) and dry winter/spring season (2004) of the first-order forested watershed. Harder also provided a most comprehensive review of the studies conducted so far on this watershed. Some of the information on the Santee experimental watersheds is also reported in a recent publication by Amatya et al. (2004a).

Recent Ongoing Studies

Recent studies on the Santee Experimental Forest watersheds aim to:

- Use the historical flow and water quality data from the first-order control watershed (WS 80) and sample storm events from the second-order watershed (WS 79), for estimating reference loads for comparison with developed watersheds in the region, and also for developing a Total Maximum Daily Load (TMDL) for Charleston Harbor, in collaboration with Atlanta-based Tetra-Tech, Inc. and Charleston-based JJ&G Engineering Consultants (Miller and Amatya 2004).
- Use the historical data from three experimental watersheds (WS 79, WS 80, and WS 78) for the comparison of rainfall-runoff relationships, flow duration curves and flood frequency analyses (Amatya and Radecki-Pawlik 2005).
- Test the hydrology of the control watershed (WS 80) using a physically-based distributed model (MIKE-SHE) and apply the model for evaluation of management impacts in collaboration with the US Forest Service, Southern Global Change Program.
- Use field-measured data and water budget from the control watershed (WS 80) to refine the testing of DRAINMOD model and compare results with the Thornthwaite water balance model (Thornethwaite and Matther 1955).

Rationale for Continuing Future Studies

The hydrologic and water quality effects of silvicultural management practices including prescribed burning, harvesting and thinning have been a major area of research in the southeastern United States. The Southern Forest Resource Assessment (SOFRA 2002) emphasized a need for research to assess the long-term cumulative non-point source impacts of silvicultural activities on water quality and overall watershed health. The dominant water quality issues are sediment, roads (as sources of sediment), nutrients, fires, (as sources of sediment and nutrients), pesticides and water temperature (Jackson et al. 2004). Although studies to address some of these issues have been done in the past (Riekerk 1989; Ursic 1991; Shepard 1994; Amatya et al. 1997; Sun et al. 2000, 2001; Xu et al. 2002; Amatya et al. 2004b), these studies were either mostly limited to hydrology or covered only a shorter period.

Prescribed burning as a forest management tool, as developed in the Atlantic Coastal Plain (Richter et al. 1982), specifically at the Santee experimental watersheds, was shown to have insignificant effects on the quality of ground and surface water. It reduces fuel loads, controls certain tree pathogens, improves wildlife habitat, and restores desired ecosystems. Few data are available, however, on the effects of this management tool on the hydrology and water quality of wetlands (Jackson et al. 2004). Similarly, solid data on forest fertilization effects and the effects of various best management practices (BMPs) on water quality are lacking for poorly drained coastal forests.

In order to understand and assess these impacts on forested wetlands as affected by year-to-year variation in climate, it is necessary to develop water and nutrient budgets using long-term data. Long-term hydrologic data are essential for understanding hydrologic processes, as baseline data for assessment of impacts and conservation of regional ecosystems. At the same time, they are also very crucial for developing and testing hydrologic and water quality models for answering questions that are difficult to investigate by monitoring, either due to spatial and temporal scale issues, or to complex interactions of parameters on these poorly drained low-gradient systems.

A large quantity of data for wet pine flats (managed plantations) and their impacts on hydrology and water quality in the coastal North Carolina exists in the literature (Amatya et al. 2004b). These systems are established on artificially drained lands, and also intensively managed for timber production. However, little information is available on naturally drained forests of pine mixed with hardwood stands. The forests at the Santee experimental watersheds are managed and operated by the Francis-Marion National Forest for forest and wildlife conservation practices, reducing risks of wild fire, and also for timber management.

A recent study comparing an artificially drained managed pine forest with conventional ditches (25 ha) in coastal North Carolina with a naturally drained less managed mixed (pine-hardwood) forest (200 ha) in coastal South Carolina showed that the latter had much shallower water table depths with higher frequent outflows as compared to the artificially drained one, even though the latter had lower average annual rainfall (Amatya et al. 2003b). This suggests that drainage alone does not necessarily determine total outflow, which may also depend upon the soil type and the argillic horizon. Therefore, data from these headwater coastal forested watersheds, which are distinct from the drained, managed pine forests, are extremely valuable and need analysis and interpretation for scientific studies and assessment of impacts.

As envisioned by earlier Forest Service researchers in the 1960s, the information on water budgets and effects of watershed sizes on precipitation-runoff relationships, hydrograph shapes, flow patterns (magnitudes and distributions) can be very useful for planners and designers in forest management, water and nutrient management, flood control structures, wetland restoration and conservation in the naturally drained low gradient forested lands of the coastal plain. Such data are becoming even more vital as the population pressure and development near the coastal waters continues to increase in the southeastern U.S. The long-term data available for these experimental watersheds for 20 years or more can serve as a reference for evaluating impacts of developing these coastal forests and also as a basis for developing predictive equations in similar ungaged basins in the region (Wagener et al. 2004). Furthermore, these data can be used to analyze the trend of outflows as affected by changes in land use and climatic variation. As an example, flow and water chemistry data from the experimental control watershed (WS 80) for the period 1976-81 and 1989-92 and the recent (2004) storm event sampling data on the second-order watershed (WS 79) are being used as a baseline for reference, undeveloped watershed loads for comparing loads from developed lands in the Charleston Harbor watershed, for which a water quality model is being developed (Lu et al. 2005). These experimental watersheds are also continuously being used as a field laboratory for learning forest hydrogeologic research by students at the College of Charleston, South Carolina.

With the support from the US Forest Service, Southern Research Station, the Center is doing its best to keep up these experimental watersheds as the only long-term coastal forest experimental station in the Southeast for continuing eco-hydrologic studies, along with other scientific studies including prescribed burning, regeneration and management of bottomland hardwoods, restoring wetland hydrologic functions, and carbon sequestration on the coastal forest ecosystems to provide the knowledge needed for their sustainable management. These objectives are consistent with the recommendations of a recent workshop to discuss the role of coastal zone in global biogeochemical cycles (Siefert 2004), and may also help advance hydrologic science in the 21st century (CUAHSI 2003). Most importantly, continuing research at Santee Experimental Forest will help realize the visions of our Forest Service predecessors who installed the experimental watersheds in 1963 as a pilot laboratory for South Carolina and adjacent states (Young 1967).

Future Planned Studies

Future research efforts at the Santee experimental watersheds will:

- Compare the hydrology and water quality of two first-order watersheds (WS 77, treatment) and (WS 80, control) using data before and after Hurricane Hugo.
- Use both the first-order paired (WS 77, WS 80) and part of the second-order (WS 79) watersheds for studying both the plot- and watershed-scale effects of biomass removal by thinning and prescribed burning on nutrient cycling and transport.
- Study the water quality effects of partial prescribed burning on the treatment watershed (WS 77) using the paired watershed approach with WS 80 as a control.
- Revitalize the watershed-scale study on the third-order Turkey Creek Watershed (WS 78). This is consistent with one of the Forest Service goals (2004-08) to monitor water quality impacts of activities on National Forest lands.

Revitalization of the Watershed-Scale Study on Turkey Creek Watershed (WS 78)

As a result of continued collaborative efforts to develop and expand the studies on existing experimental watersheds at Santee Experimental Forest, a recent study proposal to

revitalize the abandoned watershed-scale study at Turkey Creek watershed (WS 78) (Figure 1) was funded by the Forest Service Southern Research Station Challenge Cost Share Program matching the funds provided by National Council of Air and Stream Improvement (NCASI), Inc. The 5,000-ha watershed has 52% forest cover (mostly within the Francis-Marion National Forest), 28% wet shrubs and scrub, 14% wetlands and water, with the remaining 6% developed for agricultural lands, roads and open areas (Figure 2).

The main objectives of the study are to resume the hydrologic monitoring of the watershed, followed by water quality sampling. The data from past and current monitoring will be used: (a) to compare the flow dynamics among three experimental watersheds of various sizes; (b) to examine the pre- and post-hurricane flow dynamics; (c) to study the effects of land use change and, possibly, the climatic variation on the water yield and flow dynamics (Figure 2); (d) as baseline data for evaluating impacts; and (e) to develop and test DRAINMOD-based and other watershed scale hydrologic models for these poorly drained sites to predict the flow dynamics, water budget and impacts on hydrology and water quality. These modeling studies will also be able to specifically address questions about the cumulative effects of harvesting, thinning, prescribed burning, and biomass removal on hydrology and water quality. Other benefits may include predicting the spatial and temporal distribution of surface and groundwater tables, wetland hydrologic functions, and nutrient and sediment exports. The results will help the national forest manage its lands, roads and trails for operational purposes such as reducing fire hazards, restoration, water management, and transportation needs. The watershed may also be a potential site for studying effects of various forest BMPs, land management practices, and ecological and biogeochemical processes including carbon sequestration and methane (CH_4) gas flux dynamics. Furthermore, the site may be a candidate for testing new monitoring technologies such as ADV (Acoustic Doppler Velocity) measurement on slow-moving streams, remote sensing for deriving LAI for over- and under-story vegetation, temperature, soil moisture, and albedo, and Doppler-based precipitation, as needed for large scale hydrology modeling.

The current supporters and collaborators in this study include: the US Forest Service, Southern Research Station, for funding support; National Council of Air and Stream Improvement (NCASI), Inc., for partial funding support; Center for Forested Wetlands Research, SC, as principal investigator (PI); College of Charleston, South Carolina, as Co-PI, research collaborator; University of Krakow, Poland, as a research collaborator; Francis-Marion National Forest, SC, for watershed GIS database and other information support; the US Geological Survey, SC, for installation, servicing and data collection at stream gaging station; Tetra-Tech, Inc., Atlanta, Georgia, as a cooperator in data digitizing and sharing, and South Carolina Department of Transportation for giving access for installation of the gaging station.

Preliminary Work on Turkey Creek Watershed

So far, work on the Turkey Creek experimental watershed (WS 78) has encompassed the following activities:

1. Processing and analysis of daily flow data from the watershed for 1964 to 1976.

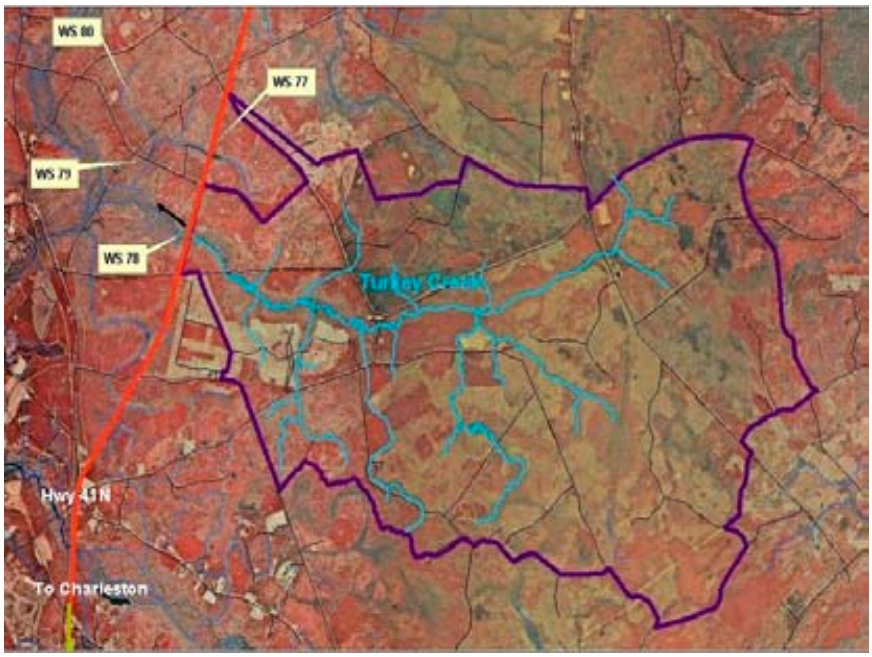

Figure 2. Land use distribution map of 5,000-ha Turkey Creek watershed (WS 78).

2. Flow frequency duration analysis.

3. Development of flood frequency curves and comparison with smaller watersheds (WS 80 and WS 79) in the vicinity.

4. Determination of rainfall-runoff relationships and comparison with WS 80 and WS 79 (Figure 3).

5. A collaborative agreement with the Agricultural University of Krakow, Poland for conducting the hydrologic study on Turkey Creek watershed.

6. A paper documenting the preliminary results of comparison of stream flow dynamics of watersheds (WS 77, WS 80, and WS 79) for the 2005 ASAE Annual conference (Amatya and Radecki-Pawlik 2004).

7. Acquisition of satellite imagery, aerial photographs, and GIS data layers on topography, hydrography, soils, and land use (US Forest Service, Francis-Marion and Sumter National Forest Office, SC).

8. Acquisition of similar GIS data layers from Berkeley County Office, SC.

9. Acquisition of historic aerial photographs, GIS layers and data base on forest management practices within Turkey Creek watershed (Francis-Marion National Forest).

10. A cooperative agreement between the Center and College of Charleston for the installation of a stream gaging station at the outlet of Turkey Creek watershed and for a student assistant for data processing and field work.

11. A cooperative agreement between the College of Charleston and USGS District Office in Columbia for the complete installation, servicing and real-time data retrieval, QA/QC and data sharing through the Internet.

12. An agreement between USGS and the South Carolina Department of Transportation (DOT) for the installation of and access to the monitoring gage within the right-of-way of the new bridge being built at Turkey Creek on Highway 41N.

13. A first cooperators' project meeting took place on 9 December 2004. The USGS collaborator reported that the gaging station on Turkey Creek will be installed by January 2005. Questions and discussions on multiple hydrology related research issues such as spatial moisture predictions, flooding, ET estimates, sampling for mercury, assessment of geomorphological characteristics, etc., were raised by the cooperators.

14. A temporary stream gaging station and a rain gage were installed on 16 December 2004. They will collect data until the permanent gages are installed after the construction of the new bridge on Highway 41 (Turkey Creek).

15. A PhD candidate from the Civil and Environmental Engineering Department at Florida A&M University has planned to conduct his field research related to wetland hydrologic functions on this watershed.

16. A fourth project cooperators' meeting is planned for 27 July 2006.

17. Turkey Creek Watershed initiatives were recently featured in Forest Service Southern Research Station's Compass Magazine (From Mountain Headwaters to the Sea), Issue 5, Spring 2006.

The re-initiation of the large, forested watershed study (5,000 ha) on the South Carolina coastal plain, with support from the USFS Southern Research Station and the NCASI, Inc., completes the development of a multi-scale hydrology and ecosystem monitoring framework. The current milestone, re-initiating the gaging of the Turkey Creek Watershed, represents the fulfillment of a gaging network encompassing 1st-, 2nd- and 3rd-order streams; thereby facilitating the examination of the interactions of land use or disturbance regime with streamflow and nutrient export dynamics at multiple scales. For example, historic stream flow data prior to Hurricane Hugo (1989) may be examined with post-disturbance data. The Turkey Creek Watershed Study is a multi-collaborator effort, with precipitation and stream flow data being collected continuously as a part of the US Geological Survey's real-time stream monitoring network. The College of Charleston has installed deep groundwater table wells, and the Francis Marion National Forest is helping to install multiple shallow wells to enable the assessment of surface-subsurface flow interactions, and stream water quality sampling stations will be installed by the Forest Service in cooperation with the USGS during summer 2006.

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Appendix A. Santee Experimental Paired Watersheds Characteristics

a. Established in 1965 within the US Forest Service's Francis-Marion National Forest, South Carolina
b. A paired watershed approach on flat, poorly drained soils of lower Atlantic coastal plain
c. WS 80: 200 ha – Control; WS 77: 160 ha – Treatment, WS 79: 500 ha – 2nd-order watershed
d. On 1st-order headwater streams - Tributary of Turkey Creek within the Cooper River Basin
e. Surface elevations from 4.0 to 10.0 m above mean sea level
f. Soils: Primarily loams strongly acidic characterized by seasonally high water tables and argillic horizons at 1.5 m depth
g. Vegetation: Loblolly pine (*Pinus taeda*), longleaf pine (*Pinus palustris*), baldcypress (*Taxodium distichum*) and sweet gum (*Liquidambar styraciflua*)
h. Mean annual rainfall: 1220 mm; Mean annual temperature: 18°C

Satellite image of three experimental watersheds (77, 79, and 80) draining to Turkey Creek (a new watershed scale study) within Santee Experimental Forest with gaging stations (triangular symbols) and Santee Headquarters Weather Station.

Watershed related Web sites:
http://www.srs.fs.usda.gov/charleston/santee.html
(For general information)
http://www.fsl.orst.edu/climhy/hydrodb/harvest.htm
(For metadata and data harvesting)
The monitoring and watershed studies are maintained by US Forest Service, Southern Research Station, Center for Forested Wetlands Research (SRS-4103), 2730 Savannah Highway, Charleston, SC 29414. For further information about the study sites contact: Dr. Devendra M Amatya, Ph.D., P.E., Research Hydrologist, Tel: 843-769-7012; damatya@fs.fed.us

Understanding the Hydrologic Consequences of Timber Harvest and Roading: Four Decades of Streamflow and Sediment Results From the Caspar Creek Experimental Watersheds

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The Caspar Creek Experimental Watersheds were established in 1962 to study the effects of forest management on streamflow, sedimentation, and erosion in the rainfall-dominated, forested watersheds of north coastal California. Currently, 21 stream sites are gaged in the North Fork (473 ha) and South Fork (424 ha) of Caspar Creek. From 1971 to 1973, 65% of the timber volume in the South Fork was selectively cut and tractor yarded, and from 1985 to 1991, 50% of the North Fork basin was harvested, mostly as cable-yarded clearcut. The South Fork logging resulted in annual suspended sediment load increases exceeding 300%. Mass-wasting has been predominantly associated with roads, landings, and tractor skid trails in the South Fork. Accelerated mass-wasting and renewed sediment mobilization in the South Fork have occurred since 1998. Peak flow increases detected following North Fork logging are attributable to reduced canopy interception and transpiration. These recovered to pretreatment levels about 10 years after logging, followed by renewed increases from pre-commercial thinning. Annual sediment loads increased 89% in the partially clearcut North Fork and 123% to 238% in 4 of 5 clearcut sub-basins. Twelve years after logging, elevated storm-event sediment yields persist in some clearcut tributaries.

Keywords: *experimental watershed studies, road effects, sediment yield, peak flows, erosion, timber harvesting*

Introduction

For more than four decades, researchers have investigated the effects of forest management on streamflow, sedimentation, and erosion in the Caspar Creek Experimental Watersheds. The California Department of Forestry and Fire Protection and the USDA Forest Service, Pacific Southwest Research Station, began a simple paired watershed study in 1962 with the construction of weirs on the two major Caspar Creek tributaries, the North Fork (NFC) and the South Fork (SFC). Today, researchers operate 21 gaging stations within the experimental watersheds and use data loggers programmed with sophisticated sampling algorithms, instream turbidimeters, and automated pumping samplers to measure water and sediment discharge. Although much of this research is devoted to quantifying the impacts of modern forest management, it also provides valuable data on hydrologic recovery and the lingering effects of more than a century of timber harvest and roading in the Caspar Creek basin.

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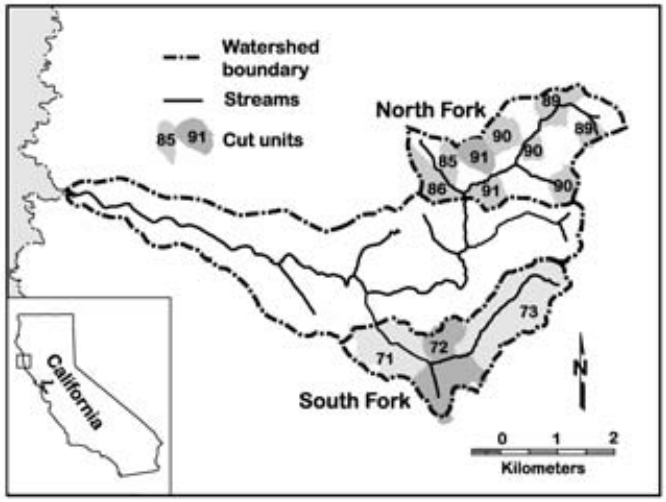
Methods

Site

The Caspar Creek Experimental Watersheds are located about 7 km from the Pacific Ocean and about 10 km south of Fort Bragg in northwestern California at lat 39°21′N, long 123°44′W (Figure 1). Uplifted marine terraces incised by antecedent drainages define the youthful and highly erodible topography with elevations ranging from 37 to 320 m. Hillslopes are steepest near the stream channel and become gentler near the broad, rounded ridgetops. About 35% of the basins' slopes are less than 17 degrees, and 7% are steeper than 35 degrees. Soils are well-drained clay-loams, 1 to 2 meters in depth, derived from Cretaceous Franciscan Formation greywacke sandstone and weathered, coarse-grained shale.

Figure 1. Caspar Creek Experimental Watersheds.



The climate is typical of low-elevation coastal watersheds of the Pacific Northwest. Winters are mild and wet, characterized by periods of low-intensity rainfall delivered by the westerly flow of the Pacific jet stream. Snow is rare. Average annual precipitation is 1,170 mm. Typically, 95% of precipitation falls during the months of October through April. Summers are moderately warm and dry with maximum temperatures moderated by frequent coastal fog. Mean annual runoff is 650 mm.

Like most of California's north coast, the watersheds were clearcut and broadcast burned largely prior to 1900. By 1960, the watersheds supported an 80-year-old second-growth forest composed of coast redwood (*Sequoia sempervirens*), Douglas-fir (*Pseudotsuga menziesii*), western hemlock (*Tsuga heterophylla*), and grand fir (*Abies grandis*). Forest basal area was about 700 m^3/ha.

Measurements

The 473-ha North Fork of Caspar Creek and the 424-ha South Fork of Caspar Creek have been gaged continuously since 1962 using 120° v-notch weirs widening to concrete rectangular sections for high discharges. During the early 1980s, three rated sections were constructed upstream of the North Fork weir and 10 Parshall flumes were installed on North Fork subwatersheds with drainage areas of 10 to 77 ha.

Stream discharge was initially recorded using mechanical chart recorders. These were replaced in the 1980s with electronic data loggers equipped with pressure transducers. Early suspended sediment estimates were derived from sediment rating curves, manual depth-integrated sampling, and fixed stage samplers (Rice et al. 1979). Statistically based sampling algorithms that trigger automated samplers were used beginning in the 1980s (Lewis et al. 2001). In addition, the sediment accumulation in the settling basin upstream of each weir has been surveyed annually.

Periodic field surveys have documented the location, size, and disposition of landslides and fluvial erosion. Erosion features greater than 7.6 m^3 (10 yd^3) have been inventoried annually since 1986 in the North Fork, and since 1994 in the South Fork.

Treatments

After establishing a calibration relationship between the North Fork and the South Fork (1963 to 1967), a main-haul logging road and main spurs were built in the South Fork. The road right-of-way occupied 19 ha, from which 993 m^3/ha of timber was harvested. The entire South Fork watershed was logged and tractor yarded between 1971 and 1973 using single-tree and small group selection to harvest 65% of the stand volume. Roads, landings, and skid trails covered approximately 15% of the South Fork watershed area (Ziemer 1981). Almost 5 km of the main-haul and spur roads (out of approximately 10 total km) were decommissioned in 1998.

A study of cumulative effects began in 1985 in the North Fork watershed. Three gaged tributary watersheds within the North Fork were designated as controls while seven were designated for harvest in compliance with the California Forest Practice Rules in effect in the late 1980s. Two units (13% of the North Fork watershed) were clearcut in 1985-86. After calibration, clearcut logging began elsewhere in the North Fork in May 1989 and was completed in January 1992. Clearcuts occupied 30-99% of treated watersheds and totaled 162 ha. Between 1985 and 1992, 46% of the North Fork watershed was clearcut, 1.5% was thinned, and 2% was cleared for road right-of-way (Henry 1998).

In contrast to the harvest treatment of the South Fork in the 1970s, state rules mandated equipment exclusion and 50% canopy retention within 15 to 46 m of watercourses providing aquatic habitat or having fish present. Most of the yarding (81% of the clearcut area) was accomplished using skyline-cable systems. Yarders were situated on upslope landings constructed well away from the stream network. New road construction and tractor skidding was restricted to ridgetop locations with slopes generally less than 20% and affected only 3% of the watershed area. Four harvest blocks, 92 ha total, were broadcast burned and later treated with herbicide to control competition (Lewis et al. 2001). Pre-commercial thinning in 1995, 1998 and 2001 reduced basal area in treated units by about 75%.

Results

Streamflow

Previous publications detail the magnitude and duration of streamflow enhancements following timber harvest in the Caspar Creek basins (Ziemer 1981, 1998; Lewis et al. 2001; Keppeler and Lewis, in press). In the North Fork, the average storm peak flow with a two-year return period increased 27% in the clearcut watersheds (Ziemer 1998) and 15% in the partially clearcut watersheds. Ongoing measurements show a return to pre-treatment flow conditions on NFC approximately 10 to 11 years post-harvest except for a renewed response to the pre-commercial thinning. Of particular interest is that even under the wettest antecedent moisture conditions of the NFC study, increases averaged 23% in clearcut watersheds and 3% in partially clearcut watersheds. These results are explained by wetter soils in logged units resulting from reduced transpiration and increases in net precipitation due to reduced canopy interception after clearcutting (Reid and Lewis, in press).

Sediment Loads

Sediment load estimates for the North Fork and South Fork are the sum of the sediment deposited in the weir pond and the suspended load measured at the weir. Comparison of sediment loads produced following the 1971-73 harvest of South Fork and the 1989-92 harvest of North Fork must be made cautiously. Improved and more intensive sampling methods greatly enhance the accuracy of load estimates for the latter study. Large landslides in the North Fork in 1974 and 1995, and the 1985 harvest in the North Fork complicate the analysis.

South Fork suspended sediment loads increased 335% (1,475 kg ha^{-1} yr^{-1}) after road building and averaged 331% (2,877 kg ha^{-1} yr^{-1}) greater during the 6-year period after tractor logging. Annual sediment load (including suspended and pond accumulations) increased 184% for the 6-year post-harvest period 1972-1978 returning to pretreatment levels in 1979 (Lewis 1998).

North Fork annual sediment loads increased 89% (188 kg $ha^{-1}yr^{-1}$) in the partially clearcut watershed and between 123% and 238% (57 to 500 kg ha^{-1} yr^{-1}) in 4 of 5 clearcut basins during the 1990-96 post-harvest period (Lewis 1998). The load decreased by 40% (551 kg ha^{-1} yr^{-1}) in one clearcut basin. Sediment loads in some North Fork tributaries remained elevated through hydrologic year 2003, twelve years after harvest (Keppeler and Lewis, in press).

Although Thomas (1990) reported that SFC sediment concentrations appeared to be returning to pre-treatment levels in the early 1980s, analysis of more recent data suggests renewed sediment mobilization. The 1998 and 1999 pond depositions were the largest on record at SFC, but not exceptional at NFC. A double mass plot of pond accumulations indicates an increase in deposited sediments at SFC relative to NFC starting in 1998. The same is true to a lesser extent in suspended sediments (Figure 2). Regression analysis of SFC versus NFC pond accumulations indicates a significantly higher slope for the period 1998-2004 compared to 1974 -1997.

Since the suspended sediment data have better temporal and spatial resolution, Lewis' 1998 analysis of NFC was extended using storm load data from control tributary gages H and I to investigate whether the relative change in suspended sediment was due to changes in the North Fork, changes in the South Fork, or both. A plot of the percentage departures from the prelogging (1986-1989) regression of NFC versus HI, shows elevated sediment levels for 1993-1998 only (Figure 3). An analogous plot for SFC versus HI shows elevated sediment levels for some small events in 1993-1997, but most consistently for all

Figure 2. Double mass curve of South Fork pond accumulations and suspended sediment relative to North Fork 1986 through 2004.

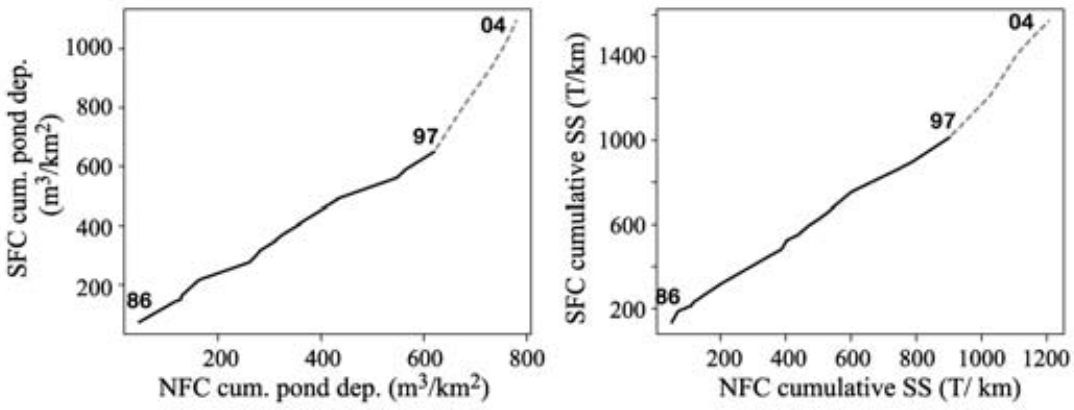
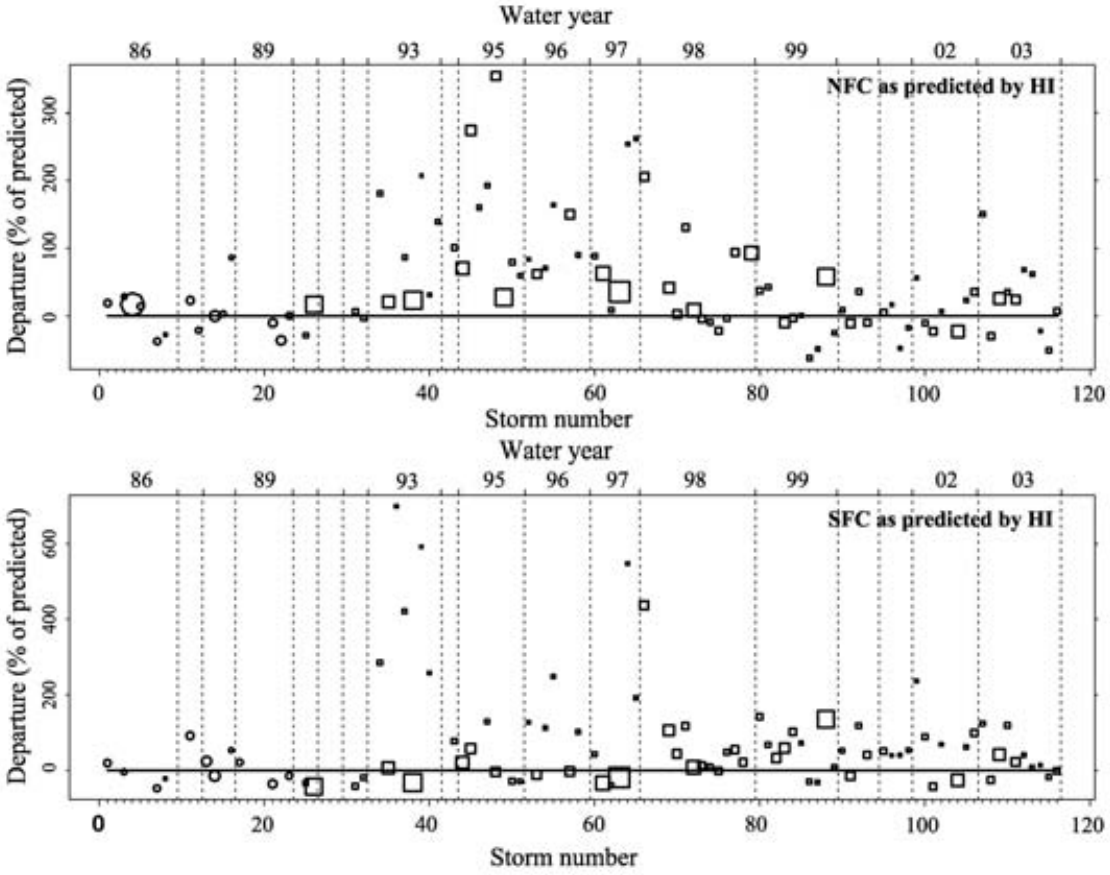


Figure 3. Suspended sediment percentage departures from the 1986-1989 regressions of NFC and SFC versus two untreated North Fork Controls (HI). Marker size is relative to HI storm load.



size events in 1998-2003. Thus the change in relation between NFC and SFC starting in 1998 appears to be a combination of declining loads at NFC and increasing loads at SFC.

To be more rigorous and quantitative about the suspended sediment changes, the gaging records were broken into three periods: NFC prelogging (1986-1989), NFC postlogging (1990-1997), SFC "episode" (1998-2003). These periods included 23, 41, and 52 storm events, respectively. Log-log regression models were fit relating NFC and SFC to HI for the three periods and tested to determine if a unique slope or intercept was appropriate for each period (Figure 4). For the NFC model, a parallel regression model with three intercepts and one slope was adequate. For the SFC model three intercepts and three slopes needed to be retained. Nine post-hoc comparisons of intercept and slope for each period were made. The NFC parallel regression for the 1990-1997 period was significantly different (higher) than either of the other periods, and the SFC 1990-1997 regression had significantly different (lower) slope than the 1998-2003 period. The SFC 1986-1989 slope was similar to the SFC 1998-2003 slope, but did not differ significantly from the 1990-1997 period, possibly due to the smaller number of storms in 1986-1989 compared to 1998-2003 (Table 1).

Table 1. Comparison of regression and intercepts (NFC and SFC) and slopes (SFC only) for three different time periods. Bonferonni's procedure was used to limit the experimentwise error rate to 0.05 which requires setting the pairwise comparison error rates to 0.05/9 = 0.0056. By this criterion, the only significant differences were (1), (3), and (9).

	Comparison	Significance (p)
1	NFC 90-97 intercept to NFC 86-89 intercept	0.000014
2	NFC 98-03 intercept to NFC 86-89 intercept	0.50
3	NFC 98-03 intercept to NFC 90-97 intercept	0.00000032
4	SFC 90-97 intercept to SFC 86-89 intercept	0.039
5	SFC 98-03 intercept to SFC 86-89 intercept	0.096
6	SFC 98-03 intercept to SFC 90-97 intercept	0.40
7	SFC 90-97 slope to SFC 86-89 slope	0.096
8	SFC 98-03 slope to SFC 86-89 slope	0.983
9	SFC 98-03 slope to SFC 90-97 slope	0.00037

Table 2. Summary of post-disturbance Erosion Features greater than 7.6m³.

	South Fork Caspar				North Fork Caspar			
	#	Volume (m^3)	m^3/ha	Delivery	#	Volume (m^3)	m^3/ha	Delivery
Post-disturbance[1]	130	65312	154	na	116	6496	14	40%
road-related	115	41706	98	68%	7	424	1	8%
wind-related	5	13985	33	na	74	1466	3	29%
> 1000 m^3	18	52120	123	na	1	3605	8	46%
100-1000 m^3	38	10507	25	na	5	944	2	26%
HY1990-2004	38	5804	14	61%	147	9121	19	45%
road-related	34	5557	13	63%	10	2495	5	52%
wind-related	4	264	1	21%	86	1732	4	27%
> 1000 m^3	0	0	0	na	2	5618	12	52%
100-1000 m^3	12	4961	12	62%	5	944	2	26%

[1] *Includes hydrologic years 1968-1976 on South Fork, 1990-1998 on North Fork.*

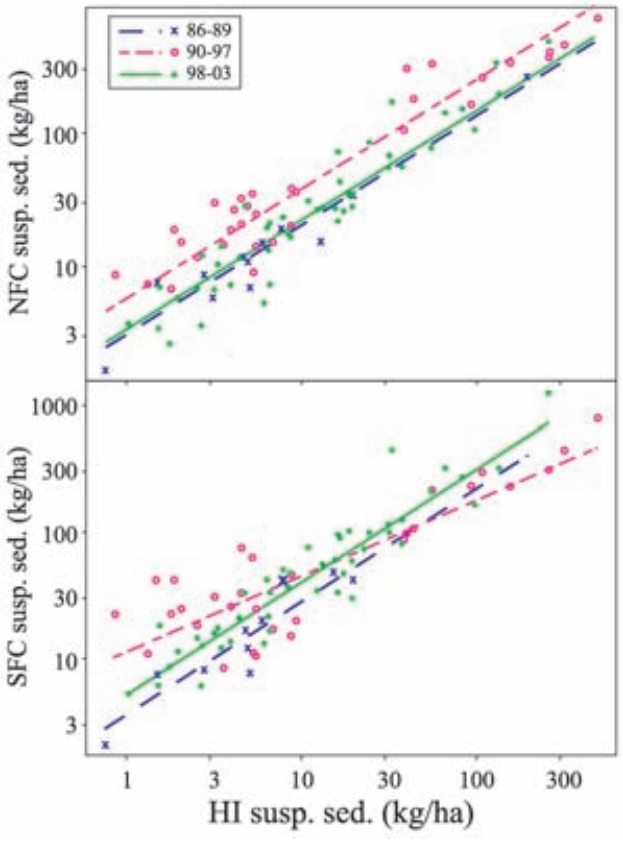
Based on the 1986-1989 relations, the observed sediment from NFC exceeded the predicted sediment by 49% in 1990-1997 and by 12% in 1998-2003. The corresponding numbers for SFC were -20% and +45%, but the only significant difference for SFC was the slope between the last two periods. Based on the 1990-1997 period, the observed sediment from SFC 1998-2003 exceeded the predicted sediment by 36%. If the 1986-1989 and 1990-1997 periods are combined to predict suspended sediment for 1998-2003, the observed sediment from SFC exceeded the predicted sediment by 47% (185 kg ha^{-1} yr^{-1}). (Compared to the 1986-1989 regression, the combined regression predicts lower loads in large storms above ~50 kg/ha at HI.) Thus, it is only during relatively large storm events (> 20 kg/ha at HI) that SFC suspended sediment systematically exceeds the pre-1998 relationship (Figure 4).

Erosion

Erosion inventory data helps to explain sediment load changes. As with sediment loads, improved protocols provide more detailed information on mass-wasting processes than is available for the earlier SFC inventories. Inventories have been more frequent and more intensive on the North Fork since 1986 and the South Fork since 1994. Nonetheless, the contrasts are quite apparent. During the 1970s, the South Fork landscape experienced mass-wasting an order of magnitude greater than that which followed NFC harvesting of the 1990s. SFC erosion has been predominantly related to the roads, landings, and skid trails. In contrast, most North Fork erosion features have been associated with windthrow disturbances and typically displaced and delivered smaller volumes of material. Two large landslides, one related to a preexisting mid-slope road, account for more than half of NFC mass-wasting (Table 2).

Another episode of road-related landsliding commenced in the South Fork in the mid 1990s. Of the 31 SFC landslides documented between 1995 and 2004, 94% are road, landing, or skid trail related. These more recent landslides displaced 4,123 m^3 and had an average delivery ratio of 85%. A deteriorating network of logging roads and skid trails continues to deliver sediment to the stream channel and explains much of the recently enhanced SFC sediment production previously discussed. This

Figure 4. Suspended sediment regression results by period for North Fork (NFC) and South Fork (SFC) versus control (HI).



renewed sedimentation may also be a manifestation of the extreme stormflows of 1998 and 1999 and the erosional costs of recent road decommissioning. The 1998 road decommissioning effort removed almost 18,000 m^3 of fill from aging stream crossings, but treatment-related erosion contributed 750 m^3 of sediment.

Conclusions

Timber harvest and road building affect runoff processes, sediment yields, and erosion, but the response is highly variable. Caspar Creek studies document increases in peak flows, suspended sediment loads, and erosion after two very different harvest treatments. California's modern forest practices rules appear to mitigate, but do not eliminate, these impacts.

Erosion and sedimentation from ground extensively disturbed by road building and tractor yarding remain elevated decades after harvest. The present condition of the South Fork watershed is typical of many of the tractor-yarded lands in the redwood region that are entering yet another harvest cycle. Greater understanding of the interactions between proposed activities and prior disturbances is crucial for improved forest management. Thus, a third phase of research is underway to examine the effects of re-entry on the previously tractor-logged South Fork watershed. Much remains to be learned regarding restoring forest ecosystems and mitigating harvest impacts. The Caspar Creek Experimental Watersheds will continue to serve as a resource for furthering this research endeavor.

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Forest Road Erosion Research at the Coweeta Hydrologic Laboratory

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The Coweeta Hydrologic Laboratory, Southern Research Station, USDA Forest Service, has been conducting basic and applied research addressing erosion and sedimentation from forest roads for over seventy years. This research has resulted in development of local, state and federal forest road construction standards, development and application of forest road bioengineering and National Forest System road best management practices (BMPs). Our most recent research has documented the effects of large-scale forest road reconstruction and BMP implementation on erosion rates, stream sedimentation and water quality in the southern Appalachian Mountains. Currently, we are developing and validating three methods to differentiate between natural and anthropogenic sediments in streams. These methods allow us to accurately quantify the direct impacts of forest roads on stream sediment budgets, sediment residence time and sediment transport rates.

Keywords: *Roads, road management, sedimentation, erosion control, best management practices, forest practices, watershed management, water pollution*

Introduction

The Coweeta Hydrologic Laboratory in Otto, North Carolina, is a research work unit of the USDA Forest Service, Southern Research Station (Figure 1). Coweeta was established in 1934 as an experimental forested watershed. The research mission focused on investigating the impacts of watershed management activities on water yield and water quality and expanding our knowledge and basic understanding of forest watershed hydrology.

The scientists and engineers who worked at Coweeta in the early years recognized that erosion and sedimentation from gravel roads was a major threat to forestry operations, water quality and water supply, aquatic ecosystems, hydrologic and hydraulic infrastructure. Consequently, scientists at the Coweeta Hydrologic Laboratory have conducted a wealth of research addressing the impacts of forest road construction, forest best management practices, road use, and road maintenance practices on hydrology, water quality and road longevity since 1934. Sun et al. (2004), Jackson et al. (2004) and Swift (1988) have previously summarized much of the history of forest road research conducted at Coweeta. In this paper, we provide an overview of these earlier works to set the historical context for a subsequent review of our contemporary forest road research.

Historical Forest Road Research of the Coweeta Hydrologic Laboratory

When the Coweeta Hydrologic Laboratory was established in 1934, engineers at the time recognized that erosion of forest roads was a serious problem (Figure 2). Road erosion reduced road life, increased maintenance expenses, damaged vehicles and harmed the aquatic environments. Some of the earliest research studies were conducted by C. R. Hursh, who recognized the inherent erodibility of cut and fill slopes and employed what we now call bioengineering to stabilize roadways (Figure 3). Significant reductions in soil loss from forest roads were accomplished by mulching or vegetating the adjacent cut and fill slopes (Hursh 1935, 1939, 1942). Project specifics including an evaluation of different plant types and bioengineering methods are summarized by Swift (1988). While improving and facilitating the construction

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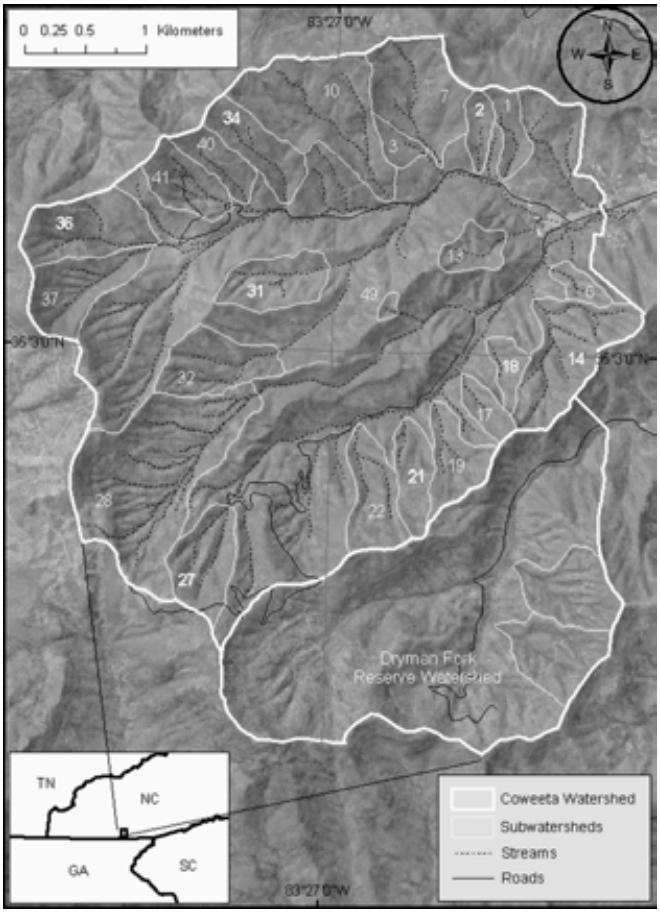
Figure 1: Coweeta Hydrologic Laboratory and its Experimental Watersheds.



of roads was a major motivation for this research, Hursh laid the foundation for subsequent research that specifically addressed the impacts of roads on stream water quality.

In 1942, a research demonstration project was initiated on Watershed 10 (Figure 1) to scientifically document the impacts of mountain logging practices on water quality. Typical logging practices, such as using ephemeral channels and riparian areas for skid trails (Figure 4), generated 408 m^3 of soil loss per km of road constructed (Lieberman and Hoover 1948a). Sediment delivery to streams was high and total suspended solids peaked at 5700 ppm (Lieberman and Hoover 1948b). Road erosion was so severe that downstream fish populations were significantly reduced (Tebo 1955), the roads became unusable and were decommissioned (Swift 1988).

Progressing from lessons learned in the exploitive logging experiment, Coweeta scientists conducted forest harvesting experiments to demonstrate how sound road building and watershed management practices accommodate water quality preservation and timber harvesting. Two watersheds were contracted for harvesting in 1955: Watershed 40 was to be harvested while managing for preservation of water quality and the adjacent Watershed 41 was harvested to

Figure 2: Erosion of an old logging road (photo by C.R. Hursh).

Figure 3: Example of early bioengineering to stabilize a cut slope road embankment (photo by C.R. Hursh).

Figure 4: Skidding logs in the riparian area during an early logging experiment at the Coweeta Hydrologic Laboratory (photo source unknown).

facilitate timber extraction. Road construction practices on Watershed 40 were tightly controlled. Swift (1988) provides a discussion of specifics including road placement, width, engineering and vegetative methods. The implemented construction practices included contour roads, skidding logs away from streams and preventing stream disturbance. While these techniques protected water quality, they were deemed impractical by potential users because of perceived implementation and management costs (Swift 1988).

The Stamp Creek Demonstration Project in northeastern Georgia addressed the perceived cost limitations of adopting improved road designs and best management practices (Black and Clark 1958). From 1956 to 1960, forest harvesting was conducted on the Stamp Creek watershed with consultation on road design from Coweeta Hydrologic Laboratory scientists. Road maintenance and construction techniques employed were economically feasible because the roads were specifically designed to require minimal maintenance. Road quality and timber access improved, facilitating forest harvesting operations while minimizing impacts on water quality (Swift 1988).

These, along with other sustainable forest road construction practices, were employed in the multiple resource watershed management experiment in 1962. This experiment on Watershed 28 applied the multiple-use management concept that provides simultaneous benefits of forest products, fisheries and wildlife, and recreation needs while enhancing water yield and preserving water quality for municipal needs. New road building techniques such as out-sloping and broad based dips (Figure 5) were used to replace center crowned roadbeds, water bars, ditches and culverts to drain runoff. Hewlett and Douglass (1968) described these road engineering methods that further reduced road runoff and erosion. The experiment was so successful that the road building methods were adopted as standards for forest road construction by the national forests in Region 8 (the Southern Region) of the USDA Forest Service (Swift 1988).

Figure 5: Example of a properly constructed broad based dip from the Conasauga River Large-Scale Watershed Restoration Project, Cohutta Ranger District, Chattahoochee National Forest, USDA Forest Service (photo by M.S. Riedel).

Forest road research continued at Coweeta, striving for the goal of the "self maintaining road". Swift (1984a, 1984b) began a series of experiments to directly quantify where, when and how sediments were eroded from forest roads and to develop specific road engineering practices that would eliminate sediment sources. Swift and Burns (1999) and Swift (1988) have synthesized much of the knowledge about techniques learned from these comprehensive studies. Some of the most important findings include;

- Soil losses are greatest immediately after construction (Swift 1984a).
- Coarse gravel and grassing of roadbeds reduces erosion (Swift 1984a).
- Bare cut and fill slopes accounted for 70 to 80 percent of the total soil losses.
- Vegetating cut and fill slopes and graveling roadbeds reduced erosion to less than 10% of pre-treatment (Swift 1984b).
- The use of vegetated filter strips and brush barriers on fill slopes retains the majority of eroded sediments within the roadway (Swift 1985, 1986).
- Nearly 100% of the sediment yield increase to streams following total forest harvest originated from stream crossings representing only 1% of the total watershed area and 17% of total road length (Douglass and Swift 1977).
- Erosion and sedimentation from forest road stream crossings may affect the sediment budgets of streams for decades (Figure 6).
- Proper design of stream crossings, isolating roads from adjacent streams, and diverting road runoff onto the forest floor greatly reduce and may even prevent stream sedimentation (Douglass 1974; Swift 1985; Swift and Burns 1999).

Current Forest Road Research of the at Coweeta Hydrologic Laboratory

Current research of the Coweeta Hydrologic Laboratory represents a logical progression from the foundation of knowledge developed from the historical research. We have further advanced our ability to: (1) predict forest road erosion and sediment yield; (2) implement and evaluate effectiveness of forest road best management practices; and (3) quantify and understand stream channel sedimentation

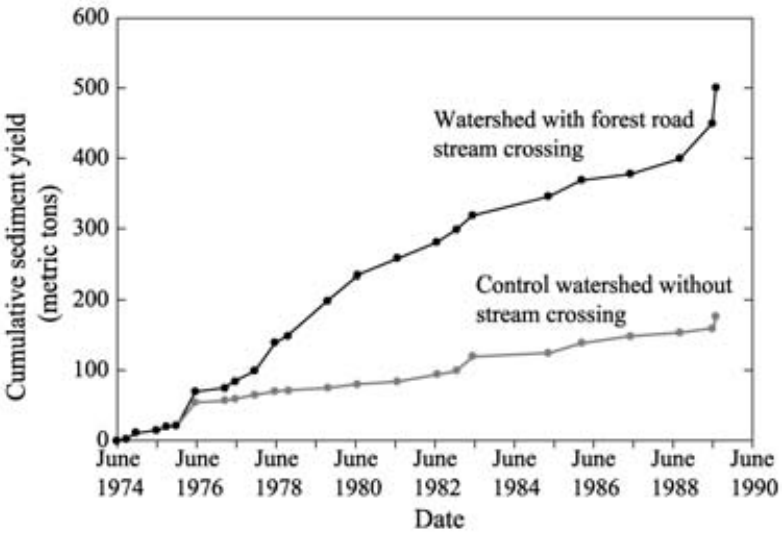


Figure 6: Cumulative sediment yield from a stream with road crossings as compared to a control watershed with no road crossings (adapted from Swank et al. 2000).

and sediment transport, sediment budgets and sediment cycling, and fluvial sediment dynamics.

Prediction of Erosion and Sediment Yield From Roads

The ability to accurately predict forest road erosion and sediment yield is crucial to preventing and mitigating stream sedimentation impacts. This is especially true with cumulative effects analysis when the long-term operation of hundreds of miles of forest roads across all landscape scales represents a large and chronic sediment source.

L.W. Swift developed a spatially explicit sediment transport model for the southern Appalachians (EPA 2000) that was incorporated into a spatially explicit GIS based soil erosion model (McNulty et al. 1995; McNulty and Sun 1998). Greenfield et al. (2001) further developed the model, incorporated empirically based sediment routing functions and the ability to estimate average annual stream sediment yields. This model, the "Sediment Tool", was incorporated into the U.S. Environmental Protection Agency's Watershed Characterization System (WCS) (EPA 2000). The Sediment Tool is a spatially explicit, GIS based, finite element, lumped parameter model which generates estimates of soil erosion, sediment routing and sediment yield. While this model is used for TMDL analysis and development, it had never been validated for such an application.

Riedel and Vose (2002a) customized data and data structure for WCS and the "Sediment Tool" to incorporate National Forest System roads, forest road management practices, and the highest quality terrain data in the remote mountains of the Chattahoochee National Forest in northern Georgia. They monitored road erosion and sediment yield from a wide variety of unpaved roads in the region. While they were able to qualitatively calibrate the model to observed data, they found model sensitivity to road characteristics was limited by the governing equations within the model and the resolution of the input digital elevation models. Simulated roadbed erosion and sediment yields were biased and did not agree with observed data.

Riedel and Vose (2003) subsequently monitored road erosion and sediment yield on a subset of the road sites after reconstruction and implementation of forest road best management practices (BMPs). The Sediment Tool did not accurately predict road erosion, sediment yield and BMP performance. Riedel and Vose concluded such application was beyond the capabilities of the model and that it should be better suited to larger scale applications such as land cover change analyses. Bolstad et al. (2006) have further validated the model on a larger scale across five watersheds in the southern Appalachian Mountains. These watersheds include two forested controls, a watershed with mountain home development impacts, another affected by valley agricultural practices, and one with mixed land use.

Implementation and Effectiveness of Forest Road Best Management Practices

Forest road research at Coweeta has long addressed the reduction of road erodibility, road sediment yield and stream sedimentation through the development of forest road BMPs. Clinton and Vose (2002) conducted one of the first comprehensive studies investigating forest road erosion that included paving as a BMP. While paving logically reduces the erodibility of forest roads, threats from potential impacts on stream sedimentation and the delivery of total petroleum hydrocarbons (TPH) were documented for the first time. As expected, the paved road system generated the least sediment, aggregate base gravel roads generated more and the unimproved road

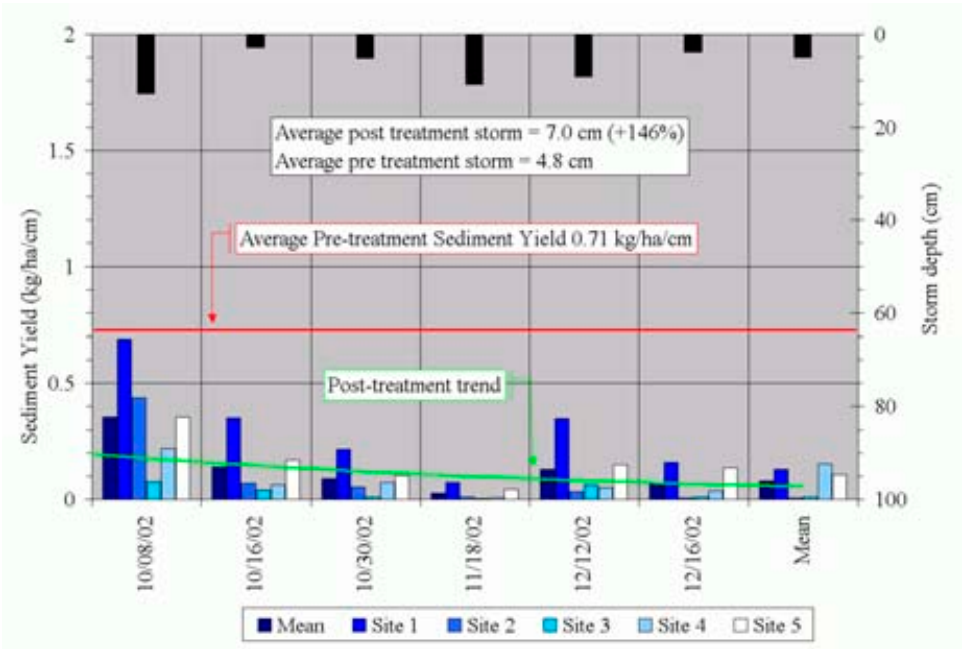


Figure 7: Comparison of pre and post-treatment sediment yield following reconstruction of a forest road with best management practices in the Conasauga River Large-Scale Watershed Restoration Project, Cohutta Ranger District, Chattahoochee National Forest, USDA Forest Service (Riedel and Vose 2003).

generated the greatest amount of sediment. The distances of sediment transport away from the road bed were, in order of decreasing distance, paved, improved gravel, improved gravel with sediment control and unimproved gravel. While TPH were found in runoff water at the edge of newly paved roads, the concentrations were extremely low. No TPH were found in collected runoff below the road, nor in stream water or stream bottom sediments, suggesting that TPH sorbed to sediments before reaching the streams. Clinton and Vose found gravel roads with failed BMPs (due to improper installation, lack of maintenance, or both) provided little, if any reduction in sediment yield as compared to gravel roads with without BMPs.

Riedel and Vose (2003) monitored sediment yield and transport in the Chattahoochee National Forest beginning in autumn 2001. During the summer of 2002, road reconstruction and installation of BMPs were completed along more than 20 miles (32 km) of forest roads (Figure 5). Sediment yield from these roads was monitored through autumn 2002. Despite a 46% increase in rainfall from the pre- to post-treatment period, road reconstruction reduced average sediment yield by 70% (Figure 7) (Riedel and Vose 2003). Specific examples of the road reconstruction and BMP implementation are reported by Riedel and Vose (2003).

Stream Channel Sedimentation and Sediment Transport

The transport of sediments sourced from gravel roads as bedload, despite the potential implications for aquatic ecosystems, has historically received very little research attention. Riedel et al. (2003), having previously identified road sediments deposited in the streambed and noticing ecological impacts (Riedel and Leigh 2004), initiated a pilot streambed mobility study. Several transects of scour and deposition pins were installed along a study reach, immediately adjacent to an unpaved gravel road (Figure 8). The stream scoured up to 10 cm of sand from its bed, exposing buried riffles and partially clearing pools of sediment (Figure 9). The sand and fine gravel in this stream were very dynamic. In-stream scour and deposition occurred frequently. No in-stream deposition occurred during small events, when road runoff was negligible. During larger events, road runoff and in-stream sediment deposition occurred. These results indicate that the implementation of forest road BMPs facilitates stream restoration, because mountain streams are capable of clearing the road sediments from their substrate if external sediment sources are eliminated.

Sediment Budgets and Sediment Cycling

Riedel and Leigh (2004) and Riedel et al. (2003) investigated methods of differentiating between natural and road derived sediments in stream channels. Van Lear et al. (1995) reported roads account for 85% of the potential sediment supply for streams in this region; however, no studies have attempted to directly validate this. Sediment samples from roads, native geology, soils and streambeds were gathered from a watershed in northern Georgia and numerous experimental watersheds at the Coweeta Hydrologic Laboratory. The samples were analyzed for total elemental composition using a triple acid digest. This allowed for the differentiation between geologically old,

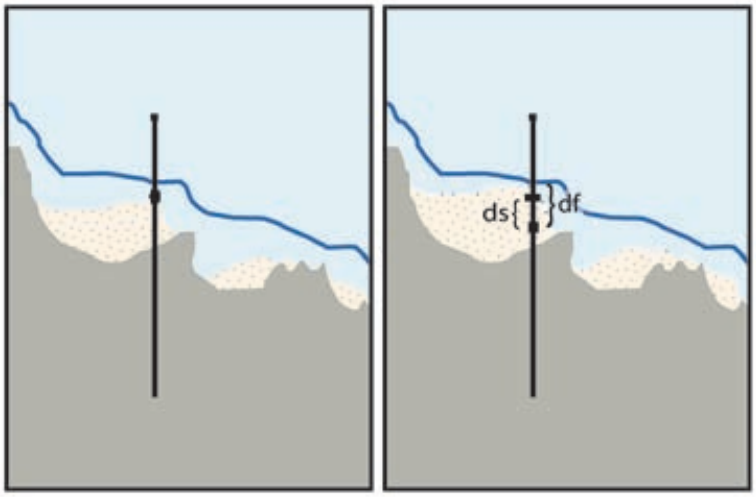
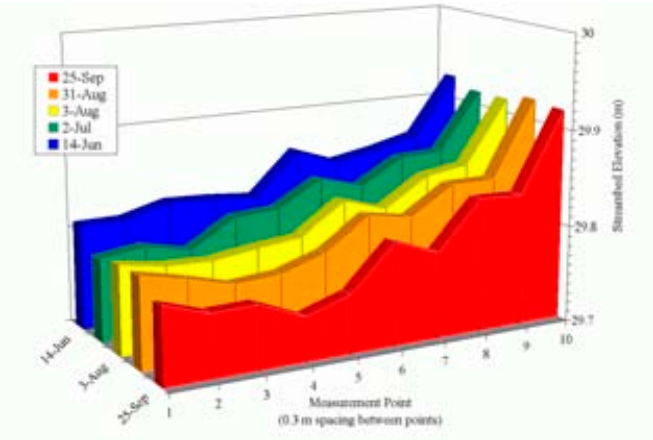


Figure 8: Conceptual diagram of scour and deposition pins installed in a stream channel. A loose washer is placed on each pin before installation. The elevations of the washers resting on the sediment surface are measured. Following a storm event, the depths of sediment on the washers and the distances the washers have fallen are measured to reveal streambed scour (ds), streambed deposition (df) and net streambed change (df-ds) during the storm event.

Figure 9: Net scour of a streambed cross-section over a 3½-month period (Riedel and Leigh 2004).



native sources of coarse streambed sediments (sand-size and finer) and fresh quarry-sources of streambed sediment such as road aggregate. Elevated sodium and strontium were clear indicators of road sediments and in-channel sedimentation from excessive road sediments. At these study sites, 50 to 75% of stream sediments finer than 2 mm were sourced from roads (Riedel and Leigh 2004).

Fluvial Sediment Dynamics

Riedel and Vose (2002b) monitored streamflow and water quality in mountain streams of northeastern Georgia to determine the impacts of gravel roads on suspended sediment budgets. An EPA benchmark stream with minimal sediment impacts served as a reference with which to compare results from three other mountain streams. Total suspended solids (TSS) concentrations were not representative of suspended sediment because the organic and mineral components of TSS were highly variable between streams. Excessive loading of suspended mineral sediment was linked to gravel roads adjacent to the affected streams. Mineral sediment loading was highest in autumn during peak road use for recreational and hunting activities. They concluded TSS could not be reliably used for the establishment of Total Maximum Daily Loads (TMDLs) for forested streams, because it did not differentiate between the suspended organic matter derived from naturally occurring allochthonous inputs versus mineral sediments from development and roads.

With additional monitoring, Riedel et al. (2003) determined that during larger storm events, road runoff and in-stream sediment deposition occurred. The two undisturbed forest streams showed no sedimentation impact because they were sediment supply limited, whereas the two streams with road impacts experienced sedimentation because sediment supply exceeded transport capacity. The authors hypothesized that the most significant impact of roads on aquatic ecosystems in this region was from streambed sedimentation. Consequently, TSS based TMDLs may not address the causes of sediment impairment of aquatic ecosystems.

In subsequent work, Riedel et al. (2004) determined that water quality parameters on these streams varied significantly on a seasonal and storm event basis. TSS

data on the benchmark stream and a forested stream exhibited strong hysteresis (lag between effect and cause), were elevated on the rising limbs of hydrographs, and declined rapidly on the recession limbs—further evidence of sediment supply limitations. While there was weak hysteresis apparent in the constituent concentrations and loadings of the impaired streams, it was not statistically significant. They developed a "hydrograph threshold" approach to constructing sediment rating curves that facilitated the development of sediment based TMDLs that directly linked loading rates to discharge frequency and duration relationships.

Summary

The impacts of forest harvesting on sediment yield are directly related to skid trail layout and road building and maintenance activities associated with gaining forest access and removing timber from the woods. When roads and skid trails associated with forest harvesting are properly constructed and maintained, forest harvesting generally has a minimal impact on stream sedimentation. Conversely, poor logging practices and the incorrect design and maintenance of forest roads cause significant stream sedimentation. Many of the historical and often ill-conceived methods of forest road construction and maintenance caused large increases in forest soil erosion and stream sedimentation. Based on decades of research to improve road construction and maintenance, numerous practices that minimize erosion and sedimentation have been identified. Examples of these practices are coarser paving gravels, grassed roadbeds, the construction of broad based dips, brush sediment barriers along road margins and road buffer strips.

Sedimentation of streambeds may also be prevented by the proper use and maintenance of forest road best management practices. Indeed, in steep mountain streams, forest road reconstruction and adoption of BMPs may facilitate stream restoration because the reduction of road sediment yield allows streams to flush themselves of previously deposited road sand and fine gravel. Historical and current research suggests the long held ideal of a "self-maintaining" forest road may nearly be attainable.

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The Entiat Experimental Forest: A Unique Opportunity to Examine Hydrologic Response to Wildfire

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Water is generally regarded as the most important natural resource in the interior Columbia River basin (ICRB). Public agencies managing forested headwater source areas are under increasing pressure to document water quantity and quality, and the effects of background and anthropogenic disturbances that influence them. Fire is widely recognized as the primary disturbance process affecting ecological systems in the ICRB. For these reasons land management agencies seek a more complete understanding of processes that generate and maintain streamflow as well as effects of fire and post-fire treatments on water quantity and quality. Although effects of wildfire are issues of major concern, they remain poorly understood at the catchment scale, largely because site specific data from both before and after wildfire are rare. The Entiat Experimental Forest (EEF) in central Washington State provides this type of hydrologic record of fire effects, owing to a severe wildfire during the summer of 1970, following ten years of stream gaging as part of a controlled land use experiment. Data collection continued after the fire through 1977. The entire dataset provides an archive for assessment of hydrologic response and model formulation, calibration, and testing. Research at the EEF is being revived to model effects of fire on water quantity and quality, including effects on water source, flowpath, timing, and post-fire recovery of hydrologic processes. We are taking a diagnostic approach to gaging to understand internal catchment behavior and develop a functional characterization of the EEF catchments. Change detection modeling employing the Hydrologiska Byråns Vattenbalansavdelning [HBV] rainfall-runoff model is being applied by: (1) comparing observed runoff to runoff simulated from pre-fire parameters, (2) comparing simulations based on pre-fire parameters to simulations based on post-fire parameters, and (3) directly contrasting pre-fire with post-fire parameter values. Preliminary modeling results suggest that effects of the 1970 fire included greater snow accumulation, earlier initiation of snowmelt runoff at lower mean air temperatures, more rapid melt, increased soil moisture, and sharply increased runoff. Gaging at other catchments in the larger Entiat River subbasin creates a foundation for nested watershed monitoring and modeling to address spatially distributed hydrologic processes in this portion of the ICRB.

Keywords: *hillslope hydrology, conceptual catchment modeling, rainfall-runoff modeling, HBV runoff simulation model, fire effects*

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Introduction

Water is generally regarded as the most important natural resource in the interior Columbia River basin (ICRB). It is essential for human consumption, ecosystem function, and habitat for aquatic organisms, including sensitive species. Water supports a multi-billion dollar economy in agriculture, power generation, recreation, mining, and manufacturing. Public agencies managing forested headwater source areas are under increasing pressure to document effects of background and anthropogenic disturbances on water quantity and quality.

Fire is widely recognized as the primary disturbance process affecting ecological systems in the ICRB. Fire can affect snow accumulation, snowmelt, surface runoff, subsurface water routing and storage, timing and quantity of streamflow, chemical and thermal water quality, aquatic habitat of sensitive species, and human water use. For these reasons land management agencies seek a more complete understanding of processes that generate and maintain streamflow, and of the effects of disturbance, such as fire and post-fire treatments, on water quantity and quality.

Major wildfires are bringing increasing attention to potential effects of fire and associated land management activity, such as fire suppression and salvage logging, on water quantity and quality. This is particularly true in the western U.S. and some European countries where large, severe wildfires are perceived to be occurring with greater frequency (Conedera et al. 2003; Pierson et al. 2001; Rieman et al. 2003; Robichaud and Elsenbeer 2001). Similarly, effects of post-fire rehabilitation on runoff, peak flows, erosion, sedimentation, and other fire-affected processes is receiving increasing attention (Robichaud et al. 2000).

Fire has been an important disturbance process in the ICRB for millennia (Hessburg and Agee 2003; Wright and Agee 2004). Damage to forest vegetation and the litter layer by fire can expose soil to rainsplash and hasten delivery of precipitation to the soil surface, thereby increasing runoff and surface erosion (Johansen et al. 2001; Robichaud and Brown 1999). Soil infiltration capacity can be reduced when surface pores are sealed by ash or fine sediment made available by destruction of soil structure and mobilized by rainsplash, and by fire-induced formation of hydrophobic (water repellant) compounds on the soil surface (DeBano et al. 1977; DeBano et al. 1998; Giovannini et al. 1988; Martin and Moody 2001; Robichaud and Hungerford 2000; Wells 1981; Wright and Bailey 1982). Reduced infiltration through these mechanisms and reduced evapotranspiration caused by damage to vegetation can result in increased runoff, flooding, sediment mobilization and delivery to channels, and debris flows (Beschta 1990; Cannon et al. 2001; Conedera et al. 2003; Elliott and Parker 2001; Krammes and Rice 1963; Meyer and Wells 1997; Tiedemann et al. 1979; Wells1987). Increased peak flows can increase channel bed and bank erosion, further increasing sediment concentration in streamflow (Beschta 1990; Swanson 1981; Wondzell and King 2003). Large volumes of soil and nutrients can be transported to channels by fire-related debris flows (Helvey et al. 1985; Meyer et al. 2001).

Fire can also affect water quality by increasing nutrient losses to erosion, reducing nutrient uptake, and increasing leaching (Beschta 1990; Richter et al. 1982). Fire can volatilize nitrogen in vegetation and litter, increase nitrification, and mineralize cations, which may be redistributed and converted to more soluble salts. Increased runoff can result in increased total cation and bicarbonate losses (Grier 1975; Tiedemann et al. 1979; Wells et al. 1979). Fire can also increase stream water temperature, primarily by increasing exposure to solar radiation (Anderson et al. 1976, Beschta 1990; Tiedemann et al. 1979). Recovery of pre-fire watershed conditions depends largely on recovery of terrestrial plant communities, with associated increases in infiltration and evapotranspiration (Pierson et al. 2001; Swanson 1981; Wright and Bailey 1982).

Despite the importance of wildfire as an ecological and social issue, relatively few hydrologic data exist beyond the plot and hillslope scales. Fire data at the catchment scale are mostly associated with paired watershed studies of prescribed fire effects on water quantity and quality. Catchment scale hydrologic effects of wildfire are less well known, because pre-fire data are rarely available (Moody and Martin 2001). Previously published work having site-specific, pre-wildfire data includes a study from the San Dimas Experimental Forest in southern California (Hoyt and Troxell 1934) and one from a eucalyptus forest in Australia (Langford 1976).

Another of these rare "natural fire experiments" comes from the Entiat Experimental Forest (EEF), located in central Washington State (Helvey 1980). Data from the EEF provide a resource for model formulation, calibration, and testing of wildfire effects on catchment scale runoff. These data also provide an opportunity to contrast long-term hydrologic recovery between catchments that were or were not subject to post-fire rehabilitation treatments (Woodsmith et al. 2004). In this paper we focus on effects of fire on runoff. We present background information on the EEF and historical data collection. We then discuss our objectives and approach to current and future investigations, and the preliminary results of hydrologic change detection modeling.

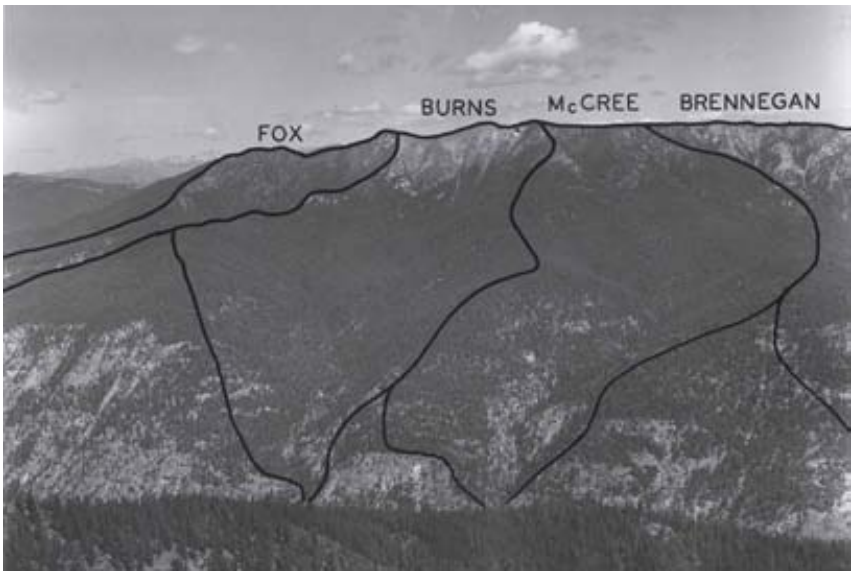


Figure 1. The Entiat Experimental Forest, looking toward the northeast.

The Entiat Experimental Forest

The EEF consists of three adjacent catchments, McCree Creek, Burns Creek, and Fox Creek, each approximately 500 ha in size (Figure 1). They are subwatersheds in the Entiat River subbasin in central Washington State on the east slope of the Cascade Range about 55 km north of Wenatchee at latitude 47°57'N, longitude 120°28'W. Catchment elevations range from 549 to 2134 m, mean aspects from 205 to 237 degrees, mean channel gradients from 27 to 29 percent, and mean hillslope gradient is about 50 percent. Mean annual temperature at 920 m elevation is 6.7°C. Mean annual precipitation is 58 cm; most falls from November to May, and only 10% falls from June to September. Seventy percent of precipitation is snow, and hydrographs are dominated by snowmelt. Annual peak flows occur in May or June. During the period 1962-1970, fifty percent of the time discharge was greater than 12.7, 20.7, and 19.2 liters per second (L/s) and mean maximum daily flow was 164.4, 243.7, and 167.2 L/s in McCree, Burns, and Fox Creeks respectively (Helvey 1974; Helvey et al. 1976a; Tiedemann et al. 1978).

Bedrock is primarily granodiorite and quartz diorite. Glaciofluvial sediment is abundant on the lower slopes. Glacier Peak is 56 km to the northwest, and pumice deposits from multiple eruptions vary from a few centimeters to more than six meters in thickness. Soils are well-drained Entisols. Prior to a severe fire in 1970 the forest overstory consisted predominantly of ponderosa pine (*Pinus ponderosa* Laws.) and Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) at higher elevations. Stand-replacing wildfire had apparently not occurred in the 200 years prior to 1960, although fire scars on large trees indicated a history of periodic fire (Helvey et al. 1976a).

Studies on the EEF were originally established to examine effects of timber harvesting and road building on quantity, quality, and timing of streamflow. Site selection criteria included: (1) three or more 2.5-15.5 km2 catchments; (2) similarity among catchments in climate, physical characteristics, and vegetation, all of which should represent much of the forested land east of the Cascade Range crest in Washington State; (3) absence of disturbance by recent fire, heavy grazing, logging, or road building; and (4) reasonable year-round access (Helvey et al. 1976a).

Historical Data

Data collection in the EEF began in 1960 and continued through 1977. During the period 1960-1970 discharge data were collected using sharp-crested, 120-degree, V-notch weirs near the mouth of each of the three experimental catchments. Weir ponds had capacities of 20-50 m^3. Stage height was measured using a stilling well float and punch tape recorder.

Following 10 years of calibration, the EEF catchments burned unexpectedly on 24 August 1970 as part of a 486 km^2, lightning-caused wildfire complex (Helvey 1980; Martin et al. 1976). Tiedemann et al. (1978) describe fire effects in the EEF as severe and uniform. However a few small patches, generally less than 10 ha, of mature ponderosa pine survived. By the end of the 1971 growing season, land surface cover by native and seeded plants averaged only 8.6 percent (Tiedemann and Klock 1973). During the fire, discharge in McCree Creek declined from 6.25 to 1.71 L/s, and immediately after the fire, strong diurnal discharge patterns were nearly eliminated owing to reduced transpiration (Berndt 1971).

After the fire two contour roads were constructed in McCree and Burns catchments, dead trees were logged, and

grass and clover seed and nitrogen fertilizer were applied by helicopter (Helvey 1980). Fox Creek was designated an experimental control and not seeded, fertilized, roaded, or logged (Tiedemann and Klock 1976). Effects of wildfire on streamflow quantity, quality, and timing became primary research objectives, and were examined until the cessation of data recording in 1977 (Helvey 1980).

In mid-March 1972 record high air temperatures and an exceptionally deep snowpack produced flows greater than three times the maximum measured during calibration in McCree Creek. On 18 March a debris flow, apparently initiated by failure of weathered granitic material on steep slopes, destroyed the McCree Creek weir. Intense rainstorms on 9 and 10 June initiated a similar failure and debris flow in Fox Creek, destroying that weir (Helvey 1974). These weirs were replaced during the summer and autumn of 1972 with Parshall flumes at the gauging sites. Post-fire gaging records for McCree and Fox Creeks were incomplete owing to persistent sedimentation in the flumes. During 1973-1975 those missing data were estimated from discharge at the Burns weir (Helvey 1980; Helvey and Fowler 1999). Record quality, based on U.S. Geological Survey standards (Corbett 1943), was excellent for all stations until 1972. Records for Burns were good for 1972-1977 and fair to poor for Fox and McCree (Helvey and Fowler 1999). During the first post-fire year total water yield from the EEF was 50% greater than predicted using the Entiat River and nearby Chelan River as controls (Helvey 1974). The most complete post-fire discharge data were from Burns Creek. During water years 1972-1977 measured runoff in Burns Creek exceeded predictions by 10.7 to 47.2 cm, using the Chelan River as a control (Helvey 1974).

Precipitation was measured in shielded weighing-bucket gages with a 203-mm orifice. Only one gage in the study area, approximately 200 m from the Burns Creek weir, covered the entire period of record. After 1972 storage gages were installed at nine locations distributed throughout the McCree and Burns catchments. High elevation gages were serviced only once each year due to difficult access, but a more frequent schedule was kept where feasible. These other gages provided data for periods of approximately one year each. An additional six gages within 48 km of the EEF have records covering the study period (Bowles et al. 1975).

Water temperature sensors and punch tape recorders were installed in 1968 at the three gaging stations and temperature was recorded hourly. Three additional recorders were installed in Fox Creek in the fall of 1972 (Helvey and Fowler 1999). Mean daily maximum water temperatures during December 1969 to February 1970 were approximately 3°C, and 10 to 11°C in July and August before the 1970 fire (Helvey 1974; Helvey et al. 1976b). During the first two post-fire years mean daily maximum water temperatures increased in Burns Creek by 5-6°C based on control data from the Entiat River (Helvey 1974; Helvey et al. 1976b). In general stream temperatures peaked in the summer 1973 and declined until the end of data collection in 1977 (Helvey and Fowler 1999).

Beginning in 1966 air temperature and humidity measurements were made using a hygrothermograph and chart recorder at the Burns weir weather station. Daily maximum and minimum values were recorded (Helvey and Fowler 1999). Mean daily maximum air temperatures during December 1969 to February 1970 were -1.1°C, and 32.2°C in July and August before the 1970 fire (Helvey 1974; Helvey et al. 1976b). Tests for post-fire changes in mean monthly air temperature were inconclusive (Helvey et al. 1976b). Aerial measurements of midslope soil and plant surface temperatures were made on 29 August, 1969, near the time of maximum daily air temperature. Mean values ranged from 19.8 to 22.9°C (Tiedemann et al. 1978). Post-fire vegetation development for the years 1971-1974 is summarized in Tiedemann and Klock (1976).

Current and Future Investigations

The EEF provides a rare opportunity to investigate hydrologic recovery from severe wildfire, post-fire salvage logging, and rehabilitation treatments by drawing from its rich data record and initiating new studies of fire effects on water quantity, quality, and temperature (Woodsmith et al. 2004). In 2003 we began reanalyzing the EEF historical records and reinstrumenting the three gaging stations with redundant stage height recorders (pressure transducers and capacitance rods) and water temperature sensors. We reinstrumented the former Burns weir (920 m) and Fox Creek (650 m) weather stations with rain, air temperature, humidity, barometric pressure, and wind speed sensors, all recording to data loggers. During spring 2004 two similar weather stations were added, one on the eastern McCree catchment divide (1300 m) and one on the Burns-Fox divide (2000 m) (Figure 1). In addition, Parshall flumes with recording pressure transducers were installed on Burns Creek and on one of its tributaries at about 1200 m elevation, and 30 self-contained, logging water temperature sensors were installed along the entire length of Burns Creek.

Objectives of current and future research include: (1) reanalysis of historical data to assess fire effects on runoff; our results will be compared to those previously published for the EEF using traditional paired watershed approaches; (2) contrasting hydrologic recovery between

catchments where post-fire rehabilitation measures were applied (McCree and Burns) vs. no treatment (Fox); (3) assessment of post-fire hydrologic recovery, including analysis of the new hydrologic record for signatures of the 1970 fire and post-fire treatments; (4) analysis of water sources, flow paths, and timing of water delivery, with emphasis on the Burns Creek subwatershed where the most complete historical record exists; and (5) with improved understanding of catchment hydrology, evaluating hydrologic change associated with current land management practices, including fuels treatments, and transportation network management. Results will serve as a platform for virtual experiments simulating fire under current conditions. In future work we will use eleven other gaged catchments in the Entiat River subbasin to form the basis for nested hydrologic monitoring in this portion of the ICRB.

Approach

Following methods in McDonnell and Vache (in press), we are taking a diagnostic gaging approach to understand internal catchment behavior and develop a functional characterization of the EEF catchments. We are identifying first-order controls on hydrologic processes and investigating how these are linked to produce runoff at the subwatershed scale. This leads to a simple model structure that corresponds directly to the basic conceptual understanding of the catchment hydrology to test thinking about hydrologic processes and process linkages. Model structure and instrumentation are being developed concurrently to determine what to measure, where, and in what order. This approach to functional characterization of a catchment can be described in five steps (McDonnell and Vache in press) (Figure 2):

1. ***Field reconnaissance to investigate process scales*** – the representative elementary watershed (REW) is identified. This is the minimum catchment area at which hydrologic processes are representative of a larger scale. Determination of this area is commonly done through dilution gaging at a large number of tributary junctions to look for a relatively constant relationship between runoff rate and catchment size. At this threshold scale larger basins can be thought of as superpositions of smaller units.

2. ***Delineation of the dominant runoff producing zones and processes*** – these are represented as reservoirs in conceptual box models. These zones can be identified through longitudinal stream surveys using water temperature, conductivity, or pH as initial tracers. Anomalies at tributary junctions indicate reservoirs with different residence times, subsurface storage volumes, or exposure to disturbance.

3. ***Development of a simple, lumped, conceptual model to test thinking about catchment processes and characterize first-order process controls (Figure 3).*** This approach can incorporate "soft data" or qualitative knowledge of catchment behavior, such as the proportion of the catchment subject to saturation. Commonly this is knowledge that cannot be used as direct numbers,

Figure 2. A diagnostic approach to understanding internal catchment behavior and developing a functional characterization of catchment hydrology (McDonnell and Vache, in press).

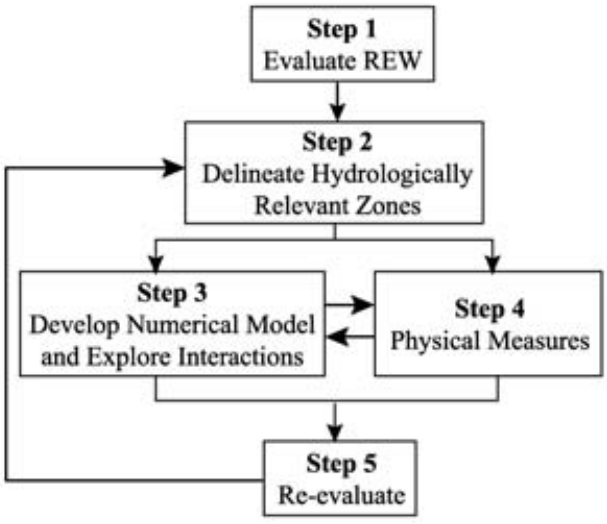
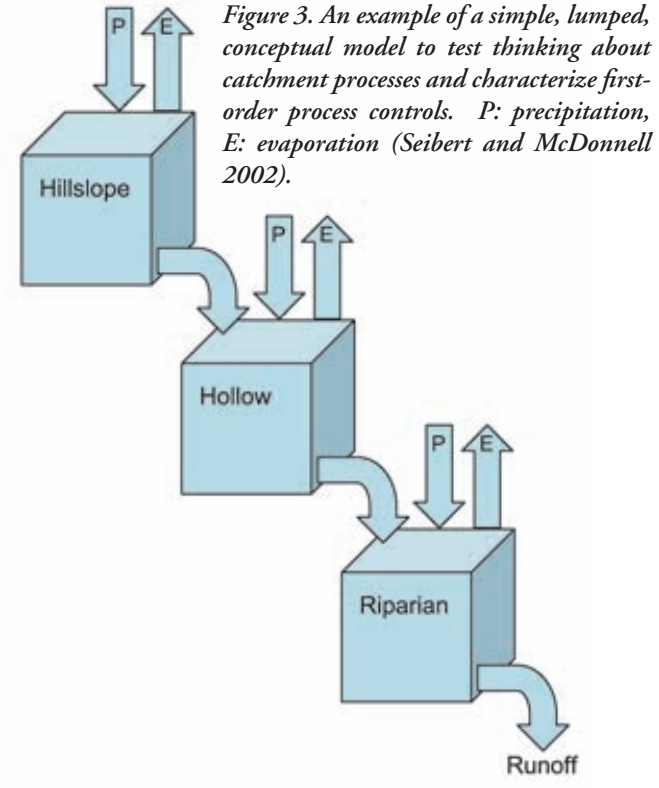


Figure 3. An example of a simple, lumped, conceptual model to test thinking about catchment processes and characterize first-order process controls. P: precipitation, E: evaporation (Seibert and McDonnell 2002).



but can be used as fuzzy measures of model simulation and parameter value acceptability. This injects some experimentalist common sense into the calibration process, providing a more "real" model of the catchment that better captures the key processes controlling catchment response (Seibert and McDonnell 2002).

4. ***Physical measures and characterization of dominant runoff producing processes*** – reservoirs, pathways and constants are added to the simple box model. The developing model focuses further instrumentation, gaging, and watershed characterization. Results are used to explore and represent the dynamic nature of the system and provide a useful framework for gauging. Only fundamental controls on hydrologic processes are included. The emphasis is on realistic internal dynamics, rather than forcing model efficiency. This step can include feedback to step 3, and acts as a springboard to more complex approaches. Visual modeling software is useful for this step. Figure 4 provides an example from McDonnell and Vache (in press) of an application from another study area.

5. ***Develop more complete measurements and understanding of runoff processes including more detailed characterization of flow sources, pathways, and ages.*** This can include: more rigorous gaging including at tributary junctions, quantification of details of runoff response to rainfall, identification of thresholds in reservoir connections, and analysis of stream and groundwater chemistry to characterize water source areas and residence times. Improved understanding may force re-evaluation of earlier models.

To further understanding of internal catchment behavior we will install a series of nested discharge measurement stations to assess longitudinal contributions of groundwater to stream discharge, thereby delineating dominant runoff producing zones and processes. We will further analyze water sources and pathways using tracers, including water temperature, conductivity, and others (McDonnell and Tanaka 2001). Analyses of stable isotopes, in particular ^{18}O, in stream water can be extremely valuable in defining water age. This allows determination of the proportion of "old" vs. "new" water in runoff and leads to definition of runoff sources and flowpaths. The role of physiographic and landscape characteristics in the composition of water will be assessed following the approach of McGlynn et

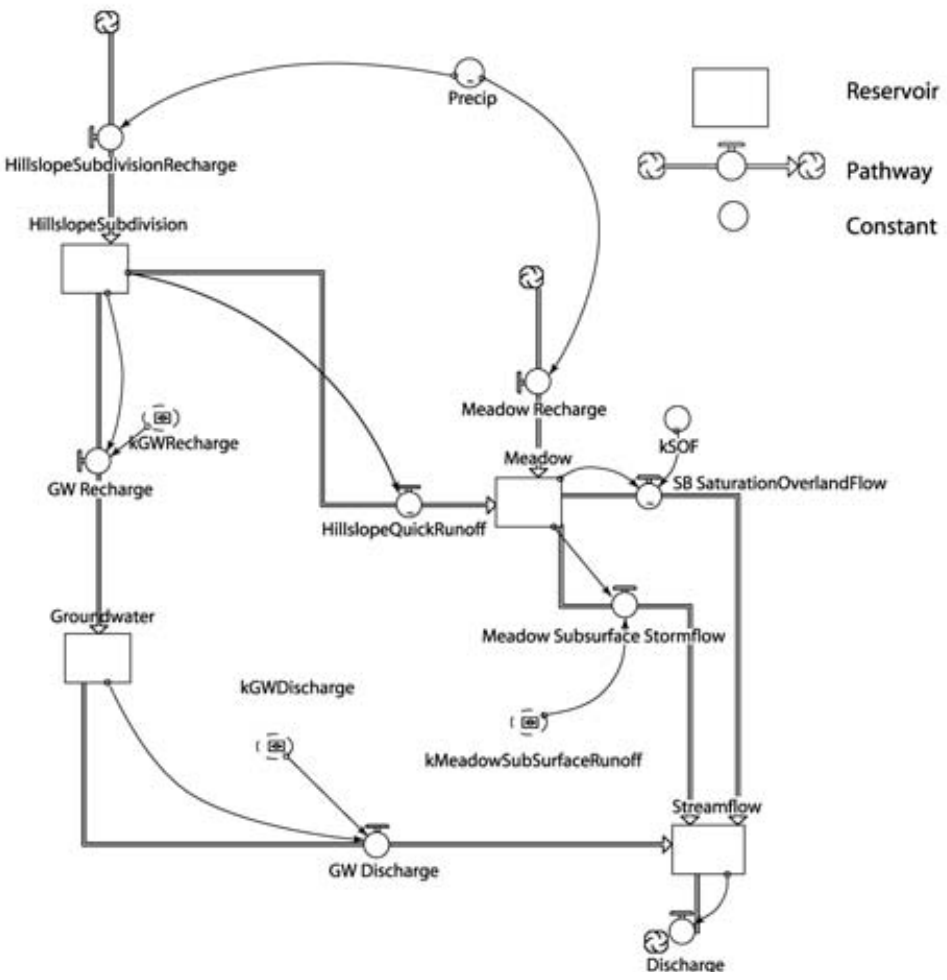


Figure 4. An example of a refined conceptual model of runoff processes using "STELLA" (High Performance Systems Inc.)[1] visual modeling software (McDonnell and Vache 2004). Details in this example are not relevant to the Entiat study area.

1 The use of trade names is for the information and convenience of the reader. Such use does not constitute an official endorsement by the U.S. Department of Agriculture of any product to the exclusion of others that may be suitable.

al. (2003), who found that streamwater composition was controlled by the distribution of tributaries, related sub-catchment area, and the associated mean water residence time of each. Distinctions among water sources, flowpaths, and ages have important implications in assessment of the effects of disturbance including fire. For example, studies in other areas have indicated that the majority of runoff can be "old" groundwater, rather than storm event water, implying that immediate effects of disturbance may be strongly damped by the influx of pre-disturbance water, possibly from other parts of the catchment.

The HBV Model

We are employing the Hydrologiska Byråns Vattenbalansavdelning [HBV] rainfall-runoff model (Bergstrom 1995) as a tool for change detection, whereby the effects of the 1970 fire will be assessed through the gaging record. We use EEF field data to make the HBV model more distributed and more tailored to the specifics of the EEF catchments, following methods of Seibert and McDonnell (2002). Early post-fire and current gage data will be analyzed to see if change can be detected relative to the 1960s pre-fire condition. HBV is a simple, conceptual model for runoff simulation, which is widely used in Nordic countries. It is semi-distributed in that it accommodates division into sub-catchments and elevation and vegetation zones. HBV lends itself to conceptualization of a catchment as a series of linked reservoirs that can be represented as boxes in simple flow diagrams (Figure 5) (Seibert 1996).

The HBV model simulates daily discharge using daily rainfall, temperature, and potential evaporation as input. Rainfall and temperature values are the weighted means among stations and are corrected for elevation by zone. Potential evaporation estimates are normally monthly mean values based on the Penman formula or evaporimeters. The long-term mean of the potential evaporation for a certain day can be corrected to its value at day t by using deviations in temperature from its long-term mean and a correction factor (Seibert 1996).

Precipitation is simulated to be either snow or rain depending on whether the temperature is above or below a threshold temperature (TT). All precipitation simulated to be snow (that falling when the temperature is below TT) is multiplied by a snowfall correction factor to account for losses to evaporation and sublimation and measurement error, which tends to be greater than for rainfall measurement. Typical correction factor values for forested areas are about 0.8. Snowmelt is calculated using a simple degree-day method. Meltwater and rainfall are retained within the snowpack until they exceed a certain

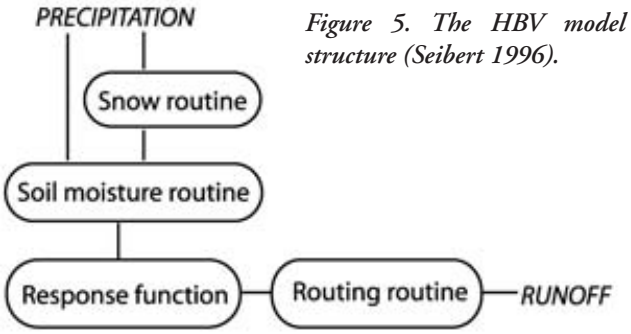


Figure 5. The HBV model structure (Seibert 1996).

Submodel	Input data	Output data
Snow routine	Precipitation, temperature	Snow pack, snowmelt
Soil routine	Pot.Evap., precipitation, snowmelt	Act.Evap., 'soil moisture', groundwater recharge
Response function	Groundwater recharge, (pot. ET)	Runoff, 'Groundwater level'
Routing routine	Runoff	Simulated runoff

fraction of the snow water equivalent. Liquid water within the snowpack refreezes according to a refreezing coefficient applied to TT (Seibert 1996). The refreezing coefficient, snowfall correction factor, and TT are adjustable model parameters, rather than empirically derived quantities.

Rainfall and snowmelt (P) are divided into water filling a conceptual soil box and groundwater recharge depending on the relation between water content of the soil (SM), its largest value, field capacity (FC), and the parameter 'Beta'. At low soil moisture all rain and snowmelt goes to soil moisture storage. At field capacity (maximum soil moisture storage), all rain or snowmelt goes to groundwater recharge (Figure 6). Actual evaporation from the soil box equals potential evaporation if SM/FC is above LP, while a linear reduction is used when SM/FC is below LP (Figure 7) (Seibert 1996).

Groundwater recharge is added to an upper groundwater box or reservoir. From there water percolates to a lower groundwater box at a maximum rate. Runoff from the groundwater boxes is computed as the sum of two or three linear outflow equations depending on whether or not recharge in the upper groundwater box is above a threshold value. Outflow at time t is proportional to water storage (S) as determined by the coefficient "k" (Figure 8). The first estimate of the groundwater response parameter (k) is taken from the slope of hydrograph recession curves. Finally, simulated groundwater outflow is transformed

Figure 6. The HBV soil moisture routine – contributions from rainfall or snowmelt to soil moisture storage and to the upper groundwater zone. FC is the maximum soil moisture storage, BETA is a parameter that determines the relative contribution to runoff from rain or snowmelt (Seibert 1996).

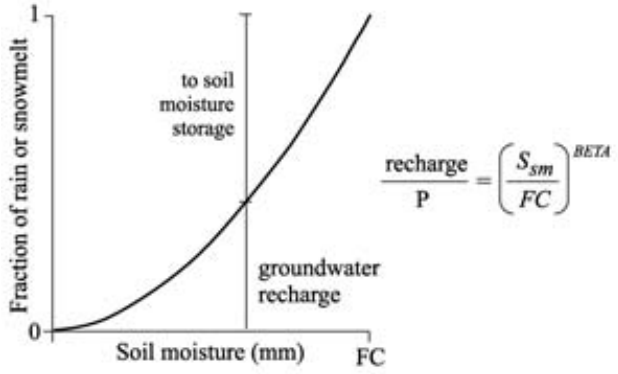
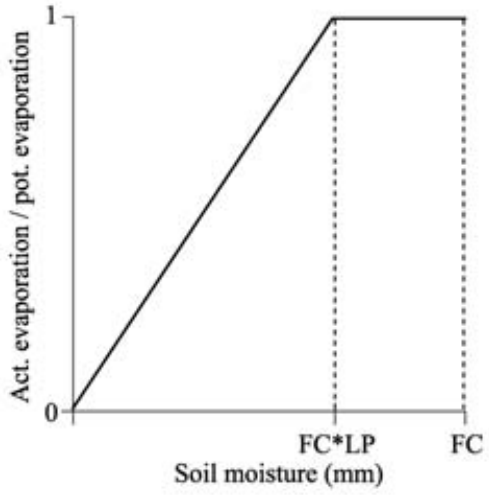


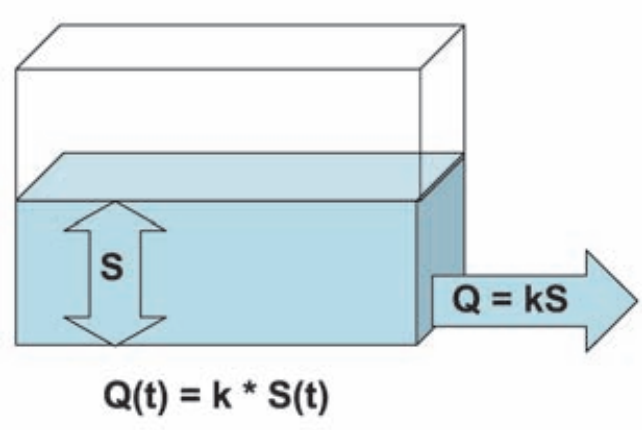
Figure 7. The HBV model – change in actual evaporation depending on soil moisture storage. FC is a model parameter and not necessarily equal to measured values of 'field capacity'. LP is the soil moisture value above which actual ET reaches potential ET (Seibert 1996).



to simulated catchment runoff by a weighting function, which distributes runoff from one time step onto the following days (Seibert 1996).

Distributions of reasonable parameter values are developed using a Monte Carlo approach. Parameter values are chosen randomly within a specified range for each run, and a large number of model runs, each generated by a distinct parameter set, are performed. Working with a set of parameters, rather than a single value, allows computation of parameter confidence intervals and reduction in parameter uncertainty (Seibert 1997). Best fit parameter sets are selected through an assessment of the fit of simulated to observed runoff data based on visual inspection of fit, accumulated difference between

Figure 8. The HBV model – simple linear reservoir response function. The model of a single linear reservoir is a simple description of a catchment where the runoff Q(t) at time t is proportional (k) to the water storage S(t) (Seibert 1996)



simulated and observed values, and statistical criteria. Commonly, the coefficient of efficiency is used to evaluate model fit. This coefficient compares the prediction by the model with the simplest possible prediction, a constant observed mean value over the period. Alternatively multiple objective functions can be used, with measures combined through fuzzy logic algorithms (Seibert 1996; Seibert 1997).

Application of the HBV Model

We employ the HBV model to evaluate hydrologic change in the EEF data (Seibert et al. 2004), and report preliminary results here to illustrate the approach. Publication of final results is forthcoming. Change was evaluated by: (1) comparing runoff simulated from pre-fire parameter sets to observed runoff (simulation vs. observation); (2) comparing simulations based on pre-fire parameter sets to simulations based on post-fire parameter sets (simulation vs. simulation); and (3) directly contrasting pre-fire with post-fire parameter values. The simulation vs. observation approach involves calibrating parameter sets using pre-fire data, simulating pre- and post-fire runoff from these parameter sets and driving variables, then contrasting simulated to measured runoff. This is done by contrasting the statistical central tendency and dispersion of residual (observed minus simulated) distributions for the larger peak flows. Dispersion of this distribution provides a measure of parameter uncertainty. The simulation vs. simulation comparison is done by calibrating separate parameter sets for pre- and post-fire runoff data. Separate simulations of the larger post-fire runoff events are run for these parameter sets using post-fire driving variables. Simulated values are then compared to a hypothetical

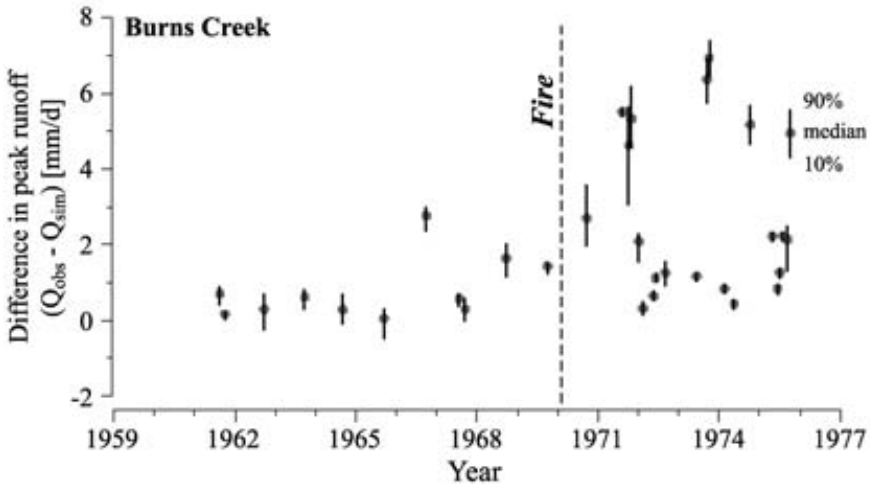


Figure 9. Observed minus simulated runoff based on pre-fire parameter sets. Severe fire occurred on 24 August 1970. Data points are median values of the 100 best-fit parameter sets. Vertical bars represent the corresponding distribution of runoff values (Seibert et al. 2004).

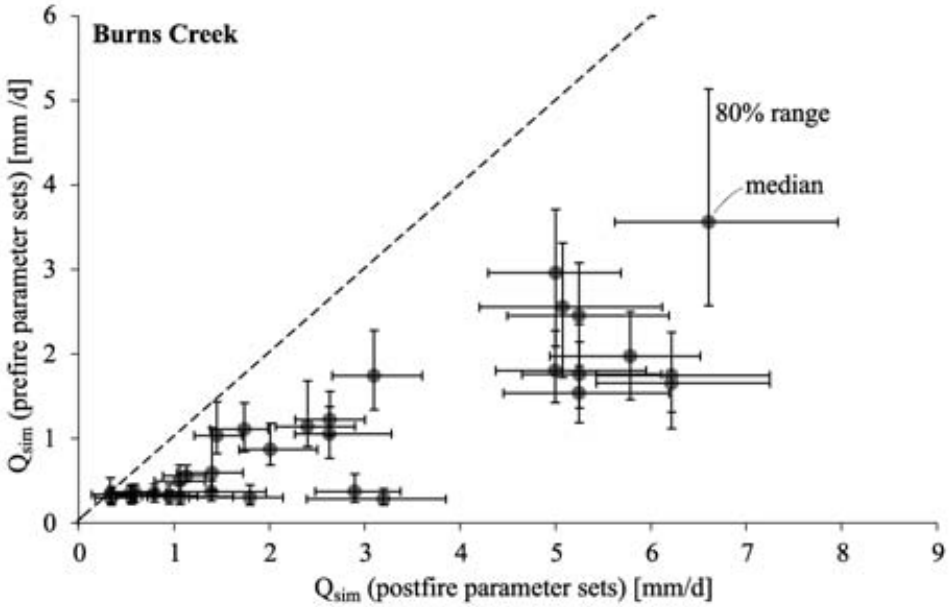


Figure 10. Post-fire runoff simulated from post-fire parameter sets vs. pre-fire parameter sets. Data points are median values of the 100 best-fit parameter sets. Bars represent the corresponding distribution of runoff values (Seibert et al. 2004).

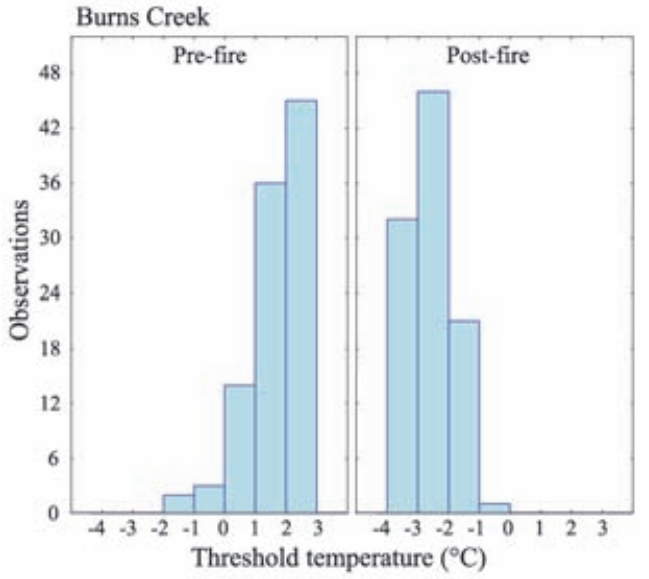
zero-change result. To directly contrast pre- with post-fire parameter values, separate parameter sets are calibrated, then pre- and post-fire values of central tendency of each parameter are contrasted (Seibert et al. 2004).

Each of these three approaches was applied to the EEF data. One million model runs were performed, and the 100 best fit parameter sets selected from these. The simulation vs. observation approach indicated a general increase in post-fire median runoff (Figure 9). Error bars in Figure 9 indicate distribution in runoff among the 100 best-fit parameter sets. Similarly, the simulation vs. simulation approach indicated a consistent increase in post-fire runoff (Figure 10).

Pre- and post-fire parameter sets were directly compared for all three EEF subwatersheds. Results indicated post-fire increases in soil moisture, reducing available storage for storm event water by approximately half. Modeling further indicated a 50% increase in the snowfall correction factor, implying greater snow accumulation, a 3°C post-fire decrease in temperature threshold (Figure 11), implying onset of snowmelt approximately one-month earlier than normal for the pre-fire period, and a 50% increase in rate of snowmelt calculated by the degree-day algorithm. These changes combined to produce modeled post-fire peak flow increases of 100% or more (Seibert et al. 2004). Our modeling results are in general agreement with findings of Helvey (1980) based on a conventional paired watershed approach, using the Chelan River as a control. Helvey computed measured minus predicted runoff based on pre-fire calibration, and determined that post-fire annual runoff increased from 1.7- to 3-fold relative to the pre-fire mean.

Although validation of the physical basis for these changes in adjustable parameter values is beyond the scope of this paper, the modeled shifts in values are physically reasonable. Fire related reduction in evapotransporation

Figure 11. Distribution of the threshold temperature (TT) parameter among the 100 best-fit pre- and post-fire parameter sets (Seibert et al. 2004).



should increase soil moisture; reduced canopy interception should lead to greater snow accumulation; and increased turbulent exchange at the snow-air interface should increase the efficiency of snowmelt processes leading to initiation of runoff at lower mean air temperatures (earlier in the season) and higher rates of snowmelt.

Summary

In recent years interest in the hydrologic recovery of burned areas has increased. Effects of fire on soil and vegetation can lead to increased runoff, peak flows, flooding, water yield, erosion, sediment load, turbidity, mass soil movements, and debris flows that alter water quantity and quality and may threaten human life and property (Beschta 1990; Conedera et al. 2003; DeBano et al. 1998; Meyer et al. 2001; Robichaud et al. 2000; Swanson 1981; Tiedemann et al. 1979; Wells et al. 1979; Wondzell and King 2003). Despite increased interest, few data exist at the subwatershed scale that document the effects of wildfire on runoff characteristics. The EEF is the site of one of very few published studies that chronicle a "natural fire experiment" before and after wildfire.

Our objectives are to review and expand upon previous analyses of existing hydrologic data and to renew data collection and analyses in the EEF. We seek to increase understanding of the effects of severe wildfire and post-fire land management on water quantity, quality, and timing, as well as long-term hydrologic recovery following severe disturbance such as fire. Increased predictive capability regarding effects of severe wildfire and mechanisms and rates of hydrologic recovery will inform land management responses to these events. For example, improved knowledge of long-term hydrologic recovery following wildfire could help guide decisions regarding the relative value and advisability of various post-fire rehabilitation approaches. Increased understanding of catchment hydrology at the subwatershed scale will improve evaluation of hydrologic change associated with a variety of land management practices. Availability of gaging records for the Entiat River subbasin creates an opportunity to scale up this new knowledge from the subwatershed scale to larger areas within the ICRB.

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Discharge and Sediment Loads at the Kings River Experimental Forest in the Southern Sierra Nevada of California

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The Kings River Experimental Watershed (KREW) is now in its third year of data collection on eight small perennial watersheds. We are collecting meteorology, stream discharge, sediment load, water chemistry, shallow soil water chemistry, vegetation, macro-invertebrate, stream microclimate, and air quality data. This paper primarily examines discharge and sediment data from six watersheds between 1600 m and 2400 m in elevation in the Sierra Nevada, California. The discharge discussion focuses on water year (Wy) 2004, which was relatively dry. The sediment discussion examines bulk mass data from Wy2001 through Wy2004, and presents some detailed analysis of the sediment load beginning with the Wy2003 dataset. Sediment loads in kilograms per hectare were low with the exception of Wy2003. Meteorology data from two stations at the top of the watersheds and two stations at the bottom is presented. Between 2007 and 2009, six of these eight watersheds are planned be harvested, undergo prescribed burns, or both, to quantitatively measure the effects of these USDA Forest Service land management practices.

Keywords: *watershed management, hydrologic processes, sediment yield, fire, thinning, stream ecology, streamflow*

Introduction

Sixty percent of California's water originates from small streams in the Sierra Nevada, yet there is very little information about how these streams are affected by land management activities near the source. Sierra Nevada stream water is considered some of the highest quality water in the state. The quality of aquatic and riparian (near-stream) ecosystems associated with streams is directly related to the condition of adjacent uplands within their watersheds. Past management actions such as timber harvesting, road construction, and fire suppression have altered the vegetation structure of watersheds and have affected headwater streams. Forest Service management believes that prior to European settlement, circa 1850, the western slope of the Sierra Nevada was more open and had predominantly uneven-aged stands. This historic stand structure was extremely resistant to stand-replacing wildfires. Restoration of the Sierra Nevada's forest watersheds to historic or desired conditions requires active management, such as reintroduction of frequent, cool fires and removal of accumulated fuel loads.

The Kings River Experimental Watershed (KREW) is a long-term watershed research study being implemented on the Sierra National Forest to provide much needed information for forest management plans regarding water quantity and quality (Figure 1). This experimental watershed research is designed to: (1) quantify the variability in characteristics of headwater stream ecosystems and their associated watersheds; and (2) evaluate the effect of fire and fuel-reduction treatments on riparian and stream physical, chemical, and biological conditions. This is an integrated ecosystem project at the watershed scale and is part of a larger adaptive management study that began in 1994 as a collaborative effort between the Sierra National Forest, Southern California Edison, and the Pacific Southwest Research Station of the Forest Service. This larger study was designed to evaluate the effects of management actions aimed at recreating an uneven-aged forest that is resistant to wildfires. The KREW staff will evaluate the effects of mechanical thinning, prescribed

Furniss, M.J., Clifton, C.F., Ronnenberg, K.L., eds., 2007. *Advancing the fundamental sciences: proceedings of the forest service national earth sciences conference, San Diego, CA, 18-22 October 2004*. PNW-GTR-689. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station.

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Figure 1. Kings River Experimental Watershed is located on the Kings River, which drains into the San Joaquin River basin. It is part of the Kings River Project, Sierra National Forest, which is a 60,000 ha collaborative study between research and management.

fire, and thinning with fire combination treatment on the watersheds.

Stream monitoring is a well-developed science; however, the majority of work addresses large streams and rivers. Watershed research has been conducted in the United States since the early 1900s, but none of the long-term studies are in ecosystems similar to the Sierra Nevada, and most studies were designed to evaluate severe management actions such as clearcuts and stand-replacing fires. Critical information is lacking because few integrated ecosystem studies exist (Naiman and Bilby 1998). Such studies are essential for understanding stream-watershed ecosystem processes and functions for adaptive management.

The Kings River Experimental Watershed consists of eight watersheds that vary in size from 49 to 228 ha. The Providence Site is composed of four adjacent watersheds (1,500 to 2,000 m in elevation) in mixed-conifer forest – D102, P301, P303, and P304. The four Bull Site watersheds, ranging in elevation from 2,100 to 2,500 m (B201, B203, B204, T003) are in mixed-conifer forest with a large red fir (*Abies magnifica*) component approximately 15 km southeast of the Providence Site. These elevation bands were selected because this is where most Forest Service management activity in the Sierra Nevada has traditionally taken place. The KREW staff is collecting the standard watershed measurements of discharge, sediment load, and a suite of meteorology measurements; the first years of this baseline data are presented in this paper.

Other watershed and stream characteristics are being studied because KREW is an integrated watershed study. Stream water, soil water, and snowmelt are analyzed for various anions and cations every two weeks, and more often during peak spring runoff and storms. Air quality is monitored for ozone, ammonia, and nitric acid. Riparian and upland vegetation and stream macroinvertebrates are surveyed annually. Fuel loading and channel morphology will be measured prior to treatment implementation and periodically once the treatments are completed.

Methods

Discharge Methods

Stream discharge is measured with Parshall-Montana flumes (Figure 2). The KREW streams have approximately a 500-fold difference between lowest and highest flow over a 20-year time span, but Parshall-Montana flumes can capture accurately only a 50-fold difference; therefore two flumes, one large and one small, are on each stream. The two-flume design permits precise flow measurements (from standard tables) from 0.75 L/s (0.03 cfs) to 900 L/s (32 cfs). Less precise, but still acceptable, measurements over the range from 0.3 L/s (0.01 cfs) to 1,400 L/s (49 cfs) will be used. All of theWy2004 data from the four Providence streams and most of the data from the two Bull streams are from the small flumes, with 7.6 and 15.2 cm throats respectively. All discharge, meteorology, and sediment data are reported based on the water year which begins on 1 October of the previous year and ends on September 30 of the stated year (Wy2004 runs from 1 October 2003 to 30 September 2004).

Isco®[1] 730 bubblers were chosen to measure stage on the small flumes because freezing does not destroy the instrument. The bubbler relays data to an Isco 6712 sampler, which also takes water samples for chemical analyses. The Isco sampler and bubbler receive electricity from a 12V DC system powered by a 50W solar panel. The stage data is relayed via radio telemetry back to the Fresno office. The backup device on the Providence small flumes is a Telog® WLS-31 pressure transducer. The KREW staff measure stage in the large flumes (61 to 122 cm throat width) using Aquarods that sit in stilling wells. Both the Telogs and the Aquarods are downloaded to a laptop on a monthly basis. Visual stage readings are recorded every

[1]The use of trade or firm names in this publication is for reader information and does not imply endorsement by the U.S. Department of Agriculture of any product or service.

Figure 2. The two-flume design on the B201 stream allows KREW staff to precisely measure a wide range of flows. The 3-inch Parshall Montana flume (foreground) measures most flows, and the 2-foot Parshall Montana flume (background) measures large rain events.

two weeks except during spring runoff when the sites are visited weekly. All data is stored and managed in the Isco Flowlink® program.

All of KREW's eight watersheds are located within the rain to snow transition zone where many precipitation events drop a combination of rain and snow. In order to better understand the factors that control stream discharge, this paper uses meteorology and discharge data to examine aspects of the water cycle. For this analysis the discharge from the Wy2004 hydrograph was divided into the following four categories: baseflow, rain event flow, snowmelt flow, and soil water. Baseflow was determined by looking at the discharge for the lowest flow period of Wy2004, 1 September to 15 September. Baseflow for the year is derived by multiplying this daily average by 366 (2004 was a leap year. The authors expect this water has been in the ground for at least six months and originates in perennial springs.

Rain event flow (quickflow) is all runoff above baseflow that occurred from the start of each rain event until the flow drops back to where it started, or 24 hours after the rain stops, whichever comes first. Rain events that did not increase the hydrograph by at least 20 percent were ignored. Using the above criteria, six rain events occurred in most of the KREW watersheds. In the Wy2004 hydrograph, these six events and their associated tails had a combined duration of approximately 300 hours. Snowmelt flow is runoff above baseflow that occurs between the start of spring runoff (7 March 2004) and two weeks past the date on which the snow depth sensor at the closest meteorology station indicates zero. The D102 watershed had two distinct snowmelt periods and was handled slightly differently. The authors believe that the snowmelt flow water resides briefly in the shallow soil as it moves to the stream. Soil water was determined by taking total discharge for Wy2004 in each watershed and subtracting baseflow, snowmelt flow, and rain event flow as defined above. We expect that this water is stored in the soil between two weeks and six months.

Meteorology Methods

KREW has four meteorology stations; a station is located at the bottom and the top of each group of four watersheds (Figure 3). Seven parameters are measured at 15-minute intervals: temperature, relative humidity, solar radiation, wind speed, wind direction, snow depth, and precipitation. In Wy2004 there was one functioning snow pillow that measured snow water equivalence. Meteorological data are logged and processed by Campbell Scientific, CR10X data loggers and relayed back to Fresno via radio telemetry. The KREW staff visit each meteorological station once each month and record manual measurements to ground truth the sensors.

Figure 3. Sensors on a 6-meter tower at the upper Providence meteorology station measure temperature, relative humidity, solar radiation, wind speed, wind direction and snow depth (left). The 3-meter high Belford® gauge measures total precipitation (right).

Rainfall amounts reported here are typically an average value of the four precipitation gauges. For the six large events the totals generally vary by 10-15 percent between meteorology stations. The small events (< 25 mm) were more difficult to present in a comprehensive manner, as different sites recorded, and most likely received, very different amounts of precipitation. For small events, the data from the Upper Providence station, which is at a middle elevation for KREW, is presented instead of an average of all stations. Brief showers (< 5 mm) were excluded from the precipitation dataset because they generally did not occur at all four meteorology sites and several load-cell sensors do not exhibit sufficient precision to measure minute changes.

Sediment Methods

Sediment catchment basins exist on all eight streams, but only five of these had been constructed and were being analyzed in Wy2003 and Wy2004 (Figure 4). The basins vary in size from 25 m^2 to 200 m^2 and are slightly more than one meter deep at their deepest point. They are all lined with pond liner to make sure each year's sediment is clearly defined. These ponds are dug out by hand each September. After a total wet weight is measured, a representative sample is dried and used to determine the dry mass for each basin.

Starting in Wy2003 the organic and mineral fractions were determined. The organic fraction is made up of three components: large organic matter such as sticks that are removed by hand, coarse organic matter such as twigs that are floated off of an oven-dried sample, and fine organic matter that is burned off for 24 hours at 500°C. The dry weights of the three components are added together to arrive at a total organic fraction.

A representative sample of the mineral fraction is dried at 110°C until the sample loses less than one percent weight between hourly weighings (usually after 12 hours). A standard sieve analysis is then performed to determine a particle size breakdown using 2, 1, 0.5, 0.25, 0.125, and 0.065 mm sieves.

Figure 4. The B204 sediment catchment basin, lined with commercial pond liner, traps sediment behind a 1.2-meter-high log structure. Sediment is removed each fall, weighed wet and subsampled. A dried subsample is analyzed to determine organic and mineral fractions and particle size distribution.

Results and Discussion

Discharge and Meteorology Results

The 2004 water year had two large storms (>125 mm of precipitation); storms of this magnitude may produce bankfull flows and move sediment. The 25 December 2004 storm came primarily as rain at all elevations and moved minor amounts of sediment, while the 26 February 2005 storm delivered snow (Figure 5). The timing, magnitude, and duration of these events was statistically normal. Four other storms each provided about 50 mm of precipitation. Whether these smaller precipitation events deliver rain or snow, the soil can usually absorb the majority of the moisture, and surface runoff is limited to rock outcrops and human-compacted areas such as roads. While there was a normal distribution of these events from November through February, a typical year would have seen about three more equivalent events in March and April.

The 80 mm of rain in November recharged the shallow soil moisture but did not produce discharge peaks associated with surface flow. The smaller December events also had little effect on the hydrograph. The hydrograph response to fall storms varies very little by watershed elevation or size, so the water from the distal portions of the watershed (> 50 m from the stream) is not rapidly arriving at the stream.

The large 25 December 2004 event produced between 5,000 and 7,000 cubic meters of water in each of the four analyzed watersheds (Figure 5); this converts to about 5 mm of depth spread over each watershed. Only 5 mm of the total 130 mm that fell as precipitation was measured as discharge in the streams. The next three precipitation events were snow. The last major precipitation event on 25 February 2005 fell as snow in all except the lowest elevation areas (D102 watershed).

Water that drained out of the watersheds as a direct result of rainstorms was on average only about 7 percent of the total yearly discharge (Figure 6). This value is strongly correlated with watershed elevation, with the lower elevation watersheds having the highest percentage of their discharge derived from rainstorms. Water that originated in melting snowpack accounts for an average

Figure 5. For water year 2004, the hydrographs of four watersheds are very similar in the fall and early winter, but differ in the spring. The precipitation record (lowest graph) shows only two large storms (>125 mm) and four mid-sized events (>50 mm).

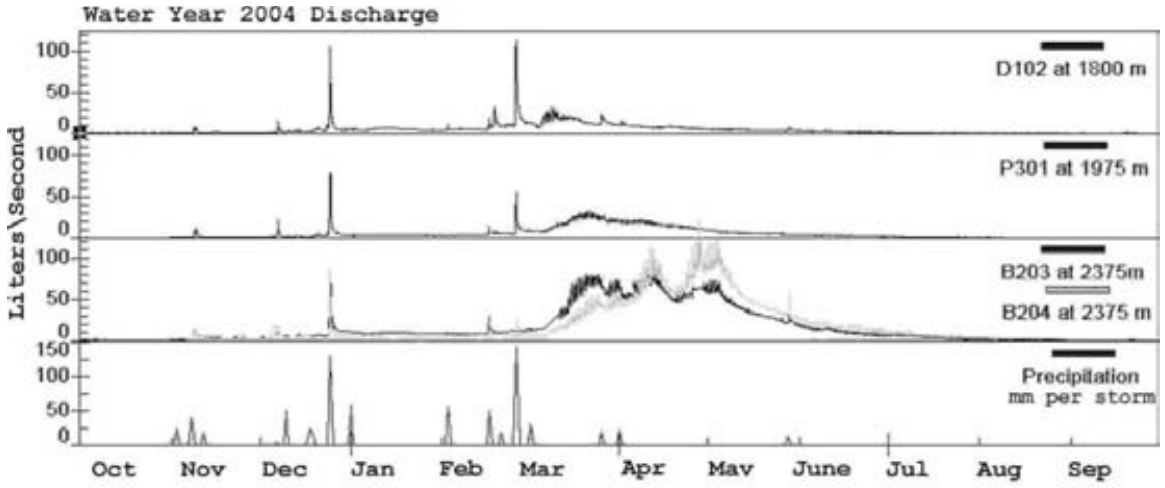
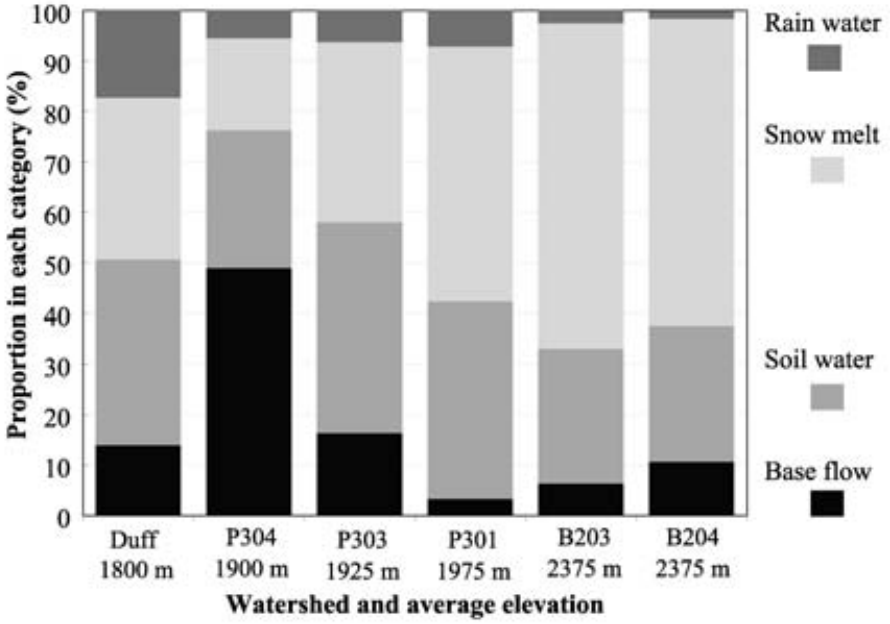


Figure 6. The annual discharge from six watersheds is divided into source components. The percentage of water from snow melt correlates with increasing elevation. Rainwater is a relatively small percentage at all elevations.



of 37 percent of the total discharge from the four lower watersheds, and was also strongly correlated with elevation, but in a reverse direction from rainfall water. Because the two highest watersheds (B203 and B204) produce twice the annual discharge of the lower watersheds, and because 68 percent of their discharge is generated by melting snowpack, 57 percent of the total water from the six analyzed watersheds came from snowmelt.

The average baseflow contribution to the annual discharge is 17 percent, but this value was skewed by P304, where baseflow accounts for 56 percent of discharge. If P304 is excluded, baseflow contributes an average of 11 percent of the annual discharge in the other five watersheds. Small perennial watersheds may have a larger baseflow component, because without good groundwater sources they would not be perennial during the late summer in the Mediterranean climate that characterizes the southern Sierra Nevada. The lower elevation watersheds rely almost entirely on baseflow from 1 July through 1 October. While these baseflows are important to stream biology, macroinvertebrates, and riparian plants in the lower elevation watersheds (P303 and D102), the last three months of the water year produced less water than the three days around the 25 December storm.

Water derived from the soil is difficult to estimate. The soil percentages (Figure 6) do not show a clear pattern, but the amount of water contributed per hectare from soil is similar for all watersheds. During Wy2004, soil water estimates for Providence watersheds varied from 462 m^3/ha in D102 to 711 m^3/ha in P304. For B203 and B204, shallow soil water contributed 1,085 m^3/ha and 984 m^3/ha respectively. The soil profile stored and then released

approximately 6 cm of moisture at 1,900 m of elevation and approximately 10 cm of moisture at 2,375 m. While we have not yet developed a full water budget, it can be concluded that very little of the moisture that entered the soil's lower profiles was released back to the streams.

In watershed P303, monthly total discharge never exceeded precipitation (Figure 7). Of the total precipitation during Wy2004, only 13 percent contributed to streamflow. At higher elevations at B203, 40 percent of the total precipitation flowed down the stream (Figure 7). From a regional viewpoint, the watersheds at 1,900 m can not be expected to contribute significantly to storage in California reservoirs during dry years. At 2,375 m, slightly more precipitation falls, but a much larger percentage of that water will flow into the reservoirs.

We acknowledge that this data is a snapshot of one dry year which had only 70 percent of the average annual precipitation. It was not an extremely anomalous meteorological year, as there are 14 drier years during the 90-year period of record at Huntington Lake precipitation gauge, approximately 25 km north of KREW and at a similar elevation. Three-week-long dry periods, such as the one that occurred in January, are not unusual in the southern Sierra Nevada.

Sediment Results

Sediment loss rates per hectare vary by three orders of magnitude among the five watersheds over the four-year dataset (Figure 8). Within a single watershed the rates vary by a factor of 100 during the four years. Between neighboring watersheds, but in the same water year, rates also vary by a factor of 100.

Figure 7. Watersheds vary in the amount of precipitation that becomes discharge. In watershed P303 at 1,925 m elevation, only 13 percent of the incoming precipitation results in discharge (top graph), whereas in watershed B203 at 2,375 m 40 percent of precipitation contributes to discharge. (bottom graph). Precipitation greatly exceeds discharge until March when spring snow melt begins.

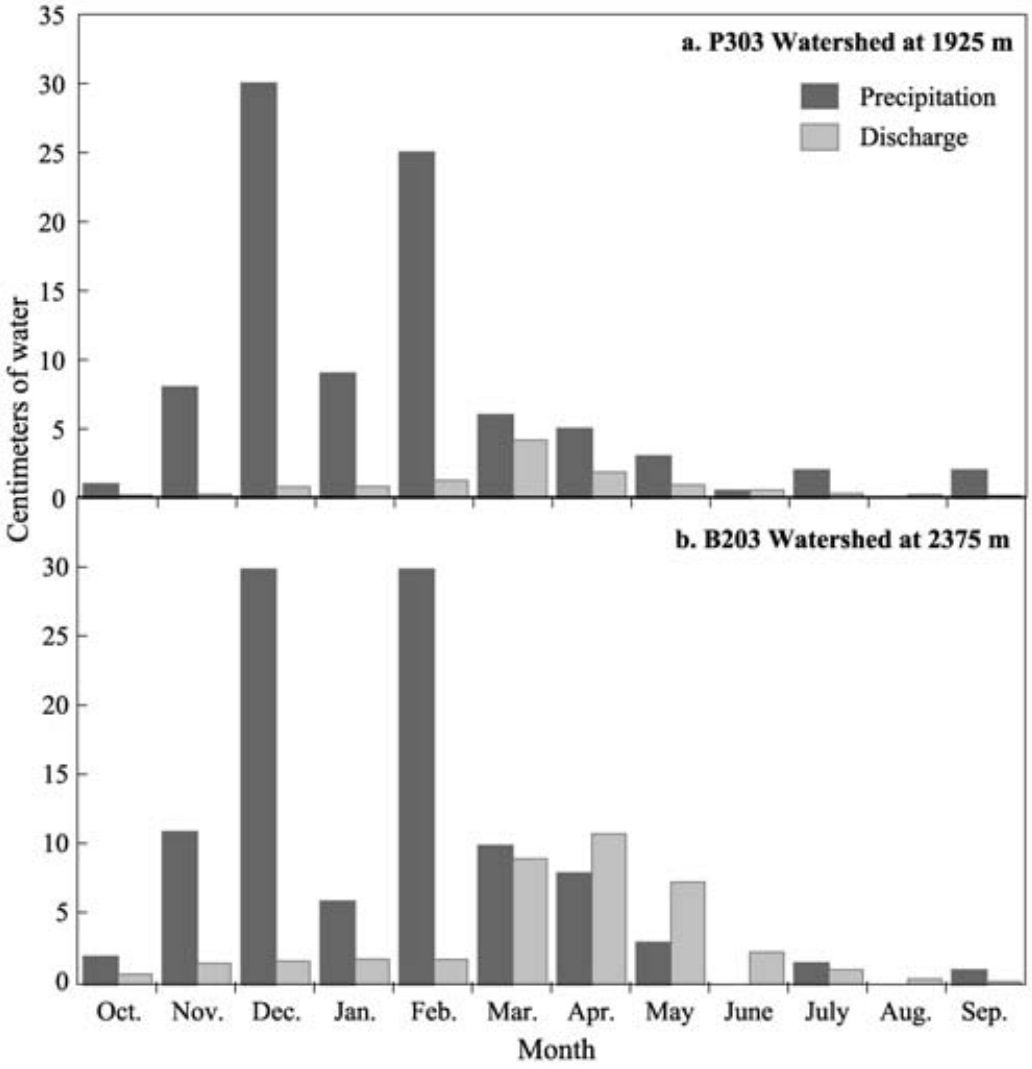
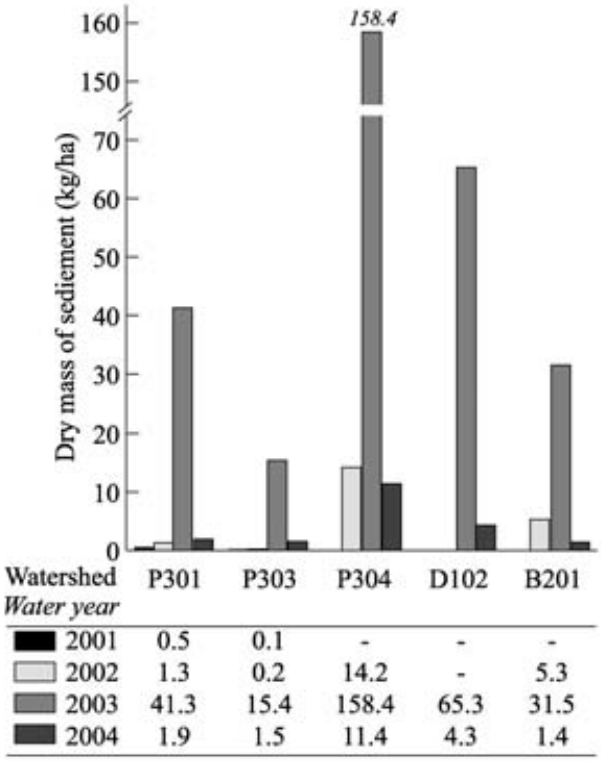


Figure 8. The dry mass of sediment captured in each basin varies by orders of magnitude between years and between adjacent watersheds.



These data indicate only 0.002 mm loss of soil depth each year (average of all basin data and an average soil density of 1.2 g/cm^3). Based on this four-year period, one might conclude that it would take 500 years to loose a millimeter of soil depth. This conclusion is misleading because erosion can be almost non-existent and then greatly increase during infrequent but intense rainfall events.

On average the basins captured 17 times more sediment in Wy2003 than in Wy2004. The total rainfall was similar (a 300 mm difference); however, the magnitude and intensity of the single largest event was very different. In Wy2003, 290 mm of rain fell in 30 hours during the 7 November storm. For a steady rainfall, that amount averages to 9.7 mm per hour, but 27 mm actually fell during the most intense hour of this storm. In Wy2004, 142 mm fell in 60 hours during the 24-25 December storm. This amount represents an average of 2.3 mm per hour, but only 11 mm fell during the most intense storm hour (Table 1). With hard rain falling (> 5 mm per hour), we observed no overland flow in undisturbed areas of the watersheds under the forest canopy. The overland flow and sediment movement seen in Wy2004 probably came predominantly from roads, unstable stream banks, or erosion just below large rock outcrops. The percentage of precipitation that falls as rain versus snow also affects soil loss.

The datasets from the P301, P303, D102, and B201 sediment basins show similar patterns in their organic fraction and mineral fraction particle size (Table 1). The organic component was between 20 and 30 percent in both years, with the total average mass of organics contributed per hectare small: 5 - 10 kg/ha in Wy2003 and 0.5 kg/ha in Wy2004. Since the magnitude of the largest rain event in Wy2004 was small, we suggest that the organic matter was primarily leaves and sticks falling off the trees directly above the stream rather than material being transported by overland flow.

In the future KREW staff will present data from all eight watersheds and track changes in the size distribution of the mineral fraction. Seventy sediment fences were constructed in 2003 and 2004 to quantify erosion from graveled roads, natural surface roads, and undisturbed hillslopes. Fourteen headcuts were surveyed in 2003 and will be resurveyed in the future. The combination of these efforts will give us a better understanding of where sediment originates and how it moves through the watershed.

Conclusions

The KREW project has the instruments in place to continue with baseline data collection at eight streams and watersheds, four meteorological sites, and 70 sediment fence locations. At the Bull Site, spring snow melt supplies the majority of the discharge. At the Providence Site, baseflow is a significant contributor to the P304 hydrograph and rain water is important to the D102 hydrograph. Such knowledge allows us to adjust our sampling for other attributes such as stream chemistry and efficiently plan field visits based on response characteristics. Spring snow melt began several weeks earlier than usual in Wy2004 at all elevations; this is a trend that has been observed during the last 50 years in the southern Sierras and has been predicted to continue with climate change (Brown and Binkley 1994). The five sediment catchment basins constructed prior to Wy2004 showed that rates of soil loss vary greatly between watersheds but are all correlated to the peak discharge. We will have sediment data for the additional three streams starting with Wy2005.

Burning and thinning treatments are scheduled to occur between 2007 and 2009 with the Providence Site starting in 2007 and the Bull Site starting in 2008. By that time, KREW will have baseline datasets of sufficient duration and precision to discern whether there are measurable changes that result from these low-severity treatments. This watershed experiment is designed to improve our knowledge of how headwater ecosystems function, and to

Table 1. The mass of mineral and organic fractions in annual stream sediment loads and the median particle size are reported with respect to peak discharge and storm intensity. During pretreatment years, organic matter is consistently between 20 and 30 percent of the total dry weight in the KREW sediment basins.

Water Year 2003	**P301**	**P303**	**P304**	**D102**	**B201**
Mineral mass / area (kg/ha)	28.0	12.0	113.8	49.3	26.5
Organic mass / area (kg/ha)	13.3	3.4	24.6	16.0	5.0
Median particle size (mm)	0.500	0.500	0.125	0.250	0.250
Peak discharge (L/s)	110	–	120	170	100
Water Year 2004	**P301**	**P303**	**P304**	**D102**	**B201**
Mineral mass / area (kg/ha)	1.7	1.4	6.7	3.8	1.2
Organic mass / area (kg/ha)	0.6	0.4	7.5	1.6	0.5
Median particle size (mm)	0.500	0.500	0.125	0.250	0.125
Peak discharge (L/s)	80	85	44	113	22

Averages for all Measured Watersheds	**Bulk Mass *(kg/ha)***	**Peak Discharge *(L/s)***	**Largest Storm Event *(mm/hr)***	**Most Intense Hour *(mm)***
WY 2002	0.3	33.0	–	–
WY 2003	58.4	125.0	9.7 for 30 hours	27.0
WY 2004	5.1	68.8	2.3 for 60 hours	11.0

support extensive modeling exercises for the watersheds both before and after treatments. Modeling will include soil erosion, stream discharge, nutrient fluxes, and air pollution and climate change effects. Eventually comparisons between treatments and responses can be made for KREW and other long-term, forest watershed experiments in the western United States. Such comparisons are important to identify differences and similarities among stream and watershed responses for different ecoregions, to increase our understanding of ecosystem processes and thus facilitate the customization of standards and guidelines for adaptive management.

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Section 3. Watershed Protection and Restoration

Part 1. Monitoring and Restoration

Overleaf:
Bond Falls, West Branch Ontonagon River, Ottawa National Forest, Upper Peninsula of Michigan. Photo by Gary Whelan, Michigan Department of Natural Resources, Fisheries Division.

The Role of BMPs in 303(d)-Listed Waters: A New Alternative to TMDLs

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Total Maximum Daily Load Analyses (TMDLs) are being conducted nation-wide to address 303(d) listed waters. The TMDL strategy can be broken into two basic phases; first is the detailed calculation of a permissible load that will attain state water quality standards. Second is the creation and execution of a plan to achieve load reductions identified in phase 1. Currently, most states are focused on the first phase in order to meet court ordered deadlines. Implementation is usually deferred pending completion of the court's decree, which will make more resources available for phase 2. However, determining TMDL targets has proved problematic in wildland forest environments when applied to non-point source pollutants such as sediment, because discerning between anthropogenic and natural sediment is difficult, and because a reliable quantification of instream loads is complex. Natural sediment discharge is highly variable as a result of various watershed interactions driven by stochastic disturbance events (fire, drought, flood, wind, insects, disease, and others). The expense of data collection needed to reliably establish numeric targets can easily exceed the cost of simply fixing the obvious problems. July 2004 Environmental Protection Agency [EPA] guidance states that where an existing regulatory program, such as watershed restoration and implementation of Best Management Practices (BMPs), is expected to achieve water quality standards, a TMDL is not required (Category 4B) (USEPA 2004a). While the 4B option has been used very infrequently, the potential benefits of streamlining the TMDL regulatory process to focus on remediation instead of the dubious quantification of permissible loads is obvious.

Keywords: *total daily maximum load (TMDL); 303(d) listed waters; watershed restoration; best management practices (BMPs); Category 4B*

Introduction

Under Section 303(d) of the Clean Water Act (CWA), states are required to identify waters where existing water quality does not meet state water quality standards. Most states have interpreted this direction and listed waters degraded by nonpoint sources without regard for whether any existing regulatory process is in place. All National Forest System (NFS) lands require the implementation of best management practices (BMPs) to identify and treat existing water quality problems and to prevent future ones (Forest Service Manual 2532.03). Currently, 18,318 NFS stream segments or 2,201 streams have been included on state lists of impaired waters, often with little or no quantitative information (EPA, unpublished 1998 data – as of October, 2004, this was the most recent complete compilation of 303 data). Generally, listing has not considered existing BMP and ongoing watershed restoration programs designed to achieve the same result. These lists of impaired waters are formally updated by the states every two years. Once on the list, the landowner must either show that the listing is in error or submit to the establishment of a Total Maximum Daily Load (TMDL) and eventually a restoration plan. Some within the various state water quality regulatory community feel that Forest Service programs are inadequately funded to achieve restoration in a timely manner. They may see the TMDL process as a lever that will result in accelerated restoration. In practice on NFS lands, just the opposite may occur, as fixed resource dollars are spent on needlessly complex TMDL assessments, leaving even less for the repair of often easily identified water quality problems.

Guidance issued by EPA in July 2004 pursuant to Sections 303(d) and 305(b) of the Clean Water Act for reporting assessment and listing of stream status (USEPA 2004a) contains information on the components of the required report for 2004. The states are required to place water bodies in one of five categories:

Furniss, M.J., Clifton, C.F., Ronnenberg, K.L., eds., 2007. *Advancing the fundamental sciences: proceedings of the forest service national earth sciences conference, San Diego, CA, 18-22 October 2004*. PNW-GTR-689. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station.

Category 1: All designated uses are met;
Category 2: Some of the designated uses are met, but there is insufficient data to determine if remaining designated uses are met;
Category 3: Insufficient data to determine whether any designated uses are met;
Category 4: Water is impaired:
4A – a TMDL(s) has been completed,
4B – existing control measures are expected to result in the attainment of water quality standards (WQS) in a reasonable period of time, a TMDL is not needed, and
4C – waters are impaired entirely by something other than a pollutant.
Category 5: Water is impaired: a TMDL is needed.

As mentioned earlier, EPA's 1998 data lists 18,318 impaired segments on NFS lands. Often, multiple segments are located on a single stream, so the active number of listed streams is 2,201. The situation is particularly acute in Montana, which is reported to have nearly one half of all 303(d) listed segments in EPA's Region 8 (including North Dakota, South Dakota, Nebraska, Wyoming, Colorado and Utah [Personal communication, Julie DalSoglio, EPA Region 8, 8 June 2004]).

NFS streams have had a particularly high incidence of listing across the country, principally because they represent a very high percentage of monitored small streams, not necessarily because they represent poor water quality. Real problems exist on NFS lands, but the listing process in combination with ambiguous state standards for sediment and temperature have resulted in some very questionable results.

In Montana, each watershed with one or more Category 5 segments may require preparation of a TMDL. A TMDL is the calculation of the amount of pollutant that a waterbody can receive from point and nonpoint sources, plus natural background and a margin of safety, without exceeding water quality standards. In Montana, for example, the TMDL assessment process uses a watershed approach that may include multiple impaired segments. To reach a reasonable level of scientific credibility, the process has evolved into a complex study with many of the same data requirements as the six-step watershed assessment process currently employed in the USDA Forest Service (RIEC and IAC 1995). Costs for completing approved TMDLs in Montana have generally ranged between $150,000 and $300,000, and completion and approval can take more than two years (personal communication, Ron Steg, EPA R-8). These represent all state and federal costs to create the TMDL but do not include restoration and monitoring. Estimated federal costs are approximately $50,000 per TMDL, which represents the cost of collaboration with state agencies.

Point sources are derived from a specific location while nonpoint sources are derived from the general landscape rather than a discrete discharge point. The actual TMDL equation also includes provisions for a margin of safety and future human growth.

On NFS lands in the western United States, sediment, temperature, or both, are most commonly the pollutants of concern. In cooperation with the Montana Department of Environmental Quality (MDEQ) and EPA Region 8, personnel from national forests in Montana have contributed large amounts of time to assist the state in meeting a court-imposed schedule for TMDL completion [See 20 September 2000 Court Order in Friends of the Wild Swan, Inc. v. US EPA, No. CV-97-35-M-DWM (D. Mont.)]. In some cases Forest Service personnel have written the entire TMDL and in others they were active contributors to the process. Where available, both EPA and MDEQ have provided supplemental funding. The following forests are currently working with EPA and MDEQ on TMDL projects:

Helena National Forest
- Participant in the Blackfoot Headwaters TMDL

Kootenai National Forest
- Funded by EPA to complete the Yaak TMDL

Lolo National Forest
- Collaborator on Upper Lolo TMDLs
- Funded by MDEQ for the St. Regis TMDLs
- Team member and partially funded for Prospect Creek TMDL
- Participant in Bobtail Creek TMDL

Flathead National Forest
- Developed the Big Creek TMDL
- Funded by EPA to complete TMDLs for the Flathead Headwaters
- Participated in the Swan TMDL

Beaverhead National Forest
- Team member on the Ruby TMDL

Though these ten projects represent a large effort on the part of forest staff, a number of additional TMDLs will be written for NFS watersheds over the next five years.

Evolution of the BMP Alternative

State and Congressional interest in pursuing opportunities for speeding up the TMDL process on national forests grew following a United States District Court ruling in Montana (Sierra Club Inc.; Alliance for the Wild Rockies v. Deborah Austin as Lolo National Forest Supervisor), which stated that a project involving timber harvest and watershed restoration could not continue until the TMDL was completed because, without knowing the maximum allowable load, there was no standard to judge impacts against. This decision was appealed to the 9th Circuit Court, and the TMDL portion of the case was eventually overturned. However, litigants have indicated continued interest in pursuing TMDL related issues, and since implementation and monitoring are still on the horizon for most TMDLs, future grist for litigation seems assured.

These events caused the Montana State TMDL Advisory Group (appointed by the state Governor) to request that MDEQ begin exploring alternative ways to speed the TMDL process. Montana's Senator Max Baucus became interested and assigned a Congressional Fellow to help resolve the issue. As a result, a meeting was held on 4 and 5 May 2004 with representatives from the Washington offices of EPA and the Forest Service, Senator Baucus's office, MDEQ, Montana State Lands, and the Northern Region (R1) of the Forest Service. Placing waters into EPA Category 4B was discussed as one alternative that could be useful in speeding the recovery of degraded waters.

Preliminary investigation of the 4B process and its possible benefits showed that there were theoretically widespread benefits. There were a number of 303(d) listed waterbodies on NFS lands that several members of the review team were familiar with, where it was highly likely that the cost of treating the pollutant sources using existing restoration BMPs would be significantly less than the cost of producing the TMDL. Bristow Creek on the Kootenai NF and Taylor Fork on the Gallatin NF were identified as initial test watersheds.

As a result, discussion and development of the Taylor Fork Category 4B report was begun. Identified restoration needs were funded and the majority of needed work was completed in the 2005 field season. The final Taylor Fork 4B report was submitted to Montana DEQ in August 2005. This effort could result in a significant breakthrough in the regulatory process, since it redefines the role of restoration, BMP application, and monitoring to significantly speed the recovery of degraded waters, though other priorities have slowed MDEQ's review and approval of the report.

Category 4B as Described by EPA

The choice of whether to pursue Category 4B remains with the states and affected agency. Current regulations do not require TMDLs for all listed waters. When to establish TMDLs and when they are not appropriate is described by EPA guidance (USEPA 2004a). It states "....it best serves the purposes of the Act to require the State to establish TMDLs and submit them to EPA for approval only where such TMDLs are needed to 'bridge the gap' between existing effluent limitations, other pollution controls and water quality standards (WQS)." For waters with sufficient controls, EPA states "...establishing TMDLs would not contribute to accomplishing the goals of the Act and could draw resources from areas where there are water quality problems [50 FR 1775, 11 January 1985]. To use category 4B, the state must demonstrate that "other pollution control requirements (e.g., best management practices or needed restoration) required or agreed upon by local, state or federal authority" [see 40 CFR 130.7(b)(1)(iii)] are expected to address all water-pollutant combinations and attain all WQSs [water quality standards] in a reasonable period (USEPA 2004a)."

What does the Forest Service have to do to demonstrate that Category 4B applies to a given situation? Recent EPA guidance (USEPA 2004a) identifies the information necessary to support a determination that waters may be moved to Category 4B:

1. Identification of the controls to be relied upon: What are the problems and what BMPs or restoration will be prescribed?
2. A description of the authority under which the controls are required: Are BMPs required as a component of Forest Plans or other relevant National Environmental Policy Act [NEPA] documents?
3. Documentation that the controls are adequately stringent to result in attainment of applicable water quality standards within a reasonable period of time. In most cases this can be a straightforward literature review or practical examples of similar restoration applied to similar situations, however, more extensive modeling can also be done if warranted.
4. Assurances that the controls will be implemented. A watershed restoration plan with a line officer's signature and a proposed schedule, for example, will usually suffice.

The TMDL approach and BMP application have substantial overlap as well as important distinctions. However, the practical differences are few. First, the watershed restoration-BMP (4B) approach does not require

the calculation of a TMDL. Second, the 4B approach requires the identification and repair of the problem immediately or within a reasonable timeframe. The TMDL approach defers restoration work until phase 2, and in many states, actual restoration is voluntary. Third, both approaches require monitoring sufficient to attainment of water quality standards. In either case, should monitoring show inadequate improvement, additional measures can be implemented. If standards are not achieved, the state retains the authority and option to require a TMDL.

Both the TMDL and 4B approaches demonstrate the need to assure that either the load reductions identified in the TMDL, or the watershed restoration and BMPs identified as 4B controls, are stringent enough to achieve water quality standards. According to EPA's guidance on development of sediment TMDLs (USEPA 1999), this "linkage" analysis can range from simple to complex. The more simple approaches mentioned in the guidance include linkage analyses based on empirical, index, or inference approaches. The more complex methods rely on mathematical or process models. The appropriate level of analysis depends upon several technical and practical factors such as the pollutant at issue, the hydraulic characteristics of the waterbody, the relevant temporal and spatial representation needs, the level of accuracy needed, and stakeholder interests. Ideally, the linkage analysis will be supported by monitoring data, allowing the analysis to associate waterbody responses with flow and loading conditions. When dealing with natural background loadings as well as wide fluctuations in pollutant loadings from nonpoint sources, the professional judgment of resource experts is often used to construct the linkage analysis. This approach relies on established principles as well as any new approaches documented in the literature relevant to the pollution situation in question. Where qualitative approaches to linkage are used, all assumptions, theories that provide the basis for linkage, expert and literature citations, and provisions for follow-up monitoring should be identified (USEPA 2004b).

The following steps would be taken after a waterbody is moved to category 4B:

1. Monitor the implementation of the restoration measures and BMPs to ensure they are completed and correctly put into practice.
2. Monitor the effectiveness of the restoration measures and BMPs towards achieving standards. This could include monitoring the effectiveness of the BMPs and restoration practices in meeting compliance with water quality standards, or through monitoring of appropriate surrogate measures such as upslope or in-channel measures. A statistically valid sub-sample or benchmark site could be used in the monitoring design. The Northern Region proposes adopting the R-1 Draft Aquatic Ecological Unit Inventory Technical Guide for physical channel measurements (tiered to PACFISH/INFISH Biological Opinion protocols, the aquatic conservation strategies for federal lands). These data can then be compared to other similar watersheds from the greater population of measured streams.
3. Based on monitoring results, either redesign or add new watershed restoration measures or BMPs where needed, or provide information on the need to modify the water quality standards target.

If monitoring shows that controls are not implemented or they are not effective (e.g., BMPs are not implemented fully, or the monitoring data shows no trend towards meeting standards), the control measures would be adjusted or redesigned where needed. If after modifying or adapting controls, progress towards water quality standards is not taking place, consideration will be given to re-instating the waterbody back into Category 5 of the state's Integrated Report. In some cases it may be determined that modification of the water quality standard or target is appropriate because local natural geologic or thermal conditions preclude ever reaching the established numeric criteria.

Summary

TMDLs will only be developed for waters classified as "Category 5". Placing waters in Category 4B rather than conducting TMDL analysis may hold several advantages. First, Category 4B may prove more cost effective and result in more rapid restoration of water quality. Second, the approach may also reduce the threat of projects being litigated for not having TMDLs in place. To date, few if any agencies have attempted to place waters in Category 4B.

EPA and MDEQ are currently working with the Northern Region of the USDA Forest Service to develop a list of Category 4B waters on NFS lands. This approach could greatly speed the recovery of water quality and reduce costs by eliminating TMDL preparation by emphasizing thorough identification of restoration needs, conducting the restoration, and designing a pragmatic approach to monitoring. Managers are likely to also find this approach attractive since it is more efficient, fosters new partnerships, provides agencies more flexibility when administering multiple use responsibilities, and builds upon existing BMP and restoration programs.

The Gallatin National Forest Taylor Fork Category 4B report was formally submitted to Montana DEQ under

a Regional Forester cover letter in August 2005. Due to other priorities, the state has not given an official response to the report. However, all essential restoration projects have now been completed, and it is anticipated that ongoing monitoring will demonstrate water quality standard attainment and the waterbody will be reclassified as Category 1 (all designated uses are met). As a result, there will no longer be a need for completion of a TMDL and the Taylor Fork 4B will become a tangible demonstration of the effectiveness of the Category 4B approach.

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Best Management Practices (BMP) Implementation Monitoring: Keys to Success and Pitfalls to Avoid

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Implementation Monitoring determines whether Best Management Practices (BMP), mitigation measures, and standards and guidelines were applied to a project as planned. The Clean Water Act, Forest Plans, the National Environmental Policy Act (NEPA), and the Forest Service Soil and Water Conservation Handbook provide the legal framework and guidance for Implementation Monitoring. Since the early 1990s, BMPs have been an integral part of the NEPA process. NEPA decisions rely heavily on stated and implied assumptions of BMP implementation and their effectiveness in achieving the goals of state water quality standards. Implementation Monitoring tracks whether or not a given practice was successfully applied from project planning through completion, and when or where in the process implementation may have failed. Conclusions are carried directly into accountable actions, creating a feedback loop to improve procedures if necessary. An interdisciplinary monitoring approach fosters trust, respect and communication between specialists and project administrators. The feedback loop works best when an interdisciplinary team evaluates a project that they planned, and when local line officers convey tangible support for the process. At a minimum, participants should include watershed specialists and project administrators. It is not an accusatory process and must focus on maintaining meaningful feedback. Excessive focus on numeric ratings may sabotage the feedback loop. A database with querying capabilities aids efficient reporting of results. The implications of effectiveness monitoring results depend on whether the BMP was implemented successfully. Tracking BMP implementation, and subsequently effectiveness, is fundamental to our credibility as land and water stewards.

Keywords: *Best Management Practices, BMPs, water quality, watershed management, monitoring programs, interdisciplinary, hydrology/water*

Introduction

The authors have spent a combined total of 18 years on the Tongass National Forest, Alaska, meeting the challenges of conducting reliable and repeatable Best Management Practices (BMP) Implementation Monitoring surveys. Our objective in giving an oral presentation at the San Diego meeting of 18-21 October 2004 was to share with others the keys to success that worked well for us, as well as defining pitfalls to avoid when developing or conducting a BMP Implementation Monitoring program.

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Discussion

A Best Management Practice, or BMP, is defined by 40 CFR 130 as a practice, or combination of practices, that have been determined to be most effective and practicable in preventing or reducing the amount of pollution generated by diffuse sources to a level compatible with water quality goals. The Forest Service Handbook (FSH) 2509.22 defines BMP Implementation Monitoring as determining whether necessary BMPs were actually applied to an activity as planned. Put more simply and plainly, we can ask the question "Did we do what we said we would do?" Watershed specialists may be challenged, as we have been, to explain why BMP Implementation Monitoring is needed. Current direction and support for BMP Implementation Monitoring occurs at the national, regional, state, forest, and project levels, and includes:

- the Clean Water Act [As amended through P.L. 107-303, 27 November 2002]

- the National Forest Management Act [1976]
- National Environmental Policy Act [1970]
- the EPA Water Quality Standards Handbook [(EPA-823-B-94-005) August 1994]
- the USFS Soil and Water Conservation Handbook [FSH 2509.22, See *http://fsweb.r10.fs.fed.us/directives/fsh/2509.22/*]
- state Non-point Source Pollution Control Strategies or Programs, as developed by individual states
- Memoranda of Understanding (MOUs) between the USFS and states
- Forest Plans, Environmental Analysis (EAs), Environmental Impact Statements (EISs), and Cumulative Effects (CE) documents

How do we do we conduct BMP Implementation Monitoring in such a manner that we expedite getting the job done; document that we did it; and create and maintain the documentation that we implemented the BMP as we said we would? Based on our experiences in developing the Implementation Monitoring process on the Tongass National Forest, we suggest eight important steps:

1. Ensure that Line and Staff support is in place.
2. Incorporate interdisciplinary input into the monitoring process.
3. Field test data collection form(s) and review for database management and analysis requirements.
4. Present the process to Line and Staff Officers.
5. Revise process and forms if needed after management review.
6. Select database managers; design and develop database considering intended uses of data.
7. Randomly select project(s) for monitoring; do the pre-work (project documents); conduct monitoring in an interdisciplinary group setting.
8. Enter data queries as needed to generate monitoring report(s).

Staff and Line support is critical to ensuring that the Implementation Monitoring process is initiated and maintained. Their support may encourage reluctant participants to be involved more constructively. The design of land management activities should never occur without interdisciplinary input, and conducting BMP Implementation Monitoring is no different. Without interdisciplinary input, the "feedback loop," which allows all of us to change how we do business, would be compromised from the start of the monitoring process. Field-testing of data forms and databases helps users to figure out what formats will be most efficient, effective, and accurate for recording information, data entry, and querying.

As the BMP monitoring process and forms evolve, review the progress in BMP implementation that is being made with management. Ensure that management's data information needs are being met. If input is received from management, or from other resource representatives, it is important to be flexible and willing to revise the forms and process as needed. This will help ensure that the process is useful, functional, and applicable to a variety of information needs. Once the data forms have been finalized, it is important to take the time to make sure that the design of the database is well thought out. Database entry screens should be the same as the data entry forms, to maximize efficiency of data entry.

The random selection of monitoring sites ensures equal treatment of projects. A quick and easy way to do this is to consecutively number all units, then use a random numbers table for selections.

Random review of data entry printouts should be conducted once data is entered. We suggest printing out 10-20% of the data to review for input errors by comparing to the original data entry forms.

The BMP Implementation Monitoring process starts with tracing the incorporation of BMPs in various project planning documents, long before they are implemented on the ground. As resource concerns are identified, they should be incorporated into field notes, planning documents, and contracts, all of which are completed prior to project implementation. During Implementation Monitoring, these documents form the basis for tracking the development of BMP recommendations from planning to on-the-ground project implementation. Before evaluating how well a BMP has been implemented on the ground, tracking its incorporation into planning documents and contract records should be completed.

The following example shows how BMP language may occur in NEPA documents:

> "Best Management Practices (BMPs) - Section 313 of the Clean Water Act and Executive Order 12088 require that Best Management Practices (BMPs) that are consistent with State Forest Practices and other applicable State Water Quality Regulations be used to mitigate the impacts of land disturbing activities. Site-specific application of these BMPs are designed with consideration of geology, land type, hydrology, soil type, erosion hazard, climate, cumulative effects, and other factors in order to protect and maintain soil, water, and water related beneficial uses. All appropriate Best Management Practices will be followed in the layout and harvesting of the selected units (USDA Forest Service 2004)."

Another example shows a more specific incorporation of a BMP into this EIS:

"Road 46631 - Site Specific Design Criteria, Erosion Control: An erosion control plan for construction and maintenance will be developed by the contractor and approved by the Contracting Officer (BMP 14.5). All areas of organic or mineral soil exposed during construction shall be grass seeded and fertilized (BMP 12.17, 14.8 [Alaska Region FSH 2509.22, see *http://fsweb.r10.fs.fed.us/directives/fsh/2509.22*, accessed May 2006])."

After BMP recommendations are made in the EIS, the next step is to incorporate them into the appropriate contract. The following example shows how the BMP is referenced as part of a road construction contract. Without this step, some BMPs cannot be tracked from planning to the project on the ground.

"Road construction shall be performed in accordance with all contract provisions and specifications as established in clause B 5.211. All areas of organic or mineral soil exposed during construction shall be grass seeded and fertilized (BMP 14.8 E1). During road construction, minimize sediment input into streams. Excess and/or unsuitable material excavated during bridge/culvert construction shall not be placed on the slopes adjacent to the stream or in the stream channel (BMP 14.17)." (excerpt from Road Construction Contract 12-11-010-1545-12, Road 6420-5, Tongass National Forest)

At a minimum, watershed specialists and project administrators should be involved in the BMP monitoring process. They should confirm what is being successfully implemented as well as identify areas of concern. This includes developing action items that define what needs to be clarified, improved or developed, and identifying personnel who will be involved in resolving each action item. All of this should be accomplished while out in the field, including all relevant documentation, to ensure accurate communication of issues and to avoid surprises. Ensure that a cooperative feedback loop using the results of monitoring has been developed. This will help ensure that the information collected, and recommendations made, are actually used to improve future projects.

Collecting all the information that has been discussed above on a single-page form is a challenge. What is a good format to use? We suggest a form that documents the item(s) monitored, whether or not the BMP is applicable in that setting, to what degree implementation occurred, corrective actions needed as a result of a failure to implement a BMP correctly, and where in the process implementation failed (see Figure 1 for an example). A variety of forms are currently in use across the nation, and a standard format may be developed through the Washington Office.

A simple but effective visual demonstration of the importance of properly implemented BMPs can be seen by comparing the results of two culvert replacement projects shown in Figures 2a and 2b.

Figure 1: Example of BMP Implementation Monitoring Form.

Item Monitored	Applies	BMP Rating[1]	Corrective Action Needed?	Departure Occurred[2]	Comments
BMP 12.7/14.5/14.8 Measures to minimize surface erosion - Erosion Control Plan - Measures to limit sediment transport; ditch dams, sediment basins, silt fences - Seeding	yes	Not implemented	Clean ditches, culverts, and seed cut-slopes	Contract, Project Administration	

[1] BMP rating (rate after unit closure): Y (3, 4, or 5) = BMP fully implemented; D (2 or 1) = Departure from full BMP implementation; n (0) = BMP not implemented. Note: higher number designates a higher degree of implementation).

[2] Departure occured during Site Evaluation (SE), Environmental Analysis (EA), Contract (CT), Layout (LO), or Administration (AD).

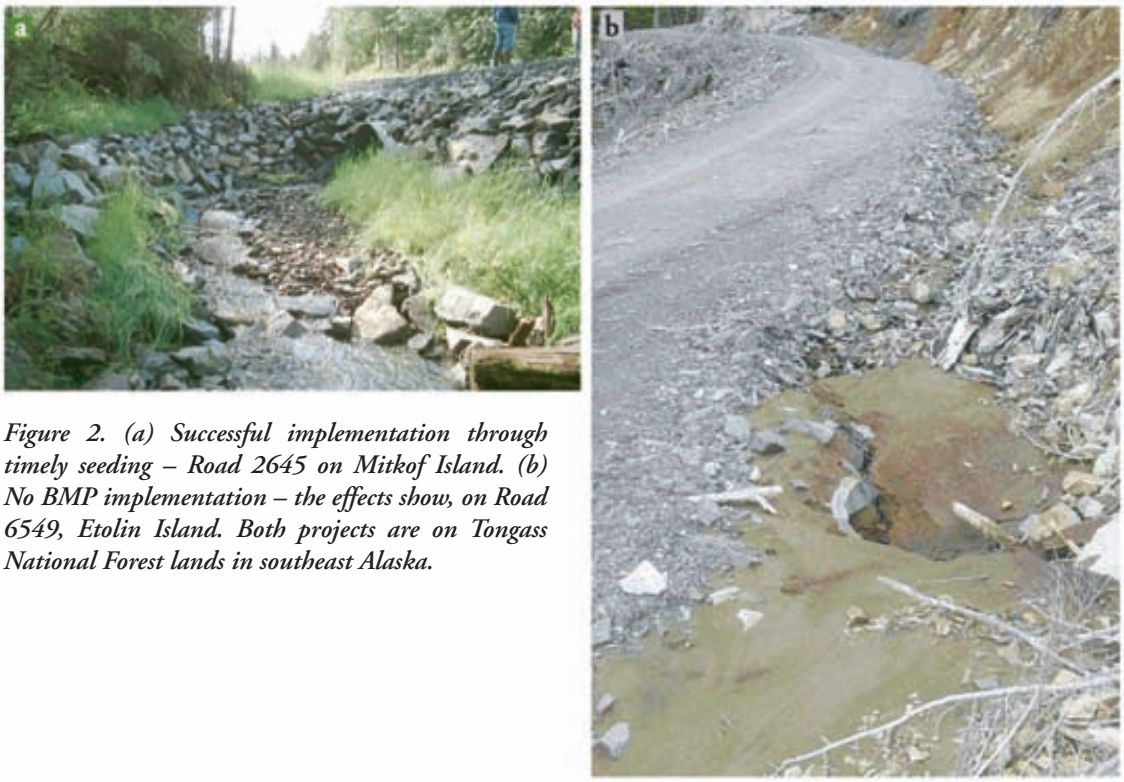

Figure 2. (a) Successful implementation through timely seeding – Road 2645 on Mitkof Island. (b) No BMP implementation – the effects show, on Road 6549, Etolin Island. Both projects are on Tongass National Forest lands in southeast Alaska.

The following quote illustrates the need for BMP clarification and lack of compatibility with existing road specifications, as defined by an interdisciplinary Implementation Monitoring team.

"Contract enforcement of erosion control is inadequate due to the disparity between BMPs and road construction specifications. The road construction contract did not incorporate enforceable time erosion control requirements for seeding…road segments are routinely accepted as final without seed and seed may not be applied until the following year (BMP Implementation Monitoring Report, Tongass NF [USDA Forest Service 1992])."

After defining an accountable action item, and those who need to be involved to define a solution, the next step is for those people to work together. In the Tongass NF example, the interdisciplinary monitoring team worked together to resolve a discrepancy between the erosion control BMP and road specifications. They developed the corrective on-site actions for seeding, evaluated and documented what went wrong in getting the seed applied, and revised the seeding specification to ensure that the BMP was enforceable.

Accountable action items and the "feedback loop" go hand in hand. A review of BMP implementation can find things that were done well, along with areas needing improvement. Accountable actions recognize both situations. Documenting where in the process implementation failed will help direct what type of outcome from the feedback loop is most needed to alleviate future problems. Outcomes could include commendations, BMP or contract revisions, training needs, increased communication, and specialist presence in the field.

In relation to the Tongass program, three elements were essential to developing and maintaining the process, which is still being used on the forest.

1. Engage managers.
2. Keep the process local and include project administrators.
3. Encourage and reward interdisciplinary co-operation, interaction, and innovation.

Involve district personnel in monitoring their own projects; they can tell the story of the project on the ground best as they often have helped develop and implement projects selected for monitoring. By involving both the specialists and the project managers, immediate feedback regarding BMP recommendations, design, and implementation is facilitated. Encouragement and reward go a long way toward fostering cooperation, improving trust and interaction, breaking down the perception of others being "territorial" about their disciplines, and fostering innovative ways to deal with resource concerns on the ground.

We identified four common pitfalls to avoid in implementation monitoring:

1. "Gotcha!" attitudes and surprises. Don't undertake monitoring with a mean-spirited, punitive, or fault-finding attitude.
2. Focusing on numeric ratings at the expense of meaningful feedback.
3. An excess of self-congratulation.
4. Waiting until you are back in the office to agree on major findings and needed actions – decide while you are still in the field.

The monitoring process is subjective; resist the temptation to "fight" for a particular rating or result (the Tongass NF uses a 1-5 scale). Strive for concise rating definitions. Make every effort to achieve objective evaluations of how well practices are implemented. Balancing the acknowledgement of good work versus identification of where improvement is needed can be tricky. Excessive praise could mean that there is something to hide.

Agree early and explicitly in the process that discussions will be respectful and focus on building credibility and trust. Talk about the problems, concerns, and the successes, while on the ground.

First and foremost, an established Implementation Monitoring program allows us to demonstrate our track record and verify our assertions that we are credible stewards of the land. With a feedback loop created as an integral part of the monitoring process, we ensure that issues are documented and accountable actions (solutions) are defined. This is essential not only to improving BMP implementation, but also to improving how BMPs are designed and written. A well-designed database provides the ability to query data efficiently and share information with other forest staff and the public. Interdisciplinary participation results in improved communication and trust, and therefore fewer "dropped balls" and crises to handle.

Another benefit of an established Implementation Monitoring process is that the stage is set for effectiveness monitoring. Effectiveness monitoring tells us how well the BMP worked, but its implications may differ depending on whether or not the BMP was fully implemented.

Summary

There is substantial direction in place in federal and state regulations requiring BMP Implementation Monitoring. A well-established and repeatable implementation monitoring program sets the stage for effectiveness monitoring, and fosters interdisciplinary cooperation. Perhaps most importantly, BMP Implementation Monitoring is fundamental to our credibility as land and water stewards.

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A Regional Protocol for Monitoring BMP Implementation and Effectiveness on Timber Harvest Operations

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The US Environmental Protection Agency (EPA) has cited a need for baseline monitoring information on forest harvesting to demonstrate compliance with the Clean Water Act and to respond to criticism of the silvicultural exemption. Historically, monitoring by state forestry agencies has been sporadic and anecdotal with little measurable evidence recorded. The Northeastern Area Association of State Foresters, Water Resources Committee initiated a project to develop and to test a standardized Best Management Practices (BMPs) protocol which provides the needed data for the 20-state Northeastern Area. A Phase 1 version of the protocol was developed in the fall and winter of 2001. Training and data collection occurred in nine states during the summers of 2001 and 2002, producing 97 samples and 21 quality control samples. Examples are provided to show the types of information that could be produced. However, they are not statistically sound because of the limited amount of data collected in each state. Beta testing is continuing through 2004 and 2005.

Keywords: *BMPs, Best Management Practices monitoring protocol, Northeastern Area*

The Need for a Monitoring Protocol

The term Best Management Practice (BMP) was originally defined in the 1987 Clean Water Act (CWA) to refer to precautionary activities designed to protect water resources during timber harvests. Currently, timber harvesting activities are exempt from the permitting requirements of the CWA when BMPs are used to protect water resources. In response to litigation, the US Environmental Protection Agency (EPA) is required to show evidence that the requirements of the exemption are being implemented. As a result, the EPA has long sought a standard BMP monitoring protocol that would provide measurable data that are reliable and comparable among states.

In its Technical Bulletin #820 published in January 2001, the National Council for Air and Stream Improvement, Inc., stated: "Most States recognize the potential for water quality impairment from timber harvesting, especially soil erosion and sedimentation caused by roads and stream crossings. The States repeatedly report a serious lack of monitoring information, and generally fall back on widely accepted generalizations about the impact of timber harvesting on water quality (NCASI 2001)."

Beard et al. (1999) stated that there is a serious problem in environmental monitoring because of measurement inconsistency. Results are often criticized and open to various interpretations. The only way to assure reliable information is to gather it in a consistent and well-documented manner. Sources that influence data collection errors and the consistency of monitoring results include timing of the measurements, location, external environmental factors, and most notably, change in personnel. All of these factors must be considered in any BMP monitoring protocol to ensure consistency of data and compatibility for analysis.

Furniss, M.J., Clifton, C.F., Ronnenberg, K.L., eds., 2007. *Advancing the fundamental sciences: proceedings of the forest service national earth sciences conference, San Diego, CA, 18-22 October 2004*. PNW-GTR-689. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station.

Generally, state forestry agencies are in agreement that BMP monitoring should be implemented; however, barriers exist that hinder the states from having an effective monitoring program. Major hurdles have included costs, staff, time, variability of BMP practices among states, selection of practices to be monitored, activities monitored, and the method to be used to analyze the data.

How This Protocol Differs

This monitoring protocol is designed to assess the effectiveness of BMP use with respect to water quality goals and further identify easily discernible benchmarks at which BMPs are considered acceptable for protecting water quality. It evaluates the use of BMP principles, not individual practices. The premise is that it does not matter ***which*** practice is used to slow and disperse waterflow, but that practices ***were*** used and were successful in meeting the desired goals, such as preventing erosion and sedimentation. The impact of sediment on water quality has been adequately researched elsewhere and is beyond the scope of this protocol. This monitoring protocol is not intended to replace instream or biological assessments, but to produce a consistent site evaluation of BMP use and effectiveness.

The BMP principle approach permits the evaluation of data from a variety of practices or a combination of practices across a region. BMP principle categories used in this protocol include planning the operation, controlling waterflow, stabilizing disturbed soil, controlling and disposing of chemical pollutants from machinery, and minimizing undesirable impacts on a water body, such as heat and slash. By usng BMP principles, individual states maintain control of their BMP practice specifications, thus meeting their needs while allowing for regional analysis of monitoring results.

Under this protocol, all data are collected based on standard measures of physical evidence. States determine the acceptability of the degree of water quality protection provided by BMPs based on their unique resource situations. The protocol monitors and measures what happens during and after a harvest, but the acceptability of the level of protection is determined by the individual States. For example, sediment levels acceptable in the Mississippi River may not be acceptable in Appalachian trout streams.

This method also fosters continuous improvement by allowing state forestry agencies and other educators to focus training efforts on identified problems or weaknesses in BMP implementation. Taken together, these characteristics add considerably to the credibility of BMP monitoring results.

Protocol Components

Data Dictionary. The BMP monitoring protocol consists of a series of questions with an array of answer choices, which functions much like a dichotomous key. The questions and related answer choices were programmed into a Trimble GEO 3 GPS unit[1], but have since been programmed into other data collecting units using Windows-based pocket PC software.

Participants. During the pilot phase of this project, nine states and one industrial landowner were trained in the use of the protocol and the GPS data collection equipment. The participants included: New York City, Watershed Agricultural Council; state of New York, Department of Environmental Conservation; state of New Hampshire, Department of Resources and Economic Development, Division of Forests and Lands; state of Maine, Department of Conservation, Maine Forest Service; state of Maryland, Department of Natural Resources, Forest Service; state of West Virginia, Department of Commerce, Division of Forestry; Commonwealth of Pennsylvania, Department of Conservation and Natural Resources, Bureau of Forestry; state of Ohio, Department of Natural Resources, Division of Forestry; state of Indiana, Department of Natural Resources, Division of Forestry; and MeadeWestVaco, Maine.

What is Monitored and Where?

The protocol focuses monitoring on the following logging, road construction, and road maintenance activities: At haul road water crossings; at skidder water crossings; at haul roads or landings within filter/buffer zones; within state-specified filter/buffer zones; and the slope distance outside the filter/buffer zone.

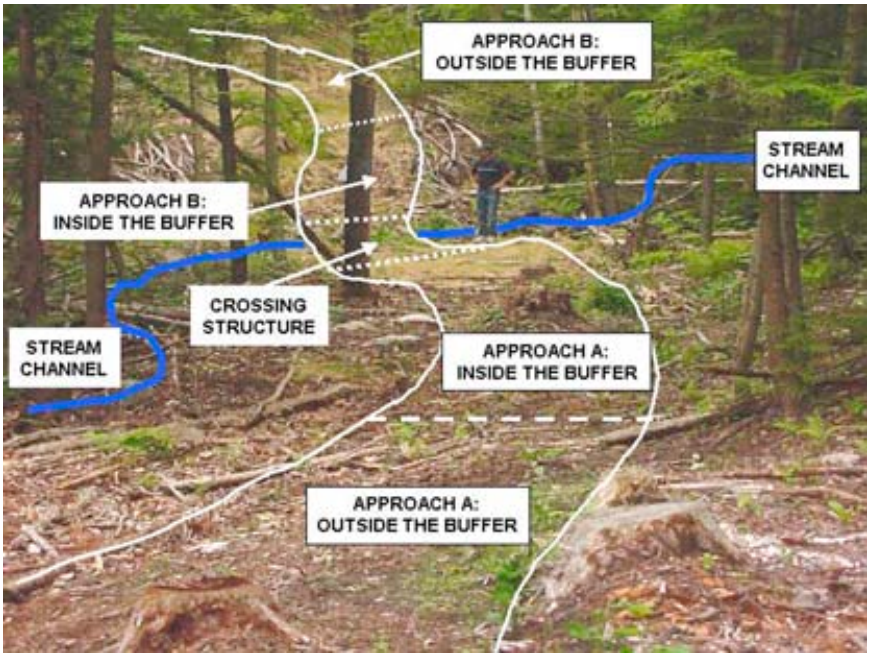
Monitoring activities within these focus areas will improve efficiency by focusing efforts in locations that typically have the highest potential to affect water quality.

Focus Areas. The protocol is made up of a series of question sets relating to each of these focus areas (Figure 1). The outline of the protocol includes:

1. **General focus area.** This focus area gathers information on landowners, the timber sale contract, location and year logged, acres harvested, and other site information.
2. **Haul road water body crossing and attribute focus area**

[1]The use of trade or firm names in this publication is for reader information and does not imply endorsement by the U.S. Department of Agriculture of any product or service.

Figure 1. Protocol focus areas.



Approaches "A" and "B", on either side of the stream
Inside and outside the buffer evaluation
Crossing structure evaluation (fords, bridges, and culverts)

3. **Skidder water body crossing and attribute focus area**
   Approaches "A" and "B", on either side of the stream
   Inside and outside the filter/buffer evaluation
   Crossing structure evaluation
4. **Filter/buffer focus area**
   Filter/buffer attributes
   Shade evaluation
   Woody debris recruitment potential
   Slash additions to water body evaluation
   Inside and outside the filter/buffer evaluation
5. **Chemical pollutants focus area.** Determines whether oil, gas, anti-freeze, brake fluid, battery lead, and other materials and containers were left at the site and if the products have the potential to reach surface water or groundwater.

Sample Unit. A "sample unit" was defined to eliminate averaging the evaluations of multiple water crossings on large harvest sites.

A sample unit is a contiguous harvest unit that includes either a riparian zone or a water body crossing, or both (see Figure 2). It is bounded by any combination of water bodies and the boundary of the harvest area or a land ownership boundary. The sample unit starts when a water body is crossed or a riparian area entered. A new sample unit begins each time a water body is crossed and ends at the next water body, the edge of the harvest area, or the land ownership boundary, whichever is encountered first.

Sampling. The first phase of the project was not intended to gather reliable data, but to test the protocol under a variety of site conditions throughout the Northeastern Area. Sampling was neither random nor unbiased. Each participating state chose ten sites to sample with the intent of testing the protocol on as many diverse sites and conditions as possible. The diversity of sample units was based on soils, topography, geography, or other characteristics that were identified as important to the individual state or company.

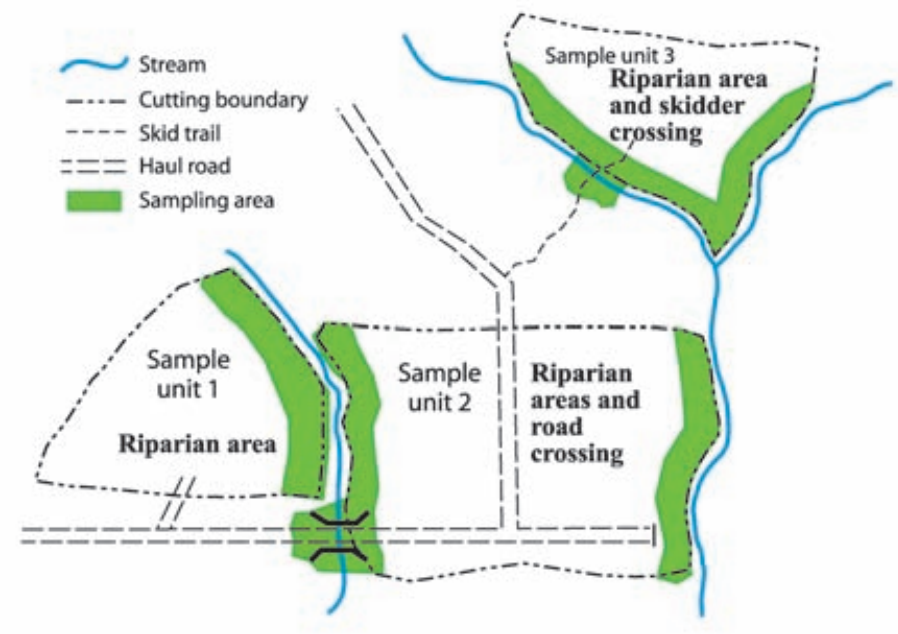
Different monitoring teams revisited three of the ten sites in each state to conduct a blind quality control sample. The returning monitoring team had access to only the general information section of the initial sample data in order to locate the sample unit. The quality control sample was used to determine which questions were producing consistent results and which questions needed to be clarified. The goal was to strive for a repeatable process, which returns consistent evaluations by different individuals.

Electronically Managing Data

Purpose. The protocol is intended to be used to collect field data across a wide geographic area and simplify data entry.

Equipment. The question sets were programmed into Trimble GEO 3 GPS units using Pathfinder Office Software version 2.90. Revised question sets have since been programmed to run on several types of data collecting

Figure 2. Sample Units.



equipment using Microsoft WindowsTM pocket PC software.

Collecting Data. Data were collected during the 2001 and 2002 field seasons. All GPS locations were collected based on the World Geodetic System (WGS) 84 datum and sent to the Maine Forest Service for analysis.

Processing Data. The participants sent data files to the Maine Forest Service by e-mail or CD-ROM. Data processing was a little more time consuming than anticipated because of entry errors. However, this resulted in greater use of drop-down lists in subsequent versions of the protocol, streamlining the process and eliminating most recording errors.

Data from individual states were combined in ESRI ArcInfo and exported to Microsoft Excel for data comparison.

Reporting Results Using the Pilot Project Data

Note: *The data were collected in 2001 and 2002 to test the monitoring protocol and analyzed to demonstrate how the results could be illustrated. Therefore, these data are not a statistically meaningful representation of conditions on the ground, but simply a test of the procedure and examples of possible data outputs.*

Ninety-one sample units were observed. Of these, 79 were water crossings involving a culvert, bridge, or ford; 37 were haul road crossings; and 46 skidder crossings. Results of the data collecting can be grouped into six BMP categories (Figure 3).

In summary, the results show that:

- Sediment was not discharged on 25 of the 91 sample units.
- Fish passage was not blocked at 66 of the 79 water crossings.
- Stream channels were unaltered at 73 of the 79 water crossings.
- Plastic containers or chemical spills (Hazmat) were not found on 84 of the 91 sample units.
- Slash from the current harvest operation was not added into stream channels on 22 of the 41 riparian areas observed.
- There was less than 40 percent shade reduction on 7,356 m (24,135 ft) of the 9,808 m (32,180 ft) of surveyed filter/buffer strips.

The BMP implementation and effectiveness monitoring results (Figure 4) are based on 395 total observations in 91 sample units during the initial protocol testing in 2001. An "observation" should not be confused with a "sample unit." While conducting monitoring within a sample unit, many observations are made in Approaches A and B, inside and outside the filter/buffer, and at the crossing itself. Specific examples of results include:

- Soil was stabilized and waterflow was effectively controlled 80 percent of the time when BMPs were adequately implemented.
- The first three bars represent 198 observations that recorded no soil movement, i.e., those observations were stable. However, the remaining 197 observations indicate that there was either soil movement or a sediment discharge into a water body. For example, there was soil movement 26 percent of the time and discharge 40 percent of the time when BMPs were not applied (4th bar set).
- Although BMPs were applied, they failed to prevent soil movement 19 percent of the time.

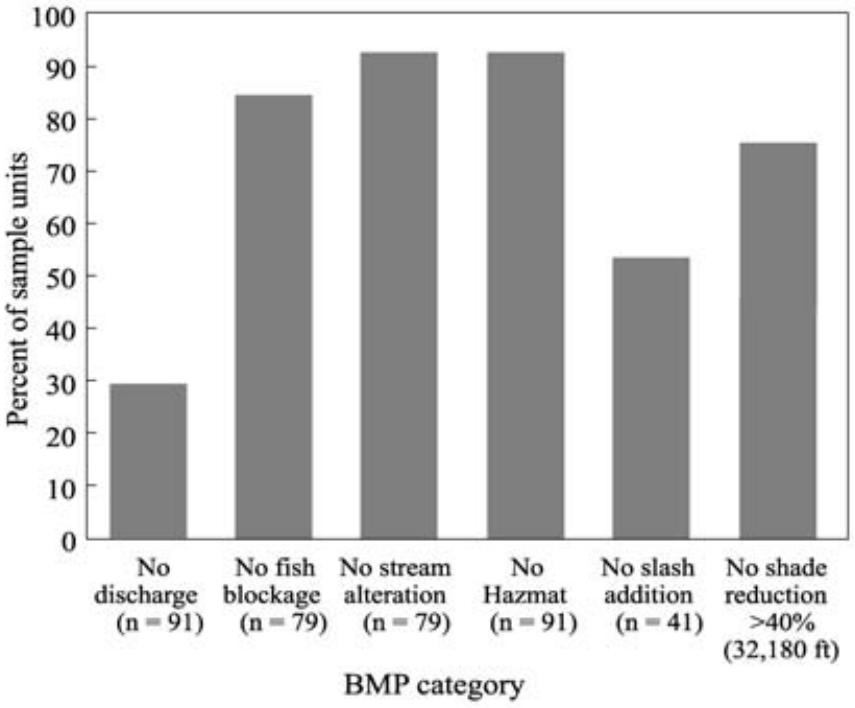


Figure 3. Overview of BMP categories by "sample unit".

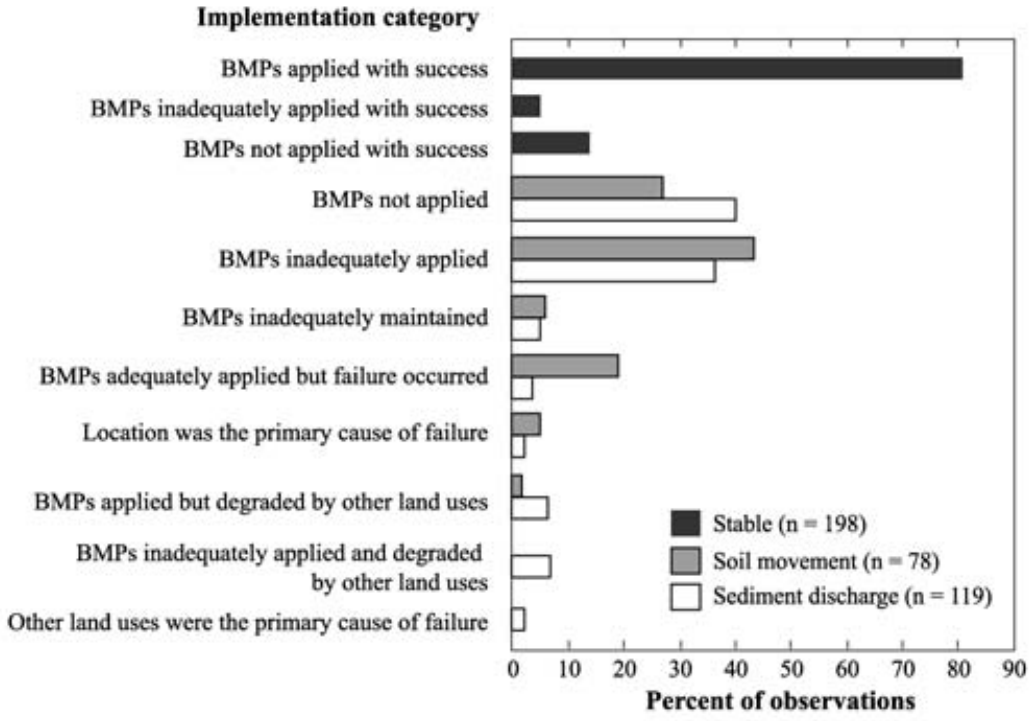


Figure 4. BMP implementation and effectiveness for soil stabilization and waterflow control based on BMP practice functionality.

- BMPs rarely failed due to impacts of other land uses (OLU).

Haul road crossings. Data can be assessed by sediment delivery mechanism and primary cause of sediment discharge at haul road crossings. There were 37 sample units with haul road crossings. Sediment discharges resulted from sheet flow, soil slumping, and soil dropping into the water body at 20 locations (Figure 5). The second highest discharge category was direct ditches at seven of the locations.

For haul road crossings (Figure 6), the road structure or design was the primary cause of soil discharges (38 percent of discharges). Instability of the crossing structure (22 percent) and maintenance of the crossing structure (16 percent) were also noticeable contributors to soil discharges from haul road crossings.

Data input is done in the field using a variety of recording devices that use Windows software for portable PCs. Once

Figure 5. Haul road discharges by discharge category.

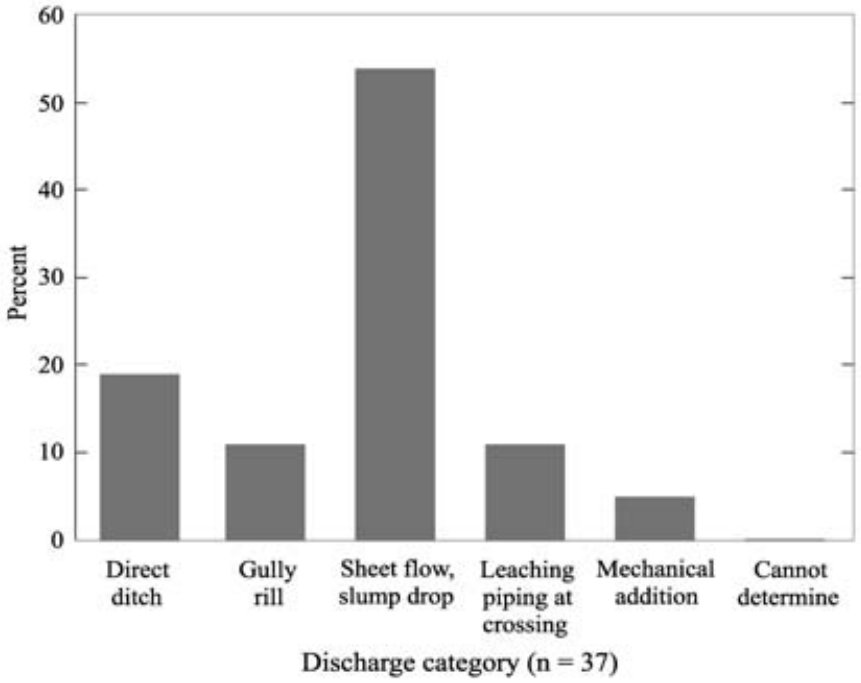
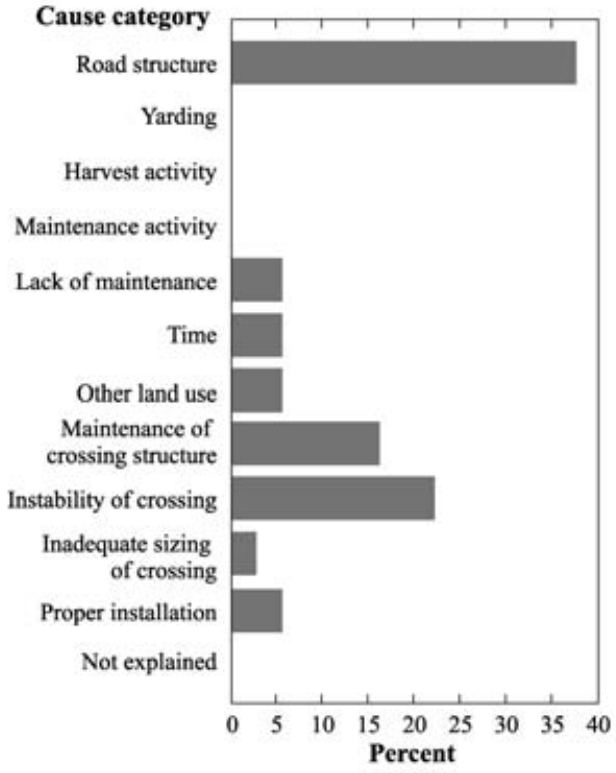


Figure 6. Haul road discharges by cause.



data are collected, the files are uploaded to a desktop computer and automatically combined with previous files in a Microsoft Excel spreadsheet. No additional office work is needed, which reduces error and saves time.

A standard data summary generator creates the types of data, which has been discussed above. Further refinement of the data will be possible with additional queries.

The results of the data can be used to focus training on improving BMP design specifications or installation and implementation errors. Specific examples include: Adjusting riparian buffer widths; using crossing structures with larger openings and open bottoms; and improving maintenance of roads and crossing structures.

Conclusions and Recommendations

The approach to BMP monitoring using this BMP protocol appears to account for most of the topographic, soil, and geographic differences in the test area. Evaluation of BMPs based on their principles and desired function is a key component that allows the development of a standard BMP monitoring protocol which is workable across broad geographic and political variables.

An analysis was done comparing sample units with their quality control samples to determine how well different individuals independently evaluated the same site. We found that, for any given question, the participants usually came up with the same answer for the quality control sample as in the original sample. The goal was to attain a 90 percent match on most questions. The data show we fell short of our goal; however, based on comments during the training and suggestions after data collection, it appears that most of the improvements needed to obtain a 90 percent match can be accomplished by editing the text of some of the questions and answers. The other improvements regarding consistency among observers will come from training and added experience as the protocol is used.

There was a need to edit the protocol questions as well as to reduce and combine specific questions and answers. Improvements to user friendliness were accomplished by automating the movement to subsequent questions based on the selected answer.

Since the data were collected electronically in a compatible database format, there was no data entry other than the initial electronic entry in the field. This greatly reduces costs of data entry, reduces errors, and allows the data to be transferred easily by e-mail and entered directly into the main database.

Data collection with the Trimble GPS unit was successful overall during the 2001 and 2002 field seasons. It is our goal to reduce costs, increase user friendliness, and keep the amount of data entry required at the office to a minimum. At the suggestion of participants, the protocol has been adapted to more economical and user-friendly Pocket PCs, Palm Pilots, and other hand-held equipment.

Based on the data and participant comments, this project has moved to the next phase, which expanded the use of an edited version of the current protocol. Beta testing with new equipment and an updated version of the protocol was conducted during the 2004 and 2005 field seasons.

Once the data are analyzed, it is our hope that the participants and additional states will accept the standardized protocol to facilitate the gathering and assessment of data over the Northeastern Area. We will continue to assist states in the development of an effective BMP monitoring program and encourage states to conduct their monitoring using the protocol. States will be able to develop their own sampling design, generate automated reports, and maintain a database. The data should be of immeasurable value in improving BMP effectiveness and verifying enforcement of the CWA.

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Monitoring Exposed! WARM: A Database Tool to Share and Query Watershed Resources Monitoring Information

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Forest specialists and managers often lack access to monitoring information collected within unit boundaries and across administrative units. The inability to effectively use existing monitoring results has led to repeated National Environmental Policy Act (NEPA) challenges, inefficient and ineffective best management practices (BMP) application, and poor feedback for the adaptive management process. The objective of the Watershed Resources Monitoring (WARM) database is to create an electronic repository for easy storage and retrieval of various monitoring information reports relevant to individual and multiple forests. Although originally developed to address monitoring information needs in the Intermountain Region (USDA Forest Service Region 4), the application is available to all national forests. The system was initially developed as a module within the Lotus Domino[1] database application for Wildlife, Fish, and Rare Plants (WFRP) reporting. Now a separate module, WARM houses reports generally referred to as "gray literature," including those produced by forest staff or partners and that do not appear in any other professional journal, book, or other library-available publication. This Forest Service Intranet-based tool allows users to locate actual monitoring information collected and documented within specific watersheds, across individual forests, or about specific management or conservation practices. Examples of database content and utility are illustrated, including an explanation of how information queried from the National Resource Information System (NRIS) and Infra[2] can be used and linked. Future module development may include creating an interactive map for querying and expanding support of the system and tools.

Keywords: *watershed, monitoring, data and information management*

Introduction

Hydrology program managers in the USDA Forest Service Intermountain Region identified the need for a better way to share monitoring information among units. They acknowledged that our inability to effectively utilize existing monitoring results has lead to repeated National Environmental Policy Act (NEPA) challenges, inefficient and ineffective best management practices (BMP) application, and poor feedback for the adaptive management process. These deficiencies have prompted federal agencies to propose a new regulation that compounds and exacerbates the difficulties of project planning and implementation for various watershed activities.

In response to this need, Intermountain Regional Office staff collaborated with the Stream Team, Pacific Northwest Region and Pacific Northwest Research Station, and the Natural Resource Information System (NRIS) Water and Tools teams to prepare a project proposal for developing a tool to share monitoring information. The objective was to create a Forest Service Intranet-based system that allows users to easily store and retrieve various types of watershed resources monitoring information relevant to one or more districts, forests, or regions. The Watershed Resources Monitoring (WARM) database is the result of this effort.

Watershed Resources Monitoring (WARM) Database

What It Is and Isn't

The WARM database was built as a module of the Wildlife, Fish, & Rare Plants (WFRP) intranet reporting system. Using the front end development and

Furniss, M.J., Clifton, C.F., Ronnenberg, K.L., eds., 2007. *Advancing the fundamental sciences: proceedings of the forest service national earth sciences conference, San Diego, CA, 18-22 October 2004*. PNW-GTR-689. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station.

[1]The use of trade or firm names in this publication is for reader information and does not imply endorsement by the U.S. Department of Agriculture of any product or service.

[2] USDA Forest Service's Infrastructure information database

structure of the WFRP system leveraged the funding to offer users customized features including look-up tables, partnership documentation, a photo database, and querying capabilities. Another advantage of building on the WFRP system is that the platform made the module available to all National Forest System, units rather than only to those in the Intermountain Region.

The WARM module has recently been separated from WFRP, creating a stand-alone system. The intranet-based tool allows users to enter and edit monitoring reports and query the system for information collected within specific watersheds, across individual districts or forests, or related to specific management or conservation practices.

Concept

The vision for the WARM database is that it will serve as corporate memory for monitoring information. Although there are several corporate databases in use, all of them deal with primary or factual data. These data are generally not useful to managers until they have been interpreted through some analysis process to extract meaningful assessments about a site or project. This interpreted information can now be stored in the WARM database so that authors, peers, managers, and other forest specialists have access to this assessment or monitoring information. Therefore, the WARM database bridges the gap to store interpreted information in one database that is currently not housed in other existing corporate databases (Figure 1).

Database Features

The modular design of the WARM data entry features allows users to create new reports at any level of detail desired, from a single site evaluation to an annual forest monitoring report. There are some mandatory fields that establish a basic record, while all others are optional. The structured fields each include a description accessible by clicking on the term.

Entering or Editing Reports. Users can create and store new or previously written reports. New reports can be generated on the spot by filling in the fields. This option is valuable for single event monitoring and brief monitoring reports. Existing reports can be stored by cutting and pasting text into the mandatory and summary fields, and creating a link to the full report (for this to work, the document must be link-accessible at least through the Forest Service Intranet). This option is best for very large or detailed reports and older ones that have good information but may take too long to enter. The linking capability reduces data entry redundancy and allows authors to reference other relevant documents, photos, or websites. By linking a photo directly into the system, it is captured as a corporate photo and is accessible by any other user through a browser tool.

All reports entered in the system are finalized (closed) upon the author's certification though an electronic signature. This step allows the author to enter information in multiple sessions, and allows others to review and provide feedback prior to indicating that the report is final. Appendix 1 depicts examples of the data entry and editing screens. The data fields supported by WARM are listed in Appendix 2.

Querying and Reports. WARM accommodates two forms of querying and includes a standard report. Report records can be queried to find a specific, individual report, or to find sets of reports that meet the searcher's criteria. The report query enables the user to locate a specific report by entering the geographic area of interest and selecting a report from the list generated. This option is useful if the user knows the exact report wanted. For broader searches, the query tool allows the user to search based on location (district, forest, region, state), author, topic or keyword, hydrologic unit code, and primary/secondary lithology, as shown in Appendix 3. The query tool then returns a list of reports that can be copied and pasted into the text of an email and forwarded to others for viewing. This query tool option is more versatile than report query because users can search for multiple reports meeting a set of criteria.

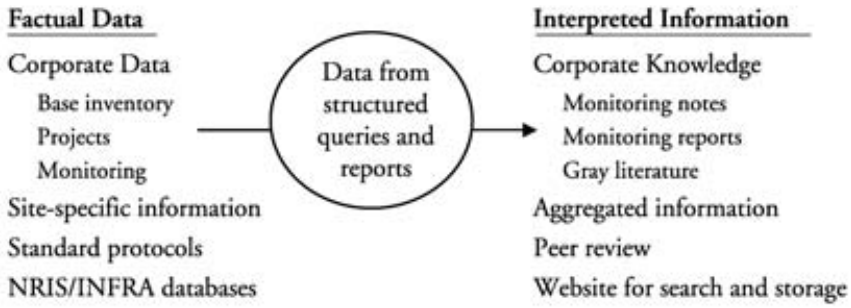


Figure 1. Concept for how factual data is transformed to interpreted data for storage in the Watershed Resources Monitoring (WARM) database.

One standard report form exists for all data entered, to maintain a consistent format across entries. Completed reports can be submitted to supervisors or partners to demonstrate accomplishments. An example report is shown in Appendix 4.

Expected Benefits of Using the WARM Database

Several benefits of using the WARM database, as identified by USDA Forest Service program managers, include improving documentation, corporate memory, and information sharing. First, by querying for information relevant to a local project, National Environmental Policy Act (NEPA) documentation is expected to improve as specialists use applicable monitoring to document rational thought processes and support best professional judgment. Second, as watershed specialists move in and out of different positions, information stored within the WARM database will serve as the corporate memory for monitoring results and will facilitate efficient adaptive management processes. Third, monitoring information will be easily shared, since any employee using a Forest Service computer will have access to all completed monitoring reports. Access to such information is expected to improve understanding of management activity effects and allow specialists to better integrate monitoring activities across forest boundaries, improving efficiencies.

Future Database Improvements

Since the WARM database is a new application, there may be opportunities to improve features, templates, look-up tables, and reports. The initial vision for the database included a mapping tool that would allow users to query for reports using an interactive map and based on hydrologic unit code, latitude and longitude, or UTM coordinates. As map querying tools continue to develop, this feature would be a desirable addition. The existing query tool could be edited to add or delete specific fields or to use look-up ranges. Existing look-up fields may contain only cursory choices, so the parent tables can be easily edited by a regional administrator. The site could also be expanded to share templates, examples, technical guides, and other databases as appropriate. Most possibilities for changes and improvements are limited only by funding availability and regional administrator approval.

Accessing the WARM Site

Report viewing is open to all Forest Service computer network users, with data entry and editing privileges granted as determined by the regional office or forest. Authorized network users can enter the database using their internet name and password at the following URL: *http://wodata01.fs.fed.us/fsfiles/unit/wo/wfrp/wrproject.nsf*

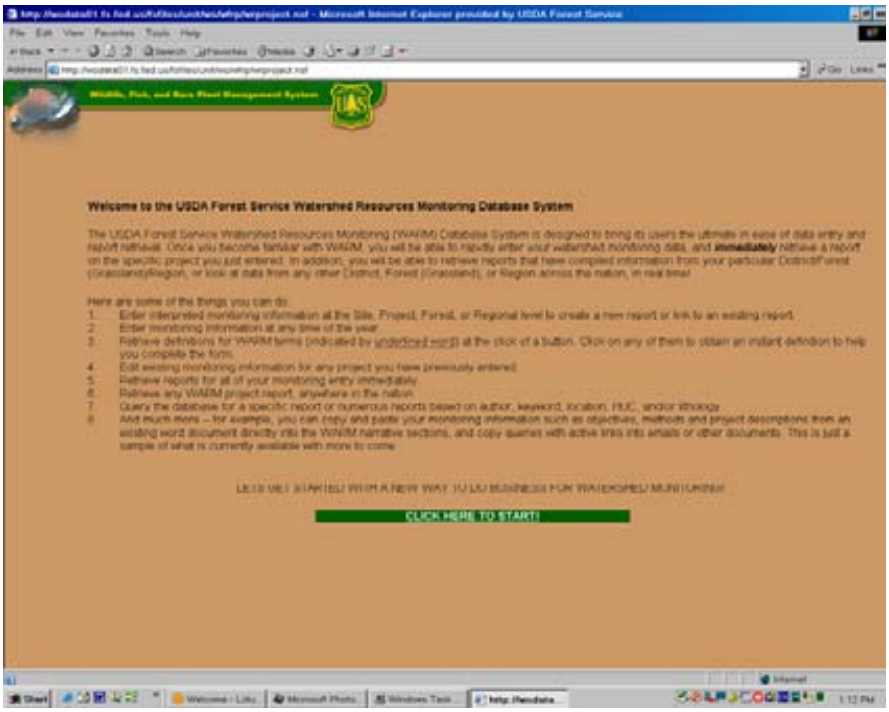
Additional instructions are available from the Intermountain Region FSWeb site, which includes how to obtain an internet password, a Microsoft PowerPoint™ slide show illustrating the features of the database, and the full documentation about the fields and look-up tables. The URL for the site is: *http://fsweb.r4.fs.fed.us/unit/bpr/watershed/fsweb/databases/databases.htm*.

Summary

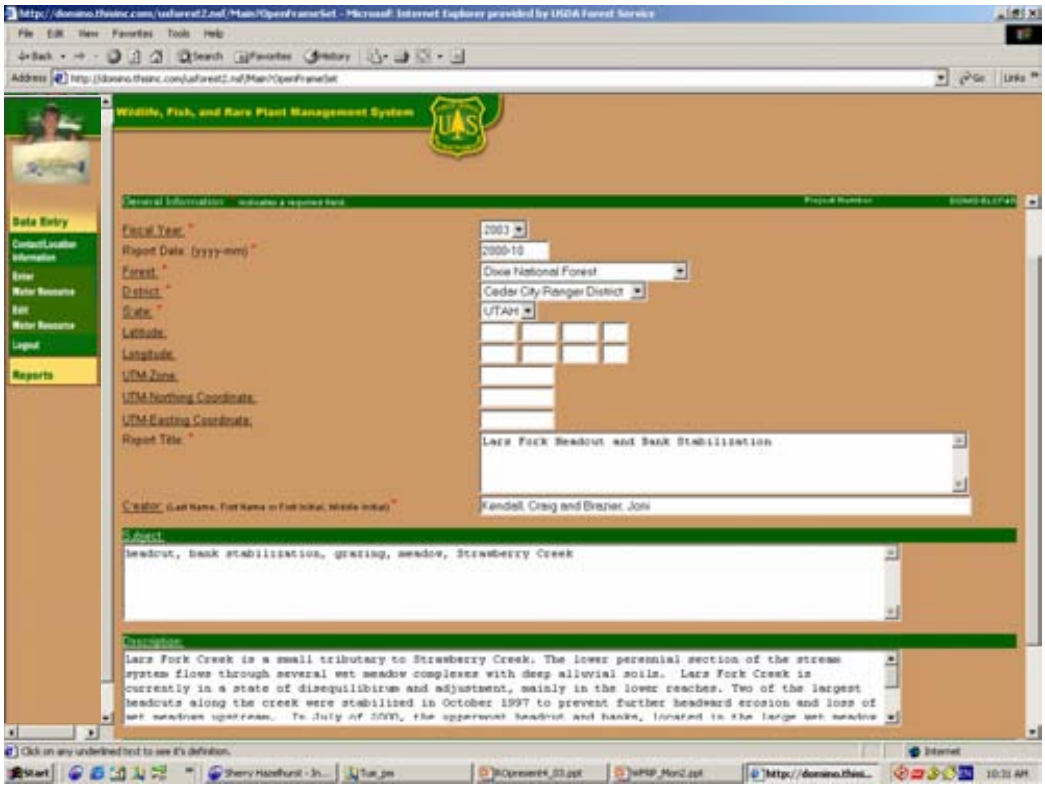
The WARM database provides a powerful tool for compiling, editing, storing, querying, and most importanly, sharing monitoring reports among Forest Service watershed specialists. If developed to its full potential, it may greatly assist in the assessment, monitoring, restoration, and management of watersheds on National Forest System lands.

Appendix 1. Examples of Watershed Resources Monitoring data entry and edit screens.

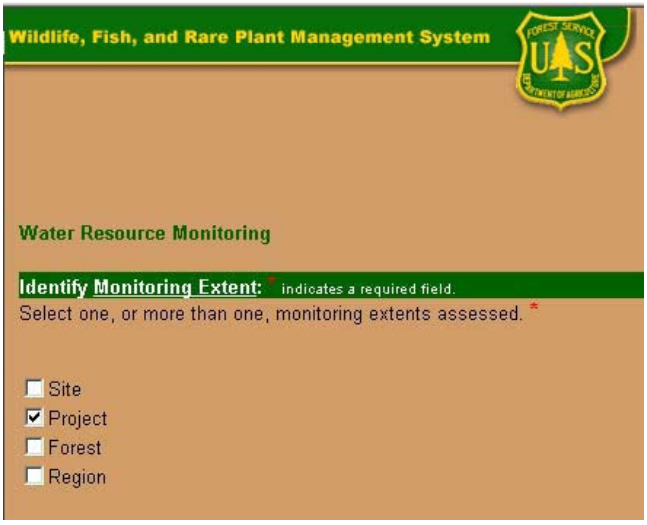
The initial sign-in screen will ask for your internet name and password. Once you have gained access, the following screen will appear:



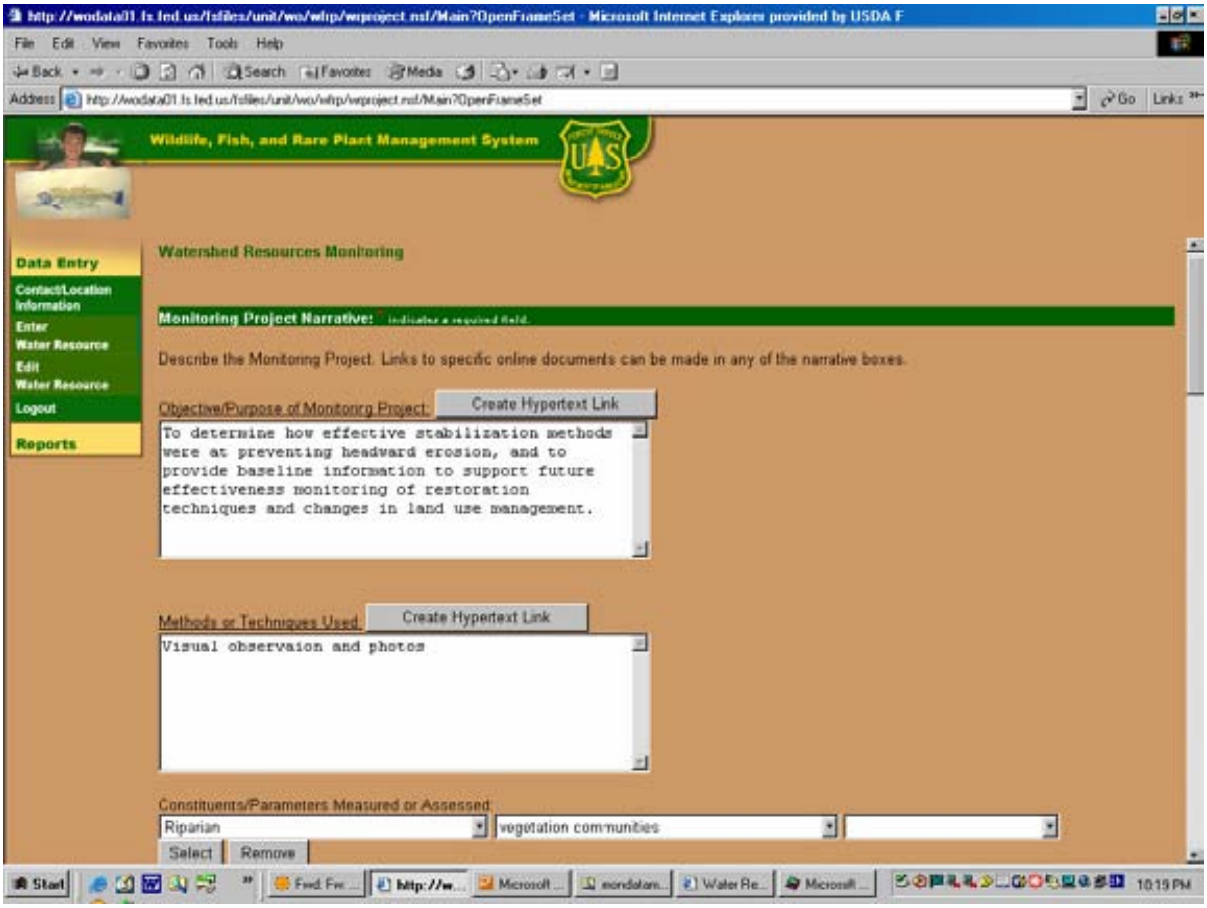
The first data entry/ edit screen includes most of the header information common to most documents.



The monitoring extent and purpose screens allow multiple entries for each, with a purpose identified for each extent:



The first data entry/edit screen includes most of the header information common to most documents.



Appendix 2. Watershed Resources Monitoring database documentation.

Watershed Resources Monitoring Database Documentation

Objective

The objective of this database is to provide users a system for easily storing and retrieving various types of watershed resources monitoring information relevant to individual and multiple forests.
This intranet-based website allows users to locate actual monitoring information collected within specific watersheds, across individual forests, or about specific management or conservation practices.

Data Entry Screens and Fields (Screen titles indicated by gray, shaded lines)

General Information:

Fiscal Year: Required

Report Date: Required (Format yyyy-mm)

Region: Required (automatically populated from your initial log-in information)

Forest: Required (may be automatically populated from your initial log-in information)

District: Required (may be automatically populated from your initial log-in information)

State: Required (may be automatically populated from your initial log-in information)

Location Coordinates: Latitude/Longitude may be entered in degree/minutes/seconds or decimal degrees (make selection). UTM coordinates may also be used to record location: enter Zone, Northing coordinate, and Easting coordinate for a complete record.

Report Title: Required

Creator: Required (Format: Last Name, First Name or First Initial, Middle Initial)
The person(s) or organization(s) responsible for making the content of the report.

Subject: Keywords, key phrases, or classification codes that describe the topic of the report.

Description: An account of the content of the resource, which may include an abstract, table of contents, reference to a graphical representation, or free-text account of the content.

Partnership or Non-Partnership Project: (Select one)

Identify Partners:

Partners may be selected from an existing list. An extensive partner list exists; however, if a new partners needs to be added, contact your regional administrator.

Identify Monitoring Extent:

Select one, or more than one, monitoring extent assessed. (Required)

- **Site:** photo point, reach, station, plot
- **Project:** e.g. restoration, road obliteration, road maintenance/upgrade, range, recreation, prescribed fire, wildfire, vegetation management, wildlife, multiple projects
- **Forest:** e.g. forest plan, cumulative effects, species viability
- **Region:** e.g. regional plan, cumulative effects, species viability

For each selection above, Identify Purpose:

Identify Monitoring Purpose:

Select one, or more than one, purpose for conducting the monitoring. (Required)

- **Baseline:** To characterize single or multiple constituents or parameters at a specific point in time.
- **Reference:** To characterize constituents or parameters over a period of time to serve as a basis for comparison.
- **Condition/Trend:** To determine changes in single or multiple constituents or parameters over a specified period of time, generally greater than 10 years.
- **Implementation:** To determine if the measure, practice, project, or plan was put in place as recommended/required.
- **Effectiveness:** To determine if the measure, practice, project, or plan accomplished intended/specified goals.
- **Validation:** To determine if assumptions made were correct.
- **Hypothesis Testing:** To test an unproven theory.

Monitoring Project Narrative:

Describe the Monitoring Project: Links to specific online documents can be made in any of the narrative boxes.

*Note: to avoid retyping text you have already written, you can simply copy text from an existing Microsoft Word document and paste it in many of these data entry fields.

Objective/Purpose of Monitoring Project: Clearly state your monitoring project objectives or purpose. A few sentences are all that is necessary. Number them if you like.

Methods or Techniques Used: State methods, protocols, or techniques you used to accomplish the monitoring project.

Constituents/Parameters Measured or Assessed: This is a three-level list of parameters from which you may select up to any 15. Selections can be made at any of the levels depending on the need to specify. To add parameters, please contact your regional administrator. The following headings are the first level from which the individual parameters are grouped:

Air Quality
Best Management Practices
Climate/Precipitation
Fisheries Habitat
Riparian
Soils
Species (communities, population, individuals)
Stream Channel Morphology
Water Quality/Quantity
Wetlands

Monitoring/Sampling Frequency: Select one item as listed from the following lookup terms: continuously, two or more times a day, daily, weekly, monthly, annually, seasonally, after storms, biennially or greater, randomly, other.

Monitoring Duration: Select one item listed from the following lookup terms: one time, one season, 2-3 seasons, one year, 2-5 years, 5 or more years.

Primary Lithology: Terrestrial Ecological Unit Inventory (TEUI) label most closely corresponding to one of the following: igneous extrusive, igneous intrusive, sedimentary, metamorphic, undifferentiated, unconsolidated, unknown

Secondary Lithology: Terrestrial Ecological Unit Inventory (TEUI) label most closely corresponding to one of over 400 types listed, e.g. Actinolite-Epidote Marble to Wyomingite.

Land Type Association (LTA): Description: Terrestrial Ecological Unit Inventory (TEUI) label corresponding to the landscape scale description.

Hydrologic Unit Code(s): The hydrologic unit(s) in which the monitoring was conducted. At least a 3rd-level HUC should be listed, and at least one HUC is mandatory. HUC levels 1-6 should correspond to USGS data standards. HUC levels 7-9 may be forest assigned, as no data standards exist for these levels.

Results Summary: State your results here.

Report Peer-Review Status: Reports may or may not be reviewed, depending on many factors including the resource(s) being addressed, issues, importance, uniqueness of data, monitoring plan, analysis rigor, etc. None = no peer-review. Local Review = at least one specialist at the district or forest has reviewed report for content, analysis, and accuracy. Broad Review = review from both a forest specialist and at least one other source, e.g., another forest, regional office, Washington Office, university, research group, or other credible scientist.

Contact Name/Phone/Email: List the name and contact information for the creator or data steward for this report.

Links to Full Report and/or other information: Internet or Intranet Web addresses with associated documents, maps, graphics, or presentations e.g. monitoring plan, forest plan, environmental analysis, ecosystem assessment, biological analysis, hydrologic condition assessment, total maximum daily load analysis or implementation plan, GIS map, Powerpoint presentation. Attachments should be in commonly accessible formats, e.g., Microsoft application files, HTML, PDF, MIME.

Add Graphic Attachments:

1. Select the file to attach (if separate from a previously linked report):
2. Enter an optional caption for the graphic (limit 50 characters):
3. Attach graphic to form:

Graphics may be attached elsewhere via links. However, those attached here will be printed in the report. Those linked will need to be accessed through the link. Graphics can also be retrieved from the master file by browsing with new captions added for your project. Graphics previously added may be deleted in the editing process.

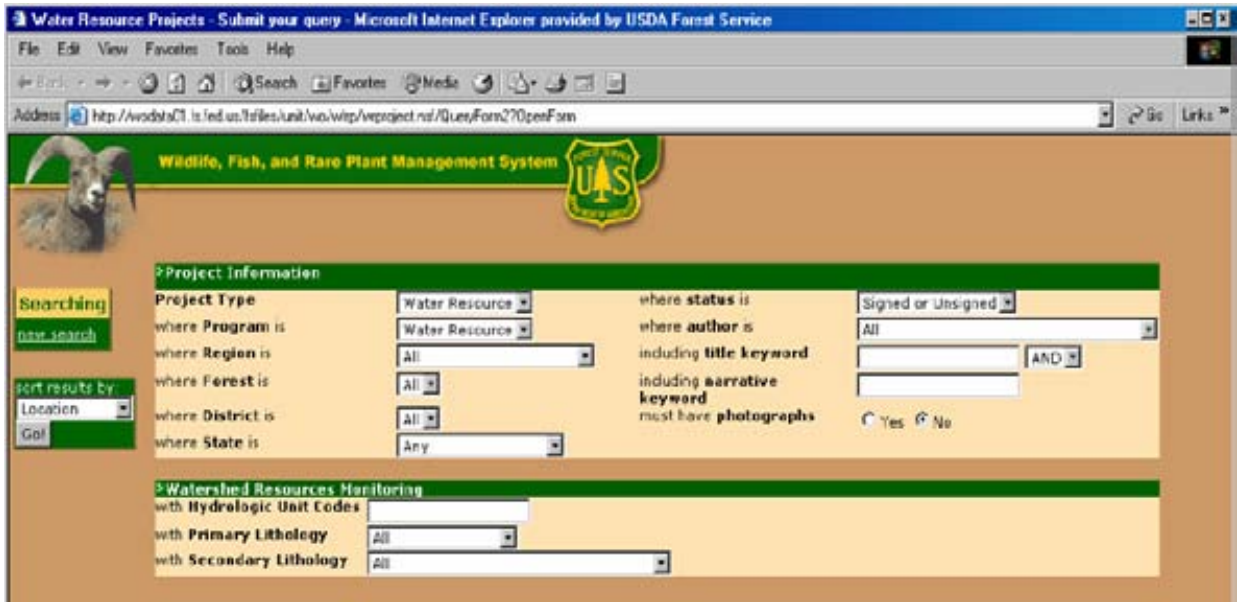
Certification of Data Validation

Your signature is required prior to final data being entered into the database. This signifies that information on the form is accurate and based on project work plans, monitoring data, published literature and other information available at the District of Forest Office.

Select the “Save and Sign Final Data” button if you have completed entry and review.
Select the “Keep Data for Later” button to store provisional information until such time as it has been completed.

Appendix 3. Example of Watershed Resources Monitoring query tool screen.

he query tool was adapted from the Wildlife, Fish, and Rare Plants database and adapted for our use in Watershed Resources Monitoring:



An example of query output follows. The individual reports can be accessed by clicking on the title links.

Appendix 4. Example Watershed Resources Monitoring report.

Lars Fork Headcut and Bank Stabilization
Cedar City Ranger District
Dixie National Forest
USDA Forest Service, Intermountain Region

Brazier, Joni and Kendall, Craig
2000-10

Description: Lars Fork is a small tributary to Strawberry Creek. The lower perennial section of the stream system flows through several wet meadow complexes with deep alluvial soils. Lars Fork Creek is currently in a state of disequilibrium and adjustment, mainly in the lower reaches. Two of the largest headcuts along the creek were stabilized in October 1997 to prevent further headward erosion and loss of wet meadows upstream. In July 2002, the uppermost headcut and banks, located in the large wet meadow complex less than 1/4 mile upstream from headcut #1 & #2 were sloped back using a backhoe. The headcut and channel were armored with rock, and banks were covered with erosion cloth. Clumps of *Carex* were transplanted from the wet meadow to the creek bottom with the backhoe. A solar-powered electric fence was put up around the area to protect it from trampling and grazing until vegetation can get re-established. The site was monitored in October 2000 using visual observation and photos.

Keywords: headcut, bank stabilization, grazing, meadow, Strawberry Creek

Hydrologic Unit Codes:
160300010103

Report Peer-Review Status: Local Review

Monitoring Extent	Purpose
Project	Baseline Implementation Effectiveness

Objective/Purpose of Monitoring Project: To determine how effective stabilization methods were at preventing headward erosion, and to provide baseline information to support future effectiveness monitoring of restoration techniques and changes in land use management.

Methods or Techniques Used: Visual observation and photos

Constituents/Parameters Measured or Assessed:
Stream Channel Morphology bank characteristics/stability
Riparian vegetation communities

Primary Lithology: Unknown

Secondary Lithology: Alluvium

Land Type Association:

Monitoring/Sampling Frequency: annually

Monitoring Duration: 2-5 years

Results Summary: Up to this point, headcut stabilization seems effective. Vegetation from work done on headcut #1 and #2 in 1997 is slowly re-establishing, and the headcuts do not appear to be migrating. It is unknown at this time how effective the soil barriers will be in preventing high flows from flowing around the armored headcuts. Cattle broke through the electric fence protecting the upstream headcut, and some trampling of erosion cloth on the banks occurred. Some vegetation was noticed starting to sprout through the cloth when the site was checked on October 25, 2000. It is too early to tell how effective this project is at preventing further headward erosion. Some of the willow cuttings had sprouted new growth when checked on October 25. It is too early to tell how successful all of the cuttings have been at getting established.

Photographs

Figure 1: PP #7. Looking upstream on main channel (7/2000)

Contact Name/Phone/Email: D2 Hydrologist, Joni Brazier, jdbrazier@fs.fed.us, 435-865-3238

Links to Full Report and Other Information: On file at D2 Watershed Files; also included in 2000 Watershed Monitoring Results, Dixie National Forest (hard copy and CD). All photos attached to full report. *http://fsweb.r4.fs.fed.us/unit/bpr/watershed/fsweb/inventory_ monitoring/DNFLarsCk2000.doc*

Aquatic Restoration Through Hydropower Licensing, Bond Falls Project, Michigan

Mark A. Fedora
USDA Forest Service Eastern Region, Ironwood, MI

Hydropower dams and diversions have the potential to alter many watershed and aquatic processes. The effects of multiple dams in a watershed can have negative cumulative effects at a watershed scale. The Federal Energy Regulatory Commission (FERC) originally licensed many hydropower dams in the Midwest US in the 1940s and 1950s, prior to the passage of legislation such as the Federal Power Act, as amended (1986). Today the facilities and operations of many of these hydropower projects are being reexamined as the original licenses expire. License proceedings, administered by FERC, provide an opportunity to gain a better understanding of cumulative effects on watershed processes, and to design measures to protect and restore specific features of the watershed in the future, including instream flows, substrate, channel stability, large wood, and water quality. The relicensing of the Bond Falls Hydroelectric Project on the Ottawa National Forest provided the opportunity for natural resource agencies and others, in conjunction with the licensee, to review the ongoing effects of the project, and to clearly define the resource conditions that the project must maintain or restore in the future. The licensing process was long and contentious with many competing interests. The new license was recently issued based on a negotiated settlement among the interested parties. The settlement provides for an improved flow regime, a mitigation fund to address project-related resource impacts, and a framework for the implementation team to work through issues using an adaptive management approach.

Keywords: *aquatic restoration, hydropower, negotiation, settlement, consensus*

Background

The Bond Falls hydroelectric project is located in the Ontonagon River watershed in the western portion of Michigan's Upper Peninsula (Figure 1). The project affects approximately 250 kilometers of rivers and streams. Eighty-two percent of the rivers and streams affected are a part of the Ottawa National Forest (Figure 2). The Victoria Dam and powerhouse were constructed in 1931 on the West Branch of the Ontonagon River, the same year that the Ottawa National Forest was established. It is a 12.3-megawatt facility, or enough to provide power to about 13,000 residences at full capacity.

In 1937 the Bond Falls reservoir and diversion canal were constructed. The canal diverts water from the Middle Branch of the Ontonagon River to the West Branch via the South Branch, Sucker Creek, Bluff Creek and Roselawn Creek. Dams were constructed at the outlets of two

Figure 1. The Bond Falls Project lies in the Ontonagon River watershed of Michigan's Upper Peninsula.

Furniss, M.J., Clifton, C.F., Ronnenberg, K.L., eds., 2007. *Advancing the fundamental sciences: proceedings of the forest service national earth sciences conference, San Diego, CA, 18-22 October 2004*. PNW-GTR-689. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station.

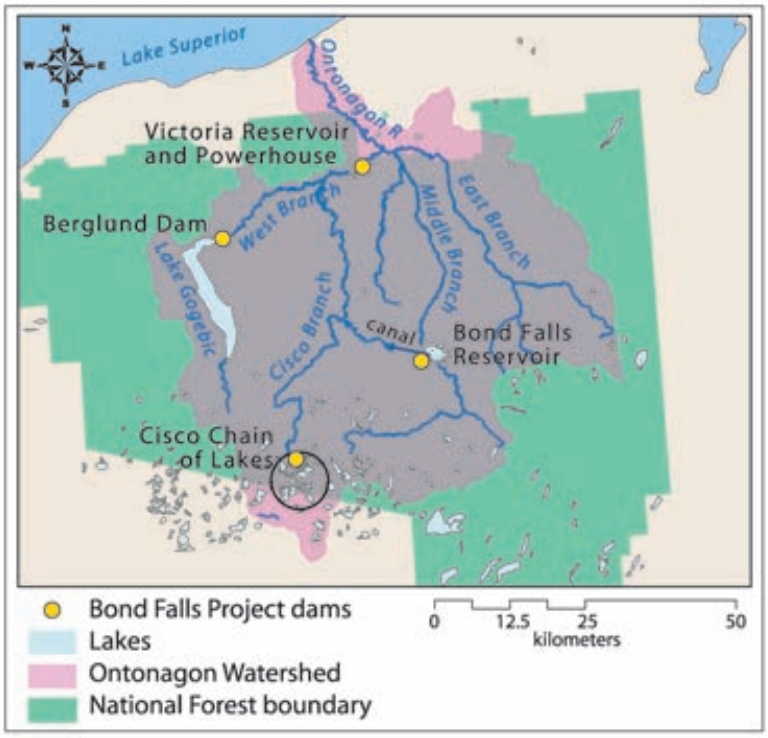


Figure 2. Reservoirs and rivers associated with the Bond Falls hydroelectric project, within the Ottawa National Forest.

other natural lakes, providing additional reservoir storage capacity for hydropower production. The total reservoir storage capacity available for use is 104.5 cubic kilometers. The mean annual daily discharge at the powerhouse is about 24.6 cubic meters per second (cms).

The original license for the project was issued in 1952 for the project for a 50-year term, retroactive to 1939. In 1985 the Federal Energy Regulatory Commission (FERC) initiated the re-licensing of the project by conducting agency and public meetings. Upper Peninsula Power Company (UPPCO) formally applied for a new license in 1987. The original license expired the following year; however, dam safety issues delayed the licensing process for another three years while the Victoria Dam was reconstructed to meet current safety standards, as required by the FERC. In 1992 several segments of rivers affected by the project were designated as recreational or scenic rivers under the Wild and Scenic Rivers Act (P.L. 90-542, as amended). Additional resource studies were conducted from 1992-1995, and the FERC declared that the project was "ready for environmental assessment" in 1996.

Resource agencies and non-governmental organizations (NGOs) recommended license conditions to the FERC that were much different from the way the power company proposed to operate the project. In 1997, the FERC encouraged the interested parties to enter into settlement negotiations in attempt to come to an agreement. The settlement agreement process had been previously used successfully in Michigan on another contentious hydropower project, and the decision was made by all parties to attempt to use a similar process for Bond Falls. The parties included agencies and NGOs that had widely divergent interests (Table 1). The Cisco Chain and Lake Gogebic Riparian associations and North Shore Riparian Owners chose not to participate in the settlement process.

In 1999, after approximately three years of difficult negotiations, the parties had reached a draft settlement. The final settlement was signed the following year, and the FERC developed draft and final environmental impact statements from 2001 to 2002. The license was issued in August of 2003, fifteen years after the original license expired.

Issues

The key issue that the parties needed to resolve was water management. Specific issues included the timing, magnitude and changes in flow rates, and water level elevations in the reservoirs. The power company contended that any changes in the existing water management operations would adversely affect the project economics. Understanding how the components of the project had been historically managed and how resources are affected is critical to understanding the outcome of the negotiated settlement.

Table 1. Parties to the negotiated settlement and their primary interests.

Party	Primary Interest(s)
Cisco Chain Association	Water levels at Cisco Lake
Keweena Bay Tribe	Natural resources, tribal rights
Lake Gogebic Riparian Association	Water levels at Lake Gogebic
Michigan Department of Natural Resources	Fisheries, wildlife, recreation
Michigan Department of Environmental Quality	Water quality
Michigan Hydro Relicensing Coalition	Represented the interests of six conservation non-governmental organizations
North Shore Riparian Owners	Water levels at Lake Gogebic
Upper Peninsula Power Company	Project economics
USDA Forest Service	National resources

Victoria Reservoir, Bypassed Reach of the West Branch, and the Ontonagon River

Victoria Dam is a 13.7-meter high concrete structure, constructed just upstream from a natural waterfall. During its initial licensing period, the powerhouse was operated as a "peaking" facility, with discharges ranging from zero to 22.7 cms on a daily basis. The power plant was operated during periods of peak energy demand, depending on inflows. A flume bypasses 2.6 kilometers of river between the dam and the powerhouse. Because there was no minimum flow requirement for the bypassed reach, it was often dewatered. A reproducing population of the State Threatened and Forest Service Sensitive lake sturgeon (*Acipenser fulvescens*) occurred historically in the river below the project (Schoolcraft 1821). The Michigan Department of Natural Resources has a goal of restoring this population. The waterfall is a migration barrier to fish; therefore, upstream fish passage was not an issue. The bypassed reach is relatively steep with cobble to bolder substrate, potentially suitable spawning habitat for lake sturgeon.

West Branch of the Ontonagon River and Lake Gogebic

Bergland Dam, at the outlet of Lake Gogebic, regulates the water level of the 57 square kilometer lake. The dam has raised the elevation of the natural lake by 1.2 meters. Many private residences surround the lake; a priority under the original license was to maintain a full pool during the summer recreation season. By placing a priority on lake water elevations, the river below the lake would frequently be reduced to leakage flows (about 0.1 cubic meters per second) during the summer resulting in adverse effects on the aquatic system downstream. During the winter UPPCO was allowed to draw down the reservoir 0.6 meters (to be used downstream for hydropower generation) and refill the lake in the spring.

The lake is about 19 km long and oriented approximately north-south. When the lake is at or near full pool and there is a strong wind from the south, waves pound against the north shore contributing to shoreline erosion. North shore residents have complained that they are losing their shoreline and have asked UPPCO to lower the water levels and mitigate the damage by installing erosion control structures. Meanwhile, residents on other portions of the lake said that they would be adversely affected by lower water levels, as lower levels would expose navigation hazards and their docks would be in water that was too shallow for boat access.

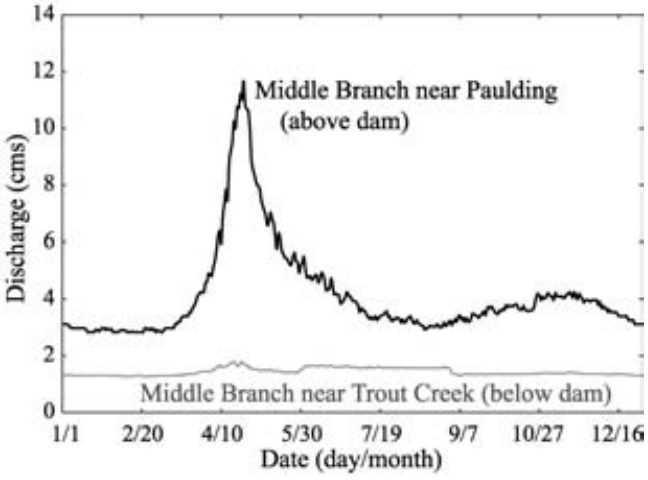
Cisco Chain of Lakes and the Cisco Branch of the Ontonagon River

The Cisco Chain of Lakes consists of about a dozen lakes that are interconnected. The 3.4-meter high dam at the Cisco Lake outlet controls the water level in all lakes. Water levels are very important to the residents on the lakes to provide for navigation between the lakes. Similar to Lake Gogebic, lake water levels took precedence over streamflows in the original license, frequently reducing flows in the Cisco Branch to leakage (about 0.01 cms). During the winter UPPCO would draw down the lakes 0.3 meters to gain 4.9 cubic kilometers of water for power production.

Bond Falls Reservoir, Middle Branch of the Ontonagon, and the Diversion Canal

The Bond Falls Reservoir is a 13.7 m earthfill dam on the Middle Branch of the Ontonagon River, just upstream from Bond Falls. The natural flow of the Middle Branch joins the Ontonagon River downstream from the Victoria powerhouse. Water is diverted through a constructed canal that discharges to tributaries to the South Branch. The

Figure 3. Median of daily mean discharge values upstream (Middle Branch near Paulding) and downstream (Middle Branch near Trout Creek) of Bond Falls Reservoir, 1942-2003.



South Branch joins the West Branch above the Victoria Reservoir. Discharges in the canal varied from zero to 10.8 cubic meters per second (cms). The effects of the diversion on the mean daily flows below the Bond Falls reservoir can be readily observed using data from the upstream and downstream gages (Figure 3). The additional flows in the small tributary streams created tremendous changes in stream channel morphology. Rapid fluctuations in flow eroded streambanks, resulting in an unstable stream system with adverse effects on benthos and fish populations (Taft 1995).

Annual water level fluctuations at the Bond Falls reservoir were as much as 7.3 meters. The reservoir provides habitat for the Federally Threatened bald eagle (*Haliaeetus leucocephalus*). Other species of interest that may be affected by reservoir elevation fluctuations include the State-Threatened and Forest Service Sensitive common loon (*Gavia immer*) and trumpeter swan (*Cygnus buccinator*). The entire assemblage of plant and animal species that depend on the near-shore environment can also be adversely affected by large fluctuations in water levels.

Other Issues

A number of other issues were considered in the negotiation process, including sub-standard recreation facilities, water quality, wildlife habitat, fish passage, fish entrainment, nuisance plants, and woody debris management. Recreation facilities were mostly old and did not meet current standards regarding accessibility or adequacy. Water quality concerns included meeting state standards for dissolved oxygen and temperature below project facilities. Wildlife habitat issues raised included how land and vegetation would be managed around the reservoirs to provide the needed wildlife habitat – particularly old-growth habitat. The Bond Falls Project area provides habitat or potential habitat for 46 threatened, endangered or sensitive species. Upstream fish passage was an issue only at the Bergland and Cisco dams, as the other dams are located directly above natural waterfalls. A fish entrainment study conducted as a part of the licensing process found that about 235,000 fish per year were entrained (drawn into the generating flow) and the turbines killed approximately 71,000 fish (RMC Environmental Services 1996). Resource agencies and NGOs also wanted UPPCO to take responsibility for the prevention, inventory and control of invasive plants (primarily purple loosestrife [*Lythrum salicaria*] and Eurasian watermilfoil [*Myriophyllum spicatum*]). Woody debris management concerns surrounded the fate of debris that accumulated in the reservoirs at the dams that otherwise would have continued to move downstream. Recreation issues, including fishable and boatable rivers, were closely related to the aquatic issues concerning the volume and timing of flows and water levels.

Negotiation and Settlement

The Forest Service formed a small interdisciplinary team to review reports, conduct independent analyses, conduct water quality monitoring, and participate in the negotiations leading to settlement. The Forest Service team included a wildlife biologist, a fisheries biologist, a hydrologist and a recreation specialist. Other agencies and NGOs were more narrowly focused in their interests and generally had only one representative. The power company had a lot at stake in the negotiations and was primarily represented by three to four individuals, including a contracted consultant at some meetings.

The strength of the Forest Service negotiation position stemmed from several laws that had been enacted since the original license was issued. Most notable was the Federal Power Act (FPA), as amended in 1986. Section 4(e) of the FPA allows the Forest Service to condition the license to assure the operations of an existing or proposed hydroelectric project are consistent with the goals established in the Forest Land and Resource Management Plan. The 1986 Ottawa National Forest Plan established many goals related to aquatic and recreation resources that were not being met under the original license (USDA Forest Service 2002).

The negotiations were long and contentious. The parties initially met about every six weeks during the negotiation process. But with little pressure from the FERC and an apparent lack of strong commitment to the process by

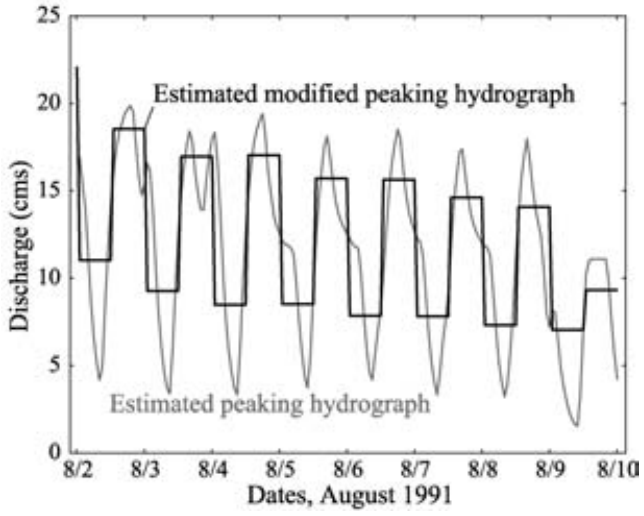
UPPCO, meetings were sometimes cancelled or dates slipped further. With the passage of so much time between meetings, the parties would often have to go back and review everything that was agreed to previously. The process was further delayed after Wisconsin Public Service (WPS) acquired UPPCO in 1998. With the introduction of new faces at the negotiation table, the process slowed as agreements had to be reviewed, explained and discussed again.

The parties tackled the minor issues first, to gain confidence and build trust in each other. They followed an outline that eventually led them to negotiate the most difficult issues – flows and water levels. Flows and water levels were modeled to try out various operating scenarios. Results from the operations model were combined with aquatic habitat modeling to estimate the effects of differing operations on habitat and recreation values. The power company used the modeling results to estimate economic impacts. The parties used the models as a basis for communicating interests and to help solve the complex problem of allocating resources. Using modeling results and independent analyses, negotiations continued for more than three years before a settlement was reached.

Results of the Negotiated Settlement

Some of the most significant results of the settlement included more natural flow levels in the rivers, reduced fluctuations in reservoir elevations, and the establishment of a mitigation fund and an implementation team to meet other resource needs.

Figure 4. Estimated discharge below the Victoria hydroelectric plant and simulated discharge under a "modified peaking" condition. Simulated discharge was based on the rules defining "modified peaking" according to the terms of the settlement.



Flows in the Middle Branch of the Ontonagon River

The flows in the Middle Branch are linked to the water levels and canal discharges from the Bond Falls Reservoir. The Middle Branch flows were the most contentious issue, as this river had perhaps the highest resource potential of the various project river segments, and had been severely affected by operations under the previous license. From the perspective of UPPCO/WPS, every drop of water that goes down the Middle Branch is a drop that does not go through the turbines at Victoria. Studies were conducted using the Instream Flow Incremental Methodology (IFIM) to determine flows that would support viable populations of aquatic species and recreational uses of the river. Flows in the Middle Branch are dependent on water levels in the reservoir and discharges in the canal. Water level fluctuations and canal discharges had to be moderated in order to achieve a more natural runoff pattern in the Middle Branch.

The parties agreed to a minimum flow that varied through the year to better emulate a more natural hydrograph and meet the needs of aquatic species and recreation. The winter drawdown of the reservoir was limited to 2.4 meters and the maximum discharges to the canal were limited to 5.0 cms. These changes served to allow for higher flows in the Middle Branch during the spring to provide channel-maintenance flows.

Victoria Dam and Power Plant Operations

The parties agreed to change the operations of the power facility from a peaking facility to a run-of-river operation during sturgeon spawning season, and a "modified peaking" facility during the remainder of the year. Modified peaking was defined as the minimum discharge on any day had to be at least half of the maximum discharge of the previous day (Figure 4). This provision assured that the stream channel below the facility would be constantly wetted and aquatic resource values protected.

During the sturgeon spawning periods, minimum flows of 4.2 cms would be released into the bypassed reach to provide sturgeon-spawning habitat. Flows would be maintained through June 15 to assure that young fish would reach rearing habitat in Lake Superior.

West Branch Minimum Flows

Operations at Bergland Dam at the outlet of Lake Gogebic would be modified under the terms of the settlement to provide a minimum flow of 0.9 to 1.4 cms, depending on water level elevations. Minimum flows would be reduced as water levels decline in the reservoir.

The minimum flows were designed to provide adequate, if not optimal, habitat to protect aquatic, aesthetic, and recreation resource values of the river.

Mitigation and Enhancement Fund, Implementation Team

A mitigation and enhancement fund was established to provide resources to address other issues through the term of the license. The settlement provided for the establishment of an implementation team, consisting of representatives of all parties to the settlement. The team operates by consensus to determine priorities for funding proposed projects. Potential projects include recreation improvements, fish entrainment prevention, water quality monitoring, fish passage facilities, wildlife and fisheries habitat improvements, erosion control, telemetry for gaging, wildlife and fisheries studies, and nuisance plant inventory and control. The licensee will contribute monies to the fund on an annual basis, amounting to $2.46 million (year 2000 dollars) over the 40-year term of the license.

Implementation

Issues regarding the implementation of the terms of the license arose immediately. In 2003, drier-than-normal conditions during late summer meant that flow conditions and water levels could not be met at the West Branch Ontonagon River and Lake Gogebic, respectively. Provisions within the settlement call for the power company to consult with the implementation team when conditions cannot be met. The team then makes a decision and notifies the FERC. When the same conditions could not be met the following year, the team met and decided on temporary changes in target elevations and "trigger" water levels for 2005 to help alleviate the problems. This adaptive management strategy will help the team to work through the complicated provisions of the settlement to best meet the needs of the affected parties and resources.

Since the license was issued, the team has reviewed and agreed to the content of many implementation plans prepared by UPPCO/WPS including: the management of water quality, recreation resources, wildlife habitat, Threatened and Endangered species, woody debris, erosion, and project operations and monitoring. The plans will help guide the team in the coming years as priorities are set and projects are implemented.

Acknowledgments. I would like to thank Bob Evans for his unwavering and excellent work on this project from the very beginning of the licensing process, for inviting me to work on this project, and for his review of this manuscript. I'd also like to thank my mentor, Dale Higgins, for his fine work in conducting hydrologic modeling for this project.

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TRTR Funds–Successes in Watershed Restoration in the Eastern Region

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Eastern national forests are largely comprised of lands that were cut over, burned, farmed and mined. In over 100 years of National Forest System management we have made great progress in improving the condition of the "lands nobody wanted," but considerable work remains to address impacts to the aquatic component. Sediment continues to be the primary contaminant of concern in our aquatic systems. High historic sediment levels are sustained by persistent contemporary input, primarily from roads and trails. To improve the condition and health of our eastern watersheds, we need to address the delivery of sediment from our gravel and gravel-sand roads and trails. In addition to being a source of sediment, many of the road and trail crossings are impediments to passage by aquatic organisms. The Roads and Trails for States (TRTR) program, which returns to the Region ten percent of the prior year receipts collected from National Forests, has enabled the USDA Forest Service Eastern Region to make significant progress in addressing many of our road and trail stream crossing problems. Our TRTR program uses an integrated process to address sediment problems at many of our high priority road and trail stream crossings. TRTR projects range from improving high use hiking trails on the White Mountain National Forest (New Hampshire) to replacing open slotted bridges on the Chippewa National Forest, Minnesota. Our landownership pattern presents challenges but also offers numerous opportunities for partnering with others to achieve success. Many forests have leveraged their TRTR funds with partners to achieve transportation, recreation and riparian-habitat objectives.

Keywords: *watershed restoration, sediment, aquatic habitat impairment, stream crossings, transportation management*

Background

Eastern national forests differ markedly from the larger forests west of the 100th meridian. The Eastern Region of the USDA Forest Service (Region 9) is vast, extending from Minnesota to Maine, south to West Virginia, and west to Missouri. While the western forests are prominent on the landscape, eastern forests seem like mere flecks scattered across the eastern half of the nation (Shands 1979). Land ownership within national forest boundaries is fragmented and the percentage of federal ownership varies by forest.

While there is some public domain land in the East, eastern national forests were formed primarily of land purchased following passage of the Weeks Act in 1911. The Weeks Act authorized Congress to appropriate money to purchase forest reserves for the purpose of conserving forests and the water supply (Conrad 1997). No single law has been more important in the return of the forests in the eastern United States. The lands acquired to build the region were the "lands nobody wanted" (Shands 1977). Historical logging and burning, farming and burning, and mining and abandonment, left behind vast acreages of stump fields, severely eroded hillslopes with numerous gullies, thousands of acres of drained wetlands, and miles of sediment-clogged stream channels and lakeshores.

In 1920 there were 1,402,000 acres (567,800 ha) of national forests in what is now the Eastern Region (USDA 2004a). Today this figure is 12,061,766 acres (4,885,015 ha) or approximately 55 percent of the land within the administrative boundary (USDA 2004a). Ownership within watersheds varies from over 90% on the White Mountain National Forest in New Hampshire to less than 1% for some of the watersheds on the Wayne National Forest in Ohio. These intermingled lands that comprise a national forest are owned by states and counties, as well as private individuals and timber companies.

Today, because of high human population densities and relatively small public land acreages in the East, national forests here have been called "islands of green in a sea of people." Many Eastern Region national forests are within a day's drive of major metropolitan areas such as St. Louis, Minneapolis, Chicago, Cleveland, Detroit, Pittsburg, Philadelphia, Washington, DC, New York and

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Boston. People seeking recreational opportunities can readily travel to these national forests. Off-highway vehicle use, motorbike riding and horseback riding have increased significantly in recent years, and the demand for these uses is a major forest plan revision issue on most forests.

Recreational activities involving aquatic resources have also increased and present significant resource management challenges. The Eastern Region, with more than 962,000 acres (389,600 ha) of lakes and more than 15,300 miles (24,600 km) of streams, has more of these resources than any Forest Service region outside of Alaska (Schmal 2004). Lakes and wetlands dominate the forests in Minnesota, Wisconsin and Michigan, with streams dominant in Missouri and West Virginia. All Eastern Region forests contain both free flowing and flat water. It is public interest in accessing and using the eastern national forests that sets the stage for potential impacts to the riparian and aquatic resources, ultimately effecting watershed function and health.

The Problem

The intermingled land ownership patterns of eastern national forests bring challenges and opportunities. Transportation management is one of the challenges. There are approximately 30,000 miles (48,300 km) of inventoried Forest Service roads and more than 12,000 miles (19,300 km) of inventoried Forest Service trails in the region (USDA 2003). In addition to what has been inventoried, there are many unauthorized and unmanaged user-developed roads and trails. The existing network provides access to recreational areas and serves as a conduit for the harvest of wood products. But the existing roads and trails were not initially designed to address aquatic and riparian resource needs.

Many existing roads follow old railroad beds and have surfaces of native gravels and sands, often with stream crossings at the lowest elevation in the watershed. Drainage structures comprised of corrugated metal pipes are common and many bridges are open-slotted (the bridge travel surface is not solid). In parts of the region, crossing structures are non-existent, and low water crossings or fords are used instead. These existing crossings are major contributors of sediment to the aquatic resources.

Excessive sediment has both physical and biological effects. The addition of sediment can alter stream channel morphology (e.g., increase width-depth ratios) and reduce the carrying capacity of the channel. During high runoff periods, the crossing may be overtopped, causing subsequent removal of road surfacing material and erosion of stream banks. High sediment levels rarely kill adult fish, but can harm eggs and juvenile fish. Many streams with important fish habitat in the forests of the Great Lakes region are Rosgen "C" types. These are perennial streams with sinuous, low-gradient, low-relief channels, and well-developed floodplains (Rosgen 1996). Much of the deposited sediment stays in the channel where it can bury important food, spawning, and cover habitat.

Consider the "Brill Cream" slogan that was popular twenty years ago, "A little dab'll do ya." If you are a fish or other aquatic organism living in a low gradient stream or a stream with numerous undersized culverts or open-slotted bridges, "A little dab of sediment will do you in". Fish habitat studies in Michigan and other parts of the country have shown that the addition of inorganic sediments can seriously alter habitat conditions, thereby affecting food sources which can then limit reproductive potential of certain fish species (Hansen et al. 1982). Fish and other aquatic organisms need pools for cover and the addition of inorganic sediment fills the pools, further altering the stream channel and habitat.

Older culvert crossings frequently impede aquatic organism passage. While most culverts were designed to meet the hydraulic design criteria, they are undersized when consideration is given to debris, sediment and aquatic organism passage. These culverts may effectively pass water during moderate and high flow conditions but still serve to block or inhibit upstream aquatic organism passage due to increased velocity during high flows and insufficient water depth during low flows. Changes in stream configuration over time, including scour and ponding around the upstream end of culverts, have also resulted in raised inlets in many cases. The issue of raised inlets was noted as the second most significant issue identified from the integrated stream crossing inventories on the Huron-Manistee National Forests, Michigan (CRA and USFS 2004). Raised inlets are a significant concern because they block downstream passage of aquatic organisms during low flows and pond water upstream of the crossing. This can accelerate bank erosion and sedimentation.

Trail stream crossing problems are also prevalent throughout the region. Many of the existing trails were initially developed by users. Limited effort was expended on location, design or installation, and best management practices were not applied. While some trails have culverts, many more do not. The existing culverts were installed to provide drainage to protect the trail, but may not meet variable flow conditions or aquatic organism passage needs.

Across the Eastern Region, erosion of sediment from our existing road and trail network further alters streams working to recover from prior land use practices. This is especially true when viewed from a cumulative perspective across a watershed.

Roads and Trails for States Program (TRTR) – "The Hero"

Interest in improving road and trail stream crossings in the Eastern Region began in the late 1980s and parallels the "Rise to the Future" initiative. This initiative was created in 1986 by Chief Max Peterson and implemented the following year by Chief Dale Robertson. In 1988, the Eastern Region started hiring fish biologists. Assessments of aquatic habitat conditions were initiated, followed by habitat improvement projects. An evolutionary process occurred in the Eastern Region. Fish biologists knew sediment was harmful to fish and their habitat. Early aquatic habitat restoration work focused on repairing individual sites, such as an eroding stream bank. These eroding stream banks were thought to be "the problem". This evolved to treating all actively eroding sites on a river. But still stream sedimentation and aquatic habitat impairment continued. Concurrent with concerns about sediment in the East, Dr. Jerry Franklin and other scientists were examining the relationship between the health of aquatic systems and what was occurring in the watershed (Franklin 1989; Verry 1992). From knowledge gained through discussions both within and external to the region, larger landscape inventories, and in many cases, watershed inventories were initiated. These larger-scale inventories identified road and trail stream crossings as major sources of sediment on most Eastern Region national forests.

While the Huron-Manistee National Forests led the region in this effort, other eastern forests also initiated road-stream crossing inventories. These road-stream crossing inventories identified over 14,000 culverts in the region, with large numbers of problem crossings-raised inlets, perched outlets, high flow velocity issues, low flow passage organism passage problems, to name a few (Schmal 2004). While the focus was on national forest lands, it was apparent that problem crossings were not exclusive to the national forests. The challenge was how to meet the need to address these problems and stay within existing program constraints.

Within the Forest Service, Soil and Water Resource Improvement funds can cover the installation of land treatment and structural measures for erosion control, rehabilitation of abandoned roads and trails, and stream bank and gully stabilization (USDA 2004b). But these funds are not appropriate to fund erosion control work or perform other maintenance, including replacing stream crossing structures on existing roads or trails. Maintenance work should be implemented using road and trail maintenance funds, but the need far exceeds our region's annual appropriations. This issue was not unique to the Eastern Region. Alternative funding sources were needed. In 1913, a statute was written that addressed this need. The original statute in 16 USC Sec. 501, Title 16, Chapter 2, stated that:

"On or after March 4, 1913, ten per centum of all moneys received from the national forests during each fiscal year shall be available at the end thereof, to be expended by the Secretary of Agriculture for the construction and maintenance of roads and trails within the national forests in the States from which such proceeds are derived".

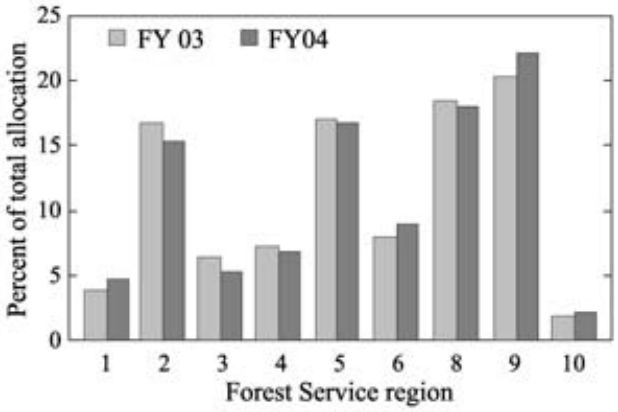
But it was not until 1996 that Congress authorized use of ten percent of the prior year's receipts from national forests, "…to repair or reconstruct roads, bridges and trails on national forest system lands…..for the purpose of reducing risks to human health and safety and public property, and to enhance ecological functions, long-term productivity, and biological integrity (USDA 1998). The program was called "Roads and Trails for States" and the agency assigned the program the "TRTR" fund code.

All regions started receiving TRTR funds in 1998. The TRTR funds were viewed as "the hero" in the Eastern Region because program direction enabled forests to use the funds to address environmental problems caused by existing roads and trails. Initially, the funds went back to the forest based on the forest's collection of receipts, but in subsequent years, regions were directed to select and fund the highest priority projects based on factors including watershed condition, watershed integrity, and partnerships, and other relevant considerations, regardless of which forest initially generated the funds (USDA 1999).

TRTR Program in Region 9

The Eastern Region has been successful with the TRTR Program for several reasons. A number of forests had inventories of road and trail stream crossings that included assessment of problem crossings. Crossing needs were known, and project designs to address both the transportation and aquatic resource needs existed or were nearing completion. Secondly, the national program direction emphasized program integration. Implementation of the TRTR program offered support to those forests where engineering, fisheries, watershed and recreation were working together. The added value from this internal integration has been tremendous and will continue to have significant program benefits. Lastly, the region's percentage share of TRTR funds has been significant (Figure 1). Our annual allocation of approximately 3 million dollars along with program direction that gives priority to projects with partnership potential, has opened the door to working across boundaries with a variety of partners. For partnerships to work, all partners need to bring

Figure 1. Percentage share of TRTR funds for fiscal year 2003 and 2004 by Forest Service Region. Regions: 1. Northern, 2. Rocky Mountain, 3. Southwestern, 4. Intermountain, 5. California, 6. Pacific Northwest, 8. Southern, 9. Eastern, 10. Alaska



something to the table. Without a stable source of funding, maintaining and expanding partnerships is difficult at best. Across the Eastern Region, most forests are working with external partners to address road and trail stream crossing needs. By leveraging TRTR funds with partner funds they are able to correct road-trail stream crossing problems and accelerate watershed restoration on "the lands nobody wanted".

There are many TRTR success stories in the Eastern Region that exemplify "working together" with both internal and external partners. Five projects described below provide representative examples of the region's use of TRTR funds to address environmental problems associated with our existing roads and trails.

Chippewa – Woodtick Road Relocation (Figure 2)

The Chippewa National Forest in north-central Minnesota has been an active participant in the TRTR program. The forest has a long-standing commitment to restoring the health of watersheds from the impacts of past land use practices. While addressing road stream crossings has been a major focus of the TRTR program on the Chippewa, the success story involves the relocation of a road and the restoration of a large connected complex of wetlands.

Forest Road (FR) 2107 was a gravel-surfaced, system road open seasonally to public highway traffic (Figure 2a, c). The road bed was frequently flooded in the spring or during heavy rainstorms and required frequent maintenance. The road had been in place for many years and was partially located in a wetland. The purpose and need for the relocation project was to reduce long-term maintenance costs, improve safety, and restore water flow within the wetland through which the road passed. The project had been previously identified and listed on the Chippewa's road maintenance inventory. In 2002 the project was selected as the Forest's number one priority for TRTR funds because of the opportunity to address both transportation issues and watershed restoration concerns.

The proposed action involved relocating 3,500 feet (1067 m) of FR 2107 by constructing a permanent bypass for the portion of the existing roadway that ran through a wetland (USDA 2002c). The relocated roadway would provide a 22-foot-wide (6.7-m) driving surface with 3:1 side slopes. The bypass would traverse uplands that include open fields and forest. It would diverge north and west from the existing roadway to form a new junction with Minnesota Trunk Highway 371, approximately 1,000 feet (305 m) north of the current junction. The bypassed portion of the roadway would be removed and restored to approximate the topography and native vegetation that were present before the road was constructed.

Construction of the new road segment cost $159,000 and was funded using TRTR. Removal of the old roadbed and restoration of the adjacent topography and vegetation was accomplished through a partnership between the Chippewa National Forest and Cass County (Figure 2b, d, e). The county paid for the removal of the grade in exchange for use of the fill on a nearby project and to obtain credit for wetland restoration that offset wetland losses on the Forest due to other county highway projects. The value of the County contribution was $25,000. The National Forest contributed $15,000 of TRTR funds to cover surface re-contouring, topsoil costs, and the creation of a few small sandy areas suitable for turtle nesting.

The strength of this project was the partnership that formed and helped to elevate the importance for the project. The result was an improved and safer access to national forest resources, the restoration of flow through 19 acres (7.7 ha) of wetland, and the direct restoration of almost two acres (0.81 ha) of wetlands.

Hiawatha – Sturgeon River Bridge Replacement (figure 3)

The Hiawatha National Forest is located in Michigan's Upper Peninsula, between Lake Superior and Lake Michigan. As with other Lake States' forests, it has numerous lakes, wetlands and rivers. Many of the rivers are classified as wild and scenic rivers, including the Sturgeon River, the site of this success story.

The Sturgeon River Bridge crossing has long served as a chronic source of sediment to the Sturgeon Wild

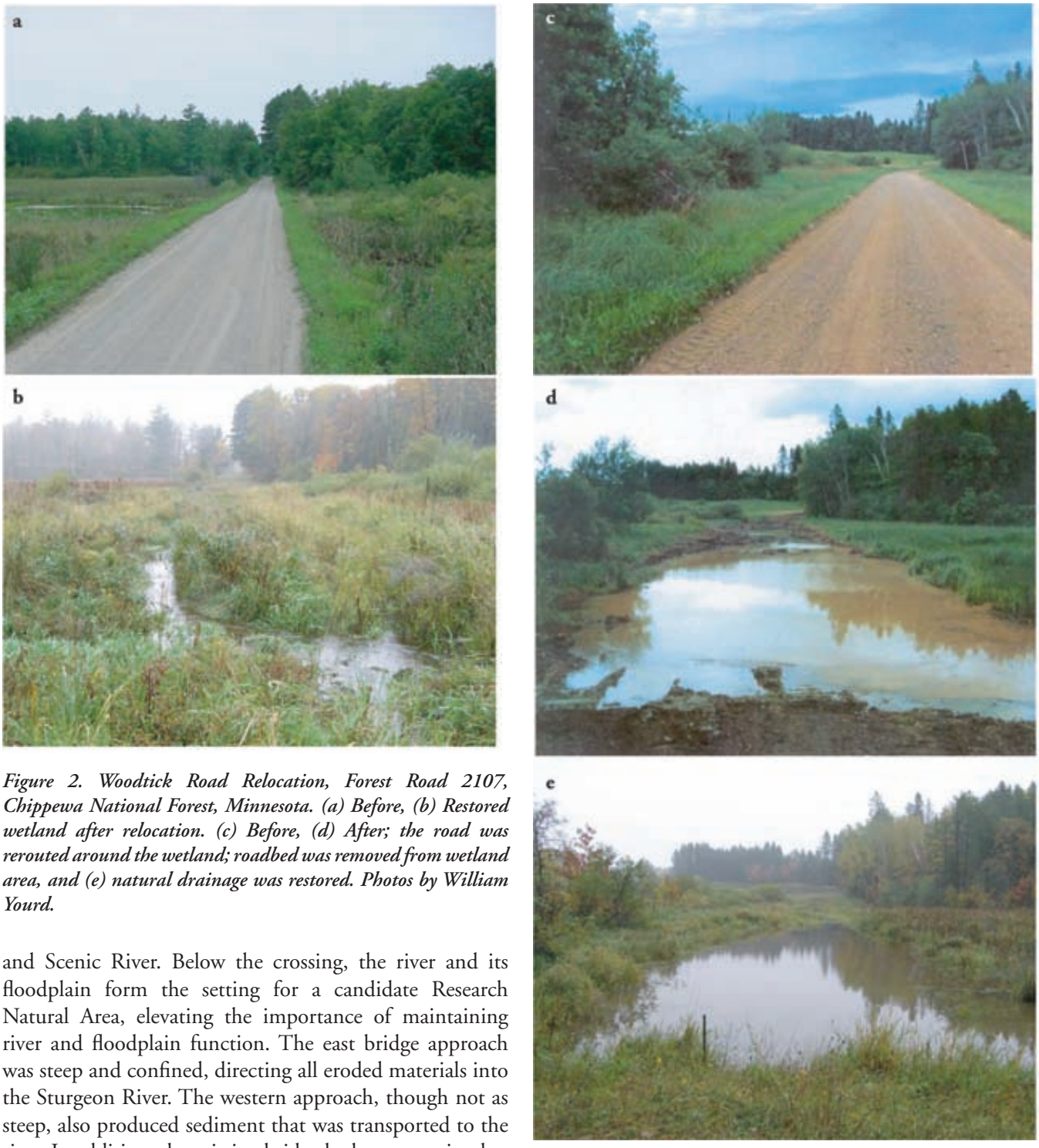


Figure 2. Woodtick Road Relocation, Forest Road 2107, Chippewa National Forest, Minnesota. (a) Before, (b) Restored wetland after relocation. (c) Before, (d) After; the road was rerouted around the wetland; roadbed was removed from wetland area, and (e) natural drainage was restored. Photos by William Yourd.

and Scenic River. Below the crossing, the river and its floodplain form the setting for a candidate Research Natural Area, elevating the importance of maintaining river and floodplain function. The east bridge approach was steep and confined, directing all eroded materials into the Sturgeon River. The western approach, though not as steep, also produced sediment that was transported to the river. In addition, the existing bridge had a center pier that continuously caught large woody debris being transported downstream by the river. The bridge abutments intruded into the bankfull area of the river, constricting the channel, with resultant upstream sediment deposition and increased width-depth ratio (Figure 3a).

Support for this project came from within the forest as well as from private contacts, including county and township road commissions. The Forest Hydrologist, Fish Biologist, Wild and Scenic River Planner and Recreation staff all worked together with the Forest Engineer to assess the site and to develop a conceptual design for the structure that met all the resource needs. Actual bridge design and National Environmental Policy Act (NEPA) documentation was contracted with a private engineering firm. Funding for the bridge came from the Capital Resource Improvement Program in addition to TRTR funds. The the entire project cost $521,000 and took four years to accomplish.

Figure 3. Sturgeon River Bridge, Hiawatha National Forest, Upper Peninsula of Michigan. (a) Before, (b) After. Former road was narrow, with native road surfacing material; stream crossing was at the lowest elevation on the road and this allowed runoff to flow down the road and deposit sediment into the Sturgeon River, a cold-water, low gradient stream. The new crossing was slightly elevated, provided more sunlight to the roadbed; the bridge was replaced; the approaches and crossing were hardened and runoff drains were constructed. Photos by Richard Kell.

The project included removal of the old structure, followed by installation of a single span bridge that spanned the entire bankfull width, establishment of functioning ditches and drainage relief structures, and hardening the road approaches to the river (USDA 2002b). Because of the magnitude of the project, the construction activities occurred over three years.

As a result of the work accomplished, the following benefits were achieved:

- a reduction in sediment delivered to downstream aquatic habitat,
- the restoration of the free flowing characteristics of the Wild and Scenic River, and
- a safer, wider bridge with regulation guardrails

The new Sturgeon River Bridge is now complete and an outstanding example of one of the larger, more complex stream crossing projects accomplished with TRTR funds (Figure 3b).

Green Mountain – Catamount Trail Bridge Replacement (figure 4)

The Green Mountain is a small but very special national forest in southern and central Vermont. As with many eastern national forests, there are non-Forest Service recreation sites within and adjacent to the national forest. The Catamount Trail, a cross-country ski trail running the entire length of Vermont, is an example of a trail that has access points on the forest. One segment of the trail crosses Burnt Meadow Brook. This section of the Catamount Trail has been in existence for a number of years, and passes through the grounds of the Macartney House, a pristine country inn, which is operated under a special-use permit from the forest. The existing bridge was in need of replacement from a structural standpoint, and the approaches and decaying native log abutments were causing sedimentation (Figure 4a).

Figure 4. Burnt Meadow Brook Bridge replacement, Catamount Trail, Green Mountain National Forest, Vermont. (a) Before, (b) After. Photos by Richard Gaiotti.

As a result of discussions between the forest TRTR coordinator and members of the Catamount Trail Association, Macartney House and the State of Vermont, a partnership developed and plans were made to replace the Burnt Meadow Brook Bridge (USDA 2002a, 2002d, 2002e). The Burnt Meadow Brook Bridge was the largest of nine bridges replaced on the Catamount Trail on the Manchester Ranger District, during the summer of 2003. The Forest Service, using TRTR funds, agreed to share the cost of its construction with the Catamount Trail Association, which had received grants from the State of Vermont. The new Burnt Meadow Brook Bridge has a standard Forest Service trail bridge design with steel stringers and treated timber mudsills, railing, and decking. Heavy equipment was used to transport the stringers to the site and set them in place. All other work was performed by a ten-person Vermont Youth Conservation Corps (VYCC) crew, with Forest Service and Catamount Trail Association personnel. The Catamount Association, Forest Service, and Macartney House shared in providing logistical and technical support.

The new bridge (Figure 4b) met the resource needs and assured safe access across Burnt Meadow Brook while providing a worthwhile and rewarding project for the VYCC crew.

Hoosier – Charles Deam Wilderness Trail Restoration (Figure 5)

The Hoosier National Forest comprises 200,000 acres (81,000 ha) on two units in southern Indiana. The northern unit of the forest includes the Charles C. Deam Wilderness, the only congressionally designated wilderness in the state of Indiana. This wilderness is a popular weekend destination for local residents from nearby Bloomington, Indiana, a city of 120,000 people. In the last decade, both horseback riding and hiking have steadily increased. Much of the wilderness is covered with lush second growth hardwood forests. The existing network of trails, many of which follow the old road system built in the late 1800s, has been maintained but was not designed to accommodate the increased horse traffic (Figure 5a). Many trails were originally built without adequate cross-drainage. There were numerous damaged areas with increasing concern for erosion, runoff, and subsequent sedimentation to Monroe Reservoir, the municipal water supply for Bloomington, Indiana.

An Environmental Assessment released in 2001 analyzed several trails in the Charles C. Deam Wilderness (USDA 2001). The Environmental Assessment focused on improving trails where improper drainage and flooding was causing sedimentation into the Monroe Reservoir. Knowing that any trail restoration work must comply with wilderness requirements, the forest began contacting western forests with mule strings that might be available to assist with the work. The Bridger-Teton National Forest in Idaho reported they had two mule packers and eight

Figure 5. Charles Deam Wilderness Trail, Hoosier National Forest, Indiana. (a) Before, (b) After. Several sections of this popular, heavily used hiking/horseback riding trail were located lower on the slope, with little consideration for cross drainage. This project involved closing and rehabilitating some of the wetter sections, moving the trail father upslope, adding cross drains, and also surfacing. Photos by Eric Solerno.

mules that handled their trail restoration work during the summer season. But during the winter and late spring, these resources were available and willing to work. A partnership formed between the forests, and since 2000, two packers and eight mules have spent the month of May on the Hoosier National Forest performing trail restoration work both inside and outside wilderness. In that period, 11.5 miles (18.5 km) of trail have been constructed or reconstructed to move them up out of the low areas and more than 500 tons (453 metric tons) of gravel have been hauled by mules and placed to harden the trail surface (Figure 5b).

This partnership is both innovative and definitely a "win-win" situation for both national forests and the resources.

Huron-Manistee – Landscape Approach Through Partnerships (figure 6)

The Huron-Manistee National Forests' motto is "United by Rivers". The forests' location in central Lower Michigan makes them accessible to over 60 million people who are within a day's drive (Leefers et al. 2003). A prized feature is the deep groundwater-fed rivers that support world-class fishing, as well as providing habitat for a variety of endangered, threatened, and sensitive species. Viewing the mixed land ownership patterns within the watersheds as an opportunity, the forests took a collaborative approach using partnerships to tackle problems on a landscape scale.

In the mid 1990s, the forest partnered with local Resource Conservation and Development Councils, and initiated watershed-wide inventories focused on stream crossings (NMRC&D and USFS 1992; NMRC&D and USFS 1994; HPRC&D and USFS 1996; CRA and USFS 2004). The partners developed a rating system to assess potential for sediment delivery and fish passage impairment. Over 1170 crossings were identified at the watershed level (within 5th-level Hydrologic Units). A majority of crossings were off the national forest; only 220 were on National Forest System lands. Sediment was the most frequent problem, with county roads accounting for a majority of the problems. Of the county crossings, 70% were rated "severe" or "moderate". In addition to sedimentation problems, 160 crossings had fish or aquatic organism passage problems.

Using the inventory results, the forest has successfully integrated the TRTR Program into their watershed restoration efforts. During the period 1998-2002, 46 projects have been completed with nine different county road commissions, upgrading road-stream crossings, addressing aquatic organism passage, and improving roads

Figure 6. Road improvements on the Huron-Manistee National Forest, Lower Michigan. (a) Before, photo by William Fowler, (b) After, photo by Robert Stuber. Former road was narrow, with native material for road surfacing; drainage structures were undersized with many acting as barriers to aquatic organism passage. Road surfacing was hardened; alignment improved, some of the crossings were elevated; drainage structures were replaced with at least one bridge added; side slopes were stabilized and outlet drains provided to catch and direct runoff. This was a 2-mile long project that occurred over three years.

in riparian areas (Figure 6). Almost $2.7 million has been expended, of which 40% or $1.1 million has been contributed by the partners. Benefits include over 92 miles (148 km) of stream habitat improvement downstream from the projects. The partners' funding has come from multiple sources including Clean Water Act, Section 319 grants, Department of Transportation Intermodal Surface Transportation Efficiency Act [ISTEA, 1991] and Transportation Equity Act for the 21st Century [TEA-21, 1998] funds, and Clean Michigan Initiative funds.

Working together, the forest and its partners have been able to leverage funds to accomplish work that no one partner could do alone, providing multiple benefits to the

public, the resources and to the watersheds. There is still more work to do and it continues annually, with the goal of improving aquatic habitat and watershed function.

Closing

Eastern national forests are largely comprised of lands that were cut over, burned, farmed and mined. In over 100 years of managing these national forests we have made great progress in improving the condition of the "lands nobody wanted", but considerable work is still needed to address impacts to the aquatic resource. The Roads and Trails for States program has enabled the Eastern Region to address many of the existing road and trail stream crossings that are contributing sediment and restricting aquatic organism passage. Continued implementation of this program using integrated teams and partners ensures that the transportation system can co-exist with maintenance of valuable riparian and aquatic habitats.

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The Alkali Creek Story: 40 Years of Gully Control

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In the early 1960s, Burchard Heede of the Rocky Mountain Forest and Range Experiment Station designed and implemented a whole-basin (356-hectare) gully restoration plan in Alkali Creek, Colorado. This modest experiment and its results still serve as some of the benchmark research in gully control 40 years later. The project elements included perimeter fencing for cattle exclusion, check dams in a variety of forms, headcut control measures, revegetation, and conversion of several gullies to vegetation-lined waterways. These original designs are presented along with a discussion of findings after approximately twelve years, as well as the present status four decades after project implementation.

Keywords: *watershed restoration, gully control, check dams, vegetation-lined waterways, riparian vegetation*

Introduction

Many of the specific details of the Alkali Creek experiment are chronicled in detail in a number of publications by Burchard Heede (e.g., Heede 1976, 1977). Therefore this paper focuses on how the project came into being, what was done and why, and the resulting changes after four decades.

Study Area

Location

The study site is located in the headwaters of Alkali Creek on the Rifle Ranger District of the White River National Forest, approximately 32 km south of Silt, Colorado. Alkali Creek is a tributary to West Divide Creek, which enters the Colorado River at Silt. The 356-hectare study site ranges in elevation from 2,320 to 2,560 m.

Climate

The annual temperature varies from a maximum mean monthly temperature of 27°C in July to a minimum mean monthly temperature of -16°C in January. Between 1962 and 1974 the project area received about 48 cm of precipitation annually. Precipitation throughout the year was fairly evenly distributed with a low of 3 cm in January to a high of nearly 6 cm in September (Heede 1977). Snow is typical between October and April.

Furniss, M.J., Clifton, C.F., Ronnenberg, K.L., eds., 2007. *Advancing the fundamental sciences: proceedings of the forest service national earth sciences conference, San Diego, CA, 18-22 October 2004*. PNW-GTR-689. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station.

Vegetation

The project area is representative of the oakbrush-sagebrush-grasslands of the western slope of the Rocky Mountains in Colorado. Sagebrush (*Artemisia* spp.) and grasslands primarily occupy the valley bottoms and southern aspects while thick stands of oakbrush (*Quercus gambeli*) dominate the upper parts of the northern aspect. Typical grasses include Kentucky bluegrass (*Poa pratensis*), western wheatgrass (*Agropyron smithi*) and small amounts of introduced crested wheatgrass (*Agropyron cristatum*). Small amounts of serviceberry (*Amelanchier alnifolia*) and snowberry (*Symphoricarpos albus*) are present along with occasional groups of aspen (*Populus tremuloides*) near the valley bottom.

Geology and Soils

The parent geology of the project area is the Tertiary Wasatch formation, which is composed of clay shale and sandstone. The sandstone varies from fine- to coarse-grained and, in places, is strongly calcareous.

The soils are formed predominantly from shale and beds of sandstone (Fox and Nishimura 1957). Mechanical analysis of the soil done in the mid-1960s showed the distribution of clay, silt, and sand averaged 52%, 28%, and 20%, respectively, with the clay content as high as 65% (Heede 1977). Coarse materials, such as gravel or boulders, are essentially absent from the gullies.

Soil properties were measured in the early 1960s during project design. The disturbed soils in the valley bottoms, where grazing pressure was concentrated, typically had infiltration rates that were 4 to 5 times lower than adjacent upslope oakbrush areas with relatively light grazing impacts. The compaction of valley floor soils decreased the amount of precipitation needed to generate overland flow and led

to the subsequent erosion of gullies into the fine grained soil. Recovery of soil porosity and permeability would eventually be a key component in the stabilization of the drainage network.

Gully Stream Flows

Stream flows in the gullies typically occur only during the spring snowmelt and at times of intense summer thunderstorms. During 1963 and 1964, the measured peak spring runoff in the project area was 0.57 to 0.71 m^3/s (20 to 25 ft^3/s). Heede (1977) determined these to be normal precipitation years bases on regression with nearby long term weather stations in Collbran and Glenwood Springs, Colorado. Measured peak discharges in 2005, an average precipitation year, did not exceed 0.09 m^3/s (3 ft^3/s). These measurements corroborate past observations in project file memos of considerable overland flow during snowmelt prior to project implementation versus little evidence of overland flow today.

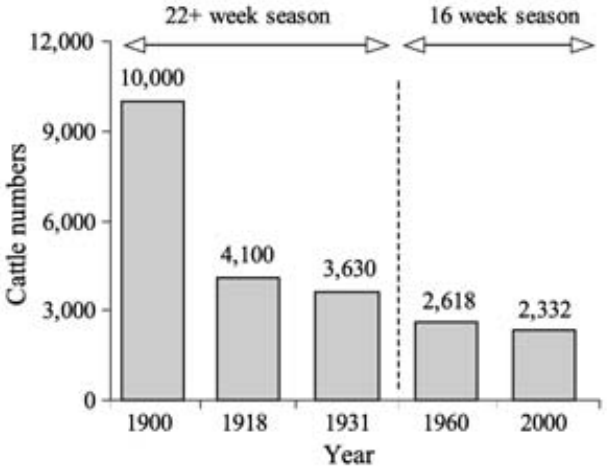
Grazing History

The Alkali Creek watershed is a small part of the 182-km^2 West Divide cattle allotment. The south aspects of the project area also serve as winter range for elk (*Cervus elaphus nelsoni*) and mule deer (*Odocoileus hemionus hemionus*).

Cattle grazing likely began in the watershed commensurate with the settlement along the Colorado River and its tributaries in the late 1800s. Local ranchers estimate that as many as 10,000 head of cattle grazed the present allotment boundaries in the early 1900s. Figure 1 shows the change in cattle numbers within the West Divide allotment over time. A notable feature of Figure 1 is the reduction in the grazing season from 22 weeks to 16 weeks that occurred in the mid 1950s. This reduction occurred in the early part of the season, which kept the cattle off the soils soon after snowmelt when moisture content was more likely to be optimum for detrimental soil compaction.

As early as 1916 there are written accounts in the allotment files from the range conservationist discussing the poor condition of the watershed. This led to decreasing stock numbers through the 1940s. In the late 1940s, a range conservationist named Carl Henderson began documenting the range conditions in the Alkali watershed. There are numerous summaries and field reports in the allotment file that chronicle "excessive overland flow from depleted range." His recommendation was to cease grazing in Alkali Creek altogether. The proposal at the time was a 31 percent reduction in cattle numbers, which he described as "too little, too late." Figures 2, 3, and 4 show the conditions that Carl Henderson saw on the ground. The soil pedestal supporting the large boulder in Figure 2 illustrates the significant loss of topsoil (and therefore water storage) in the area prior to 1957.

Figure 1. Bar graph of cattle numbers on the West Divide allotment. Data from the White River National Forest grazing allotment file records and from Heede (1977).



The series of photos in Figure 5 depicts the type of changes that occurred on the landscape between 1915 and present. There are anecdotal accounts of being able to cross the gullies shown with on horseback or in a wagon in 1915 (note the line and dots for reference). Between 1915 and 1949 considerable gully incision occurred. The gully widened and stabilized with less bare ground visible by 2004.

Project Development

The gully network, along with the efforts of Carl Henderson to elevate the issue of range condition to the District Ranger, led to the development of the Alkali Creek

Figure 2. Soil pedestal supporting large boulder in 1957 photo. Note camera at the pedestal base for scale. Photo by P. Hauk.

Figure 3. Gully development through former cattle watering location at Mud Springs in 1949. Gully depth is approximately 5 meters. Photo by C. Henderson.

Figure 4. Main gully in 1947 near the downstream end of the eventual project area. Photo by C. Henderson.

Soil and Water Project. The project had a scope larger than active gully control, and included the following:

1947-48 – Construction of stock ponds to distribute cattle away from streams.

1951 – Seeding of 49 ha of disturbed ground with grasses.

1952 – Contour trenching on selected hill slopes to enhance water infiltration.

1953 – Seeding of 53 ha of disturbed ground with grasses.

1958 – Perimeter fencing to exclude cattle from a 356-ha area in Alkali Creek.

1959 – Boy Scouts plant 500 New Mexican locust trees (*Robinia neomexicana*), all of which died.

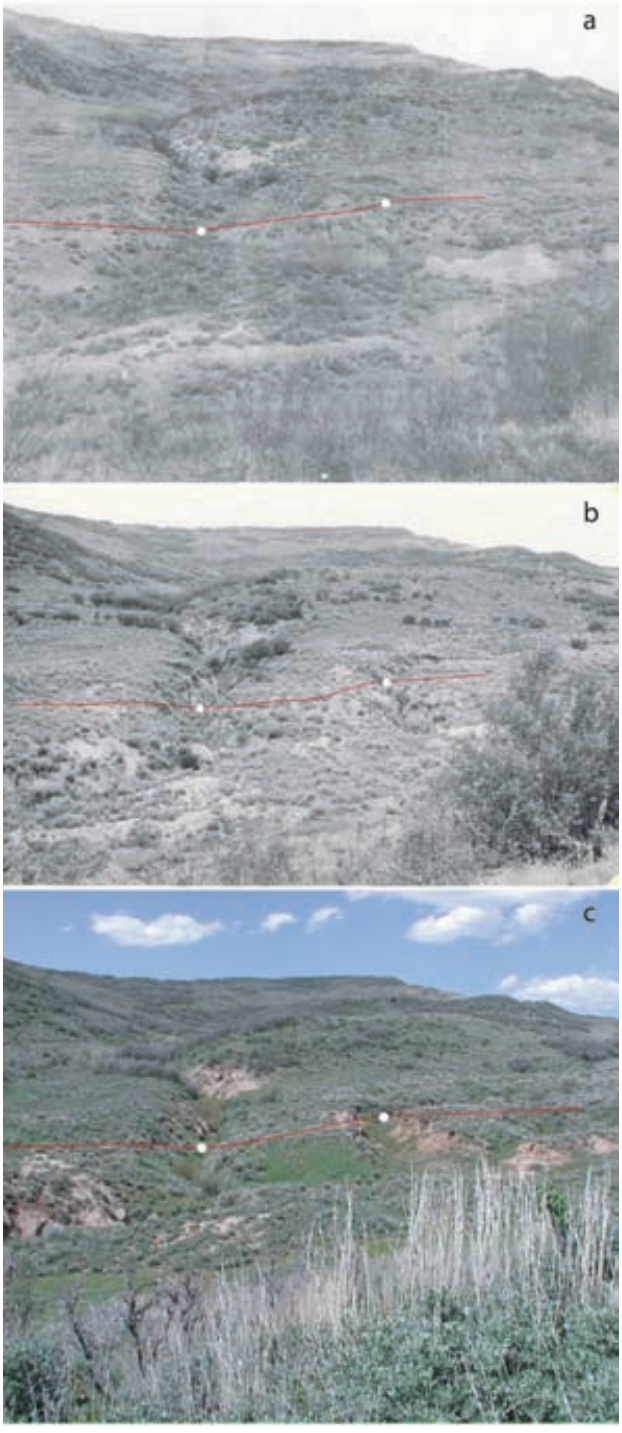
1960 – Cooperative agreement between the White River National Forest, the Rocky Mountain Regional Office (FS Region 2), and the Rocky Mountain Forest and Range Experiment Station for an experimental watershed/gully restoration project in the fenced area of Alkali Creek.

1961-1964 – Gully treatments installed.

Burchard Heede was the principal investigator from the Range and Experiment Station in Fort Collins, Colorado. He designed the gully restoration project, prepared the construction plans, and evaluated the results. The White River National Forest provided the labor and equipment needed to accomplish the survey work and project implementation. The Rocky Mountain Regional Office, Division of Watershed Management, provided funding for the project.

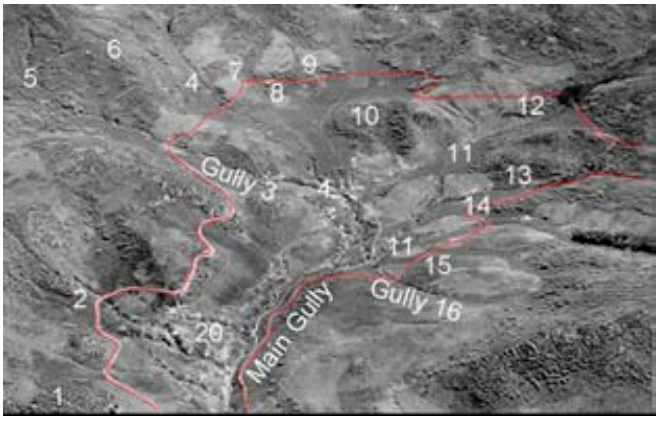
Initial survey and design work began soon after the agreement was in place and the first gully control structures were installed in 1961. A road was constructed in 1962

Figure 5. (a) Gully No. 4 as photographed from control point CP-39 in 1915. Note that it can still be crossed by wagon or on horseback (see horizontal line and dots for location). File photograph. (b) By 1949 the gully had deepened considerably, with very steep side walls. Photo by P. Hauk. (c) By 2004, the gully had stabilized and the side walls had flattened and become more vegetated. Photo by M. Weinhold.



to provide equipment access to the gullies higher in the basin. Figure 6 shows the location of the access road and the numbered gullies proposed for treatment. Project implementation was largely complete in 1963, with maintenance occurring throughout 1964.

Figure 6. Oblique view of the Alkali Creek project area. The red line shows the alignment of the access road. The numbers identify gullies proposed for treatment. File photograph.



Treatments included an assortment of check dams, headcut treatments, and vegetation-lined waterways. The type and number of structures are shown in Table 1. A variety of treatment types with different unit costs was intentionally used because cost effectiveness was a key component of the project evaluation program.

Table 1. Gully treatment types employed at Alkali Creek, Colorado.

Structure Type	Number Used	See Figure No.
Precast concrete check dam	1	12
Loose rock check dam	56	7, 13
Gabion check dam	7	7
Single fence rock check dam	12	8
Double fence rock check dam	40	9, 11
Headcut control structure	15	
Vegetation-lined waterway	4	10, 14

Gabion and loose rock check dams (Figure 7) are essentially the same type of structure, except that the former is wrapped in a wire fence mesh for added stability. Single fence check dams, shown in Figure 8, used steel fence posts and wire fence to support the rock fill on the downstream side to reduce the amount of rock required for construction. Similarly, double fence rock check dams (Figure 9) had post and wire fences on the upstream and downstream faces of the structure, with a 60-cm-thick layer of rock between. Headcut armoring consisted of

Figure 7. Typical loose rock check dam, in this case wrapped in wire mesh for added stability. Photo by B. Heede.

Figure 8. Typical single fence check dam. Photo by B. Heede.

placing a layer of rock over the flattened headcut with a loose rock check dam immediately downstream.

Four gullies were converted to vegetation-lined waterways. While this method had been successfully employed in flat farmland across the country, this was a new approach to gully restoration on mountain slopes. The existing gullies were filled and a new, wider sinuous channel was built. Increased sinuosity extended the length of the waterway and consequently reduced the gradient. The combination of a lower gradient and shallow, wide cross section decreased the erosive energy of the water so that a thick layer of vegetation would prevent gully development. The sequence of construction is shown in Figure 10.

Results and Discussion

The photo pairs in Figures 11 through 14 clearly show the recovery that occurred in the Alkali Creek watershed over the last four decades. In each case, the initial photo was taken soon after project implementation in the early

Figure 9. Typical double fence check dam. Photo by B. Heede.

1960s and the second photo was repeated in 2004. An effort was made to reoccupy the same photo point and provide a person in the same location for scale.

A striking result of this project was that none of the 131 gully control structures failed permanently. This high rate of structure stability was unique for the 1960s when check dam failure was the order of the day. On the other hand, nearly half of these check dams required some sort of maintenance between 1961 and 1964. This maintenance was primarily targeted at filling pore spaces in the rock structures created by poorly graded, large rock that did not meet design specifications. No maintenance has occurred since 1964.

There are several reasons for the high success rate of the structures built in Alkali Creek. Perhaps the most important was vegetation management. This primarily occurred through grazing management with the construction of the perimeter fence around the project area in 1958. This not only allowed the vegetation to recover, but it allowed soil properties to recover as well. These two parameters, increased vegetation and increased infiltration, would ultimately reduce the amount of overland flow, the original driving force for gully formation and enlargement. The perimeter fence is still maintained today.

A second reason for success was that detailed structural and hydraulic designs were developed for each gully control structure. Careful attention was given to design flows, structure dimensions, keying structures into the gully sidewalls, and overflow scour protection. Burchard Heede was a hydraulic engineer and he approached the work of gully control very quantitatively. This is clear in his summary publications on Alkali Creek (Heede 1977) and gully control in general (Heede 1976) where literally all aspects of design and evaluation are captured in formulae. For example, he provides a formula for calculating everything from the notch depth in a spillway to the

Figure 10. (a) Vegetation lined waterway construction sequence. Original gully configuration. (b) Shaping the new waterway after filling and compacting the old gully. (c) Completed waterway after establishment of vegetation. Note that the new flow line is offset from the original gully location. Photos by B. Heede.

Figure 11. (a) Double fence check dam at the base of the main gully (structure M0) during peak snowmelt runoff in the spring of 1964. Photo by B. Heede. (b) The same double fence check dam during the fall of 2004. Photo by M. Weinhold.

number of fence posts needed to construct a double fence check dam.

A third reason that no structures failed is that, in retrospect, the project area was over-treated. Approximately 44 percent of all check dams did not see enough flow in the first 12 years to have measurable sediment deposits. Only 27 percent of the check dams filled entirely, and these were primarily located along the main gully. This over-treatment was related to a gully's position in the watershed: nearly two-thirds of second order streams collected no sediment. As such, confining check dams to third- and fourth-order streams would have reduced project costs by 30 percent (Heede 1977). Even gullies that were not directly treated saw some benefit due to the establishment of base-level control provided by treatments at the confluence with larger, more active gullies.

Another result of the Alkali project, which had been observed in other gully restoration projects, was that ephemeral flow in the lower reaches of the main channel became perennial seven years after treatment. This was likely due to the water storage provided behind the

Figure 12. (a) Precast concrete check dam at the base of the main gully during spring runoff in 1964. Photo by B. Heede. (b) The same structure during the early summer of 2004. Photo by C. Hirsch. Note that the right half of the structure is covered by willows.

Figure 13. (a) Rock check dam on the main gully (structure M5) during spring runoff of 1964. Photo by B. Heede. (b) Same rock check dam in the fall of 2004. Photo by M. Weinhold.

sediment-filled check dams along the length of the main gully.

The vegetation-lined waterways were not immediately stable, due to their dependence on a robust layer of vegetation prior to exposure to overland flow. In some cases, burlap strips were buried perpendicular to the thalweg of the waterways to slow the flow during the first few runoff seasons and prevent rill formation (see Figure 14a). The burlap rotted away after several years. Fertilization was also necessary at all waterway sites due to a lack of phosphorus in the disturbed soils. Fertilizer was reapplied to all four vegetation-lined waterways in spring 2005 and minor headcuts were filled with small rock.

The Legacy of Burchard Heede and Alkali Creek

Gully control has been an ongoing process in the United States since the late 1700s. Burchard Heede created his legacy in that field by bringing gully control to the mountains and to the Forest Service. Even though gully control had been occurring on national forests in the southeast prior to Burchard Heede, he made substantial gains in quantifying the science of gully control and making that research and design guidance available to users in the Forest Service and beyond. He was an advocate for treating gullies as a system, with special attention paid to gully formation processes.

The printed legacy of the Burchard Heede's Alkali Creek experiment is extensive. Publications began rolling off the press within a year of project completion. Below is a partial list of the project related publications; complete references are contained in the bibliography.

- 1964. A pavement breaker attachment to drive steel fenceposts.
- 1965. Multipurpose prefabricated concrete check dam.
- 1966. Design, construction and cost of rock check dams.

Figure 14. (a) Vegetation-lined waterway No.16 in early 1960s with burlap strips in place to disperse flow. Photo by B. Heede. (b) The same waterway in the early summer of 2004. Photo by C. Hirsch.

- 1967. Fusion of discontinuous gullies: A case study.
- 1968. Conversion of gullies to vegetation-lined waterways on mountain slopes.
- 1970. Morphology of gullies in the Colorado Rocky Mountains.
- 1971. Characteristics and processes of soil piping in gullies.
- 1974. Stages of development of gullies in western United States of America.
- 1975. Submerged burlap strips aided rehabilitation of disturbed semi-arid sites in Colorado and New Mexico.
- 1976. Gully development and control: The status of our knowledge.
- 1977. A case study of a watershed rehabilitation project: Alkali Creek, Colorado.

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Heede, BH. 1975. Submerged burlap strips aided rehabilitation of disturbed semi-arid sites in Colorado and New Mexico. Res. Note RM-302. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station. 8 p.

Heede, BH. 1976. Gully development and control: the status of our knowledge. Res. Pap. RM-169. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station. 42 p.

Heede, BH. 1977. A case study of a watershed rehabilitation project: Alkali Creek Colorado. Res. Pap. RM-189. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station. 18 p.

The Once and Future Streams: Re-creating Bailey and Karnowsky Creeks, Central Oregon Coast Range, USA

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The Bailey Creek Project reconstructed over one mile of meandering stream channel in a low-gradient valley on the central Oregon Coast. The original channel was moved, straightened and diked to accommodate agriculture over the last century. After it was straightened, the channel velocity increased, leading to incision and bank erosion, degrading water quality and fish habitat. The project's focus was restoring wetland, stream and floodplain functions to a stream that once provided excellent rearing habitat for coho salmon (*Oncorhynchus kisutch*). The new, meandering channel was built in 1999 and water was introduced in 2000. From 1999 through 2003, native trees and shrubs were planted and wood was added to the stream. Monitoring results document five times the number of juvenile coho in the project area compared to a control reach. Lessons learned from Bailey Creek were applied to Karnowsky Creek, a tidally influenced, Siuslaw River tributary with a channelization history similar to Bailey Creek. Over two miles of meandering main-stem channel were constructed in late summer 2002. In 2003, ditches were filled, water was turned into the new channel and over 130 large whole trees were placed in the new channel and floodplain by helicopter. A variety of native trees and shrubs have been planted on the valley floor. In 2004-2006, two tributaries with valley gradients of 3-5% are being restored by building new channels with step-pool morphology. Project monitoring consists of 22 channel cross-sections to track changes in the new channels' geometry, groundwater wells, photo points, low-elevation aerial photography, spawning surveys and juvenile fish snorkel counts.

Keywords: *coarse woody debris, coho salmon, channel geomorphology, fish habitat, riparian vegetation, stream reconstruction, stream restoration, wetlands*

All photos, maps and figures were taken/created by authors.

Introduction

The Siuslaw National Forest, Oregon, in collaboration with partners, has restored two low-gradient, channelized streams in the central Oregon Coast Range by constructing new, meandering streams to replace the existing ditches. Bailey Creek flows through Enchanted Valley into Mercer Lake, and then about five miles (8 km) out to the ocean just north of Florence, Oregon. Karnowsky Creek flows into the Siuslaw River estuary between the towns of Florence and Mapleton, Oregon, approximately nine river miles (14.5 km) from the ocean. Both streams flow through flat-bottomed valleys and share a similar homesteading history. The valley land was cleared for agriculture in the late 1800s, and in the early to mid-1900s the streams were channelized into ditches along the sides of these valleys to provide more pasture.

As a result of the channelization, sinuosity decreased, and stream gradients and water velocity increased. The stream downcut into the valley floor creating high, erosive banks. At Bailey Creek, sedimentation into Mercer Lake increased, creating a large delta into the lake. A repeated topographic survey of this delta from 1998-2000 showed that the delta grew over 3 meters laterally during this period. The Bailey Creek ditch was also attempting to re-create meanders in the ditch, which increased bank erosion and sediment production. At Karnowsky Creek, the larger tributary streams to the valley with gradients from 3-5% had also been channelized, and these tributaries had severely downcut three meters or more to match the main valley ditch incision.

Furniss, M.J., Clifton, C.F., Ronnenberg, K.L., eds., 2007. *Advancing the fundamental sciences: proceedings of the forest service national earth sciences conference, San Diego, CA, 18-22 October 2004*. PNW-GTR-689. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station.

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In general, the restoration of these two streams involved a process that used reference data, local flow equations, stream classification, dimensionless ratios, and cross-checking using Manning's equation. It must be stressed that this process is iterative and not linear. Many of the steps loop back or occur simultaneously due to the complex interactions of stream processes that are being recreated. When one variable changes, so do all the others. The thought process weaves all the factors together at once as opposed to following a cookbook recipe.

For both Bailey and Karnowsky Creeks, questions to be answered included the following: What type of stream should be built to fit the valley type and landscape? What should the dimensions of the new channel be, including the width, depth, cross-sectional area, gradient, sinuosity and pool depth and length? In general, the steps in the design processes for both Bailey and Karnowsky Creeks are as follows :

1. Find a relatively undisturbed stream with similar characteristics to serve as a guide for the new channel design and measure its parameters.
2. Determine the bankfull discharge of the new channel.
3. Determine the cross-sectional area for the new channel, which determines the capacity of the stream to carry its flow and maintain the channel's dimensions.
4. Determine the new channel's slope and sinuosity, which may vary downstream through the valley. Slope is the main parameter influencing a stream's energy, which in turn determines the sediment transport capacity and potential for erosion.
5. Refer to Rosgen's (1996) stream channel classification system to see if the values chosen for the new channel fall within the range of variability for the chosen channel type. This step serves as a useful reality check.
6. Determine the minimum, maximum and average radii of curvature for the meanders in the new channel. The radius of curvature influences shear stresses on banks, and will partly determine the layout of the new channel.
7. Lay out the design on a base map, and then on the ground. An accurate survey is essential for this step. Test the design, checking the sinuosity, gradient, shear stresses, and capacity of the channel to carry the predicted bankfull flows. Manning's equation, among others, is useful for this step. The layout may have to be modified several times before a satisfactory design is finished.

Bailey Creek Restoration

Enchanted Valley was acquired by the USDA Forest Service in 1991, and planning began on the Bailey Creek restoration project in 1995. Goals of the project included: improving rearing habitat for coho salmon (*Oncorhynchus kisutch*), a threatened species on the Oregon Coast; reconnecting the channel with its floodplain; restoring riparian vegetation; and reducing sedimentation into Mercer Lake, which was a major concern for homeowners along the lakeshore. Public concerns about the project included reduction of elk (*Cervus elapus roosevelti*) forage in the valley, skepticism of the project's purpose and need, and possible increased sedimentation into Mercer Lake caused by constructing a new channel. Six public working group meetings held in 1997 were aimed at working through these concerns with the public, and a compromise was reached where only the lower half of the cleared and channelized valley would be rehabilitated while the upper valley would be maintained for elk forage.

Methodology

The first step in the planning process was gathering data on existing conditions, and comparing Bailey Creek to a similar stream that had not been cleared and channelized. We enlisted a professional Forest Service surveyor to create a topographic map of the valley floor with a one-foot (0.3-m) contour interval, and we used this topographic map as our base map. Other data collected included several cross-sections of the existing ditch, pebble counts at the cross-section locations, a longitudinal profile of the ditch, and cross-sections and pebble counts of Bailey Creek upstream of the channelized section. For reference on pre-channelized conditions, we had a 1955 aerial photo. Although channelization had already occurred, the original stream channel was still visible in the pasture of the upper valley. We used this photo to determine the historic sinuosity and meander geometry. We also measured cross-sections on Leitel Creek, which flows into Tahkenich Lake, another coastal lake south of Florence, Oregon. Although Leitel Creek is surrounded by early seral industrial forestland, the valley bottom has not been cleared for agriculture and the stream has not been straightened. Given that this valley has a similar geomorphology and setting to Enchanted Valley, Leitel Creek served as a reference stream for our design.

Determining the bankfull or "design" flow was the most challenging aspect of data collection, and we used several sources of information. A master's thesis by Giese (1996) correlated flow measurements to 16 years of rainfall records for Bailey Creek. This flow information was

used along with discharge measured in the field during winter flow events, and with data from nearby gauged watersheds. Where reed canarygrass (*Phalaris arundinacea*) overhung straightened ditches at Bailey Creek, there were no discernable bankfull indicators, which greatly hampered determination of bankfull discharge in the ditch.

Once parameters of sinuosity, channel gradient, cross-sectional area, and design discharge were obtained, they were fit together into an appropriate channel geometry. Similar to our observed reference stream, Leitel Creek, the desired future condition of the new channel was one that floods frequently during the winter to re-establish seasonal wetland characteristics, but maintains a stable cross section that would not be prone to heavy bank erosion. A decision had to be made whether the new channel would be a Rosgen (1996) "C" (wide, shallow channel) or "E" channel type (deep, narrow channel). Based on the low gradient of the valley, the geomorphic setting (an old lake bed), and the cross-sections from Leitel Creek, a Rosgen "E" channel type was chosen.

To make sure that the stream frequently overtopped its banks during winter flows, riffle cross sections of the upper 1,341 meters (4,400 feet) of channel were designed 30% smaller than the existing ditch. Also, knowing that Mercer Lake backs up into the lower third of the project area every winter, the bottom 335 meters (1,100 feet) of channel was undersized by an additional 50% to facilitate inundation and sediment drop out in the floodplain. Pools and riffles were not built in the "pilot" channel at the lower end. See Tables 1-3 for the measurements of the pre-project ditch, the new design channel and the pilot channel.

The next step was translating the design parameters to a map view of the new channel. Using the newly surveyed topographic map of the valley floor as a base map, a piece of string was cut to the scale representing the length of the new channel and then taped to the upper and lower end of the project area on the map. The string was laid out so that the channel followed the low spots of the valley, and the meander length and radius of curvature averaged about 74 m (240 feet) and 16 m (52 feet), respectively. This step took several trials. Once satisfied with the layout, the "string" map was digitized onto an electronic map using a geographic information system. Points were added that represented stakes to survey on the ground. A surveyor then translated the staking points to coordinates based on the bench marks put into the original topographic survey. With these coordinates input into the total station survey equipment, the surveyor moved personnel into the stake locations by trial shots until the proper coordinates were located and center-line channel stakes were pounded in. When it was discovered that the new channel would cut through some high ground, resulting in banks that would be higher than the rooting depth of the grasses and sedges, that portion of the channel was redesigned and moved into

Table 1. Enchanted Valley specifications.

Basin size	11.4 km^2 (4.4 mi^2)
Bankfull flow	5.1-6.8 m^3/s (180-240 ft^3/s)
Average high flow	Approx. 2.3-2.5 m^3/s (80-90 ft^3/s)
Average winter base flow	Approx. 0.7 m^3/s (25 ft^3/s)
Low summer flow	Approx. 0.03 m^3/s (1 ft^3/s)
Valley slope	0.0034
Valley length	954 m (3100 ft)
Stream bank substrate	60% silt/clay, 40% sand

Table 2. Bailey Creek measurements. (based on cross-sections above channelized section)*

Parameter	Historic Channel	Ditch	Design Channel (1,340 m)	Pilot Channel (335 m)
Sinuosity	1.66	1.1	1.8	1.8
Gradient	0.0022	0.0032	0.0019	0.0019
Bankfull width	8.5-12 m (28.5-40 ft)*	4-4.5 m (13-15 ft)	6.4 m (21 ft)	3.0 m (10 ft)
Belt width	68-85 m (220-275 ft)	Not applicable	46-77 m (150-250 ft)	46-77 m (150-250 ft)
Meander length	average 77 m (250 ft)	Not applicable	average 73 m (239 ft)	average 73 m (239 ft)
Radius of curvature	average 25 m (82 ft) range 12-43 m (40-140 ft)	Not applicable	average 16 m (52 ft)	average 16 m (52 ft)
W/D ratio	No information	lower valley, 2-3 above channelized, 25	7.0	3.3
Riffle cross-sectional area	No information	8.4 m^2 (90 ft^2)	6.3 m^2 (60 ft^2)	2.8 m^2 (30 ft^2)

Table 3. Bailey Creek new channel design specifications, Enchanted Valley Stream Restoration.

Design flow	2.8 m^3/s (100 ft^3/s)	Channel cross-section area	5.6 m^2 (60 ft^2)
Flood frequency	12-20 days per year	Bankfull width	6.5 m (21 ft)
Design velocity	0.3-0.4 m^3/s (1.0-1.3 ft^3/s)	Bankfull depth	0.9 m (3 ft) in riffles, 1.5 m (5 ft) in pools
Channel length	1,684 m (5,474 ft)	Width/depth ratio	7
Rosgen type	E	Meander wave length	74 m (239 ft)
Sinuosity	1.8	Radius of curvature	16 m (52 ft) (2.5 x channel width)
Slope	0.0019 (overall)	Pool/riffle spacing	32-45 m (105-147 ft)

Figure 1: Low-elevation aerial photograph of the new Bailey Creek channel before connection to stream flow. September 2000.

the lower spots, being careful to maintain the calculated length and gradient of the new channel.

For the 1,341 meters of upper channel (design channel), a pool-riffle morphology was designed for the stream bottom, with the pools occupying approximately half of the stream length on the outside of meander bends. The entire new channel was excavated in late summer 1999, taking about a month to construct with an excavator and 18-yard dump truck (Figure 1). We used a laser level to check the gradient during the construction of the entire 1,676-meter-long channel. The outside bends of meanders were revegetated with willow (*Salix* spp.) stakes in early spring of 2000, and the new channel was connected to water in the October 2000. Also in 2000, the abandoned ditch was intermittently plugged with fill material that had been stockpiled during channel construction, leaving ponds in the unfilled areas. Since then, wood has been added to the channel, tributary channels from the valley side slopes have been connected to the main channel, and elderberry (*Sambucus racemosa*), red alder (*Alnus rubra*), Sitka spruce (*Picea sitchensis*), western redcedar (*Thuja plicata*), and several other native species have been planted in the riparian zone along the new channel.

Monitoring

Twenty-four permanently monumented cross-sections are surveyed and photographed each year to track channel morphology and vegetative changes. Low-elevation aerial photographs are flown semi-annually. Additionally, vegetation transects, spawning surveys and juvenile fish surveys are conducted yearly, and water quality surveys are done either yearly or concurrent with large storms.

Results and Lessons Learned

During the first two winters after connection, the stream overflowed its banks during peak flows, but not to the extent hoped for in the design channel section. Wood placed directly into pool cross sections in 2002 has significantly improved floodplain inundation in the design channel section. Ongoing bank erosion from the ditched channel above the project area inputs such high sediment loads during winter flows that point bars and mid-channel bars are being formed in the new channel. The channel is deepening in some places, and aggrading in others, but even as the shape of the bed adjusts, the overall cross sectional area remains fairly stable. After five years of tracking geomorphic changes in cross sections, the net overall change in cross-sectional area for the entire project reach is an estimated 0.02 m^2, well within measurement error (2004 Enchanted Valley Monitoring Report [USDA 2004]). See Figures 2-4 for changes to the constructed channel over time.

One area of concern is the connection between the old, downcut channel that was eight feet (2.4 m) below the valley floor and the new channel that is only three to four feet (0.9 to 1.2 m) deep. It was assumed that sediment would drop out upstream of the diversion point as water

Figure 2: New Bailey Creek channel at photo point 7, in (a) 1999, and (b) 2004.

Figure 3: Over bank winter flow in Bailey Creek interacting with added large wood in channel, winter 2003.

Figure 4: Willows and conifers planted along the bank of the new Bailey Creek channel, 2003.

slowed to enter the new channel at a lower gradient, and the old ditch would aggrade. Instead, a tail cut began to develop downstream of the diversion point, as the channel's longitudinal profile came into equilibrium between the two elevations (See Figure 5 for a cross sectional comparison). This situation is being monitored, but it may be necessary to remedy this cutting by adding larger substrate to the channel at the diversion point to smooth out the longitudinal profile and armor the channel bed. The existing stream bed at the old channel junction and in the rest of the constructed channel is silt loam.

Spawning numbers have been strengthening between 2000 and 2004, averaging 124 fish per kilometer per year compared to an average of 44 fish per kilometer per year during the four-year period before that (1996-1999). From 2002 to 2003 alone, there was an increase of 50 fish per kilometer. The 2003 spawning adults were the first juveniles reared in the project area that went to the ocean in the spring of 2001. The assumption is that juveniles of this year's class took advantage of both good rearing conditions in the new channel and good ocean conditions to produce the 2003 spawning numbers. Looking at other spawning counts in the surrounding area, Bailey Creek was one of the few areas that had an increase in 2003.

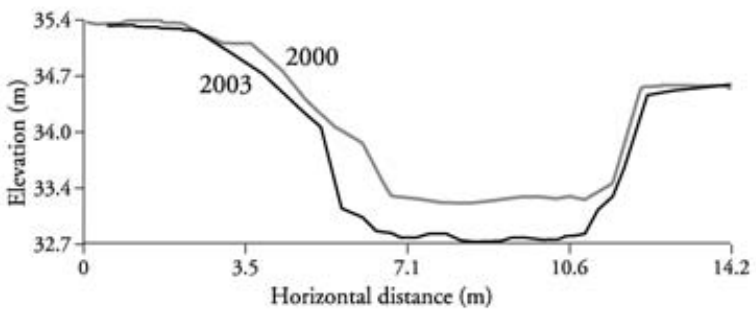

Figure 5: Permanent cross-section #24 in new Bailey Creek channel just below diversion from the old ditch to new channel. Between 2000 and 2003, the new channel down cut into silt loam bed material approximately one-third of a meter.

The new channel increased overall length by one-third, and the square meter pool volume doubled. Control data taken in the ditched channel above the project indicates that from 2001-2003, there were 1.5-2.0 times the number of juvenile coho compared to the two previous years sampled. At the same time, there was roughly a ten-fold increase in numbers of juvenile coho in the project area in 2001-2003. On a per-square-meter basis for 2003, the control estimate was 0.5 coho/m^2 while the project area estimate was 1.1 coho/m^2.

Although heavily browsed by elk, willows and planted vegetation are making progress in the riparian area of the design channel. Predictably, riparian vegetation in the pilot channel area has not done well due to the absolute dominance of reed canary grass in the lower valley that excludes all other species of plants, shrubs and trees. In the future, attempts may be made to establish willow in the pilot channel by using long willow stakes up to three inches in diameter pushed deep into the valley floor.

The Forest Service, Oregon Watershed Enhancement Board and the Oregon Department of State Lands spent $250,000 for the on-the-ground construction of 1.8 km (1.1 miles) of new meandering channel. The Forest Service spent another $250,000 on planning, design, implementation and monitoring through 2003 for an estimated total cost of $500,000.

Karnowsky Creek

The Karnowsky Creek watershed was acquired by the Forest Service in 1992. From the start, partnerships with the local Siuslaw Watershed Council and Soil and Water Conservation District were developed to assist in the restoration of the watershed. This collaboration resulted in the hiring of a student intern team to develop a whole-watershed restoration plan for the Karnowsky Creek watershed during the summer of 2001. The student team researched the history of the area, the potential for fish and wildlife habitat and plant communities, and wrote a well-researched and illustrated restoration proposal. Using this proposal, the partnership applied for funds from the Oregon Watershed Enhancement Board and the National Forest Foundation to implement the plan.

The goals of the Karnowsky Creek restoration project are similar to those in Bailey Creek: increase the amount and quality of coho salmon rearing habitat, reconnect the channel with its floodplain, and restore riparian vegetation. In addition, a network of groundwater monitoring wells is being measured on a monthly basis to see if replacing a downcut ditch with a meandering stream successfully raises the water table. Unlike Bailey Creek, there is less concern about downstream sediment deposition, which allowed a higher degree of freedom in the design from permitting agencies.

Methodology

As with Bailey Creek, the first step was producing a topographic map of the main valley and tributary valley floors with a contour interval of one foot (0.3 m) (Figure 6). Other data collected in the Karnowsky Creek watershed included several channel cross sections on the main ditch and tributary ditches, and discharge measurements taken during winter flow events. Part of the historic channel was still visible on a 1953 aerial photo, although much of that evidence of the historic channel had since been obliterated due to 70 years of agricultural use. Where the old channel was visible, it was used as a template for the new channel. Hoffman Creek was used as a reference stream, given that it is a nearby tributary of similar size and geomorphic setting that also drains into the lower Siuslaw River. Cross sections, pool dimensions, meander radius of curvature, pool/riffle ratio and reach gradient were measured throughout lower Hoffman Creek.

Unlike the pre-project ditch in Bailey Creek, there was more certainty that the main stem ditch in Karnowsky Creek had come into equilibrium with bankfull flows, and the size of the ditch would be a more accurate guide to the size of the new channel than using a flow equation. Bankfull discharge was calculated for the existing ditch by comparing results from a regional equation for small watersheds developed at Oregon State Univeristy (Adams et al. 1986), regional U.S. Geological Survey equations, and Manning's equation. As with Bailey Creek, a channel that overtops its banks frequently was the desired future condition, therefore, the new channel's cross-sectional area was designed 33% smaller than the ditch. It was assumed that the channel could more easily adjust to increase its cross-sectional area if it was undersized, than to decrease its cross-sectional area if it had been oversized.

Desired width/depth ratio, slope, and sinuosity of the new channel also had to be determined. The width/depth ratio is important, given that it is a major control on shear stresses on the banks and velocities within the channel. To determine whether the stream should be a Rosgen "C" (width/depth ratio > 12) or an "E" channel (width/depth ratio < 12) (Rosgen 1996), we used the width/depth ratio from Hoffman Creek (9.5), and referred to Rosgen's (1996) classification system to make our choice. We ran several width/depth combinations through Manning's equation and shear stress equations to compare the existing ditch's estimated discharge and shear stress with that calculated for the new channel. We decided on a width/depth ratio of 9.3; in other words, a relatively narrow channel. The

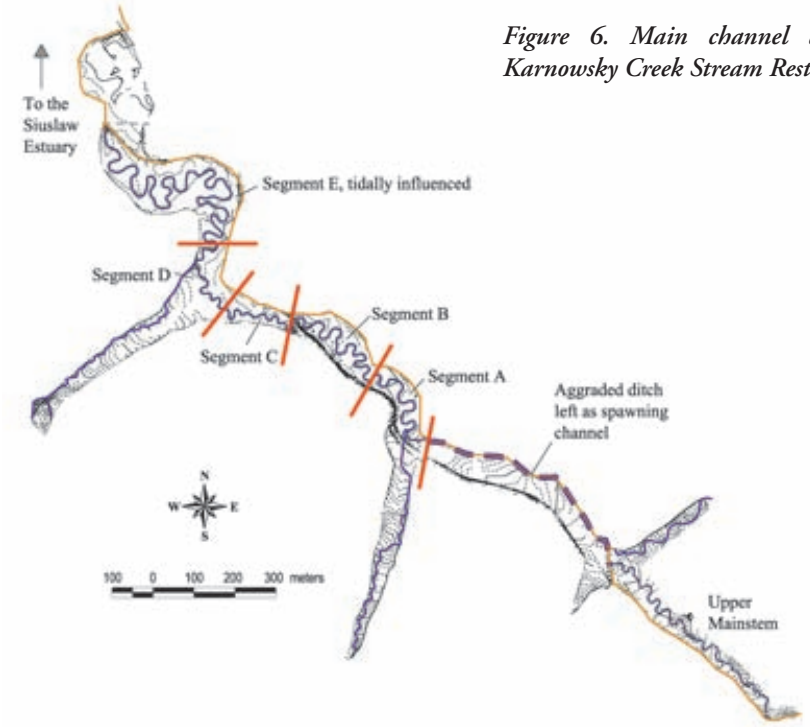

Figure 6. Main channel design segments, Karnowsky Creek Stream Restoration.

rationale was that the vegetation and root strength present in the valley will support the higher shear stresses and velocities found in an "E" channel, and a narrower, deeper channel would result in less direct solar heating in the stream in summer. Unlike the design for Bailey Creek, more variation in the size and shape of the meanders was included in the design for Karnowsky Creek (Williams 1986). Table 4 shows the new channel's dimensions and Table 5 shows the results of analysis with Manning's equation.

Slope and sinuosity are directly related. The upper part of the valley is slightly steeper, while the lower, tidally influenced part of the valley has a very low gradient. To fit the valley, the gradient of the newly designed stream gradually decreases from 0.39% at the homestead site to 0.11% in the tidally influenced zone. Sinuosity also increases down valley, from 1.9 to 2.8. In the tidally influenced zone, where frequent winter flooding occurs, we wanted to create as much fish habitat as possible. Therefore, two meanders were designed with narrow necks,

Table 4. New Karnowsky Creek channel dimensions by segments shown in Figure 6.

Channel Segment	Width	Riffle Depth	W/D Ratio	Cross-sectional Area	Gradient	Sinuosity	New channel length
A	4.3 m (14 ft)	0.46 m (1.5 ft)	9.3	5.6 m^3 (21 ft^3)	0.0039	1.9	393 m (1,278 ft)
B	4.3 m (14 ft)	0.46 m (1.5 ft)	9.3	5.6 m^3 (21 ft^3)	0.0028	2.2	546 m (1,773 ft)
C	4.3 m (14 ft)	0.46 m (1.5 ft)	9.3	5.6 m^3 (21 ft^3)	0.0038	1.6	356 m (1,157 ft)
D	4.3 m (14 ft)	0.77m (2.5 ft)	5.6	10.8 m^3 (35 ft^3)	0.0020	1.6	226 m (733 ft)
E	4.3 m (14 ft)	0.77m (2.5 ft)	5.6	10.8 m^3 (35 ft^3)	0.0011	2.8	1,356 m (4,406 ft)

Table 5: Testing the design parameters for the new Karnowsky Creek channel with Manning's equation.*

Channel Segment	Hydraulic Radius ("R")	Slope	Discharge "Q", m^3/s (ft^3/s)	Velocity "V", m/s (ft/s)	Calculated Ditch Bankfull Discharge m^3/s (ft^3/s)	Percentage of Bankfull Flow New Channel Will Carry
A	1.016	0.0039	14.93 (49)	0.72 (2.35)	26.51 (87)	56
B	1.016	0.0028	12.80 (42)	0.61 (1.99)	26.51 (87)	48
C	1.016	0.0028	17.37 (57)	0.50 (1.65)	26.51 (87)	66
D	0.983	0.0013	16.15 (53)	0.33 (1.07)	31.38 (103)	51
E	0.983	0.0011	13.10 (43)	0.37 (1.22)	31.38 (103)	42

**Manning's Equation: $Q = 1.486/n * AR^{2/3}S^{1/2}$, $V = 1.486/n * R^{2/3}S^{½}$*
n=roughness coefficient, 0.04 for Karnowsky Creek; A = cross-sectional area; R = hydraulic radius; S = slope

giving the stream an opportunity to cut off meanders and develop oxbows in the floodplain over the next several decades to a century. The loss of stream length would have a negligible effect on overall gradient and sinuosity.

Once the slope and sinuosity were established, the new channel was laid out on the base map and translated to the ground using the same methods developed in the Bailey Creek restoration. The new channel was fitted to the low points in the valley as much as possible. Developing the plan view involved several iterations. Points on the new channel's centerline were translated into survey coordinates, and the new channel's location was staked on the ground with the help of a professional surveyor (Figure 6). The centerline was fine-tuned and changes were resurveyed.

After we obtained the final survey data for the channel location and existing ground elevations, we entered it into a spreadsheet and calculated the expected bank heights in the new channel, assuming a constant stream gradient through a reach. The upstream and downstream locations for pools and riffles were added to aid channel excavation on the ground. As in Bailey Creek's new channel, all of the gradient change is taken up in riffles, and the upstream and downstream ends of pools are at the same elevation in the designed pool/riffle sequence.

Constructing the new mainstem channel took place in the late summer of 2002 (Figure 7). In the lower part of the valley, where wet soil conditions persist throughout the year, the excavated material was piled in mounds on the valley floor. This eliminated the need for dump trucks to haul the material, and the soil compaction that would have resulted. These mounds also provide topography in the floodplain that could be planted with spruce and cedar, allowing some elevation advantage over reed canary grass in the tidal zone.

During the first winter after construction, willow stakes were planted in the banks, and the floodplain was planted with trees and shrubs. Water was not flowing in the main channel, which gave the willows a chance to root and become established. During the second summer (2003), ditches were strategically plugged in several locations, and water was diverted into the new channel. Lessons learned in Bailey Creek were applied here. At the point of diversion, the new channel gradually slopes up from the old ditch's bed elevation, about a 0.6 m difference in elevation. Large logs were buried at grade in the new channel just downstream of the connection to prevent downcutting. In the fall of 2003, 130 large, whole trees were added to the new channel and floodplain by helicopter to create habitat and cover for fish (Figures 8 and 9).

Work during the summers of 2003 and 2004 included recreating step-pool channels in both the upper mainstem valley and three tributaries to the main valley (Figure 6).

Figure 7. Channel construction in lower Karnowsky Creek with a walking backhoe, summer 2002. Fill material taken from the constructed channel was shaped into floodplain hummocks that would later be planted with native trees and shrubs.

Figure 8. The new Karnowsky Creek channel with large wood added, winter 2003. New conifer seedlings are planted along the bank and protected by plastic tubing.

Figure 9: Lower Karnowsky Creek at high flow in new channel with added wood, spring 2004.

These intermittent channels flow through 3-5% valley gradients, and buried wood and boulders to serve as grade control are critical to channel reconstruction here. These channels were also seeded with gravels of the appropriate size for the slope and channel form of constructed riffles. Filling in of the extremely incised ditches on the valley margins was much more labor intensive than ditch filling in the lower valley. This required more haul by dump truck of borrowed fill material and layer placement of this fill in ditches to prevent robbing of the much needed water table in these side valleys and the upper mainstem. Work done in these intermittent channels will be ongoing through 2006.

Monitoring

As with Bailey Creek, annual monitoring includes low-elevation aerial photographs, 22 permanently-monumented cross sections, photo points, fall spawning surveys, and summer juvenile fish population monitoring. In addition, a network of 36 groundwater wells, set up before the project began, are being measured monthly to track changes in groundwater levels.

Results and Lessons Learned

Although the new Karnowsky Creek channel is too young to have significant monitoring results, we are already seeing abundant coho smolts and fry in the new channel. The channel functioned well through the first winter, with frequent floodplain inundation, particularly in the tidally influenced area (Figure 9). The willows and other riparian vegetation are growing very well, especially on constructed hummocks near the main channel. Point bars are already being deposited on the inside of meander bends in the lower channel, developing a natural channel morphology. Little, if any, bank erosion is evident. Some additional lessons learned include the following:

1. A strong collaborative partnership makes a large-scale restoration much stronger. Bailey Creek was primarily a Forest Service endeavor while Karnowsky Creek has many strong partners, and the second has far exceeded the success of the first.

2. Size the channel cross section based on both flow and bankfull cross section measurements if available. Accurate flow prediction is difficult in the Oregon Coast Range.

3. Variation and complexity of meander geometry is better. In nature, radius of curvature can vary from one to seven times bankfull width (Williams 1986). Much more variation was designed into Karnowsky's new channel than Bailey's, with better results.

4. Incorporating hummocks in the floodplain from construction fill can save on haul cost, limit soil compaction and provide needed elevation so native plants can out-compete exotics.

5. Armor abrupt elevation changes where water flows. Use natural materials and check elevations with a laser level to assure that neither head cutting nor downstream cutting will occur in high flow.

6. Contracts that pay equipment by the hour should be favored over lump sum construction contracts. In our case, we incurred a third of the cost using hourly contracts on the Karnowsky project. The added flexibility to make changes is also key to successful implementation.

The Forest Service, Oregon Watershed Enhancement Board and the National Forest Foundation spent $435,000 on channel construction, native vegetation recovery and helicopter wood placement on over 4.8 km (3 miles) of new meandering stream channel. When the project is completed, the Forest Service and partners will have spent an additional $165,000 on planning, design, monitoring and implementation of the design for an estimated total cost of $600,000.

Conclusions

The restoration of meandering channels at Bailey and Karnowsky Creeks has created more productive fish habitat, and appears to be on track to meet the other goals of restoring wetland habitat and reducing overall sediment production. Projects like these require an intensive data-gathering and planning effort by an interdisciplinary team of hydrologists, geomorphologists, fisheries biologists, and surveyors, and benefit from review by other technical experts.

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Advancing the Fundamental Sciences

Proceedings of the Forest Service National Earth Sciences Conference, San Diego, CA, 18-22 October 2004

Volume 2

Michael J. Furniss,
Catherine F. Clifton, and
Kathryn L. Ronnenberg,
Editors

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Middle right–Kayakers on the Cossatot River, Ouachita Mountains, Arkansas, just outside the Ouachita National Forest. Photo by A.C. Haralson, Arkansas Department of Parks & Tourism, Little Rock, Arkansas.

Bottom right–Pawnee Buttes, Pawnee National Grassland, northeastern Colorado. Photo by Terra L. Mascarenas.

Title page: Powder River, Wallowa-Whitman National Forest, northeast Oregon. Photo by Bruce McCammon.

Preface

Bruce McCammon and Bonnie Ilhardt

It is a great pleasure for us to present the proceedings of the Advancing Fundamental Sciences conference held in San Diego, California, in October 2004. This conference was attended by nearly 450 Forest Service earth scientists representing hydrology, soil science, geology, and air. In addition to active members of the earth science professions, many retired scientists also attended and participated in the week's events. Even though it rained much of the week, attendees maintained a high level of enthusiasm and participated actively.

The week was filled with memorable, but transient, events. A variety of keynote speakers reminded us of our history, challenged us with new thoughts, and reaffirmed our responsibility for proper stewardship of the unique physical resources on Forest Service lands. Panel discussions allowed the pioneers of the physical science disciplines to be recognized for their careers and acknowledged for their contributions. Speakers took the opportunity to present new work and interact with their peers. Poster displays gave many people an opportunity to present their work and explain its importance. Everyone who attended will remember the three-part play "The Life and Times of Forrest Stump." The play presented a snapshot of a hypothetical physical scientist's career beginning when physical scientists were new to the agency and ending when he retired after a long and distinguished career. The skit struck close to home for many and left the crowd howling with laughter and asking for more. Conference critiques showed clearly that the variety of events during the week led to the success of the conference.

These proceedings are the durable product of the conference and come to you only as the result of hard work by authors, reviewers, and editors. These proceedings include 60 technical papers that have been through a series of peer and editorial reviews. Fifty-six people participated as reviewers of the technical papers. Each paper was improved through incorporation of two sets of peer-review comments. Our thanks go to each of the people who volunteered to be a reviewer. Special thanks go to Michael Furniss, Caty Clifton and Kathryn Ronnenberg for coordinating the reviews, providing a high level of editorial consistency, and for preparing this proceedings.

We hope that these proceedings will serve as a valuable reference for your work in the future.

Bruce McCammon
Retired, Pacific Northwest Region
Conference Chair

Bonnie Ilhardt
Eastern Region
Conference Co-chair

Editors' Note

Michael J. Furniss, Catherine F. Clifton, and Kathryn L. Ronnenberg

Most earth scientists like rain. We know it is the source of much we hold dear, sustaining the systems we study and love, necessary for flowers to grow and flourish and bloom. But… rain for a week? In San Diego? It was an unusual deluge that greeted us in southern California, but fitting. It accompanied an unprecedented gathering of more than 400 Forest Service earth scientists for a first-ever national conference. It was a landmark event. Good times, along with the precipitation, were in abundance. The weather lifted rather than dampened the mood as we ran through downpours, arriving soaked and excited for the next encounter.

Many attendees expressed surprise that "there are so many of us." We have a lot in common through our work, but until that week, we'd never seen so many soil scientists, geologists, hydrologists, and air specialists together in one place. There was a strong sense of a "community of practice": of shared goals, common experience and participation that reached across the Nation.

We were, perhaps, the largest such collection of public lands earth scientists on Earth. The conference was a celebration and expansion of our collective knowledge, experience, identity, history, and a glimpse of our future potential. We commend the conference organizers for this extraordinary, multidisciplinary conference, for their recognition that knowledge from one branch is unable to advance without knowledge from another, and that together we are a stronger, more sustainable community.

Two thousand four was also the year of the Forest Service Centennial celebration. The sense of history was in the air, as retirees mixed with newer hires. We took stock of the five or six decades that earth scientists have contributed to the Forest Service, the ways times have changed, and the many ways we have advanced the agency and the conservation of earth resources.

The conference program offered a broad diversity of plenary and themed sessions, workshops, and field trips, and received rave reviews throughout the week. The book you hold contains submitted technical papers from the themed sessions. These 60 peer-reviewed papers represent a wide spectrum of earth science investigation, experience, research, and innovation in the Forest Service. Take the time to read and enjoy them, but don't stop there. You are encouraged to give an author a call or email to discuss what you read and how it relates to your work. Load up the CD in the back and review the keynote talks. Check the intranet web site for more memories and resources.

Let this collection be a portal into the rich pool of expertise, engagement, and collaboration that is our community of practice. The bonds formed and strengthened in San Diego can help sustain us in the decades to come. Our community was in full bloom that week, but it exists between conferences. Just as flora (and maybe conferences) need rain, communities of practice need cultivation to flourish. We have many ways to connect across forests, regions, and stations, to inform and support each other. In so doing, each of us can help nurture our community of practice.

We encourage you to call or email someone from another region. Email someone you know but haven't seen since San Diego. Create and participate in informal events that connect people. Convene discussions on common challenges, both remote and in person. Share experiences, successes, and failures. We each have the ability to cultivate and sustain our community of practice. Everything works when we participate and contribute. There is no better time than now.

Advancing the Fundamental Sciences: Proceedings of the Forest Service National Earth Sciences Conference, San Diego, CA, 18-22 October 2004

Contents, Volume 1

Page

Preface i
Bruce McCammon and Bonnie Ilhardt

Editors' Note iii
Michael Furniss, Catherine Clifton, and Kathryn Ronnenberg

I. Concurrent Session Papers 1

Section 1. Applied Science and Technology
Part 1. Fire and Smoke 1

Erosion Risk Management Tool (ERMiT)–A Probability-Based Erosion Prediction Model 3
Peter R. Robichaud

Hillslope Erosion Rates in Areas With Volcanic Parent Materials and the Effects of Prescribed Fires in the Blue Mountains of Eastern Oregon and Washington, USA 7
Robin M. Harris, Catherine F. Clifton, and Steven M. Wondzell

Long-Term Ecological Changes With Postfire Emergency Seeding 20
Jeff Bruggink

NcNally Postfire Discharge and the Relationship of Sierra Nevada-Wide Flood Frequency Curves and Local Kern River Discharge Curves 27
Terry A. Kaplan-Henry

The Effects of Selected Postfire Emergency Rehabilitation Techniques on Small Watershed Sediment Yields in Southern California 36
Peter M. Wohlgemuth and Peter R. Robichaud

Detecting Smoke Plumes and Analyzing Smoke Impacts Using Remote Sensing and GIS for the McNalley Fire Incident 43
Ricardo Cisneros, Andrzej Bytnerowicz, Brad Quayle, and Trent Procter

Sierra Nevada Framework Smoke Monitoring: Testing Implementation Through a Pilot Program 50
Trent Procter

Air Quality and Prescribed Fire Management–Moving Toward a Solution Space 53
Tom Robison

Advances in Fire Convection Dynamics 60
Brian E. Potter, Joseph J. Charney, Warren E. Heilman, and Xindi Bian

Contents Page

Part 2. Watershed Management 67

Using Stream Channel Reference Data to Guide Land Management Decisions 69
Pete Bengeyfield

Sediment From a Small Ephemeral Gully in South Carolina 76
William F. Hansen and Dennis L. Law

Quantifying the Effects of Livestock Grazing on Suspended Sediment and Stream Morphology 85
Pete Bengeyfield

Using Multiple Fine-Sediment Size Classes to Evaluate the Condition of Trout Spawning Habitat 94
Pamela J. Edwards, Thomas C. Cain, and Charles J. Gagen

Water Quality Effects of Blue-Green Algal Blooms in Diamond Lake, Oregon 102
Mikeal Jones, Joseph Eilers, and Jacob Kann

Delineation of a Karst Watershed on Prince of Wales Island, Southeast Alaska 111
Katherine M. Prussian and J.F. Baichtal

An Examination of References for Ecosysems in a Watershed Context: Results of a Scientific Pulse in Redwood National and State Parks, California 118
Tom Lisle, Ken Cummins, and Mary Ann Madej

Part 3. Surface and Groundwater 131

Chronic Misapplication of the Relationship Between Magnitude and Frequency in Geomorphic Process as Illustrated in *Fluvial Processes in Geomorphology* by Leopold, Wolman, and Miller 133
Tim Sullivan and Walt Lucas

The Evolution of Channel Maintenance Science in the Forest Service 136
John Potyondy

Forest Service Channel Maintenance Flows in the Klamath Basin 145
Michael L. McNamara and Tim Sullivan

Keeping Our Streams Flowing: Tonto National Forest Groundwater Policy 157
Richard Martin and Grant Loomis

USDA Forest Service Policy on Managing Groundwater Resources 166
Stephen P. Glasser

Section 2. Experimental and Research Watersheds 171

The Forest Service Barometer Watershed Management Program, a Historic Viewpoint 173
Larry J. Schmidt and Byron Beattie

Contents Page

Development of Watershed Hydrologic Research at Santee Experimental Forest, Coastal South Carolina 180
Devendra Amatya and Carl Trettin

Understanding the Hydrologic Consequences of Timber Harvest and Roading: Four Decades of Streamflow and Sediment Results From the Caspar Creek Experimental Watersheds 191
Elizabeth Keppeler and Jack Lewis

Forest Road Erosion Research at the Coweeta Hydrologic Laboratory 197
Mark S. Riedel, Lloyd W. Swift, Jr., James M. Vose, and Barton D. Clinton

The Entiat Experimental Forest: A Unique Opportunity to Examine Hydrologic Response to Wildfire 205
Richard D. Woodsmith, Kellie B. Vache, Jeffrey J. McDonnell, Jan Seibert, and J. David Helvey

Discharge and Sediment Loads at the Kings River Experimental Watershed in the Southern Sierra Nevada of California. 217
Sean M. Eagan, Carolyn T. Hunsaker, Christopher R. Dolanc, Marie E. Lynch, and Chad R. Johnson

Section 3. Watershed Protection and Restoration
Part 1. Monitoring and Restoration 225

The Role of BMPs in 303(d)-Listed Waters: A New Alternative to TMDLs 227
Bruce Sims and Chris Knopp

Best Management Practices (BMP) Implementation Monitoring: Keys to Success and Pitfalls to Avoid 232
Julianne Thompson and Jenny Fryxell

A Regional Protocol for Monitoring Best Management Practices Implementation and Effectiveness on Timber Harvest Operations 237
Karen Sykes, Dave Welsch, Roger Ryder, and Tim Post

Monitoring Exposed! WARM: A Database Tool to Share and Query Watershed Resources Monitoring Information 244
Sherry Hazelhurst and Ken Heffner

Aquatic Restoration Through Hydropower Licensing, Bond Falls Project, Michigan
Mark A. Fedora 255

TRTR Funds–Successes in Watershed Restoration in the Eastern Region
Bonnie Ilhardt and Kristine Smith 261

Contents Page

The Alkali Creek Story: 40 Years of Gully Control 271
Mark Weinhold

The Once and Future Streams: Re-creating Bailey and Karnowsky Creeks, Central Oregon Coast Range, USA 279
Johan Hogervorst and Barbara Ellis-Sugai

Contents, Volume 2

Part 2. Roads 289

Lessons Learned From Management Response to Flood-Damaged Roads in the Western Washington Cascades 291
James Doyle and Gary Ketcheson

Erosion and Channel Adjustments Following Forest Road Decommissioning, Six Rivers National Forest 297
Carolyn Cook and Adam Dresser

Roads in the River: Encroachment, Implications, and Solutions 310
Bill Shelmerdine

Road Decommissioning Effectiveness Monitoring Techniques 318
Carolyn Napper

Section 4. Valuing the Earth Sciences
Part 1. Soil 329

Ten-Year Results From the North American Long-Term Soil Productivity Study in the Western Gulf Coastal Plain 331
D. Andrew Scott, John Novosad, and Gala Goldsmith

Soil Compaction Study of 20 Timber-Harvest Units on the Ouachita National Forest 341
Kenneth R. Luckow and James M. Guldin

Monitoring to Improve the Understanding of Herbicide Fate and Transport in the Southern Sierra Nevada, California 352
Jerome V. DeGraff , Brent Roath, and Earle Franks

Part 2. Geology 361

Jökulhlaup in the Wind River Mountains, Shoshone National Forest, Wyoming 363
Liz Oswald and Ellen Wohl

Contents Page

Reclamation, Remediation, and Hydrologic Monitoring of the Minnie Mine and Mill Site, Okanogan County, Washington 368
Rodney T. Lentz

The Role of Geology in Sediment Supply and Bedload Transport Patterns in Coarse-Grained Streams 383
Sandra E. Ryan

A River Runs Underneath It: Geological Control of Spring and Channel Systems and Management Implications, Cascade Range, Oregon 391
Anne Jefferson, Gordon E. Grant, and Sarah L. Lewis

Hubbard Glacier, Russell Fiord, and Situk River: A Landscape in Motion 401
Robert Gubernick and Steven Paustian

Part 3. Air 419

Using the Critical Load Concept to Protect Ecosystems from Acidification 421
Deborah Ulinski Potter and Cindy Mitchell Huber

The Potential Effects of Acid Deposition: What's a National Forest To Do? 428
Stephanie J. Connolly, Thomas C. Cain, Jeremy S. Vestal, and Pamela J. Edwards

Methylmercury Contamination: Impacts to Aquatic Systems and Terrestrial Species, and Insights for Abatement 438
Charles E. Sams

Part 4. Water 449

A Short History of Watershed Management in the Forest Service: 1897 to 2100 451
Stephen P. Glasser

The Marginal Economic Value of Streamflow From National Forests: Evidence From Western Water Markets 458
Thomas C. Brown

An Army of Watershed Specialists: Good Working Relationships Encourage Everyone to Value Watersheds 467
Scott Tangenberg

Section 5. Partnership and Collaboration 473

Forest Sustainability Criteria and Indicators: A Common Language for the 20 States Served by the Northeastern Area 475
Constance A. Carpenter and Sherri Wormstead

Contents Page

Beyond Boundaries: Resource Stewardship in the Skagit River Basin–Communities and National Forests in Partnership 478
Greta Movassaghi and Mary A. Carr

Ecological Management Decision-Support Model of the Applegate River Basin 507
Mike Mathews

Klamath Adjudication–Lesssons Learned 513
Holly R. McLean

The Coastal Initiative–Innovative Partnerships to Restore Watersheds 516
Karen Bennett

The Pathfinder Project: A Collaborative Effort to Provide for Instream Flow Management 522
John M. Almy and Gary Shellhorn

Cooperative Forest Watershed Management in Maryland: Watershed Restoration Across Land Ownerships 537
Anne Hairston-Strang

II. Poster Abstracts 543

Excavator Subsoiling Applications: Integration of Subsoiling With Grapple Piling and Road Obliteration 545
J. Archuleta and M. Karr

Application of Water and Sediment Models in Hydropower Relicensing 545
Margaret Beilharz

Detecting Water Yield Increase in a Downstream Direction 546
Gregory S. Bevenger

Land Type Associations of Weber County, Utah 546
Jeff Bruggink, DeVon Nelson

Forest Practice Changes in Response to Soil Protection Guidelines on the Umatilla National Forest 546
Craig R. Busskohl

Low-Water Crossings and Channel Functions: What Works and What Doesn't 546
Kim Clarkin, Suzan Hixson, Gordon Keller, Terry Warhol

Hemlock Dam Removal–The Issues and the Story So Far 547
Bengt Coffin

Contents Page

Protecting and Restoring Riparian Area Structure and Function Along Forest Highways and Low-Volume Roads 547
James E. Doyle and Roy Jemison

Movement of Sediment Associated With Lowered Reservoir Levels in the Rio La Venta Arm of the Presa Netzahualcoyotl, Chiapas, Mexico 547
Juan de la Fuente, Bonnie Allison, Saul Bezares, Sue Hilton, Tom Lisle, Alisha Miller, Brenda Olson, Rebecca Quinones, Jose Velasquez

Turbidity Threshold Sampling in Watershed Research 548
Rand Eads, Elizabeth Keppeler, Jack Lewis

Monitoring of Stream Channel Cross Sections on the Chequamegon-Nicolet NF 548
Sara Eckardt and Dale Higgins

The 1997 Flood in Northern California: Applications to Refining Landslide Hazard Assessments in the Klamath Mountains, North-Central California 548
Don Elder, Juan de la Fuente, Polly Haessig

Monitoring in the Upper South Platte Watershed, Colorado: Before and After Wildfire 549
Deborah Entwistle, Lee MacDonald, Kevin Bayer, Ken Kanaan, Jennifer Hall

Improving Project-Level Soil Interpretations With Geospatial Technologies 549
Don Fallon, Eric Winthers, Haans Fisk

A Simplified Nitrogen Deposition Collector: A Tool for Evaluating Ecological Impacts 549
Mark E. Fenn

Fishxing 3.0: Software and Learning Systems for Fish Passage Through Culverts 550
Michael Furniss, Susan Firor, Antonio Llanos, Kathleen Moynan, Michel Love, Jeff Guntle, and Robert Gubernick

Managing Low-Water Crossings on Roads 550
Leslie S. Gonyer

Abandoned Mine Inventory, Assessment, and Restoration: Case Studies on the Klamath National Forest, California 550
Polly A Haessig, Edward K Rose, Don Elder, and William Snavely

Applying Hydrology to Forest Management–Examples Over a Career 550
William F. Hansen

Guidance for Intermountain Region Hydrology Specialist Reports–Field Review Notes, Technical Assessments, and NEPA Specialists Reports 551
Ronnie-Sue Helzner and Sherry Hazelhurst

Contents Page

The Rebirth of a Stream–the Enchanted Valley Stream Restoration Project 551
Johan B. Hogervorst and Barbara Ellis-Sugai

Mapping Air and Natural Gas Resources–the Management Value of Integrating Disparate Information 551
Melody R. Holm, Jeff Sorkin, and Janice Wilson

The Effectiveness of Aerial Hydromulch on the Cedar Fire in Controlling Water Movement and Erosion 552
Ken Hubbert, Pete Wohlgemuth, and Pete Robichaud

Energy Development in the Eastern United States and Air Pollution Impacts on Aquatic and Terrestrial Resources 552
Cindy Huber, Chuck Sams, and Andrea Stacy

Using BARC for Fire Disturbance Analysis 552
Kevin Hyde

Lichen Air Quality Biomonitoring Partnership on the Salmon-Challis National Forest 553
Gary L. Jackson and Larry St. Clair

Restoration of Bluewater Creek Riparian Rangeland Meadow in the Zuni Mountains of Western New Mexico 553
Roy Jemison

Relationships Between Hydrology, Exotic Plants, and Woody Fuel Loads in the Middle Rio Grande of New Mexico 553
Roy Jemison

Beyond Statistics: Landscape Controls That Mask Apparent Effects of Harvest Activities on Soil Saturation 554
Adelaide Johnson, Kellie Vache, and Rick Edwards

Modern Stromatolites and Benthic Phototrophs in Ultra-Oligotrophic Waldo Lake, Oregon 554
Al Johnson

Low-Volume Roads Engineering Best Management Practices Field Guide 554
Gordon Keller and James Sherar

Lessons Learned Between BAER Assessment and Implementation on 2003 Southern California Fires 555
Allen King

Modeling the Role of Evapotranspiration in the Unsteady State of the Groundwater Regime in Watershed-Scale Projects 555
Tom Koler

Contents Page

Influence of Prescribed Fire on Fish and Streamwater Mercury Concentrations 555
Randy Kolka, Jason Butcher, and Trent Wickman

Influence of the Intensity of Silviculture on Soil Carbon 555
Randy Kolka, Rachel Tarpley, Marty Jurgenson, and Brian Palik

Application of a LIDAR-Generated Digital Elevation Model to Active Landslide and Geomorphic Process Mapping and Interpretation. 556
Benjamin R. Kozlowicz and Mark E. Smith

Native Plants and Fertilization Help to Improve Sites and Stabilize Gullies on the Sumter National Forest 556
Dennis L. Law and William F. Hansen

Coordinated Interagency Response to the Aspen Fire 556
Robert E. Lefevre, Salek Shafiqullah

Ecological Classification, Organic Layer, and Large-Scale Prescribed Fire Monitoring on the Superior National Forest 556
Barb Leuelling and Jeff Tepp

Effects of Forest Management in the Caspar Creek Experimental Watersheds 557
Jack Lewis, Elizabeth Keppeler, and Tom Lisle,

Restoration of Cherry Creek–Lessons From a Southwestern Stream 557
Grant Loomis and Tom Moody

Characteristics of Peak Flow Return Intervals for Small-Drainage-Area Watersheds of the Southern Cascades of Eastern Oregon: Implications for Culvert Sizing 557
Walt Lucas

Effects of Pine-Bluestem Restoration on Soil Quality on the Ouachita National Forest and Implications for Improved Air Quality and Watershed Condition 558
Ken Luckow and Hal Leichty

How to Lighten Your NEPA Workload 558
Tom Mainwaring and Carl Leland

Quantifying Measurement Error for Accurate Testing of Channel Cross-Sectional Change 558
Daniel A. Marion

Ecosystem Mapping and Soil Survey in the Western Upper Peninsula of Michigan 558
Sarah E. Mase

Geomorphic and Hydrologic Effects of High-Elevation Summer Storm Events 559
Alisha Miller, Tuli Tannaci, Juan de la Fuente, Abel Jasso, and Steve Bachmann

Contents Page

A Comparison of Northern California Sediment TMDLs 559
Alisha Miller and Juan de la Fuente

Stream Restoration at Road Crossings in Wisconsin 559
Jim Mineau and Dale Higgins

The 1997 Flooding in Two Northern California Klamath National Forest Streams: Geomorphic Effectiveness and Sediment and Large-Wood Budgets 560
Zackary J. Mondry

Drought, Storms, and Streamflow and Stream Temperature Monitoring on the Coconino and Prescott National Forests, Northern Arizona 560
Zackary Mondry

Evaluation of Habitat Variability, Channel Changes, and the Effectiveness of Restoration Projects in an Eastern Washington Stream 561
Mark Muir, Susan Bolton, Robert Wissmar, and Pete Bisson

Tools to Evaluate the Effect of ATVs on Soil Physical Properties 561
Carolyn Napper

Impacts of an Historical Wildfire on Hydrologic Processes: A Case Study in Arizona 561
Dan Neary

Regulatory Tools for Watershed Management 561
Karen Nelson

Spatial Data Analysis of Soils Within the Kisatchie National Forest Using Geographical Information Systems 562
John C. Novosad, Wayne H. Hudnall, and Jacqueline A. Prudente

Streamflow Analysis of the Little Popo Agie River Near Lander, Wyoming 562
Liz Oswald, Greg Bevenger, and Laurie Porth

Ground-Penetrating Radar and Seismic Refraction as Tools for Characterizing Aquifer Properties in Recently Active Glacial Moraine Settings, Tongass National Forest, Alaska 562
Noel S. Philip, Steven D. Sheriff, and Robert A. Gubernick

The Stream Systems Technology Center 562
John Potyondy

Monitoring Soil Erosion Following Wildfires in North-Central Washington State 563
Kenneth J. Radek

Climate Variability and Change in the Southern Appalachians 563
Mark S. Riedel

Contents Page

Estimating Impacts of Cattle Grazing on Stream Sediment Budgets 563
Mark S. Riedel, Kenneth N. Brooks, and Elon S. Verry

Gradient Analysis of Soil, Vegetation, and Climate on the Tonto National Forest 564
George T. Robertson and W.H. Moir

Rehabilitation of the Left Hand Canyon Dispersed Recreation Area 564
Theresa Stevens Savery

Long-Term Soil Productivity of Western Gulf Coast Loblolly Pine Stands 564
D. Andrew Scott, John Novosad, and Rodney Peters

The Dosewallips Washout: A Reach Analysis Case Study to Evaluate Road Management Solutions and Consistency With the Aquatic Conservation Strategy 565
Bill Shelmerdine and Dan Cenderelli

The Olympic National Forest Road Management Strategy–Aquatic Risk Assesment 565
Bill Shelmerdine, Robert Metzger, Scott Hagerty, and Robin Stoddard

Keeping Water on the Land Longer 565
Janice Staats

Forests on the Edge: Projecting Housing Development on Private Forests Across America's Watersheds 566
Susan Stein, Mark D. Nelson, Dave Theobald, Ronald E. McRoberts, and Mike Eley

Automated Water Quality Monitoring in the Clackamas River Watershed, Mount Hood National Forest 566
Ivars Steinblums

Soil Moisture Monitoring at SNOTEL Climate Stations on National Forest Lands in Oregon and Washington 566
Sheila Strachan

An Application of the Hillslope Erosion Model (HEM) to Determine Erosion Predictions and Interpretations for Terrestrial Ecosystem Survey (TES) 566
Steven Strenger, Steve Sebring, and Wayne A. Robbie

A Comparison and Evaluation of Stream Substrate Embeddedness Techniques 567
Traci L. Sylte

Dunham Creek Rehabilitation: Early-Day Riparian Harvest Gone Bad–the Consequences, the Remedy, and Highlight for Riparian Health Management First and Foremost 567
Traci L. Sylte

Contents Page

Analysis of Relationships of Stream Shading vs. Vegetation Density and Spectral Radiance 567
Bárbara Gutiérrez-Teira, Charles H. Luce, and David Nagel

Sediment Transport and Production From Two Small Watersheds in Central Idaho 568
Robert Thomas, John King, Robert Kenworthy, and Nick Gerhardt

Integrated Forest Plan Monitoring Program: Tongass National Forest Riparian and Aquatic Synthesis 568
Julianne Thompson and Emil Tucker

Real-Time Smoke Monitoring–Current Instrument Evaluation and Telemetry Systems 568
Andy Trent

Effects of Prescribed Fire on Mercury Concentrations in Water and Fish in the Larch Lake Watershed, Superior National Forest, Minnesota 569
Trent R. Wickman

State Water Quality Exceedence: Fecal Coliform and *E. coli* 569
Kirk Wolff

Development of ELTP Layer for the Hoosier National Forest, Southern Indiana 569
Andrey V. Zhalnin, George R. Parker, and Patrick C. Merchant

III. Author Index 571

IV. Conference Organizers and Producers 573

V. Manuscript Reviewers 575

VI. Contents of Multimedia CD-ROM 577

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See page 577 for a preview of the introductory screen.

I. Concurrent Session Papers

Section 3. Watershed Protection and Restoration

Part 2. Roads

Overleaf:
Decommissioned road on Montague Island, Prince William Sound, Chugach National Forest, Alaska. Photo from the USDA Forest Service.

Lessons Learned From Management Response to Flood-Damaged Roads in the Western Washington Cascades

James Doyle
Gary Ketcheson
Mt. Baker-Snoqualmie National Forest, Mountlake Terrace, Washington

In the Pacific Northwest, within the western Washington Cascade Range, floods are a dominant natural disturbance affecting forest ecosystems. Following flood events, a major management focus for the forests, Mt. Baker-Snoqualmie National Forest (USDA Forest Service Region Six) over the past 20 to 25 years has been to fix or repair flood-damage roads with the traditional "replace-in-kind" approach driven to a large extent by the limitations posed by the primary funding source (Federal Highways-Emergency Relief Federally-Owned [ERFO] Program). Over this time period, a pattern was detected by forest personnel (engineering and aquatic) that at many road failure sites, previous flood damage had occurred and the fix or repair had been unsuccessful in preventing future flood damage. Forest personnel began to identify a number of problems at these sites, including undersized road crossing structures, improper spacing, orientation, location, and number of drainage structures. Beginning in the late 1980s, forest engineers and aquatic specialists, after assessing the mechanism of failure at a number of these sites, began to develop road-stream crossing designs based on this knowledge. The resulting flood repair effort was a major departure from the traditional "replace-in-kind" approach. By the early 1990s some national forests in Region Six were broadening their road-flood repair efforts from a site by site basis to approaching the repair work with a view to the entire road system and within a watershed context. The Mt. Baker-Snoqualmie National Forest has developed and implemented a suite of successful road restoration treatments and techniques to address flood-damaged roads. Since 1990, the Forest has experienced four major flood events (1990, 1995/96, 1997, 2003). A vital component of documenting this management departure from the "replace-in-kind" approach to road flood damage repair has been the development of a database that contains records of flood-damaged road sites from 13 ERFO-qualifying flood events on the Mt Baker-Snoqualmie National Forest (1974-2003). This paper will highlight some interesting and revealing queries from this historical information.

Keywords: *floods, roads, restoration, ERFO, road-stream crossings*

Introduction

The Mt. Baker-Snoqualmie National Forest (Washington) covers 1.7 million acres (687,900 ha), stretching along the western Cascade Range from the Canadian border on the north to Mt. Rainier National Park on the south. The Cascade Range can be separated into two distinct geological regions, with the approximate division occurring at Interstate 90 (I-90) from Seattle east to Snoqualmie Pass. Much of the present configuration of the Cascades is the result of glacial activity that began about one million years ago. Continental glaciers are believed to have advanced into and withdrawn from the Puget Sound region at least four times during the Quaternary Period; the last glacier retreated about 10,000 years ago. The differences, north and south of I-90, in geology, topography, bedrock, and soils are important because the aquatic environment resources are influenced by the character of the geologic material. Glacial ice, a powerful agent of erosion, abraided and scoured the North Cascades topography at an accelerated pace. Valley floors were broadened and deepened and valley walls were over-steepened. Many predominant features of the landscape were caused by glacial activity: jagged peaks, cirque basins, lakes, and hanging valleys. The rugged topography resulting from glacial modification is most pronounced north of I-90. The soils of the forest are complex and varied. There are over 200 unique soil mapping units, based on soil type, geologic type, and topographic shape. There are differences in soils in the north half and south half of the forest (split by I-90), due to the differences in bedrock and the extent of glaciation and volcanism (USDA FS 1990).

Furniss, M.J., Clifton, C.F., Ronnenberg, K.L., eds., 2007. *Advancing the fundamental sciences: proceedings of the forest service national earth sciences conference, San Diego, CA, 18-22 October 2004*. PNW-GTR-689. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station.

Forty-one percent of the forest is designated as wilderness (eight Wilderness Areas). The diverse vegetation communities of the forest are a result of extremes in elevation, aspect, soil depth and climate. The forest contains three primary forest zones (western hemlock [*Tsuga heterophylla*], Pacific silver fir [*Abies amabilis*], and mountain hemlock [*Tsuga mertensiana*]). Thirty-six percent of the forest is designated as riparian area containing over 2,000 miles (3,200 km) of fish-bearing channels, (5,000 miles [8,000 km] of perennial, non-fish channels) and 13,000 acres (5,261 ha) of lakes. A diversity of aquatic species reside in these waterbodies; anadromous and resident salmonid fish species include: Chinook (*Oncorhynchus tshawytscha*), coho (*O. kisutch*), sockeye (*O. nerka*), pink (*O. gorbuscha*) and chum (*O. keta*) salmon, steelhead and rainbow trout (anadromous and resident *O. mykiss*, respectively), cutthroat (*O. clarkii clarkii*), brook (*Salvelinus fontinalis*) and bull trout (*S. confluentus*). Other fish species present include grayling (*Thymallus arcticus*), whitefish (*Prosopium williamsoni*), and sculpin (*Cottus* spp.) (USDA FS 1990).

The Mt. Baker-Snoqualmie is a designated urban national forest in the U.S., with about 7 million people residing in the forest's zone of influence. About 20 million people cross through the forest over a one year period with about half stopping to recreate a day or more on the forest (USDA FS 2000). Recreational sites include four ski area complexes, 1700 miles (2720 km) of trails, and 50 developed campgrounds. Summer recreation activities include camping, picnicking, hunting, fishing, hiking, mountain climbing, mountain biking, boating, swimming, canoeing, kayaking, white-water rafting, off-highway vehicle (OHV) use, auto touring, and berry picking. Winter recreation includes downhill and cross-country skiing, snow-shoeing, snowmobiling, and winter mountaineering.

Flood Disturbance

Winter storms in the Pacific Northwest (October-February) are of three general types. The first and most common is a low pressure system in the northern Pacific that draws moisture easterly across the Pacific and produces light to moderate rain with snow in the mountains above 4,000 feet (1,220 m). The second type is a low pressure system in Alaska that moves southeast over a high pressure ridge located along the California coast. This system draws cold air and moisture from the Gulf of Alaska across the Pacific Northwest and can deposit large amounts of snow as low as sea level, but mostly above 1,000 feet (305 m). The third type, varying in intensity, is known as a Pineapple Express. This is a low pressure system that draws warm moisture from the Pacific around the Hawaiian Islands, having torrential rain and wind, with freezing levels as high as 10,000 to 12,000 feet (3050 to 3660 m). When a cold Alaska system is followed by a Pineapple Express, major floods occur. Hillslope saturation occurs rapidly, with snowmelt caused by the warm wind and rain at mid-elevations. The high elevation snowpack densifies, but often does not contribute significant amounts of runoff (USDA FS 1992). Flooding occurs on both small and large channels and landslides are common. The effects of these rain-on-snow storms in the Western Cascades has been well documented (Copstead and Johansen 1998; Furniss et al. 1998).

Management Response: Traditional vs. Current

The traditional Mt. Baker-Snoqualmie National Forest response to flood damage was a rapid mobilization to assess damage and assist anyone stranded or imperiled by the flood. Complete damage assessment was made as soon as possible using a procedure involving the use of a Damage Situation Report (DSR). The DSR form was developed in partnership with the Federal Highway Administration [FHWA] 30 to 40 years ago to document and record site damage. These forms were and still are the basis for securing Emergency Relief Federally Owned (ERFO) funds to repair flood damaged sites. ERFO funding was basically limited to a "replace-in-kind" philosophy. All flood repair work and coordination was done exclusively by forest engineering personnel.

The current flood management approach still involves the rapid mobilization by forest personnel to assess damage and assist anyone stranded or imperiled by the flood. However, DSRs now include a supplemental sheet detailing the cause and initial result of failure. Discussions with FHWA personnel on the adequacy of fixing or repairing sites with ERFO's "replace-in-kind" occur, comparing documented new flood damage to forest roads history. The FHWA determines funding taking into account the needs of Endangered Species Act, Clean Water Act, and Forest Plan standards, and the potential for the site to fail again. The forest requests supplemental flood funding when ERFO funds aren't adequate. All this work is done in an interdisciplinary fashion with the aquatic program sharing lead responsibility with engineering.

Flood Damage to Roads

One of the highlights of this paper is documenting some of the initial information we are gleaning from our roads-flood damage database (Table 1). This database contains 935 records from 13 flood years (from 1974 to 2004)

Table 1. General history of flood damaged roads on the Mt. Baker-Snoqualmie National Forest from 1974 to 2003. The impact location "both" indicates that areas both north of and south of I-90 were affected by the event.

Flood Year	# of Floods	Flood Date	# of Sites	Impact Location
1974	1	13 January	72	Both
1977	3	25, 29 Nov.; 12 Dec.	61	South of I-90
1979	2	13-15 and 17-20 Dec.	57	North of I-90
1980	1	24-27 Dec.	74	Both
1982	3	5 Jan., 12 Dec., 10 Jan. 1983	90	Both
1984	2	4 Jan., 16 Nov.	41	Both
1989	1	11 Nov.	25	North of I-90
1990	2	9-10 and 22-24 Nov.	124	Both
1991	1	8 Jan.	97	South of I-90
1994-95	2	26 Dec. 1994, 14 Jan. 1995	7	North of I-90
1995-96	3	8 Nov., 28-30 Nov. 1995, 1-3 Jan. 1996	223	Both
1999	1	6 Jan.	14	North of I-90
2003	1	18-23 Oct.	50	North of I-90

on road sites that were flood damaged and subsequently fixed or repaired. More than one flood event occurred in some years (1977, 1979, 1982, 1984, 1990, 1994-95, and 1995-96). Six flood years resulted in damage throughout the entire forest (1974, 1980, 1982, 1984, 1990, and 1995-96). Most of the flood impacts have occurred north of I-90, in a geological zone containing the forest's most dissected landscape and most unstable soil types.

Flood return intervals are not available for all these flood events, but information exists to compare their relative severity. The post-1990 floods, especially the floods in 1990, 1994-95, 1995-96, and 2003, are the floods of record in many of the forest's river basins, most located in the geologic zone north of I-90. These four flood years caused road damage at 404 sites. The database includes ERFO DSR records and other non-ERFO funded flood repair records.

Flood damage to roads, as discussed in this paper, is separated into two general categories; damage to road fills, and damage to the road drainage system. Sidecast fills may sag or settle from consolidation, saturation, or both. Subsidence may open surface cracks that accept water rapidly, often resulting in failure of the fill material. On steep slopes, the failure may travel long distances. Poor ditch drainage and plugged culverts can also cause road prism or fill failures by saturating the sub-grade (Forman and Sperling 2003).

Road ditches need to be constructed and maintained to carry the expected flows. Cutslope ravel or slumping, hillslope creep, and vegetation reduces ditch capacity and efficiency. Where ditches do not function properly, roads will fail during a flood event. Proper ditchline function depends on proper sizing and spacing of ditch-relief culverts and cross-drain or channel crossing culverts. If the ditch relief culvert is inadequate or cross-drain culverts and stream crossings plug, roads will fail, releasing sediment into the channel in amounts that may exceed the transport capacity of most channels. Undersized culverts also do not allow passage of bedload sediment, resulting in upstream deposition. Many of these undersized culverts also are barriers for fish passage.

Many arterial roads in the Western Cascades (state highways and high-volume forest roads) are located along river corridors, encroaching upon or crossing floodplains and river terraces. Bridges are expensive, and are typically built to minimal lengths, often constricting the channel floodplain width. Where topography doesn't dictate otherwise, bridges are usually built with minimal freeboard above design flows. This doesn't allow for passage of large organic material, such as whole trees with the root ball attached (Forman and Sperling 2003).

Roads adjacent to rivers create persistent management challenges. Normal river channel and floodplain processes, such as channel migration, transport of sediment and large organic material, and the dissipation and storage of flood flows, are altered. The proximity of smaller channels and roads can also lead to the creation of new channels due to flood damage. When road crossings divert flood flows, new undesirable diversion channels often develop through the road prism (Havlick 2002).

Causes and Patterns of Failure - Structures

In characterizing road failures in the Cascades, we have documented the following observations. The most common failure is one involving a culvert. Most often the culvert inlet is partially or completely plugged with bedload and organic debris, forcing most of the flood water over the road. This may result in saturation and failure of a fill slope, or erosion and piping along a culvert, slicing through the entire road prism.

Culvert blockages can be the result of improper sizing, too small a culvert, spacing too far apart, improper alignment, culvert rusting resulting in physical collapse, or inadequate maintenance.

Bridge damage during floods is most often caused by the erosion or scour of the riprap protecting the abutments. Bank scour increases under a bridge that constricts the floodplain. If the span width is too narrow, or if the rip rap is not keyed into the streambed to the normal depth of scour, floods may remove the riprap. Over time, channel migration across the floodplain will result in bridge damage, including bridge approach loss, bridge abutment damage, and even loss of bridge decking.

The database reveals that 56 percent of the 935 sites involved culvert failures, 16 percent involved fill or cutslope failures, 11 percent were due to road and channel encroachments, 7 percent involved damaged to bridges, 5 percent were due to ditchline failure, and 5 percent to landslides on the road.

Causes and Patterns of Failure - Land Related

Road failures during floods can often be related to landform and land use patterns. Knowing what landforms have unstable slopes that are prone to debris avalanches can benefit road location and drainage design, maintenance, and repair approaches. Land uses that alter runoff and erosional processes should be accounted for in the road drainage design. Mt. Baker-Snoqualmie National Forest examples of these landforms are sensitive watersheds with a legacy of intensive timber harvesting and road building, such as Canyon, Deer, and Finney Creeks. Flood damage to road systems, especially repeated failures at the same sites, should be documented in forest-wide assessments such as road analysis (USDA FS 1999).

Flood Damaged Road Repair

Traditionally, repair of Forest Service roads that have been damaged by floods in the Pacific Northwest has been strongly influenced by the available funding sources. The kind and amount of funding has, until recently, dictated the kind and type of repair.

The best example of this has been funds allocated by the Federal Highway Administration under the Emergency Relief Federally Owned (ERFO) program. These federal emergency repair funds were typically allocated based on the principle, "replace-in-kind". The cost of the repair had to be equal to or less than the original cost. This approach has resulted in a history of repeated failures on many road systems and at individual road sites after one or more documented flood events.

For example, plugged or damaged culverts were either cleaned and repaired, or were replaced with the same size culvert at the same location following a flood event. These sites were often documented as failing again from subsequent flood events. Another example of a "replace-in-kind" project was loss or damage to road bridge approaches or abutments. In most cases, the fix was to replace the approach with the same type and amount of material as in the original construction, or to replace the bridge abutment or armoring with the same amount and type of material.

Road prism damage such as ditchline scour, cut-slope, fill slope or retaining wall failures were usually fixed or repaired using the original specifications. Damage from channel erosion or channel diversion into the road prism was usually addressed with the same design standards as in the original construction.

By the mid-1980s, after learning from six major flood events (1977-1984), the forest began to recognize that this "replace-in-kind" approach to repairing flood damaged roads was not effective forest management. A new approach was initiated.

After observing and documenting numerous road and channel site failures, we began developing new techniques and technologies for dealing with road and stream crossing structures, road prism construction, and road / channel encroachments. For example, we designed and installed low-water fords and sloped-concrete box culverts that could not only pass high water but also the bedload and organic debris typically mobilized and transported during flood events.

Beginning in the mid 1990s, bridge span widths were increased at existing bridge sites, spanning, at a minimum, the bankfull channel, and where warranted, the entire flood-prone channel width. Bridge replacement design called for abutments to be installed outside the active channel width. In addition, culverts were replaced by bridges at sites with a history of failure, or where they posed a barrier to fish passage.

Cross-drain structures were increased in number and relocated to better mimic the natural channel drainage network along flood-prone road segments. In addition, more detail was given to the inlet and outlet controls at many of these culverts (constructing inlet catch basins and trash racks; outlet grade control structures and energy dissipaters). In a few cases, road segments from 100 feet (30 m) to over 2 miles (3.2 km) were either realigned or relocated away from recurring channel encroachment locations.

By the mid 1990s, rock and log deflectors replaced the traditional riprap-constructed groins used to deflect channel encroachments on road embankments. Also

during this time, our focus regarding road flood damage prevention and action moved beyond the site concern to the road system and watershed scale. Guidance from planning processes such as watershed analysis and road analysis promoted an interdisciplinary approach to looking for solutions at the watershed scale. The focus is not just on treating the symptoms but attempting to address the causes of road flood damage, especially at chronic failure sites.

The most common type of repair done over this 30-year flood period was fixing or replacing culverts (Table 2). At many sites, both a primary repair and a secondary treatment were needed; for example, replacing a damaged culvert with a bigger culvert, and replacing the lost road fill. Repairing, or replacing culverts was by far the most frequently used treatment (554 sites). Fifty-three sites involved repairing or replacing bridges, and 256 sites involved primarily road prism treatment (fill, cutslope, fillslope, ditchline, etc.). Sixty sites primarily involved road re-alignment, re-location or decommissioning, and twelve sites involved installing channel rock or log deflectors to reduce the risk of further channel and road encroachment.

The amount of federal funds spent on repair of flood damaged roads on this national forest from 1974 to 2003 is pretty staggering. FHWA funds covered 96 percent of the cost. Over half of the total costs are due to the floods of record in 1990 and 1995-96. This table also shows that the cost to repair roads damaged by floods is increasing over time. In the 1970-1989 period, 420 sites were repaired with a total cost of $11.9 million, while during the 1990-1999 period, 465 sites were repaired costing $38.3 million (both values in 2003 dollars).

The database supports the forest's contention that road damage would have involved more sites and cost more in the 1990-1999 time period without the road restoration that began in the early 1990s. During the 1990-1999 flood period, chronic flood damage failure sites on roads in sensitive watersheds such as Canyon, Deer, and Finney Creek did not recur following major road restoration (decommissioning, stormproofing, upgrading) in these watersheds.

The total costs of forest flood repairs over the 1974-2004 timeframe were $53,336,750; pro-rating this total over the 30-year period gives an annual value of $1,777,892-more than the forest's annual road maintenance budget (about $1,000,000 per year) for the same period. If the forest had a higher annual road maintenance budget, some of this flood damage might have been avoided by conducting more road restoration.

Since 2000, the region has been receiving decreasing annual road restoration and maintenance budgets, hampering the forest's capacity to stormproof additional road segments and systems. Future floods will provide additional information as to the effectiveness of road restoration in treated watersheds as well as the results of little or no treatment in other watersheds.

The amount of road prism (fill, fillslope, cutslope) lost or eroded away by these floods is also staggering. Most of this material ended up in stream and river channels, and had impacts on fish habitats. The forest has not attempted to estimate the volume of this transport and deposition to the stream channel network.

Lessons Learned

The most basic lessons learned from an aquatics management viewpoint of management's response to flood damaged roads can be summed up in four statements:

1. ***Be involved early and stay engaged.*** Don't wait to be asked by engineering, offer assistance immediately and be active in all phases of project development and implementation.
2. ***Bring the big picture to the table.*** Look beyond the site for remedies and consider the whole road system and a watershed context. The traditional approach has been focused entirely at the site scale.

Table 2. Costs of repairing flood damaged roads on the Mt. Baker-Snoqualmie National Forest from 1974 to 2003 (cost figures adjusted to 2003 dollars).

Time Period	Fund Source	# of Projects	Repair Category	Amount ($)
1970-1979	FHWA-ERFO	190	Road prism, culverts	$10,561,546
1980-1989	FHWA-EFRO	221	Road prism, culverts	$946,451
1980-1989	CFS	9	Culverts, bridges	$380,845
Total		*420*		*$11,888,842*
1990-1999	FHWA-ERFO	411	Road prism, culverts	$33,252,382
1990-1999	WR-JITW	42	Road removal, culverts	$3,500,000
1990-1999	CFS	12	Culverts, bridges	$1,550,000
Total		*465*		*$38,302,382*
2000-2003	FHWA-ERFO	50	Prism,culverts, bridges	$6,695,526
Grand Total		***935***		***$53,336,750***

3. ***Become a forest resource historian.*** Document the history of previous failure and subsequent repair.

4. ***Advocate for fixes or repairs that look into the future.*** Promote higher structure design standards and longer design lifespans.

5. ***Be committed to data management.*** Communicate and document the management legacy for others to build on, and in doing so, inspire others.

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Erosion and Channel Adjustments Following Forest Road Decommissioning, Six Rivers National Forest

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Although watershed restoration through road decommissioning has become common in the last decade, few studies have attempted to investigate the success or failure of such projects. This study examines 117 km (73 miles) of decommissioned roads, including 262 stream crossings, on the Six Rivers National Forest, northwestern California, to quantify erosion and identify failure mechanisms and potential areas for improvement. Although most crossings had experienced some adjustment, erosion was generally minor. The average amount of erosion for stream crossings was 21 m^3 (28 yd^3), which represents 4.5% of the amount of fill excavated. Of this volume, 40% of the erosion was due to channel adjustment and 60% was due to bank failures. Erosion from the roadbed between crossings was very small and was observed only in areas of highly unstable geology. The amount of erosion appears well correlated with the timing and intensity of storm events. Large storm events occurring the first winter after decommissioning produced elevated erosion levels. After several dry winters, erosion was very minor, even from large storm events.

Keywords: *roads, decommissioning, obliteration, erosion*

Introduction

It has long been recognized that roads, particularly roads in steep, mountainous terrain, can have significant impacts on water quality and aquatic ecosystems by: accelerating erosion and sediment loading, altering channel morphology, and changing the runoff characteristics of watersheds (Furniss et al. 1991). Where forest roads are located in steep terrain, mass soil movement is a common mechanism of erosion and sediment delivery (Lyons and Beschta 1983). Also common are road-stream crossing failures that occur when culverts fail to pass wood, sediment or storm discharge. The plugging of culverts may result in the loss of the roadbed at the stream crossing or the diversion of the stream offsite, both of which may generate large erosional features and sedimentation of adjacent water bodies. Road cuts can also intercept groundwater and reroute subsurface water into streams. This increase in stream discharge may result in channel enlargement including downcutting and bank erosion.

On Six Rivers National Forest, northwestern California, roads are the leading source of management-related sediment inputs, predominantly associated with mass wasting features such as shallow debris slides and debris torrents. The majority of road-related erosion and sediment delivery are associated with large storm events that trigger culvert failures, stream diversions, and mass wasting such as debris slides and smaller slumps within the roadbed. With declining road maintenance funding, the risk of road failures and elevated sediment delivery is increasing, particularly in the event of large storms.

In an effort to reduce erosion and sediment delivery associated with forest roads, a road-decommissioning program was initiated in the early 1990s on Six Rivers National Forest. Over the past decade, the forest has decommissioned approximately 341 km (212 mi) of forest roads. Road decommissioning efforts target abandoned and low-use roads with high erosion and sedimentation risks. The focus of road decommissioning efforts has been on improving water quality and aquatic ecosystems through reducing sediment introduced to streams, and on reducing the risk of future sediment delivery from roads in the event of a large storm.

The primary road decommissioning treatments on the Six Rivers has been the removal of culverts and the associated fill in stream crossings, and recontouring the stream crossing to as close to the original channel morphology as possible or practical. Roads were not completely obliterated (i.e., fully recontoured) as is typically done in the Redwood National Park restoration program (Madej 2001), but rather were placed in a free-draining condition. Where areas of instability were evident, road fill between stream crossings was recontoured, but in areas where there were no signs of instability, the roadbed was

Furniss, M.J., Clifton, C.F., Ronnenberg, K.L., eds., 2007. *Advancing the fundamental sciences: proceedings of the forest service national earth sciences conference, San Diego, CA, 18-22 October 2004*. PNW-GTR-689. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station.

left in place. Generally speaking, the upper to mid slope location of the majority of forest roads on Six Rivers National Forest and the geology in many of the areas was such that leaving the majority of the road prism intact was seen as a low risk and a means to cost-effectively decommission more miles of road. In addition to culvert removal and occasional outsloping of the roadbed, installation of water bars or rolling dips was also employed to make the road free-draining. In some cases, the roadbed was ripped or sub-soiled, or trees were planted to speed up revegetation. In all cases, the ultimate objective of the road decommissioning treatment was to make the road free-draining, maintenance-free, and hydrologically benign relative to future erosion and sedimentation risk.

Because of the relatively new emphasis on road decommissioning in recent years on national forest lands and on private timber lands, little attention has yet been given to understanding the extent of erosion and sedimentation that occurs after a road has been decommissioned. There is a general recognition that there will be short-term effects associated with road decommissioning. These short-term effects are considered small given the long-term gain in reducing the larger sedimentation risk if more roads were to fail during large storm events. However, few studies have quantified the sediment lost due to post-decommissioning erosion and channel adjustments. A recent post-treatment decommissioning study was conducted in Redwood National Park (Madej 2001). Madej found that on stream crossing sites, post-treatment sedimentation was small and the majority of the post-treatment erosion and sedimentation were attributable to treated roadbeds. Regardless of treatment, post-project erosion and sedimentation were low when compared to untreated sites. For the period 1980 to 1997, an average of 50 m^3 (66 yd^3) of sediment delivery per stream crossing occurred (Madej 2001). Klein (2003) conducted a post-treatment erosion and turbidity monitoring study on decommissioned roads in the Mattole River watershed in northern California. Klein reported an average of 11 m^3 (15 yd^3) of sediment delivery associated with restored stream crossings. During the first winter after treatment, erosion and elevated turbidity within the restored stream crossings was common but the erosional responses diminished considerably over the winter sampling period. Dunkley et al. (2004) assessed the effectiveness of road deactivation ('decommissioning') techniques in reducing the incidence of landslide initiations but did not assess the volumes of erosion and sedimentation associated with landslides. On the Clearwater National Forest in Idaho, a study was conducted to assess the short-term total suspended-solid concentrations resulting from stream crossing obliteration (Brown 2002). The Clearwater study determined that turbidity and suspended sediments increased during stream crossing restoration and that total sedimentation could be reduced if sediment traps were installed. No analysis was conducted to determine how long the turbidity and suspended solids lasted after the restoration work ceased.

Project Objectives

In light of the extensive road decommissioning that had occurred over the past ten years on the Six Rivers National Forest and the high likelihood that more roads will continue to be decommissioned in the near future, assessing road decommissioning projects was identified as a critical step that would quantify the extent of post-treatment road decommissioning erosion and sedimentation, and improve future road decommissioning projects through incorporating lessons learned. The objectives of the post-treatment road decommissioning assessment were to:

1. Quantify the amount of fill removed and the amount, types and locations of post-project erosion. Assess the effectiveness of treatments in reducing sediment inputs
2. Identify successful or unsuccessful treatment techniques (e.g., ripping, leaving road prism intact, and so on)
3. Identify criteria that would facilitate predicting when future projects may need special treatments (e.g., stream power, slope gradient, slope position)
4. Identify any limiting factors contributing to less than fully successful road decommissioning

These objectives are aimed at assessing the relative risk of implementing road-decommissioning projects and quantifying the nature of the short-term post-treatment erosion risk. This information is particularly relevant given the extent of threatened and endangered anadromous fisheries within the Six Rivers National Forest and the potential for road decommissioning projects to result in adverse effects on these fisheries and water quality.

Project Area Description

Six Rivers National Forest is located in northern California within the Klamath Mountains and California Coast Ranges Geomorphic Provinces. The Klamath Mountains Province has been uplifted relatively rapidly and is deeply dissected, contributing to the ruggedness of the terrain. Both rugged and gentle terrain is found in the Coast Ranges, and drainage systems are generally smaller in area. Topography throughout the Forest is typically steep (slopes ranging from 30 to 80 percent), well dissected, and forested, although there are extensive areas of grassland in

the south and barren areas of ultramafic rock in the north. The large number of older, deep-seated landslides and younger, shallow landslides is due to rapid downcutting by streams through weak bedrock and overlying surficial materials in response to the rapid uplift, as well as the active tectonic environment. Over 90 percent of the high and extreme landslide hazard areas occur adjacent to stream channels on slopes steeper than 65 percent which typically occur in inner gorges of stream channels, recently active landslides, toe zones of deep-seated landslides, and fault zones of weakened bedrock. In general, roads located on slopes steeper than 50% have a greater risk of failure and sediment delivery (USDA 1999, Appendix 2). Roads located within these areas pose a higher risk of erosion and sedimentation during large storm events.

The geology of Six Rivers National Forest is complex and can be categorized in four groups: (1) sedimentary and metasedimentary rocks; (2) metaigneous [or metavolcanic] rocks; (3) ultramafic intrusive rocks; and (4) igneous rocks. The sediments and metasediments include graywacke, shale, schist, and chert of the Franciscan Complex, slate, phyllite and sandstone of the Galice Formation, and pre-Cretaceous metavolcaniclastic rocks of the Rattlesnake Creek and Hayfork Terranes. The metavolcanic rocks are mainly associated with the Galice and Rogue formations or part of the pre-Cretaceous terranes, or occur as isolated blocks in the Franciscan Complex. The ultramafic rocks are predominantly serpentinite, dunite and serpentinized peridotite. The igneous rocks range from diorite and quartz diorite to gabbro, and most occur as relatively small intrusive bodies or inclusions in mélange.

Six Rivers National Forest is characterized by a Mediterranean climate with cool, moist winters and warm dry summers. Precipitation is moderately heavy over most of the forest. It ranges from around 1,270 mm (50 inches) on the middle to southern portion of the forest and up to 3,048 mm (120 inches) on the more northerly portions of the forest. Roughly 90 percent of the total precipitation falls in the six-month period between November and April. Stream runoff is mainly from rainfall, and snowmelt makes up only a minor part of total runoff. The largest storm runoff is usually associated with rain-on-snow events. The relatively high rainfall in combination with steep terrain poses challenges for maintaining forest roads, particularly during large storm events.

To examine the effect of rainfall on decommissioned roads, monthly rainfall from each ranger district was analyzed. Information about individual storm intensities would be more relevant, but this data is not available. Instead, the highest monthly rainfall of the year was used to create an annual maximum series. Rainfall with a return period of 5 years or greater was used to designate that year as a "wet" year. Rainfall return periods were similar to flood discharge return periods for the few stream gages that exist nearby.

Since the decommissioning program began, three large storm events have occurred. Intensity varied from district to district (Figure 1), but most decommissioning sites have experienced at least an 18-year storm. The largest event was the "1997 New Year's Day Flood" which had a return period between 22 and 52 years (Figure 1). Such heavy rainfall should reveal decommissioned sites that are erosion prone or inadequately restored.

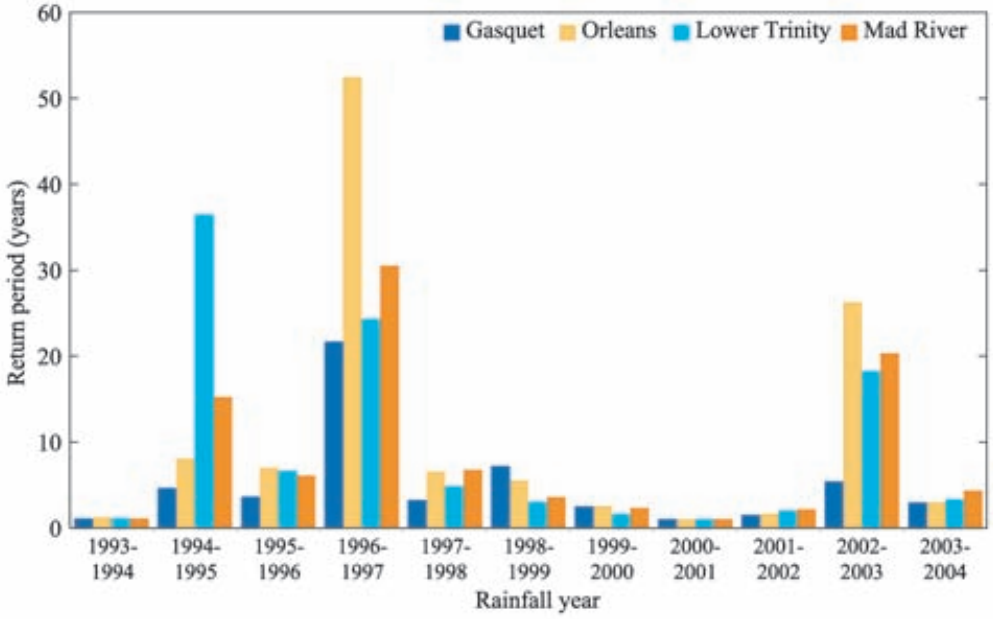


Figure 1: Recent monthly rainfall return periods for the Gasquet, Orleans, Lower Trinity, and Mad River Ranger Districts, coastal northern California ,from 1993 to 2004.

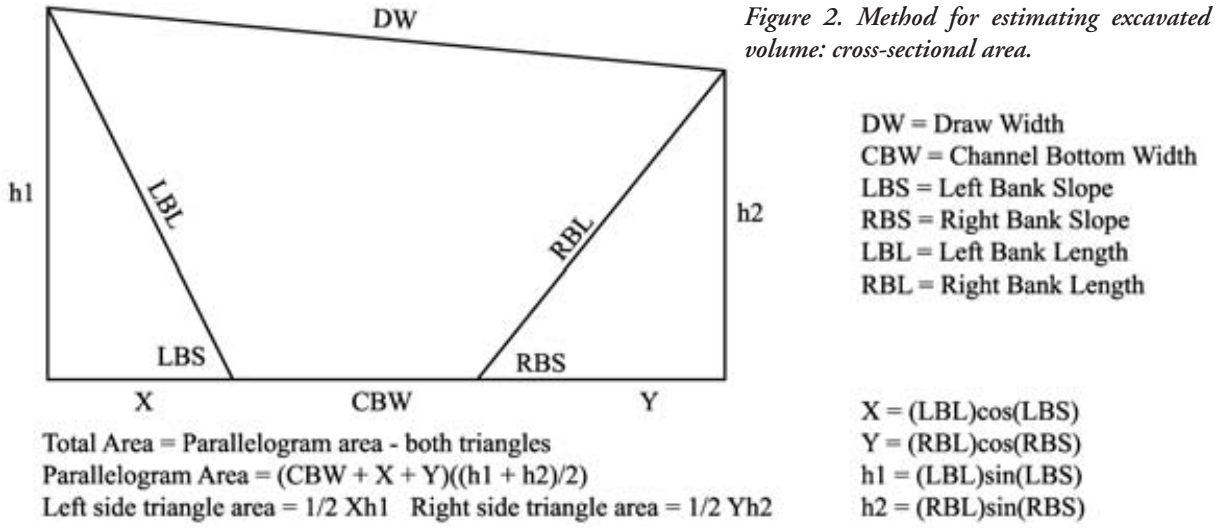


Figure 2. Method for estimating excavated volume: cross-sectional area.

Methods

A total of 117 km (73 mi) of previously decommissioned roads were assessed, or 34% of the total miles of decommissioned road (341 km or 212 mi of road decommissioned). Decommissioned roads were haphazardly selected based on age since treatment; however, attempts were made to get a cross section of different geologic terrains as well as a variety of stream crossing treatment sizes (i.e., large fill volumes versus small fill volumes). The intent of the post-treatment road decommissioning monitoring was to sample as many roads as possible that had weathered large storm events and thereby had treatments that were "tested" by winter storms. Eighty-eight percent of the sampled decommissioned roads had experienced at least three winters of post-treatment adjustment, including storm events with at least an 18-year recurrence interval.

Decommissioned roads were assessed to determine the effectiveness of the treatments at stream crossings as well as the roadbed between the stream crossings. Methods and questions assessed are discussed below.

Estimating Excavated Stream Crossing Fill Volume

The post-treatment road decommissioning monitoring protocol required that the amount of material excavated from stream crossings be measured along with the volume of any post-treatment erosional features. A simplified model of the excavated crossings was used to facilitate rapid measurement of fill volume (see Figure 2 and Figure 3). In using the model, two cross-sections were measured (using a tape and clinometer), along with channel length and slope. The cross-sections were modeled as parallelograms. Total area of the cross-section was calculated by subtracting the area of the two triangles on the sides from the parallelogram area.

This method allowed estimating excavated fill volume for stream crossings that had a significant road gradient going through the channel, yet kept the measurements simple. When measuring the channel bottom width, due to post-treatment adjustments, estimates of the original channel bottom configuration were made to estimate the total fill volume excavated. Total volume for the excavated stream crossing was calculated by scaling the cross-sectional areas by the appropriate distance along the channel (Figure

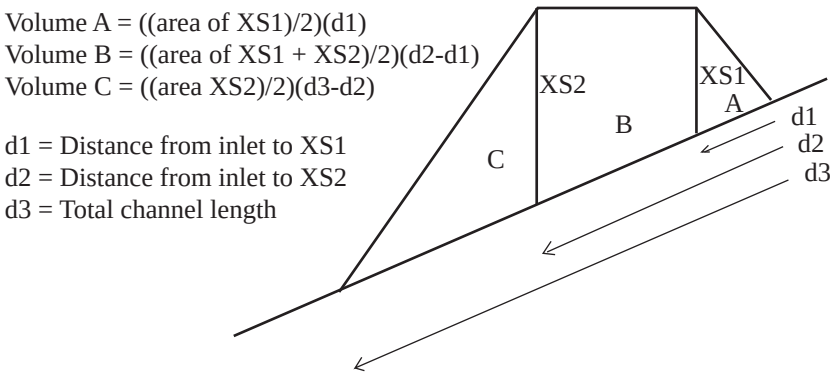


Figure 3. Profile measurements for estimating fill volume.

3). Cross-sectional area was assumed to be zero at the upstream and downstream end of the crossing.

Most crossings were adequately measured with two cross-sections. In the case of very small crossings, only one cross-section was needed. In such instances, the profile was viewed as a rectangle with sides equal to the cross-section and bottom equal to the total channel bottom length. The upstream cross-section was located where the inboard edge of the old road meets the excavated crossing. The downstream cross-section was placed at the widest point of the excavation. Where significant road curvature exists, excavated fill volume may be slightly over-estimated.

Measuring Post-Treatment Erosional Features

Post-treatment erosional features in both excavated stream crossings and on the roadbed between stream crossings were measured. All visible erosional features were measured using average width, average length and average depth, which yielded estimates of total volume of material eroded. The type of feature was also noted (e.g., channel incisement, slump, gully, rill, debris slide, and so on). Sheet erosion was not measured. When possible, the cause of the erosion was noted and discussed. An estimate of percent delivery of sediment to watercourses from all erosional features was made. For the purposes of this study, all reported erosion volumes within stream crossings were considered 100% delivered sediment.

In addition to measuring the excavated and eroded volume, post-treatment assessments were made to determine if the erosional features had stabilized or were still susceptible to chronic future adjustment and sedimentation. For sites with large post-treatment erosion, evidence as to whether or not poor contract design or implementation was a factor was also assessed.

Post-treatment erosion was compared to the following independent variables: hillslope position, hillslope gradient, stream power, storm return interval, and size of excavation. The intent of the analysis was to identify interactions that might serve to predict when the intensity of road decommissioning design needs to be elevated because the risk of post-treatment adjustments are high. In other words, under what circumstances are the risks of post-treatment erosion and sedimentation high and how can they be reduced?

Results and Discussion

Approximately 117 km (73 mi) of decommissioned roads (or 34% of the total length of decommissioned roads) were monitored for post-treatment erosion (stream channel and sideslope erosion at the crossings, and erosion of the roadbed between stream crossings). The majority of these roads and stream crossings had experienced large storms (18-year or greater return period) during the winters of 1995, 1997 and 2003. High intensity storms were considered a good test of the type and magnitude of post-treatment erosion that occurs on typical road decommissioning projects in the Six Rivers National Forest.

Stream Crossings

A total of 262 stream crossings were assessed for post-treatment channel erosion. These stream crossings were predominantly perennial streams but intermittent and ephemeral streams were also assessed. Post-treatment stream channel erosion was quite common, and was generally not large when compared to the amount of material excavated during the initial stream crossing restoration. On average, the amount of post-treatment erosion occurring within stream crossings was 4.5% of the total volume of fill excavated, or 21 m^3 (28 yd^3) (Table 1).

Post-treatment erosion on larger stream crossings (greater than 765 m^3 or 1000 yd^3 of fill) was more variable. The average post-treatment erosion on the larger stream crossings was approximately 3.2% of the total fill excavated but varied from 0 to 16%. Large post-treatment adjustments were rarely observed. In approximately 80% of these large sites, post-treatment erosion was less than 4.5% of the total fill excavated or under 111 m^3 (146 yd^3) (Table 1). The majority (64%) of the inventoried stream

Table 1: Stream crossing excavations and post-treatment erosion.

Excavated Stream Crossing Volume (yd^3)	Percent of Stream Crossings (%)	Volume Excavated (yd^3)	Average post-treatment erosion (yd^3)	Range of post-treatment erosion (yd^3)	80% of sites eroded less than # (yd^3)	Percent of excavated fill volume lost to post-treatment erosion (%)
0-400	64	153	6.7	0 to 156	5.7	5.1
400-1000	20	612	21	0 to 284	25.1	3.3
>1000	16	4692	124	0 to 621	146	3.2
All sites	100	967	28	0 to 621	20	4.5

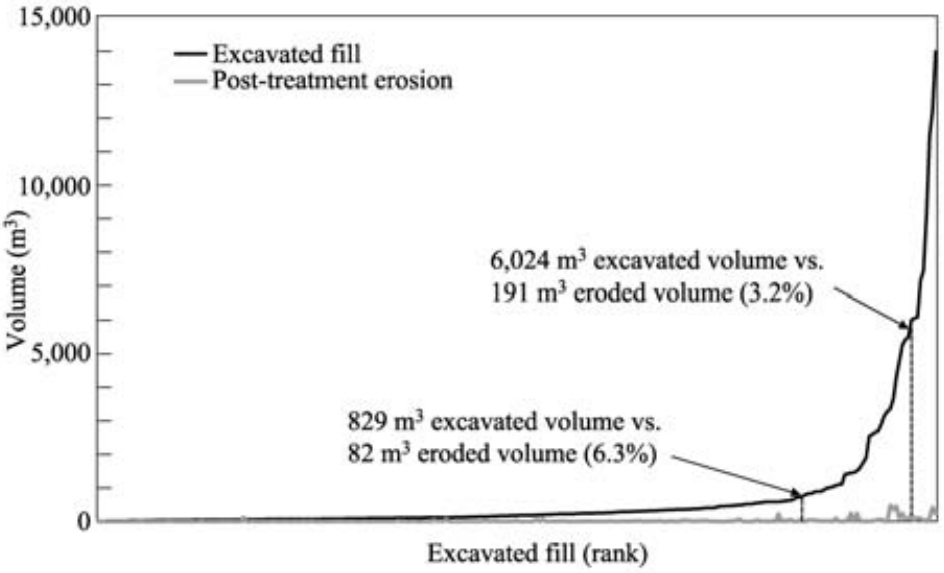


Figure 4. Stream crossing excavation and erosion volumes.

crossings had excavated fill volumes under 305 m³ (400 yd³) and these stream crossings had very small amounts of post-treatment channel adjustments and erosion (average of 5 m³ or 6.7 yd³). Stream crossings larger than 305 m³ (400 yd³) experienced slightly more post-treatment erosion (average of 16 m³ or 21 yd³) but these quantities were small compared to the volume of material excavated from the stream crossings.

While the total volume of post-treatment erosion increased with the size of the excavation, the relative proportion of post-treatment erosion compared to fill volume excavated decreased from 5.1% for small stream crossings to 3.2% for large stream crossings (Table 1). Post-treatment channel erosion remained fairly constant regardless of stream crossing size (Figure 4). While occasional large stream crossing restoration sites have significant post-treatment channel erosion, on average the post-treatment channel erosion on these larger treatment sites is small considering the amount of fill removed.

Photo 1: Typical stream crossing erosion due to post-treatment channel incisement.

On Six Rivers National Forest, approximately 40% of measured post-treatment stream crossing erosion was attributable to channel downcutting or widening, and 60% was attributable to channel bank or sideslope failures. Post-treatment channel downcutting or widening was commonly found at most treatment sites (Photo 1) but excessive downcutting may indicate inadequate restoration design or contract implementation (Photo 2). Rills and gullies were only rarely observed on channel sideslopes and usually only associated with a nearby spring. The bulk of channel sideslope failures were attributable to oversteepened slopes and could be a result of inadequate restoration design or implementation (Photo 3). Depending on the size of the stream crossing restoration site, oversteepened slopes led to shallow slumps and small debris slides. Channel sideslope failures are an inherent risk in restoring stream channels, particularly in naturally steep and incised topography, regardless of the quality of contract design and implementation. Nevertheless, in some instances inadequate channel design, such as too narrow a stream channel configuration or too shallow a depth of excavation, resulted in channel incision, which led to oversteepened and unstable sideslopes (Photo 4). The data indicate that while the total post-treatment erosion was small, a greater emphasis on designing and excavating less steep channel sideslopes would likely reduce post-treatment erosion to

Photo 2: Atypical and excessive post-treatment channel incisement (note exposed root across channel indicative of depth of erosion).

Photo 3: Incipient slope failure due to oversteepened channel side slope.

even smaller volumes, especially in stream crossings that are not topographically constrained by narrow, incised valleys.

Post-treatment erosion on excavated stream crossings is widely recognized as an inherent short-term effect that is offset by larger long-term gains in reducing the risk of major sedimentation resulting from culvert and fill failures. Fill failures and diversions of road stream crossings have been shown to be significant contributors of fluvial hillslope erosion (Best et al. 1995; Weaver et al. 1995). Furniss et al. (1998) assessed stream crossing failures on non-decommissioned forest roads in Washington, Oregon and Northern California and found that after the winter floods of 1995 and 1996, significant portions of road fill were lost due stream crossing failures. Figure 5 illustrates the proportion of stream crossing fill eroded where streamflow overtopped the road. The Furniss et al. data indicate that in approximately 35% of the culvert failures sampled, over 25% of the stream crossing fill eroded, and that 44% of the failures had between 1 and 25% of the stream crossing fill eroded. While the total percentage of storm-related stream crossing fill erosion on non-decommissioned roads varies, it is clear that the proportion lost due to post-treatment road decommissioning erosion is significantly smaller than the erosion that occurs during large storm events. Post-treatment road decommissioning erosion on the Six Rivers varied between 3.2 to 5.1% of the total stream crossing fill volume and was typically considerably less than the volume of erosion that occurs on untreated roads during large storm events.

Photo 4: Channel bank failure due to oversteepened slope and inadequate channel width

A general assumption of stream crossing restoration is that the risk of post-treatment erosion and volume of sediment generated increased with size of the stream channel being restored. Data from this assessment indicate that while the total volume of erosion increased with larger stream crossings, the total volume of material was small compared to the total material excaved (typically 3 to 5%) (Figure 4). Photos 5 and 6 are examples of typical small and large stream restoration sites with very limited post-treatment channel erosion and sedimentation.

Figure 5. Proportion of road-stream crossing fill eroded where streamflow overtopped the road. From: Furniss et al. (1996).

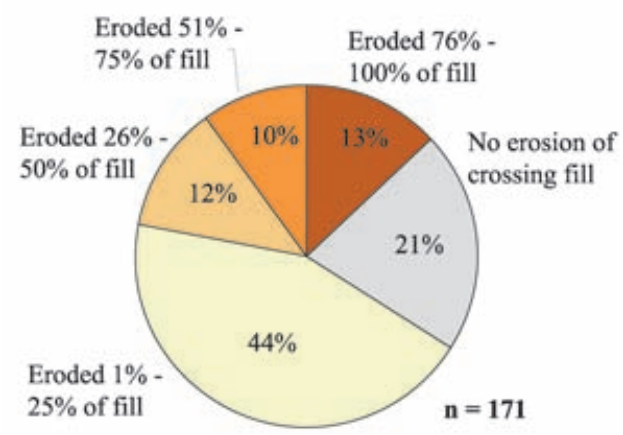


Photo 5: Typical large size restored stream crossing - 5N13B.

Photo 6: Typical small to moderate size stream crossing excavation - Road 2N14H.

Restoration of stream crossings must be carefully planned and executed, but even the best-designed projects have some post-treatment channel erosion. Some of these erosional features can be avoided while others are unpredictable and probably unavoidable. During site excavation, unforeseen conditions may occur and best guesses are made of original channel bottom depths and configurations, only to find out the next year that the channel has downcut, indicating that the original channel was clearly not reached during the initial excavation.

A relatively small proportion of the decommissioned roads (8%) were identified as warranting further monitoring for future channel adjustments and erosion pending the next large storm event. The majority of the decommissioned roads were determined to be in a stable condition and did not pose a significant future sedimentation risk. In others, the short-term impact had largely abated. Sites that warranted future monitoring were mostly associated with roads located in steep inner gorges and large perennial streams (typically 3rd-order or larger) where post-treatment channel erosion had varied between 1 to 15% of the total fill excavated. In these sites, roughly 229 to 459 m^3 (300 to 600 yd^3) of erosion occurred. In general, it is more difficult to minimize post-treatment erosion at decommissioned crossings with deeper channels and higher stream power within the inner gorge. A very small percentage of the sites warranted continued monitoring because of poor contract implementation.

Roadbed

Few surface erosional features attributable to road decommissioning were found on the remaining roadbed between stream crossings. The total volume of all erosional features associated with the 117 km (73 miles) of inventoried roadbed was 2,646 m^3 (3,460 yd^3) (total erosion and associated sediment from restored stream crossings was 9,213 m^3 (12,050 yd^3) or approximately 78% of total post treatment erosion). Roadbed fillslope failures occurred on two roads located in inherently unstable Franciscan mélange terrain (less than 1% of total miles of roads treated). Approximately 2,263 m^3 (2960 yd^3) of fill were associated with post-treatment fillslope failure on mélange terrain and 5% of this material was delivered to adjacent watercourses. The erosional features that produced the greatest erosion were associated with fillslope failures (2,523 m3 or 95%), followed by gullies (76 m^3 or 3%) and cutslope failures (42 m^3 or 1%).

The decision early on in the road-decommissioning program to minimize obliteration and recontouring of the road prism between stream crossings was validated by the relatively small proportion of sedimentation generated from post-treatment roadbed slumps and fillslope failures and by those few failures that occurred being limited to inherently unstable terrain. However, this conclusion should be re-evaluated after a major storm event, such as following a 50-year or greater recurrence interval storm.

Photo 7: Untreated roadbed on decommissioned road.

Photo 8: Outsloping associated with unstable roadbed.

Photo 7 shows a typical untreated roadbed left between restored stream crossings. Photo 8 is an example of road prism outsloping where slope stability was a concern.

Small gullies were the most common erosional feature on the roadbed between stream crossings, but did not account for a large amount of erosion (76 m^3 or 100 yd^3 total). Unlike fillslope failures however, gully erosion resulted in almost 100% sediment delivery to adjacent watercourses. Gully erosion was largely attributable to poor road drainage due to either faulty contract design or incomplete implementation of contract specifications.

Roadbeds between stream crossings were generally not ripped. Rolling dips and waterbars were installed between stream crossings to improve drainage of springs and seeps from road cutslopes. Limited post-treatment erosion was evident as a result of these practices.

Other Post-Treatment Variables

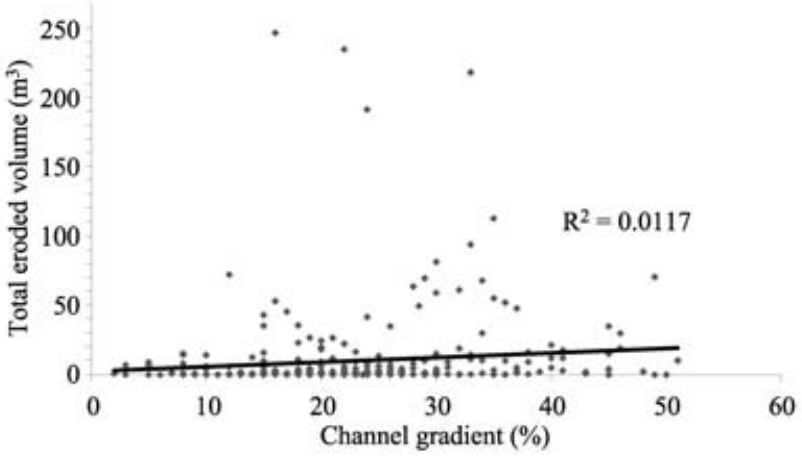
Independent variables such as geology, hillslope gradient, channel gradient, location in the inner gorge, storm history, drainage area, stream power, contract design and contract implementation were assessed to determine whether they influenced post-treatment erosion on decommissioned roads. Due to the high variability of post-treatment erosion within stream crossings, statistical relationships with the variables listed above were not significant. Storm history, geology, drainage area and location in the inner gorge appear to be useful predictors of increased erosion.

The influence of channel gradient on post-treatment adjustments was examined, but no statistical relationships were evident (Figures 6 and 7). We hypothesized that steeper channel gradients would result in more erosion, but this was not supported by the data.

Geology and post-treatment erosion were also evaluated, and some generalizations can be made. All treated sites were classified into five types of parent material: diorite rock, metasedimentary rock, mica schist, sedimentary and metasedimentary rock, and sheared metasedimentary rock. A means test was conducted and diorite and mica schist parent materials showed statistically significant lower post-treatment erosion rates than those sites located in sedimentary and metasedimentary rock (95% confidence interval) (Figure 8).

This finding is counter-intuitive because diorite parent material is generally non-cohesive and highly erodible. Further examination of the data reveals that all of the

Figure 6. Channel gradient regressed against total erosion.



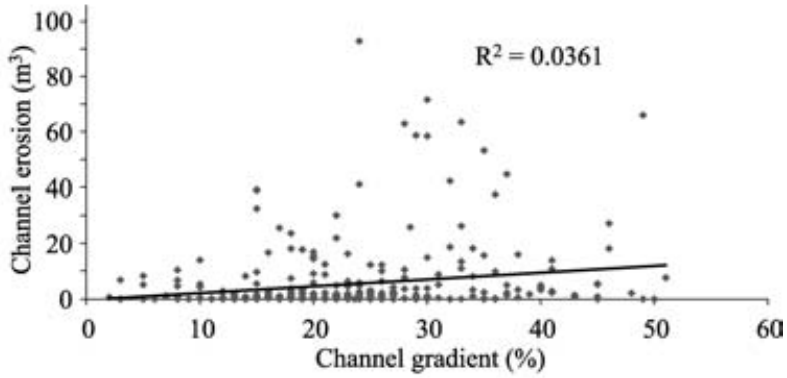
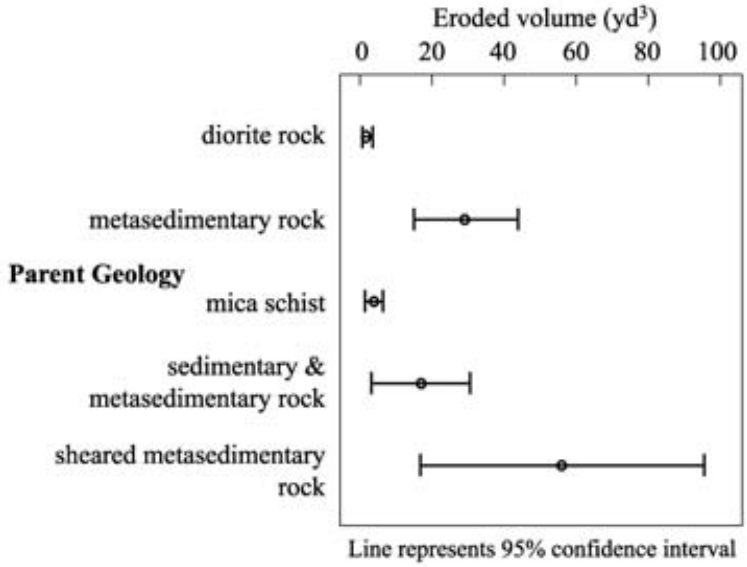


Figure 7. Channel gradient regressed against channel erosion.

Figure 8. Means test between eroded volume and parent material.



treated stream crossing sites within dioritic parent material are above 1,220 m (4,000 feet) in elevation and may be protected from winter storms due to presence of a seasonal snow pack. Treatment sites located in lower elevation diorite parent material are likely still highly susceptible to post-treatment erosion. (Qualitative observations of post-treatment erosion on low elevation sites in diorite parent material support this hypothesis; however, insufficient time was available to include these sites in this study).

Bedrock geology might also be an influence in post-treatment erosion associated with roadbed fillslope failures. Field data indicated however, that post treatment slope failures on roadbeds were extremely limited and located only in the Franciscan mélange terrain. The slope failures on these sites were not clearly attributable to the road decommissioning and could have resulted from the unstable geologic and geomorphic terrain. Overall, a relationship between post-treatment erosion and differing bedrock geology was not evident in the analysis.

The amount of in-channel erosion observed was compared to excavated volume, drainage area, and hillslope gradient as well as stream power. Hillslope gradient was defined as the average gradient of hillslope through which stream channel dissects and stream power was defined as drainage area times channel slope. No correlation was observed between either hillslope gradient (Figure 9) or stream power (Figure 10) and the amount of observed erosion. This was surprising, especially in the case of stream power which had been found to be a good predictor of erosion in the Franciscan terrain of Redwood Creek by Madej (2001). A multiple regression was conducted on post-treatment erosion, excavated volume, and drainage area on decommissioned stream crossings in Six Rivers. These variables were significantly related ($n = 52$, $r^2 = 0.55$, $p = 0.0001$)

Contract design appeared to influence the amount of erosion at some stream crossings, primarily where excavation did not reach the original channel grade, or where post-treatment channel sideslopes were overly steep. These were generally some of the earliest decommissioning project sites with inadequate pre-project surveys. Standard procedure currently is to survey all but the smallest crossings to ensure good contract design. Therefore, faulty contract design should not be a cause for significant erosion in the future.

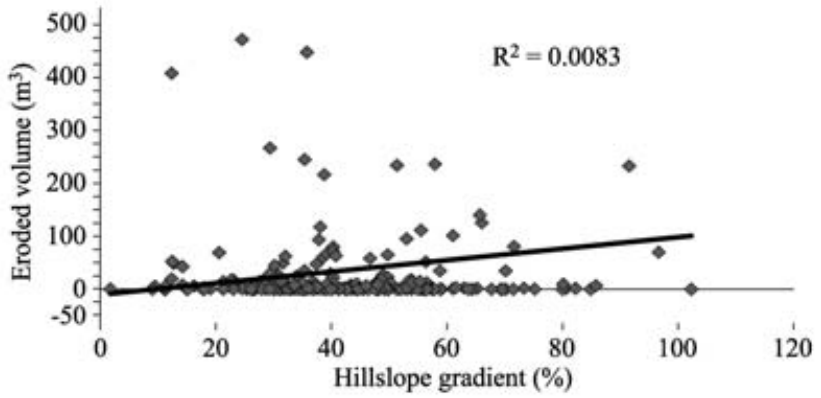


Figure 9. Hillslope gradient regressed against eroded volume.

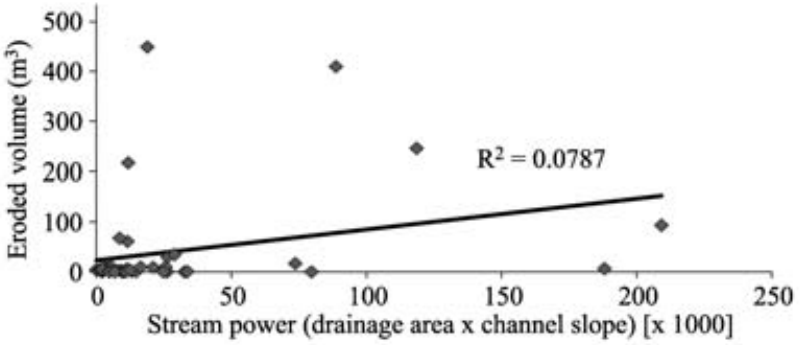


Figure 10. Stream power regressed against eroded volume.

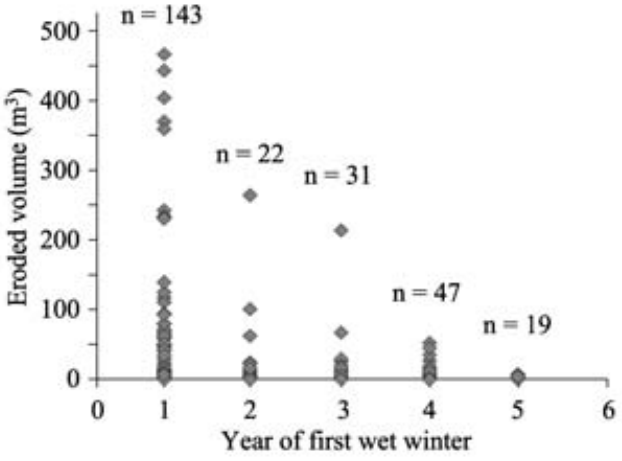


Figure 11. Erosion related to the year of the first wet winter after decommissioning.

Quality of contract implementation did not consistently relate to the amount of post-treatment erosion. In fact, some of the largest erosion was associated with the best-implemented contracts, as determined by the level of on-site inspection during treatments. The large amounts of post-treatment erosion primarily occurred at large or sensitive crossing sites that experienced an unusually wet first winter.

The amount of rainfall, particularly during the first winter, was found to be a good predictor of erosion. Each treatment site was classified into one of five categories reflecting the number of years since the site had experienced a wet winter. For purposes of this analysis, a wet winter was defined as the wettest monthly rainfall occurring with a recurrence interval of 5 or more years. In some cases (such as Bluff Creek), just weeks after completing the decommissioning, a 50-year storm event occurred. This storm produced some of the greatest observed post-treatment erosion, even though the project was well designed and implemented.

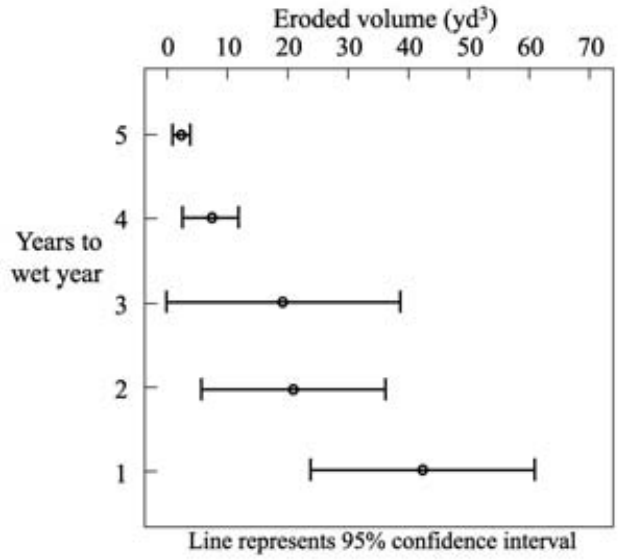
Relatively dry winters allow treated sites to revegetate and increase stability to the point where they can withstand a large storm with little erosion. Comparing the post-treatment erosion volumes in relation to time between storm events indicates that after four dry years, erosion from a wet year is minimal (Figure 11). There also appears to be a substantial reduction in erosion after only one dry winter (Figure 11).

While the relationship between time since storm events and post-treatment erosion is clearly visible in Figure 11, statistical analysis of the data show large variability. Comparing post-treatment erosion and years since first wet winter indicated that there was a high variability of erosion in sites that had a greater than 5-year storm event the first year following treatment ($r^2 = 0.35$, $p = 0.001$). This variability is due to lack of data on rainfall intensities of the storms, or knowing whether these storms were associated with rain-on-snow events, or the timing of the storms. Seasonal timing of large storms is important because if they occur in the late fall just after the completion of the decommissioning treatments, the recently treated channel

slopes are highly vulnerable due to the unconsolidated nature of the disturbed soils; these disturbed soils become progressively more consolidated as the winter progresses due to the settling and compaction associated with raindrop impact. Despite the weak statistical significance between post-treatment erosion and years between large storms (r^2 = 0.35), a means test revealed there was a significant difference in post-treatment erosion between the sites that experienced a greater than 5-year recurrence interval storm the first year after treatment when compared to sites that had not experienced a storm greater than 5-year recurrence interval four and five years after treatment (95% confidence interval) (Figure 12). Further examination of the sites that experienced a greater than 5-year storm recurrence interval the first year after treatment revealed a significant relationship between the amount of excavated volume and post-treatment erosion (r^2 = 0.59). Sites that are exposed to large storm events close to completion of the treatment have a greater likelihood of experiencing post-treatment erosion than sites that have had at least four to five years to stabilize under milder winter conditions.

The amount of erosion was also correlated to whether the stream crossing was located in the inner gorge or not. Inner gorge was defined as any slope greater than 65% and adjacent to a stream channel. Crossings in the inner gorge produced about 4.5 times as much erosion as crossings not in the inner gorge. The 34 sites located in the inner gorge averaged 89 yd^3 (68 m^3) of erosion per year, where as the 226 sites outside the inner gorge yielded an average of only 20 yd^3 (15.3 m^3) of erosion per year. A means test was conducted and the observed differences between post-treatment erosion within the inner gorge were statistically different (95% confidence interval, $p < 0.001$) from those outside the inner gorge and the observed differences were not a function of sample size. Greater post-treatment erosion within the inner gorge occurred because crossings in the inner gorge tend to be larger, on steeper slopes, and have more water. Faulty contract design or implementation at these inner gorge sites will generally have more severe consequences on post-treatment erosion than at sites with smaller stream crossings in more gentle terrain. In extremely incised and narrow inner gorge stream crossings, the natural topography can severely hamper the creation of stable channel side slopes. In these instances, it must be recognized that the ability to fully reconstruct the stream crossing close to its original morphology without risk of some sedimentation and post-treatment erosion is limited. However, the volume of material saved will likely be much larger than the amount lost due to post-treatment adjustments. Data indicate that in inner gorge areas, where the risk is highest, opportunities need to be explored to reduce the risk of post-treatment adjustment by minimizing overly steepened stream channel sideslopes where possible. While more costly, designing stream crossings so that the fill removal extends to and mimics the gradient of the surrounding valley walls will reduce the risk of post-treatment sideslope failure.

Figure 12: Means test between eroded volume and years to first wet year.



The duration of post-treatment erosion was not assessed in this study, however qualitative observations over many years indicate that the bulk of post-treatment erosion and channel adjustments occurs the first year after treatment and rapidly diminishes over subsequent winters. Klein (2003) conducted a post-treatment erosion and turbidity study on decommissioned stream crossings in the Mattole River watershed, coastal northern California, and found that peak turbidity levels downstream of treated sites occurred as a result of the first few winter storms during the first year but that, by and large, erosional response in the sampling sites diminished considerably over the winter sampling period.

Conclusions

Total erosion from decommissioned roads was found to be relatively minor and not likely to persist. Average post-treatment erosion on stream crossings was 21 m^3 (28 yd^3), which is 4.5% of the fill excavated. This amount is much smaller than the amount of erosion that could occur if the culverts failed during large storm events. Larger crossings produced greater amounts of erosion, but a smaller proportion of the excavated fill. Approximately 40% of erosion was from channel adjustment (primarily downcutting with some widening) and 60% was due to sideslope failures (usually from over-steepened slopes that resulted in shallow soil slumps). Over-steepened slopes in

many restored stream crossings were due to inadequate contract design or implementation, but in other sites the over-steepened slopes were due to natural topographic constraints. Leaving the roadbed between stream crossings intact and only outsloping visibly unstable portions of the roadbed was shown to be a viable option in designing road decommissioning projects with limited risk of post-treatment erosion. Erosion from the roadbed between stream crossings was very small and occurred only in unstable mélange terrain. Analysis of data indicated that hillslope gradient, channel gradient, channel sideslope gradient, and stream power were not good predictors of post-treatment erosion. The amount of post-treatment erosion was best predicted by the storm history following treatment. When large storm events occur during the first winter after decommissioning, post-treatment erosion is above average and the amount of post-treatment erosion is influenced by the volume of material excavated. The risk of post-treatment erosion will be considerably less if the site does not experience a large winter storm until 4 or 5 years after treatment.

Post-treatment road decommissioning monitoring indicates that while there is a short-term risk of increased erosion and sedimentation, the amount of erosion is minor when compared to the volume of material removed, and that road-decommissioning treatments are effective in reducing long-term sedimentation risks. Recommendations for future work include assessing the extent and duration of sedimentation effects from decommissioning treatments on local aquatic fauna (e.g., macro-invertebrates), as well as assessing the magnitude of changes to the local hydrology of affected streams.

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Roads in the River: Encroachment, Implications, and Solutions

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In recent years, forest road management issues have focused more frequently on roads within riparian areas. This includes every aspect of managing existing roads, from prioritizing aquatic habitat restoration, to understanding risks and watershed health, to road location, storm damage repair, and road maintenance. Current direction and changes in priority (i.e., Northwest Forest Plan, Aquatic Conservation Strategy), suggest a change in the way that encroachment problems are approached. Watershed analysis and management under the Aquatic Conservation Strategy (ACS) imply an understanding of processes, cause and effect, and managing (reducing or eliminating) hazards in priority areas such as Key Watersheds, riparian areas, and areas adjacent to important aquatic species habitat. Traditional standards of practice, such as bank hardening and revetment construction, can be very effective for protecting infrastructure, but are increasingly viewed as being incompatible with aquatic resource objectives. These techniques are now closely scrutinized, and approaching such problems in the traditional mode invites controversy. Designs and solutions should reflect this change of attitude. Questions now being asked at the planning and design phase include: What do we know about natural conditions, active processes, and the range of natural variability? Can the design at a site emulate local processes or a designated reference condition? Looking at analysis at several scales often provides insights. Examples from the Olympic National Forest, Washington, illustrate these considerations and some of the links between site conditions, physical processes, and the resulting design solutions.

Keywords: *road management, channel geomorphology, aquatic habitat, stream channel, bank hardening*

Introduction

Lands administered by the USDA Forest Service contain considerable areas of steep, mountainous terrain that present a challenge for road managers and designers. Within the steepest and most dissected terrain, the flattest and most stable locations are often along lower valley slopes and in valley bottoms adjacent to streams. Further complicating the situation, the valleys in mountainous regions are often narrow, making road and stream interactions more likely. From a road management perspective, these same valley bottom areas are usually the preferred locations for the most important or highest standard roads. While these areas are preferred for road location, they create conditions where roads are most closely connected to the stream network.

In the past decade, land managers for the Forest Service and other resource agencies have become increasingly concerned with these road-stream interactions in both the long-term and short-term management of the transportation network. Both the Aquatic Conservation Strategy in the Northwest Forest Plan (USDA and USDI 1994), and the National Road Management Policy (USDA FS 1999; Federal Register 2001) address these issues and provide guidelines and direction for management. Such policies suggest that a better understanding of physical conditions and geomorphic processes will result in better management and better decision making. This concept applies to land management at the watershed or larger scale as well as design and implementation decisions at the site or project scale.

Roads in the River Margin

This presentation focuses on problems associated with roads located in and along channel margins. Road washouts and other problems range from simple encroachment to more complex encroachment in an active or changing landscape (Figures 1 and 2). Complex encroachment problems often require a more comprehensive assessment and more complicated or creative design solutions. Site assessments confined to the immediate washout area are often inadequate for determining the best solutions. They may fail to address causal mechanisms, processes that operate at a larger scale, trends, or off-site and long-term impacts. Problems in the most complex or sensitive environments are more likely to encourage solutions that rely on avoidance of the problem.

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Figure 1. An example of simple encroachment: Site assessment may be limited to the area at and immediately adjacent to the site. Designs solutions may be limited to the immediate washout area.

Figure 2. Encroachment within an active landscape: North Fork of Calawah River, Forest Road 2923. Assessment included evolving or active slope processes at washout.

Figure 3: The Dosewallips washout. The photos are taken from the 2610 road at the downstream end of the washout, looking upstream. In the left hand photo (a) , the line of coarse rocks near mid-channel indicates the approximate location of the former toe of the road fill. The bank on the right (b) is 20 to 30 m high. The washout is approximately 100 meters long. Photo (a), D. Cenderelli; photo (b), T.E. Davis.

Three examples from the Olympic National Forest are offered to illustrate several of these points. The discussion closes with some thoughts on revetment designs and project development for solutions that are more consistent with natural resource objectives.

Case Example 1: The Dosewallips River Washout

In January 2002, a 100-m section of Forest Road 2610 was washed out by the Dosewallips River (Figure 3). The Dosewallips is a key watershed, a high priority for restoration, protection, and recovery of aquatic species. The watershed has high-value fisheries including a threatened stock of Chinook salmon (*Oncorhynchus tschawytscha*). The watershed upstream of the washout has had minimal timber harvest and has a low road density. The headwaters are within Olympic National Park. The primary road use is recreation traffic; both the national park and the national forest maintain campgrounds beyond the washout, and the national park has trailheads accessing a system of trails into the backcountry.

The Environmental Assessment (EA) following the washout considered a range of alternatives. Initially, the preferred alternative was to re-establish the road in its former location. The design was developed concurrently with the EA and the assessment of potential impacts. Early in the process, several assumptions were made that suggested this was a reasonable course of action. These assumptions included the following: (1) the road had been in this location for 80 years or more; (2) salmon habitat within the main channel adjacent to the washout is rather marginal (coarse, steep, and uniform); and (3) overall salmonid habitat in the upper watershed is of high quality and is functioning naturally.

Because of the high ecological values in the watershed, and questions raised during public review of the draft EA, it became evident that a more detailed analysis was needed. An intermediate level (reach) assessment was conducted in order to better describe the potential long-term and off-site impacts to fish habitat and listed fish stocks (Cenderelli et al. 2003). The reach assessment consisted of a more comprehensive evaluation than the EA, focusing on the following factors:

- Temporal assessment, evaluating change over time using historic air photos dating from 1939
- Geomorphic characterization of the river channel extending upstream and downstream of the washout.
- Hydrologic characterization including flood history and response.
- Characterization of the channel bed sediments
- Characterization of sediment sources, terraces and sources of spawning gravels
- Assessment and characterization of aquatic habitat.

Geomorphic Setting

The unique nature of the washout area was not fully appreciated prior to the reach assessment. The washout is located in an area where the river is incised into a series of glacial outwash and fluvial terraces; four distinct terrace sets were identified and mapped. This section of river was designated the Terrace Transition section. Figure 4 shows the Terrace Transition and adjacent geomorphic types. Table 1 displays some of the characteristics.

The Terrace Transition section and the link to the high quality habitat in the Alluvial Unconfined response reach downstream are important associations in this part of the watershed. A similar association was not found in the upper watershed. Although it is limited to slightly more than one meander wavelength, only about 850 m long, the Terrace Transition section supplies a substantial amount of high quality spawning-sized gravels to areas immediately downstream. The long-term trend has been toward increasing erosion from the bend at the washout, and decreasing erosion at the other high bank in the upper meander bend. Revetment construction would eliminate the source of spawning gravels in the lower bend.

Additional findings from the reach assessment included:

1. Temporal and spatial variability is more significant than initially assumed.
2. The long-term trend in river planform is toward expansion at the downstream meander bend and increasing bank erosion at the washout.
3. The recommended mitigation should emulate the natural processes and links that would be diminished by revetment construction. Encouraging meander development and associated bank erosion with log (large woody debris, LWD) complexes is an appropriate mitigation, although it will not compensate for eliminating the high bank as a source of spawning gravel.

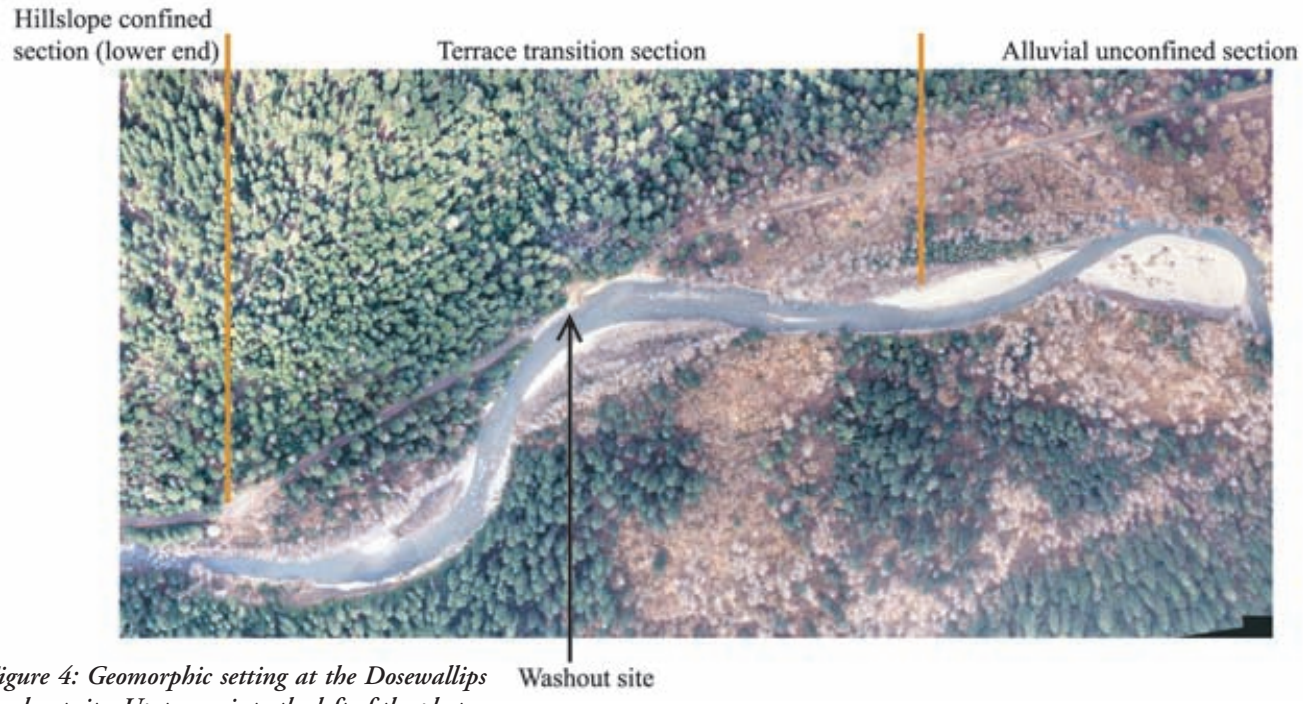

Figure 4: Geomorphic setting at the Dosewallips washout site. Upstream is to the left of the photo.

Table 1: Dosewallips River, characteristics of designated channel geomorphic units.

	Hillslope Confined	Terrace Transition	Alluvial Unconfined
Gradient	2% to 4%	< 1% to 2%	< 1%
Confinement	Confined	Moderate confinement	Unconfined
Bed material	Boulders and bedrock	Cobble and gravel	Gravel
SPF*	Transport	Transport (supply)	Response
Comments	Hard, dominated by non-deformable bed and banks	High sediment supply from adjacent banks; hillslope interaction high	Frequent split channels and abundant wood (log jams); Habitat value is high
Rosgen Class	B1 and B2	F3 to F4	C4

**SPF: Sediment processing function (Montgomery and Buffington 1993)*

Summary of the Dosewallips Example

- Initial assumptions were based on a limited scope, site level assessment.
- An intermediate level or reach assessment was needed to accurately describe potential impacts on fish and fish habitat.
- The relationship between upstream (sediment poor), the washout area (high sediment and spawning gravel supply), and the downstream response reach is more important than conditions at the washout site. The aquatic habitat immediately adjacent to the washout is considered rather marginal.
- Because the original preferred alternative would create substantial adverse impacts at the reach scale, to a resource that is very limited in the watershed (Chinook salmon spawning habitat), it is not consistent with Aquatic Conservation Strategy objectives.

Case Example 2: The Upper Dungeness River, Forest Road 2860

The 2860 Road is an example of simple encroachment, as compared to the setting of the Dosewallips washout. The valley bottom is narrow, but is the only suitable location for a road through this area. The road has been in this location for over 40 years. The channel is steep, coarse and predicted to be rather insensitive to change. The washout site is shown in Figure 5.

Similar to the Dosewallips, the Dungeness is a high value watershed with regard to fisheries, water quality, and watershed restoration. This section of the river supports populations of four species of Pacific salmon. Bull trout (*Salvelinus confluentus*) also occur, and along with the local Chinook salmon population are federally listed as threatened species. It is a popular recreation area, so reducing access is controversial. Significant channel attributes at the washout site are shown in Table 2.

Figure 5: The Upper Dungeness River at the 2860 Road washout. Boulders in mid-channel and the constriction formed by the road encourage accumulation of logs and diversion of flow along the toe of the fill. This has been a chronic problem area.

Table 2: Upper Dungeness channel geomorphic unit characteristics.

Type	Hillslope Confined
Gradient	2% to 4%
Confinement	confined
Bed material	boulders and bedrock
SPF*	transport
Comments	hard, dominated by non-deformable bed and banks
Rosgen Class	B1 and B2

**SPF: Sediment processing function (Montgomery and Buffington 1993)*

High quality Chinook spawning habitat is concentrated 1200 m downstream of the washout, in the area around East Crossing Campground. The channel in this area is a lower gradient unconfined alluvial channel type, classified as Rosgen channel class C3 (Rosgen 1994). It is the first response reach (Montgomery and Buffington 1993) downstream of the washout.

In previous years this road segment was treated with a traditional approach, meaning that washouts and erosion were repaired by armoring the bank. The coarse, steep nature of the hillslope-confined channel adjacent to the site suggested limited need for concern about impacts on aquatic habitat; the need for access dominated the decision-making processes. Site assessment limited to the washout area did not provide information that was compelling enough to change the management of the road. Ultimately, however, it was larger scale considerations and concern for watershed values that governed the decision process. The final decision was to decommission the road and campground and provide alternate access to trails and recreation opportunities in the upper watershed.

The proximity to high-value aquatic habitat, watershed-scale values, and the character of the stream channel through the stream-adjacent road segment directly influenced the design of the decommissioning. An intensive level of road decommissioning was done where the road was most directly connected to the river (Figure 6). In locations where the connection to the river was not as strong, or the impact was interpreted as low, the intensity of decommissioning was reduced.

Summary of the Dungeness River Example

- The final decision (decommissioning) was based on factors well beyond the site scale, including watershed values and linkages to downstream habitat conditions.
- Interdisciplinary and interagency involvement throughout the project was a key to success, as was extensive contract oversight.
- The final design included high and intermediate levels of road decommissioning and was based on identified risk, site conditions, and interpreted channel sensitivity.

Case Example 3: The Walter Creek revetment, Road 2350, Milepost 9.95

In this example, the repair contract was awarded as a traditional riprap revetment following a simple site investigation. However, during construction, problems were encountered and the project could not be built as designed. Because the problem surfaced during the construction phase, a solution was needed quickly. An interdisciplinary group, including design and construction engineers, a fisheries biologist, the construction contractor and the equipment operator, developed a preliminary solution on-site. The site was quickly re-surveyed and the new design was accomplished the following day. In this example assessment was limited to the immediate washout area.

Figure 6: High intensity decommissioned section through former washout; roadway and all associated fill have been removed. Straw mulch indicates former road and area disturbed by excavation. Two of the log complexes placed for structure and stabilization can be seen on the left. Note the lower intensity of treatment at the far (upstream) end.

The solution involved lowering the fill and installing internal reinforcement (reinforced soil slope) to steepen the slope and reduce encroachment. Figure 7 shows this phase during construction.

Figure 7: Construction at Walter Creek. Note the installation of geotextile fabric reinforcement through steepened section of the revetment.

Structure was added along the channel margin, including logs keyed into existing boulders but not into the revetment. The structures were designed to reduce erosional forces on the revetment, but ultimately provided complexity to the channel. The use of logs embedded into the foundation or footprint of the road was avoided because of a concern for decaying logs compromising long-term performance. The slope above the riprap was covered with a turf

Figure 8: Walter Creek Revetment, Rd 2350 milepost 9.95 - photo of completed project.

reinforcement mat, filled with topsoil and planted. The completed project is shown in Figure 8.

Summary of Case Examples

The preceding examples show a range of sites and conditions. They involve changes in approach that span the project development process from assessment to implementation. The list below provides a summary.

- All of the projects started out as conventional riprap revetments.
- All began with assumptions made from a limited (site) level assessment
- All changed substantially and none were implemented as initially envisioned; Walter Creek has been implemented as a riprap revetment although it is not a traditional design.
- The Dosewallips is a complex site in an evolving environment. Potential solutions are complex, expensive, and extend well beyond the limits of the washout. The assessment was comprehensive.
- The Dungeness, by comparison, is a relatively simple encroachment problem involving a more limited assessment, though still extending well beyond site boundaries. The solution was based on issues and values beyond the site level.
- Walter Creek is a much more straightforward example. It involves site level assessment only, and the solution is limited to the washout area. Nevertheless, the design incorporates features not typically found in conventional revetments.

Table 3: Conceptual elements useful for evaluating bank protection designs.

Variable	Habitat Components	Traditional Revetment Designs
Texture	rough	smooth
Variability	high	low/uniform
Hydraulic efficiency	inefficient	efficient
Structure	complex (messy)	simple (neat)
Overall impression	soft	hard

Design Solutions: Some Thoughts on Non-traditional Approaches

Traditional solutions such as riprap revetments are effective techniques that have stood the test of time and should not be abandoned. Design methods such as those developed by the Corps of Engineers (USACoE 1991), the Federal Highways Administration (USDOT FHA 1989) are appropriate starting points for projects involving riprap. However, natural resource professionals and regulatory agencies are calling for more creative solutions that minimize adverse impacts on the stream environment. With this in mind, consider the range of conditions within the variables listed in Table 3.

Several variables in Table 3 are often an objective of, or are affected by, bank protection measures. These variables highlight some key differences between desirable aquatic habitat conditions and traditional riprap design objectives. Column 2 lists conditions with respect to these variables that are often associated with high quality aquatic habitat. It is often rough, highly variable, hydraulically inefficient and structurally complex. These are also components that perform important energy dissipation functions within streams. Column 3 suggests that traditional engineering designs favor opposing conditions with respect to these variables; they tend toward efficiency, uniformity, and predictablility. The stream environment is dynamic and variable, while analysis and design necessitates simplifying assumptions. Incorporating elements that increase variability and turbulence also increases uncertainty, risk, and cost. In the search for more compatible designs, the challenge is to develop an integrated approach that seeks the best compromise between engineering efficiency and natural habitat values.

A Contemporary Design Example: The Big Quilcene Revetment

The Big Quilcene Revetment, shown in Figure 9, offers a fine example of a non-traditional, or some would say a more contemporary, bank hardening design using riprap. Rootwads and short rock spurs have been incorporated along the toe, and soil bioengineering techniques using brush layers and jute matting were used in the upper

Figure 9: Big Quilcene River revetment just upstream of Highway 101. Note the irregular shaped rock toe incorporating rootwads and built to a limited height with brush layers installed above.

section. These techniques are intended to soften some of the effects of riprapped banks, and increase hydraulic roughness.

In this example the height of the rock armor (H) is somewhat lower than recommended in traditional designs. Many newer designs set the top of the rock to the height of lower discharges such as the predicted 20-year recurrence interval flood (Q_{20}), or even lower. Because shear stresses or erosional forces are concentrated near the channel bed, and drop off rapidly toward the water surface, the top of the structure need not be as hard or be designed to resist the maximum shear stress. Closer to the surface, soil bioengineering, plantings, or other soft techniques can be used (USDA NRCS 1992). Designers must be careful to recognize the uncertainty involved in predicting flood height, and therefore the risk involved when basing rock height (H) on lower flow levels.

Conclusions

In many instances, traditional approaches based on simplifying assumptions or a limited scope of analysis have been costly. At complex sites such as the Dosewallips washout, this approach has led to complete redesigns and repeating several steps of the environmental assessment phase or National Environmental Policy Act (NEPA) analysis. Conducting design concurrent with NEPA analysis is risky at these sites.

Many streambank protection projects are still approached in a traditional mode, which is to replace and fortify what was previously there. Approaches for treating road encroachment problems have changed in the last decade, particularly for natural resources management and regulatory agencies. There is an increased emphasis on understanding physical and biological processes and finding solutions that are consistent with the range of natural conditions. Road management in this environment is not business as usual, and assessments and designs should reflect this. Road management agencies, highway departments, and the consultants that often work for them do not necessarily have this philosophy.

The scale of the assessment will often have to be expanded beyond the immediate project area in order to determine the best solutions. Design and on the ground implementation should maximize the use of available structure. Many improved designs use the same components that provide stability in undisturbed stream analogs or nearby reference conditions.

Early interdisciplinary or interagency involvement is valuable, and in some cases is essential, at any phase of these projects. The degree of involvement is directly related to site complexity and to larger scale issues such as watershed values. Involving regulatory agencies after designs have been completed, or only after a problem has been encountered during construction is asking for trouble.

Manuals such as Washington State's Integrated Streambank Protection Guidelines (WDFW et al. 2002) and the Federal Interagency Working Group's Stream Corridor Restoration Manual (FIWG 1998) provide excellent guidance for road management and design along stream and river margins. These guides address habitat impacts, and attempt to integrate an understanding of changes in channel processes into road management and design.

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Road Decommissioning Effectiveness Monitoring Techniques

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National forest road decommissioning techniques are a key tool in effective watershed restoration. Although land managers have been involved in road decommissioning over the past three decades, there is little consistency in road decommissioning monitoring. This document provides a framework for developing and implementing a monitoring plan that responds to the specific needs and unique ecological conditions of each forest.

Keywords: *road decommissioning, effectiveness monitoring, watershed restoration*

Introduction

The Road Decommissioning Effectiveness Monitoring Techniques report presents a framework that an interdisciplinary team (IDT) can use to develop a road decommissioning monitoring program. Additional forms, references and examples of monitoring plans can be found by visiting the links at the end of this document.

As the group that needs this information most is the IDT, this report takes the form of instructions to the team. However, all other readers with interest in the subject will find the information useful.

Several national forests have developed road decommissioning monitoring plans and this report builds on their work. Rather than advocating one method for each monitoring project and budget, this document enables users to select a monitoring technique for each situation.

In the late 1970s, Redwood National Park (RNP) started to decommission unneeded roads. Park geologists tried to reduce the adverse environmental effects of roads and road crossings including erosion, mass wasting, and sedimentation. Techniques to decommission roads evolved from monitoring results. Treatments changed from hand tools and revegetation to dozers and excavators. The same kind of heavy equipment that created the road now decommissioned the road.

At the same time, national forests across the country began decommissioning roads. Flood events that occurred during the 1980s and 1990s also showed the vulnerability of the transportation system and the negative results of poorly designed and located roads.

Furniss, M.J., Clifton, C.F., Ronnenberg, K.L., eds., 2007. *Advancing the fundamental sciences: proceedings of the forest service national earth sciences conference, San Diego, CA, 18-22 October 2004*. PNW-GTR-689. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station.

Road decommissioning reduces chronic sediment delivery, restores hillslope hydrology and reduces impacts to aquatic, riparian, and terrestrial ecosystems of roads crossings. The Forest Service has different levels of decommissioning treatments to reduce road hazards. Forest Service personnel have learned which decommissioning treatments are effective for different climatic conditions, geology, and soil type. Forest IDTs develop monitoring plans for evaluating the effectiveness of decommissioning treatments.

What is Road Decommissioning?

Road decommissioning is defined as: "Activities that result in the stabilization and restoration of unneeded roads to a more natural state." (36 CFR 212.1, Forest Service Manual 7705 - Transportation System [[USDA FS 2003]]). The Forest Service Manual (7712.11- Exhibit 01) identifies five levels of treatments for road decommissioning which can achieve the intent of the definition. These include the following:

1. Block entrance
2. Revegetation and waterbarring
3. Remove fills and culverts
4. Establish drainageways and remove unstable road shoulders
5. Full obliteration, recontouring and restoring natural slopes

These five treatments give the IDT a range of options for stabilizing and restoring unneeded roads. Watershed Analysis (WA) and Roads Analysis (RA) help determine what treatment level or combination of treatments is appropriate. In some situations blocking the entrance may meet restoration objectives. In other situations, restoring hillslope hydrology may require full obliteration recontouring. Local factors such as climate, geology,

topography, soil, and road design and construction also factor into the stabilization and restoration objectives.

Components of a Monitoring Plan for Road Decommissioning

The following steps (adapted from Kershner 1997) will help the interdisciplinary team establish their monitoring plan:

1. Obtain management and leadership support. Monitoring dollars will always be limited, as will available resources to conduct the monitoring. Link monitoring results to management decisionmaking and goals. Identify some linkages from scoping questions in NEPA analysis: What are the commonly asked questions that management has to answer about road decommissioning? Will the monitoring effort provide information that is critical for policy making and reporting to the public? Can the monitoring obtain results in a useful timeframe?

2. Define the participants. Jointly develop the monitoring goals and objectives. Ensure that the team has the technical expertise to set protocols, collect the data, and analyze the data.

3. Determine the overall goal or goals. Use findings in the RA and WA, Land and Resource Management Plan (LRMP) goals, and aquatic conservation strategies, as available and appropriate. The following are sample goal statements from the Aquatic Conservation Strategy for the Northwest Forest Plan (FEMAT 1993)

> *Maintain and restore the physical integrity of the aquatic system including shorelines, banks and bottom configurations.*
>
> *Maintain and restore the sediment regime under which aquatic ecosystems evolved. Elements of the sediment regime include the timing, volume, rate, and character of sediment input, storage, and transport.*
>
> *Maintain and restore the habitat to support well distributed populations of native plant, invertebrate, and vertebrate riparian-dependent species.*

These goal statements are broad and general. Although teams often want to further break down the goals, be patient during this step and look at the ecosystem from a broad perspective.

4. Select objectives that fit the goal(s).

A well-written objective statement clearly shows the expected outcome. Make it specific, concise, and most importantly, observable or measurable. Objectives can also be time-specific statements of measurable planned results, responding to pre-established goals that you can find in the WA, RA, or Land and Resource Management Plan (LRMP) for the forest. If specific, measurable objectives are not available, locate indicators of similar "healthy" systems and use these for objectives. Select monitoring objectives that best indicate change and measure them in the locations that are responsive to change. (Kershner 1997)

5. Design monitoring to detect change to: (a) distinguish treatment effects from other variations, and (b) take replicate samples over space and time. Consider the geographic extent of the plan and minimize the variability from site to site, by selecting areas of similar size, geology, morphology, stream discharge, and other unique or important characteristics. Sample number and statistical significance of the monitoring should be included in the initial monitoring design. Use pretreatment inventory data as a benchmark of pre-restoration condition.

6. Prioritize and schedule monitoring activities: identify what needs doing and prioritize it. For example, evaluate cover effectiveness the first year if a mulch or seed mix is a component of the treatment. Monitoring the type of cover for vegetation composition and species dominance may require sustained monitoring over several years. Evaluating the change in riparian vegetation community composition and spatial arrangement at a road decommissioning site may require less intensive monitoring but over a longer duration.

7. Implement the road decommissioning treatment. The FSM 7712.11 identifies five treatment levels for road decommissioning. Depending on the site, a combination of treatments may be implemented.

8. Analyze data and report results. Complete an annual report on the monitoring results and present the findings to the district and/or forest leadership team. Seek opportunities to share the team's findings during field trips with the forest leadership team or other interested groups.

9. Use new information to adapt goals and objectives. "Whether monitoring demonstrates success or failure of outcome predictions, what is learned from monitoring will illuminate analysis and decisionmaking in the future." (USDA 1999)

Monitoring Plan Development

The previous section provided a framework for organizing a road decommissioning monitoring program. Use information from the Watershed and Roads Analysis to identify watershed restoration goals and objectives. Identify restoration goals and objectives and select the appropriate treatments. The monitoring plan provides the feedback mechanism for answering questions on both implementation and effectiveness.

Seek guidance and feedback from forest Line Officer's on questions, activities, resources and schedules. The interdisciplinary team needs the staff for the design, analysis, interpretation and annual reporting of findings to managers and the public.

Designing a Road Decommissioning Effectiveness Monitoring Plan

Designing a road decommissioning effectiveness monitoring plan can be difficult. This section is designed to provide a framework for a team to fully develop each component of a monitoring plan. The four most common monitoring methods currently being used for road decommissioning effectiveness are shared. Depending on the resources available for monitoring, a team can select different methods for different areas. The monitoring level of intensity may vary from year to year and the team may want the flexibility to capture more or less information in a given year.

Table 1 gives examples of goal and objective statements that a team can use as a starting point for items #3 and #4 of Components of a Monitoring Plan. Tables 2 and 3 illustrates a technique to link Watershed and Roads analysis findings to restoration objectives, treatments, and finally, measurable indicators for monitoring treatment effectiveness.

In researching current monitoring methods used by Forest Service, state, or private watershed groups, the following four monitoring methods were repeatedly cited as tools to monitor decommissioning effectiveness:

- Quantitative measurements of channel cross-sections, vegetation, and soil erosion rates.
- Qualitative measurements using Best Management Practices (BMPs).
- Photo-point monitoring using "before" and "after" photographs.
- Tracking spreadsheets that answer who, what, where, how much, and when.

Table 1: Examples of goal and objective statements from forest LRMPs.

Generic Goal Statements	Measurable Objective Statements:
Maintain and restore the sediment regime under which aquatic ecosystems evolved. Elements of the sediment regime include the timing, volume, rate, and character of sediment input, storage, and transport.	Keep ground-covering litter, duff, and/or vegetation on at least 90% of non-rocky riparian areas.
	Roads occupy less than 3% of all near-stream areas within a sub-watershed.
Improve juvenile steelhead habitat to restore runs of summer steelhead.	Remove identified unneeded crossings to achieve < 2 crossings per mile of perennial stream.
Restore spawning and rearing habitat for summer steelhead in the subwatershed.	Increase Channel Bank Stability to obtain an upward trend in stability, with target of 85% stability for reaches.
Restore hillslope hydrology and improve infiltration on compacted road prisms.	Upward or stable trend in W/D measures, as compared to reference stream data, measured at flat water habitat types.
Restore watershed functions to improve water quality, fish and wildlife habitat, and scenic value	Increase structurally complex rearing habitat for juvenile steelhead as measured for deep pools and woody debris frequency in the current administrative policy.
Maintain and restore habitat to support well-distributed populations of native plant, invertebrate, and vertebrate riparian-dependent species.	Increase the numbers of juvenile steelhead to meet downstream migrant numbers defined as optimal in state management plan.
Maintain and restore the timing, variability, and duration of floodplain inundation and water table elevation in meadows and wetlands.	Decrease the percentage of fines in spawning gravel to less than 10% during spawning and incubation.
Maintain and restore the physical integrity of the aquatic system, including shorelines, banks, and bottom configurations.	Decrease near stream road density to 1 mi/sq mi in key watersheds.
Maintain and restore spatial and temporal connectivity within and between watersheds. Lateral, longitudinal, and drainage network connections include floodplains, wetlands, upslope areas, headwater tributaries, and intact refugia.	Decrease soil compaction to less than 5% in near stream areas within a sub-watershed.
	Upward trend in bank angle, with target of 100° average for reaches. Maintain streambanks to ensure the protection of the aquatic systems to which species are uniquely adapted.

Table 2: An example of a table used to illustrate the linkages between watershed process, watershed analysis (WA), and restoration objectives to treatments and monitoring indicators.

Process or Attribute	WA findings and Results	Restoration Objectives	Restoration Treatment	Monitoring Indicator
Channel morphology (width to depth ratio)	Identify the appropriate goal based on findings from WA, RA, and previous inventory or monitoring records.	Identify the specific objective based on channel type classifications.	Link WA, objectives, to identify priority areas. Select decommissioning level that obtains objective	Channel cross sections
Sediment regime	Identify existing sources and change to temporal and spatial scale	Consider direct and indirect indices to include on site and off site effects. Link to regulatory agency direction.	On-site cover techniques including natural mulches and large woody debris	Change in contributing source areas; In stream pool fines; amount of material removed at stream crossing.
Channel and floodplain function	Identify change in channel type as a result of management inputs.	Determine restored channel classification	May include channel stabilization thru redesign	• channel cross sections • streambank erosion • amount of material removed at cross section.
Species composition and structural diversity	Locate PNV information to determine natural species composition.	Identify composition and time frames to achieve goal.	Identify seed and cutting sources for vegetation establishment. Consider risk associated with noxious weeds.	Vegetation monitoring (Releve plots, line or belt transects
Erosion and mass wasting processes	Identify existing sources, and change in frequency and magnitude.	Determine "natural triggers" and reduce management induced triggers.	Restore hillslope hydrology and vegetative recovery.	Change in contributing source areas; in stream pool fines; amount of material removed at cross section

Regardless of which monitoring method or combination of methods is selected, the monitoring team must develop goals and objective statements for the monitoring. Table 1 provides sample goal and objective statements for a monitoring plan. Remember that goal statements are broad and can commonly be found in the LRMP. Objective statements are specific, concise, and measurable, and generally harder to pinpoint. Write objectives from the best data available.

Indicators

Item #5 of the components of a monitoring plan requires that monitoring be designed to detect change. Indicators are the measure or record of change. Select indicators that can be observed and measured. The following are examples of indicators used for road decommissioning monitoring:

1. Channel adjustment both above and below a road crossing
2. Erosion rate changes including surface erosion (existing road prisms) to changes in mass wasting frequency and extent (landslides)
3. Sediment sources associated with roads (chronic vs. pulse)
4. Revegetation of hillslopes and riparian areas to desired species
5. Amount of material removed from crossing(s), and miles of road decommissioned

Some of these indicators are direct indicators of change while others are indirect. Select direct or indirect indicators depending on resource availability (personnel and funding), priority, and treatment type.

Table 2 provides a template for tracking WA findings, and linking restoration objectives to treatments and

indicators. The table focuses the monitoring team on determining which process or processes a road modifies. In the first example, the removal of a culvert, ford, or bridge modifies channel morphology at stream crossings. In addition, roads paralleling a stream channel can modify channel morphology by constricting the channel.

Other changes to processes occur with roads crossing meadows. In many cases channels have aggraded above culverts and degraded at the culvert outlet. In meadows, roads can affect channel and floodplain functions. It is not uncommon for channels to change from a Rosgen C Type to an incised gullied channel. The team faces the task of determining how to decommission the road and what type of channel stabilization is necessary. Monitoring treatment effectiveness may focus on recovery of the channel and floodplain. The team must determine the best indicators.

Levels of Intensity of Effectiveness Monitoring

With different intensity levels for conducting effectiveness monitoring, forests use a mixture based on the values at risk, project design, and availability of personnel and resources.

The four monitoring methods commonly used by forests are:

1. Quantitative measurements with repeat evaluation on excavated channel cross sections, vegetative recovery transects, and evaluation of erosion rates on site.
2. Use of BMP evaluation protocols to assess implementation and treatment effectiveness.
3. Photo comparisons of treatments, including key indicators of change in channel cross section and revegetation.
4. Tracking tools, quantifying amount of material removed, length of road decommissioned, and treatment type.

Quantitative Measurements

Quantitative measurements refer to measurements taken in the field such as stream channel dimensions, amount of erosion, and revegetation.

The team and forest management may be implementing road decommissioning with the goal of improving juvenile steelhead (anadromous *Oncorhynchus mykiss*) habitat to restore runs of summer steelhead. However, the team may select as indicators, direct measures of channel cross section, erosion, and revegetation. If the road decommissioning treatment results in a stable stream channel, reduced erosion, and healthy revegetation, the conditions exist for an improved juvenile steelhead habitat.

Several forests use direct stream measurements to evaluate treatment effectiveness.

Common goals for this type of monitoring are to quantify the effectiveness of road decommissioning projects to reduce or eliminate sediment inputs. Additional goals include identifying both successful treatments' techniques and limiting factors. The team must know if treatments are effective for a particular site.

Teams conducting this level of monitoring divide the decommissioning work into three areas: 1. Road prism stabilization; 2. Stream channel excavations; 3. Revegetation and effective soil cover. Road prism stabilization may involve random transects across numerous segments of the treated prism. The team must ask: is there adequate cover to reduce erosion? What is the type and composition of the soil cover? Did the treatment improve infiltration? On a fully decommissioned road the team samples the re-contoured area from the toe of the fill slope to the top of the cut bank. Soil transects can be line-intercept transects or grid and measure bare soil, litter, plants, downed material, rilling, and compacted soil. (San Dimas Technology and Development Center Website, *http://fsweb.sdtdc.wo.fs.fed.us/programs/im/fy04/rdmt/*)

For monitoring stream channel excavations the team has several choices. Obtaining baseline inventory data of the volume of material in the crossing is valuable. Data may be found in the National Environmental Policy Act (NEPA) document or restoration contract. The monitoring questions at road crossings include the amount of horizontal and lateral adjustment of the stream channel, and surface erosion or mass wasting. A longitudinal channel profile and cross sections may be established.

Secondly, an "as-built" longitudinal channel profile and cross-section survey taken immediately after decommissioning and prior to storm events can serve as a benchmark. The design for the removal of the crossing should be based on reference stream channel characteristics. (Harrelson et al. 1994; Rosgen 1996)

Lastly, to expedite cross section measurements the team can use a simplified model of the excavated crossing. Many forests use this model in the inventory phase, modeling the cross section as parallelograms. The team calculates the total area of the cross section by subtracting the area of the two triangles on the sides from the parallelogram area. (San Dimas Technology and Development Center Website, *http://fsweb.sdtdc.wo.fs.fed.us/programs/im/fy04/rdmt/*).

The line intercept transect used on the road prism stabilization can measure surface erosion and effective soil cover. Mass wasting documentation is evaluated during the years after implementation, or if an event occurred that triggered some instability. Data collected for mass wasting

is an estimate of size (L x W x D) and amount of material moved. The team can determine how much of the material stayed on the hillslope and how much entered a stream.

Revegetation monitoring goes beyond measurement of effective soil cover to prevent surface erosion, and records the species composition and community types present. Monitoring protocols are available to determine the effectiveness of the treatment on revegetation.

Use protocols that best capture the type of vegetation the area is capable of producing. For example, the Greenline protocol is useful for monitoring meadow or riparian vegetation response to road decommissioning. (Winward 2000) In drier sites other protocols may better capture the species composition and community types present. In forested areas, the Forest Inventory Analysis (FIA) inventory protocols may be used to track changes in vegetation type.

Strengths of the Actual Measurements

When measurement data is linked to specific monitoring questions and succinct objective statements, the effectiveness of the treatment can be assessed. However, with general objectives and poorly defined monitoring questions, the determination is difficult even with actual measurements.

Actual measurements can help separate out and categorize the sample pool by independent variables, such as: bedrock geology, soil type, hillslope position, hillslope gradient, size of excavation, time since implementation, and contract method. The team can more easily manipulate the data to keep independent variables from confounding the results.

The team can take actual measurements for erosion, stream channel adjustments, and vegetation with a variety of proven and effective protocols. Depending on the monitoring plan questions, more emphasis may be given to stream channel adjustments than to erosion from the decommissioned road prism.

Limitations of Actual Measurement Monitoring

To ensure the accuracy of measurements and documentation, all monitoring protocols require training and spot-checking. Personnel need thorough training. To collect good data requires confidence in the use of equipment and a thorough understanding of the assumptions and questions underlying the monitoring plan.

Actual data collection takes more time than photo documentation, tracking, or BMP monitoring, because the crew will not be able to sample as many sites in the available time.

As with all monitoring, the team needs to design the method of data analysis before any data is collected. For actual measurement monitoring, a database may be necessary to expedite analysis of the data. Database development is not difficult, but the IDT must have the necessary skills or access to skills to ensure this step is taken prior to data collection.

Best Management Practices

Best Management Practices (BMPs) are a set of practices, procedures and programs that comply with requirements of Sections 208 and 319 of the Federal Clean Water Act (PL92-500). Section 208 of the Clean Water Act states that the agencies responsible for implementing the State Water Quality Management Plan must be designated as a Water Quality Management Agency (WQMA). In California, the Forest Service has a Management Agency Agreement (MAA) with the State Water Resource Control Board designating the Forest Service as the WQMA for NFS lands in California. BMPs are identified for all land-disturbing projects. Each forest monitors the implementation and effectiveness of the BMPs for road decommissioning. (San Dimas Technology and Development Center Website, *http://fsweb.sdtdc.wo.fs.fed.us/programs/im/fy04/rdmt/*)

Each Forest Service region implements a BMP program. The monitoring reports vary from region to region, depending on what agencies are designated as responsible for implementing the State Water Quality Management Plan. Currently there is emphasis to develop a national BMP effectiveness program that is similar to the Forest Service Region 5 (Pacific Southwest Region) program.

Region 5 BMP Effectiveness Program (EP) monitoring includes the following:

- Annually develop a sample pool of all road decommissioning projects (old and new)
- Conduct an in-office review of NEPA documents, timber sale contracts, and restoration contracts to identify the water quality issues and objectives for the project.
- Conduct a field review comparing the planning document objectives to the on the ground results.
- Using the established protocols for ground cover and revegetation, rilling, compaction, slope failure, and traffic control, complete the data sheet.
- For effectiveness evaluations of stream crossings, use numeric indicators for channel adjustment, including downcutting and lateral channel adjustment. (Refer to attached R-5 BMP form and protocol link, San Dimas Technology and Development Center Website at *http://fsweb.r5.fs.fed.us/unit/ec/water/*

final_bmpep_protocols/Final_BMPEP_Forms-Onsite_Evaluations_06_10_02.pdf)

- Attach photographs to the data sheets at the time of field review.
- Conclude the effectiveness of the treatment with data entry into the BMP database (R5) analysis of the indicators.

Strengths of BMP Monitoring

The BMP format is useful for several reasons. First, review of water quality considerations in the decommissioning plan tells the reviewer what the planning team identified as the water quality values at risk. The office review may also highlight missing information about water quality objectives.

Second, the field review for implementation puts the reviewer at the site, during or shortly after the work is completed. Implementation monitoring can allow for mid-course corrections if the situation requires.

Finally, a second field review within two years after project implementation assesses treatment effectiveness.

Limitations of BMP Monitoring

Limitations to BMP monitoring are training, qualifications and timely evaluations.

The monitoring team should ensure that personnel resources are trained and available to conduct the BMP evaluation. Well-qualified and trained personnel reduce subjectivity and error.

BMP monitoring must occur within two years of implementation. However, if only mild weather conditions prevail during the first two years, they may not test the treatment fully. Consider the climatic factors and design storm the treatment was designed for when monitoring. Some types of problems with road decommissioning results become evident only after a large storm event.

BMP monitoring lumps dissimilar sites and treatments as one. Stratify BMP records by treatment types, geology, climatic regimes, and other variables when designing the monitoring plan.

Photo-Point Monitoring

Photographs or digital photos are a common tool for detecting changes and trends in road decommissioning projects (Hall 2002). Photo monitoring is a simple, cost effective, and reliable procedure that documents the properties of a site. Repeat photos taken from the same location and angle are useful "change indicators" and can be sampled with dot grids to document change in vegetation and other attributes. In addition, photos can augment other more intensive monitoring.

In photographing road decommissioning work it is important to capture the appropriate scale, timing, location, and representative photo points. If this is the selected monitoring tool, or one used in combination with other monitoring, there are some key points that should be included in the monitoring plan to improve photo point monitoring quality.

Identify measurable objectives for photo documentation, including what and where to monitor. Questions related to why, when, and how to monitor should be included as a component of the monitoring plan.

Photo-point monitoring is used for implementation, effectiveness, and trend monitoring, with some attributes being easier to photograph than others. Commonly used indicators include soil cover, streambank stability, vegetative composition and revegetation of riparian areas. Table 3 provides information on the indicator, type of monitoring, and frequency.

Keys to reliable and repeatable photo monitoring:

Hall (2002) outline a useful set of instructions for effective photo point monitoring.

1. Take the photo from the same point, in the same direction each time the photo is repeated. Identify the location with tags or GPS readings to enable anyone to get back to the same site. Take a copy of the photo to the field for the correct settings. Don't set up a photo monitoring and record keeping system so that only you can get back to the site. A lot of invaluable information has been lost by poorly documented and maintained photo records.
2. If possible, use a camera that documents the date the photo is taken on the face of the photo. Use a white board or a photograph identification form with large letters to identify within the photo what the subject is, and its location.
3. Take the photos on or about the same time of year. Include a consistent tool for scale in each photo. Depending on what you are monitoring the scale will change, meter boards are often used for vegetation and stream bank stability. Select the appropriate tool and maintain consistency.
4. Maintain a photo notebook or use 3 X 5 cards to capture any additional information on the photo. This can be useful if other people are collecting the data. Many monitoring systems are now being designed that link Personal Desk Recorders (PDRs), Global Positioning Systems (GPS) and photographs together.

Table 3: Items to consider when using photo-point monitoring for effectiveness monitoring of road decommissioning treatment.

Indicator	Considerations	Type and Time to Monitor
Channel Adjustment – channel cross section	This indicator is best to be measured directly and the use of photographs is in addition to the before and post treatment data. Photographs during or after an event help us understand what conditions look like during an event which can help us in design. Post event photos can capture any change in channel adjustment as a result of the event.	***Effectiveness:*** Good quality photos can be used later in years that are not more intensively monitored and where change does not appear to be significant. ***Event:*** after storms that may "test" your design. In-channel measurements right after an event may not be feasible.
Soil Cover	If the treatment required a soil cover (mulch or natural) to be applied photos can be used to quantify cover. Use close-up shots of a defined plot that may be 1 square foot in size.	***Implementation:*** taken during or immediately after project is completed.
Soil Cover	Photos can be taken each year to evaluate effectiveness of cover.	***Trend and Effectiveness:*** should be taken at the same time of year.
Mass Wasting	It is hard to obtain before photos of this unless you have a specific area that you are concerned about. Otherwise most photos will be event driven or effectiveness monitoring.	***Event:*** Photos taken after an event help to link weather conditions with effect. ***Trend:*** On -going monitoring of stream bank conditions or identified unstable areas taken annually can provide information on recovery.
Revegetation of Riparian Areas	The treatment may prescribe a certain number or density of cuttings, transplanting of sod plugs, or native seeding.	***Implementation:*** During or right after to identify if the treatment was done correctly.
Revegetation of Riparian Areas	Good monitoring site selection is important since vegetation can increase dramatically. In some cases when vegetation is NOT the objective, it can obscure the indicator.	***Effectiveness:*** annually during and or at the close of growing season.

This is a good way to ensure that all the data is together, and that both the data and the photo point can be relocated.

5. Ensure the photo quality is adequate for its intended use. Not all digital cameras are created equal. Adjust the settings to be sure the highest resolution and image size is always used.

Tracking Methodologies

Tracking methodologies are a tool to record completed road decommissioning treatments.

The objective of tracking tools is to record what was done, when it was done, and how much material was removed. The Forest Service tracks annual road decommissioning miles using INFRA (the FS infrastructure maintenance database). Accomplishments may also be tracked with spreadsheets or other database tools. Key information to record in spreadsheets includes the following:

- Date of activity
- Road number
- Road treatment
- Road length
- Number of road crossings treated
- Road crossing volume removed

This information may be recorded by watershed. Records can be obtained from inventory data on the condition of the road and the size of the road crossings. The database can be linked to GIS and photo documentation of each site.

Conclusion

Interdisciplinary teams have several approaches available to monitor road decommissioning effectiveness. Each team needs to consider the goals and objectives of monitoring that are built on findings and assumptions stated in the WA and RA process. Monitoring can answer questions the interdisciplinary team has on the processes that are restored

by road decommissioning. For more information on road decommissioning effectiveness monitoring and monitoring forms, go to *http://fsweb.sdtdc.wo.fs.fed.us/programs/im/fy04/rdmt/*

Road Decommission Monitoring Techniques Links

http://fsweb.r5.fs.fed.us/unit/ec/water/final_bmpep_protocols/Final_BMPEP_Forms-Onsite_Evaluations_06_10_02.pdf.Link to Region 5 BMPEP for forms and protocol.

http://fsweb.r5.fs.fed.us/unit/ec/water/water-best-mgmt.pdf. Background information on R-5 BMP authority and procedures.

http://www.stream.fs.fed.us/ Link to Stream Team website

http://www.stream.fs.fed.us/publications/PDFs/RM245E.PDF Link to document on how to establish Stream Channel Reference Sites.

http://www.watershed.org/wmc/index.php - links to Watershed Management Council newsletter and database

http://www.mattole.org/ community based restoration and monitoring efforts.

http://www.cnps.org/archives/forms/releve.pdf - Vegetation Monitoring sample method use Releve' technique.

http://www.cnps.org/archives/forms/releveform.pdf - actual data form

http://www.firelab.org/firemon/pd.htm for information on ECODATA plot inventory.

http://www.fs.fed.us/pnw/pubs/gtr526/ Photo Monitoring tools

http://www.fs.fed.us/pnw/pubs/gtr503/gtr503f.pdf Photo Monitoring tools

http://anrcatalog.ucdavis.edu/pdf/8067.pdf Photo Monitoring for Better Land Use Planning and Assessment - Good resource for why and how to monitor.

http://fsweb.f5.r6.fs.fed.us/aquatics/monitoring/index.shtml Good example of watershed restoration effectiveness monitoring plan.

http://fsweb.wo.fs.fed.us/directives/fsm/7700/ References Transportation System and Roads Analysis process.

http://www.wildlandscpr.org/roads/RRtoolkit.htm Provides information on current wildlife monitoring of road decommissioning projects.

http://fsweb.nris.fs.fed.us/about_us/index.shtml NRIS website information.

http://www.fs.fed.us/rm/pubs/rmrs_gtr047.pdf Provides information on how to monitor vegetation in riparian areas.

http://fsweb.sdtdc.wo.fs.fed.us/programs/im/fy04/rdmt/ Link to San Dimas Technology and Development Center website for road decommissioning. Contains existing monitoring reports and forms by other forests.

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Section 4. Valuing the Earth Sciences
Part 1. Soil

Overleaf:
Pinchot Pass, Kings Canyon National Park, Sierra Nevada, California. Photo by Michael J. Furniss.

Ten-Year Results From the North American Long-Term Soil Productivity Study in the Western Gulf Coastal Plain

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Forest management operations have the greatest potential to reduce soil productivity through altered soil fertility and air/water balance, which are most affected by organic matter removal and compaction, respectively. The objectives of this study were to assess the early growth response to compaction, organic matter removal, and weed control on the ten locations of the Long-Term Soil Productivity study on the Kisatchie, DeSoto, and Davy Crockett National Forests (Louisiana, Mississippi, and Texas). Three levels of compaction (none, moderate, severe) and three levels of organic matter removal (stem only, whole tree, and whole tree plus forest floor) were applied in a factorial design at each site, and half of each treatment plot was kept free from interspecies competition with herbicides. Soil compaction had no negative impacts on tree growth at ten years; most sites responded positively to compaction due to the reduction of shrub understory competition. Removing more organic matter than the stems reduced stand volume on eight of the ten sites by more than 15 percent. This study indicates that harvesting operations that remove tree branches and foliage, and site preparation operations that remove the forest floor, such as site preparation burns, can have negative impacts on long-term soil productivity.

Keywords: *long-term productivity, soil compaction, nutrients, forest practices, guidelines for management, monitoring, vegetation management, loblolly pine,* Pinus taeda *L.*

Introduction

The North-American Long-Term Soil Productivity (LTSP) study began as a collaboration of the National Forest System and Forest Service Research in 1989. The study was founded to answer fundamental questions regarding the long-term consequences of soil disturbance on forest productivity, through carefully designed trials throughout the nation. The originality, scope, and careful design encouraged other partnerships to form among the Forest Service, forest industry, and academia. Fifteen years later, the comprehensive program has over 100 installations in the U.S. and Canada that comprise the world's largest coordinated research network addressing basic and applied science issues of forest management and sustained productivity.

Furniss, M.J., Clifton, C.F., Ronnenberg, K.L., eds., 2007. *Advancing the fundamental sciences: proceedings of the forest service national earth sciences conference, San Diego, CA, 18-22 October 2004*. PNW-GTR-689. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station.

The LTSP program was founded in response to the National Forest Management Act of 1976 (NFMA). The NFMA states that the Secretary of Agriculture must ensure, through research and monitoring, that forest practices do not cause a lasting reduction of the productivity of the land. This mandate was clarified somewhat by the report of a committee of independent scientists (Code of Federal Regulations 1985) that, in part, stated that the Forest Service must monitor the effects of forest prescriptions on "significant changes in land productivity". The Forest Service recognized that clear, scientifically-based definitions of "significant changes in land productivity" and monitoring criteria would be needed to avoid dispute. The term "land productivity" is quite subjective, and can refer to any number of forest attributes and functions. However, at its most fundamental nature, land productivity can be considered a site's capacity to capture carbon in growing plants, i.e., net primary productivity (NPP). Because NPP, the sum of all dry matter produced per unit area per unit time, fluctuates greatly due to climate, stand development, and other factors not related to the

land, it was also decided that a 15 percent departure from a baseline would be deemed "significant" (USDA Forest Service 1987).

The Forest Service needed some metric other than NPP to monitor, however, because the intensity of effort required to measure NPP makes it impractical under operational monitoring conditions. Tracking stand growth through time, while operationally possible, does not assess soil productivity per se; differences in climate, stocking, genetics, vegetation management, and other practices affect forest productivity without affecting soil productivity (Burger 1996; Powers 2001). An alternative is to relate land productivity to measurable soil processes (Burger and Kelting 1999). The Forest Service adopted this approach, which is based on the following rationale (Powers and Avers 1995):

1. Forest management practices disturb soils
2. Soil disturbances affect soil properties and processes
3. Soil properties and processes determine site productivity

The approach has been used to develop preliminary monitoring protocols (Powers and Avers 1995; Powers et al. 1998; Page-Dumroese et al. 2000) based on the best scientific data available and personal experience. It has also been verified in research settings (Kelting et al. 1999).

Unfortunately, it is impossible to directly measure all soil properties and processes. Therefore, careful experimentation was needed to determine, for each region, what soil properties and processes were most indicative of productivity. Thus, the National Forest System asked Forest Service Research to develop a coordinated study to address these issues. A detailed review of the literature regarding forest management and site productivity determined that the two most fundamental causes of productivity loss following forest management activities were organic matter removal and soil porosity loss (Powers et al. 1990). The review also concluded that scant direct evidence of productivity loss was available, largely because previous studies were not designed well enough to clearly determine cause and effect. Previous studies of soil physical disturbance were confounded by different levels of organic matter removal and weed control, and studies of harvest intensity have been confounded by soil physical disturbance. Many of these studies were further complicated by uncontrolled differences in climate, stocking, and weed competition (Morris and Miller 1994).

Therefore, the founding principles of the LTSP study were that (1) soil is the key factor controlling site productivity that is affected by management, (2) the fundamental measure of productivity is vegetative carrying capacity, expressed as dry biomass accumulation, and (3) removal of site organic matter (slash and/or forest floor) and soil compaction are the most common causes of long-term productivity loss. The LTSP design was chosen to specifically address these problems and focus on the long-term cause and effect relationships between organic matter, soil compaction, and site productivity. The specific hypotheses LTSP was designed to test are shown in Table 1.

Powers et al. (2004) reported on the 10-year findings from selected installations on the southern Atlantic and Gulf coastal plains and in the Sierra Nevada Mountains in California, highlighting major trends. They found that little evidence existed for universal impacts of either soil compaction or organic matter removal, but the presence of understory vegetation caused a clear and widespread reduction in planted tree growth. Within a given region, however, generalized findings may not apply. Scott et al. (2004) reported on the 5-year results from 13 loblolly pine (*Pinus taeda*) sites across the soutern US, and found that results from one site were not necessarily indicative

Table 1. Hypotheses of the Long-Term Soil Productivity Study.

Hypothesis	H_0	H_a
1	Pulse changes in site organic matter and/or soil porosity do not affect the sustained productive potential of a site.	Critical changes in site organic matter and/or soil porosity have a lasting effect on potential productivity by altering soil stability, root penetration, soil air, water and nutrient balances, and energy flow.
2	If impacts on productivity occur from changes in organic matter and porosity, they are universal.	The biological significance of a change in organic matter or porosity varies by climate and soil type.
3	If impacts do occur, they are irreversible.	Negative impacts dissipate with time, or can be mitigated by management practices.
4	Plant diversity has no impact on the productive potential of a site.	Diverse communities affect site potential by using resources more fully or through nutrient cycling changes that affect the soil.

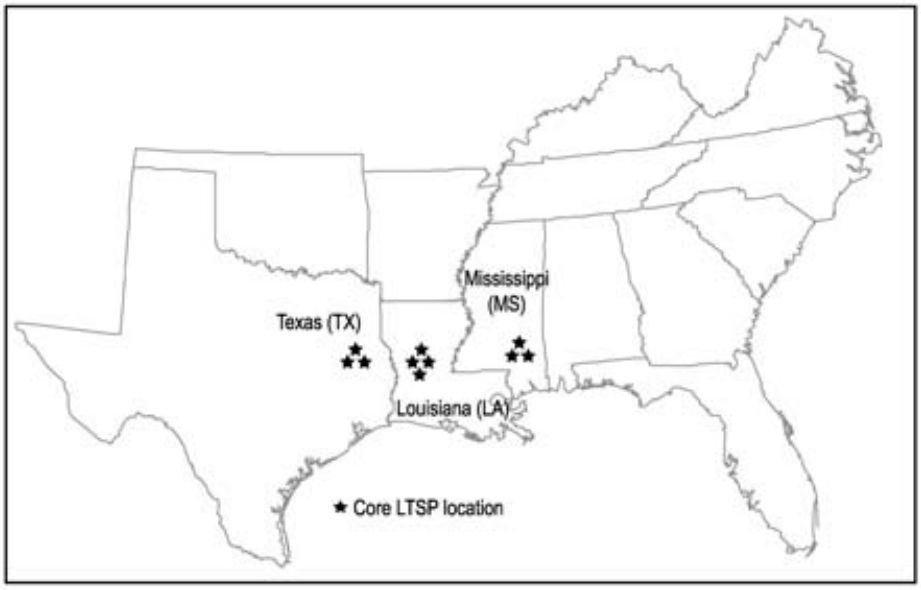


Figure 1. Ten locations of the North American Long-Term Soil Productivity study in the western Gulf Coastal Plain.

of other sites in the same area. Accordingly, the objectives of this paper are to: (1) determine how soil compaction and organic matter removal at harvest and stand diversity after harvest affected the site productivity of loblolly pine at age 10 years in the western Gulf Coastal Plain; and (2) determine soil or site indicators of productivity response to soil compaction and organic matter removal.

Materials and Methods

Study Sites

Ten locations of the LTSP study were installed in the southern United States Gulf Coastal Plain from 1990 to 1995 (Figure 1). All sites are located in the humid-temperate-subtropical Southern Mixed Forest or Outer Coastal Mixed Forest Province (Bailey 1995). Four sites were installed in the Kisatchie National Forest in Louisiana, while three sites each were installed in the DeSoto National Forest in Mississippi and the Davy Crockett National Forest in Texas, respectively. The soils were common Ultisols and Alfisols found on coastal plain uplands and terraces, and were formed from marine and alluvial sediments (Table 2). The surface soils ranged in texture from fine sandy loam to silt loam and overlaid heavier textured subsoils. The understory on the Louisiana and Texas plots was characterized by shrubs and small trees common across much of the southern coastal plain, including sweetgum (*Liquidambar styraciflua*), wax myrtle (*Morella cerifera*), yaupon (*Ilex vomitoria*), and assorted oaks (*Quercus* spp.). The understory in Mississippi was dominated by inkberry (*Ilex glabra*).

Treatments

Nine treatments were imposed in a 3 by 3 factorial design following a clearcut harvest of the existing stand, with organic matter removal and compaction as the main treatment factors and vegetative diversity as a split-plot factor (Figure 2). The three organic matter removal treatments were stem-only harvest, whole-tree harvest, and whole-tree harvest plus forest floor removal. The three levels of compaction were no compaction (no mechanical equipment was allowed on plots during harvesting), moderate compaction, and severe compaction. Severe compaction was defined as 80% of the root-growth limiting

Table 2. General site data for the ten locations of the Long-term Soil Productivity study in the Gulf coastal plain region.

Location	National Forest	Soil Series	Year Established	Previous Stand	Understory
LA 1	Calcasieu RD, Kisatchie NF	Malbis	1990	Loblolly	Grass
LA 2	Catahoula RD, Kisatchie NF	Glenmora	1992	Loblolly	Shrub
LA 3	Catahoula RD, Kisatchie NF	Metcalf	1993	Loblolly	Hardwood
LA 4	Catahoula RD, Kisatchie NF	Mayhew	1993	Loblolly	Hardwood
MS 1-3	Chicksawhay RD, Desoto NF	Freest	1994	Slash plantation	Shrub
TX 1-3	Davy Crockett NF	Kurth	1997	Loblolly/shortleaf	Shrub

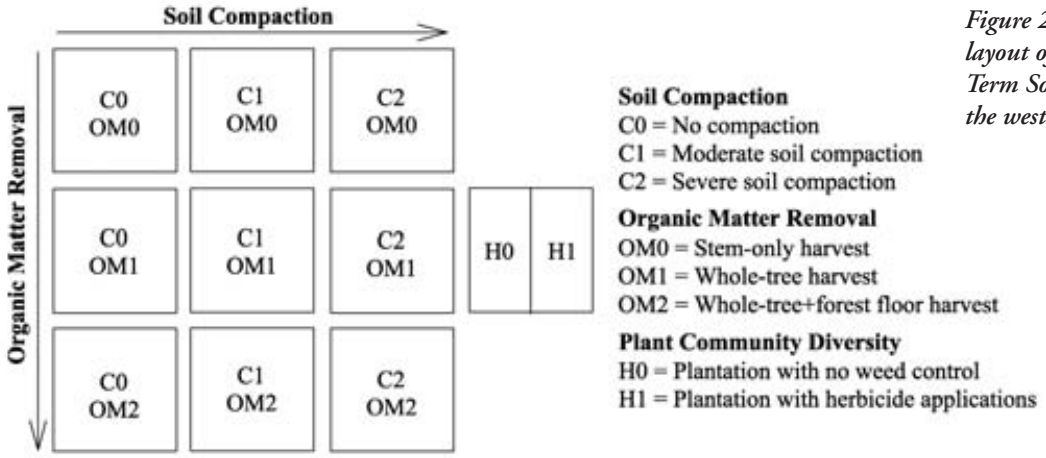


Figure 2. Treatment design and plot layout of the North American Long-Term Soil Productivity study sites in the western Gulf Coastal Plain.

bulk density, as determined from soil texture (Daddow and Warrington 1983). A field-based Proctor test was used to determine load and compaction level relationships at each site. Moderate compaction was defined as the geometric mean bulk density between the no compaction and severe compaction levels. The two experimental compaction levels were induced by pulling a multi-tire road compactor with two levels of ballast across the plots six times (Figure 3). After treatment installation, container loblolly pine seedlings from ten known half-sib families were planted at a 2.5-by-2.5-m spacing. Each 0.4-ha treatment plot was split into two 0.2-ha subplots (Figure 2). One of the subplots was kept clear of competing vegetation by manual removal and directed-spray herbicide applications (primarily glyphosate). Competing vegetation was allowed to grow freely on the paired subplot. Volunteer pines were controlled manually on all plots. Measurement plots were the interior 0.1 ha of each subplot.

Measurements

At age 10 years (age 5 in Texas), we measured tree height and diameter at breast height (dbh) of all pine trees in the 0.1-ha measurement plot with height poles and calipers. Pine volume was estimated using equations from Baldwin and Feduccia (1987). Prior to treatment, five soil samples were collected to 15 cm with a push probe sampler on each of three transect lines across each measurement plot and bulked by transect line. Mehlich III available soil P (phosphorus) (Mehlich 1984) and exchangeable Ca, Mg, and K (calcium, magnesium, and potassium) (Gillman 1979) were determined for each sample on a Hewlett-Packard 8453 colorimetric spectrophotometer[1] and a Perkin-Elmer 2100 atomic absorption spectrophotometer, respectively. Soil carbon was determined on a LECO CNS analyzer and converted to soil organic matter. Soil bulk density samples were collected prior to treatment, at age

Figure 3. Wobble-wheel road compactor and dozer used to compact soils in the western Gulf Coastal Plain Long-Term Soil Productivity sites. Photo by Allan Tiarks.

[1]The use of trade or firm names in this publication is for reader information and does not imply endorsement by the U.S. Department of Agriculture of any product or service.

5 years and at age 10 years, with a custom core extractor from ten random locations throughout each measurement plot in the four Louisiana sites. The sampler extracted a 5-cm diameter by 30-cm length soil core, which was then separated into 0-to-10-cm, 10-to-20-cm, and 20-to-30-cm sections. The soils were dried at 105°C to a constant weight, and bulk density was recorded.

Data Analysis

The main effects of soil compaction, organic matter removal, and stand diversity (competition control) on loblolly pine growth were compared using analysis of variance (ANOVA), and the means were separated using a Duncan's Multiple Range Test at P = 0.10 (SAS Institute 2000). The relationship between soil P and relative productivity was determined with least-squares regression. The influence of compaction level and stand age on bulk density was determined with a mixed-model analysis of variance.

Results and Discussion

Main Treatment Effects on Loblolly Pine Growth

Early stand volume production was generally increased by soil compaction, decreased by whole-tree harvesting, and increased by chemical weed control. Soil compaction increased volume growth in Louisiana and Mississippi by 16 and 24%, respectively (Table 3). It had no impact on volume growth of the pine trees in Texas at age 5. Compaction intensity had no effect. The moderate and severe compaction treatments had the same influence on stand growth in each state.

Organic matter removal had no significant effect on stand volume across the four blocks in Louisiana, but intensive organic matter removal clearly decreased productivity in Mississippi and Texas (Table 3). In Mississippi, the whole-tree harvest and whole-tree+forest floor harvest treatments reduced volume production by an average of 24% relative to the stem-only harvested treatment. In Texas, the whole-tree harvest treatment reduced productivity at age 5 by 26% compared to the stem-only treatment, and removing the forest floor increased this reduction to 65%.

The plantations with simple vegetative communities produced much more timber than the diverse communities. Across the Louisiana and Mississippi sites, chemical control of competing vegetation increased pine productivity by almost 50% compared to the plantations with no chemical weed control (Table 3).

Site-Treatment Interactions and Response to Compaction

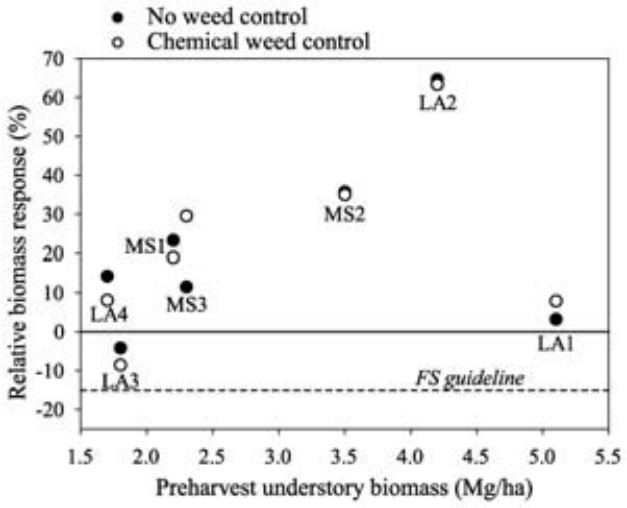
Compaction had the greatest positive impact on the relative volume of loblolly pine on the LA2, MS2, MS3, and MS1 sites (Figure 4), and the positive impact of compaction was related to the quantity and type of preharvest understory (less than 7.6 cm dbh). The LA2, MS2, MS3, and MS1 sites all had a heavy understory of shrub species and small hardwood trees (Table 2). The LA2 site was dominated by wax myrtle, yaupon, and sweetgum. The Mississippi sites were dominated by inkberry. The LA1 site, which had the most understory biomass before harvest, showed no positive response to compaction. The understory at LA1 was almost exclusively grass, due to frequent cattle grazing and prescribed fires. LA1 was also compacted before treatments due to the history of cattle grazing, and the experimental compaction was less effective at changing bulk density at this site (Tiarks et al. 1991). The LA3 and LA4 sites had little understory biomass and showed little response to compaction. These sites, however, had the greatest hardwood biomass (greater than 7.6 cm dbh) of all the sites (data not shown). The LA3 site was the only site to exhibit a negative response to the compaction. The Metcalf soil on LA3 was originally classified as an

Table 3. Stand volume response at age 10 to soil compaction, harvest intensity, and chemical weed control in three replicated LTSP study sites in the western Gulf coastal plain.

Treatment	Stand Volume (cubic meters per hectare)		
	Louisiana	Mississippi	Texas[2]
No Compaction	96b[1]	64b	4.8a
Moderate compaction	115a	79a	5.1a
Severe Compaction	107a	80a	5.1a
Stem-only harvest	111a	89a	6.9a
Whole-tree harvest	102a	66b	5.1b
Whole-tree+forest floor harvest	105a	70b	2.4c
No weed control	83b	62b	4.7a
Chemical weed control	129a	87a	5.3a

[1]Means within a column followed by the same letter are not significantly different at P < 0.10.
[2]Texas data were from age 5.

Figure 4. Average loblolly pine volume response at age 10 on compacted soils relative to the uncompacted soils as a function of the preharvest understory biomass on across the Louisiana and Mississippi Long-Term Soil Productivity study sites.



Alfisol when the study was installed, but was reclassified as a Vertisol. The soil texture at LA3 and LA4 averaged 29% clay in the upper 30 cm, whereas the average clay content of the LA1, LA2, and the MS sites was only 19% in the upper 30 cm.

The positive response of the planted pines to compaction on the sites with heavy shrub-based understories indicates that the understory plants were negatively impacted by compaction. The compaction probably did not have a direct effect on the plants; breaking stems and exposing roots would likely increase sprouting and dominance of these species. Compaction did not have an additive effect with the herbicide treatments. While the herbicide treatments were quite effective on relative loblolly pine productivity on all plots (Table 3), the herbicide application on the compacted plots had no additional impact compared to the uncompacted plots (Figure 4). Therefore, it is likely that the compaction had an indirect impact on the understory plants by increasing soil strength and reducing aeration. The planted pine probably responded because this indirect impact on the soil was not as important as the reduction of competition for resources.

In the early stages of the LTSP study, many foresters and scientists expected the soil compaction treatment to have the greatest negative impact on productivity. Soil physical disturbances are visually unappealing, and evidence of compaction-induced productivity losses in southern pine stands is abundant (Hatchell et al. 1970; Tiarks 1990; Aust et al. 1995; Miwa et al. 2004). One explanation of the lack of negative response may be that we did not achieve enough soil disturbance or the right form of disturbance to have a biological impact on the planted pines. This was definitely the case at the 20-30 cm depth, where the compaction treatments had no impact on bulk density in Louisiana (Table 4). The form of physical disturbance we created (compaction) is only one form of disturbance caused during forest management activities such as logging. Rutting and churning, unlike simple compaction, disturb not only the soil porosity, but they also disturb soil structure and may have a greater impact than simple compaction (Tiarks 1990). While compaction is usually the dominant forest management-induced soil disturbance, these results can not be applied to rutted or churned sites and may explain discrepancies between these data and previous studies.

Another explanation is that these trees are still quite young and only recently attained full canopy closure. Short-term results are not always indicative of long-term results, especially when multiple processes are functioning. For example, while the early productivity of the planted pines was improved by the compaction, it appears this increase was caused by a reduction in understory plants that were more susceptible to changes in soil properties. After canopy closure, when intraspecific competition for site resources will be greater than interspecific competition, soil properties will likely have a greater relative impact on pine productivity than before canopy closure. Essentially, as the stand matures, understory competition will be less important to pine productivity relative to near-surface soil

Table 4. Compaction effect on bulk density at three depths across four LTSP sites in Louisiana immediately after treatment and ten years after treatment.

		Bulk Density (megagrams per cubic meter)		
Depth	Compaction	Age 0	Age 10	Change[2]
0-10	Uncompacted	1.32b[1]	1.26b	-0.07b
	Moderate	1.41a	1.27b	-0.14a
	Severe	1.43a	1.30a	-0.13a
10-20	Uncompacted	1.48b	1.39c	-0.08a
	Moderate	1.54a	1.46b	-0.07a
	Severe	1.56a	1.48a	-0.07a
20-30	Uncompacted	1.51b	1.45c	-0.06a
	Moderate	1.52ab	1.47b	-0.05a
	Severe	1.53a	1.49a	-0.03a

[1]Means within a column and soil depth followed by the same letter are not significantly different at P = 0.10.

[2]Discrepancies between the difference of the Age 0 and Age 10 data and the change in bulk density data were due to rounding. All changes in bulk density from age 0 to age 10 were significantly different at P = 0.05.

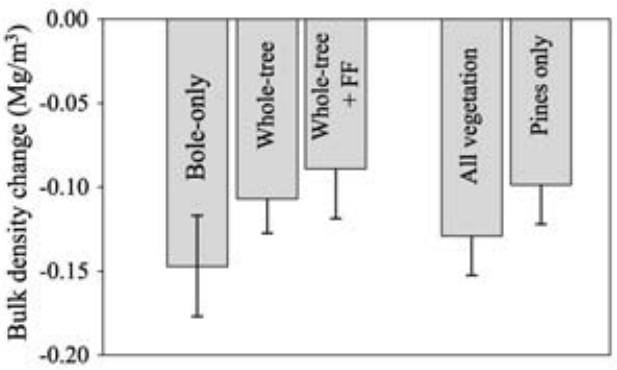
properties. Because of this, we also wanted to assess how well the soil has recovered from compaction to indicate whether long-term responses to compaction would be similar to or different from short-term responses.

Soil Recovery from Compaction

Bulk density in the surface soil at the four Louisiana sites was significantly increased by compaction at all three depths. The degree of compaction had no relative impact; the moderate and severe treatments resulted in similar bulk densities immediately post-treatment at all depths (Table 4). The bulk density of the compacted soils remained elevated over that of the uncompacted soils 10 years after treatment. The recovery of the bulk density was greatest in the surface 10 cm, but was significant at all depths (Table 4). Although recovery was significant at the lower two depths, it did not differ based on compaction intensity (Table 4), organic matter removal, or herbicide application. The surface 10 cm recovered differently depending on the treatment. Whole-tree and whole-tree+forest floor harvesting reduced the bulk density recovery from almost 0.15 Mg/m^3 to about 0.10 Mg/m^3 (Figure 5). Chemical weed control also reduced the recovery by about 0.03 Mg/m^3.

Natural recovery of soils from compaction occurs primarily through three mechanisms (Miwa et al. 2004). The first and generally most important process is shrinking and swelling of 2:1 expanding clays. The second, much less common in the southern coastal plain, is freezing and thawing. The third process is through biological disturbance; root penetration and biopedoturbation. The recovery of the deeper surface layers was unaffected by organic matter removal and chemical weed control. In the surface 10 cm, however, the recovery was reduced by removing tops and forest floor and by controlling the non-pine vegetation chemically. Removal of the forest floor and weeds may have altered the soil warming and cooling cycles and changed the freeze-thaw dynamics, but these treatments more likely altered bulk density recovery by affecting biopedoturbation. Coarse woody debris serves as a host for many insects and other ground-dwelling organisms (Harmon et al. 1986). Termites decompose the coarse woody debris and transport soil into the decomposing material (Tiarks et al. 1999). This soil juxtaposition caused by organisms is a natural amelioration for soil physical disturbances. The understory control probably lowered the bulk density recovery by reducing the number of fine roots exploiting the surface soil. Prior to canopy closure, the fine roots from the understory were probably much more numerous than the fine roots from the developing pine stand, and therefore had the most direct impact on soil compaction amelioration.

Figure 5. Change in bulk density of the surface 10 cm over ten years on the Louisiana LTSP sites as a function of organic matter removal and chemical weed control. Error bars represent one standard error.



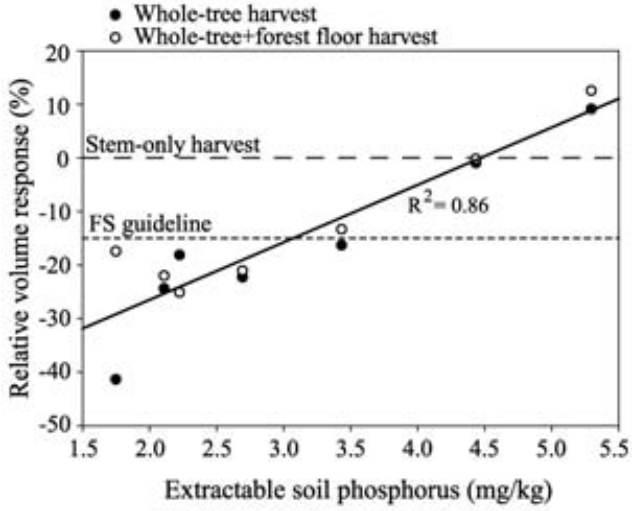
Site-Treatment Interactions and Response to Organic Matter Removal

At age 5 years, productivity loss due to whole-tree harvesting and whole-tree+forest floor harvesting was clearly related to site productivity as measured by the stem-only biomass growth at that time; productivity loss was greatest on sites with the lowest productivity (Scott et al. 2004). However, this measure would not be useful in assessing stands prior to harvest for potential declines.

We studied the relationship between surface soil nutrients and productivity loss. The soils were essentially either fertile or very infertile with respect to calcium, magnesium, and potassium (data not shown), which provided little insight regarding whether or not the harvesting reduced productivity. Soil phosphorus (P) was clearly related to the harvest intensity impact. The linear relationship between preharvest soil P concentrations and the relative biomass response was highly significant ($p < 0.0001$) and explained 86% of the variation (Figure 6). Whole-tree harvesting reduced productivity by 15% or more on the sites with less than 3.1 mg/kg of Mehlich III available P. This is very similar to the 3 mg/kg soil critical level reported for determining sites responsive to P fertilizer (Wells et al. 1973), and may be a good monitoring criterion for determining sites susceptible to productivity loss caused by organic matter removal.

Coastal plain soils, while ranging in texture from coarse sands to heavy clays, have widespread nutrient limitations. While soil N deficiencies are more widespread and have been more of a concern with respect to harvesting intensity, phosphorus deficiencies are common as well across the

Figure 6. Loblolly pine response at age 10 on the whole-tree and whole-tree+forest floor harvested plots relative to the stem-only harvested plots as a function of preharvest available soil phosphorus across the Louisiana and Mississippi Long-Term Soil Productivity sites.



southeastern United States (Allen 1987). Organic matter decomposition and nutrient release is of even greater importance to nutrient availability on weathered soils with infertile parent material. Research from Australia (Farrell 1984) and New Zealand (Smith et al. 2000) has indicated that harvest residues should be maintained on sandy sites to ensure productivity, largely due to reductions in N availability. Soil texture has been considered a primary variable in the role of organic matter and sustained forest productivity (Vance 2000), but data from these loamy Gulf coast LTSP sites show that soil texture is not exclusively indicative of low fertility in this region.

In many commercial harvesting operations in the southern pine region, whole-tree harvesting occurs by default since much of the tree crown biomass and slash is often concentrated near landings, even when efforts are made to redistribute the material through the stand. Therefore, additional care should be taken on soils with low available P to redistribute the slash evenly or consider P fertilization.

Conclusions

The LTSP study is the single largest study of forest management practices and soil productivity in the world. It was designed to help national forest planners meet the letter and spirit of several pieces of legislation by ensuring that forest management practices do not degrade soil productivity. It was also designed to develop and validate monitoring criteria that could be used in planning and monitoring protocols. The national forests and ranger districts in the Gulf Coastal Plain with LTSP installations benefit by having the sites in the planning and monitoring phases. They help in the National Environmental Planning Act (NEPA) process by providing research data on long-term effects. Referencing the LTSP study results adds to the credibility of their NEPA evaluations. The Forests also benefit from the close relationship to Forest Service Research, and vice versa. Several other studies on soil productivity and management have been implemented in the region based on this mutual interaction.

Soil compaction, organic matter removal, and stand diversity all had substantial impacts on the growth of planted loblolly pine across 10 sites in the western Gulf Coastal Plain. Soil compaction had a positive impact on loblolly pine growth at 9 of the 10 sites, but was clearly related to the preharvest understory type and biomass. Sites with shrubby species such as yaupon, wax myrtle, and inkberry benefited from compaction by reducing the understory growth. While we cannot forecast whether the remaining elevation in bulk density on the compacted plots will have a negative effect on overall soil productivity in the future, the 10-year improvements in soil properties suggest that these sites are recovering well from the experimental compaction. Harvesting practices that leave coarse woody debris on site and allow herbaceous and woody plants to grow will generally increase this natural amelioration. Removing tree tops, with or without removing the forest floor, reduced productivity by more than the allowable 15% on 8 of 10 sites. The degree of productivity loss was clearly related to available soil P; sites with less than 3.1 mg/kg of available P lost more than 15% productivity by whole-tree harvesting. Care should be taken on these sites to ensure that logging slash is redistributed evenly across the stand to return the nutrients to the whole stand or fertilization should be considered.

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Soil Compaction Study of 20 Timber-Harvest Units on the Ouachita National Forest

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A soil compaction study was performed on 20 timber harvest units on both rocky (15-35% by volume gravel) and non-rocky (<15% by volume gravel) surface soils of the Ouachita National Forest in Arkansas, to determine if these areas met the USDA Forest Service Southern Region (R8) soil quality standards for compaction and affected area extent. The compaction standard states bulk density cannot increase more than 15% from its natural (undisturbed) level and not more than 15% of an activity area can be adversely affected. Eight of the study units exceeded this standard. These eight units generally contained less than 15% rock fragments in the top 8 inches (20 cm) of soil, and seven of the eight had been harvested during the moist season (December-June) using rubber tire skidders. The non-rocky soil units, when harvested during the dry season (July-November), resulted in about 20-50% less compaction than when harvested during the moist season. Non-rocky soils with a sandy loam surface tended to compact less during dry season but more during moist season equipment operation than the non-rocky loam or silt loam soils. Compaction also averaged about 30-50% less on the rocky soils than on non-rocky soils. On the rocky soils, logging equipment operation during either the dry or moist season did not show a difference, and only native surface roads and log decks tended to have a greater than 15% bulk density increase. Compaction due to timber harvest activities that had occurred at least 15-20 years earlier averaged about 9% bulk density increase for the non-rocky soils and 7% for the rocky soils, and indicated that partial recovery had occurred. An analysis of surface infiltration rates found that a 15% density change resulted in more than 60% reduction in infiltration. This study also found that a 15% density change can be visually determined by change in soil structure.

Keywords: *compaction, bulk density, infiltration, soil structure, soil quality standard*

Introduction

Forest land managers are concerned with soil compaction and its effects on long term productivity of the land. Regionally and nationally there has been growing evidence to support this concern. On the Ouachita National Forest, Arkansas, little previous work has been done to determine the degree and extent of compaction that may occur on our soil types. Because the soils on the Ouachita National Forest are typically rocky, it has generally been concluded that compaction is not a serious problem.

Turton et al. (1997) analyzed compaction on six Phase II Ecosystem Management Research sites on the Ouachita, and found compaction to be significant only on multiple pass skid trails in single tree selection and group selection treatments, where soil rock content was relatively low. They found that those soils with the greater percentages of rock content resulted in lower amounts of soil compaction.

Kluender et al. (1994), in their assessment of impacts of alternative harvesting methods in mixed pine/hardwood stands on six harvest units on the Ouachita NF, found that compaction was significant only on the single tree selection treatment units. They attributed this result to the more concentrated traffic pattern or increased number of passes on fewer skid trails on these units. In another site impact study of five harvest treatments on 23 stands in the Phase II Ecosystem Management Research plots, Stokes et al. (1997) found the percent area extent in primary and secondary skid trails to be 22.4, 21.9, 20.5, 14.6 and 14.3 for the clear cut, seed-tree, shelterwood, group selection and single tree selection harvest treatments, respectively.

Froelich et al. (1980) found that the most critical period for compaction to occur is when soil moisture levels are between field capacity and saturation. This information is essential but still leaves the land manager with unanswered questions and situations when dealing with soil compaction at the operational level considering the various soils on the forest. Our study was designed to further our knowledge

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of compaction, its effects on surface infiltration and its degree and extent on the Ouachita's soils, and relate this to the USDA Forest Service Southern Region (Region 8) soil quality standard for compaction and area extent (UDSA Forest Service 2003). The compaction standard states that bulk density cannot increase more than 15% from its natural (undisturbed) level in the top 20 cm (8 inches) of soil, and that no more than 15% of the unit area can be affected.

Methods

Treatment units were initially selected for their compaction potential. A review of compaction research shows that soils and harvest units that show high amounts of compaction would have been subjected to intense heavy equipment activity, would contain low proportions of rocks, would probably be sandy loam textured soils, and would have been operated on during the moist season when soils would have a greater chance of being moist. Several units were selected that met these criteria. Similar soils and treatment units were also selected that had been harvested during the dry season, or that had a loam or silt loam surface texture, to help determine the importance of operating season or surface texture to compaction. To determine the influence of soil rockiness on compaction, treatment units were also selected that contained moderate percentages of rocks (approximately 15-35% gravel size rocks) in the top 20 cm (8 inches) of soil. Some of these rocky units had been harvested during the moist season and some during the dry season.

The study site soils are of the Carnasaw and Sherless Series. The Carnasaw soil is a clayey, mixed, thermic, Typic Hapludult, 100-150 cm (40-60 inches) deep, overlying soft shale bedrock with small amounts of sandstone. The Sherless soil is a fine-loamy, mixed, thermic, Typic Hapludult that is 50-100 cm (20-40 inches) deep over soft sandstone bedrock with small amounts of shale. For this study, those soils containing from 0-15% (field estimate by volume) rock content in the top 20 cm (8 inches) of soil are referred to as "non-rocky soils", and those soils containing from 15-35% rocks as "rocky soils". The density readings of the rocky soils were corrected for rock content differences among groups, and directly related to their non-rocky counterpart soils. The predominant rock size (which typically accounted for 50-100% of the rock present) was 2-19 mm and consisted mainly of sandstone fragments.

This study was performed on small, 0.8-2.0 ha (2-5 acre) subplots of timber harvest units. Most of the harvest units had been harvested within the past year with a few not yet harvested at time of selection. Treatments included single tree selection, group selection, shelterwood or seed tree harvest with harvest volumes mainly in the 23-35 m^3/ha (4,000-6,000 board foot/ac) range. Random transect monitoring was conducted using a Troxler 3440 moisture/density gauge to determine soil density within the 0-20 cm (0-8 inch) soil depth. Each day of use the gauge was tested for calibration and accuracy. To further validate the accuracy of the moisture/density gauge readings, and note any natural changes in the sample itself, the soil at each reading site was excavated by shovel, and field examined for USDA soil texture, estimated percent by volume rock fragments, and estimated amount of roots or buried debris present for possible gauge reading interference. In addition, an estimate of soil moisture at each reading site was made by feel. To further validate soil moisture readings from the Troxler gauge, selected soil samples of the 0-20 cm (0-8 inch) depth were collected and oven dried for 24 hours at 105°C. to gravimetrically determine moisture content. During the physical examination of each reading site, evidence of soil compaction was also recorded. This included noting changes in soil structure and the degree and depth of this structural change according to the 2002 NRCS Field Book for Describing and Sampling Soils (USDA NRCS 2002).

Random transects were set up using a tape with points measured at 3-m (10-foot) intervals and averaging about 75 sample points per unit. Each transect point was given one of six levels of visual disturbance ratings. These six levels included: undisturbed (or natural); evidence of previous impacts but not disturbed this entry (old disturbance); 1-2 pass tractor logging or other heavy equipment operation; 3 or more pass tractor logging not on the primary skid trail (these multi-pass areas are hereafter referred to as secondary skid trails); primary skid trail; and log deck or native surface road.

Identifying old disturbance sites required assessing such density gauge and field indicators as: (a) a site with a slight soil surface depression made from previous entry tire tracks; (b) a thinner layer of semi-decomposed litter relative to that of the natural undisturbed areas; (c) a change in soil structure from the natural state; and (d) greater density readings with no apparent cause other than prior disturbance. The final determination would typically include a combination of the above indicators with highest priority given to change in soil structure.

Surface infiltration measurements were performed on selected harvest units and sites of known degree of compaction to determine what effect density change may have on infiltration. Each infiltration measurement was made by carefully driving one 15-cm-tall x 10-cm-diameter x approximately 2-mm-thick steel ring, 3-5 cm into the soil by placing a short piece of 2 x 4 wood over the ring and

using a 2-pound hammer. Water was then carefully applied to fill the rings while not disturbing the soil surface inside the ring. A period of 30 minutes was given for the water to soak into the soil, with additional water added to the ring and any leakage outside the ring stopped by soil mounding as needed. Readings were then recorded of water draw down inside the ring over time. The final surface infiltration recording was the average of the two or three individual ring recordings, and reduction in infiltration was the difference between those of the compacted sites vs. the undisturbed site infiltration recordings for each unit.

To determine whether bulk density values were different on individual treatment units between levels of disturbance, data were analyzed using one-way analysis of variance (ANOVA). To determine if these bulk density disturbance values were affected by the interaction from soil rockiness, season of equipment operation, or soil texture, data were analyzed using two-way analysis of variance (ANOVA), in which the classification variables of mean bulk density (BD) by texture, season of equipment operation, and soil rockiness were compared with the 'treatment', or disturbance variables. The analysis was conducted using the General Linear Models (GLM) procedure, with comparisons of means among classification and treatment interactions conducted with Sidak's test (SAS Institute 1989).

In instances where mean bulk density of the natural condition varied among classification variables, data were transformed by expressing all BD observations as a percentage of mean natural BD within each classification. ANOVA tests using Sidak's mean comparison test were then performed on the result, essentially a means of testing whether the percentage increases in BD above the natural conditions were significant between classification variables by treatment. Individual unit results are summarized in Table 1, and combined interaction unit results in Table 2.

Results

During this study additional data were collected to examine a number of variables including type of harvest method employed and volume per unit area removed. The analyses of these data were not found to be significant and therefore are not discussed here. Those variables that did prove to be significant included season of equipment operation, soil rockiness class, and surface texture class of the non-rocky soils. The fine sandy loam and loamy fine sand textured surface soils are hereafter referred to as sandy loam textured soils.

Table 1 shows bulk density means by individual harvest unit by two soil rockiness classes (non-rocky = <15%, and rocky = 15-35% gravel rock) where present, as measured against six different compactive disturbance levels. Also represented in this table is the average percent of area receiving 15% or greater soil density increase over that of the undisturbed condition by soil rockiness class, and the overall percent weighted area extent of each unit area receiving 15% or greater density increase from all data when both the non-rocky and rocky classes (if applicable) are combined. As the data show, eight harvest units did not meet the regional soil quality standard for compaction and area extent of impact (Table 1).

Soil Rockiness

Non-rocky soils compacted more, and with less effort, than the rocky soils. Nearly all units containing the rocky soils showed lower bulk density levels and smaller areas of excessive compaction relative to their non-rocky counterparts (Table 1). Of the 16 units that contained only or mostly non-rocky soil (see Table 1), eight exceeded the proposed compaction threshold. In contrast, none of the four units in which half or more of the area was made up of the rocky soils (shaded in Table 1) exceeded this threshold.

When data from these individual units are compared a clearer picture emerges. Figure 1 and Table 2A compare the mean bulk density and percent compaction of all the non-rocky soils to that of the rocky soils by disturbance level. Both the rocky soils and the non-rocky soils show significantly different mean bulk densities at all levels of disturbance, including old disturbance vs. their undisturbed levels. The data also show that rocky soils have significantly lower mean bulk densities than non-rocky soils on primary and secondary skid trails and areas receiving 1-2 equipment passes.

Mean bulk density change for the non-rocky soils, as compared to undisturbed areas, was about 22% on the landings and native surface roads, 19% on the primary trails, 13% on secondary trails, 7% on areas receiving 1-2 passes, and 9% from old disturbance areas. Analysis shows these densities to be different from the natural level at the 95% or greater confidence level. In contrast, the rocky soils show bulk density to be about 19% greater than natural levels on log decks and native surface roads. On primary skid trails, secondary skid trails and areas receiving 1-2 equipment passes this drops to about 10%, 8% and 5%, respectively. The old disturbance averaged about 7% above natural levels for rocky soils. Based on these data, the rocky soils appear to be 30-50% less compactable than the non-rocky soils for primary and secondary skid trails, and areas receiving from 1-2 equipment passes.

Total depth of the compacted soil layer was related to the level of disturbance and rock content of the soil.

Table 1. Comparison of mean bulk density (in g/cm³) by disturbance level, percent of area receiving greater than 15% increase by soil rockiness group, and percent overall weighted area exceeding the compaction standard of 15% change in bulk density. Shading indicates units where rocky soils predominate.

Unit ID	Surface texture	Season of operation	Soil rockiness	Bulk Density Measurements[4] (g/cm³)						Change in Treatment Area (%)	
				Undisturbed density	Old disturbance	1 to 2 passes	Secondary skidtrail	Primary skidtrail	Log deck/ temp. road	>15% change in density by class	>15% change in density, total area
1	fsl[1]	moist	non-rocky[3]	1.36a	1.45b		1.47b	1.57c		9	
			rocky	1.36a	1.43b	1.43b	1.41	1.45c		0	4
2	fsl	moist	non-rocky	1.38a	1.41a	1.51b	1.58	1.77c		22	22
3	fsl	dry*[2]	non-rocky	1.35a	1.45b		1.49c	1.52c		2	2
4	fsl	dry*	non-rocky	1.38a	1.44ab		1.47b			0	0
5[5]	fsl	moist	non-rocky	1.37a	1.48c	1.44b	1.50c	1.51c	1.49c	7	7
6	l	dry	non-rocky	1.28a	1.44	1.33b	1.40	1.51c	1.47c	13	
			rocky	1.28a		1.26a	1.33	1.45b		11	13
7	sil	moist	non-rocky	1.33a	1.39a	1.47b	1.50	1.58c		22	
			rocky	1.33a			1.40	1.52b		22	22
8	sil	dry*	non-rocky	1.32a	1.42b	1.41b	1.49c	1.48c	1.61d	6	6
9	l	dry	rocky	1.32a	1.40	1.37b	1.42	1.43bc	1.49c	9	9
10	sil	moist	rocky	1.31a	1.35ab	1.38b	1.44c		1.44c	8	8
11	sil	moist	non-rocky	1.34a	1.41ab	1.41ab	1.42	1.64c		14	
			rocky	1.34a			1.48b	1.41ab		8	11
12	sil	moist	non-rocky	1.34a	1.45b	1.43b	1.52	1.60d	1.65d	24	24
13	sil	moist	non-rocky	1.31a	1.37b	1.43c	1.48		1.55d	24	24
14	l	moist	non-rocky	1.31a	1.40b	1.40b	1.53c	1.55c		32	
			rocky	1.31a	1.30a		1.49			14	30
15	sil	dry	non-rocky	1.31a	1.47	1.4	1.53	1.54		26	
			rocky	1.31a		1.42b	1.47			7	16
16	sil	moist	non-rocky	1.28a	1.40b		1.37b			2	2
17	l	moist	non-rocky	1.30a	1.42	1.39b	1.47			11	
			rocky	1.30a	1.42	1.38b	1.44	1.46c	1.66d	17	13
18	fsl	moist	non-rocky	1.31a	1.45b	1.40b	1.54	1.62c	1.69d	28	28
19	fsl	dry	non-rocky	1.34a	1.45b		1.41b	1.53c		8	8
20	fsl	moist	non-rocky	1.34a	1.50b	1.49b	1.56bc	1.62c	1.74d	40	40

[1] fsl = fine sandy loam; l = loam; sil = silt loam

[2] * indicates that unit was initially operated on when the soil was too wet, and logging operations were temporarily suspended until conditions improved.

[3] Non-rocky = 0-15% by volume gravel in surface 20 cm (8 inches); rocky = 15-35% by volume gravel in surface 20 cm.

[4] Bulk densities followed by different letters are significantly different at $P > 0.05$. Bulk densities without a letter had too few samples for statistical analysis

[5] This unit was logged using a team of mules instead of a rubber tire skidder.

Table 2. Mean bulk density values (in g/cm^3) and significance for four levels of recent disturbance plus old disturbance as measured against undisturbed bulk density.

A. Comparison of non-rocky (0-15% gravel) soils to rocky (15-35% gravel) soils

	undisturbed	1-2 pass	secondary trail	primary trail	log deck/road	old disturbance
non-rocky soil	1.32	1.41	1.49	1.57	1.61	1.44
rocky soil	1.32	1.38	1.43	1.45	1.57	1.42
signif. by soil rockiness:	ns	*	***	***	ns	ns
signif. by disturbance level:	a	b	d	e	f	c

B. Comparison of dry vs. moist season logging on non-rocky soils

	undisturbed	1-2 pass	secondary trail	primary trail	log deck/road	old disturbance
dry season	1.32	1.38	1.47	1.51	1.55	1.45
moist season	1.33	1.43	1.5	1.6	1.67	1.44
significance by season of ops:	ns	**	**	***	***	ns
significance by disturbance level:	a	b	d	e	f	c

C. Comparison of dry vs. moist season logging on rocky soils

	undisturbed	1-2 pass	secondary trail	primary trail	log deck/road	old disturbance
dry season	1.31	1.37	1.42	1.44	1.49	1.41
moist season	1.32	1.39	1.44	1.46	1.61	1.42
significance by season of ops:	ns	ns	ns	ns	*	ns
significance by disturbance level:	a	b	c	c	d	bc

D. Comparison of non-rocky sandy loam vs. non-rocky loam or silt loam soils

	undisturbed	1-2 pass	secondary trail	primary trail	log deck/road	old disturbance
sandy loam	1.35	1.46	1.51	1.64	1.72	1.45
loam/silt loam	1.31	1.38	1.48	1.54	1.56	1.44
significance by soil texture:	ns	**	ns	**	**	ns
significance by disturbance level:	a	b	d	e	f	c

E. Comparison of dry vs. moist season logging on non-rocky loam or silt loam soils

	undisturbed	1-2 pass	secondary trail	primary trail	log deck/road	old disturbance
dry season	1.30	1.36	1.45	1.51	1.55	1.43
moist season	1.32	1.40	1.49	1.55	1.59	1.44
significance by season of ops:	ns	*	**	*	ns	ns
significance by disturbance level:	a	b	d	e	e	c

F. Comparison of dry vs. moist season of logging on non-rocky sandy loam soils.

	undisturbed	1-2 pass	secondary trail	primary trail	log deck/road	old disturbance
dry season	1.36	1.46	1.49	1.52	no data	1.45
moist season	1.34	1.46	1.53	1.65	1.72	1.45
significance by season of ops:	ns	ns	**	*		ns
significance by disturbance level:	a	bc	c	d	e	b

G. Comparison of dry vs. moist season of logging on rocky loam or silt loam soils.

	undisturbed	1-2 pass	secondary trail	primary trail	log deck/road	old disturbance
dry season	1.31	1.37	1.42	1.44	1.49	1.41
moist season	1.33	1.41	1.47	1.47	1.47	1.37
significance by season of ops:	ns	ns	ns	ns	ns	ns
significance by disturbance level:	a	b	c	c	cd	b

ns not significant
* significant at P > 0.05
** significant at P > 0.01
*** significant at P > 0.001
different letters following disturbance levels are significantly different at P>0.05.

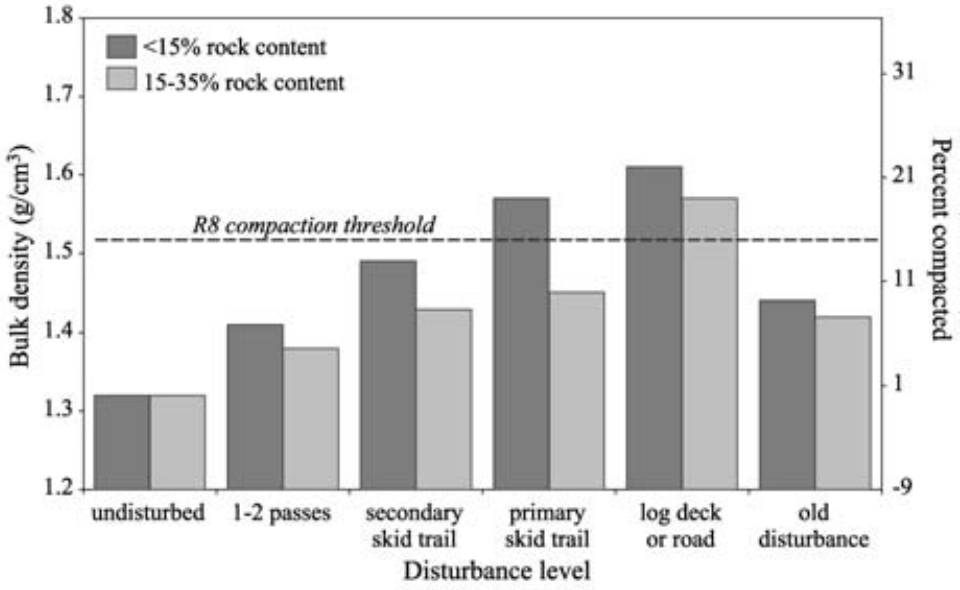


Figure 1. Comparison of mean bulk density of non-rocky and rocky soils.

From visual observation only the first few inches tended to be compacted where 1-2 passes had been made. On primary skid trails, log decks and native surface roads this compacted layer would typically include the entire 20 cm (8 inches) of soil examined. The rocky soils tended to display a less prominent visual degree and depth of impact as compared to the non-rocky soils for the same levels of disturbance.

Season of Equipment Operation

Twelve of the 20 harvest units monitored were logged during the moist season (December-June), and eight during the dry season (July-November). Of the eight units in Table 1 exceeding the proposed compaction standard, seven were yarded during the moist season. Only one of the eight units harvested during the dry season (unit 15) did not meet the standard.

A review of Figures 2 and 3, and Tables 2B and 2C, shows that the non-rocky soils compact more than rocky soils and season of logging operation significantly affects bulk density on the non-rocky soils, but not for the rocky soils. Moist season logging operation proved to be significant for all recent levels of disturbance for the non-rocky soils, but was not significant at any level of disturbance for the rocky soils. Figure 2 shows mean bulk density for all non-rocky soils data (excluding areas where mule logging was used) by dry or moist logging operating season. This figure clearly indicates that moist season equipment operation results in the greatest change in bulk density. These analyses show changes in mean bulk density to be 20-50% smaller on the non-rocky soils on primary and secondary skid trails, and areas receiving 1-2 passes, when logging operations were conducted during the dry season. On the rocky soils, equipment operation performed during the dry season vs. the moist season showed only a slight and insignificant change in mean bulk density by disturbance levels.

Unit 5 (Table 1) was the only unit harvested not using conventional rubber tire skidders. This unit was logged using a team of mules. The log deck and native surface haul road were driven on by a 2-axle haul truck with a mounted log loader. This unit was one of the five non-rocky soil units harvested during the moist season that met the proposed soil quality standards for compaction. In fact, of the 7% area extent not meeting the compaction standard, more than half was due to old disturbance compaction caused from a previous entry or entries.

The most serious degree and extent of compaction were found on the non-rocky soil units that were harvested when these soils were very moist but not saturated. Examples of this situation were experienced with units 2, 14 and 18 (Table 1). Soil moisture conditions on these units were known to be very moist from personal field observation at the time of equipment operations. Similarly, on units 3, 4, and 8, where harvest activities were first commenced and then halted during very moist soil conditions (near saturated soil moisture) and later completed during the dry season, compaction did not show up as a serious problem. Instead, soil puddling or displacement became the major concern where deep tire tracks had been made earlier when the soils were too moist.

Units 10 and 13 (Table 1) were also harvested during very moist soil conditions. On these units no primary skid trails were present, as the tractor operator would often change trail routes in order to prevent further deep tire

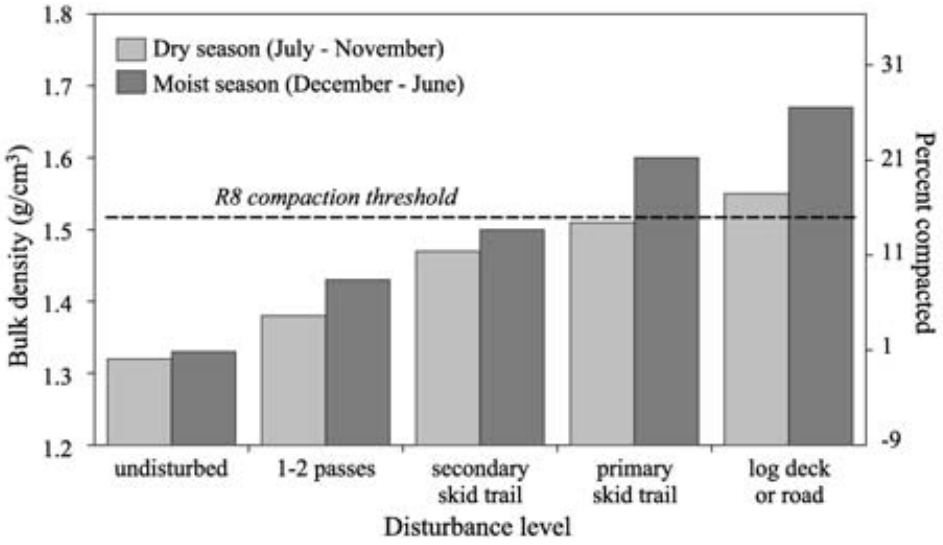


Figure 2. Comparison of mean bulk density of non-rocky soils by season of equipment operation.

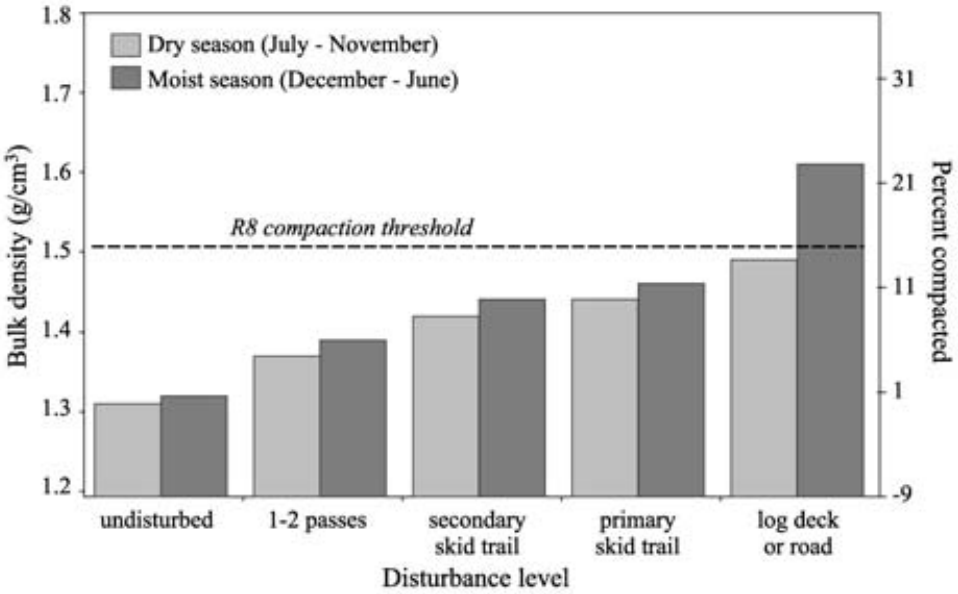


Figure 3. Comparison of mean bulk density of rocky soils by season of equipment operation.

tracks or other obvious damage to the soil resource. This highly dispersed equipment logging practice resulted in a greater area of impacts from the equipment. For unit 13, which contained non-rocky soil, 24% of the area received greater than 15% compaction. Unit 10, a rocky soil, faired much better. Only 8% of the unit area was greater than 15% compacted.

Soil Texture

Changes in surface texture on non-rocky soils affected the degree of compaction (Table 2D). The sandy loam textured soils suffered greater changes in density levels than the loam or silt loam textured soils at all four recent disturbance levels. Analysis shows density changes due to texture are significant for log decks and native surface roads, primary trails, and areas receiving 1-2 equipment passes.

When logging equipment operating season is also considered, the non-rocky loam and silt loam soils, and the non-rocky sandy loam soils, continue to show significant differences in bulk density both by disturbance level and season of operation (Table 2E and F). Moist season logging resulted in significant increases in compaction on primary and secondary skid trails from both textural groups. In addition, there was a significant density increase for 1-2 pass equipment operation for the loam and silt loam soils during moist season operation.

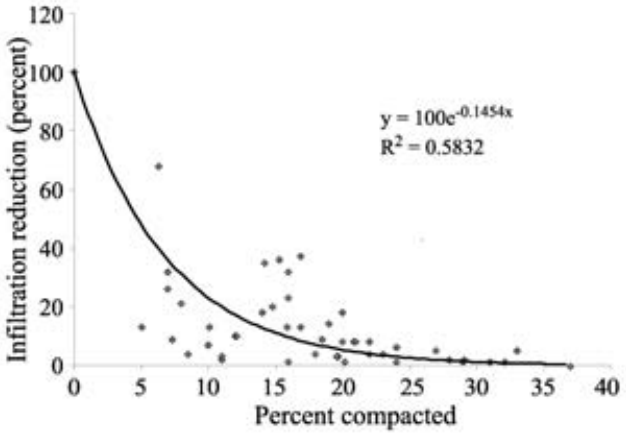
Analysis of all data found the percentage of samples exceeding the 15% compaction standard on loam and silt loam soils by dry season vs. moist season equipment operation to be 0% vs. 2% for 1-2 pass areas, 30% vs. 42%

for secondary trails, and 52% vs. 71% for primary trails, respectively. For the sandy loam soils, the numbers were 0% vs. 10% for 1-2 pass areas, 8% vs. 36% for secondary trails, and 33% vs. 82% for primary trails when logged during the dry vs. moist season, respectively. These data indicate that the sandy loam soils tend to compact less than the loam and silt loam soils during dry season equipment operation, but more during moist season operation. For the rocky soils with loam and silt loam surface textures our data indicated no significant differences by disturbance level between dry vs. moist season equipment operation (Table 2G).

Surface Infiltration

Surface infiltration measurements were performed on both undisturbed sites and selected disturbed sites within units 6, 8, 12, 14, 18 and 20 to determine the relative change in infiltration as a result of density change (Figure 4). Over 50 measurements were recorded from soils with density changes ranging from 5% to greater than 30% relative to the undisturbed density levels. This study found infiltration rates had been significantly reduced. Surface infiltration rates have dropped by over 60% from the undisturbed levels when density levels had increased by 15 percent or more (Figure 4).

Figure 4. Reduced surface infiltration caused by compaction.

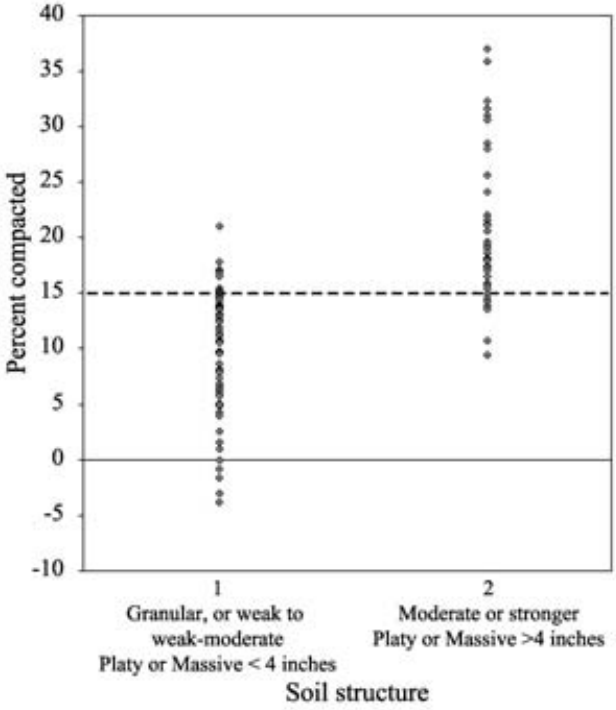


Soil Structure Change vs. 15% Compaction

Physical changes in soil structure were examined, including degree and depth of structural change, to determine if structure could be used to identify a 15% change in soil density. Soil structure had briefly been examined during data collection at all sites, but was more intensely examined on 113 sites during later follow-up work. These follow-up sites included both rocky and non-rocky soils and soils with sandy loam, loam or silt loam textures. On these harvest units the surface soils, in an undisturbed condition were granular in structure, and typically identified as a moderate medium granular structure (USDA NRCS 2002). Those surface soils in a strongly compacted condition (25% density change or greater) nearly always contained a moderate or strong platy structure which typically included the entire 20-cm (8-inch) depth being analyzed.

To determine whether the soil exceeded the Region 8 compaction threshold (15% density increase over the undisturbed level) required more detailed observation of structure. Those soils with a 5-15% density change typically contained a weak or weak-moderate (an inter-grade between weak and moderate) platy or massive structure that was less than 10 cm (4 inches) in total thickness beginning at the surface. In contrast, those soils with a 15-25% density change typically contained a moderate or moderate-strong (an inter-grade between moderate and strong) platy or massive structure that was greater than 10 cm (4 inches) in total thickness (Figure 5). This structure and affected depth combination resulted in a 95% probability of correctly determining whether the soil had either greater than, or less than, a 15% density change. Neither soil rockiness nor soil texture altered this structure or depth combination in relation to change in compaction.

Figure 5. Use of soil structure to determine 15 percent change in bulk density (Region 8 compaction threshold).



Confidence level that 1 ≤ 15% and 2 ≥ 15% density change: P ≥ 0.05

Discussion

We found soil compaction to be a serious concern on some soils on the Ouachita National Forest, especially when silvicultural harvest operations using conventional rubber tire skidder logging equipment are conducted during the moist season, when antecedent soil moisture levels are high. Other studies have also found that moisture condition of the soil itself at the time of heavy equipment operation is the most important precursor to compaction (Day and Holmgren 1952; Froelich et al. 1980; Hatchell et al. 1970). Day and Holmgren (1952) using three different levels of compactive force, found the soil to be 2.4 to 3.0 times more compacted when these forces were applied to moist soil vs. dry soil. Our study comparing moist vs. dry season logging did not show as large a difference. This is probably due to the fact that antecedent soil moisture conditions fluctuate during both moist season and dry season. They tend, however, to remain generally wetter during the moist season and drier during the dry season.

Results from individual units in our study known to have very moist soils during equipment operation (units 2, 13, 14, and 18) indicate that the soils in these units were up to twice as compacted as similar dry units. These very moist soil units would be more in line with Day and Holmgren's (1952) findings above. During very moist soil conditions, equipment logging operations also tended to become more and more dispersed. This is typically done with the good intention of desiring to avoid unnecessary or severe impacts to the soil. This dispersal practice, however, has not worked well to reduce equipment impacts, particularly on non-rocky soils which are most susceptible to compaction, as demonstrated in unit 13 of our study.

Our study found that, for non-rocky soils during moist season equipment logging, a secondary skid trail exhibited about the same degree of change in bulk density as a primary skid trail did on the same soil during dry season logging (Table 3). Both of these mean bulk density changes (14%) are close to exceeding the compaction standard of 15%. Similarly, primary skid trails, log decks and temporary roads were about 50% more compacted during moist season equipment logging vs. dry season logging (Table 3). These findings are in line with those of Hatchell et al. (1970), who concluded that one equipment pass under moist soil conditions was equivalent to four equipment passes under dry soil conditions. The 20-50% decrease in mean density levels from dry season logging (relative to the moist season) found on our non-rocky soils indicates that managing the season of heavy equipment use can be an effective way to help minimize compaction on a forest wide scale.

Our results indicate that soil bulk density increases somewhat proportionately to increasing levels of disturbance. Figures 1-3 show a stair-step pattern of mean

Table 3. Change in mean bulk density (g/cm³) and percent compaction by disturbance level, by soil rockiness group and season of equipment operation.

Soil Rockiness Group	Dry Season Equipment Operation	Percent Increase in Bulk Density (% compacted)	Moist Season Equipment Operation	Percent Increase in Bulk Density (% compacted)
0-15% gravel rock soils "Non-Rocky"				
Natural (undisturbed)	1.32		1.32	
1-2 passes	1.38	5	1.42	8
Secondary trail	1.47	11	1.50	14
Primary trail	1.51	14	1.60	21
Log deck/road	1.55	17	1.67	27
Old disturbance	1.45	10	1.44	9
15-35% gravel rock soils "Rocky"				
Natural (undisturbed)	1.32		1.32	
1-2 passes	1.37	4	1.39	5
Secondary trail	1.42	8	1.44	9
Primary trail	1.44	9	1.46	11
Log deck/road	1.49	13	1.60	21
Old disturbance	1.41	7	1.42	8

density levels from the natural (undisturbed) levels to the greatest change at the log deck/native surface road disturbance level. On non-rocky soils, mean soil density increased from 5% at 1-2 passes, to 11% on secondary skid trails, and 14% on primary trails under dry season operations, versus 8%, 14% and 21% for these same disturbance levels, respectively, during moist season equipment operations (Table 3). This compares closely with Hatchell's (1970) findings where they found compaction to be twice as great on primary skid trails as on secondary trails on nine treatment units in South Carolina and Virginia.

When considering the use of rubber tire skidders in logging operations, for non-rocky soils we can expect log decks, native surface roads, and primary skid trails to be excessively compacted under most antecedent soil moisture conditions. Under moist soil conditions, however, secondary skid trails may similarly be excessively compacted. As Stokes et al. (1997) have shown from their study on area extent in primary and secondary skid trails for typical silvicultural systems on the Ouachita National Forest, operating logging equipment during dry soil conditions can make the difference if a unit passes or fails the Region 8 soil quality standard for compaction for harvest units having non-rocky surface soils.

We found that surface soils containing between 15-35 percent by volume of gravel rock content resulted in 30-50 percent less density change than soils containing from 0-15 percent by volume gravel rock. These results are in line with an unpublished independent follow-up study by Barkhimer (2000). Barkhimer used a modified Proctor Test to compare two levels of gravel rock content on loam and sandy loam soils collected from the Ouachita National Forest. He found that between antecedent soil moisture levels of permanent wilting point and field capacity, the soils were 0-20% less compactable when 15% by volume gravel rock was added, and 40% to more than 100% less compactable when 35% by volume gravel rock was added to these soils.

For rocky soils, our study found no significant differences between dry season vs. moist season equipment logging (Table 2). Neither season of equipment operation nor soil texture played a significant roll in soil compaction on rocky soils. Mean density levels exceeded the 15% compaction standard only on log decks and temporary roads during moist season logging operations (Table 3). Primary skid trails tended to exceed the compaction standard only under very moist soil conditions. Generally, however, the area extent of soil compaction itself did not exceed the soil quality standard. Other than for very moist soil conditions and high traffic areas such as log decks and temporary roads, the 15-35% rock content of these soils tended to be effective in buffering against excessive compaction. By extrapolating these results to soils containing greater than 35% rock content we would expect even less compaction to occur.

Old disturbance sites exhibiting compaction did not reflect the same lower dry season/higher moist season density fluctuation we typically found with current levels of disturbance (Tables 2 and 3). This is because season of equipment operation during prior entries could not be determined, as these records have long since been discarded. The result is that there is an equal chance this old disturbance could have occurred during either period. We would therefore expect to find little or no change in mean bulk density due to the current season of operation, as was typically the case. Average percent compaction found on old disturbance areas was about 9-10% for the non-rocky soils compared to about 7-8% for the rocky soils (Table 3). This represents an approximate 20% reduction in bulk density change on rocky soils as compared to that found on the non-rocky soils. Although this 20% change did not prove to be significant (Table 2), it is to be expected and supports the above findings that rocky soils are less compactable than non-rocky soils.

Surface infiltration was studied to determine what effect compaction might have on soil infiltration rates on this Forest. This work indicated that a relatively small increase in soil density caused by compactive forces will result in a large decrease in infiltration rate. Surface infiltration drops rapidly from undisturbed soil density levels to almost no infiltration as soil density increased to 25% or greater (Figure 4). This can have a negative impact on both soil productivity and the watershed's natural hydrologic functioning. A reduced infiltration rate can result in less water entering the soil profile for future plant uptake and growth. In addition, water not entering the soil adds to overland runoff, resulting in increased on-site erosion, channel destabilization and downstream flooding.

Our study found some evidence that old disturbance areas have partially self-mitigated since the previous harvest entry. The old disturbance compaction we observed in this study was caused from harvest equipment activities that occurred at least 15-20 years earlier. Old disturbance areas are composed of secondary or primary skid trails and areas that received 1-2 equipment passes. Temporary roads and log decks are not included in old disturbance level findings from this study, as these areas were reused again during the recent entry.

The amount of natural soil bulk density mitigation since the last disturbance can be estimated by comparing the average density change from the three current disturbance mean density levels of the primary and secondary skid trail densities and areas receiving 1-2 passes, to the old

disturbance density level. By multiplying this difference by a 15-20 year recovery period, and relating this back to the current old disturbance density level, we estimate it would take from 50-80 years for skid trail soil density levels to recover to near natural density levels. This estimated recovery period is in line with other findings. Perry (1964) estimated a 40-year recovery period for reduced infiltration rates on old compacted woods roads to approach natural rates on a southern Arkansas soil. In the Pacific Northwest, it has been suggested that it would take 100 years or more for compacted areas to recover to near natural density levels (Froelich et al. 1980).

Our study also examined changes in soil structure vs. degree of compaction. Altered soil structure, as a result of compaction, has commonly been used to help determine when a soil has, or has not, exceeded a given compaction standard. Altered soil structure is visible in both degree and extent when examined with a spade. Our intent was to calibrate this structural change, degree and extent with soils on the Ouachita National Forest to equate to a 15% soil density change (our Region 8 soil compaction standard).

This study determined that there is a 95% probability that Ouachita National Forest soils exhibiting a moderate or stronger platy or massive structure, with a total affected depth of 10 cm (4 inches) or greater, equates to a 15% or greater density change. Conversely, those soils exhibiting a granular structure, or, a weak, or weak-moderate (intergrade between weak and moderate) platy or massive structure, with a total effected depth of less than 10 cm (4 inches), equates to less than 15% density change (Figure 5). This structural change information can be used as an indicator in future monitoring efforts in determining whether our forest land management practices meet the Region 8 soil quality standard for compaction.

Conclusion

Soil compaction has been shown to result in a rapid loss of surface infiltration. Compaction has been found to be a concern on the Ouachita National Forest on non-rocky soils where conventional harvest equipment logging occurs during moist antecedent soil conditions. Compaction can be minimized on non-rocky soils by logging during dry soil conditions. On rocky soils, logging during moist soil conditions is not as great a concern, as the soil rock content acts as a buffer to compaction. We have also shown that the Region 8 soil quality compaction standard of 15% density change can be detected visually by noting change in soil structure.

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Monitoring to Improve the Understanding of Herbicide Fate and Transport in the Southern Sierra Nevada, California

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Reforestation efforts on the Sierra and Stanislaus National Forests (California) in the 1990s included use of the herbicide, hexazinone. This herbicide is the most water-soluble and water-mobile of those approved for use under a Regional EIS (Environmental Impact Statement) for vegetation management. To better understand hexazinone movement in soil and water typical of areas being reforested, monitoring at operational units was carried out. Two monitoring efforts are described here. In the first, instrumentation to detect hexazinone in the soil, vadose zone water, and surface water runoff was used to monitor the effectiveness of a stream buffer zone. Initial chemical application was to a 6.1 by 7.6 m test plot upslope from an instrumented area. Water and soil samples were collected after five significant storm events. The following year, an operational chemical application was made to the unit containing this instrumentation. Samples were collected after four significant storm events. Hexazinone was detected in the vadose zone to a depth of 1.8 meters and for a slope distance of 6.1 meters. The difference between the test plot and operational applications was an order of magnitude greater concentration detected in both vadose water and surface runoff. While hexazinone did penetrate into the buffer zone, it was well below concentrations of concern. In the second monitoring effort, on the Stanislaus National Forest, groundwater monitoring wells were installed in selected reforestation units to verify levels of hexazinone entering groundwater and examine its persistence. A total of five monitoring wells were sampled. Wells sampled the unconfined upper aquifer above competent bedrock and typically varied between 2.9 m to 10.1 m in depth. If hexazinone was detected, typically 1 to 2 years had passed between hexazinone application and detection in groundwater samples. While the concentrations generally dropped after initial detection, it took between 2 to 3 more years before it fell below the detection limit. Monitoring demonstrated that hexazinone detected in groundwater was well below the concentration established by the State of California as a water quality goal.

Keywords: *herbicides, monitoring, water quality, groundwater, surface water, soil*

Introduction

The Forest Service Pacific Southwest Region (R-5) (Figure 1) published an Environmental Impact Statement (EIS) in 1974 to address reforestation methods (USDA Forest Service 1988). In the years following, public concern regarding use of herbicides and possible effects of vegetation management on the forest environment changed, as did environmental regulations and the herbicides registered for silvicultural use (USDA Forest Service 1988). A moratorium on herbicide use in the Pacific Southwest Region was instituted in 1984 in response to federal court rulings.

In response to these changes, a final Environmental Impact Statement (FEIS) for vegetation management for reforestation was issued in December 1988 (USDA Forest Service 1988). The Record of Decision (ROD) issued in February 1989 selected an alternative that provided for the limited use of herbicides in reforestation efforts (USDA Forest Service 1989). The ROD reiterated several mitigation measures for herbicide use from Table 2-7 of the FEIS. One of these measures stated, "Do not use hexazinone, picloram, dalapon, or dicamba where they are expected to enter groundwater or surface water, such as when soils are very sandy or have low clay or organic matter contents." A clarifying letter to Forest Supervisors on 30 October 1990 from the Regional Forester noted that this mitigation measure did not mean a zero tolerance

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Figure 1. The Pacific Southwest Region showing the location of National Forests relative to geographic features in California. Note the Sierra and Stanislaus National Forests in the southern Sierra Nevada.

for the stated herbicides entering groundwater or surface water. Rather, a site specific analysis should identify high risk situations where this mitigation would be applied. Another mitigation measure in Table 2-7 of the FEIS stated, "Monitor herbicide residues in soil and ground and surface water to identify patterns of herbicide persistence and mobility at sensitive sites." This direction clearly required monitoring to validate site specific analyses and decisions on hexazinone use.

Of the four chemicals noted in the mitigation measure, only hexazinone was considered appropriate to the treatment prescriptions. Neary et al. (1983) noted hexazinone has high water solubility (33,000 ppm by weight at 25°C), making it likely to move off-site with storm runoff and leach to groundwater. Therefore, it became the focus of concern for much of the groundwater and surface water monitoring on reforestation projects in the southern Sierra Nevada. Earth scientists working on national forests in the southern Sierra Nevada were faced with predicting the pattern for mobility and persistence of hexazinone as input to environmental documents prepared for reforestation projects. They also needed to define locations where hexazinone should not be used in vegetation management prescriptions.

Unit 505 Monitoring – Sierra National Forest

Test Plot Applications

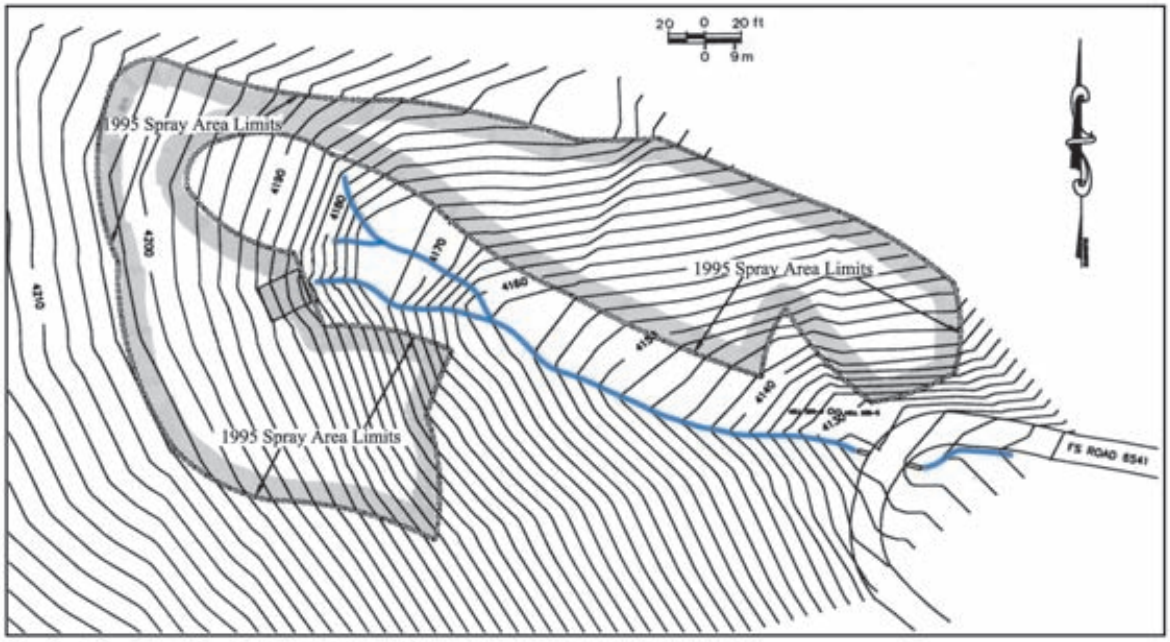
The Sierra National Forest undertook a number of small reforestation projects in the early 1990s. The mixed conifer forests in these areas were generally second-growth, following the cutting of the old-growth during the early 1900s. Harvest of this second-growth forest in the 1980s had occurred partly in response to the combined effect of drought and insect attack. Unlike earlier logging efforts, the recent harvest had included clear-cut units. In some of these harvest units, grass and brush competition significantly hampered re-establishment of conifers in subsequent reforestation efforts. Mechanical methods were not wholly successful in reducing this competition. Herbicide application was then undertaken to improve the success of reforestation efforts.

Buffer zones are a common mitigation to prevent impacts to water quality. In 1993, a question arose about the adequacy of buffer zones applied to Class 4 channels. Class 4 channels are the minor drainage ways that typically channel water into more defined channels only during snowmelt runoff or during intense rain storms. A buffer 7.6 meters on either side of the Class 4 channel centerline was excluded from application of herbicides for individual reforestation projects on the Sierra National Forest. The widespread distribution of Class 4 channels would lead to serious problems in operations to apply herbicides if the buffer zones needed to be wider than 7.6 meters.

A site was chosen in 1993 for an intensive monitoring effort to examine the adequacy of the 7.6-meter buffers on Class 4 channels. This monitoring effort clearly represented implementation of the mitigation measure, "Monitor herbicide residues in soil and ground and surface water to identify patterns of herbicide persistence and mobility at sensitive sites." While scientific literature on hexazinone persistence and mobility was available for the southeastern United States, no studies had been done for the southern Sierra Nevada, and it was questionable whether results from such a different and distant region could be applied to central California conditions.

The chosen site, Unit 505, was one of several herbicide treatment units in an approved vegetation management plan for part of the Bass Lake Ranger District of the Sierra National Forest. Unit 505 lies within the Lewis Creek watershed about 5 km north of the town of Oakhurst, California. The vegetation, slope, and soil present in Unit 505 are representative of many areas where hexazinone was being considered as a treatment option. The elevation is 1340 m, on generally east-facing slopes. Soil mapped as Holland Series overlies the Tonalite of Bass Lake at this

Figure 2. A detailed topographic map showing the outline of the Unit 505 operational area (wide gray shaded border). The alignment of the Class 4 channel is shown in blue. The larger rectangle is the outline of the protective fence with the inner rectangle delineating the application area and instrumented area within the buffer zone.



site. At the beginning of the study, the ground surface was covered by grasses with scattered concentrations of bear clover.

The monitoring plan specified establishment of a 6.1 m by 7.6 m plot (46.5 m^2) for applying hexazinone, adjacent to the upper boundary of the buffer zone of a Class 4 channel (DeGraff et al. 1994) (Figure 2). Transect lines for soil samplings were established within the application area and the adjacent buffer zone in order to determine the concentrations of hexazinone at the ground surface where the herbicide was applied, and where herbicide attached to soil particles might be washed down slope. Leaching to shallow groundwater was evaluated using pressure vacuum lysimeters, consisting of PVC tubes with a ceramic tip, installed on three lines parallel to the slope contour. The first line was at the application plot/buffer boundary, while the second and third lines were placed at 3.1 m and 6.1 m down slope from the boundary, respectively. Along each line, three sets of 0.6-m- and 1.2-m-long lysimeters were installed, with a set in the center of the line and the others 1.5 m to either side of the center set (Figure 3). The exception to this array was along the line placed 6.1 m down slope, where a 1.8-m-long lysimeter was added to this arrangement. Vadose zone water was collected from the lysimeters by placing a vacuum on each one following each storm event. Fluid was extracted two to five days later into sample bottles.

Surface runoff was intercepted at a 4.6-m distance down slope from the application plot/buffer boundary where a stiff plastic barrier was embedded into the soil. The barrier was attached to a pipe that directed the collected surface water into a container housing a 1000-mL sample bottle. After each storm event, the filled or partially filled sample bottle was collected for analysis.

On 15 March 1994, liquid hexazinone was applied to the plot using a backpack sprayer (Figure 4), at the treatment rate of 1.4 kg of active ingredient per 0.4 ha prescribed for the operational treatment of Unit 505.

Figure 3. A view down slope from the application area toward the Class 4 channel that runs from left to right across the background. The clusters of lysimeters are visible on the boundary of the application area and buffer zone and along the line 3.1 m down slope. A black plastic barrier at 4.6 m diverts surface runoff to the surface water sampler.

Figure 4. A view of the monitoring installation in Unit 505 surrounded by a protective fence. The application area is visible in brown following the initial hexazinone treatment.

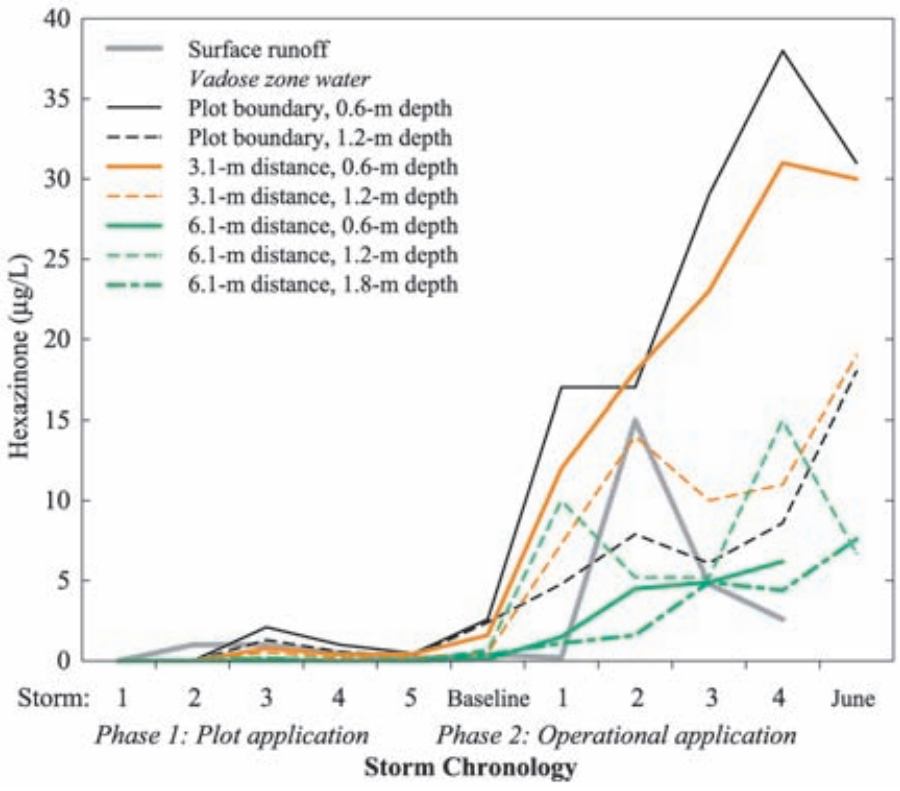
No hexazinone applications had previously occurred in this unit or anywhere else within the watershed where this unit is located. The absence of hexazinone residues was confirmed by sampling of soil transects in the application area and by testing soil excavated during lysimeter installation prior to application.

Five significant precipitation events affecting the application area took place between 15 March 1994 and 31 May 1994. A total of 185.4 mm of precipitation was recorded between these dates at the daily storage gauge located at Batterson Work Center, about 4 km from the site and 1305 m lower in elevation. Daily precipitation totals ranged from 27.9 mm to 2.5 mm, with the events on 24 March, 8 April, and 19 May being generally light rainstorms. Some of these events were preceded by one to two days of lower precipitation. A rainstorm on 23 April continued through 25 April and turned to snow with falling temperatures. The fifth storm event was a thunderstorm on 30 May yielding some intense rainfall.

No hexazinone was detected in surface water after the first storm event on 24 March (Figure 5). The highest concentration in surface water of 1.0 µg/L was found after the second storm on 8 April. The 23 April sample was lost due to breakage during transport. However, the remaining two storm events yielded surface water hexazinone concentrations of 0.49 µg/L on 19 May and 0.11 µg/L on 30 May. It should be noted that the surface water sample for the 19 May storm event was taken earlier from preceding rainfall. The change to snowfall on 19 May resulted in no surface runoff at that time.

No hexazinone was detected in vadose zone water withdrawn from the lysimeters after the first storm (24 March) or the second storm (8 April) (Figure 5). After the third storm (23 April), hexazinone was detected in the 0.6-m lysimeters at the application plot/buffer boundary and in the line 3.1-m down slope, but not at 6.1 m down slope, where the 0.6-m lysimeters are down slope from the surface water intercepting barrier. It was also detected in the 1.2-m lysimeters on the plot boundary, and at the lines

Figure 5. Chart comparing concentrations of hexazinone found in the surface runoff and vadose zone water following plot and operational applications.



3.1-m and 6.1 m down slope. Hexazinone was detected in the 1.8-m lysimeters installed only along the line 6.1 m down slope. As expected for a material leaching into the soil, the concentrations detected at any depth were highest for the points closest to the application area and decreased down slope. Similarly, the concentrations at any particular line of lysimeters decreased with depth. With subsequent storms, this pattern of concentration values persisted but with decreasing concentrations. The highest concentration detected in vadose water was 2.1 µg/L.

Surface soil was collected from both the application area and the buffer zone. Within the application area, soil samples were collected at the beginning of the months of April, May, June and September. Samples were soil plugs 7.6 cm deep, collected along two transects and combined for analysis. The highest 1994 concentrations found in the application area were 910 µg/L (April), 880 µg/L (May), 330 µg/L (June), and 40 µg/L (September). Surface soil sampling within the buffer zone took place along transects aligned at 1.5 m and 3.1m down slope from the application plot/buffer zone boundary. These samples were 2.6 cm-deep plugs of soil collected after the first, third, and sixth storm events. Buffer zone sampling attempted to determine how much hexazinone was transported down slope via attachment to surface soil particles. Hexazinone was detected at 15 µg/L (1.5-m transect) and 13 µg/L (3.1-m transect) in the surface soil of the application area after the third storm. It was not detected in samples taken after the first or sixth storm events. Hexazinone may have been present at concentrations less than 10 µg/L, as the extraction process from soil resulted in this higher detection level than analysis of water samples.

The plot results showed that hexazinone would penetrate at least 4.5 m into the 7.6-m buffer zone in surface water, at least 3.1 m in surface soil, and leach to a depth of 1.8 m at 6.1m into the buffer zone. This demonstrated that a larger quantity of the chemical was moving into the buffer zone than anticipated. Sampling also found higher concentrations of hexazinone in vadose zone water than in surface runoff. However, no concentration detected exceeded the then-current 200 µg/L regulatory limit for hexazinone. This 200 µg/L limit was the State of California adopted water quality goal, and represents the Environmental Protection Agency's lifetime health advisory value (EPA 1988), which represents the portion of an individual's total hexazinone exposure from drinking water, and is meant to limit lifetime adverse health effects due to exposure to carcinogenic substances. The highest detected value within the buffer zone, the 15 µg/L surface soil value, is clearly significantly lower than the State of California regulatory limit for this chemical.

Operational Application

To ensure that plot results represented actual operational results, a second phase of monitoring involved the planned treatment of Unit 505 with hexazinone (Figure 4). The same instrumentation was left in place to monitor surface soil, surface runoff , and leaching into the soil. Treatment of the unit took place on 15-16 March 1995. Again, backpack sprayers were used to apply the hexazinone at the rate of 1.4 kg of active ingredient per 0.4 ha.

Prior to the first storm following treatment, the samples were collected of surface water runoff, soil from transects within the buffer zone, and vadose zone water from the lysimeters. Nearly one year after the plot treatment, surface water runoff was found to have concentrations of hexazinone at 0.9 µg/L, at non-detectable concentrations in surface soil, and at maximum concentration of 2.6 µg/L in vadose zone water. This represented the baseline situation prior to the operational application in March 1995.

Four significant storm events occurred following the operational application of hexazinone to Unit 505, between 20 March and 15 May 2004. As measured at the storage gauge at Batterson Work Center, these storms generated a total of 160 mm of precipitation. Daily totals on 22 March, 17 April, 5 May, and 15 May ranged from 16.5 mm to 30 mm. Rainfall the day preceding the storm peak day ranged from 0 to 17.3 mm.

Hexazinone detected in surface water during the 22 March storm event was at 0.2 µg/L (Figure 5). During the second storm (14 April), the maximum concentration of 15.0 µg/L was found in the surface water sample. The third storm sample (5 May) and fourth storm sample (15 May) were found to have 4.8 and 2.6 µg/L of hexazinone present, respectively.

Hexazinone concentrations in vadose zone water jumped from the maximum pre-application value of 2.6 µg/L to 17 µg/L after the first storm event (Figure 5). It was 18 µg/L after the second storm event. Concentrations increased to 29 and 38 µg/L following the third and fourth storm events, respectively. All the samples extracted from the lysimeters, regardless of depth or position on the slope, were found to have concentrations of hexazinone greater than the those found during the baseline analysis before the first storm event. The distribution of concentrations among the lysimeters at each sampling event was similar to that encountered following the plot application; the values detected at any depth were highest for the points closest to the application area and decreased down slope. Likewise, the concentrations at any line were greatest at the shallowest depth and decreased with depth. The difference between the plot application and the

operational application was that while this pattern of concentration values persisted, it was with increasing rather than decreasing concentrations. A general decrease in concentrations of hexazinone was not detected until post-rainy season sampling in June 1995 when the highest concentration had dropped to only 31 µg/L.

Again, transects aligned at 1.5 m and 3.1 m down slope from the application plot/buffer zone boundary were used for surface soil sampling. Samples were collected in the upper 2.5 cm of soil after the first and third storm events, and in follow-up monitoring in June 1995. Unlike sampling after the first storm following plot application, hexazinone was detected in samples taken after the first storm event. The maximum concentration along the 1.5-m transect was 1200 µg/L and along the 3.1-m transect at 20 µg/L. Sampling after the third storm detected hexazinone at 20 µg/L (1.5-m transect) and 30 µg/L (3.1-m transect) in the surface soil of the application area. This dropped to 10 µg/L along both transects in the follow-up sampling done in June 1995.

The concentrations of hexazinone detected after operational application were significantly higher in surface and vadose zone water and in surface soil compared to the plot application. However, the patterns of change in concentrations found over time and space were similar (Figure 5). Hexazinone concentration was highest in the surface water from the second storm event following each application. In the vadose zone, the peak concentrations lagged one to two storms behind the surface water peak, and the pattern of changing concentrations down slope and at depth was similar. Again, the maximum concentration of hexazinone in surface water was about half the maximum concentration detected in vadose zone water. However, the concentrations of hexazinone for both plot and operational applications were below the water quality goal of 200 µg/L, except for one surface soil sample at the 1.5-m transect taken after the first storm event following operational application. Higher concentrations persisted longer in the vadose zone after the operational application than after the plot application.

The Unit 505 monitoring clearly showed that hexazinone in the surface water runoff and on surface soil penetrates a significant distance into the buffer zone for Class 4 channels. It also demonstrates that leaching of hexazinone in the vadose zone water moves laterally down slopes into the buffer zone and vertically to at least a 1.8-m depth. However, it also shows that the concentrations are unlikely to approach or exceed the State of California water quality goal for hexazinone, except for surface soil washed about a meter into the buffer zone during the first storm following operational application.

Post-wildfire Reforestation Monitoring–Stanislaus National Forest

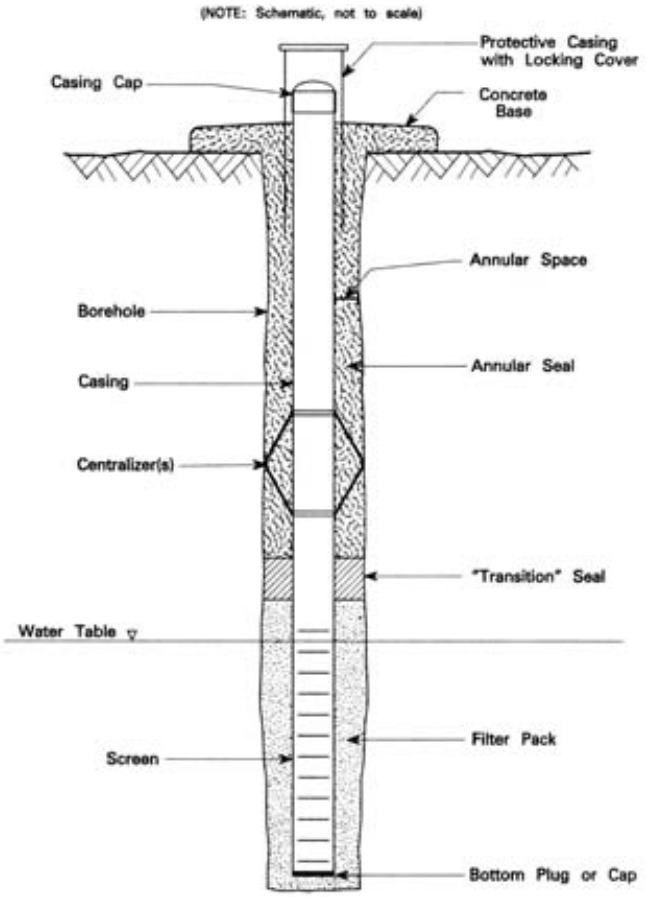
In August 1987, several major wildfires were ignited by dry lightning on the Stanislaus National Forest. These wildfires expanded into each other to create the Stanislaus Complex wildfire that eventually burned 59,489 ha on the Mi-Wok and Groveland Ranger Districts (Frazier and Grant 2003). Reforestation efforts experienced significant problems in grass and brush competition and resulted in plans to use herbicides to improve seedling survival and growth. Public opposition delayed implementation of this work until the late 1990s. Several additional wildfires adjacent to the Stanislaus Complex, such as the Arch Rock and Ruby fires, added more areas in need of reforestation during this time.

Hexazinone was one of the herbicides planned for use in this reforestation effort. Development of the alternatives excluded use of hexazinone on any treatment unit where a reasonable chance existed for it to contaminate existing wells. In order to validate the mitigation measure, "Do not use hexazinone, picloram, dalapon, or dicamba where they are expected to enter groundwater or surface water, such as when soils are very sandy or have low clay or organic matter content," monitoring of both water sources was undertaken.

Logistical and physical conditions constrained the location of groundwater monitoring. Where possible, groundwater and surface water monitoring was co-located to demonstrate whether concentrations of hexazinone in surface water were strictly due to surface runoff or included a base flow concentration from groundwater. Efforts were made to identify monitoring sites within each major drainage of the project area where units to be treated with hexazinone were located. A major physical constraint on final selection was whether a road existed to allow the drill rig to install a groundwater monitoring well at the down slope end of the treatment unit.

Monitoring wells were installed to enable sampling of groundwater at the base of the unconfined upper aquifer extending from the ground surface to the base of the overlying regolith. This permitted installation of the monitoring wells using a hollow-stem auger. Drilling would cease at auger refusal when it penetrated to the regolith-rock interface. The drill hole was logged, as was the installation of the monitoring well. Each monitoring well was a 5.1 cm diameter well cased with a combination of PVC pipe and stainless steel screening (Figure 6). Wells were installed to the standards for monitoring wells promulgated by the California Department of Water Resources Department (CDWR 1991).

Figure 6. A schematic diagram illustrating a typical monitoring well installation and its main components (CDWR 1991). Wells used on the Stanislaus National Forest were too shallow to require a centralizer.



On the four reforestation projects, a total of twelve groundwater monitoring wells were installed. While most monitoring wells were drilled in areas of granitic bedrock, several were within volcanic or metamorphic bedrock areas. Of the twelve wells, one was destroyed by reforestation work after its initial baseline sampling took place. Seven others were rendered unusable because of a decision to modify the treatment by omitting use of hexazinone, or due to lack of sufficient rainfall following application for mobilizing hexazinone.

Groundwater was sampled from each well using a bailer (Figure 7). Bailers were dedicated for each well to avoid cross-contamination, and water present within the well casing was purged prior to taking a sample. The volume of water present was determined by using an electric water level indicator to measure the depth to water. Calculations would then determine how many times the bailer would have to be used to remove the entire stored volume. The temperature and pH of the water was taken prior to starting the purge and after the first and second purges were completed. Typically, the temperature dropped and a shift in pH was noted between the pre-purge and first purge values. If the second purge values were identical to those after the first purge, it was concluded that a water sample would be representative of the groundwater present around the well screen. In some instances, a third purge was done because of continuing differences in temperature and pH. Following purging of the well, a water sample was collected using the bailer and placed in 1000-mL glass bottles provided by the commercial laboratory where the samples would be taken for analysis. Duplicate samples were included among those collected from different wells to provide a check on laboratory analysis. The bottles were placed in cooled chests and transported to the laboratory to avoid exceeding the appropriate hold time prior to analysis. The same analysis laboratory was used for all the samples taken from the Stanislaus National Forest projects.

For any particular monitoring well, groundwater sampling took place just prior to the initial application of hexazinone to the treatment unit. This provided a baseline to demonstrate that hexazinone was not already present in the groundwater. Initial post-treatment sampling took place after the first major storm event following application of hexazinone. A major storm was defined as one that provided fifty or more millimeters of rainfall to the unit. In subsequent years, samples were collected in the spring following the winter rainy season, or after snowmelt took place, depending on the elevation of the monitoring well location.

Figure 7. The senior author (DeGraff) purging monitoring well BS-45 with a bailer on the Stanislaus National Forest. A second bailer is used to collect the sample after well purging. A housing installed flush to the ground surface protects the well between sample events. See Figure 6 for details.

Among the four wells successfully used to sample groundwater, hexazinone was not detected at concentrations that approached, much less exceeded, the State of California water quality goal of 200 µg/L (Table 1). It should be noted that the Environmental Protection Agency revised its health advisory during this period. This resulted in the State of California easing its water quality goal for hexazinone to 400 µg/L. The rate of application for hexazinone, in pellet form, for the treatment units where the groundwater monitoring wells were sited varied from 33.6 to 41.4 kg/ha.

Hexazinone was not detected during the year of application in any of the monitoring wells (Table 1). For wells where application was ground based, it was detected in the first year following application (second year sampling). For wells where aerial application took place, hexazinone was not detected until the second year following treatment (third year sampling). However, the sample size is too small to make any inference from this observation. What is not surprising is the delay before detectable amounts of hexazinone were found in groundwater samples. Neary et al. (1993) had noted that movement of hexazinone in shallow groundwater took from months to a year following hexazinone application before detection. Based on the Stanislaus National Forest sampling, hexazinone demonstrated multi-year persistence, lasting from one to four years following detection. Again, this is too small a sample upon which to base broad conclusions.

Conclusions

Both the Unit 505 monitoring and post-fire groundwater monitoring well results demonstrate that hexazinone used in reforestation efforts in the southern Sierra Nevada does enter unsaturated and saturated groundwater zones. Monitoring to date does not find those detected concentrations approaching or exceeding the initial State of California water quality goal of 200 µg/L or the later less restrictive value of 400 µg/L.

On the Sierra National Forest, Unit 505 monitoring demonstrated that hexazinone can penetrate a significant distance into the 7.6-m buffer on either side of a Class 4 channel centerline. The detectable concentrations are a full magnitude lower than the State of California water quality goal. The pattern of mobility at these sensitive sites clearly shows peak concentrations of hexazinone in surface water following the first storm event and a gradual rise to peak concentrations of hexazinone in the vadose zone water after several storm events.

On the Stanislaus National Forest, monitoring well results yielded persistence information that has implications for groundwater monitoring in future reforestation projects. Plans for monitoring of the saturated groundwater zone should extend for two years of sampling following the year of application to ensure detection of hexazinone. Once detected, hexazinone will likely persist for one to four more years.

Monitoring for herbicide impacts to groundwater requires a significant commitment of time, personnel and funding. However, monitoring information is important to improving project design and demonstrating expected performance to a sometimes skeptical public.

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Table 1. Well number, application data, and detected concentrations of hexazinone (in µg/L) for monitoring wells used on Stanislaus National Forest reforestation projects.

Well	Application Method	Application Rate (kg/ha)	Concentration of Hexazinone (in µg/L) for Year 1	2	3	4	5	6	7
MW 26-12	Ground broadcast	34.7	ND	**2.6**	**3.1**	*NS*	**0.56**	**0.44**	ND
MW 26-21	Ground broadcast	41.4	ND	**0.99**	**2.2**	**0.16**	ND	---	---
MW 26-56	Aerial broadcast	33.6	ND	ND	**0.29**	**0.76**	**0.71**	ND	---
MW BS-45	Aerial broadcast	33.6	ND	ND	**0.17**	**0.28**	ND	---	---

ND - substance absent or below detection limit of test
***NS* - no sample taken**

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Section 4. Valuing the Earth Sciences
Part 2. Geology

Overleaf:
Beartooth Range, Gallatin National Forest, Montana.
Photo by Pete Bengeyfield.

Jökulhlaup in the Wind River Mountains, Shoshone National Forest, Wyoming

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A jökulhlaup burst from an ice-dammed lake at the head of Grasshopper Glacier in the Fitzpatrick Wilderness of Wyoming's Wind River Range during early September 2003. The 12-hectare lake drained an estimated 3.2 million cubic meters of water, down slope, underneath the glacier, and down tributary valleys into the Wind River valley. The outburst flood was recorded at a USGS gage (06221400; drainage area 245 km^2) on the Dinwoody River approximately 33 km downstream from the ice-dammed lake. Jökulhlaups can be triggered by volcanic, seismic, and meteorologic events, and perhaps by climatic warming. Satellite images of the Wind River Mountains show dramatic recession of the glaciers since 1986. Work by Naftz et al. (2002) on the Upper Fremont Glacier (10.5 km south of Grasshopper Glacier on the Continental Divide) shows a warming trend and temperature increase of 3.5°C at high elevations over the past fifty years. It is likely that the Grasshopper Glacier jökulhlaup was triggered by local conditions within the glacier and the outburst lake created by this climatic warming trend. Reconnaissance surveys in the summer of 2004 characterized the geomorphic effects and addressed the hazards associated with the jökulhlaup. Five distinct sedimentation patterns formed in reaches of the river downstream from the glacier. Outburst floods in the Wind River Range will probably recur in the near future, as the glaciers continue to recede.

Keywords: *channel geomorphology, flood processes, geology/geomorphology, glaciation, hydrologic processes, sedimentation, streamflow, woody debris*

Background

A jökulhlaup, or glacial outburst flood, burst from an ice-dammed lake at the head of Grasshopper Glacier in Wyoming's Wind River Range during early September 2003. The 12-hectare lake drained an estimated 3.2 million cubic meters of water downslope, underneath the glacier, and down tributary valleys into the Wind River valley. The outburst flood was recorded at a USGS stream gage (06221400; drainage area 245 km^2) approximately 33 km downstream from the ice-dammed lake. During the period 1956-2001, annual peak snowmelt flow at the gage averaged 23 cubic meters per second (range 14-42 cubic meters per second). On 9 September 2003, the gage recorded a peak of 36.5 cubic meters per second, which rose from a base flow of 7 cubic meters per second on 6 September (Figure1).

Grasshopper Glacier lies on the Continental Divide between high-level erosion surfaces and the eastward-facing cirque walls of the mountain front. The glacier, which flows from south to north, drops 2.8 km from approximately 3647 m down a slope of 0.11 to its snout at 3435 m elevation. Grasshopper Glacier is presently about 2.5 km wide and covers approximately 364 hectares. The catchment of the outburst lake is at most 2.8 km^2, and only a small remnant of the glacier remains in the cirque above the lake. Ice at the margin of the lake is 18-21 m thick. (Figure 2)

The Grasshopper Jökulhlaup

The outburst flood entrained subglacial sediment as it flowed for 2.8 km beneath Grasshopper Glacier. The sediment-laden flood then followed the steep, narrow valley of Grasshopper Creek to the Downs Fork and its confluence with Dinwoody Creek. Here, where the valley widens in a broad u-shaped glacial valley, the flood ponded in an ephemeral lake at the low gradient Downs Fork Meadows 13 km downstream. The flood then continued to step down the valley for another 23 km, to Mud Lake, the gage site, the Dinwoody Lakes, and on to the Wind River. Along most of this route, the flood

Furniss, M.J., Clifton, C.F., Ronnenberg, K.L., eds., 2007. *Advancing the fundamental sciences: proceedings of the forest service national earth sciences conference, San Diego, CA, 18-22 October 2004*. PNW-GTR-689. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station.

Figure 1. Grasshopper Glacier is located in the Fitzpatrick Wilderness, on the Shoshone National Forest, in the Wind River Range about 30.5 km south of Dubois, Wyoming. The USGS stream gage site on Dinwoody Creek is located at the eastern margin of the watershed on the Wind River Indian Reservation. Dinwoody Creek crosses Wyoming Hwy. 287 downstream of the gage site, and is tributary to the Wind River. Map base is USGS topographic series Thermopolis Sheet 1:250,000.

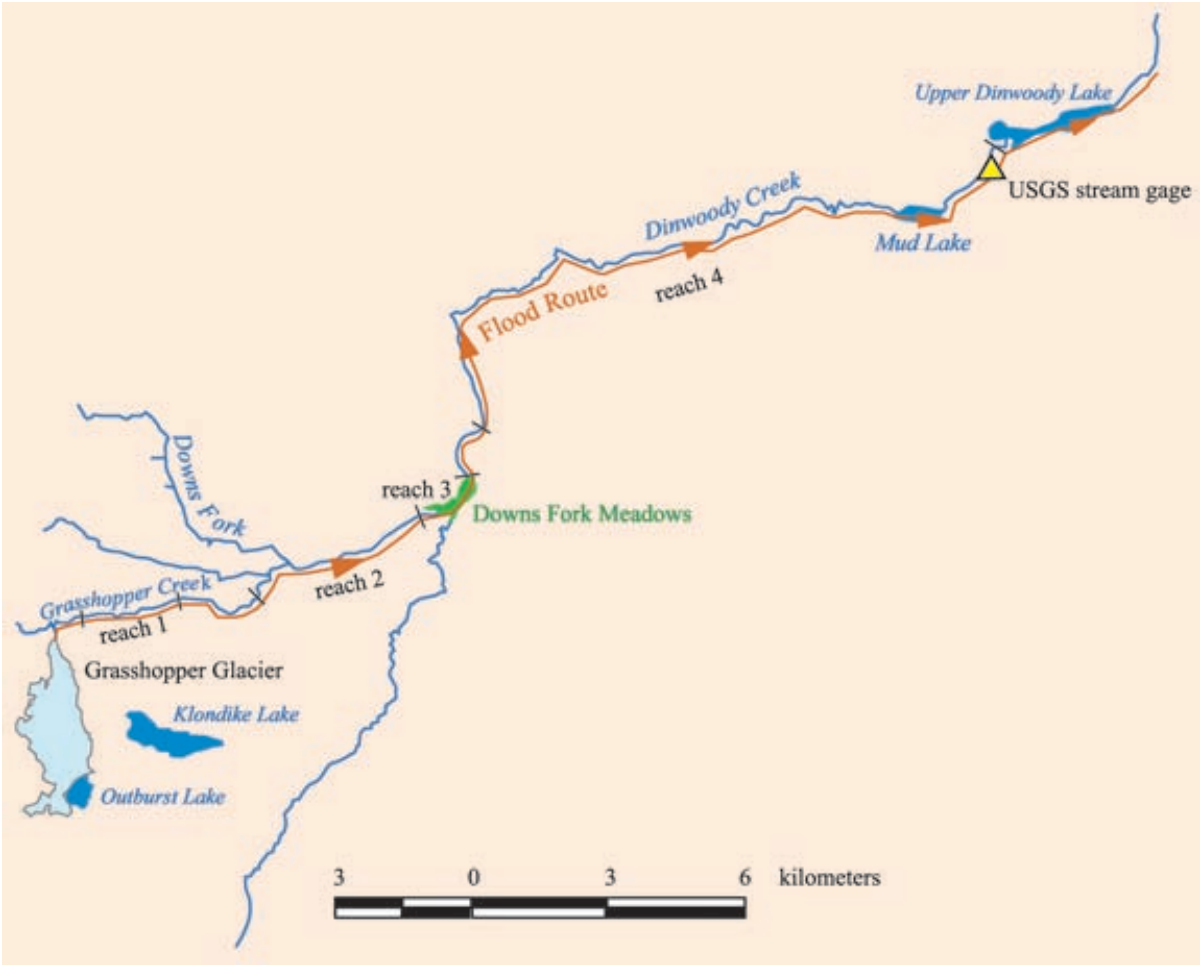

Figure 2. Ice-dammed lake that drained from head of Grasshopper Glacier. The view is to west. The lake drained beneath glacier to the north, and flooded to the north then east down the drainage of Grasshopper Creek, to Downs Fork Creek, and to Dinwoody Creek.

traversed glaciated terrain of granites, migmatites, and gneiss. Paleozoic sedimentary rocks crop out near Mud Lake.

Aerial surveys about two weeks after the flood showed the jökulhlaup had deposited bedload in apparently braided channels from the head of Grasshopper Creek down to the confluence with the Downs Fork. Floodwaters scoured the abutments of the Downs Fork Bridge, then overtopped the bridge and deposited large woody debris, creating a debris jam on the bridge. Suspended sediment roiled through the ephemeral lake at Downs Fork Meadows. When the lake level subsided, 0.6-1.5 m of granitic silty sand were deposited over an area of approximately 28 hectares. Suspended sediment transport continued down Dinwoody Creek, where 1-meter-high standing waves were observed. The creek avulsed from its pre-flood meandering course through the meadow, creating numerous overflow channels, and filling the pre-flood channel with sediment. Downstream nearly 33 km from the outburst lake, Mud

Lake practically filled with sediment. Fine sediment was carried into the Dinwoody Lakes, and was still present in Dinwoody Creek (where it crosses Wyoming Highway 287) at unusually high levels in mid-November 2003.

Jökulhlaups have been attributed to volcanic, seismic, and meteorologic triggers (Cenderelli and Wohl 2001, 2003; Walder and Costa 1996). The warmer summers and shorter, warmer winters likely to accompany climatic warming may also increase the incidence of jökulhlaups as glacial ice melts and thins more rapidly. No direct correlation was found between regional meteorologic or seismic events and the Grasshopper Glacier jökulhlaup, but the jökulhlaup did occur during unseasonably warm weather in the fifth year of a severe regional drought.

The rapid recession of glaciers worldwide is well documented. Satellite images of the Wind River Range (courtesy of Sky Truth, John Amos) show particularly dramatic recession since 1986. Work by Naftz et al. (2002) on the Upper Fremont Glacier, 10.5 kilometers from Grasshopper Glacier, indicates a warming trend and temperature increases of 3.5 degrees Celsius at high elevations in this region during the past 50 years. It is hypothesized that accelerated warming in the high elevation areas of the Wind River Range, as documented in the ice-core record, caused melting and recession of the glaciers, producing increased meltwater which eventually filled the ice-dammed lake perched on the bedrock floor above Grasshopper Glacier, and caused the glacial outburst flood (Naftz et al. in press).

Field reconnaissance surveys conducted in summer 2004 recorded the geomorphic effects of the jökulhlaup as the flood eroded, transported, and deposited sediment and shaped the river and its valley along the flood route. From the draining of the ice-dammed lake (Figure 2) and subglacial entrainment of sediment, five distinct sedimentation patterns were documented in reaches downstream from the glacier. These five reaches are characterized in a downstream direction by: 1) "outwash" deposition of expansion bars; 2) log jams, stream bed aggradation and overbank deposition; 3) channel avulsion and aggradation, and deposition from ponding in an ephemeral lake; 4) in-channel depositional filling of riffles and pools; and 5) silt and clay deposition in lakes and irrigation systems. Also in a downstream direction, median grain size progressively decreased from boulders to cobbles at the expansion bars, to gravels, sands, silts and clays toward the gage site.

Table 1. Summary of characteristics of studied reaches of Grasshopper Creek.

Reach	Distance Below Glacier (km)	Average Valley Gradient	Figure
1	4.2 - 6.1	0.045	3
2	8.2 - 13.2	0.025	4
3	13.2 - 15.3	0.013	5
4	16.7 - 21.2	0.025*	-
5	32 - 38.6	NA	-

**in depositional areas*

Outwash deposition of expansion bars occurred in the most upstream reaches (Table 1) of Grasshopper Creek (Figure 3; Reach One: 4.2 km to 6.1 km; distance measured from outlet of outburst lake at head of the glacier). Valley slope averages about 0.045. Bar deposition spread out across the entire valley bottom, up to 0.2 km wide and 1.4 m high. Log jams, stream bed aggradation, and overbank deposition occurred in a lower-gradient reach with 0.025 average slope (Reach Two: 8.2 km to 13.2 km distant from the outburst lake). Sixteen log jams were recorded that persisted in the valley at the time of the survey. The largest

Figure 3. Expansion bars deposited by flood in upper reaches of Grasshopper Creek. The view is upstream.

Figure 4. One of the many log jams on the Downs Fork. The view is downstream

log jam was at a maximum up to 12 m wide down the length of channel, 35 m across the width of channel, and up to 3.5 m high from the channel bed (Figure 4). At the Downs Fork bridge, large woody debris had been removed in order to "save the bridge". Channel avulsion and aggradation, log jams, and deposition of suspended load in an ephemeral lake occurred in the Downs Fork meadow area, with 0.013 average slope (Reach Three: 13.2 km to 15.3 km) (Figure 5). In-channel depositional filling of riffles and pools occurred below Dinwoody Falls, to below Shangri-La Meadows, and on to the lower reaches of the Dinwoody valley (Reach Four: 16.7 km to 21.2 km and beyond). Slopes averaged 0.025 at depositional areas of these reaches. Silt and clay deposition in lakes and irrigation systems occurred in the lower reaches of the Dinwoody valley at Mud Lake, the Dinwoody Lakes (Reach Five: 32 km to 38.6 km), and irrigation canals and ditches that traverse the lower Dinwoody River to the Wind River floodplain.

Conclusions

No known fatalities, and only minor structural damage to the Downs Fork bridge and disruption of the Downs Fork outfitter camp, occurred in the Fitzpatrick Wilderness as a result of the jökulhlaup. There is an increased flood risk in the upper reaches of the flood area due to aggradation of stream channels. Log jams that formed during the flood created significant geomorphic effects on the river valley. The flood produced a local impact on irrigators of the upper Wind River Indian Reservation, not only due to the siltation of irrigation ditches, but also due to the diminishing glacial reservoirs which the irrigators rely on for late-season irrigation. It is likely that continued warming and melting of glaciers in the Wind River Range will result in future and perhaps more frequent outburst flood events.

Figure 5. Aerial view of Downs Fork Meadows in late September 2003, showing extent of flood deposition in ephemeral lake, channel avulsion, and overbank flows. Left is downstream.

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Reclamation, Remediation, and Hydrologic Monitoring of the Minnie Mine and Mill Site, Okanogan County, Washington

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The Minnie mine, a small cyanide heap leach gold mine near Carlton, north-central Washington was abandoned in the early 1990s. The presence of cyanide and heavy metals in the heap and process waters necessitated a series of removal and remediation actions taken by the US Forest Service under CERCLA and a parallel state law, the Model Toxic Control Act. Some contaminated fluids were batch treated using conventional methods and disposed of by land application (controlled distribution of treated solutions over a specified land area). An innovative pilot-scale In-line System process was successfully used to treat free and complexed cyanide in 45,000 liters of process pond sludges. A soil cap was constructed over arsenic-contaminated, spent ore heap materials to isolate them from people and wildlife. Suction lysimeters were installed below these solids, along with monitoring wells up- and down-gradient, to monitor potential arsenic mobilization. The capped heap, mine pit and associated disturbances were reshaped and successfully revegetated. Eight years of monitoring shows no significant down-gradient arsenic mobilization at the site.

Keywords: *mine restoration, hydrology, groundwater quality, pollution, costs, CERCLA, MTCA*

Introduction

This paper describes the successful efforts to restore the abandoned Minnie mine and millsite in north-central Washington (Figure 1) and to remediate hazardous wastes associated with the site. The paper also highlights the unanticipated efficiency and cost impacts resulting from compliance with parallel federal and state cleanup laws.

Beginning in 1983, Cordilleran, Inc., operator of the Minnie mine, initiated cyanide heap leach technology to recover gold and silver from oxidized quartz-sulfide ore mined in a small open pit located on National Forest System Lands. This operation resulted in the placement of approximately 6,300 metric tons of crushed and cement-agglomerated ore upon a 26 m by 36 m pad underlain by a 30-mil polyvinyl chloride (PVC) geomembrane liner and compacted soil. Pregnant (gold-bearing leachate) and barren (stripped and recycled fluid) process ponds constructed adjacent to this pad were about 15 m by 15 m, by 2.5 m deep, with a capacity of approximately 280,000 liters of ore heap leachate each (Figure 2). Ponds were double lined with 36-mil Hypalon liners separated by geotextile fabric and a leak detection monitoring system. A small carbon absorption/electrowinning plant was constructed to recover precious metals from the leach solutions.

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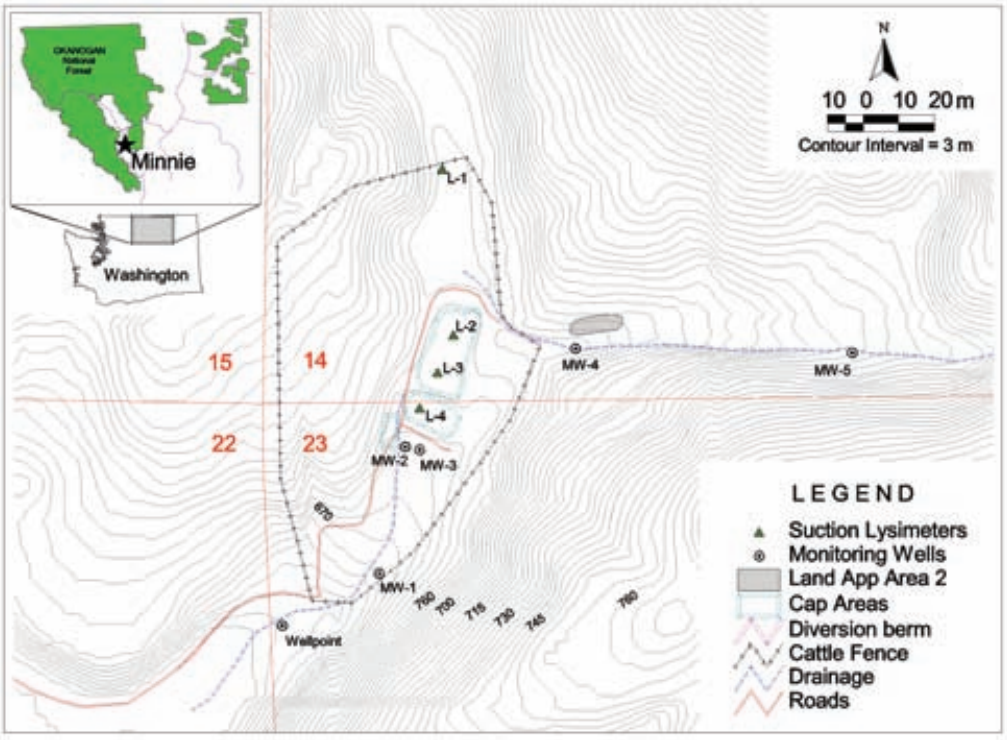
The operator discontinued heap leach operations by early 1986, but site closure implementation was delayed. Due to corporate reorganization and lack of funds, the company was searching for a buyer that was interested in restarting operations. Meanwhile, it became necessary to treat and pump process pond fluids to reduce cyanide concentrations and avoid spring-time overtopping of the ponds. Cordilleran completed some emergency work but their cash problems continued. The Forest Service's goal during this period was to work toward final site closure while maintaining safe conditions and holding the operator responsible for all costs. When it became apparent that the owner was unable to comply with their operating plan, the agency completed site work that was necessary to protect ground water, wildlife, and human health. Repayment agreements were executed by the claimant to compensate the USDA Forest Service for the cost of that effort. A buyer for the mine never materialized and eventually the claimant declared bankruptcy; the Forest Service inherited sole responsibility for cleanup in late 1990 and the operation's $7,200 reclamation bond was forfeited.

Site remediation was complicated and delayed by the interaction and perceived differences between parallel Federal and state environmental cleanup laws; the Comprehensive Environmental Response, Compensation and Liability Act, as amended (CERCLA or "Superfund", 42 USC §§ 9601) and Washington Model Toxics Control Act (MTCA, Chap. 70.105d Revised Code of Washington [RCW}). Washington Department of Ecology manages

Figure 1. Minnie mine facilities: (h) processed ore heap, (l) pad liners, (p) pregnant process pond, (b) barren process pond, (r) recovery plant. Photograph taken after the 1985 Minnie wildland fire (unrelated to the mine operations).

Figure 2.
Minnie mine site location.



the MTCA program. Considerable time and energy were invested to resolve issues of authority and even report formats. While the Forest Service initially attempted to satisfy the intent of MTCA using CERCLA documents, the agency eventually produced two sets of documents for the final removal actions.

CERCLA/MTCA Process and Reports

The National Oil and Hazardous Substances Pollution Contingency Plan (NCP, 40 CFR 300) sets forth procedures for undertaking CERCLA cleanup actions and defines federal agency roles, including the Forest Service. Regarding abandoned mines, the process begins with a site assessment, which determines if a release or threat of a release of a hazardous substance has occurred. This step usually generates two reports, a Preliminary Assessment (PA) and a Site Inspection (SI), both of which document conditions at the site and the evidence of the threat or actual release of hazardous substances. If a release is evident, a Potential Responsible Party (PRP) search is conducted and documented. This step looks for parties that may be responsible for the contamination and that could participate in and pay for any cleanup actions. Cleanup response may take the form of a Removal or Remedial Action. Most Forest Service mine responses use

the Removal process. Such responses demand simple to moderate levels of analysis and may be time critical in nature. Remedial action responses are typically evoked for large, complex projects that require lengthy, detailed study or those promoted to the National Priorities List (NPL) by US Environmental Protection Agency (EPA). Both processes analyze alternative response approaches and provide for public input consistent with the level of complexity. For Removals this is documented in an Engineering Evaluation/Cost Assessment (EE/CA) and for Remedial Actions, a Remedial Investigation/Feasibility Study (RI/FS).

Regulations implementing MTCA are organized under Washington Annoted Code (WAC) Chapter 173-340. These regulations outline a process which parallels CERCLA. Under MTCA an Initial Investigation and Site Hazard Assessment replace the PA/SI. All cleanup actions are documented in a Remedial Investigation/Feasibility Study (RI/FS) under MTCA.

Environmental Concerns

Initial site concerns revolved around the presence of highly toxic free cyanide and cyanide complexes in the process fluids and processed ore heap. Heavy metal contaminants, especially arsenic, cadmium and mercury, later became more prominent in the cleanup strategy.

Short Term Risks

Shortly after mine operations ceased several immediate risks became evident. Warm summer conditions favoring evaporation tended to concentrate cyanide in the process pond fluids and natural buffering reactions decreased heap and fluid pH. The combined effect was to increase the off gassing of hydrogen cyanide (HCN) to the atmosphere (Smith and Mudder 1991) thus increasing risk to nearby wildlife and humans. A substantial number of bird and bat carcasses were discovered around the ponds in July 1986.

Because precipitation on the heap continued draining to the pregnant process pond, fluid volume accumulated over time. Spring melting of winter snows on the heap sometimes threatened to overfill the ponds, spilling contaminated fluids and menacing ground water.

Long Term Concerns

Investigations at the site revealed several tasks that must ultimately be addressed:

- The treatment of contaminated process fluids and sludges accumulating in the process ponds;
- The treatment of cyanide in the processed ore heap;
- The potential for ground water contamination from pad-liner or pond leaks and from leaching of processed and unprocessed ore materials and land application soils;
- Physical reclamation of the mine and millsite facilities; and
- Long-term protection of remedial structures and reclamation efforts from storm and surface water runoff and erosion.

Restoration and Remediation

Treatment of Processed Ore Heap

The PVC liner from a second, unused pad was pulled over the exposed heap in November, 1986 to limit precipitation influx to the process ponds, which were in danger of overtopping at the time. This cover was removed one year later to facilitate heap washing and neutralization. No analyses of the processed ore heap material are available from that time, but a qualitative field test of leachate draining from the heap in August 1988 indicated >100 ppm free cyanide (CN_{Free} = unbound CN^- & HCN). By April 1989 CN_{Free} in the heap averaged about 10 mg/kg with a maximum value of 28 mg/kg. Because of contaminated drainage from the heap, it was clear that treatment of the heap solids and decommissioning of the pad was a prerequisite to the final treatment and disposal of process fluids and pond sludges.

Treatment of heap solids was accomplished over an extended time period by natural oxidation processes, influx of rain and snow melt and by circulation of neutralized process fluids and fresh water. Natural degradation of cyanide complexes was facilitated by periodically stripping the detoxified surface layer (0.7-1.0 m in depth) from the heap. The new surface was then ripped to improve overall permeability. Stripping was cost effective at the Minnie due to the relatively small size of the heap. Surface layers were removed three times between October 1989 and April 1991. The compliance standard for solids removal and final treatment was 10 mg/kg amenable cyanide (CN_{Amen}) which represents the difference between total cyanide (CN_{Total} = free + complexed CN) measured before and after alkaline chlorination treatment (USDA FS 1992). Heavy metals in the heap also had to meet RCRA (Resource Conservation and Recovery Act) solid waste criteria. Following compliance testing, the remaining heap lift and the synthetic heap liner were machine ripped to sever their hydraulic connection to the process ponds.

Treatment and Disposal of Process Fluids

Process fluids are here defined to include all solutions or supernate that report to and reside in the pregnant and barren process ponds. The operating plan called for working solutions containing 0.025 percent or 2500 ppm CN_{Total}. Dissolved constituents in these solutions varied between the two ponds and during the treatment procedures. Analysis of pregnant pond solutions in 1986 indicated 1200 ppm weak acid dissociable cyanide (CN_{WAD} = CN_{Free} + weakly bound CN complexes). Process water quality is described in Appendix A.

Fluid treatment was initiated by the operator in 1986. The intent was to detoxify the ponds and heap and dispose of excess fluid under their state waste discharge permit by land application. Alkaline chlorination (Smith and Mudder 1991) was selected by the operator to accomplish cyanide neutralization because of its relative simplicity both in technique and reagent use. This method involved the careful mixing of calcium hypochlorite ($Ca[OCl]_2$)with the pond solutions while maintaining a pH of 10.5-11.5. The hypochlorite converts CN_{WAD} to non-toxic cyanate (CNO).

Neutralization of pond fluids continued intermittently until 1993 in coordination with heap detoxification and stripping operations. Treated process fluids were land applied under Cordilleran's default National Pollutant Discharge Elimination System (NPDES) permit on two occasions and over two areas (Appendix A). The operator's discharge permit was cancelled in 1990. Washington Dept. of Ecology imposed more stringent discharge standards thereafter, which were not attainable using alkaline chlorination and sulfide precipitation (see discussion below). Consequently, the final 103,000 liters of neutralized process fluid, designated as a dangerous waste under state law (WAC 173-303) because of elevated mercury levels, was eventually trucked to a permitted treatment/discharger on Puget Sound in October 1993.

Fluid treatment at the Minnie was complicated by: (1) continued inflow of contaminated water from the heap; (2) ongoing chemical interaction with the sludges; (3) the need to prevent overtopping of the ponds; (4) high chlorine consumption; and (5) elevated mercury levels. Chlorine consumption was very high for Minnie process pond cyanide detoxification; an estimated 15-28 kg of chlorine for each kg CN_{WAD} oxidized. Early lab tests indicate 8-13 kg of chlorine would be needed for each kg of CN_{WAD} oxidized. Excessive chlorine consumption may have resulted because of inadequate reaction monitoring, reaction with sludge components, or the presence and oxidation of thiocyanide in the fluid (Smith and Mudder 1991). The operator reported copper and mercury concentrations in treated water as high as 400 and 7 ppm, respectively. The alkalinity maintained during treatment assisted in the precipitation of heavy metals present in solution as hydroxides. Sodium sulfide was mixed in the ponds as a polishing step (Smith and Mudder 1991), especially to precipitate and further reduce dissolved mercury concentrations.

Minnie ore typically contained low mercury concentrations (Appendix A). However, elevated mercury was found in the process waters and the upper part of the heap after it was washed with treated process waters. Because of the large volume of treatment reagents used it is believed that trace amounts of mercury present in the calcium hypochlorite may have accumulated during the neutralization process.

Treatment and Disposal of Process Sludges

Process sludges are defined as the low-density solids which accumulated in the pregnant and barren process ponds since their installation. Included are various incompletely dissolved chemical reagents used during operations and treatment, detrital sediment originating from the heap, chemical precipitates, dust and vegetative matter and accompanying interstitial fluids. Approximately 45,000 liters of sludge remained in the ponds after all process fluids had been removed. Chemical and Toxicity Characteristics Leach Procedure (TCLP) analyses for the sludge solids portion are displayed in Appendix A. The values indicate high levels of cyanide and heavy metals in the sludge. TCLP extracts also exceed ground water standards for cyanide and most heavy metals.

The sludge EE/CA decision (USDA FS, 1993) supported the removal and transport of process sludges as a hazardous substance to a Resource Conservation and Recovery Act (RCRA) Class C Licensed Treatment/Storage/Disposal facility (TSD). However, cyanide levels in these materials exceeded the TSD's screening values (570 mg/L $CN_{T,}$ 30 mg/L CN_{WAD}). Rather than transporting the sludge to a more distant TSD which had additional treatment capabilities and approximately doubling disposal costs, the Forest Service chose to treat the sludge using alkaline chlorination. Assisted by the USDI Bureau of Mine's scientists, the Forest Service designed and constructed a unique, pilot-scale In-Line System (ILS) to successfully treat the process solids (Figure 3). Details of the design and use of the ILS are described by Lentz and Knott (1997). Following reduction of cyanide concentrations the sludges were transported by a licensed Hazmat contractor to the TSD in September 1993 (Figure 4). Pond liners were cleaned, examined for tears or punctures, tested and removed to a land fill as solid waste.

Figure 3. ILS design for sludge treatment.

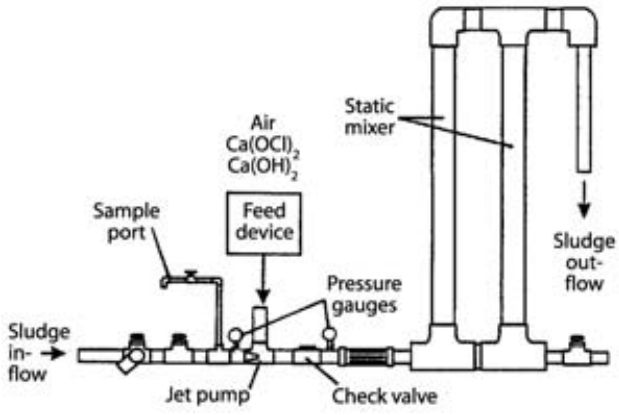


Figure 4. Following reduction of cyanide concentrations the sludges were transported by a licensed Hazmat contractor to the TSD in September 1993.

Evaluation of Ore, Heap, Process Plant, Land Application and Sub-liner Soils

A soil sampling program was developed for soils beneath or adjacent to the various mine facilities to evaluate compliance with MTCA screening levels. A total of 51 samples were analyzed: 12 beneath the heap liner; 14 beneath land application #1; 6 beneath land application #2; 15 beneath the process ponds; three from the recovery plant and three from beneath the unprocessed ore stockpile. Appendix A summarizes sampling data. Soil samples were screened against MTCA Method B soil formula values while TCLP tests were compared to MTCA Method B ground water formula values (Olympus Environmental, Inc. and USDA FS 1994a).

Process Ponds and Plant. Observations of the upper and lower synthetic pond liners and the intervening fiberglass mat (leak detection layer) showed no evidence of significant leakage through either liner. Three small, circular white stains found on the fiberglass mat may have been caused by pinhole-sized holes in the upper liner. A 2.5-cm-long tear in the lower liner (pregnant pond) about midway up the leak detection monitoring pipe (20 cm diameter PVC) was attributed to a sharp edge on the pipe. Eight centimeters of bark mulch underlying the lower liners was dry and unoxidized except for a small area around the tear which showed dark discoloration. This may have been caused by surface water moving along the leak detection pipe. Soil samples taken beneath this point and at other points beneath the ponds and at the processing plant showed no cyanide and less than screening or background levels of heavy metals. However, all but two of these samples exceeded the 1.3 ppm screening value for arsenic. For comparison, local background for soil arsenic was determined to be 26 ppm (90 percentile upper confidence limit).

Processed and Unprocessed Ore. Processed and unprocessed ore materials contained elevated metals, especially zinc, copper and arsenic, when compared to background. Nevertheless, only arsenic exceeded screening levels in these samples. The final heap samples (1993) all contained less than 0.5 ppm CN_{WAD}. TCLP leachate from processed ores exceeded ground water screening criteria for arsenic, cadmium lead, zinc and mercury (Appendix A). TCLP was run on one unprocessed ore sample. No screening levels were exceeded but the analysis did not include arsenic and lead. It is presumed that the TCLP for arsenic would have exceeded the ground water screening level.

Limited direct observations of the in situ synthetic liner found it to be in good condition where it had remained covered beneath the heap. But deterioration of the PVC was noted where it was exposed to the atmosphere, direct sunlight and mechanical impact or strain by 1990, about 7 years after installation. Some leakage was evident at the liner-outlet pipe seal. Analysis of soil underlying this connection showed substantially elevated metals compared to all other samples taken from beneath the heap liner. (880 ppm arsenic compared to 17 ppm average). All other sub-liner samples showed metal concentrations below screening levels or background. One sample exceeded the 1.3 ppm arsenic screening value.

The potential for acid rock drainage (ARD) from both processed and unprocessed ore is deemed low. Minnie mine ore is largely oxidized, containing few iron sulfide minerals. Moreover, the ore is associated with an acid-neutralizing calcium carbonate host rock (marble). Static ARD testing (modified acid base accounting) demonstrated a net neutralizing capacity of the ore, its neutralization potential/acid potential ratio or NP/AP being 9 (NP/AP ratios of 3 or greater are considered non-acid forming; USEPA 1994).

Land Application Areas. Compliance soil sampling revealed above-background levels of zinc, copper, arsenic and mercury in Land Application Area 1. Only arsenic was found to exceed the 1.3 ppm screening level. All CN_{WAD} concentrations were less than 0.5 ppm. Because Area 1 lies on mine waste rock the elevated metals may in part be attributed to background concentrations. Metals concentrations analyzed in Land Application Area 2 soils were all at or below background values. But again, arsenic exceeded the MTCA screening level.

Remedial Action and Reclamation

Final remediation and reclamation construction activities at the Minnie were completed in May 1995. The reasoning for and selection of the remedial action at the site is described in the Minnie Mine Soils EE/CA (USDA FS 1994) and the Phase I & II RI/FS (Olympus Environmental, Inc. and USDA FS 1994a, 1994b). Remedial Site work included the following activities:

- Removal of the unprocessed ore stockpile to the depressions occupied by former process ponds.
- Grading of unprocessed and processed ore storage areas and Land Application Area 1
- Distribution and mixing of ~2.2 metric tons/ha agricultural lime across the above arsenic-impacted areas to modify soil pH
- Excavation of clean native soils from an adjacent borrow area
- Distribution of native soils forming a gently sloping (<10 percent grade), 0.5-m-thick water storage cap over arsenic-impacted areas
- Installation of soil moisture sensing (gypsum blocks) and pore water sampling equipment
- Compliance sampling of cap soils
- Seeding cap of soil with native grass species
- Maintenance of the existing storm water diversion ditch/dike (as needed)

The purpose of the soil cap was two fold: (1) To isolate people and wildlife from contact with or ingestion of elevated arsenic, and to a lesser degree cadmium, found in the ore materials and land application area; and (2) to minimize infiltration of meteoric water into and through the contaminated soils. The later was based upon the capacity of the soil cap to store annual precipitation and snow melt and release it through evapotranspiration. EPA's Hydrologic Evaluation of Landfill Performance (HELP) model (Schroeder et al. 1986) was used to evaluate the cap design. The HELP model estimated a net annual infiltration rate of 2.5 cm/yr issuing from the base of the contaminated soils.

Soil pore water monitoring required the installation of four suction lysimeter/gypsum moisture block sets (Figure 5): one background station, one beneath the unprocessed ore, and two beneath processed ore material (Figure 2). Each set include identical primary and backup installations.

Other Reclamation Activities. Coincident with the remediation construction activities were other site reclamation efforts (Knott and Lentz 1996). The small open pit, waste rock and overburden stockpiles, the main haul road and a number of exploration cuts, pits and roads were reshaped and reseeded (Figure 6). The pit excavation was partially backfilled with waste rock and the remaining waste rock recontoured to blend with surrounding terrain. Approximately 300 linear meters of road was reclaimed by pulling back the fills into the road cut and recontouring. Approximately 3.2 hectares of total disturbance was graded and reshaped to blend with surrounding terrain and all areas reseeded with a native-species-dominated mix. Figure 7 shows the recent condition of the site.

Figure 5. Suction lysimeter installation (a), lysimeter/soil moisture block (b), and field installation (c). This typical lysimeter was used to monitor pore water beneath the processed and unprocessed ore storage areas.

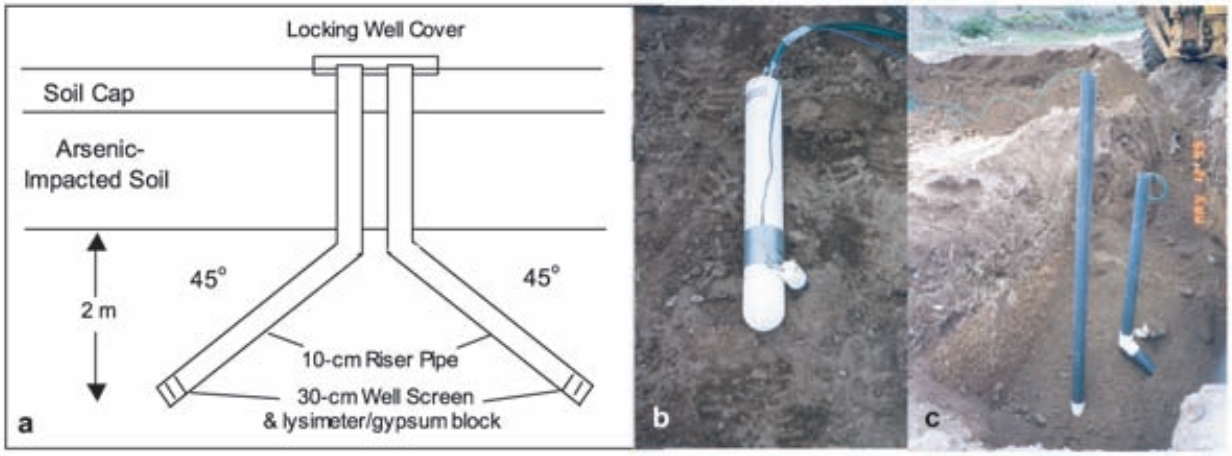


Figure 6. Comparison pre-cleanup disturbances (a) and final cap construction (b).

Site Monitoring

Monitoring requirements were designed to evaluate both cap construction and cap function. The upper 0.5 m of the cap were to meet MTCA Method A cleanup standards for arsenic (≤ 20 mg/kg) and MTCA Method B standards for cadmium (≤ 40 mg/kg). A level of 20 mg/kg arsenic was approved as the target criterion deemed to meet both metal standards. The cap and the diversion ditch and berm would be monitored for potential damage caused by erosion or deep-rooted vegetation. Background and under-cap soil pore water would be monitored, and when arsenic was present, arsenic concentrations to be determined quarterly for at least two years. Should under-cap soil pore water arsenic concentrations exceed those in the background lysimeter or, when no background sample was available, if under-cap soil pore water arsenic concentration exceeds 5 ppb arsenic, then sampling would be increased to monthly to collect statistically significant data, and the site Cleanup Action Plan (CAP) would be reopened and re-evaluated as necessary. A private drinking water well (1 mile [1.6 km] down gradient of site) was to be monitored semi-annually for 2 years.

Five up- and down-gradient ground water monitoring wells installed by the Forest Service in 1991 (Figure 2) were also monitored and sampled in conjunction with that of the suction lysimeters. A deeper, down-gradient piezometer well ("wellpoint" in Figure 2) installed by a previous operator was also monitored. Lastly, the Forest Service installed a weather station and regularly collected site weather data.

Early sampling results were evaluated in a 1995 Minnie Mine Millsite CAP Construction Report (Olympus Environmental, Inc. and USDA FS 1995). Preliminary analysis indicated background arsenic soil moisture concentrations of 11.35 mg/L, a value significantly greater than the site cleanup criterion of 5.0 µg/L arsenic. MTCA allows the use of natural background in place of the Method A cleanup standard (WAC 173-340-700(4)(d)). Therefore, the intent of the monitoring program became

the collection of sufficient data to make a statistical comparison between background concentrations of arsenic and arsenic concentrations in down-gradient monitoring wells and suction lysimeters (Olympus Environmental, Inc. and USDA FS 1995).

Monitoring of the Barnett well was discontinued after approximately two years because of low arsenic concentrations in that well and in monitoring wells closer to the site.

Monitoring Results

Site monitoring results, interpretations and conclusions are discussed in detail in the Minnie CAP Monitoring Report (USDA FS 2003). Approximately eight years of monitoring (1995-2003) detected no visible evidence of structural failure or significant erosion of the soil cap. A large, summer storm event occurred in June 1998 that tested the up-stream diversion channel. This event caused deepening of the channel but did not compromise the integrity of the armored channel berm.

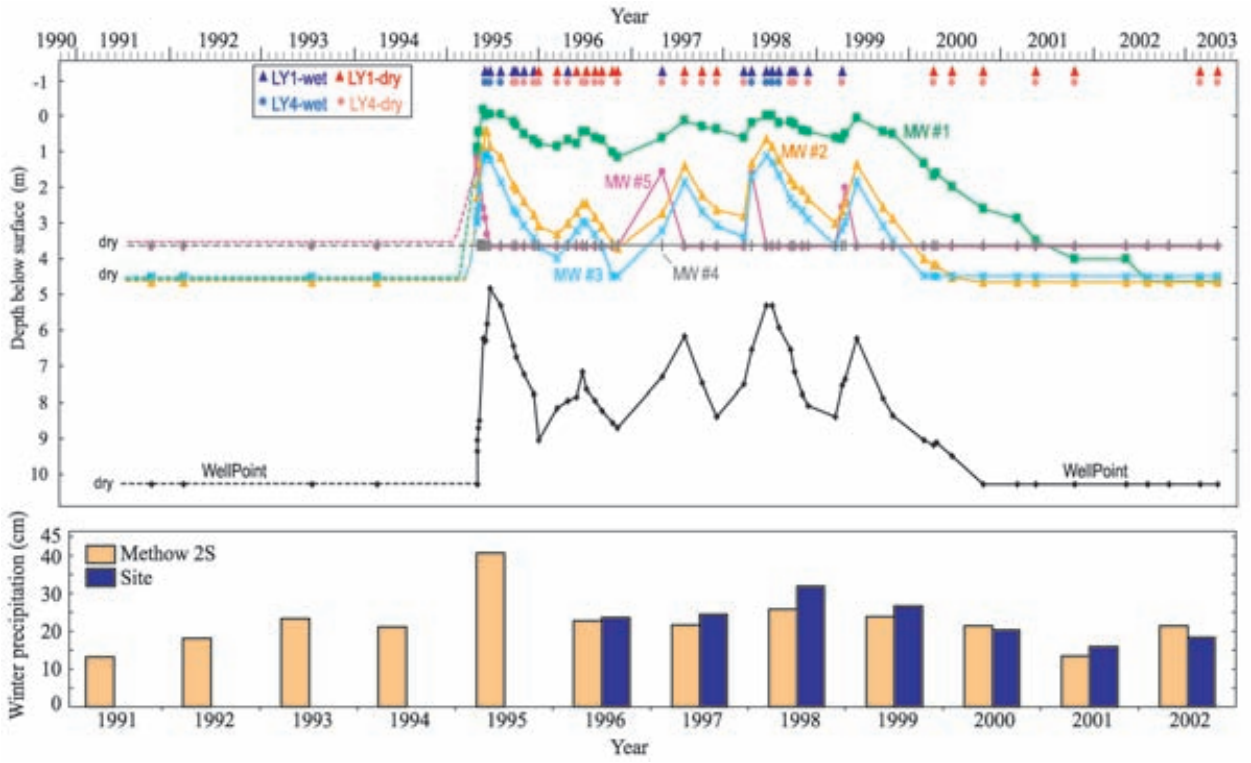
Revegetation of the soil cap and surrounding area was accomplished early and is successfully propagating (Figure 7). The CAP requirement to limit deep-rooted vegetation on the soil cap was rescinded by Washington Dept. of Ecology in 2001. Mowing of cap vegetation was therefore discontinued and sage brush has become a significant component of the cap plant community.

General Observations. Figure 8 summarizes water levels over the time period of documented observations. The condition ("wet" or "dry") of lysimeters L-1 (background) and L-4 is shown for comparison. Total winter precipitation from the nearest climatological station (Methow 2S) and the site (1995-2003) is also displayed. Monitoring data support the following general observations:

1. An anomalous occurrence of surface water and high groundwater levels at the site existed between 1995 and 2002. The change of surface and ground water manifestation was associated with unusually heavy winter (1994-95) precipitation, the first heavy precipitation year since the upper part of the drainage was denuded of timber by an August 1985 wild land fire (Figures 2 & 8).
2. Correlation of monitoring well data indicates down-drainage ground water movement on and above the bedrock/glacio-alluvial sediment interface at rates of 6-8 m/day.
3. Samples could not be drawn from the suction lysimeters when the lysimeter cups were found to be dry (i.e., when soil surrounding the lysimeter cups was unsaturated).
4. Few samples were available from L-2 and L-3, suggesting rapid transit of the spring snow melt wetting front and limited time of saturation.
5. Samples were available in L-4 only when water levels in down-gradient monitoring wells were high (within 1.3 m of the surface in MW-2).
6. Due to the return of subsurface water to normal levels it is unlikely that additional water samples will be available from L-4 or the other lysimeters.
7. The lack of observed ground water in MW-4 suggests the presence of a buried paleochannel which underlies glacio-alluvial deposits south of the existing valley .
8. The gypsum soil moisture blocks did not operate as intended. The purpose of these blocks was to help identify when adequate soil moisture was present for

Figure 7. Established site vegetation.

Figure 8. Comparison of Minnie mine ground water levels with lysimeter status and winter (Oct-Apr) precipitation.



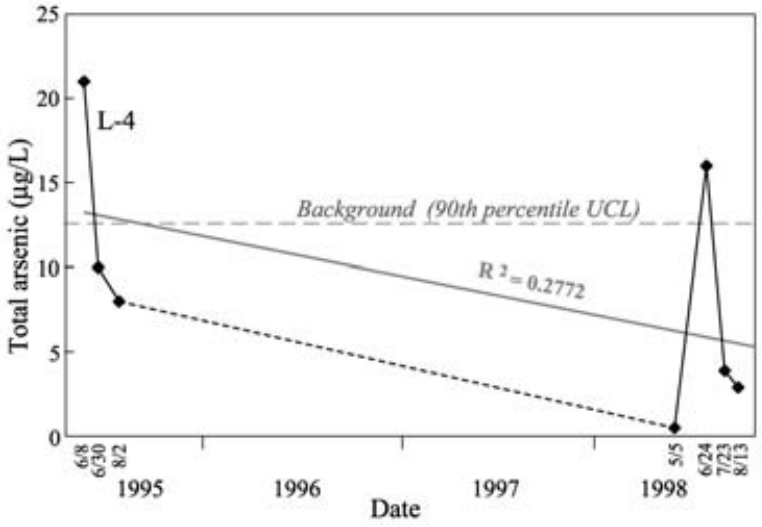
sample collection. However, in practice, soil moisture readings were consistently in the 90-97 percent range whether or not soil moisture samples could be drawn from the lysimeters. Lower moisture readings were not obtained until June 2000 and may be due to moisture block deterioration rather than actual changes in soil moisture (life expectancy is advertised at 3-5 years under irrigated soil conditions).

9. Arsenic levels in L-4 show a decreasing trend with time (Figure 9).

10. Good correlation of arsenic values in L-1 and L-4 suggests that a significant portion of the arsenic in L-4 pore water can be attributed to background arsenic levels (Figure 10).

Compliance. Compliance statistics for the Minnie monitoring stations are summarized in Table 1. Compliance requires that the 95 percentile upper confidence limit (UCL) for arsenic be less than the cleanup level, that no sample value is more than twice that standard, and than less than 10 percent of the values exceed the cleanup level. Soil sampling verified compliance with these stipulations when compared to the 20 mg/kg arsenic cap standard (Appendix A).

Figure 9. Arsenic trends in lysimeter L-4, soil pore water.



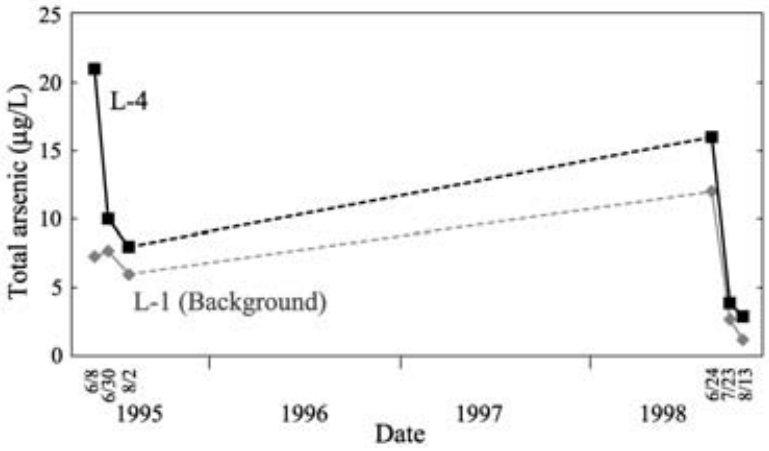


Figure 10. Correlation of arsenic values in lysimeters L-1 and L-4.

Statistical analysis of 21 background samples gives a site background value (90th percentile UCL) for arsenic in soil pore water of 12.69 µg/L. This value becomes the cleanup level for the suction lysimeters and monitoring wells.

Suction lysimeters L-2 and L-3 can not be tested statistically for compliance due to the lack of available soil pore water samples from these down-gradient points. One or no samples were collected from these stations, respectively. The single sample from L-2 showed arsenic concentrations of <1 ug/L. The apparent lack of soil moisture at these lysimeters implies compliance with soil pore water standards.

Down-gradient compliance points statistically evaluated include L-4, MW-1, MW-2, MW-3 and the Barnett well. The 95 percentile UCL for arsenic in monitoring wells MW-1, 2 and 3 were all below the 12.69 µg/L background and no samples exceeded that value.

Only seven soil pore water samples were available from lysimeter L-4. The statistical distribution of the data is lognormal and the lognormal mean, 11.07 µg/L, is below the background standard of 12.69 µg/L. However, due to the value range and small number of samples MTCAStat calculated a 95th percentile of 57.9. None of the sample values exceeded twice the background standard (25.38), but two of the seven or 29 percent exceeded background. MTCAStat estimates that some 226 samples would be necessary to obtain an upper confidence limit (UCL) of 12.5 µg/L (below background). Based upon sample availability during the past eight years this would amount to many decades of additional monitoring.

Four compliance samples from the Barnett well were available for statistical analysis. The lognormal mean for arsenic in these samples is 1.40 µg/L. No sample values exceeded background. The upper confidence limit, determined using the data set's maximum value, is 1.70 µg/L The UCL falls below the current state drinking water standard (10 µg/L) and the site's background value.

Table 1. Summary of arsenic compliance statistics for Minnie ground water monitoring samples.

Station	n[1]	Mean	Median	UCL[2]
Background	21	6.03	5	12.69
Down Gradient				
L-2	1	NA	NA	NA
L-3	0	NA	NA	NA
L-4	7	10.3	9	57.9
MW-1	22	1.73	1	2.55
MW-2	21	1.46	1	2.1
MW-3	8	2.28	2	4.33
Barnett Well	4	1.35	1.35	1.73

[1]Number of samples
[2]Upper Confidence Limit; 90th percentile for background and 95th for compliance.

Discussion. Except for suction lysimeter L-4, arsenic in all down-gradient ground water monitoring stations complies with the background standard of 12.69 µg/L. Nonetheless, the lognormal mean of arsenic concentrations in L-4 samples is below the background standard. Considering these data and the following observations the Forest Service believes that the site cleanup is protective of human health and the environment and has resulted in little or no impact to ground water quality.

Despite arsenic spikes in soil pore water from lysimeter L-4 arsenic concentrations in all down-gradient monitoring wells have lognormal means of 1.47 to 2.33 µg/L and comply with site background and the new 10 µg/L drinking water standards. Arsenic in L-4 soil pore water is decreasing, indicating diminishing availability of soluble metal in the capped material. A substantial portion of arsenic in the L-4 soil pore water can be attributed to background levels. The contribution from capped areas to ground water flow beneath the site is very small (0.04 percent) relative to the entire drainage basin. If arsenic

is being mobilized down gradient of L-4 there is no indication that it has reached the nearest monitoring well, MW-2 (100 feet down gradient), after eight years of unusually high groundwater flows (Table 1).

Based upon the monitoring results regular soil pore water monitoring at the Site was discontinued. However, if site groundwater levels rose again before 2006, sampling and arsenic analysis would resume. The Forest Service would continue to inspect the site to assure the integrity of the cap and related facilities both on an annual basis and after any unusual storm events.

Site Cleanup Costs

Final site cleanup costs totaled approximately $302,000. These costs are summarized by work type in Table 2. Physical remediation and reclamation work accounts for about fifty percent of the total cost. MTCA and CERCLA analyses and report preparation account for most of the remainder. A little more than half of the physical cleanup costs are attributable to the expense of the transporting process fluids and sludges classified as hazardous waste. MTCA compliance was a major cost item for the project.

Total costs by far exceeded monies collected from the reclamation surety ($7,200) and the collection agreements ($10,000). The discrepancy is, in large part, due to the unplanned costs associated with a CERCLA/MTCA cleanup and the divergence between the closure requirements originally approved in the mine operating plan and the actual cleanup implementation. However, process fluid detoxification costs were substantially underestimated and some tasks, such as dealing with potential process sludge, were overlooked completely in the initial mine permitting. These mistakes were recognized early during the cleanup process and the lessons relayed to other minerals administrators working in the field (Knott and Lentz 1990).

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Table 2. Summary of Minnie mine cleanup costs.

Physical Remediation/Reclamation		$145,000
Pre-CERCLA fluid trtmt/disposal (416k liters)	$ 15,000	
Sludge trtmt/remov/trnspt/disposal (45k liters)	$ 60,500	
Fluid/liner remov/trnspt/disposal (103k liters)	$ 36,500	
Misc. reclamation	$ 9,000	
Cap const/lysimeter installations	$ 24,000	
Subtotal	$145,000	
CERCLA study/documentation		$ 17,000
MTCA study/documentation		$134,000
Post construction monitoring		$ 6,000
Total		$302,000

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See following three pages for Appendix A.

Appendix A. Summary of Minnie mine sample analyses. Metals tested for are shown as their chemical symbol. As = arsenic, Ba = barium, Cd = cadmium, Cr = chromium, Cu = copper, Pb = lead, Ag = silver, Zn = zinc, Hg = mercury, Se = selenium, Na = sodium, Ca = calcium, Fe = iron, Mg = magnesium, K = potassium; CN = cyanide.

	SOLIDS DATA (ppm unless otherwise indicated)																		
AREA TESTED	As	Ba	Cd	Cr	Cu	Pb	Ag	Zn	Hg	Se	CN_{Free}	CN_{WAD}	CN_{Total}	pH	Na	Ca	Fe	Mg	K
Ore Materials																			
Processed Ore																			
8/29/1989																			
no. of analyses												0							
minimum												1							
maximum												22							
average												10.2							
8/10/1992																			
no. of analyses												14							
minimum												0.4							
maximum												18							
average												3.8							
10/27/1993																			
no. of analyses	8	8	8	8	8	8	8	8	8			8							
minimum	690	100	26	34	620	120	5.7	4900	1.2			<0.5							
maximum	1800	140	91	45	810	240	14	6900	3.7			<0.5							
average	1084	124	42	40	726	178	9	5925	1.7			<0.5							
Unprocessed Ore																			
no. of analyses	4	1	4	3	4	4	2	4	1	2									
minimum	420	170	5.2	15	150	130	2.2	480	0.14	<3.0									
maximum	640	170	7.8	20	240	200	6.2	910	0.14	<3.4									
average	492.5	170	6.45	18	180	162.5	4.2	630	<0.002 - 0.14	<3.4									
Process Pond Sludge																			
6/15/1992																			
no. of analyses	4	0	4	4	4	4	4	4	4	4	1	1	1	1	4	4	4	4	4
minimum	317		389	<35	0.8	<65	58	4.4	0.05	<0.3	94	280	860	9.62	0.4	19.6	0.6	4	0.1
maximum	1510		618	95	2.7	<93	554	5.2	0.096	<0.3	94	280	860	9.62	0.8	22.7	2.6	8.7	0.5
					weight %			weight %							weight %	weight %	weight %	weight %	weight %
Subliner-facility Soil Samples																			
Site Background																			
no. of analyses	12		17	4	17	17		12						2					
minimum	3.2		0.7	11	19	3.3		224						7.8					
maximum	54		2.3	39	100	21		170						8.2					
average	12.7		1.2	25	36.4	7.8		55.6											
90 percentile (MTCA UCL)	26																		
Beneath Heap Liner																			
no. of analyses	11	12	12	12	12	10	12	11	12			3							
minimum	5.4	61	0.6	8.2	37	0.21	0.45	27	<.07			<0.5							
maximum[1]	880	140	41	28	540	140	4.6	5100	1.3			<0.5							
average[2]	17	84	3	10	53	4	0.45	76	0.1			<0.5							

[1]These values come from the soils beneath the outlet pipe leak

[2]Average excludes anomolous sample near outlet leak

Appendix A (page 2 of 3). Summary of Minnie mine sample analyses.

AREA TESTED	As	Ba	Cd	Cr	Cu	Pb	Ag	Zn	Hg	Se	CN_{Free}	CN_{WAD}	CN_{Total}	pH	Na	Ca	Fe	Mg	K
								SOLIDS DATA (ppm unless otherwise indicated)											
Ore Materials (cont.)																			
Beneath Land App 1 (small area west of MW-2)																			
no. of analyses	12	8	14	14	14	14	1	14	14	6		6							
minimum	0.22	100	0.8	5.5	28	3.3	0.9	35	0.001	<3.7		<0.5							
maximum	160	190	6.9	54	130	58	0.9	1300	0.8	<3.7		<0.5							
average	44	139	2.4	26	63	11	0.9	280	0.18	<3.7		<0.5							
Beneath Land App 2 (small area north of MW-4																			
no. of analyses	6		4	6	6	6		6	6	6									
minimum	3		0.7	5.9	17	3		30	<0.09	<3.7									
maximum	22		1	1	3	5.5		42	<0.09	<3.7									
average	10		1	8	23	4.5		33	<0.09	<3.7									
Process Building Area																			
no. of analyses	3	3	3	3	3	3	3	3	3			3							
minimum	4.6	100	0.8	11	42	<2.2	<0.44	39	<0.08			<0.5							
maximum	7.6	150	0.9	12	54	<2	<0.44	48	<0.08			<0.5							
average	6.5	133	0.9	11	50	<2.2	<0.44	44	<0.08			<0.5							
Cap Compliance Samples																			
no. of analyses	42																		
minimum	1.3																		
maximum	26																		
average	6.05																		
95th percentile	7.56																		
								TCLP DATA (mg/L dissolved)											
Screen Value[3]	5E-05	1.12	0.008	0.08	0.592	0.005	0.048	4.8	0.002	0.08		0.32							
Unprocessed Ore																			
11/19/1992	<0.1				<0.1			0.7	<0.002	<0.1									
Processed Ore																			
11/27/1993																			
no. of analyses	4	4	4	4	4	4	4	4	4	0		1		0					
minimum	0.079	0.71	0.12	0.005	0.24	0.034	0.005	20	0.002	0		0.07		0					
maximum	1.1	0.85	0.14	0.01	0.32	0.054	0.01	33	0.01	0		0.07		0					
average	0.8	0.8	0.14	0.008	0.28	0.040	0.009	27	0.005	<.005									
no. of exceedences	4		4		0	4	0	4	4	4		0		0					
Process Pond Sludge																			
6/15/1992																			
no. of analyses	3		3	3	3	3	3	3	1	1	1								
minimum	0.25		0.04	0.03	163	0.086	1.99	5.85	0.99	<.005									
maximum	1.21		2.4	0.1	294	0.165	13	729	0.99	<.005									
average	0.84		1.56	0.06	243	0.112	9	480	0.99	<.005	150								
no. of exceedences	3		2	1	3	3	3	3	1	0									

Metals tested for are shown as their chemical symbol. As = arsenic, Ba = barium, Cd = cadmium, Cr =chromium, Cu = copper, Pb = lead, Ag = silver, Zn = zinc, Hg = mercury, Se = selenium, Na = sodium, Ca = calcium, Fe = iron, Mg = magnesium, K = potassium; CN = cyanide.

[3]From MTCA Method B Gnd Water Criteria

Appendix A (page 3 of 3). Summary of Minnie mine sample analyses. Metals tested for are shown as their chemical symbol. As = arsenic, Ba = barium, Cd = cadmium, Cr =chromium, Cu = copper, Pb = lead, Ag = silver, Zn = zinc, Hg = mercury, Se = selenium, Na = sodium, Ca = calcium, Fe = iron, Mg = magnesium, K = potassium; CN = cyanide.

	PROCESS FLUIDS ANALYSES (mg/L total constituent)																	
AREA TESTED	As	Ba	Cd	Cr	Cu	Pb	Ag	Zn	Hg	Se	CN_{Free}	CN_{WAD}	CN_{Total}	pH	Na	Ca	Fe	Mg	K
Barren Pond																			
11/14/1986	<3	<0.1	<0.04	<0.4	490	<1	5.6	250	8.6	-	10	-	340		4700	1300			
10/8/1987 (1st Land App.)	0.08	0.05	0.007	<0.01	1.9	<0.02	0.23	0.99	0.091	5.36		<0.05		11.2	5500				
Pregnant Pond																			
11/14/1986	<3	<0.1	2.9	<0.4	510	<1	10	350	1.7	-	10		1200		2100				
9/21/1989 (2nd Land App.)	0.08	0.05	0.01	<0.02	4.8	<0.01	0.2	-	0.0034	<0.1		0.05		8.6	500				

The Role of Geology in Sediment Supply and Bedload Transport Patterns in Coarse-Grained Streams

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This paper compares gross differences in rates of bedload sediment moved at bankfull discharges in 19 channels on national forests in the Middle and Southern Rocky Mountains. Each stream has its own "bedload signal," in that the rate and size of materials transported at bankfull largely reflect the nature of flow and sediment particular to that system. However, when rates of bedload transport were normalized by dividing by the watershed area, the results were similar for many sites. Typically, streams exhibited normalized rates of bedload transport between 0.001 and 0.003 kg s^{-1} km^{-2} at bankfull discharges. Given the inherent difficulty of obtaining a reliable estimate of mean rates of bedload transport, the relatively narrow range of values observed for these systems is notable. While many of these sites are underlain by different geologic terrane, they appear to have comparable patterns of mass wasting contributing to sediment supply under current climatic conditions. There were, however, some sites where there was considerable departure from the normalized range of values. These sites typically had different patterns and qualitative rates of mass wasting, either higher or lower, than observed for other watersheds. The gross differences in sediment supply to the stream network have been used to account for departures in the normalized rates of bedload transport observed for these sites. The next phase of this work is to better quantify the contributions from hillslopes to help explain variability in the normalized rate of bedload transport.

Keywords: *bedload transport, sediment supply, mass wasting*

Introduction

Differences in the underlying lithology of watersheds cause variation in the stability of the landscape and, hence, variation in the modes of sediment supply to a stream channel. While the rate and patterns of coarse sediment transported in gravel bed streams reflect many watershed factors (e.g., climate, land use, natural disturbances) the characteristics of materials supplied from hillslope and in-channel sources are of particular importance. Specifically, the size of material, the rate and volume of sediment delivered, the timing of delivery relative to high flows, and the periodicity of failures, all influence sediment supply and the stream's ability to transport sediment delivered from adjacent hillslope erosion. In areas where mass wasting processes and rates are largely comparable, one might expect similarity in the rate and patterns of sediment transport.

The primary purpose of this paper is to compare and contrast rates of bedload transport measured at bankfull discharges for a number of stream sites on national forest lands in Colorado and Wyoming. Bankfull discharge, or the flow that just fills the channel banks, was used as a reference point so that transport rates at a common discharge scaled to the size of the channel could be compared. Because comparisons are made between watersheds of varying size, the data are normalized by dividing the rate of bedload transport by the area of the drainage basin. Similarities and differences between these normalized values are discussed, using examples to compare and contrast the relationships and relate them to gross differences in geologic terrane and associated patterns of mass wasting. Specifically, the paper is divided into the following three areas:

- Commonalities in the normalized rate of bedload transport for several sites in central Colorado and southern Wyoming. These areas are underlain primarily by granite, gneiss, and schist, and have relatively low rates of mass wasting relative to those that have occurred in the past (Caine 1986).
- Substantial departure in normalized rates of transport observed in watersheds underlain by extrusive volcanic and granitic terrane on the San Juan National Forest in southwestern Colorado. Here, the normalized values are among the highest and lowest observed in this series of comparisons and are linked to gross differences in observed mass wasting patterns.
- Variations in transport rates observed at two sites in the Gros Ventre Range in western Wyoming. While

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both sites are underlain by deformed sedimentary formations common to this area, there are distinctive differences in patterns of mass wasting between these two watersheds that can be used to explain substantial variation in observed rates of sediment transport.

Study Areas

All of the study sites are located on streams where the USDA Forest Service or the U.S. Geological Survey have initiated studies on sediment transport over the past 10-20 years. The streams are located within either the Middle or Southern Rocky Mountain provinces (Hunt 1974) and are tributaries to the Snake, Platte, Colorado, Arkansas, and San Juan Rivers (Figure 1). Most sites are located near presently- or historically-operating gaging stations and represent a range of channel sizes and types (Ryan et al. 2005). Drainage areas range from 2.9 to 230 km^2 and the sites are between 2000 to 3000 m in elevation. Channels are characterized by moderate to steep gradients (0.01 to 0.05 m/m). The median grain size of the bed surfaces range from very coarse gravel to coarse cobble sizes that are poorly to very poorly sorted (Ryan et al. 2005). Channel types include step-pool, plane-bed, pool-riffle, and one moderately braided site (Table 1).

The lithology of the studied areas is quite diverse (Tweto 1979; Love and Christiansen 1985) (Table 1). Most of the sites are underlain by granite, gneiss, and schist bedrock while other streams flow through areas with sedimentary formations including sandstone, conglomerate, and limestone. The East Fork San Juan and Silver Creek, in southwestern Colorado, are underlain by complex volcanic formations consisting of layered lavas flows. Nearly all of the sites have been glaciated and are

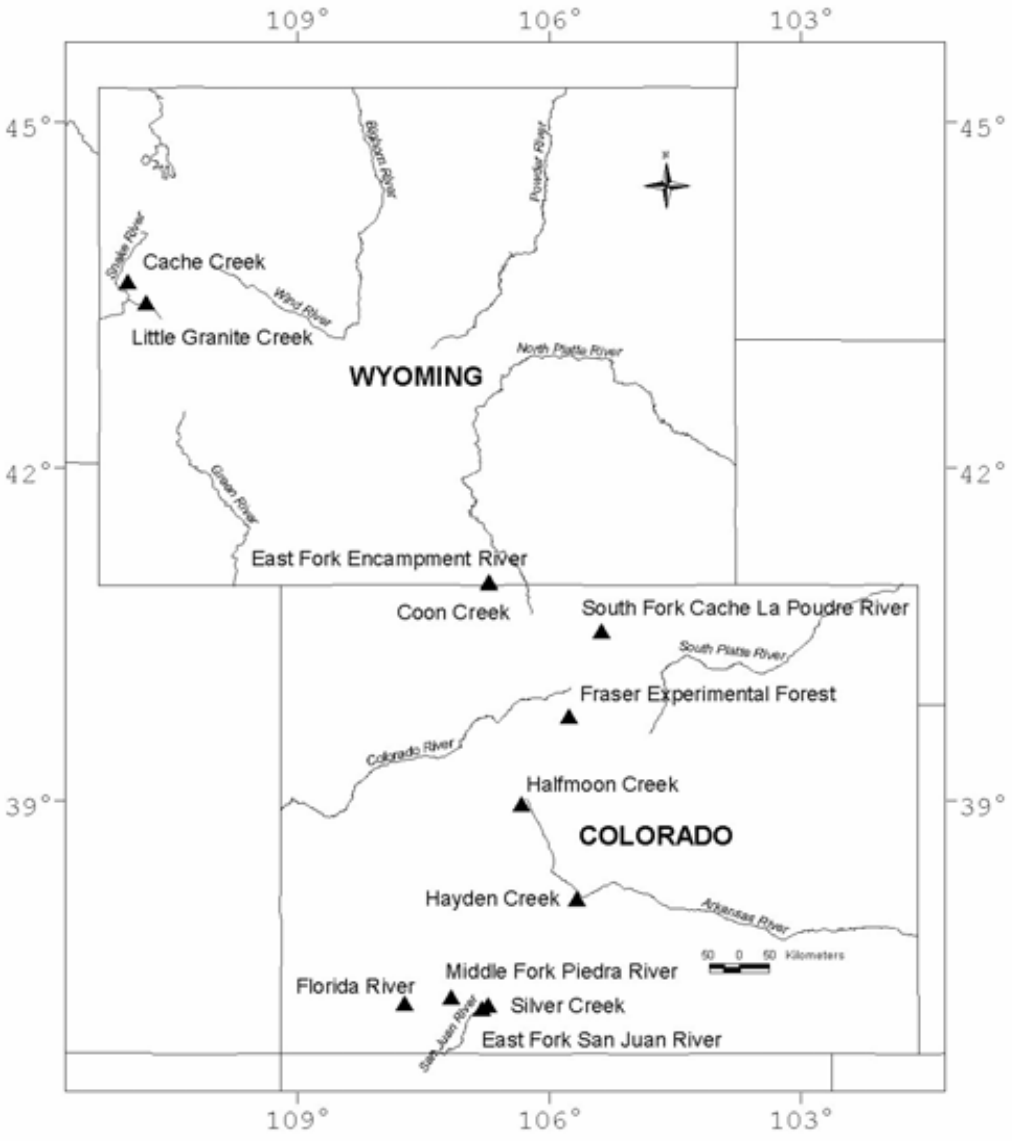


Figure 1. Map of study sites located in Colorado and Wyoming. Eight of the sites are located within the Fraser Experimental Forest, including St. Louis Creek sites 1-4, 4a, and 5, East St. Louis Creek, and Fool Creek.

Table 1. Watershed and channel characteristics.

Site	Channel Type	Management History	Drainage Area (km^2)	Bankfull Discharge $Q_{1.5}$ (m^3/s)	Transport Rate at Bankfull (kg/s)	Primary Lithology	National Forest	State
St. Louis 1	step-pool	diversion	55.6	4.41	0.115	gneiss/granite	Arapaho-Roosevelt	CO
St. Louis 2	plane	diversion	54.2	4.75	0.077	gneiss/granite	Arapaho-Roosevelt	CO
St. Louis 3	riffle	diversion	54.0	4.59	0.104	gneiss/granite	Arapaho-Roosevelt	CO
St. Louis 4	plane	free-flowing, pristine	33.8	3.61	0.048	gneiss/granite	Arapaho-Roosevelt	CO
St. Louis 4a	riffle	free-flowing, pristine	33.5	3.37	0.053	gneiss/granite	Arapaho-Roosevelt	CO
St. Louis 5	step-pool	free-flowing, pristine	21.3	2.63	0.021	gneiss/granite	Arapaho-Roosevelt	CO
E. St. Louis Cr.	step-pool	free-flowing, pristine	8.0	0.86	0.013	gneiss/schist	Arapaho-Roosevelt	CO
Fool Cr.	plane	free-flowing, harvested	2.9	0.30	0.010	gneiss/schist	Arapaho-Roosevelt	CO
Little Granite Cr.	plane	free-flowing, pristine	54.8	5.95	0.137	sedimentary	Bridger-Teton	WY
S.Fk. Poudre R.	riffle	free-flowing, some private ownership	231.0	11.44	0.283	gneiss/granite	Arapaho-Roosevelt	CO
Coon Cr.	plane	free-flowing, harvest, tie-driven	16.7	2.77	0.031	gneiss/granite	Medicine Bow-Routt	WY
E.Fk. Encampment R.	plane	free-flowing, historical harvest, tie-driven	9.1	1.45	0.007	gneiss/granite	Medicine Bow-Routt	WY
Halfmoon Cr.	riffle	free-flowing, historical harvest	61.1	6.23	0.240	gneiss/granite	Pike-San Isabel	CO
Hayden Cr.	plane	free-flowing, harvest	46.5	1.92	0.044	sedimentary	Pike-San Isabel	CO
Cache Cr.	plane	free-flowing, pristine	27.5	1.84	0.004	sedimentary	Bridger-Teton	WY
E.F. San Juan R	riffle-braided	free-flowing, some private ownership	166.0	15.66	4.742	volcanic	San Juan	CO
Silver Cr.	plane	free-flowing, pristine	15.7	1.30	0.305	volcanic	San Juan	CO
Upper Florida R.	step-pool	free-flowing, pristine	115.0	14.50	0.023	granite	San Juan	CO
M. Fk. Piedra R.	riffle	free-flowing, pristine	86	10.05	0.308	volcanic/sed.	San Juan	CO

mantled by till and glacial outwash correlative of Bull Lake and Pinedale aged deposits (e.g., Nelson and Shroba 1998). At many sites, hillslopes are relatively stable under the current climatic regime and vegetative cover, though there is evidence of active mass wasting in the past (Caine 1986). Exceptions include Little Granite Creek, in western Wyoming, where there are active, deep-seated earthflows, and the sites underlain by volcanic formations, where debris chutes and ravel from unstable terrain deliver materials directly to the stream system (Ryan 2001).

Runoff at all of the studied sites is strongly influenced by the melting of snow in spring (Jarrett 1990), though the timing of the annual peak varies between sites. Peak discharge occurs typically from early May to late June and low flow occurs in January or February. A second peak discharge can occur in late summer at the sites in the San Juan Mountains in southwestern Colorado, due to the influence of the Arizona monsoon. Most of the study sites are free-flowing, though three of the Fraser Experimental Forest sites are located in channels from which an average of 40% of the total annual flow is diverted (Ryan 1994). However, water is rarely diverted from these sites at high flow when bedload is usually sampled. Small portions of flow at East Fork San Juan and South Fork Cache la Poudre sites are diverted for household or agricultural purposes upstream of the study sites. Some of the watersheds have been deforested to different degrees (e.g., Troendle and King 1985; Troendle et al. 2001) and a few of the channels were tie-driven in the historical past (Young et al. 1994) (Table 1). Other watershed areas have been selectively cut, the extent to which is either relatively minor or unknown.

Methods

Discharges used in flow frequency analyses were gaged either by the U.S. Geological Survey or the Forest Service. For the purposes of this analysis, the bankfull discharge is approximated using the 1.5-year return interval flow

from Log Pearson type-III analysis (U.S. Interagency Advisory Committee on Water Data 1982). Previous work from these sites indicates that this value is a suitable approximation for the discharge that just fills the channel to its active floodplain (Ryan et al. 2005). Watershed area was obtained either from the metadata included with U.S. Geological Survey gaging data or was digitized from 1:24,000-scale topographic maps.

Bedload was measured using hand-held pressure difference samplers, such as a Helley-Smith bedload sampler (Helley and Smith 1971) or an Elwha sampler (Childers et al. 2000). Bedload was sampled once or twice daily over several weeks during snowmelt runoff using the Single Equal Width Increment (SEWI) method (Edwards and Glysson 1998). Bedload samples were dried and sieved using standard sedimentological methods (Folk 1968). Rate of transport was calculated using the total weight of the sample (in kg) divided by the total sampling time (number of verticals and time in seconds) and width of the sampler (in m) to obtain the unit bedload transport rate (kg m^{-1} s^{-1}). This value is multiplied by the width of the channel (m) to obtain the mean transport rate through the channel cross-section (in kg/s). The datasets used for developing bedload rating curves for individual sites contain between 40 and 200 pairs of flow and bedload observations. Bedload rating curves were developed from these data, and were then used to estimate the mean rate of bedload transport for the bankfull discharge. Additional information on these rating curves is available in Ryan et al. (2005).

Geologic type and patterns of mass wasting were evaluated at a relatively coarse scale. Geologic type was determined from published data and geologic maps available for individual areas. Patterns of mass wasting were determined from field reconnaissance or aerial photography and published maps, as available.

Results

Commonalities in Normalized Values

Measured (or dimensional) rates of bedload transport typically vary between sites, indicating that individual stream systems exhibit their own "bedload signal" where the rate and size of materials transported largely reflect the nature of flow and sediment particular to that system. Moreover, it was observed that for sites within the same watershed, increases in sediment loads moving from small tributaries to larger channels were fairly predictable. In the St. Louis Creek watershed, there was about an order of magnitude increase in the rate of transport moving from a small watershed (East St. Louis Creek, drainage area about 5 km^2) to lower St. Louis Creek (St. Louis 1; about 50 km^2) (Figure 2). The normalized rate of bedload transport at bankfull for these eight stream sites was on average 0.0018 kg s^{-1} km^{-2} (standard deviation + 0.0008) (Figure 3). By comparison, when transport rates measured at additional sites were normalized by watershed area (Figure 3), many exhibited about the same level of bedload transport per unit area at the bankfull discharge as observed for the St. Louis Creek sites. These normalized values ranged from about 0.001 to 0.003 kg s^{-1} km^{-2}. Given the inherent uncertainty in the estimate of bedload transport associated with gravel bed streams, similarity among a number of sites is noteworthy. This suggests that the transport rate is fairly predictable within and between watersheds with similar flow, sediment, and supply relationships, and that drainage area can be used to help predict rates of sediment transport for an individual site. There were, however, several notable exceptions from this range of values, including the relatively high rates of transport from the East Fork San Juan River and Silver Creek (about 0.025 kg s^{-1} km^{-2}) and the relatively low rates from Cache Creek and the Florida River (about 0.0002 kg s^{-1} km^{-2}). While these exceptions may be attributed to a number of factors, it was noted that there were distinct differences in patterns of mass wasting in these watersheds that would cause variation in sediment supply to the stream system and associated differences in rates of bedload transport. This is explored in greater detail below.

San Juan Sites, Southwestern Colorado

It is worth noting that data for all of the sites in the San Juan area (East Fork San Juan, Silver Creek, Middle Fork Piedra, and Florida River) were collected using a pressure-

Figure 2. Relationship between estimated transport rate at bankfull discharge and drainage area for main stem and tributaries to St. Louis Creek, Fraser Experimental Forest.

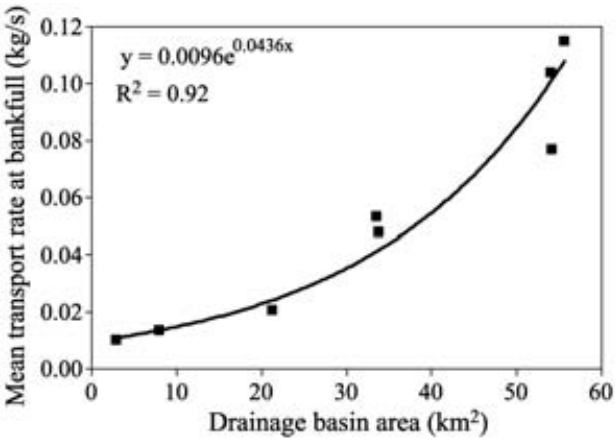
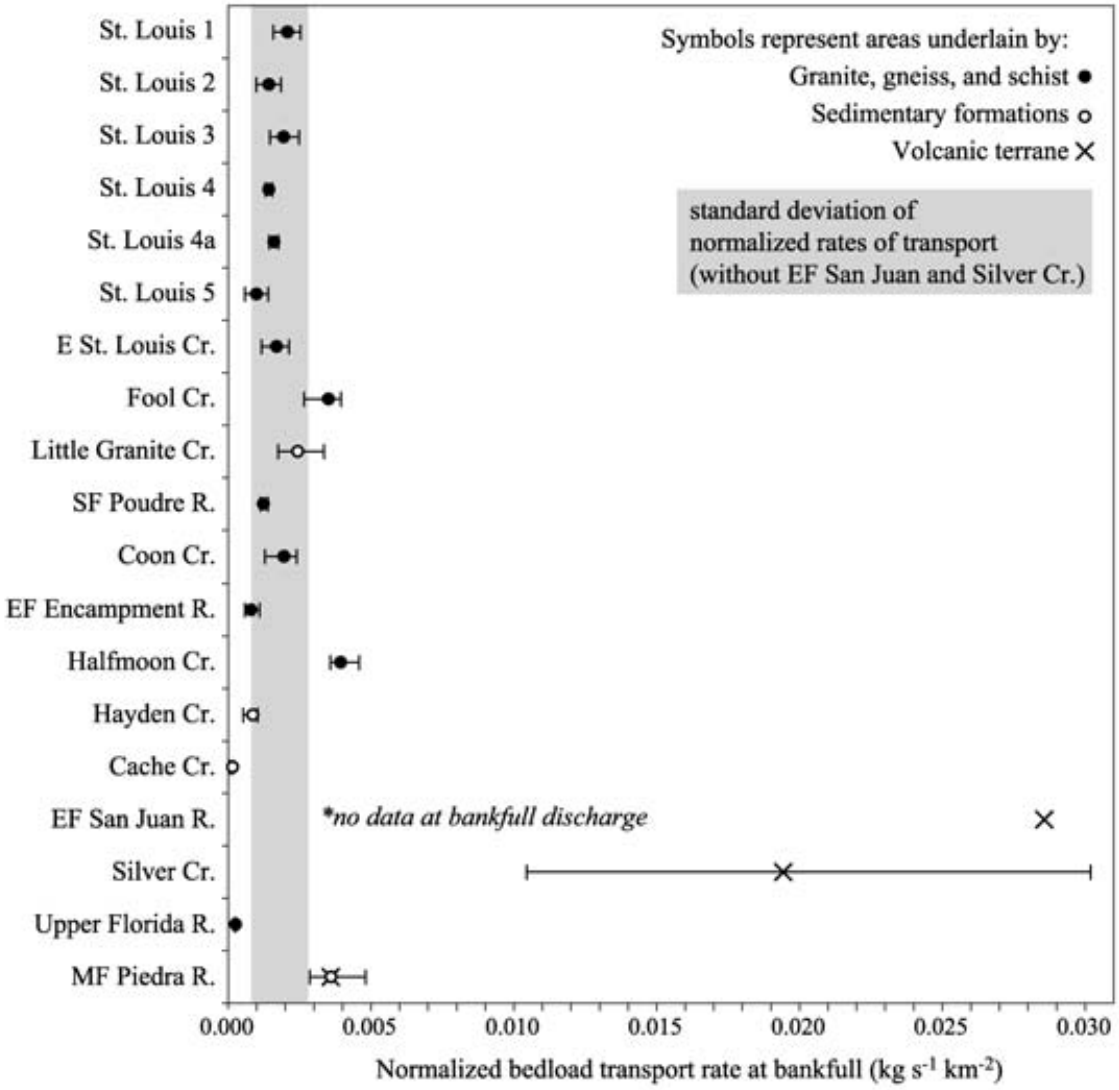


Figure 3. Normalized rates of bedload transport for 19 sites in Colorado and Wyoming measured between 1982 and 2001. Data were normalized by dividing the estimated rate of bedload transport at the bankfull discharge (and calculated 95% confidence limits) against the drainage area upstream of the sampling site. The black circles represent areas underlain by granite, gneiss, and schist, open circles represent areas underlain by sedimentary formations, and crosses represent areas draining volcanic terrane. The Middle Fork Piedra lies on a transition between volcanic and sedimentary bedrock and so two symbols are used. The area in gray represents the standard deviation of the normalized rates of transport, exclusive of the East Fork San Juan and Silver Creek sites. No confidence limits could be estimated for the East Fork San Juan site because there was no data at bankfull discharge. The wide error bars observed for the Silver Creek data are attributed to probable hysteresis effects observed in the dataset (Ryan 2001; Ryan et al. 2005).



difference sampler with a larger opening (4 x 8 inches; 10 x 20 cm) than deployed at the other sites (3 x 3 inches; 7.6 x 7.6 cm). This could explain, in part, lower rates of transport observed elsewhere (Figure 3) if the smaller sampler has a low capacity relative to the rate of bedload transport. However, not all sites where the larger sampler was used exhibit elevated rates of normalized bedload transport. Data from the Florida River indicate low normalized rates of transport, while data from the Middle Fork Piedra site suggest slightly elevated values, though not to the levels observed at East Fork San Juan River and Silver Creek (Figure 3). Hence, the differences in normalized rates of transport from these sites cannot be attributed simply to sampler type, but more likely reflect differences in sedimentation processes in the watersheds (Ryan et al. 2005).

As a causative explanation for the differences in normalized rates of bedload transport, it was observed that the San Juan sites have distinctive modes of sediment supply linked to the instability of the extrusive volcanic bedrock (Tertiary) and to the relative stability of the granite formations. In Silver Creek, precipitous, unstable hillslopes

impinge on the steep tributary, and materials from active debris/avalanche chutes are delivered directly into the channel. The channel becomes an effective conduit for transporting the delivered sediment, particularly on the rising limb of the seasonal hydrograph after the overwinter sediment supply has accumulated in the channel. Transport rates are at times high, though irregular, in this system (0.002 - 0.031 kg s^{-1} km^{-2} at bankfull), reflecting the episodic nature of the sediment supply (Ryan 2001). Sediment moved by Silver Creek and other tributaries is deposited downstream in a wide valley bottom with a braided to plane-bed channel (East Fork San Juan) that also has high rates of transport (about 0.029 kg s^{-1} km^{-2} at bankfull). This value is on the same order as the mean normalized rate observed for Silver Creek (Figure 3). The similarity in rates of transport between these two sites is likely a systematic effect, determined by sediment supplied by the upper sites (such as Silver Creek) to the mainstem.

By contrast, observed rates of sediment transport are quite low (0.0002 kg s^{-1} km^{-2}) at the Upper Florida River site. This watershed is underlain by stable granitic terrane and the channel upstream of the site flows over bedrock, signifying a relatively low supply of sediment. The primary source of material in this system is from the channel beds and banks, as there were few observed external sources of sediment, such as active landslides, upstream. Sand and fine gravel, originating from sand and gravel patches interspersed between very large particles, are transported over a largely stable, interlocking boulder and cobble bed. Because of the relative stability of the channel bed, widespread entrainment is unlikely to occur over a majority of the channel surface (Ryan 2001). Hence, the low normalized rate of sediment transport is likely due to low supplies of sediment that characterize the Florida River watershed.

Gros Ventre Range Sites, Northwestern Wyoming

The series of comparisons from St. Louis Creek and other sites in Colorado and Wyoming suggest the existence of common normalized bedload transport rates for areas underlain by similar geologic terrane. However, there can be substantial differences in sediment supply in areas where the geologic terrane is spatially variable over short distances. As an example, transport rates and patterns of mass wasting from two sites in the Gros Ventre Range in northwestern Wyoming are compared. The geology of the Gros Ventre Range consists primarily of Paleozoic and Mesozoic sedimentary rock formations, many of marine origin (Love and Christiansen 1985). These formations are highly deformed and relatively unstable. As a result, parts of the Gros Ventre Range are characterized by some of the highest densities of landslides in the United States (Wyoming State Geological Survey 2001). The area is also influenced by active faulting and a relatively high likelihood of earthquakes (Case and Green 2000). Hence, one might expect that channels draining watersheds in the Gros Ventre will exhibit high rates of sediment transport due to potentially large supplies of sediment from active mass wasting. Yet, measured rates of bedload transport from two sites in this range suggest otherwise. Normalized rates of transport from Little Granite Creek (0.0025 kg s^{-1} km^{-2}) are on the high end of the range while the rates from Cache Creek (0.0001 kg s^{-1} km^{-2}) are the lowest measured in this study. An evaluation of mass wasting patterns from the two watersheds (Wyoming State Geological Survey 2001) shows about five times the number of landslides in Little Granite Creek (118) compared to Cache Creek (23). Inspections of aerial photographs and field reconnaissance show that many of the slides in both watersheds are of the large, slow-moving, earth flow-type that often involves entire an entire hillslope (Varnes 1978). Several of the large slides identified in Little Granite Creek were observed to impinge directly on stream channels. Where these slides impinge, the toeslopes are actively raveling and the channel is pushed to the far side of the valley bottom, creating a second set of slides where the hillslope is undercut. These slides are a chronic source of sediment in this watershed, as materials deposited from the erosional faces are reactivated during high runoff. Moreover, the upper portion of the Little Granite watershed was glaciated and there are several currently active sources of sediment from glacial debris. While the upper watershed is a potential source of bedload in this system, much of the glaciated material comes off in suspension, as Little Granite Creek has an exceptionally high suspended load relative to bedload (Ryan and Emmett 2002). By contrast, there appear to be fewer chronic sources of sediment in Cache Creek, which flows through a largely stable inner gorge over most of its length above the sampling site near a U.S. Geological Survey gaging station. Hence, differences in the normalized rates of transport observed for these two sites are likely linked to variation in geologic controls, gross differences in the patterns of mass wasting, and inherent differences in sediment supply from the two watersheds. Therefore, one should be cautious in applying the sediment transport relationships even in watersheds draining similar geologic terranes without considering localized differences in sediment supply that potentially influence rates of sediment transport.

Discussion

Results from this comparison of normalized rates of bedload transport suggest that streams in many of our

watersheds exhibit comparable rates of sediment transport per unit watershed area at bankfull discharges (ranging between 0.001 and 0.003 kg s^{-1} km^{-2}). Variability in the range of these normalized values may be attributable to land use effects or recent disturbances, though this was not directly assessed in this work. However, given the inherent difficulty in obtaining reliable estimates of mean rates of bedload transport, the relatively narrow range of values observed for these systems is noteworthy. One might expect such similarity in watersheds with comparable rates of sediment supply (e.g., landslides, bank collapse, and stream bed entrainment). Other recent work on bedload transport supports the idea of similarity in processes for channels in inland western mountainous terrain, such as correspondence in dimensionless sediment transport relationships (Troendle et al. 2001) or comparable ranges of flow at which the onset of coarse sediment transport occurs (phase II) (Ryan et al. 2002; Ryan et al. 2005).

While the relatively narrow range of values suggests that many of these gravel bed systems behave in a in a similar way, the analysis also identified sites where there was substantial departure. Generally, when sediment supplies were abundant, the normalized rates of bedload transport were substantially greater than when sediment was restricted. Areas with active mass wasting from unstable landscapes, such as a volcanic terrane in the San Juan Range, had rates of normalized bedload transport that were about an order of magnitude greater than the average. By contrast, areas in relatively stable landscapes exhibited rates of normalized bedload transport that were about an order of magnitude lower. As a caveat, while this series of comparisons suggests that scaled rates of bedload transport may be transferable across watersheds in similar geologic settings, one does need to consider localized influences that contribute to differences in sediment supply before applying the sediment transport relationships broadly.

The relationships between sediment supply and normalized transport described in this paper were qualitative, relying on broad classes to describe mass wasting patterns (high, medium, or low). The next phase of this work will focus on better quantification of sediment supplied from different sources, to help in explaining variability in the normalized rate of bedload transport. Natural levels of materials transfer and the relative importance of different modes of sediment production in a watershed can be assessed through a sediment source analysis (Reid and Dunne 1996). Such an analysis can be complex, requiring field identification of a range of sources, including large landslides, instream sedimentation, and sediment contributed by different land management practices. However, such assessments are necessary in order to better define the relationships between sediment supply and transport, and to improve our capability to predict rates of bedload transport.

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A River Runs Underneath It: Geological Control of Spring and Channel Systems and Management Implications, Cascade Range, Oregon

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Long-term sustainable management of Cascade Range watersheds requires an understanding of water sources and discharge patterns from tributary streams, particularly those sourced in large-volume cold springs of the High Cascades geologic province. Focusing on the McKenzie River watershed, measurements of discharge and stream temperature combined with laboratory analysis of spring water isotopes improve our understanding of spatial and temporal recharge and discharge patterns. Summer streamflow in the McKenzie is dominated by water from approximately ten spring-fed streams, which maintain 4 to 7°C spring water temperatures and relatively steady flow throughout the summer. In winter months, streams in the Western Cascades geologic province respond rapidly to rain and rain-on-snow events and become the major water source to the McKenzie River. Spring-fed streams also respond to precipitation events, but show muted and delayed hydrograph peaks. Summer flow behavior varies among springs, even between those that are located near each other. Isotopic data reveal that recharge to large springs occurs between 1300-1800 m in elevation, which is coincident with geologically young lava between McKenzie and Santiam Passes. Recharge elevations also suggest some disagreement between recharge areas and topographic watersheds of the springs. Because of their importance to summer streamflow, water quality, and habitat in the McKenzie River basin, water resources decision-making must differentiate between spring-fed and runoff-dominated streams.

Keywords: *streamflow, groundwater processes, geology/geomorphology, springs, water temperature, Oregon Cascades*

Introduction

The Willamette River basin is home to 70% of Oregon's population, and while the McKenzie River watershed covers less than 12% of the basin's area, it provides almost 25% of the Willamette River's water during low flow periods (PNWERC 2002). The McKenzie watershed includes threatened and endangered fish runs, a complex system of federal and private dams for flood control and hydroelectric power generation, and Oregon's second largest city (Eugene), which draws 10 billion gallons (37.8 billion L) of drinking water per year directly from the river.

Recent analyses show that the Cascade Range is particularly sensitive to current and projected climate warming trends, specifically reduced snow accumulation and earlier spring melt, leading to a decline in summer streamflow (Service 2004). By 2050, Cascade snowpacks are projected to be less than half of what they are today (Leung et al. 2004), potentially leading to major water shortages during the low-flow summer season. Although not yet as contentious as the Klamath River to the south, the stage is set in the Willamette basin for significant future conflicts and demands for water.

Despite the importance of the McKenzie River's water to the region's quality of life, geologic and climatic controls on patterns of streamflow have been poorly understood. The watershed of the McKenzie River lies primarily within two distinct geologic provinces: the High and Western Cascades (Figure 1). The High Cascades are known for their active composite volcanoes and extensive Quaternary basaltic lavas, while the Western Cascades are the products

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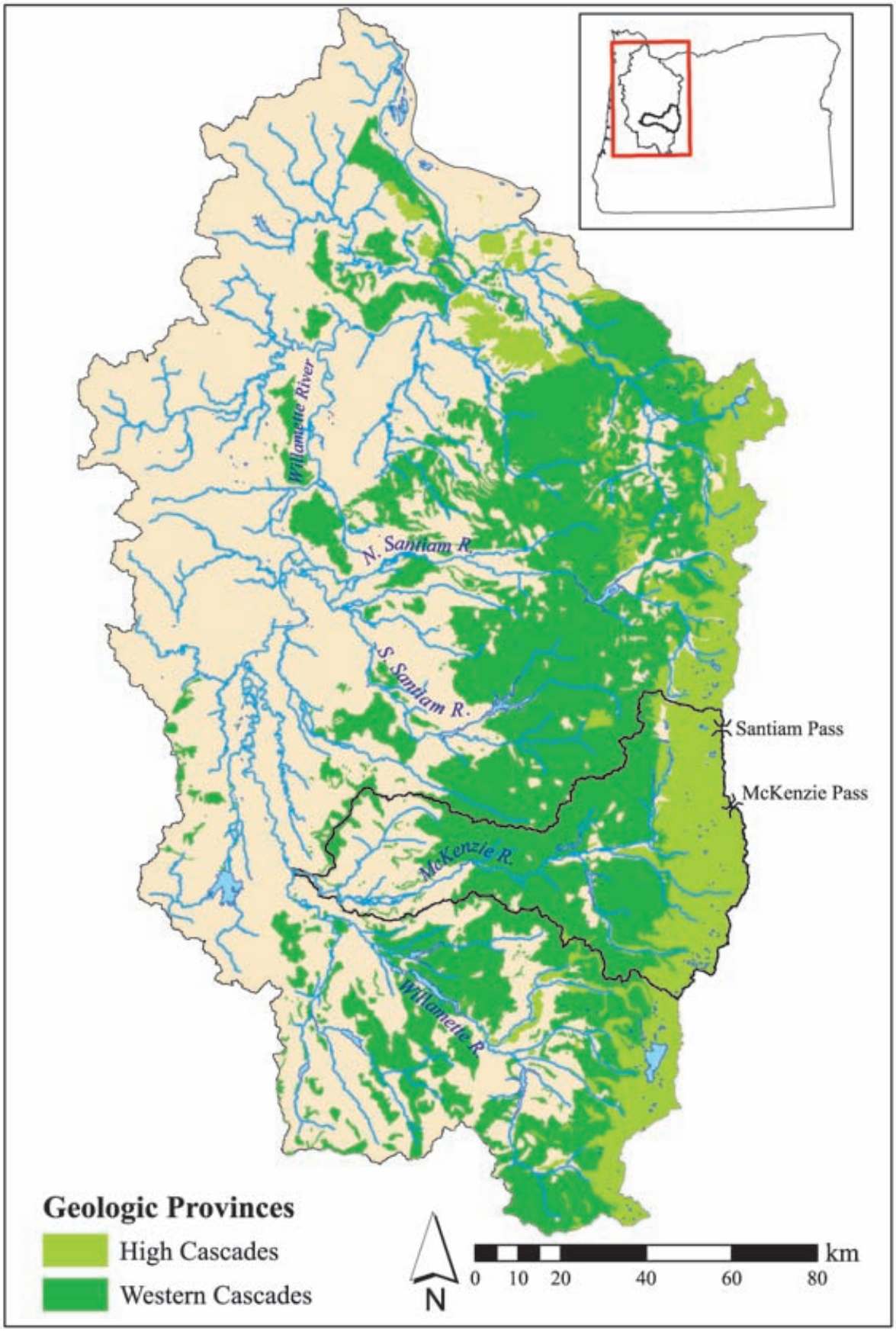
Figure 1. Forty-two percent of the McKenzie River watershed lies within the High Cascades geologic province, the most of any major Willamette River tributary. Geologic classification is based on mapping by Sherrod and Smith (2000).



of Tertiary volcanism, and have been extensively faulted, weathered, and dissected (Conrey et al. 2002). The Western Cascades have well-developed drainage networks and watersheds dominated by shallow-subsurface, runoff-dominated flow (Harr 1977), while in the High Cascades large areas lack drainage networks and many of the streams are fed by springs. Preliminary hydrograph analyses indicate that High Cascades streams show much more uniform flow and temperature through time compared to Western Cascades streams (Tague and Grant 2004). These differences have significant implications for water quantity and quality in headwater streams and for larger rivers, such as the McKenzie and Willamette, where both High and Western Cascades streams contribute to flow.

This research represents a systematic attempt to quantify volumes and sources of discharge in the McKenzie River basin. The overall goal of the project was to provide a more complete picture of flow contributions to the McKenzie River, for use in planning the sustainable long-term water management of the basin. Our objectives were to identify sources of summer streamflow to the upper McKenzie River, obtain continuous discharge records for large spring-fed streams, and use isotopic information to characterize groundwater recharge patterns.

Our field campaign focused on the upper McKenzie River basin, defined as the 2409 km^2 watershed upstream of the USGS gage at Vida. This area encompasses all of the High Cascades geology in the basin, as well as two Western Cascades tributaries with Corps of Engineers flood control reservoirs. USGS stream gages operate at four locations on the mainstem of the McKenzie River and on the tributaries Blue River, Separation Creek, Smith River, and the South Fork of the McKenzie. The USGS gages for the McKenzie River at Clear Lake and Separation Creek include a substantial spring-fed component, but do not represent a pure spring signal.

Methods

In summer 2003, discharge was measured at all McKenzie River tributaries flowing from areas of High Cascades geology. These data, combined with knowledge of some spring locations, allowed us to identify all of the major sources of summer streamflow to the upper McKenzie River. Fourteen streams were selected for continuous gaging (Figure 2), and Trutrack[1] capacitance rod water stage and temperature recorders were installed during July 2003. These streams included nine spring-fed streams, four runoff-dominated streams, and one ephemeral spring-fed stream. Selected spring-fed streams included all of the major ungaged springs that are tributary to the McKenzie River. Runoff-dominated streams were selected because they were tributary to or provided a reference site in close proximity to spring-fed streams.

Discharge measurements were made at a variety of stages in order to develop rating curves for each site, following standard USGS procedures. These curves allow interpolation from stage to discharge and result in daily hydrographs for the streams. Discharge was directly measured between four and 18 times at each site, depending on flow variability. Despite repeated measurements, peak flows had to be extrapolated from the rating curve for each site. Where there is not sufficient confidence in such extrapolations, hydrographs are truncated in high flow periods.

In mountainous regions, the isotopic composition of precipitation varies in a systematic way with elevation (Dansgaard 1964). The isotopic composition of spring water can be projected to the elevation at which precipitation has a comparable composition. Recharge elevations estimated by this method represent precipitation-weighted averages and have an error of ±60 m due to analytical uncertainty, plus some uncertainty associated with the altitude-isotope relationship. Spring water samples were analyzed for hydrogen and oxygen isotope ratios (δD and δ^{18}O, respectively) at Lawrence Livermore National Laboratory. Isotopic composition of the water was compared to a published altitude-isotope relationship for the Oregon Cascades (Ingebritsen et al. 1994).

Spring water samples were also analyzed at the University of Waterloo (Waterloo, Ontario, Canada) for tritium, a radioactive hydrogen isotope with a half life of 12.43 years. Tritium in the groundwater system indicates that it has been recharged within the last ~50 years (Clark and Fritz 1997). Tritium concentrations were greatly increased in the atmosphere as a result of nuclear weapons testing in the 1950s and 1960s, but by the 1990s atmospheric tritium activities had approximately returned to pre-bomb levels.

Results

During 5-7 August 2003, discharge measurements were made on High Cascades tributaries to the McKenzie River (Figure 3). Discharge of the McKenzie River at Vida was 50.7 m^3/s on 7 August 2003. According to our measurements, 83% (42.3 m^3/s) of this flow came from spring-fed streams. By combining locations from this project and the USGS, over 97% (49.4 m^3/s) of the flow in the McKenzie River was measured, despite neglecting most tributaries flowing from Western Cascades geology.

[1]The use of trade or firm names in this publication is for reader information and does not imply endorsement by the U.S. Department of Agriculture of any product or service.

Figure 2. Gaging sites are located on spring-fed and runoff-dominated streams in the upper McKenzie River watershed. Indicated big springs have more than 0.85 cms average annual discharge.

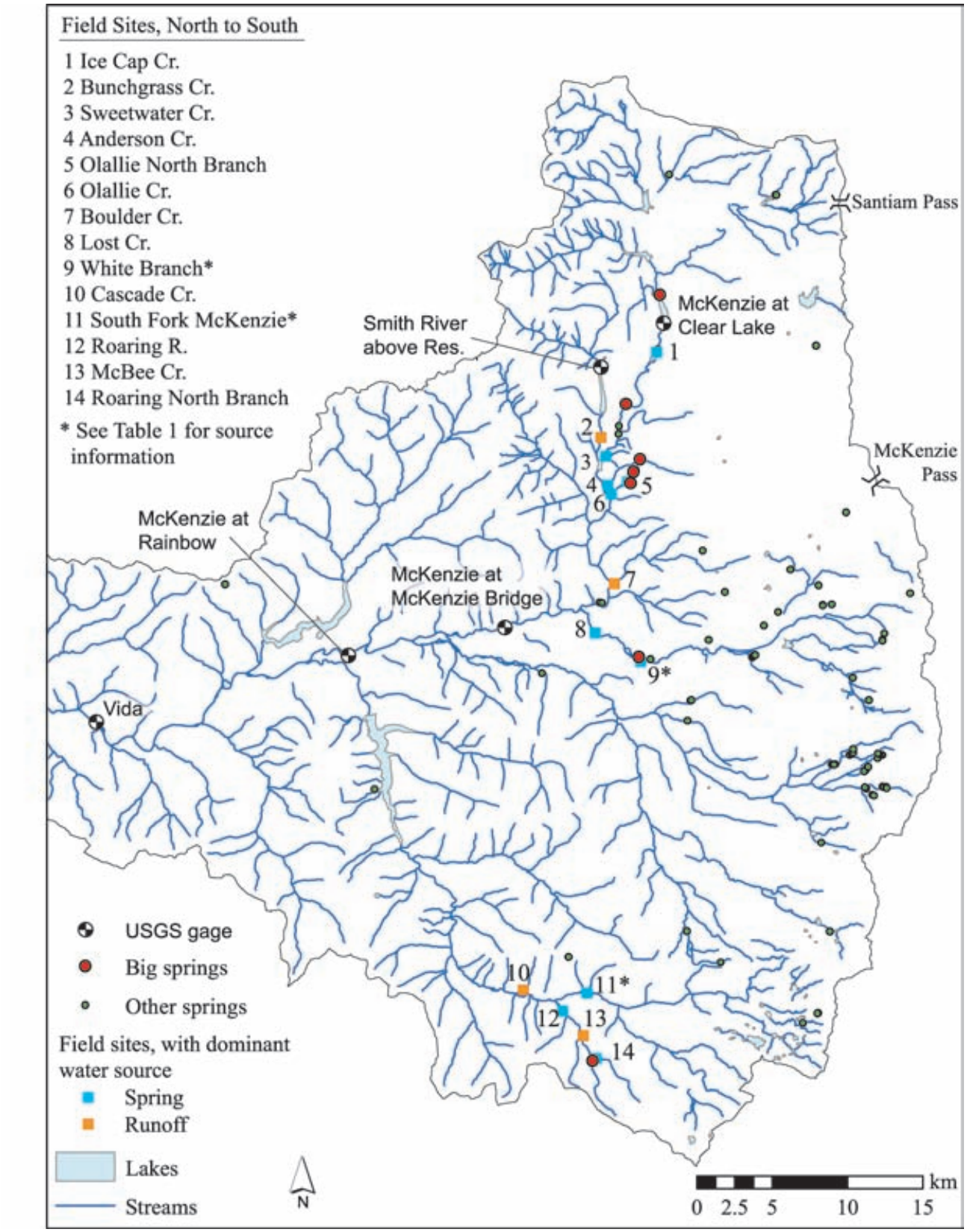


Table 1. Summary of characteristics of discharge measurement sites. For more detailed information on groundwater patterns, see Jefferson et al. (2006).

Site Name	Dominant Water Source	Mean Water Temperature (°C)†	Std Dev. (°C) †	Daily Discharge (m^3/s) 5 August 2003
Anderson Cr.	Spring	4.7	0.9	0.61
Boulder Cr.	Runoff	8.3	3.7	0.0061
Bunchgrass Cr.	Runoff	6.6	3.6	N/A
Cascade Cr.	Runoff	7.0	3.1	N/A
Ice Cap Cr.	Spring	4.5	0.2	N/A
Lost Cr.	Spring	6.9	0.3	5.8
McBee Cr.	Runoff	6.4	3.0	0.021
Olallie Cr.	Spring	5.0	0.1	4.7
Olallie North Br.	Spring	4.7	0.0	1.6
Roaring River	Spring	5.4	0.7	2.7
Roaring North Br.	Spring	4.3	0.1	0.79
South Fork McKenzie	Spring likely - location unknown	5.9	1.8	2.3
Sweetwater Cr.	Spring	N/A	N/A	N/A
White Branch	Ephemeral spring	6.1‡	1.9‡	0.11

† For period of record between 10 July 2003 and 31 March 2004.
‡ For period when stream has flowing water.

Reservoir supplementation accounted for ~10% of the flow at Vida. Without this supplementation, spring-fed streams would provide 93% of the flow in the McKenzie River.

This campaign of discharge measurements indicated that all major springs discharging into tributaries of the McKenzie River were accounted for in the gaging scheme described above. There is considerable accretion of groundwater directly into the mainstem of the McKenzie River between Clear Lake and Trail Bridge Reservoir (Stearns 1929), but direct discharge measurements are unattainable. The difference in discharge between the USGS gages at Clear Lake and Trail Bridge Reservoir minus the discharge of Smith River and Bunchgrass Creek can be attributed to this groundwater accretion. During August 2003, 10.3 m^3/s of groundwater were added to the flow of McKenzie River in the Clear Lake to Trail Bridge Reservoir reach. Additionally, there are small springs in the watershed which discharge water to the surface where it quickly infiltrates back into the ground, while other springs discharge into closed-basin lakes, where their water either evaporates or recharges the groundwater system.

Considerable differences were observed between the hydrographs of spring-fed and runoff-dominated streams in the McKenzie River watershed (Figure 4). Peak flows were 1.5 to 2.7 times greater than low flows on spring-fed steams, whereas for runoff-dominated streams peak flows were approximately 30 to 1000 times greater than low flows. Hydrographs of spring-fed streams also showed little recession during the summer, as compared to those of runoff-dominated streams. Comparison of flows from summer 2003 to spot discharge measurements in 2001-2002, and to irregular measurements from the 1910-1926 (Stearns 1929) suggests that springs have less interannual variability than runoff-dominated streams.

Two major peak flow events are represented in the gaging record: 13-14 December 2003 and 29 January 2004. The spring-fed streams exhibit a delayed peak flow compared to runoff-dominated streams, and this cannot be completely explained by elevation or watershed area. For example, all four runoff-dominated streams had their peak flow on 29 January 2004, but the spring-fed streams reached their peak flows on 30-31 January. Anderson Creek showed almost no response to rain events, while the bigger spring-fed streams showed some responsiveness. Some of this responsiveness may be due to gaging location, as the Roaring and South Fork sites are downstream of runoff-dominated tributaries.

Springs feeding the same creek exhibited different dynamics during the summer period, as illustrated by Olallie Creek and Roaring River (Figure 4, Table 1). Olallie North Branch rises through July and August and drops off in September, while downstream on Olallie Creek, below the confluence of the north and south branches, Olallie Creek exhibits a slight recession throughout the summer as well as greater fluctuations. This recession is similar to the stage record at Olallie South Branch (not shown), which contributes most of the flow to Olallie Creek. Thus,

Figure 3. By combining data from USGS gages and sites measured for this research, 97% of discharge in the McKenzie River at Vida can be apportioned. Discharges in the McKenzie River and its tributaries on 5-7 August 2003 are schematically represented by the thickness of each line. Distances are not to scale.

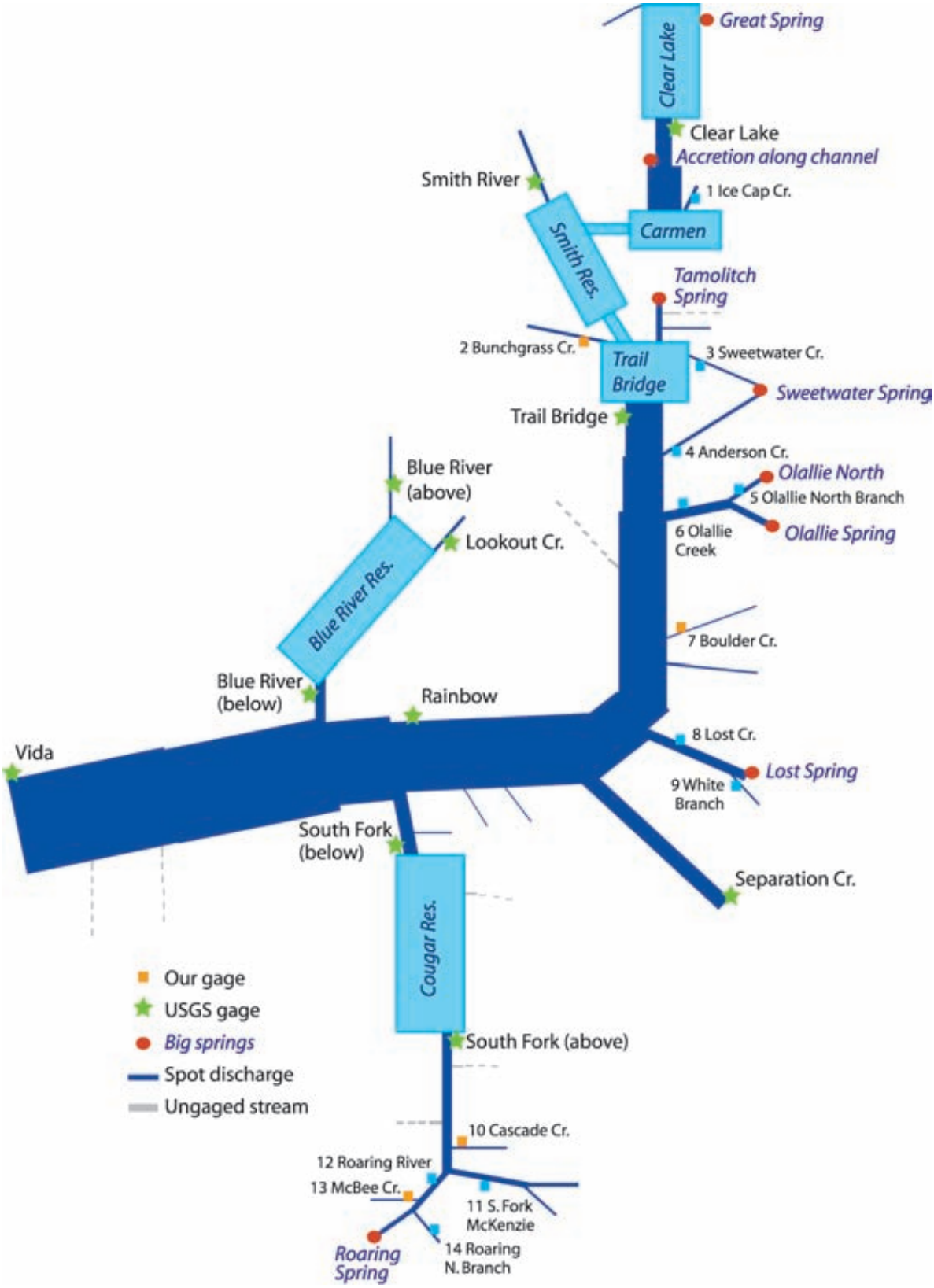
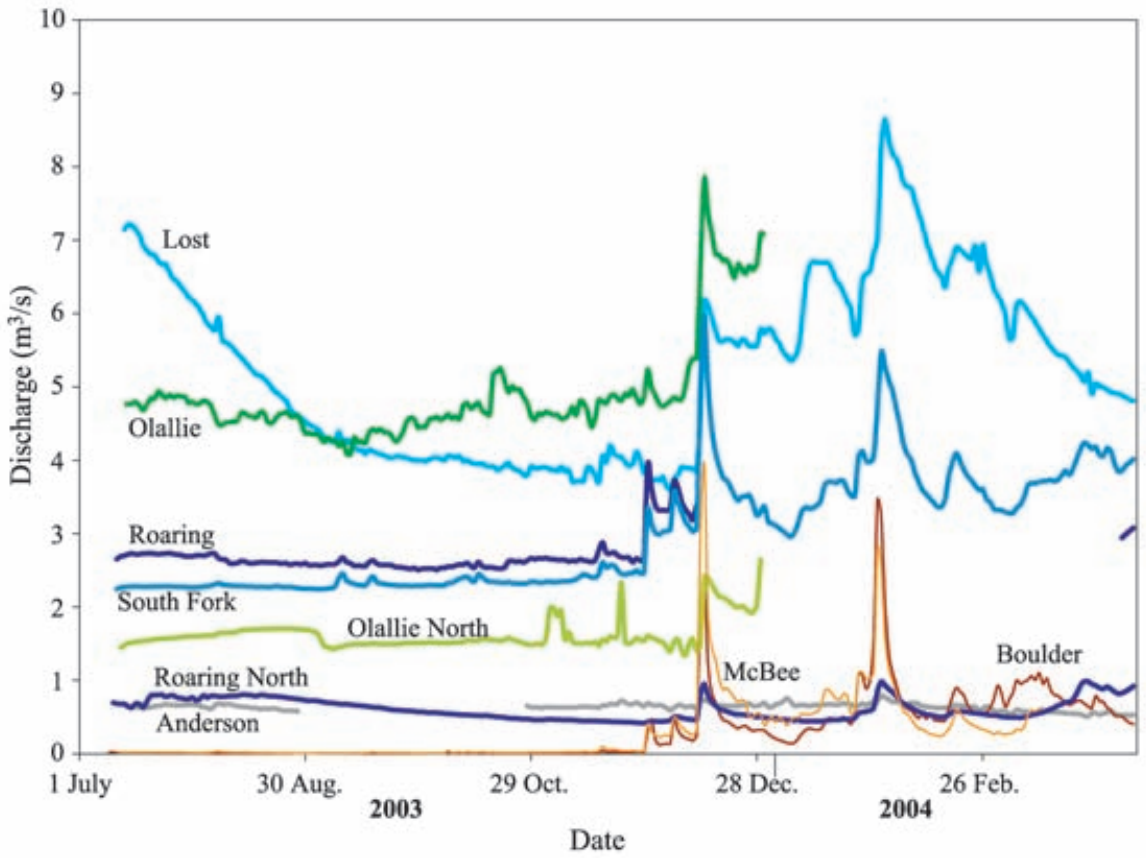


Figure 4. Spring-fed streams (thick lines) display less seasonal fluctuation and muted event response compared to runoff-dominated streams (thin lines), as exhibited by these hydrographs for 9 July 2003 to 7 April 2004. Olallie Creek and Olallie North hydrographs are truncated where there is low confidence in extrapolated discharge values. Other missing data are the result of instrument failure.



although the two branches are sourced in springs less than one kilometer apart, their summer flow behavior differs. Between 15 August and 15 September 2003, discharge from the north spring on Roaring River declined 0.15 cms, while flow at the downstream gage dropped only 0.04 cms. Increased flow from Roaring Spring (south branch) must account for the discharge measured downstream.

White Branch Creek, as measured near its confluence with Lost Creek, appears to be controlled by an ephemeral spring (Figure 5). It exhibits markedly different discharge dynamics than either spring-fed or runoff-dominated streams, despite its spatial proximity to perennial Lost Spring. The stream had a very steep recession in July-August and again in March, each time resulting in a completely dry channel. The stream did not respond to the 13-14 December peak flow event, and exhibited a five-day delay in peak flow for the end of January event. Throughout the vagaries in discharge, water temperature remained nearly constant between 6.5 and 6.7°C, within the range exhibited by Lost Spring. Only when discharge was below ~0.1 m^3/s did significant temperature fluctuations occur.

Water temperature trends also exhibited differences between spring-fed and runoff-dominated streams (Figure 6, Table 1). Temperature measured directly at springs was nearly constant throughout the year, while streams showed fluctuations likely due to cooling or heating from the surrounding air mass. However, spring-fed streams showed much smaller variation in temperature both seasonally and daily than did runoff-dominated streams.

Water samples for five springs were analyzed for tritium, and results ranged from 2.9 to 6.1 tritium units, indicating that the groundwater had been recharged within the last 50 years (Clark and Fritz 1997). Recharge elevations, based on isotopic composition of spring water samples, are at substantially higher elevations than the springs are discharging (Figure 7). The recharge elevations for the springs are concordant with the elevation of extensive young lava flows between McKenzie and Santiam Passes (Figure 2). Springs providing discharge to tributaries of the South Fork of McKenzie also recharge in this elevation range (1325-1825 m), despite less extensive areas of young lavas. Recharge elevations inferred by isotopic methods

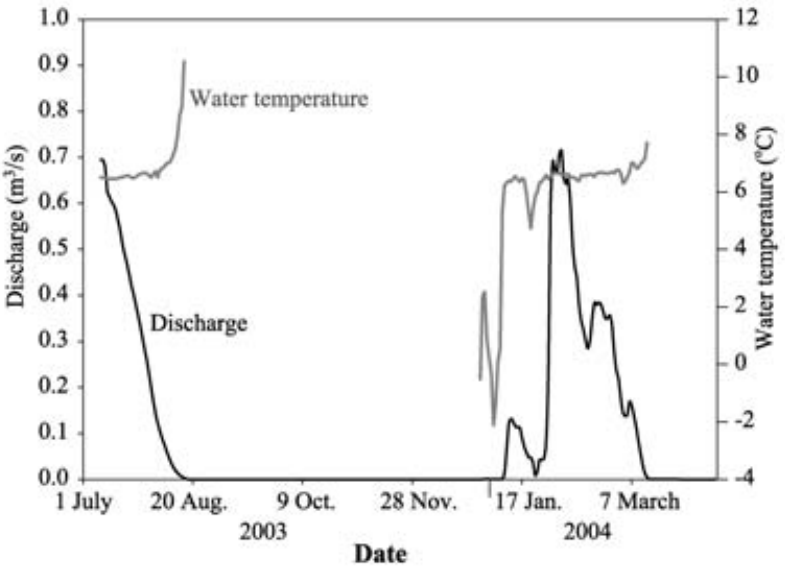


Figure 5. White Branch Creek is fed by an ephemeral spring, and its hydrograph and temperature history are dissimilar to other spring-fed or runoff-dominated streams. White Branch, as measured near Oregon Highway 242, had no water in its channel from 19 August to 25 October 2003 and from 16 March 2004 until the end of the analysis period.

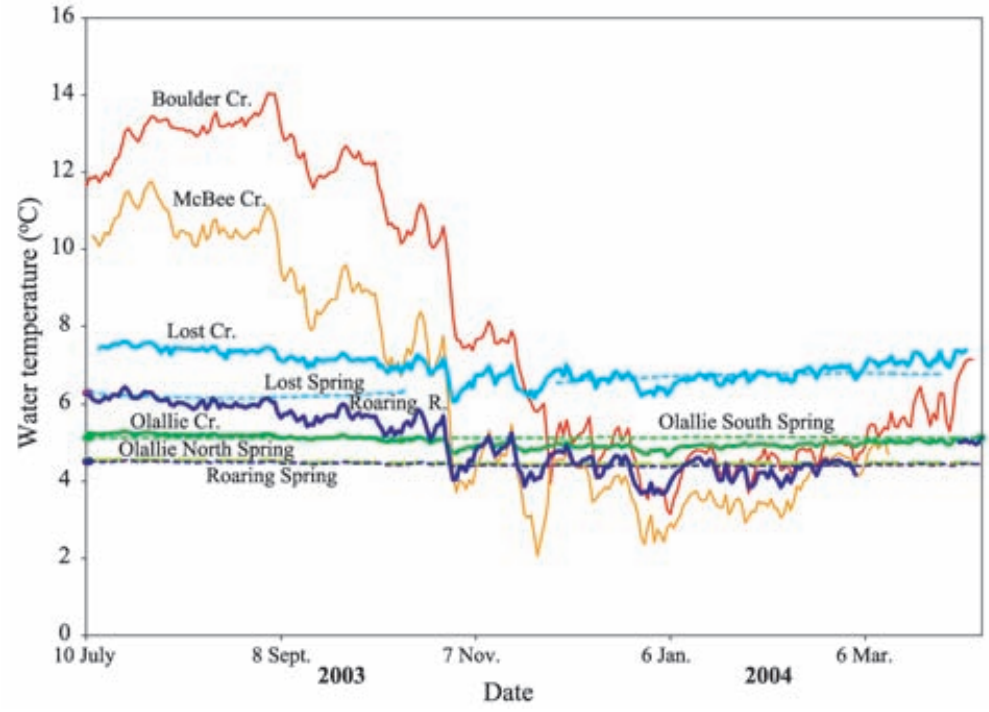


Figure 6. Water temperatures in springs (dashed lines) and spring-fed streams (thick lines) exhibit less variability than temperatures of runoff-dominated streams (thin lines). Water temperature at springs measured by Hobo Water Temp Pro sensors, and in streams, temperature was measured using Hobo or Trutrack sensors.

indicate that topographic watersheds may not be providing evenly distributed recharge to the groundwater system. In at least one case, the inferred average recharge elevation is greater than the maximum elevation in the topographic watershed, requiring significant recharge from outside its boundaries.

Discussion and Management Implications

Spring-fed streams are the dominant source of summer streamflow in the upper McKenzie River, and this flow is sourced from less than ten discrete areas in the watershed. Most of these springs occur on federal land, requiring local and federal water resources agencies to cooperate in their management and protection. The discrete nature of the source areas of water in the McKenzie suggests a number of implications for management.

Maintaining the high water quality of the springs and spring-fed streams requires consideration of several distinct environments: a) the springs themselves; b) the extensive, but often cryptic or unknown area upstream of the springs contributing flow to the springs; and c) channel and riparian areas bordering spring-fed streams. Each of these environments can potentially have different ownerships (public or private), management allocations, impacts, and consequences for water quality. We are only beginning

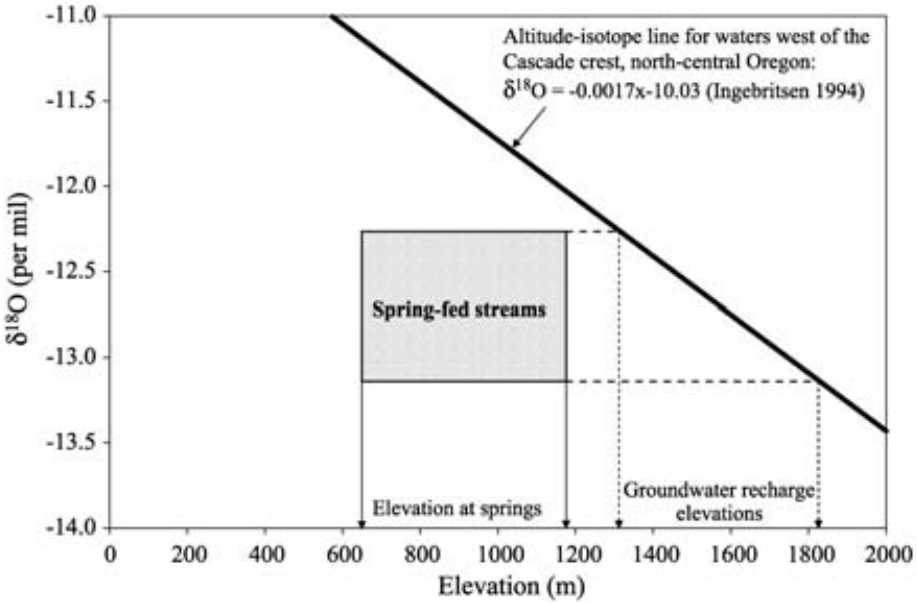


Figure 7. Mean recharge elevation for the springs can be determined by projecting their isotopic composition onto the altitude-isotope line. On average, the springs are recharging almost 800 m higher in elevation than they are discharging.

to understand the interplay of these environments and potential impacts of human and land use activities on each. Specifically, the effects of human activities and natural disturbances in recharge areas on spring water quantity and quality are not well understood. For example, most large springs in the McKenzie drainage are located on national forest lands, and are included in riparian reserves under the Northwest Forest Plan (USDA and USDI 1994). This affords a relatively high degree of protection against forest-harvest and road-building activities. However, source areas that contribute to the springs may or may not be included in riparian or other reserve or protection categories, since groundwater systems are not explicitly included in the Northwest Forest Plan. Whether land-use activities, including forest harvest, recreation, fire suppression, and fuels management, affect the flow in springs remains an open question.

Recharge elevations are significantly higher than spring locations and suggest some discordance between recharge areas and topographic watersheds. These findings emphasize the importance of further investigation into recharge area geometry, the question of whether specific portions of the landscape provide a disproportionate share of recharge to the groundwater system, and what effects human activities in source areas may have on streamflow and water quality.

It is not clear whether highlighting the location of springs (i.e., on maps or through media) will contribute to their future protection or degradation. Many springs are quite sensitive ecologically, with extensive wetland vegetation, unique habitats, and undeveloped access, and would probably be degraded by extensive human use. On the other hand, some springs are on well-developed trail systems and appear to have been quite resilient to the effects of nearby recreational uses.

Despite their importance to water supply during low flow seasons, none of the springs and few of the spring-fed streams have established long-term monitoring facilities (i.e., USGS gages). While spring-fed streams provide more consistent flow than runoff-dominated streams, they do experience higher flows in response to rain and rain-on-snow events. Thus, adequate gaging of these systems is still important for reservoir management planning. A small number of discharge measurements might be sufficient to characterize summer streamflows in spring-fed streams, but winter flows cannot be assumed to be static. Furthermore, differences in flow dynamics between spring-fed streams, even those in close proximity to each other, preclude generalizing measurements from one spring system to others.

Stream temperature, an important habitat criteria for bull trout (*Salvelinus confluentus*) and other species, is generally lower and more stable in spring-fed than runoff-dominated streams, suggesting that conservation efforts for some species might be concentrated in spring-fed streams. At a minimum, the relationship between ecosystem structure and function in spring- versus non-spring streams should be investigated, as this may have implications for regulatory standards affecting water quality and forest management.

Post-1950 groundwater recharge dates imply that the groundwater system is being actively recharged, probably in balance with the amount discharged at springs annually. This suggests that spring water may be susceptible to contamination by atmospheric deposition or chemical spills in recharge areas. Contamination of spring water may appear several years after a spill and the effects may

last for decades. Finally, a change in the overall amount of precipitation falling on the Cascades would probably have an impact on spring discharge within a few years, but a change in seasonality or form of precipitation may be less significant for spring-fed streams than for runoff-dominated streams.

Because of their importance to summer streamflow, water quality, and habitat in the McKenzie River basin, water resources decision-making must differentiate between spring-fed and runoff-dominated streams. This will require cooperation between local and federal organizations, continued assessment of long-term behavior of spring-fed streams in light of climate variability and change, and more investigation into how human and natural impacts on recharge areas could affect groundwater quantity and quality.

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Hubbard Glacier, Russell Fiord, and Situk River: A Landscape in Motion

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Hubbard Glacier, Russell Fiord and the Situk River near Yakutat, Alaska are glacial terrains and forelands in a constant state of motion. The area is an extremely active and dynamic landscape with an advancing tidewater glacier (10 km wide at tidewater), two major seismic faults, and a maximum net isostatic uplift rate of 0.44 cm/yr. The southern end of Russell Fiord is confined by a terminal moraine whereas the northern end of the fiord flows into Yakutat Bay. In 1986 and 2002, the advance of the Hubbard Glacier blocked the northern of the Russell Fiord from Yakutat Bay, temporarily creating Russell Lake. Subsequent failure of the ice or moraine dams in 1986 and 2002, respectively, produced the two largest glacial outburst floods in historic times. Both of these dams failed before the lake had risen to an elevation that would have caused it to spill over the terminal moraine at the southern end of Russell Fiord into the Situk River drainage. In 2002 the Tongass National Forest commissioned an interagency technical team to investigate the implications of the Hubbard Glacier completely closing Russell Fiord and rising lake levels overtopping the moraine at the southern end of Russell Fiord, forcing flow into the historic Situk River channel. Complete closure of Russell Fiord has major economic and safety issues affecting the City of Yakutat. The Situk River provides world class sport, subsistence and commercial fishing, which drives and supports the majority of the Yakutat economy. A sustained closure of the Hubbard-Russell ice dam will increase average daily flows in the Situk River from the current 3 to 11 cubic meters per second (cms) to over 566 cms if Lake Russell overtops the moraine, resulting in significant short and long-term changes to the river ecosystem. Hydrologic and geomorphic analyses of potential overflow scenarios were performed using data obtained from field and remote sensing technologies. The results and methods used to perform the analyses are discussed.

Keywords: *glaciers, LIDAR, flood modeling, geophysical survey, floods, ice dam stability, jokulhlaups, glacial outburst floods*

Introduction

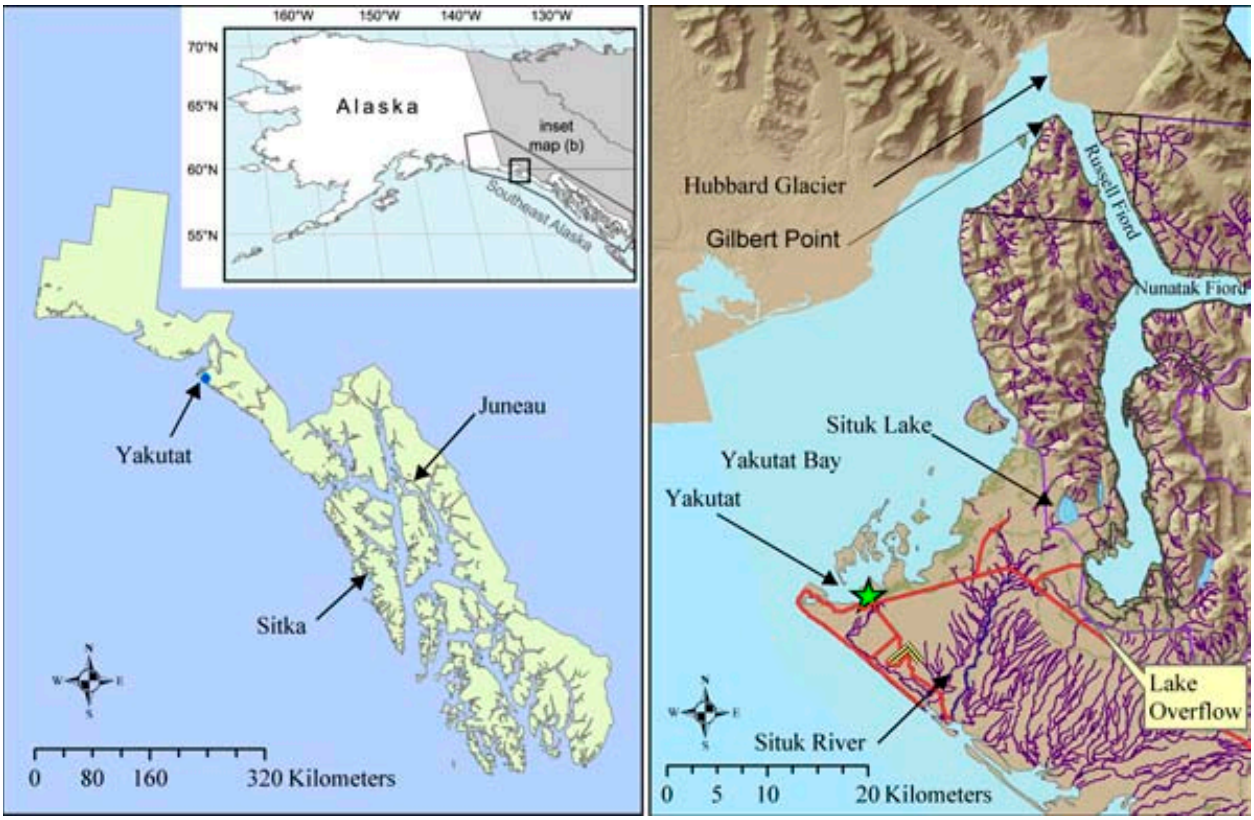
During the last 7,000 years, Russell Fiord in southeast Alaska has experienced cyclical ice damming by the Hubbard and Nunatak glaciers, forming a large lake that redirects outflow into the Situk River near Yakutat, Alaska. These cyclical events have continually altered the land and subsistence lifestyles of the local indigenous people (Tlingit). Oral traditions (deLaguna 1964) and geologic evidence (King 1995; Barclay et al. 2001) indicate that the last major ice dam failure occurred in the mid 1800s, transforming the Situk River into the present river system. The Hubbard Glacier most likely began re-advancing prior to 1791 (Barclay et al. 2001) forming temporary ice dams that created Russell Lake in 1986 and 2002. Future Russell Lake ice dam events could once again force major environmental and economic changes on the inhabitants of the area.

Background

The Yakutat forelands and coastal mountains are one of the most geologically active areas on the North American continent. Nestled in the immense landscape near the mouth of Yakutat Bay is the small community of Yakutat (Figure 1). Yakutat's economy is almost entirely based on sport, commercial and subsistence fishing on the Situk River. Continued advance of Hubbard Glacier and potential permanent closure of Russell Lake, at sometime in the future, would have severe social and economic consequences for the residents of Yakutat and its outlying area. These concerns have spurred numerous studies during the 1986 and 2002 closures to better understand the geologic, hydrologic, biologic, and sociologic implications of such a major disturbance on the community and surrounding environment. During the 2002 Russell Fiord

Furniss, M.J., Clifton, C.F., Ronnenberg, K.L., eds., 2007. *Advancing the fundamental sciences: proceedings of the forest service national earth sciences conference, San Diego, CA, 18-22 October 2004*. PNW-GTR-689. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station.

Figure 1. Vicinity maps showing southeast Alaska and the Yakutat area.



closure, the USDA Forest Service, Tongass National Forest (lead agency) convened an interagency interdisciplinary team that included the Forest Service, US Geological Survey, Alaska Department of Transportation, National Park Service, University of Alaska and Army Corps of Engineers, to assess the affects on the Situk River and the Community of Yakutat. The work of the interagency team is ongoing and this paper reflects current and pending work completed to date. During the 1986 closure, a Forest Service team of technical specialists completed a floodplain analysis on potential inundation levels for the Situk River caused by the new Russell Lake and some possible diversion alternatives. The focus of the 2002 technical team was to update previous studies with more current information; perform stability analysis of the terminal moraine and ice dam; and determine feasibility of diversion alternatives. The results of these and future studies will address the following questions:

1. Will all flow from newly formed Russell Lake flow into the Situk River?
2. If flooding occurs, what are the risks to the community or to existing infrastructure?
3. Are the 1986 flow and floodplain assessments valid?
4. Is it feasible and by what method could Russell Lake be diverted into another drainage system?
5. Is the terminal moraine at the lake outlet stable?
6. Will the ice dam forming Russell Lake be persistent and stable at the next closure?

Geology

Glaciation

Most of the Yakutat Forelands landscape was formed from glacier outwash and moraine deposition processes within the last 1,000 years (Shephard 1995). Radiocarbon dates from debris buried in glacial outwash deposits indicate that there were at least two periods of recent advance, between the 13th and 19th centuries, by glaciers originating in the Barbazon Range east of Yakutat. The Nunatak Glacier (Figure 1), advanced to within 6 miles (9.7 km) of the head of Russell Fiord during the early 1800s, resulting in the most recent overflow of glacial Russell Lake into the Situk River system (King 1995). By the late 1890s, the Nunatak Glacier had retreated out of Russell Fiord (Gilbert 1904; Tarr 1909). The Hubbard terminus in 1895 was located about 2.4 km back from Gilbert Point (Figure 1) and the mouth of Russell Fiord (Trabant et al. 1991). Over the last century, Hubbard Glacier, currently the largest tidewater glacier in North America, has been strongly advancing while other glaciers in the area have continued to retreat (Trabant et al. 2003).

This advance-between 15 and 46 m per year-is likely to continue regardless of short-term climatic influences (Trabant et al. 2003).

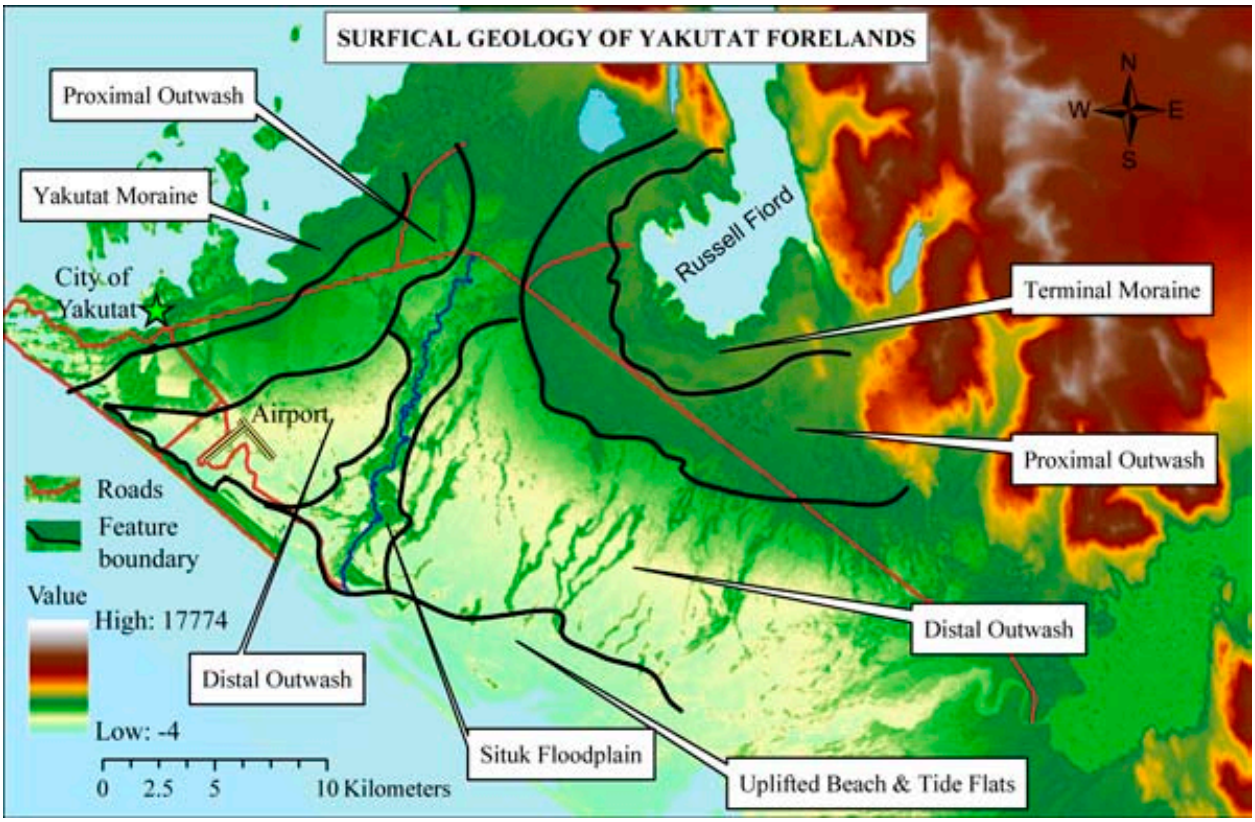
Over the last 20 years, seasonal advance of Hubbard Glacier has twice blocked the entrance to Russell Fiord, temporarily creating a large freshwater lake, Russell Lake. A shallow bedrock sill near the mouth of Russell Fiord allowed narrow fingers of ice and moraine deposits to close off the entrance to the fiord in 1986 and again in 2002. Russell Lake filled at an average rate of 0.2 m per day (Trabant et al. 2003) during the summer and early fall. In 1986, Russell Lake reached a maximum level of 26 m above sea level (maximum lake elevation in 2002 was 15 m) (Trabant et al. 2003). The incipient lake was strongly stratified by a freshwater-saltwater salinity gradient. The lower saltwater layer would have become anoxic (with no dissolved oxygen) in less than two years (Reeburg et al. 1976). However, the upper layer would be capable of supporting freshwater zooplankton and fish communities. A combination of hydrostatic pressure from the lake, erosion of the ice-moraine plug, and seasonal calving of the ice front resulted in catastrophic failure of both ice dams, producing the two largest outburst floods on record worldwide, 112,418 cms on 8 October 1986 and 52,386 cms on 14 August 2002 (Trabant et al. 2003).

Landscape Characteristics

The Russell-Situk watershed encompasses three major ecological subsections: Saint Elias-Fairweather Icefield, Puget Peninsula, Yakutat-Lituya Forelands (Nowacki et al. 2001). Headwaters in the Saint Elias Icefield reach elevations of over 2,743 meters. This ice mass covers 907 km^2 and feeds the Hubbard, Variegated, Nunatak, Hidden and Fourth glaciers. These mountain glaciers all terminate at or near sea level in Russell Fiord. The Puget Peninsula is a rugged mountain range that forms the western boundary between Russell Fiord and Yakutat Bay. Most of this area is barren rock with patches of alpine sedges, forbs and low shrubs. Lower mountain slopes have a dense cover of alder-willow shrub communities and isolated stands of black cottonwood (*Populus trichocarpa*) and Sitka spruce (*Picea sitchensis*). Russell Fiord covers an area of 199 km^2. The fiord has steep walls except for small river deltas and alluvial fans associated with the inlets of glacial rivers including Beasley Creek. These short glacial and steep mountain-slope stream segments provide very limited resident and anadromous fish habitat.

The Yakutat-Lituya Forelands is a low relief coastal plain formed by unconsolidated glacial outwash, moraine and recent fluvial deposits (Figure 2). This area has also been heavily influenced by isostatic rebound, tectonic uplift

Figure 2. Geologic map of glacial deposition, uplifted beach, and moraine features in the Yakutat area.



and subsidence, and long-shore ocean sediment transport and deposition. Vegetative cover is predominantly early successional spruce-hemlock forest and extensive bog wetland plant communities along Russell Lake (Shephard 1995).

The Russell terminal moraine (Figure 3) is a 1.6- to 3.2-km-wide deposit of unsorted glacial debris, ranging from silt- to boulder-sized glacial deposits. It extends from the south shore of Russell Fiord to the Forest Highway (FH) 10 crossing on Old Situk Creek. These better drained ablation tills are covered with a dense spruce-hemlock forest. Another, roughly 3.2-km-wide band of spruce-hemlock forest on gently sloping, proximal outwash deposits extends further to the south. Ephemeral streams exist throughout the proximal outwash zone. These outwash deposits consist mainly of highly permeable cobbles and coarse gravels (Shephard 1995).

The forelands contain numerous highly productive anadromous fish streams with the Situk River being the most prominent of these systems. Until about 1850, the Old Situk River-Situk River corridor (Figure 4) was the historic outlet to glacial dammed Russell Lake (de Laguna 1964). Narrow bands of cottonwood, alder, and conifer forests occur along current and abandoned floodplain terraces of the Situk River and its major tributary channels. Tree ring analysis of dominant conifers in the floodplain indicates that these trees were established shortly after the 1850 ice dam failure that drained historic Russell Lake (Clark and Paustian 1989).

The distal outwash (Figure 2) covers the bulk of the forelands adjacent to the Situk River corridor. This area is covered by fine-textured glacial-outwash sediment (gravel, sand, and silt). The water table is at the surface most of the year, forming the vast wetland fens and bogs in this area (Shephard 1995). Numerous small, palustrine streams initiate along the interface between the proximal and distal outwash zones.

Uplifted tidal flats and beach ridge landforms occur along the Gulf of Alaska coastline. This area, including the Situk-Arnkalin River estuary and Black Sand Spit (along the mouth of the Situk River), has recently been modified by earthquake, isostatic rebound and coastal erosion/deposition processes (Shephard 1995). The Yakutat area has had five major earthquakes since 1899, resulting in up to 15 m of uplift in portions of Yakutat Bay (Combellick and Motyka 1995). This tectonic activity altered groundwater tables and probably had long lasting effects on groundwater exchange with stream segments in affected areas. Isostatic rebound has also occurred over a much longer time span but may have resulted in more extensive changes to the lower forelands. Coastal areas near Yakutat have risen at a rate of 0.5 cm per year since 1940 (Savage and Plafker 1991). Portions of former perennial streams, such as Ophir Creek (adjacent to City of Yakutat), have become intermittent over the last few decades. Radiocarbon analysis of buried organic horizons exposed in stream banks indicates that uplifted beaches and tidal basins near the Situk River mouth were formed within the last 150 years (Shephard 1995). Long-shore transport and deposition of sediment derived from large glacial rivers is another significant agent of coastal change. Expansion of Black Sand Spit has pushed the mouth of the Situk River 2.4 km to the northwest over the last 50 years (Shephard 1995).

Figure 3. Oblique aerial view of the Russell terminal moraine. Note the parallel sequence of moraine ridges bisected by relic glacial drainage paths. The high water level from the 1986 ice dam event is marked by the band of dead trees along shoreline of Russell Fiord.

Figure 4. Oblique aerial view of the Old Situk River–Situk River corridor.

Hydrology

Unique landscape and climatic factors strongly influence major hydrologic events in the Russell-Situk watershed. The Yakutat area has a wet, cool, maritime climate

Figure 5. Russell Lake (circa 1986) looking north toward Hubbard Glacier.

typical of southeast Gulf of Alaska coast. Average annual temperature at the Yakutat NOAA weather station is 4°C . Typical mean air temperature is in the 0-5°C range during winter and 10-16°C during the summer. Normal annual snowfall is 510 cm at the coast, with a maximum of 10.2 m recorded in the winter of 1975-76. Average annual precipitation in Yakutat is 380 cm. No climatic data are available for the Russell Fiord and Saint Elias Icefields; however, annual precipitation is estimated to be between 410 cm and 559 cm. Except for periods during the summer months, precipitation in the icefield portion of the Russell Lake watershed falls as snow.

Almost 50% the Russell Lake watershed area (Figure 5) is covered by permanent snow and ice fields. Runoff into glacial Russell Lake is greatest during maximum snow and glacier melt in the summer months, and decreases considerably during the remainder of the year.

Russell Lake

The USGS lake gage at Marble Point, operated during the 1986 and 2002 ice-dam closure events, measured an average lake inflow rates from 425 cubic meters per second (cms) to 538 cms (Trabant et al. 2003; Neal 2004). A large portion of the Russell Lake watershed area is lake surface (11%) and rock or shallow alpine soils (30%), characteristics that result in rapid runoff during high intensity summer rainfall. Large spikes in the lake inflow hydrograph, as high as 2,605 cms, occurred in response to short-duration, high-intensity, summer rainfall events in August of 1986 and 2002. Rainfall intensities for these two events approached the maximum 24-hr and 12-hr August rainfall records (14 cm and 8 cm respectively) for the Yakutat weather station. It is interesting to note that even though these rainfall events were of similar intensity and duration, the peak lake inflow rate observed in 2002 was almost double the peak inflow rate in 1986. These data suggest that factors such as moraine/ice dam leakage, variability in basin rainfall distribution, or englacial runoff from Hubbard Glacier may significantly influence short-term inflow rates to Russell Lake.

Russell Lake inflow rates for selected return intervals (Table 1) were calculated using two approaches: 1) regional equations, based on basin characteristics (Curran et al. 2003); and 2) a regression model, based on 2002 lake gage data correlated to stream gage data from Situk River and Ophir Creek (Neal 2004). Russell Lake peak inflow estimates were also derived using regional equations (Curran et al. 2003). Regional equation variables include: total basin area (1,927 km^2), annual precipitation of 559 cm, and minimum January temperature of -9°C. The regression equation contains a percent of lake in the basin, set to a value of one to remove lake storage effects. Results of the both methods are listed in Table 1. It is important to note that the Russell watershed characteristics are significantly different from watershed characteristics of gaged basins used in the development of the regional regression equations, increasing the uncertainty and reducing the reliability of these inflow rates.

Neal's regression approach used lake-gage data from 16 July to 13 August 2002 when leakage from the moraine/ice dam was observed to be minimal. Stream gage data from eleven Ophir Creek and Situk River peak flow events (between 15 May and 15 October for water years 1991-2002) were used to develop a synthetic Russell Lake inflow hydrograph (Table 1) (Neal 2004). Neal's synthetic peak discharge estimates (Table 1) are much higher than peak flow estimates derived from the USGS regional equations. These estimates represent a best approximation for the range of peak Russell Lake inflows given limitations in the available data used to derive both sets of predictions.

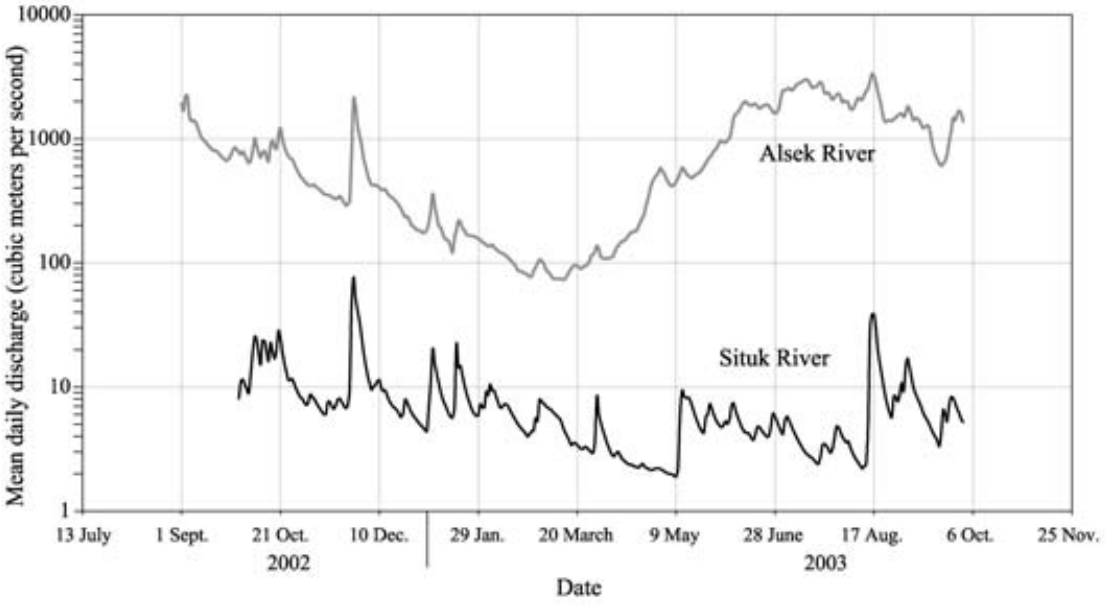
Situk River

The headwaters of the Situk River (Figure 1) emanate from the Puget Peninsula, Mountain Lake, and Situk Lakes. Major tributaries are the Old Situk River, draining

Table 1. Russell Lake inflow predictions from regression model and regional equations (after Neal 2004).

Recurrence Interval (yrs)	Synthetic Model Discharge (cms)	Regional Equations Discharge (cms)
2	4,171	2,163
50	6,397	4,078
100	6,759	4446

Figure 6. Mean daily flow hydrograph for the Alsek River and Situk River in cubic meters per second.



the Russell Moraine (also the historic overflow channel from Russell Lake) and West Fork Situk River, that drains the Redfield Lakes and the eastern portion of the Yakutat Moraine. Numerous small palustrine streams enter the Situk along the distal outwash plain. Ophir-Tawah Creek and Lost River are the most prominent tributaries in the lower Situk River watershed.

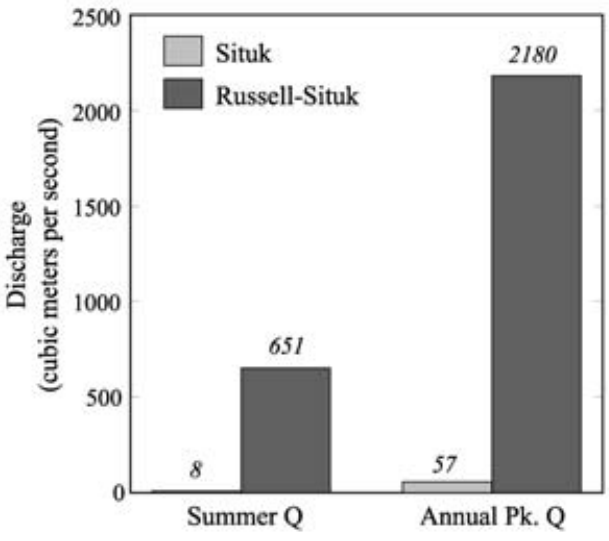
Peak flows in the middle Situk drainage basin (93 km^2) are generated by prolonged periods of high rainfall in the fall and early winter (Figure 6). Base flows are relatively stable during the remainder of the year. Groundwater derived from the moraines and proximal outwash landforms are a major component of river base flow. Storm hydrograph peaks, however, have a relatively short duration of 1 to 3 days.

The basin area for the entire Situk River drainage would increase from 215 km^2 currently, to over 2,072 km^2 with the addition of the Russell Lake basin area (Clark and Paustian 1989). Future Russell Lake overflows into the Situk River drainage will result in the dramatic changes of a one hundred-fold increase in average summer river discharge to the Situk River flow regime (Figure 7). Figure 6 contrasts seasonal hydrographs for the middle Situk stream gage and a nearby stream gage on a large glacial river, the Alsek River. The Alsek River is a much larger watershed and has lower annual precipitation, but has a geologic setting similar to Russell Lake. Glacially dominated runoff from Russell Lake will also shift peak flow timing in the Situk from the fall and winter months to the summer season (Figure 6).

Mean summer discharge in the Situk is currently between 5.7 and 8.5 cms. In contrast, Russell Lake gage measurements from 1986 and 2002 indicate that summer flows in the Situk River associated with the greatly expanded Russell-Situk drainage basin will be between 425 and 850 cms (Figure 7). Maximum daily peak discharge measured for the Situk River (from 1988 and 2004) is 92 cms. Annual peak discharge (2.33-year flood frequency) for Russell-Situk watershed is predicted to be 2,186 cms (Miles 2004).

Groundwater tables in the distal outwash zone of the lower Situk River watershed are within 1 m of the surface. A series of dry gravel borrow pits along FH 10 indicates that water tables are relatively deep in the proximal outwash zones. Proximal outwash and some moraine deposits are

Figure 7. Comparison of the current Situk River streamflow with the predicted Russell Lake-Situk River flow.



well drained, however, kettle ponds and bogs are common in depressions that have been sealed by silt deposits and fine organic material (Shephard 1995).

Due to the heterogeneity of moraine deposit sediments, permeability changes both laterally and vertically. The terminal moraine at the head of Russell Fiord has seen several glacial advances (shown in Figure 3 as parallel ridges) and retreats with associated lake formation. We speculate that these glacial advances and retreats have contributed fine materials (silt and rock flour) to the subsurface moraine material, greatly reducing hydraulic conductivity of the moraine or making it impermeable, similar to a clay plug in an earthen dam. Although field observation along the Russell Lake side (northwest corner) of the moraine face validates this assumption, additional geophysical data is required to verify consistency across the moraine.

Monthly groundwater levels are stable for much of the year, with the exception of depressed levels in June and July, which correspond to low rainfall and minimal snow pack inputs (Clark and Paustian 1989). Segments of small palustrine and floodplain tributaries (including Ophir Creek) become intermittent during short summer droughts.

The Old Situk River channel was the historic outlet of glacial Russell Lake for an unknown period of time during the early to mid 1800s. Oral history accounts of the Tlingit Indians (de Laguna 1964) and dendrochronology data from the Situk flood plain and shoreline of Russell Lake (Clark and Paustian 1989; King 1995) indicate that the Nunatak Glacier ice dam failed around 1850, severing the Situk watershed connection with the Russell Lake watershed. The 1800s ice dam location (approximately 10 km from the head of Russell Fiord) resulted in a much smaller lake (and smaller watershed area), than was associated with the 1986 and 2002 dams at Gilbert Point near the mouth of Russell Fiord (King 1995). We speculate that runoff volumes from the Old Situk Notch, which formed the relic Situk floodplain channels (Figure 4) prior to the Nunatak ice dam failure, are potentially an order of magnitude smaller than the runoff volume that would result from a semi-permanent Hubbard Glacier ice dam located at Gilbert Point.

Terrain Modeling

Data Acquisition

One of the keys to modeling Old Situk-Situk River flood plain characteristics is accurate elevation data. Terrain on the forelands has very low relief and is composed primarily of bogs and fen complexes with grass and sedge of various heights (Shephard 1995). Most streams have a riparian corridor consisting of dense Sitka spruce, willow, and devils club (*Oplopanax horridus*). The terminal moraine and proximal outwash is heavily forested with Sitka spruce and *Vaccinium* understory. Vegetation influence is always an issue in determining true ground elevations especially in areas of dense vegetation. The original 1986 floodplain assessment relied on elevation data generated by USGS using analytical photogrammetric methods from air photos flown during leaf on conditions. The ability to get sufficiently dense and accurate data reflecting actual ground elevations and not the top of vegetation with this type of technology is difficult and a potential source of modeling error, which becomes more significant in areas of very low relief.

A test flight using LIDAR (Light Detection and Ranging) technology was made in 2002 to determine if accurate elevation data could be obtained along the Situk River during leaf-on conditions. LIDAR data provides a quick way of obtaining and mapping elevation data in terrain that is logistically difficult to access. LIDAR uses a tagged laser pulse that records the return time of the laser pulse and keeps track of the airplane position and orientation (roll, pitch and yaw), yielding elevation data that is accurate to 15 cm vertically and 1 m horizontally. To validate the LIDAR elevation data, survey grade GPS controls were established to test profiles surveyed along the river corridor on the forelands and terminal moraine. All survey data were transformed into the same coordinate system (NAD 27 NGVD 88). The ground surveyed profiles were very similar to those produced by the LIDAR data. The elevation accuracy between the two data sets (Table 2) led to the acquisitions of LIDAR data for the entire Situk River floodplain and remaining areas around the terminal moraine. The data was processed with a vegetation removal algorithm similar to the method described by Haugerud and Harding (2001) to remove ~99% of the vegetation points. Although this is an automated procedure, some additional manual processing may be necessary to remove vegetation anomalies along the dense riparian corridors. The ASCII ground point files of the LIDAR data were so dense that further thinning by gridding the points was necessary for the floodplain inundation models to be continuous from the ocean to

Table 2. Comparison of LIDAR elevations to ground surveyed profiles.

Location	Mean Difference (m)	Std. Dev. (m)	RMSE
Old Situk River Notch	-0.31	0.41	0.16
Section 10 on Forelands	-0.30	0.31	0.03

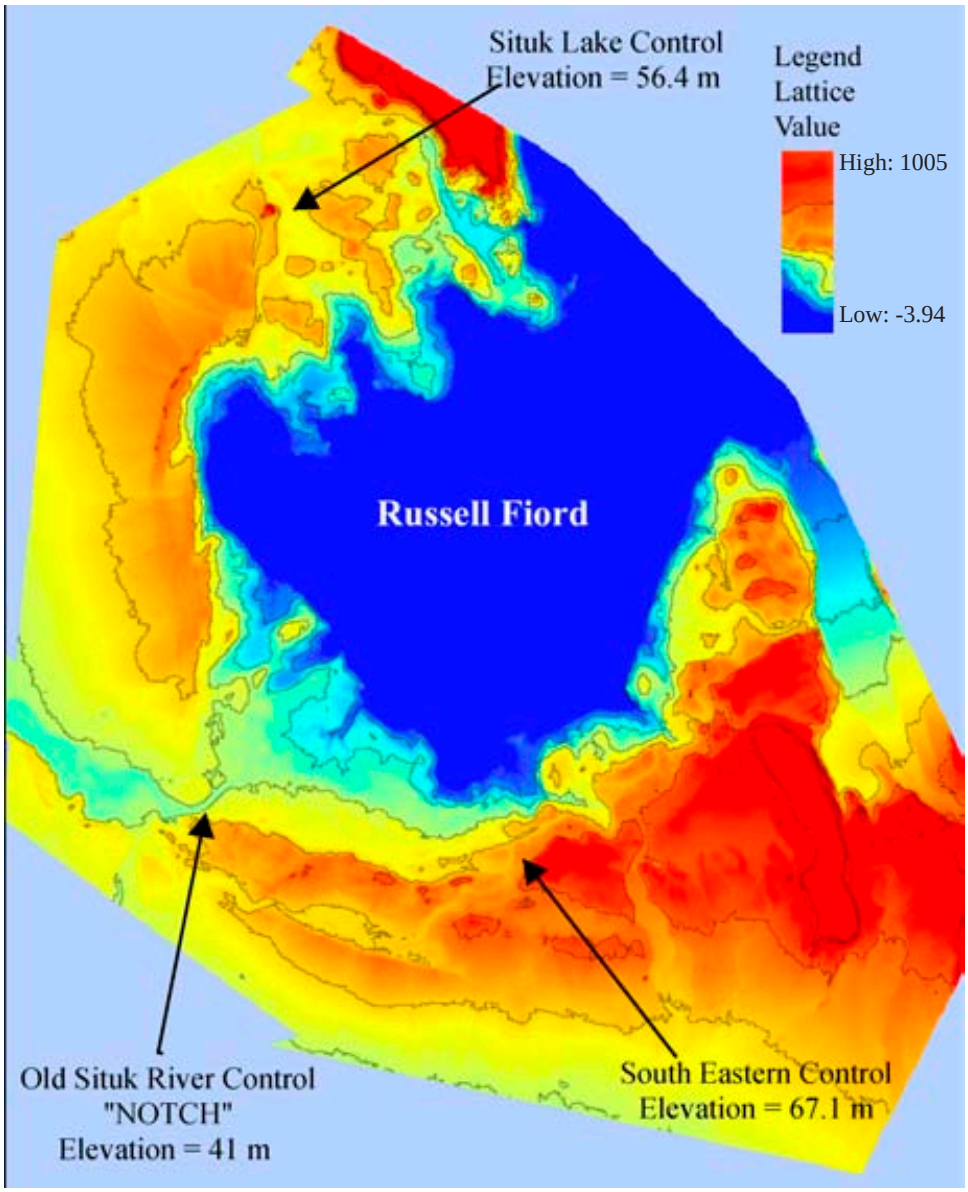


Figure 8. LIDAR derived DEM showing outflow controls for historic Russell Lake.

Russell lake boundary conditions. The LIDAR data was dense enough to show all of the geomorphic expression of the moraine and floodplain landscapes (Figure 8).

LIDAR data acquisition was difficult due to the remoteness of the project area, poor weather (low cloud ceiling and precipitation), and LIDAR operator flight requirements (minimum of 1000 m above ground level). These difficulties, in addition to needing a dedicated helicopter for ground surveys and the urgent need for data, drove costs higher than normal for both LIDAR and ground surveys (Table 3). Further LIDAR data collection efforts are planned to obtain elevation data across the forelands to determine the feasibility for creating diversion channels.

Table 3. Survey accomplishments and costs for LIDAR and ground surveys.

Year	Ground survey (km)	Ground survey costs (2004$)	LIDAR Area (hectares)	LIDAR costs (2004$)
2002	19	$275,000	12484	$89,000
2003	-	-	20914	$151,000

Lake Flow Controls

One of the purposes of the LIDAR survey was to obtain detailed topography along the terminal moraine to map all potential overflow points. All previous assessments have mentioned only the Old Situk River Notch as the main lake outlet control. The Old Situk Notch was validated as the outlet control, however, the LIDAR survey also revealed additional control elevations of several historic Holocene outlets that contain underfit streams (streams too small to

have carved their valleys). Three main Holocene lake level controls are identified (Figure 8). The identification of these other spillways is important in understanding their relations to maximum projected lake level since the current lake size (and inflow volume) is approximately double that of the last closure.

To identify historic Holocene lake controls, the LIDAR data were transformed into a lattice grid in ESRI ArcInfo[1] . The grid was then incrementally assessed using the analysis map query tool in ESRI ArcView to develop coverages that show all elevations greater than a given elevation. This process was repeated every 1.5 m until the major overflow controls were identified. The control areas (Figure 8) were then evaluated using terrain modeling software (Spectra Precision TERRAMODEL V 9.7 2000). The model's gridding process averages elevation from the point coverages to form an equally spaced set of gridded elevations. This process can slightly alter the actual control elevation. The LIDAR points were recontoured in TERRAMODEL to compare the results. As the exact location of the LIDAR points on the ground cannot be controlled due to vegetation point removal, track and swath spacing, and collection of the LIDAR sensor, the overflow elevations reported are based on the ArcView analysis with potential lower limit elevations developed in TERRAMODEL. Both methods produced similar results. Overflow and lowest possible elevations were determined for each lake control. For the Old Situk River control, values were 41 m and 40.2 m, respectively; for Situk Lake control, 56.4 m and 55.2 m; and for the southeastern control, 67.1 m and 66.5 m.

The terrain modeling results show that all outflow from Russell Lake will drain through the Old Situk River control notch when the lake levels rise above 41 m. Our floodplain analysis evaluated discharges of 566 cms for normal flow, 2186 cms for a 2.33-year flood, 4446 cms for a 100-year flood, and 6796 cms for the maximum flood, and produced estimated lake levels of 45.3 m , 49.2 m, 52.6 m, 54.6 m respectively. These estimates are well below the 56.4 m Situk Lake elevation control; therefore this outflow location will not affect Situk Lake or the 10 km of prime salmon & steelhead spawning and rearing habitat in the upper Situk River drainage (because these areas are above the mainstem junction with the Old Situk River channel).

[1]The use of trade or firm names in this publication is for reader information and does not imply endorsement by the U.S. Department of Agriculture of any product or service.

Hydraulic Flood Modeling

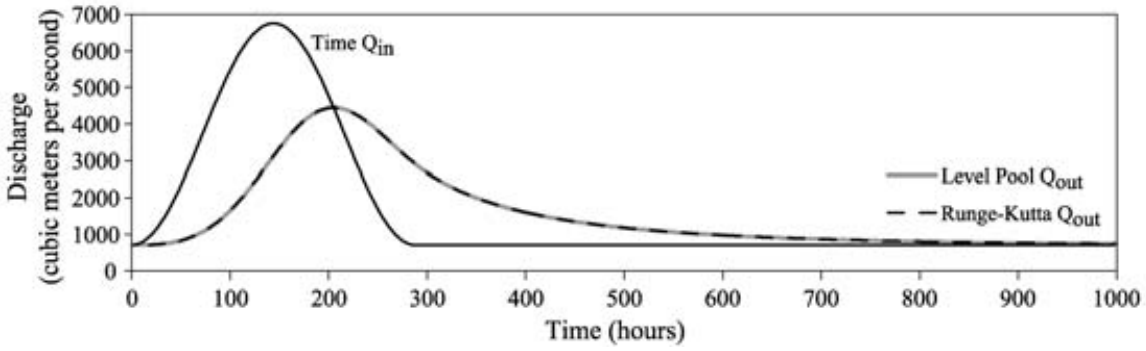
Hydraulic flood modeling was done in order to identify floodplain inundation limits with improved elevation data and determine lake levels and potential overflow points along the terminal moraine. A flood assessment of this magnitude is difficult to predict because of continual changes in channel characteristics (width, depth, shape), and the effects of roughness (form roughness, log jams) as flow progresses from initial overtopping of the moraine to some point in the future when a more stable system will develop. The geomorphic expression of the old Situk River on the proximal and distal outwash provides anecdotal evidence of historic flood limits. However, historic Russell Lake was believed to be 50% smaller than the current lake and watershed area. This factor will increase projected lake overflow volume to the Situk River corridor.

Russell Lake Outflow and Reservoir Routing

Once the lake level reaches 41 m above mean sea level, water will overtop the Old Situk River spillway. The volume of lake outflow is controlled by the height of the water above the spill crest. For the analysis, a stage-discharge relationship was developed assuming the spillway is a rigid boundary. The elevation and spillway geometry of the Old Situk River control should be sufficient to handle outflow from Russell Lake, preventing the lake from rising to an elevation that would cause outflow to occur at the Situk Lake control (Figure 8). The Old Situk River control has the capacity to convey a discharge of 7100 cms, which is 1.6 times greater than the estimated 100-year flood discharge.

Lake systems provide a storage function for inflow hence Lake outflow = inflow - storage. The elevation rise in a lake is a function of hypsometry (storage volume versus elevation) and inflow. The amount of storage for various floods needed to be calculated to determine peak outflow rates. An inflow hydrograph is the first step in the analysis; the shape and duration of this hydrograph greatly affects the model results. No inflow hydrograph existed, so a synthetic hydrograph was developed. The storm history of the Yakutat area and simulated hydrographs developed by the USGS inflow study (Neal 2004) indicated that a time to peak flow of four to six days for a "standard" was a reasonable assumption (Miles 2004). A base flow of 708 cms with six-day duration to peak inflow was used in a simple sine function to develop the shape of the inflow hydrograph. Two methods of reservoir routing (Runge-Kutta and Level Pool) were used with the data from the inflow hydrograph, lake hypsometry and outflow stage discharge relationship resulting in similar outflow

Figure 9. Russell Lake Inflow and Outflow Hydrograph for the 100-year flood.. Both the Level Pool and Runge - Kutta methods which predict similar results and are not visible separately on this graph. (Miles 2004) Qin is the inflow rate and Qout is outflow rate.



hydrographs (Figure 9) (Miles 2004). Flood routing results are shown in Table 4 (Miles 2004).

Flood Modeling

Computer open-channel flow models assume a "rigid" boundary. This rigid boundary assumes that the channel bed and margins do not mobilize or erode, changing shape with discharge. In the case of the Situk River, the distal outwash is unconsolidated fine-grained gravel and sand. Depending on flow stage, a portion or entire channel sections will be mobilized and margins will erode until the system reaches some form of "dynamic equilibrium". The modeling done to date assumes a rigid boundary, which will produce higher water levels compared to the existing topography than the likely future channel due, to incision and channel formation. Our current intent is to identify potential impacts on public safety and infrastructure, and note areas of where mobile bed conditions may exist. Two models were used to evaluate flood characteristics on the Situk: the dimensional steady state flow model HEC-RAS V3.1 from the U.S. Army Corps of Engineers (US ACoE 2003), which assumes average flow velocities perpendicular to the cross sections evaluated; and the two-dimensional flow model SMS/Flo2DH (BYU and FHA 2004), from Brigham Young University and the Federal Highway Administration, a finite element analysis that solves for flow in the horizontal plane assuming vertically averaged flow velocities for each element.

Table 4. Flood routing analysis (after Miles 2004). Routed outflow discharge results indicate a significant storage capacity in Russell Lake that substantially attenuates inflow peak discharge.

Recurrence Interval (years)	Inflow		Outflow	
	cms	cfs	cms	cfs
2	4,171	147,300	2,107	74,400
2.33 (mean annual)	4,332	153,000	2,186	77,200
50	6,397	225,900	4,174	147,400
100	6,759	238,700	4446	157,000

Modeling Assumptions

The channel cross sections used in modelling were based on the existing topography and assumed to be rigid. Even though both lateral and vertical scour is expected, the amount of channel scour cannot be reliably estimated until geotechnical drilling verifies the subsurface material characteristics of the bounding channel walls and bed. Roughness of the channel greatly effects water surface elevation. It is anticipated that log jams will form randomly through the system, causing large fluctuations in roughness. Current predictive capabilities have high uncertainty, so estimates of roughness are based on operator experience, and assume that a portion of the woody debris has been removed by high water (Miles 2004). Both models require inputs of boundary conditions. The upstream boundary condition is the outflow from Russell Lake and the downstream boundary condition used is the high tide line at ~3 m above mean sea level, where the Situk River meets the Gulf of Alaska. Both programs are capable of unsteady flow analysis, when discharge varies over time. To reduce the complexity of the model, a simplified steady state (constant) flow for peak flows was assumed. Peak flow is expected to occur for an adequate length of time, making steady flow a reasonable assumption (Miles 2004). No attenuation of peak flows was used in the model, providing a conservative analysis due to public safety concerns for Yakutat.

Model Results

The HEC-RAS model was based on seventy-eight cross sections over a 35 km (21.6 mi) length of channel. For all the flows modeled (Q_2 to Q_{100}), the Situk River control acts as a spillway using its current channel configuration,

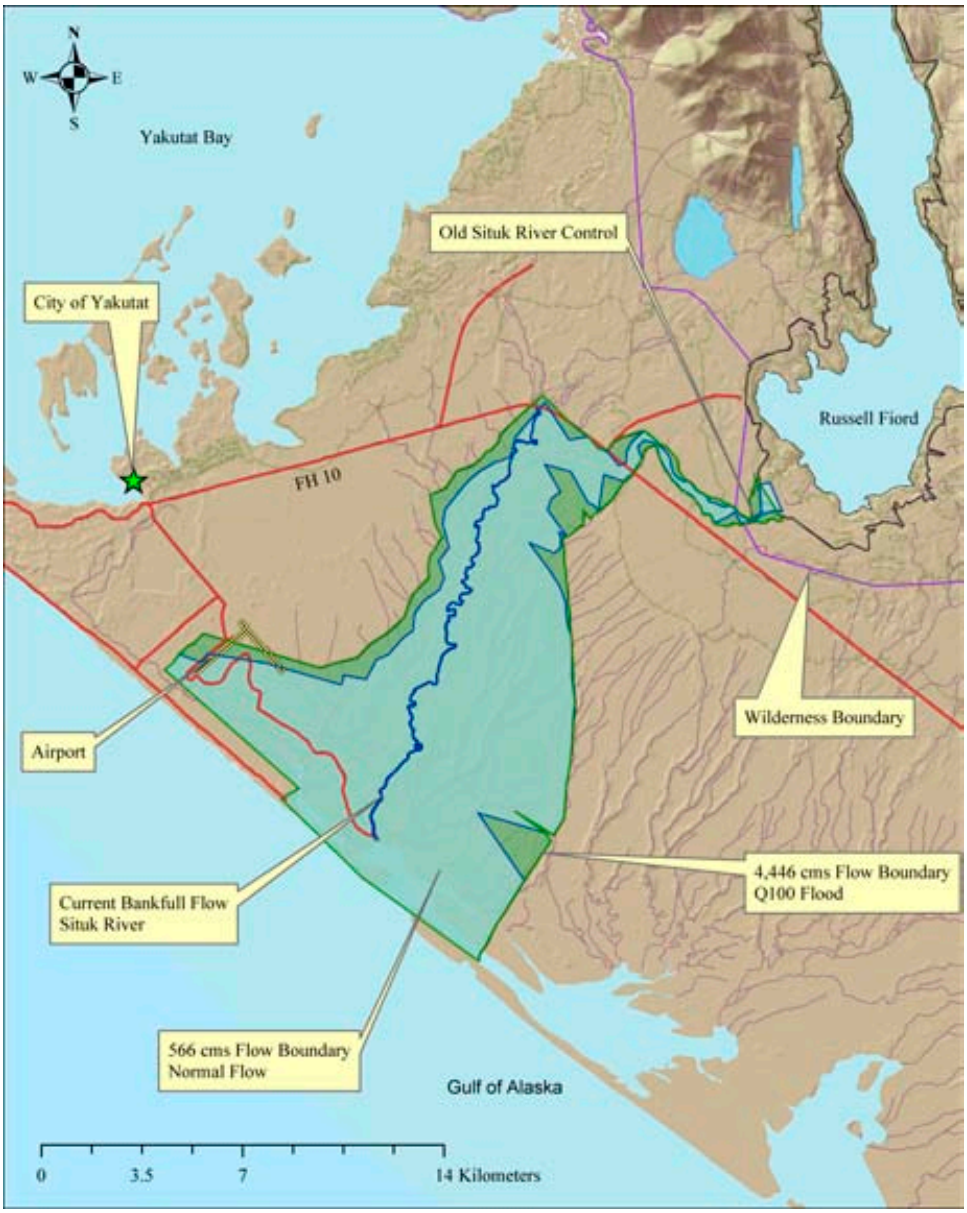


Figure 10. Floodplain inundation map based on HEC-RAS modeling and a rigid boundary assumption.

with the actual hydraulic control being approximately 732 m (2400 ft) downstream (Miles 2004). Along the Situk River control segment, the model produced supercritical flow (Froude # = 1.1 to 1.5) with extremely high velocities of Q_2 = 7.6 m/s and Q_{100} = 10.1 m/s. The two short segments of the Situk River that had supercritical flow are narrow and deeply incised sections within the moraine. These zones of supercritical flow are expected to change channel configurations from scour due to high velocities and water surface slopes. All other sections of the Situk River are, as expected, in subcritical flow regime.

Floodwaters exit the proximal outwash onto the forelands approximately 8 km (5 mi) downstream of the Old Situk River control immediately below FH10 (Figures 1 and 4). At this point topography changes, rapidly becoming less confined with well developed floodplains further downstream. In this area, floodwaters inundate the floodplain to varying widths, depending on magnitude of the flood. For the 2-year (Q_2) and 100-year (Q_{100}) flood return intervals, widths ranged from 0.6 and 1.3 km at FH10, to 7.5 and 8.0 km approximately 9.7 km (6 mi) upstream of the Situk outlet, and 14.4 km (9 mi) for both flows at the mouth of the Situk River (Miles 2004). (Figure 10)

To construct the SMS/Flo2DH model, the dense LIDAR data required "weeding" to a 15-m (50-ft) spacing and required the river corridor to be divided into three sections with a total of 27,000 elements and 56,000 nodes (Miles 2004). Only the Q_{100} flood (4446 cms) was analyzed with the 2-D model, and surface water elevations predicted were similar to those of the HEC-RAS Model (Table 5). The model could not predict a stable solution for a short

Table 5. Comparison of computed water surface elevations at selected sites (Miles 2004).

Location	River Station	Ground Elevation (m)	HEC_RAS $Q_{2.33}$ (m)	HEC_RAS Q_{100} (m)	Flo2DH Q_{100} (m)
Outlet	448.4	- 1.8	3.0	3.0	3.0
Threshold Runway 2	3210.1	3.4	Dry (3.1)	Dry (3.3)	4.6
Threshold 29	5917.2	5.6	5.6	6.1	Dry (5.5)
Mid Yakutat Forelands	6436.3	3.9	5.9	6.4	6.0
Mid Yakutat Forelands	10745.3	7.3	9.2	9.8	10.4
Situk-Old Situk confluence	21785.5	17.3	20.3	21.0	20.3
Forest Highway 10	26068.8	26.3	29.6	30.7	30.3
Area below lake control	32776.2	36.5	40.8	43.5	NC
Russell Fiord	34830.0	NA	49.2	52.6	52.6

915-m section of river immediately above FH10, because of rapidly varied flow conditions and multiple flow paths (Miles 2004).

Geophysical Surveying

Because outflow from Russell Lake will drain through the Old Situk River control notch, it was important to better characterize the subsurface conditions of this feature. In summer 2003, preliminary seismic and ground penetrating radar (GPR) surveys were conducted in the Old Situk River control notch. These surveys were intended to determine if the methods used could differentiate the thickness of the armored channel, fine-grained unconsolidated materials, and potential bedrock surface. The "Notch" is located within the Russell Fiord wilderness boundary, precluding the use of helicopters and all-terrain vehicles. Seismic and GPR surveys were used because the equipment is portable by backpack, and the methods required minimal ground disturbance and vegetation clearing. No calibration data were obtained from drilling because of limited access through the wilderness and funding constraints. This is a concern, because the geophysical assessment is based on interpretation of remotely sensed images, mapped stratigraphy near the southern portion of Russell Fiord (King 1995; Tarr 1909), observed exposures of sediments and surficial armor in the Old Situk channel, and limited drill data on the forelands near Yakutat (Yehle 1979).

The Russell Fiord terminal moraine is geologically complex, since it was probably formed by both tidewater and terrestrial glaciers. This complexity means a single survey method often may not be suitable to characterize the moraine and outwash areas, hence the decision to use both seismic and GPR techniques. Each technique has limitations and strengths, and using both geophysical techniques will improve the subsurface interpretation, as data from each can be compared and correlated.

Ground Penetrating Radar

GPR measures the contrast in dielectric properties of the subsurface materials through which electromagnetic waves of a given frequency (radio waves at 25 MHz to 1 GHz) travel (Philip 2004). As the electromagnetic waves propagate through the subsurface materials, some of the waves are reflected and absorbed, while the remaining waves are transmitted at boundaries between layers of materials that differ in physical properties and dielectric constants. Image resolution and penetration depth vary depending on the antennae frequency with greater penetration depth occurring at lower frequency antennas (25 MHz - 50 MHz) and increased image resolution occurring at higher frequency locations (500 MHz - 1 GHz) (van Overmeeren 1994). A MALA Geoscience RAMAC GPR system with Groundvision V1.3.6 software was used to record and process the data with 50 MHz unshielded antennas for maximum penetration because the unknown depth to bedrock in the notch area. Radio waves pass readily through geologic materials with low dielectric constants such as sands and gravels, while materials with high dielectric constants such as clay-rich layers can attenuate or block the signal entirely (Philip 2004). When large contrasts in dielectric constants exist, strong reflections are observed. This is the primary means of identifying subsurface features, but GPR becomes limited with depth because of reduced signal strength and resolution (Figure 11).

Deriving the GPR wave velocity allows conversion of travel time to depth and development of subsurface stratigraphic models (Philip 2004). Wave velocity in a subsurface materials can be described by the following equation:

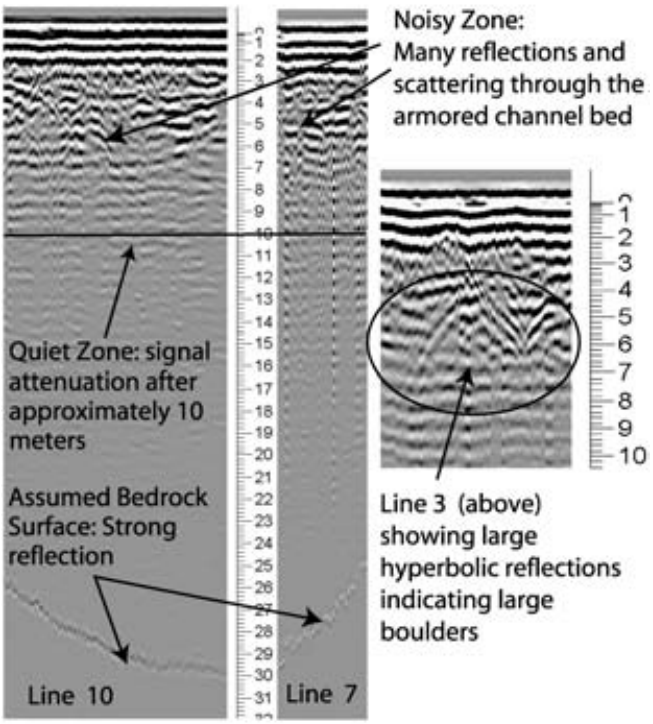
$$V = \frac{C}{\sqrt{e_r}}$$

where: V = velocity (m/s); C = speed of light in free space (m/s); e_r = relative dielectric constant.

Since e_r is unknown, a common midpoint survey was used to determine velocities. The transmitter and receivers are placed around a common midpoint, a measurement is taken and the transmitter and receiver are moved apart incremental distances until several data points are collected. A plot of T^2 vs. X^2 (2-way return time versus distance) is constructed and the slope of a best-fit line yields the squared wave velocity (Beres and Heini 1991). Four common midpoint surveys were performed with an average derived velocity of 64 m/μs with a standard deviation of 5.5 m/μs. This average velocity was used to calibrate the radar images in Groundvision V1.3.6, to determine the depth to reflection events along the GPR survey lines.

Ideally a continuous GPR survey line length should be five to ten times the depth to the surface of interest (bedrock). This was not possible because of the dense Sitka spruce stand in the Old Situk River control survey area. Twelve GPR transects varying from 10 to 40 m where surveyed. The Old Situk channel bottom is very rough, with a predominately boulder armored surface (Figure 12). This type of material made it difficult to find transects where full antenna contact could be made with the ground.

Figure 11. Ground penetrating radar images showing three distinct zones including an upper noisy zone of boulder armor, a quiet middle zone and a lower bedrock surface.



Seismic Refraction

Seismic refraction has been used successfully in various environments and conditions to measure the depths of materials and locations of the subsurface interfaces for engineering, mining and research applications. Seismic wave refraction is the travel path of acoustic waves through an upper medium, along an interface at a critical angle, and back to the surface. These interfaces are interpreted as different materials or changes in density. The propagation of acoustic waves through different mediums follows Snell's law of light refraction, which describes the geometry of wave travel paths, allowing standard techniques to recover layer velocities and depths (Philip 2004).

Seismic data are processed by taking the first arrival of the signal for each geophone, and plotting the return time from acoustic source (sledge hammer) to geophone versus the distance the wave traveled from the acoustic source. The inverse slope of the return time versus distance plot allows the determination of seismic wave velocities through the layers of material.

An acoustic source was applied to both ends of the transects to obtain forward and reverse shot data. This is a standard procedure to test for asymmetric travel times and lateral velocity changes as well as any dip angle of different material layers. A Geometrics SmartSeisSE 12-channel seismograph was used to collect seismic refraction data with Geophone spacing that ranged from 1.5 to 5 m, depending on terrain and length available for each survey transect. Data was processed with SIPWIN software from Rimrock Geophysics. This software allows the operator to input multiple spreads, acoustic source locations, and reverse lines.

Geophysical Survey Results

The GPR images show numerous reflections in the first several meters of depth, followed by a marked absence of reflections below 10 m. Large hyperbolic reflections (Figure 11) indicate large boulders in the channel subsurface that are probably similar in nature to those observed on the channel surface, and located 5 to 7 m below the channel surface. Below 10 m, signal strength is markedly weaker (Philip 2004). Though there is no clear location of the boundary, this signal attenuation is most likely caused by a clay-rich conductive layer. This clay-rich layer corresponds with the upper stratigraphic sections mapped by King (1995) in the lower Russell Fiord area that contained thinly laminated clay, silt, and sand layers at approximately the same depth. A strong reflection is shown in all GPR images at approximately 30 m below the Old Situk River control. The shape and location of this reflector is consistent

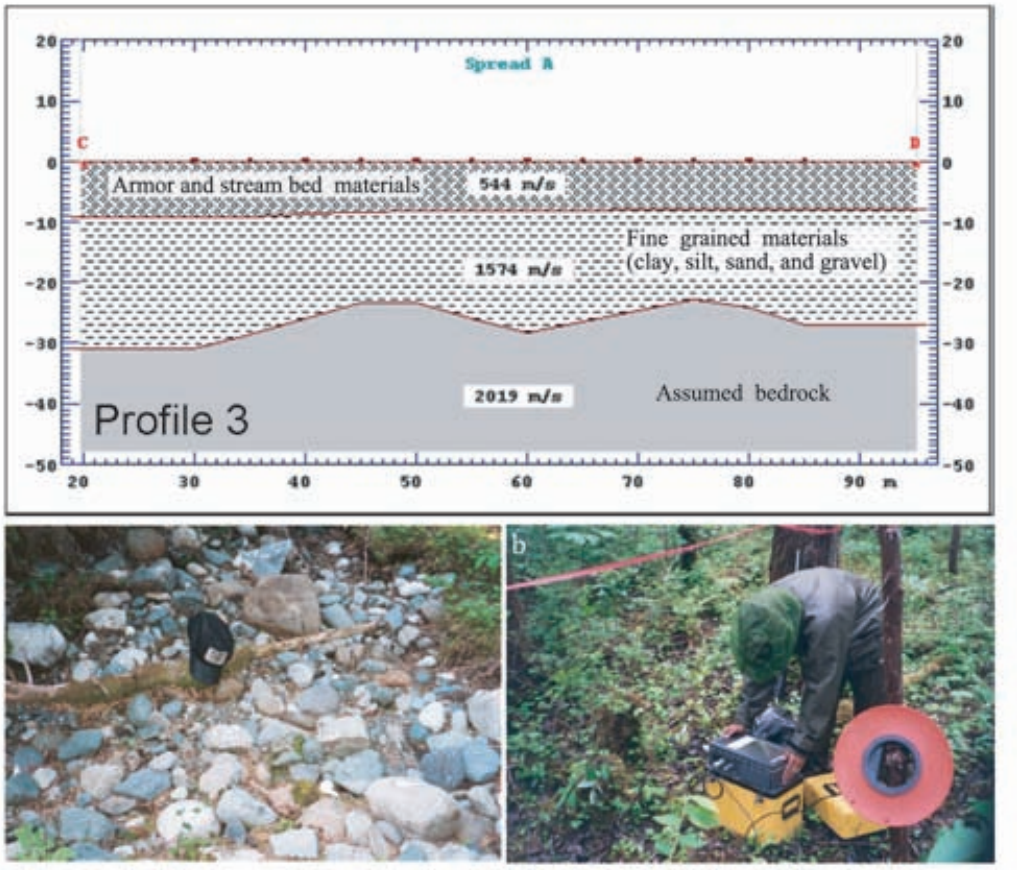


Figure 12. Seismic refraction 3-layer results with recording equipment and existing surface conditions
(a) left – Boulder / cobble armored channel bottom in the Old Situk River Notch. Heavy armor and rough surface of historic channel bottom made GPR surveying difficult and limited in scope.
(b) right – Geometrics SmartSeisSE 12-channel seismograph.

through several of the images and was interpreted as bedrock (Philip 2004). The beginning of Line 7 is nearly coincident with the end of Line 10 in the field (Figure 11) and the radar images show the bedrock reflector at the same depth at this location. The presence of this bedrock reflector is consistent across other GPR lines that cross one another. However, drilling on the moraine demonstrated that the suspected bedrock turns out to be a massive fresh water saturated silt layer of glaciolacustraine origin. The silts are slightly plastic and the high water contentand silt layer gave the strong reflection. It is important to verify and calibrate your remotely sensed data with borehole data to make it more reliable for analytical use.

The seismic data showed results similar to the GPR. The 2-layer partitioning of the data shows a change in density at ~15 m of depth. Only two seismic transects were long enough to give reasonable travel times to derive a three-layer solution. Images generated from three-layer seismic refraction data show refractors occurring at about the same depths, 10 and 30 m (Figure 12). The calculated velocities for the upper layer are <1000 m/s, and range from 1500 to 2800 m/s for the next lower layer. Calculated velocities are within acceptable ranges for near-surface sand, gravel, and clay bodies (Reynolds 1997). The lowest layer of the three-layer seismic case include a refractor around 30 m in depth. The velocities derived for the third layer are 2019 m/s and 4,444 m/s, which are reasonable value for bedrock velocity.

Both GPR and seismic had strong returns occurring in each survey line around 30 m below the surface. The agreement of this layer between GPR images suggests lateral continuity of the strong bedrock reflection, both in the area of high survey concentration and at those survey lines farther west and south (Philip 2004). There is a 1-m change in elevation of the GPR reflector over distances less than 40 m, indicating that reflection occurring as result of interaction with the water table is unlikely, because the slope is too steep for a water table surface (Philip 2004). Field observations in the Old Situk River Notch show evidence of perched water tables within the first few meters of the surface that were not identified on the GPR images because these surfaces were located within the noisy (ground-coupling) zone.

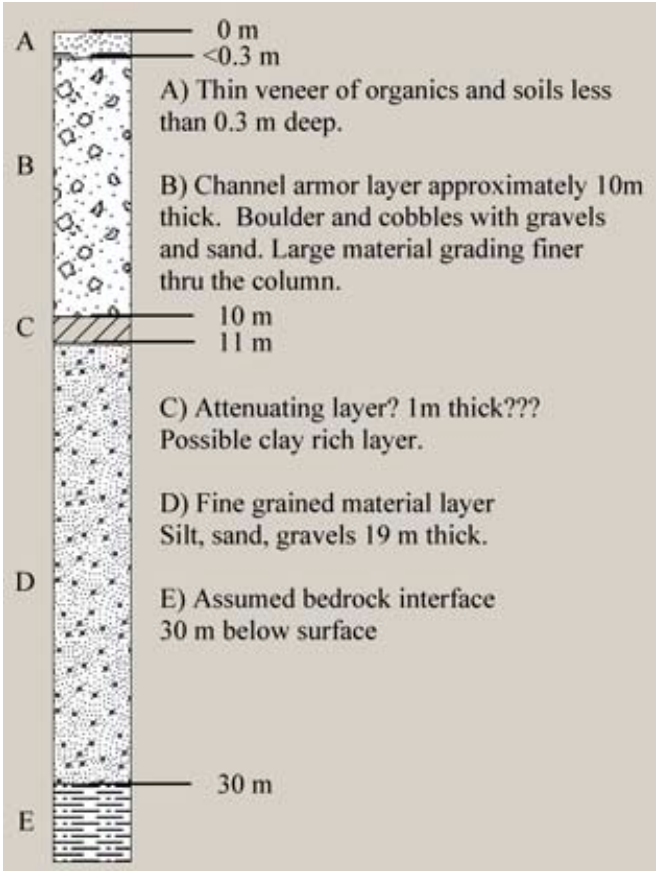
At this point the remotely sensed images are uncalibrated, since no drilling data were collected concurrent with the geophysical surveys. Stratigraphic interpretation is speculative at this time until actual drill data are collected at the Old Situk River control. These preliminary interpretations should not be solely used to make a final determination on terminal moraine or lake control stability. This determination will require a more intensive geotechnical investigation. The general stratigraphic

interpretation provided (Figure 13) is based on current data obtained from field observations, geophysical surveys and research literature.

Layer A (0 - 0.3 m) (Figure 13) is the organic and soils layer, containing forest duff, minor soil development and root mass; Layer B (0.3 - 10-12 m below surface) consists of sediments ranging in size from sand to boulders with large boulder present at an 8 m depth; Layer C (10 - 11 m or possibly greater) is interpreted as a clay-rich layer; Layer D (11- ~30 m) is composed of unconsolidated silt, sand, and gravel; and Layer E (30 m or greater) is interpreted as bedrock.

This stratigraphic interpretation is similar to the general pattern mapped in an exposure 10 km northeast of the Old Situk River control by King (1995). No bedrock was found in that particular stratigraphic section, however bedrock was observed in a waterfall on the northwest portion of the terminal moraine along with suspected bedrock ridges (not verified in the field) along the southeastern portion of the terminal moraine. Also, 14 km downstream from the Old Situk River control the depth to bedrock was 64 m below the surface, supporting the bedrock interpretation at 30 m below the surface from the GPR reflections and seismic refractions.

Figure 13. Interpreted stratigraphic column at Old Situk River control. (Modified from Philip 2004).



Conclusions

Based on the current body of work, we have addressed the following questions:

1. Will all flow from newly formed Russell Lake flow into the Situk River?

The recent modeling work assuming rigid channel boundaries indicates the Old Situk River has the capacity of 7,100 cms before flowing into the Situk Lake overflow. This is 1.6 times the 100-year flood which is assumed close to a 500-year event. If the Old Situk channel were to become clogged with icebergs, water may elevate to a point where some spillover occurs. It is anticipated that most ice will pass through the Old Situk River control or ground out before entering the channel.

2. If flooding occurs, what are the risks to the community and existing infrastructure?

All hydraulic modeling from the recent studies indicates minor impacts on the Yakutat airport area. However, the uncertainty related to debris dams formed during initial overflow or long term lateral migration of the new Situk channel would increase the risk to the airport. These risks can be mitigated by revetment protecting the airport (Miles 2004). All cabins or improvements along the Situk River would be lost during the initial flood.

3. Are the 1986 flow and floodplain assessments valid?

Results from recent work indicate slightly wider inundated areas and water levels than the 1986 study. The recent work indicates low lying portions of the airport could see some inundation at peak flow events. Elevations for the Old Situk River control determined by the 1986 study are within an acceptable margin of error from those determined by the 2002 surveying and LIDAR terrain modeling.

4. Is it feasible and by what method could Russell Lake overflow be diverted into another drainage system?

Additional studies are required to determine feasibility of a channel diversion. The Forest Service and Corps of Engineers (COE) are in the planning stages of a feasibility study, however the moraine stability study is required before feasibility assessment can commence.

5. Is the terminal moraine at the lake outlet stable?

Since flows will be larger than the previous channel forming flows, we anticipate that channel will laterally scour: To what extent is uncertain without additional geotechnical drilling and remotely sensed subsurface data. Additional work is scheduled in 2005.

6. Will the ice dam forming Russell Lake be persistent and stable at the next closure?

At this point in time we do not know when the glacier will close off. An ice stability study is in the planning stages by the COE.

Future Work

Additional work is needed to examine the stability of the terminal moraine and other lake outlet controls, moraine/ice-dam permanence, and feasibility of a diversion channel to protect the economic integrity of the City of Yakutat. Currently the USDA Forest Service is the lead agency in charge of the project. A memorandum of agreement is being negotiated between the Forest Service and the Army Corps of Engineers (COE) to determine the feasibility of constructing a diversion channel and assessing the stability of the Hubbard Glacier ice dam and moraine.

Ice-Dam Stability

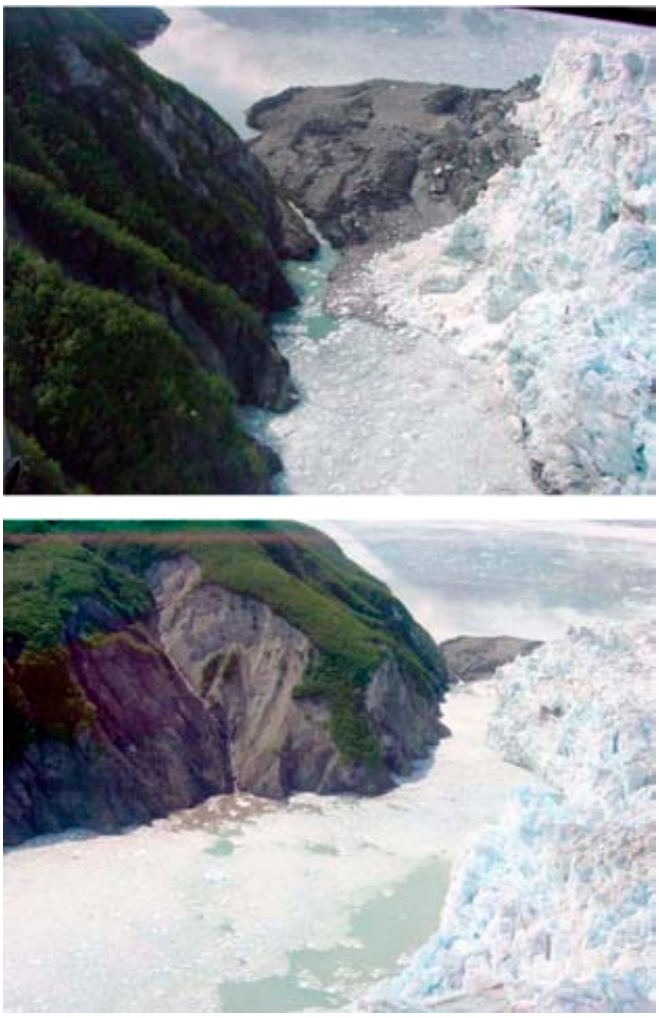
Understanding moraine and ice dam stability is an important consideration before expending large amounts of capital for a diversion project. The 1986 and 2002 damming events were relatively short lived (~3 months) and the configurations of each dam were different. The 1986 ice dam was made almost entirely of ice with small moraines at the edges. The 2002 dam was primarily composed of sediment accumulating in front of the glacier, forming a large terminal push moraine (Figure 14) that continued to build at the same rate the lake level increased. The 1986 and 2002 dams also failed in different manners. The 1986 ice dam experienced a structural failure with rapid calving around the seaward glacier face just before the ice dam broke apart. The 2002 moraine and ice dams failed when the lake overtopped and rapidly eroded the moraine, causing the dam to fail. The moraine dam was overtopped when a storm caused lake level to rise 1.5 m in two days, exceeding the growth rate of the moraine. The formation and failure mechanisms for each of these glacier dams are extremely complex, but provide the important variables that need to be considered when assessing future occurrences and developing mitigation measures.

Ice dam stability is a function of: 1) sediment accumulation around the dam, which reduces the amount of calving; 2) mass of the dam (thickness and height); 3) hydrostatic pressure in the lake, which determines the force acting on the dam and flotation of the dam; 4) bed topography and composition beneath the dam, which determines glacier mobility and subglacial outflow; 5) degree of ice fracturing and interconnectedness of the crevasse system, which determines englacial outflow; and 6) the rate of glacier advance. To better address ice dam stability, additional data will need to be collected that includes bathymetry to monitor sediment accumulation, subacoustic profiling to determine sediment thickness and bed topography, and full waveform LIDAR to characterize the crevasse system. Data collection is currently being planned and will begin in 2005 if funding is available.

Moraine and Lake Control Stability

To address public safety issues from moraine failure or catastrophic incision of the Old Situk River control spillway during large storm events, additional geophysical analysis and geotechnical drilling are required. The USFS and COE are developing plans to collect and assess this data in 2005. Geotechnical drilling, GPR and seismic surveys will be used to characterize the materials (size, composition, distribution, and permeability) of the Russell moraine in order to model the response of those materials to extreme events.

Figure 14. Oblique aerial view of 2002 moraine dam and outflow channel from Russell Fiord. (a) Entire moraine dam and overflow channel; (b) Ice choked channel with glacier face and dam.



Diversion Feasibility

An overflow of Russell Lake into the Situk River will have severe immediate economic consequences to the Yakutat economy, which is almost entirely driven by commercial and recreational fishing on the Situk River. At the request of the City of Yakutat, Alaska congressional delegation, and the Governor's office, the USFS and COE will perform a study to assess the feasibility of constructing a diversion channel. Preliminary work identified several diversion options including: 1) constructing a narrow trench in which the stream is allowed to erode and develop into a self formed channel; 2) designing and constructing a 16.3-km channel from the terminal moraine to the ocean; and 3) boring a 4.8-km diversion tunnel through the mountains that divide Yakutat Bay from Russell Fiord. The magnitude and extremely high costs of a project of this scope warrant a thorough and detailed assessment to determine the feasibility of the different diversion options. The diversion feasibility study will involve design and layout of various channel options, hydraulic modeling of flood events in the new proposed locations, and improved cost estimation. The work will commence in 2005 if funding is available.

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Photo credits: All photos were taken by Tongass National Forest employees during the course of their work.

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Section 4. Valuing the Earth Sciences
Part 3. Air

Overleaf:
Meadow near Thompson Reservoir, Fremont National Forest, south-central Oregon. Photo by Bruce McCammon.

Using the Critical Load Concept to Protect Ecosystems From Acidification

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Sulfur and nitrogen in the atmosphere are major components of acid deposition, and the anthropogenic contribution to these pollutants comes primarily from burning fossil fuel. A *critical load* is a threshold for the loading rate of an air pollutant, such as sulfur or nitrogen, above which a specific deleterious effect may occur. When critical loads are exceeded, loss of acid neutralizing capacity, stream and soil acidification, nitrogen enrichment and direct toxicity can result. Thus, elevated levels of sulfur and nitrogen can have a cascading effect on aquatic and terrestrial resources. Scientific information on ecosystem response to pollutant loading is the basis for calculating a critical load. However, policy decisions must be made to identify the levels of protection desired for selected resources within specified timeframes, and these levels are called *target loads*. Once these policy decisions have been made and the critical and target loads have been calculated, land managers are able to clearly communicate the effect of air pollution on the resources they manage. In this manuscript we present examples showing how Forest Service land managers can use the critical load concept as a communication tool and to protect natural resources from air pollution effects.

Keywords: *air pollution, acid deposition, critical load, atmospheric deposition, ecosystem thresholds*

Introduction

Overviews about acid deposition in the United States have been published by the Ecological Society of America (1999), the United States Environmental Protection Agency [USEPA] (2001), and Hubbard Brook Research Foundation (Driscoll et al. 2001a). While sulfur (S) emissions have declined in the eastern United States, especially in the northeast, nitrogen (N) deposition has continued to increase in the west. Furthermore, ecosystems have been slow to respond to declining emissions. This discussion concerns critical loads for sulfur and nitrogen; however, critical loads are also being calculated for ozone and other compounds.

Air pollutants can travel hundreds to thousands of kilometers before deposition and ecosystem degradation occurs. Therefore, the concerns for acid deposition are local, regional, national and international. Lessons applicable to the United States are being learned from approaches adopted by the European Union, i.e., the International Cooperative Programme on Modelling and Mapping of Critical Loads and Levels and their Air Pollution Effects, Risks and Trends (ICP Modelling and Mapping). In recent years, U.S. partnerships have been expanded to include joint monitoring programs with Canada (Committee on the Environment of the Conference of New England Governors and Eastern Canadian Premiers 2001).

USDA Forest Service Program Responsibility

The Air Resource Management Program of the Forest Service has the responsibility to evaluate resource conditions and to advise decision-makers about the existing and potential effects of air pollution on natural resources. This includes effects on flora, fauna, soils, cultural resources such as petroglyphs and pictographs, geochemistry, water, and visibility. Impacts are predicted for individual ecosystem components and whole ecosystems, often using mathematical models. The Air Resource Management Program also recommends goals and objectives for resource management, and ensures that monitoring programs are designed and implemented.

The program often focuses on specific wildernesses, known as Class I areas, because the Clean Air Act provided special protection for these lands. Class I areas include all international parks, national wilderness areas that exceed 5,000 acres (2023 ha) in size, national memorial parks that exceed 5,000 acres (2023 ha) in size, and national parks that exceed 6,000 acres (2428 ha) in size, and

Furniss, M.J., Clifton, C.F., Ronnenberg, K.L., eds., 2007. *Advancing the fundamental sciences: proceedings of the forest service national earth sciences conference, San Diego, CA, 18-22 October 2004*. PNW-GTR-689. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station.

that were in existence on 7 August 1977. Federal Land Managers (FLMs) have received Congressional direction to "err on the side of protecting the environment" when implementing the Clean Air Act requirements (Senate Report #95-127, 95th Congress, 1st Session, 1977). Critical loads can assist in this effort by helping us clearly communicate the effects of air pollution on resources.

Federal Land Managers have developed consistent methods for protecting resources from air pollution that include developing critical loads. These interagency methods were published as the Air Quality Related Values Workgroup (FLAG) Phase I Report (National Park Service 2000). Accordingly, the FLMs have agreed to:

- Protect the most sensitive resources;
- Ensure no unacceptable change to the resource;
- Use the best science available;
- Develop methods for establishing critical loads;
- Calculate critical loads for areas with adequate information;
- Review and update critical loads; and
- Develop strategies to obtain needed information for other areas.

The Critical Load Concept

A critical load is the amount of pollution delivered to an ecosystem that will not cause harmful changes to physical, chemical, or biological factors (Nilsson and Grennfelt 1988). It is often expressed as kilograms of pollutant per hectare per year (kg ha^{-1} yr^{-1}). The critical load quantifies a cumulative effect to an ecosystem receptor, rather than the effect of single sources of pollution. Loading rates for S and N that are greater than the critical load result in acidification or nutrient enrichment, and are not sustainable.

Critical loads are scientifically determined, and are usually calculated using steady-state or dynamic mathematical models. Examples of steady-state (mass balance) models for acidification are the first order acidity balance (FAB) model (Henriksen et al. 2002) and the Steady-State Water Chemistry (SSWC) model (Aherne et al. 2004). Dynamic models for acidification include Model of Acidification of Groundwater in Catchments, MAGIC (Cosby et al. 1985; Wright 2001) and PnET-BGC, a biogeochemistry model that simulates nutrient cycling, including soil processes such as weathering, cation exchange, adsorption and solution chemistry (Groffman et al. 2004).

The Forest Service, National Park Service and Fish and Wildlife Service have begun calculating critical loads for terrestrial and aquatic ecosystems. These calculations are site-specific (i.e., designed for individual terrestrial and aquatic ecosystems rather than large geographic areas) and apply to the most sensitive resources. Critical loads can also be empirically determined based on field observations showing ecosystem changes or experimental studies that define a dose-response relationship for resource conditions under background or "natural" loading rates compared to conditions under current and predicted (future) loading rates.

A target load is selected to incorporate agency policy, and is similar in concept to a desired future condition. Target loads could be higher or lower than critical loads based on political, economic, social, geographic, or temporal considerations. Intermediate target loads above critical loads could be applied where deposition levels far exceed critical loads (often in the east). Target loads that are more protective than critical loads can prevent degradation in more pristine environments (often in the west), or provide a safety margin for wilderness protection.

Critical and target loads are being used to communicate how pollution is currently affecting natural resources. They are also used to convey what is needed to protect resources that can be affected by air pollution in the future, and to restore resources that have been degraded. These needs can include goals for emission reductions, specific control technologies and mitigation measures.

Discussion

The Forest Service Air Program is concerned about the deposition of nitrogen, sulfur, metals and other toxic substances to both aquatic and terrestrial ecosystems. This concern is due to current conditions and increases in population, energy development and air quality permit activity (and thus subsequent emissions). Acid deposition has contributed to or caused chronic stream acidification from New England into the southern Appalachian Mountains (Driscoll et al. 2001b). It contributes to soil nutrient changes such as calcium and magnesium leaching, or aluminum mobilization, and causes stream acidification (Herlihy et al. 1993). Acid deposition has also affected tree growth in spruce-fir forests. Examples of how acid deposition affects forest resources in the eastern and western United States are presented below.

Case Studies: Eastern U.S. – Chronic Acidification

Historically high deposition, combined with watersheds having low buffering capacity, has resulted in stream acidification and likely changes in soil nutrient status in parts of the eastern United States, including the mountains of Virginia and West Virginia. In some cases of chronic stream acidification, limestone sand (calcium carbonate) is being added to the water as a temporary way to neutralize

the acids so that aquatic life won't be precluded, but it does not solve the problem of high sulfur loading rates. Liming is a common occurrence in West Virginia, and the Forest Service has limed headwater streams in St. Mary's Wilderness in Virginia. Liming, especially in a wilderness area, could be controversial, but the decision is generally made based on a desire to maintain the aquatic biota until sulfur loading is reduced through air regulations.

As a result of acidification, soil chemistry is also degraded and aluminum is mobilized in soil solutions. Nutrient cycling is affected by the leaching of nutrients such as calcium and magnesium, and there is interference with calcium uptake and other root functions. Soil nutrient change may lead to changes in vegetation growth and reproduction (Shortle and Smith 1988; Shortle et al. 1997; Lawrence et al. 2005).

Case Studies: Western U.S. – Episodic acidification, N enrichmen

Episodic acidification is defined as "the short-term decrease of acid neutralizing capacity from a lake or stream. This process has a time scale of hours to weeks and is usually associated with hydrological events" (Irving 1991). Thus, it refers to pulses of acidic input that generally are infrequent, but may cause severe damage. In watersheds where snowmelt is the dominant source of water, episodic acidification most likely would occur during early snowmelt, perhaps before ice-free conditions. This can adversely affect the most acid-sensitive aquatic biota, especially early life stages or reproducing individuals. Some phytoplankton and diatom species are very sensitive to pH and water chemistry, and occur only within a small range of pH or ionic concentrations (Mason 1992). Also, snowmelt can flush aquatic systems rapidly, causing an abrupt change in water chemistry or aquatic biota. Episodic acidification can result in an increase in inorganic-monomeric aluminum concentration, which can be toxic to aquatic life. Headwater streams, vernal pools, and high-elevation lakes with low buffering capacity are particularly susceptible to episodic acidification (Baron et al. 2000).

Fenn at al. (2003) provide an overview of the effects of eutrophication and nitrogen saturation in the western United States. Increases in nitrogen deposition and resultant changes in the nitrogen cycle can affect forest growth, health, and carbon sequestration. Since many aquatic ecosystems in the west are nitrogen limited or co-limited, small additions of nitrogen can increase primary production, especially in high elevation lakes. Lichens, diatoms and nitrate concentrations in water are especially sensitive to nitrogen enrichment. Nitrogen saturation means that ammonium and nitrate concentrations exceed demand, and this affects soil and plant calcium to aluminum ratios, aluminum toxicity, and leaching of base cations. Calcium depletion may affect the ability of trees to withstand stress, decrease the rates of decomposition and other microbial processes (Fenn et al. 1998).

Case Studies: Western US – Rocky Mountains

In 1993 the Rocky Mountain Region of the Forest Service certified impairment of visibility and aquatic ecosystems of Mt. Zirkel Wilderness, Colorado, due to emissions from local power plants. This led to a reasonable attribution study of visibility impairment in 1996-1997. This type of study is designed to identify the sources of air pollution that are affecting a particular site or area. The results of the reasonable attribution study led to revision to the long-term strategy portion of Colorado's State Implementation Plan (SIP) for Class I Visibility Protection, and most importantly, to new control strategies and emission reductions. Although the critical load had not been calculated, direct observations of aquatic chemistry supported the certification of impairment (Turk and Campbell 1987). The background information for certification noted the following conditions:

1. High elevation location along the Continental Divide - elevations of the Mt. Zirkel Wilderness range from 2,256 to 3,712 m and include alpine and subalpine lakes;
2. Watersheds composed of non-reactive bedrock with slow weathering rates;
3. A minimum of 18 lakes in the Mt. Zirkel Wilderness with observed alkalinity < 50 μeq/L, and some lakes with < 10 μeq/L;
4. Precipitation chemistry with higher concentrations of sulfur and nitrogen than background-- evaluation of sulfur isotopes indicate that local sources contribute to this condition;
5. Presence of acid-sensitive amphibians, salmonids and other biota;
6. Conceptual modeling that indicated a loss of buffering capacity had probably occurred in some lakes within the Mt. Zirkel Wilderness;
7. Potential for episodic acidification during snowmelt;
8. Potential response of aquatic ecosystems to increases in acid deposition; and
9. Proximity to sources of nitrogen and sulfur that can be transported to the wilderness by prevailing winds. This included the electric-generating stations in Hayden and Craig, CO, located west and upwind of the wilderness, and sources located at greater distances.

If critical loads were established for Mt. Zirkel Wilderness, then comparisons could be made to deposition loading rates that result from emission reductions. This would facilitate tracking progress toward the desired future condition.

Rocky Mountain National Park has also suffered impacts of atmospheric deposition. The effects of nitrogen deposition on terrestrial and aquatic systems have been subtle, yet critical loads may currently be exceeded (Williams and Tonneson 2000; Wolfe et al. 2003). High elevation watersheds have nitrogen saturation and therefore high nitrate concentrations in surface waters and soils. Changes in hydrogen ion concentration over time and an excess of nutrients during the growing season have occurred. Changes that have been observed in alpine lakes in the park include a shift in phytoplankton species and productivity and a shift in diatom community species compared to 50 years ago (Wolfe et al. 2002). The increase in nitrogen emissions can be attributed to population growth and the associated emissions (transportation, industrial, power generation and agricultural) east of the Colorado Front Range.

How Forest Service Managers Can Use Critical Loads and Target Loads

Critical loads are a way to quantify current resource conditions in terms that many audiences can understand. Some people may understand the concept of exceeding a threshold better than they can understand changes in ecosystem function due to anthropogenic pollution. The target audiences for communication about critical loads include our own decision makers, the regulatory community that sets the rules for controlling air pollution, the regulated entities, and the public whose support is needed for positive change to occur.

A primary use for the critical load concept is in the Clean Air Act's New Source Review process for evaluating permit applications to modify or build sources of air pollution. Critical loads can be used to determine how wilderness conditions would be affected by the new emissions, and to make recommendations to permitting authorities, including states, EPA and tribal governments. Another potential application for the critical load concept is land management planning. Critical loads could be incorporated into goals or objectives in Forest Plans or amendments. Progress toward meeting critical loads could be reported in assessments of resource conditions. For example, the Forest and Rangeland Renewable Resources Planning Act of 1974 (RPA) requires the Secretary of Agriculture to conduct an assessment of the Nation's renewable resources every 10 years. Critical loads could also be used to evaluate project impacts, including cumulative effects, in the National Environmental Policy Act (NEPA) process.

Since critical loads are important tools for evaluating potential impacts from new sources of air pollution, states could adopt them in their State Implementation Plans that describe how clean air will either be achieved or maintained according to national and state standards. Regional Planning Organizations (RPOs) for air pollution control could use critical loads to help measure the rate of progress toward more natural visibility conditions. Current RPOs include the Western Regional Air Partnership (WRAP), Central States Regional Air Planning Association (CENRAP), Midwest Regional Planning Organization, Mid-Atlantic/Northeast Visibility Union (MANE-VU), and the Visibility Improvement State and Tribal Association of the Southeast (VISTAS).

Aquatic Critical Loads

Various regions of the Forest Service have been using the Model of Groundwater Acidification in Catchments (MAGIC) in their efforts to protect ecosystems from air pollution. For example, the MAGIC model was used to evaluate the effects of increasing sulfur deposition on lakes in the Absaroka-Beartooth Wilderness and the Selway-Bitterroot Wilderness of Montana, and to develop critical and target load relationships for Class I areas in North Carolina and West Virginia.

The MAGIC model simulates chemistry of soil solution and surface water to predict average ion concentrations per month and year. It is also being used to help managers establish target loads (Table 1). For example, assume that an acid neutralizing capacity (ANC) of 50 μeq/L indicates no harmful effects occurring to the aquatic ecosystem, and that current sulfur deposition rate is at 10 kg S ha^{-1} yr^{-1}. Site A has current stream chemistry that is well below the pre-1900 condition, indicating that degradation has occurred. A future stream ANC of 50 μeq/L would not restore this system to "natural" conditions, but would allow most aquatic biota to live in the stream. The target load for Site A varies from 1-6 kg ha^{-1} yr^{-1} depending on how quickly recovery is desired. To improve from a current ANC of 7 μeq/L to 50 μeq/L (on the way toward the baseline ANC of 91 μeq/L) by the year 2040, would require deposition to be reduced from the current loading rate of 10 kg S ha^{-1} yr^{-1} to 4 kg S ha^{-1} yr^{-1}.

For site B, stream ANC is less than "natural," but still above 50 μeq/L, indicating that aquatic biota can survive. In this situation more deposition can be tolerated and the ANC will still remain above 50 μeq/L. In both Sites A and

Table 1. Sample target loads, in kg sulfur (S) ha^{-1} yr^{-1}, to meet desired future conditions of stream Acid Neutralizing Capacity (ANC). In this example, the current loading rate is 10 kg S ha^{-1} yr-1 and target ANC is either 20 or 50 μeq/L. Note that for Site A to improve from a current ANC of 7 μeq/L to 50 μeq/L (on the way toward the baseline ANC of 91 μeq /L) by the year 2040, would require deposition to be reduced from the current loading rate of 10 kg S ha^{-1} yr^{-1} to 4 kg S ha^{-1} yr^{-1}.

	Stream ANC (μeq/L)		Target Load for Sulfur (kg S ha^{-1} yr^{-1}) for ANC = 20 μeq/L			Target Load for Sulfur (kg S ha^{-1} yr^{-1}) for ANC = 50 μeq/L		
Site	Pre-1900	Current	Year 2020	Year 2040	Year 2100	Year 2020	Year 2040	Year 2100
A	91	7	5	8	9	1	4	6
B	82	60	43	26	13	15	10	7
C	60	21	2	3	3	6	9	13

B if the desired future condition of ANC is less than 50 μeq/L, then more deposition could be tolerated.

For the stream at Site C, ANC is only slightly above 50 μeq/L in a natural state, and the current ANC has deteriorated to 21 μeq/L. Depending on how long we are willing to wait for recovery, deposition would have to be reduced from 10 kg S ha^{-1} yr^{-1} to between 2 and 9 kg S ha^{-1} yr^{-1}.

The Pacific Northwest Region of the Forest Service has initiated a five year study, the Cascade Wilderness Lakes Project, to calculate critical loads for aquatic ecosystems. The CE-QUAL-W2 model will be modified for biological processes and dilute lakes to calculate the critical loads of ammonia, nitrate and hydrogen ion. CE-QUAL-W2 is a hydrodynamic model developed by the US Army Corps of Engineers (Wells 1997). It is a two-dimensional model for various temporal and spatial scales. The revised model will characterize hydrologic, biologic and chemical variables of the lakes. First the water budget will be calculated. Then the conservative ions such as chloride and the reactive ions such as nitrate, ammonia and phosphate will be incorporated. The major biological components that affect the reactive ions include phytoplankton, zooplankton, benthos, and fisheries. CE-QUAL-W2 incorporates hydrodynamic factors that most acid-rain related models do not, and also includes critical biological processes. Thus, both acidification and eutrophication will be modeled.

The Pacific Southwest Region of the Forest Service is developing a screening procedure for identifying acid-sensitive lakes based on catchment characteristics. This project includes predicting ANC for high-elevation lakes in California's Sierra Nevada mountains using conceptual and general linear models (Berg et al. 2005). The catchment characteristics being studied are: catchment-to-lake area ratio, lake perimeter-to-area ratio, carbonate lithology, lake headwater location, and geochemistry.

Terrestrial Critical Loads, Cooperation with Research Scientists

Air Program Managers from National Forest Systems are cooperating with scientists from Forest Service Research to better quantify critical loads. One project is developing a protocol for estimating terrestrial critical loads in Class I areas and collecting essential data at an eastern and western demonstration site. The purpose of this project is to summarize the methods available for calculating terrestrial critical loads and to form a strategy for estimating critical loads in all Class I areas. The eastern demonstration site is at Fernow Experimental Forest, West Virginia, in the Monongahela National Forest. This site contains high elevation spruce-hardwood forest, and receives loading rates of approximately 8 kg N ha^{-1}yr^{-1} and 18 kg S ha^{-1}yr^{-1}. The western site is Kings River located in the Sierra National Forest of California. The effects of nitrogen deposition from San Joaquin Valley sources on ponderosa pine (*Pinus ponderosa*), Sierran mixed conifer, fir, and alpine meadows are a concern. We hope that this collaboration will result in a broader network of air pollution study sites that is linked to the Forest Health Monitoring Program. Once the critical loads are calculated and entered into a spatial database, a map of critical loads for federal lands could be generated.

Conclusion

Critical loads are exceeded when episodic or chronic acidification has been documented or nutrient enrichment is occurring. Where critical loads are not exceeded, antidegradation is a concern, especially since the Wilderness Act states that wilderness is to be "protected and managed so as to preserve its natural conditions." It is possible that unacceptable effects may occur when critical loads are approached, if uncertainties have not been quantified or a

safety margin has not been incorporated.

Three things are needed to enable federal land managers to move forward with the critical load concept. First, we need to acquire site-specific data for soil chemistry, water chemistry and deposition rates. Second, decisions have to be made regarding the empirical data or models used to calculate critical loads. Finally, we need to complete the demonstration projects that are currently underway to collect data to populate a variety of models that can be used to calculate critical loads. Although the Air Resource Management Program is currently funding collaborative projects with Forest Service Research and Development to implement the critical loads concept, additional cooperation with researchers will be required to establish critical loads for all Class I areas.

Scientific information on ecosystem response to pollutant loading is the basis for calculating a critical load. However, policy decisions must be made to identify the levels of protection desired for selected resources within specified timeframes, the target load. Once critical and target loads have been calculated, land managers will be able to clearly communicate the effect of air pollution on the resources they manage.

Critical and target loads can be used to better communicate how pollution is affecting natural resources and what is needed to protect and restore them. The audiences for this communication are:

- Our own decisionmakers;
- The regulatory community that sets the rules for controlling air pollution; and
- The public whose support is needed for positive change to occur.

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The Potential Effects of Acid Deposition: What's a National Forest To Do?

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The mid-Atlantic region, in which the Monongahela National Forest lies, receives some of the highest rates of acidic deposition in the country. As a result of the substantial acidic inputs and growing public concern with the problem, the forest is addressing this topic in its current forest plan revision as it relates to potential effects to water quality, aquatic habitat, soil nutrient status, and forest productivity. Plan revision is approximately fifty percent complete, and the revision team is now in the initial stages of designing a multi-level monitoring plan to collect and compile data to evaluate short- and long-term effects of continued deposition and land management activities on soil and water resources. This paper briefly describes the state of the science of acidic deposition effects on land productivity, and their management implications for the Monongahela. Additionally, risk assessment analyses for the forest and monitoring strategies to continue data collection and database expansion are described. Preliminary soil chemistry data from watersheds highly sensitive to acidic inputs and base cation loss on the Monongahela National Forest are presented to illustrate the importance of including this problem in forest plan revision and project level planning, and to show how the team incorporated available data in its decision processes.

Keywords: *acid precipitation, air pollution, calcium, soil productivity, resource management*

An Introduction to Acidic Deposition and Its Effects

Acid deposition occurs when sulfur dioxide and nitrogen oxides react with water and oxygen in the atmosphere to form acidic compounds, which then fall to earth in either a dry or wet form (EPA 1998). The northern half of West Virginia has long been recognized as an area of high acid deposition. Total annual sulfur deposition on the Monongahela National Forest is the late 1980s ranged from 19 kg/ha at the lower elevations, to 26 kg/ha at high elevations (Adams et al. 1991). Few areas of the United States showed higher sulfur deposition than was found on the Forest. Current monitoring results show that wet sulfate deposition has decreased 29 percent in the mid-Atlantic region as the Acid Rain Program emission reductions have been implemented (EPA 2004). In fact sulfur deposition at Parsons, West Virginia (a lower elevation monitoring site) was down to 12 kg/ha in 2000 (*http://www.epa.gov/castnet/charts/par107ts.gif*, accessed February 2006).

Bases, such as calcium and magnesium, are also found in atmospheric deposition, and these compounds could help offset some of the negative effects of acid deposition. However concentrations of bases in atmospheric deposition have also decreased. For example, at Parsons, West Virginia, annual calcium deposition has decreased from about 4 kg/ha in 1979 to just over 1 kg/ha in 2003 (*http://nadp.sws.uiuc.edu/trends/trendRequest.asp?site=WV18*, accessed February 2006).

Soil acidification can be seen as a balance between acid inputs and mineral weathering (Binkley et al. 1989). Therefore, when soil acidifying processes (such as acid deposition and forest growth) exceed mineral weathering inputs of base cations, acidification occurs.

Changes in soil chemistry are difficult to quantify due to the long periods of time over which they occur, the complexity of the factors controlling them (Markewitz et al. 1998), and the inherent spatial heterogeneity of soils. A study of soil acidification in the Calhoun Experimental Forest in South Carolina using soil data from 1962 to

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1990 showed that the upper 60 cm of soil acidified at an accelerated rate due to acidic deposition while the naturally acidifying processes of biomass accumulation, root and microbial respiration, and organic matter incorporation also occurred (Markewitz et al. 1998).

Soil acidification increases cation leaching, decreases soil pH and base saturation, increases the N content of trees, and negatively affects many biological processes (Adams and Kochenderfer 1999). Adams (1999) found that Ca losses were particularly large when a forest soil becomes acidified. A nine-year acidification study at Bear Brook watershed in Maine showed accelerated loss of base cations from the soil, which subsequently leached into streams (Fernandez et al. 2003). Base cations also are removed from the soil by plant uptake, leaching, and harvesting (Gbondo-Tugbawa and Driscoll 2003).

The major base cations in atmospheric deposition, soils, and geologic materials are Ca^{+2}, Mg^{+2}, Na^{+}, and K^{+}. Of these Ca and Mg typically provide the greatest contribution to buffering because they usually are more abundant than K and Na and they possess a greater positive charge. Mineral weathering of soil and geologic materials control base cation availability over the long term, but the major short-term sources of base cations to soil are litter fall and atmospheric deposition (Johnson and Todd 1990; Jenkins 2002). Slope position affects base cation supplies because litter accumulates more on lower slope positions than on higher ones (Johnson and Todd 1990).

The National Acid Precipitation Assessment Program (NAPAP 1998) indicated that base cation depletion may affect the health of forest ecosystems. The health of eastern hardwood forests has not yet shown adverse effects from acid deposition on a broad scale (NAPAP 1998). However, mortality and decline of red spruce (*Picea rubens*) at high elevations in the Northeast have been significant and provide the greatest evidence of forest damage by acidic deposition (NAPAP 1998). Sugar maple (*Acer saccharum*) is also a species of concern (Likens et al. 1996; Bailey et al. 2005), since it is particularly sensitive to decreases in Ca and Mg soil pools.

Existing Conditions on the Monongahela National Forest

Aquatic Resources

The Monongahela National Forest (MNF) is the fourth largest national forest in the northeast and contains the headwaters of five major river systems: the Monongahela, Potomac, Greenbrier, Elk, and Gauley Rivers. Twelve river segments on the MNF are being studied for potential classification in the National Wild and Scenic Rivers System. Rivers and streams across the forest include more than 900 km of coldwater trout streams and provide an additional 200 km of warm water fishing. Although the State of West Virginia manages many stream segments as put-and-take trout fisheries with seasonal trout stocking, some estimates suggest 90% of West Virginia's native brook trout (*Salvelinus fontinalis*) streams occur on the MNF.

Healthy, reproducing trout populations and their associated communities have various habitat requirements. Water quality in rivers and streams is an important consideration when establishing management priorities on the forest to provide for the maintenance of healthy aquatic ecosystems. Water chemistry is one component of water quality and represents a fundamental building block for aquatic communities. For example, harmful effects to certain aquatic organisms, such as reduced reproduction, begin to occur as pH values in streams fall below 6.0; detrimental effects, such as mortality, begin to occur as pH falls below 5.0. Also, values less than 50 for acid neutralizing capacity (ANC) indicate a stream system is acid sensitive, values less than 25 suggest a system likely experiences episodic acidification during storms, and negative ANC values indicate a system is already acidic (*http://www.dep.state.wv.us*).

Water chemistry of streams and rivers is the by-product of dynamic nutrient pathways and chemical processes occurring within the contributing watershed environment-atmospheric, terrestrial, and biological. The significance of water chemistry is perhaps no more apparent than in aquatic ecosystems composed of diverse geology, particularly when these systems are exposed to acid deposition. Watersheds across the MNF exhibit a wide range of surficial geologies that have variable capacities for neutralizing acid inputs.

In 2001, the MNF initiated an effort to establish forest-wide monitoring of water chemistry properties in streams across the forest. Sample sites were strategically located to allow monitoring efforts to increase the level of understanding of the relationships between water chemistry and various local environmental factors including the geologic composition of contributing watershed areas, rates of acid deposition, and supported aquatic communities. Results of water chemistry monitoring from fall low flow and spring high flow sampling demonstrated a high degree of variability between sample locations and sample periods, as expected. For example, measures of pH ranged from 3.88 to 8.2 (mean = 6.8) during fall 2001 samples (low flow conditions) and from 3.73 to 8.55 (mean = 6.4) during spring 2002 samples (high flow conditions). Measures of ANC ranged from -166 to 2868 (mean = 407) during fall 2001 samples and from -195 to 1599 (mean = 135) during spring 2002 samples.

Variation in measures of pH and ANC between sample locations was largely explained by the variable capacity of a watershed's geology to neutralize acid inputs. Variation in measures of pH and ANC between sample periods at a given site was largely explained by the different stream discharge conditions. Except where acid mine drainage is an issue, water samples collected at low flow conditions during the late summer to early fall period are typically expected to exhibit higher pH and ANC values due to the greater influence of groundwater on stream flows, as compared to spring high flow conditions when direct inputs from melting snow and precipitation (i.e., acid rain) have greater influence.

State water quality monitoring programs are also documenting cases of stream acidification in West Virginia. In an attempt to mitigate impacts of stream acidification on native trout streams and the recreational fishing opportunities they provide, the state has developed and refined a program to treat acid impaired streams with limestone sand. Limestone sand is currently being applied to acid impaired streams on the forest and across the state to help neutralize acidity. Forest monitoring results show water chemistry downstream from treatment areas exhibits notable increases in ANC, pH, and Ca when compared to untreated water upstream. Although this action helps mitigate against many symptoms of stream acidification within the effective stream treatment zone, it does not affect the underlying cause of the condition to address risks to aquatic and terrestrial ecological processes and functions that extend beyond the treatment zones (McClurg et al. 2004).

Parent Materials

Soils of the MNF have developed from sedimentary rocks and are divided broadly into two zones that have different soil patterns, the Allegheny Plateau Province and the Appalachian Ridge and Valley Province. The Allegheny Plateau Province has relatively flat-lying bedrock. Soils on the Plateau are characterized by high moisture content, thick humus, acidic conditions, and low nutrient levels. Timber productivity in this region of the forest is more a function of soil moisture than fertility. In the Ridge and Valley Province, bedrock is folded, faulted, and fractured. Rock outcrops and escarpments are common. Soils are often shallow, shaley, droughty, and not highly productive. Most MNF soils exhibit moderate to severe erosion potential, and high hazard areas exist in areas of shale and limestone.

Elevation on the MNF ranges from 274 m to 1482 m. Rain shadow effects caused by slopes of the Allegheny Front result in an average of 153 cm of annual precipitation on the west side of the MNF and about half that amount on the east side. Soils develop under mesic and frigid climatic temperature regimes where annual air temperature is 9°C. Frigid soil temperatures usually exist above 915 m. The mountainous landscapes on the MNF result in steeply sloping topography, with many areas having slopes of 30% or greater.

Soils on the MNF have been subject to the effects of abusive cutting and burning in the late 1800s and early 1900s. Logging without regard to resource protection contributed to damaging floods, severe erosion and topsoil loss, and pollution of streams. Severe fires further increased erosion by burning so hot that soil carbon was lost to the atmosphere. Soil productivity in some areas on the MNF is irretrievable in human time frames. Although there has been some recovery for the soil resource during the past century, many forest soils on the MNF still have only thin surface horizons, which now limit their ability to neutralize acidic inputs.

Air Quality

Historic atmospheric deposition, particularly of SO4 (sulfate), from the Ohio River Valley and other Midwestern areas has contributed to acidification of streams and could affect soil productivity in parts of the MNF. Evidence of nutrient depletion in certain soils on the MNF has been found (Jenkins 2000; Schnably 2003; C. Sponaugle personal communication). Sulfate also is a primary contributor to visibility impairment or regional haze.

Sulfates are formed from atmospheric emissions of SO_2 (sulfur dioxide) from power plants and other industrial sources. The MNF receives industrial emissions primarily from sources in Ohio, Pennsylvania, Indiana, Illinois, and West Virginia. These states continue to produce some of the highest sulfur dioxide emissions in the nation, despite significant emissions reductions made during the 1990s. The combination of high emissions and limited buffering capacity of certain geologies and soils on the MNF have increased stream water acidity and possibly contributed to soil nutrient depletion.

The 1990 Clean Air Act Amendments (CAAA) Acid Rain provision mandated significant reductions in SO_2 emissions in the 1990s. The greatest percentage decreases in atmospheric SO_4 concentrations occurred in the eastern states north of Tennessee and North Carolina, and the highest absolute decrease (73%) occurred at the Bearden Knob air monitoring station on the MNF (often referred to as Dolly Sods in the literature) (Malm et al. 2000). These reductions are attributable to large reductions in SO2 emission at sources upwind from the MNF (between 1990

and 1999: Indiana: -44%, Ohio: -35%, West Virginia: -34%, Kentucky: -29%, and Illinois: -13%). In these five states, SO_2 emissions decreased by 2.5 million tons between 1990 and 1999.

Downward trends in SO_2 emissions and SO_4 deposition will affect MNF resources positively; however, they may not be enough to reverse all of the degradation that already has occurred.

According to modeling projections made by the Southern Appalachian Mountains Initiative (2002), reductions in SO_2 emissions resulting from the 1990 CAAA will not be enough to restore the chemistry of acidified streams to levels where aquatic life can thrive. Additional emission reductions will be needed to restore acidified streams and natural atmospheric visibility conditions.

The Occurrence of Acid Conditions and Acid Sensitivity on the MNF

Soil water and stream acidification are real phenomena that have been shown to occur in West Virginia. Long-term, increasing losses of base cations to stream water due to ambient acid deposition have been documented in stream water on a control watershed in the Fernow Experimental Forest, which is located in the MNF (Edwards and Helvey 1991). Other watersheds on and near the Fernow Experimental Forest that have been artificially acidified with S and N to determine effects on soils and stream water have shown mobilization of base cations in soil and consequent leaching to stream water and substantial reductions in the acid-neutralizing capacity of soil water (Edwards et al. 2002a, 2002b).

Otter Creek Wilderness is one of the most popular recreation areas in the MNF, and because it also is designated a Class I area[1] it has been intensively monitored to characterize the extent of acidic water, soils, and geology. Approximately 71 percent of the Otter Creek Wilderness is underlain by geologic material of the Pennsylvanian Epoch. The dominant geology is the Pottsville Group, which generally has very acidic strata. Many of the sandstones associated with Pottsville geology are resistant to weathering, and weathered materials produce very acidic soils with pH values ranging from 3.5 to 4.6. Only small base cation reserves exist to be weathered to the soil, so there is little to no acid-neutralizing capacity available (Jenkins 2002).

Total Ca and Mg levels measured in high-elevation soils underlain by Pennsylvanian geologic material in Otter Creek range from 513 to 1095 kg/ha and 3896 to 6662 kg/ha, respectively (Jenkins 2002). Total soil reserves of these base cations are much less than those in similar forest ecosystems. For example, Mann et al. (1988) and Federer et al. (1989) calculated average total stores of Ca in other Northeastern forest soils to be approximately 4 to 20 times greater than those in Otter Creek. Otter Creek soils also have elevated aluminum, which poses a threat to forest productivity and exacerbates soil nutrient deficiencies (Jenkins 2002). Jenkins (2002) found that most of the soils studied from Otter Creek have a Ca:Al molar ratio of less than 0.2 along with a base saturation of the effective cation exchange capacity (BSECEC) of less than 15%. This was interpreted to mean that these forests are at about a 100% risk for decline based upon work by Cronan and Grigal (1995). High Al concentrations are present in soils supporting declining spruce stands in northeastern United States and are commonly thought to inhibit Ca uptake and transport (Shortle and Smith 1988). Red spruce (Picea rubens) is a dominant tree species growing in the high elevation soils of Otter Creek Wilderness, and it is an important ecosystem component for several rare or listed species on the MNF.

While Otter Creek has been intensively monitored, more widespread continuous monitoring of soils around the MNF has taken place since before the 1970s through cooperative efforts between the USDA - Natural Resource Conservation Service (formally the USDA Soil Conservation Service) and the MNF to develop and publish county soil survey reports. While the data are not complete and the soil pits from which the data were obtained were not always located in areas of interest to the MNF, the soil data were collected across multiple geologies over time and are very useful in helping to assess soil productivity.

Since 2001, additional intensive soil data collection continues to be done outside of Otter Creek Wilderness to develop baseline soil chemistry data across the MNF, especially in areas assessed by the Soil Nutrient Sensitivity Map (described in the next section) to be highly sensitive to acidification. More than 500 soil samples have been collected across varying soil types, landscape positions, and varying aspects and analyzed for physical and chemical characteristics. Preliminary results show that soils in sensitive areas are affected adversely by acid deposition.

[1] The Clean Air Act Amendments (CAAA) of 1977 established the prevention of significant deterioration (PSD) program. These amendments designated specific Wildernesses and National Parks over a certain size as Class I areas. These federally mandated Class I areas are provided with an additional measure of protection under Title I, Part C of the CAAA, which states that one purpose of the Act is "to preserve, protect, and enhance the air quality in national parks, national wildernesses". Further more, the PSD regulations charge the federal land manager with the "affirmative responsibility to protect the air quality related values (including visibility) of any such lands," and to consider "whether a proposed source or modification would have an adverse impact on such values" (40 CFR 51.166 (p)(2)).

Base saturation values often are below 15 percent and Ca:Al ratios are less than 1.0 for soils found on ridgetops and benches. Some south-facing cove soils have soil Al levels that might indicate possible toxicity for vegetation. The data are just now becoming available and the interpretations should be ready for the 2006 forest-wide monitoring report.

Approaching Acidic Deposition Effects in Forest Plan Revision

Soil Nutrient Sensitivity

Acidic deposition and its effects on soil productivity arose as a new issue during the scoping phase of Forest Plan Revision in 2003. After a review of the literature, discussions with research scientists, and discussions with internal interdisciplinary team members, the issue was brought forward as a primary issue during Forest Plan Revision. Soil productivity issues and mitigations on disturbed lands were addressed in the Standards and Guidelines of the 1986 Monongahela National Forest Land Management Plan (USDA Forest Service, p. 79 and Appendix S), but there was no consideration of soil productivity losses caused by base cation depletion on undisturbed soils.

To address this issue in the forest plan revision, areas on the MNF susceptible to potential effects of acid deposition first were identified and mapped using a multi-step process. The initial map data layer in the analysis was the geology layer; geology was ranked as high, medium, or low sensitivity based on the geochemistry from county geology documents and personal knowledge of MNF geologists. Geology known to have substantial sources of alkalinity was assigned low sensitivity because it could provide a reasonable level of buffering capacity to soil. Geology known to have only trace amounts of alkaline producing minerals was rated as high sensitivity. Geology known to have a moderate amount of alkaline producing minerals or interbedded seams of calcite or alkaline shale received a rating of medium sensitivity due to the uncertainty about the amount of weatherable alkaline minerals or the depths of the material from the rooting zone.

The second map data layer included in the analysis was the stream layer of the MNF. Streams were analyzed for water quality impacts from acid rain and mine drainage using the current 303d listing from the state (*http://www.dep.state.wv.us*). Sources of acidity were identified in the stream layer. The correlation between geology and stream water quality is strong. Where high geologic sensitivity exists on the MNF, acid rain impaired streams are present. Some streams flow through areas of low sensitivity but remain impaired due to the large effect from upstream geochemistry, soil chemistry, and precipitation chemistry.

The third map data layer was SO_4 deposition across the MNF. Deposition data were generated by Dr. James Lynch at The Pennsylvania State University. Areas of the MNF that received high amounts of wet SO4 deposition rates were identified with this map layer (Figure 1). Other forms of SO_4 deposition also occur which are not depicted in this map, such as dry deposition and fog deposition. Some experts estimate that dry deposition may be at least as much as the wet deposition totals. Fog deposition is often not even accounted for in measurements and may be greatly underestimated at the higher elevations. Therefore, this map captures only a portion of actual deposition rates.

The combination of these three analysis layers provides an overall picture of acid deposition sensitivity across the MNF (Figure 2). In general, an area with highly sensitive geology, high rates of sulfate deposition, and acid rain impaired streams would indicate potential soil productivity problems in the surrounding watershed. An area with moderate sensitivity, high rate of sulfate deposition, and a non-acid impaired stream may indicate an area that may not be susceptible. However this area would require an assessment of any monitoring data and a site visit by a specialist. This acid deposition sensitivity layer (Soil Nutrient Sensitivity Map) is being used at the Forest Plan Revision level, the forest-wide level for analyses, and at the watershed assessment level.

Forest-wide Monitoring

While the Soil Nutrient Sensitivity Map provides a useful way to estimate a soil's sensitivity to acidic inputs or acid-causing situations (i.e., a risk assessment), the map does not provide a direct measure of soil productivity, which is very important for forest level management. Soil productivity can be predicted using available soil chemistry and acid deposition data. The MNF currently is deciding on the approach that it will take to assess soil productivity from a Forest Plan perspective. These decisions have not been finalized, but from the general direction of approach it now appears that following the initial risk assessment determined from the Soil Nutrient Sensitivity Map, specific chemical analyses of soil and water will be required for areas at high risk of nutrient depletion before management activities that might remove base cations are approved (e.g., timber harvesting or ground disturbance). Currently

Text continues on page 435.

Figure 1. Wet sulfate deposition levels across the Monongahela National Forest.

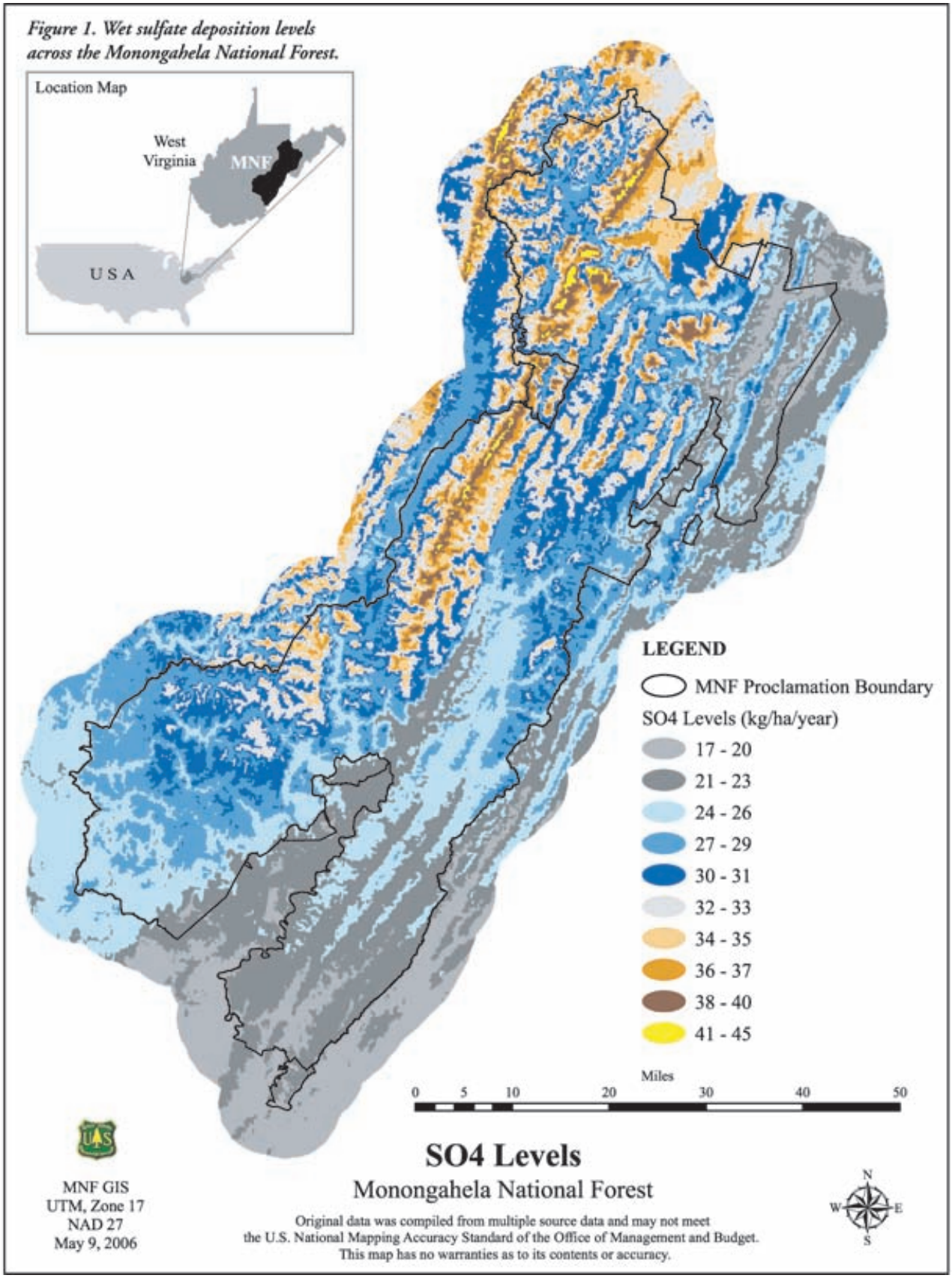
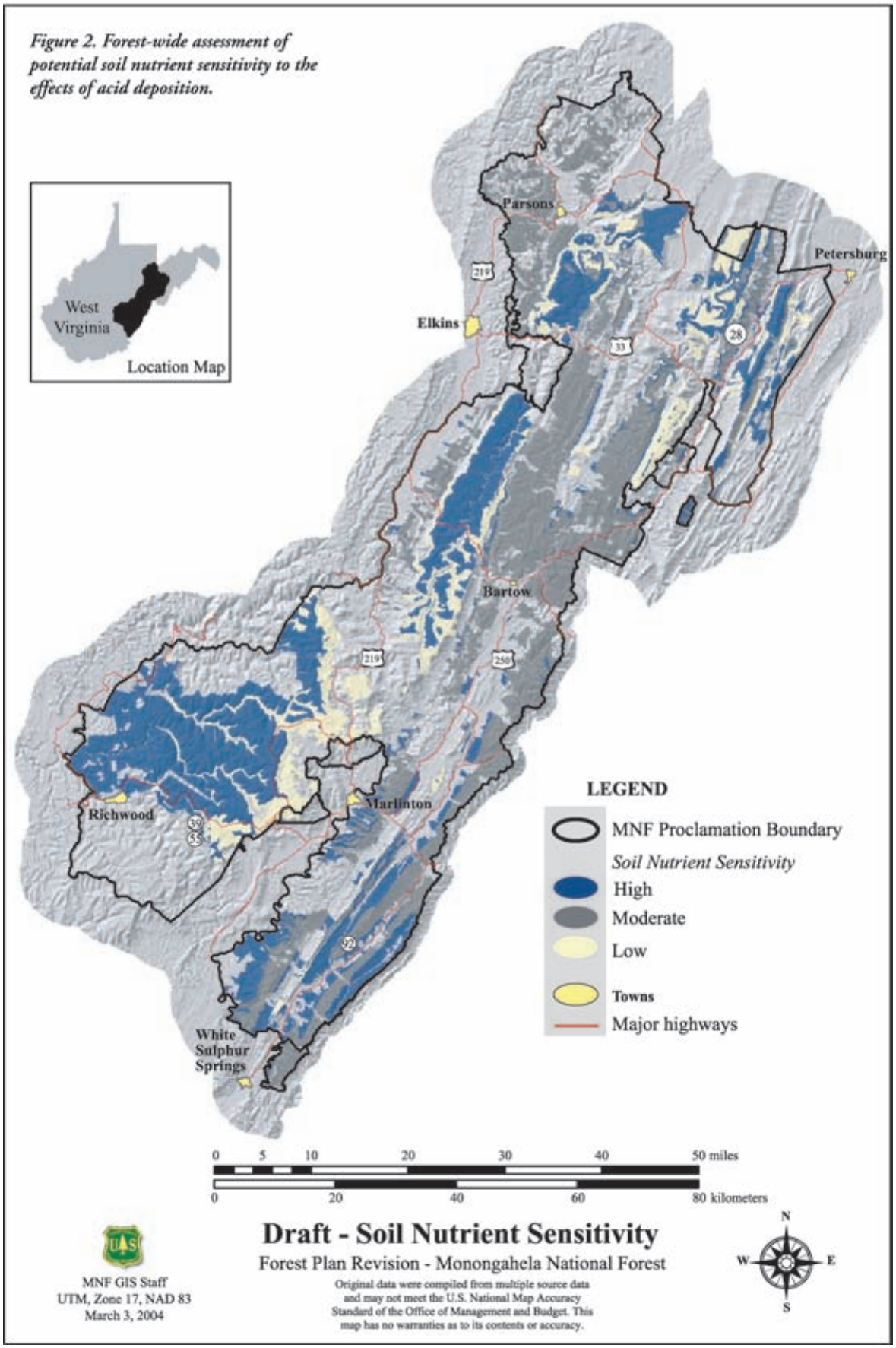


Figure 2. Forest-wide assessment of potential soil nutrient sensitivity to the effects of acid deposition.



the chemical criteria being considered for monitoring soil productivity of sensitive areas are: 1) soil Ca:Al ratios; 2) soil base saturation; 3) effective cation exchange capacity of the soil; 4) acid neutralizing capacity (ANC) of the stream water within subwatersheds (Hydrologic Unit Code [HUC] levels 6 and 7); and 5) the presence or absence of vegetative indicator species in the understory.

Critical Loads

Ultimately, the ability to calculate an array of critical loads with regard to acidic deposition and forest management alternatives is the goal that the MNF would like to achieve; critical loads provide quantitative answers to the "So what do soil conditions or acidity mean in terms of forest management?" question. A critical load is that amount of pollution below which no adverse impacts will occur. Currently, the MNF does not have all the necessary data to determine critical loads for the many combinations of deposition, geology, soil, and water chemical characteristics present on the MNF. Data collected within the MNF's various resource staff areas, routine monitoring programs, and data that will be collected as a result of the monitoring program set forth in Forest Plan Revision will be used to evaluate and refine current conditions using the Soil Nutrient Sensitivity Map and eventually to develop critical loads. The necessary stream, soil, and soil water data have been collected from a few sites on the MNF to calibrate the MAGIC Model (Model of Acidification of Groundwater in Catchments), which will be used to calculate critical loads. Determination of critical loads for the many types of sites on the MNF will provide a tool that land managers can use to better protect resources; land managers then can assess how various land management alternatives might affect desired future conditions based on an array of critical loads. At the regional or national scale, policy makers can use critical loads to determine what levels of pollutant reductions would be needed to achieve desired future conditions on larger landscape or at regional scales.

Other National Forests in Region 9

Many forests in the northeastern portion of the eastern region of the US Forest Service (areas east of the Ohio River basin and northeast of the Great Lakes) are experiencing similar effects on resources from acid deposition. The White Mountain National Forest, in New Hampshire and Maine, has assessed resource effects of acid deposition and has developed a scientific approach to effects monitoring and management of those affected resources. Research at the Hubbard Brook Experimental Forest, located in the White Mountain National Forest, indicates that long-term depletion of forest soil Ca could affect forest productivity, health, or composition, particularly of red spruce and sugar maple (Federer 1989). Currently, the Green Mountain National Forest in Vermont is assessing soil productivity in relationship to acid deposition sensitivity.

Studies on the Kane Experimental Forest and the Allegheny National Forest in northwestern Pennsylvania show that sugar maple is sensitive to soil Ca levels (Bailey et al. 2004; Horsely et al. 2000). Soils in this region have parent materials formed from the same Pottsville geologic formation underlying the Allegheny Plateau. These Pottsville-derived soils are naturally highly acidic and Ca deficient. In this area of Pennsylvania, Ca depletion has led to significant mortality of sugar maple in large areas when other pre-disposing factors, such as drought and insect infestation have been present and have served to exacerbate mortality.

Conclusion

Acid deposition is a real issue for the MNF. The relationships between air, water and soil chemistry are not always clear; however, science has shown links and associated effects. The results from forest stream monitoring sites are supported by the acid sensitive geology classification developed by combining data from the US Geological Survey with information on rates of acid deposition from the 2002 Southern Appalachian Mountain Initiative Report. That is, water chemistry monitoring on the forest indicates poor water chemistry buffering in aquatic systems located in contributing watershed areas dominated by geologies classified as higher acid sensitivity, and in some cases those systems dominated by a combination of moderate and higher acid sensitive geologies. Soil productivity monitoring is providing additional information, which will lead to the ability to model long-term cumulative effects in watersheds. This data will ultimately help land mangers answer questions about the potential long-term effects of management activities in highly sensitive areas and the forest's ability to achieve future desired conditions.

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Methylmercury Contamination: Impacts on Aquatic Systems and Terrestrial Species, and Insights for Abatement

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Methylmercury (MeHg) is one of the most widespread waterborne contaminants, and through biomagnification processes has commonly been found in prey fish at concentrations toxic to piscivorous birds and mammals. In USEPA's National Fish Tissue Survey, the Lowest Adverse Effect Concentration of 0.1 g/g wet weight was exceeded in 28% of total samples and 86% of predatory fish samples (USEPA 2002). Evidence suggests that more than a quarter of all mature fish contain methylmercury concentrations above this level. This review focuses on the leading anthropogenic sources of mercury to aquatic systems, through atmospheric deposition and the environmental dynamics of the mercury methylation process in aquatic sediments. The results of extensive mercury monitoring studies are discussed, as well as the reproductive and behavioral impacts on birds and mammals feeding on fish exhibiting realistic contaminant concentrations. Recommendations are provided for continued research and the abatement of methylmercury concentrations in fish through forest management practices.

Keywords: *mercury deposition, methylmercury, sulfate reducing bacteria, aquatic sediments*

Introduction

Methylmercury (MeHg) is one of the most widespread waterborne contaminants (USGS 2001a; UNEP 2002; USDHHS and USEPA 2004). Unhealthful levels of MeHg in fish have led to the issuance of fish consumption advisories by at least 46 states (USEPA 2004). The generation, bioaccumulation, and biomagnification of MeHg within aquatic systems has been studied for decades, following the identification of severe neurological and teratogenic impacts to humans associated with the consumption of contaminated fish in Minimata Bay, Japan in the 1950s (Eisler 1987; Ninomiya et al. 1995). MeHg has been linked to potential reproductive and immune system effects in humans and wildlife (Wiener et al. 1996; USEPA 1997d; Round et al. 1998). To protect human health, the U.S. Environmental Protection Agency (USEPA) has set a generalized, default fish tissue mercury residue criterion for freshwater and estuarine fish at 0.0175 mg per kg of fish per day (USEPA 2001). With regard to management of Forest Service lands, MeHg is recognized to be a significant risk to the viability of natural systems associated with aquatic resources (Hammerschmidt et al. 1999, 2002; Gnamus et al. 2000). Of the over 40.4 million ha (100 million acres) of freshwater wetlands within the conterminous United States, over 20.2 million ha (50 million acres) were determined to be forested wetlands, as well as 10.0 million ha (25 million acres) of emergent wetlands and 7.3 million ha (18 million acres) of shrub wetlands (Dahl 2000). While National Forest lands represent only eight percent of the contiguous United States, they contribute 14 percent of the runoff (USDA FS 2000). National Forests and Grasslands contain over 240,000 km (150,000 miles) of streams and 1 million ha (2.5 million acres) of lakes (USDA FS 2004). Anglers spent nearly 50 million days fishing on National Forests in 1996, and generated US $2.9 billion (NFF 2004). Clearly, the Forest Service has a large stake in the study, prevention, and possible abatement of mercury contamination within the nation's waters.

This review focuses on the primary anthropogenic source of mercury ultimately affecting aquatic systems - coal combustion. Much smaller contributions from wildland fire, associated with Forest Service land management activities, will share that focus. Also discussed are: subsequent mercury deposition to aquatic systems, dynamics of conversion to MeHg within fresh water aquatic sediments, impacts on aquatic and terrestrial species, proposed controls and regulatory initiatives, and suggested mitigation measures.

Sources

The bulk of MeHg within natural systems originates from methylation of atmospherically deposited mercury

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species by sulfur reducing bacteria within aquatic sediments (USEPA 1997d). Long thought to originate from mercury-laden industrial point source effluent, mercury contributions from geological processes, or both, MeHg contamination has more recently been portentously linked to long-term, long-range transport of emissions from fossil fuel combustion sources throughout the industrialized world (USEPA 1997b, 1997d; UNEP 2002; Bullock 2004). Despite the uncertainties involved in determining emission inventories, it is widely accepted that anthropogenic emissions have increased relative to natural sources since the beginning of the industrial period (Fitzgerald et al. 1998). This has resulted in atmospheric deposition of elemental and oxidized mercury species, even in remote areas (Rasmussen 1994; Sorensen et al. 1994; Morrison and Watras 1996; Eisler 1998; Fitzgerald et al. 1998; USGS 2000; St Louis et al. 2001; Blett 2002; MPCA 2004). Concern exists that most National Forest lands are characterized by relatively remote freshwater systems, many showing signs of MeHg contamination (USDA FS 2000).

The burning of fossil fuels, primarily coal, is the best characterized and most dominant anthropogenic source of mercury emissions (USEPA 1997d; Seigneur et al. 2003), representing over 30% of mercury emissions from domestic sources and 29% of global anthropogenic emissions (Seigneur et al. 2004). Approximately 40% of the 68 metric tons (75 tons) of Hg from the coal burned domestically remains in the ash and scrubber residues, while 60% is emitted to the atmosphere (ICR 2000). The ratio of mercury deposition from international and domestic sources varies considerably by location within the United States (Bullock 2004). It is estimated that North American anthropogenic emissions account for only 1.5-3% of global emissions (Bullock 2004; Seigneur et al. 2004). However, modeling studies estimate that 95-96% of mercury deposition in the eastern United States and 88-90% in the western United States comes from anthropogenic sources (Levin et al. 2000; Bullock 2004).

Comparing estimates of long-term accumulation rates of total mercury within soil of northwestern Ontario to measured flux rates within litterfall and throughfall, St. Louis et al. (2001) found they were similar, suggesting that inputs of total mercury originated from atmospheric deposition. Hanisch (1998) indicated that 40% of mercury deposition could be attributed to anthropogenic sources. Short range modeling data reported by USEPA (2001), using the ISC-3 model, indicated that from 7-45% of primary, inorganic mercury (Hg^{II}) emissions, originating from eastern U.S. sources with relatively lower stacks, are deposited within 50 km of their source. Similar western source emissions were modeled at rates from 2-38%. Regional differences were attributed to differing frequencies of precipitation events. Round et al. (1998) reported that most mercury emissions from taller stacks, including elemental mercury (Hg^0) oxidized to Hg^{II}, are deposited within 1000 km of the source. Electric utilities are recognized as the largest single source category of mercury emissions in North America (Seigneur et al. 2004), but several other source categories are known to emit large amounts of mercury (Dvonch et al. 1999).

There are distinct regional differences across the United States with respect to mercury input values per 1012 Btu for various coal types (ICR 2000; USGS 2001b). Initially, it may be assumed that the environmental impact of mercury emissions from the burning of any given coal type may be a factor of its mercury content relative to its Btu value. In addition, the ratio of various mercury species within combustion source emissions will influence the percentage of mercury initially available for methylation within natural systems (Seigneur et al. 2004). Within 14 regions, the USGS (2001b) lists Gulf Coast lignite as exhibiting the highest mercury to Btu value (20 lb Hg per 1012 Btu [9 kg Hg per 293 million kwh]) followed in order of magnitude by coal from the northern Appalachian, southern Appalachian, western interior, Fort Union, and Pennsylvania anthracite deposits. ICR (2000) data, based strictly on reported values from the utility sector, found similar regional rankings, but significantly lower mercury to Btu ratios.

While anthropogenic emissions of oxidized and elemental mercury are widespread, they are only a fraction of total global contributions (Grumet 2000). Seigneur et al. (2003) and Lindberg and Stratton (1998) identified speciation ratios of anthropogenic emissions (the relative fractions of Hg^0, Hg^{II}, and particulate mercury or Hg^P), as critical to the environmental fate of that mercury. Anthropogenic emissions vary widely in the percentage of Hg^0, Hg^{II}, and (Hg^P) forms, with Hg0 representing the vast majority of the worldwide atmospheric mercury load (USEPA 1997c; Round et al. 1998). Hg0 remains in the atmosphere for up to a year (USEPA 1997c). Conversely, Hg^{II} species, whether emitted as primary pollutants or transformed within the atmosphere from Hg^0, are much more water soluble, more easily deposited during rain events (Seigneur et al. 2003), and are principally the mercury species which undergo methylation within natural systems (USEPA 1997a). Seigneur et al. (2003) reported that up to 50% of Hg^{II} species were depleted by rainfall, whereas less than 10% of Hg^0 species were depleted. An elevated mercury deposition pattern, associated with summertime thunderstorms, became evident at ten sites across Florida in periods ranging from 2 to 5 years (Guentzel et al. 2001). This was estimated to be >50% of the mercury deposition

in southern Florida. During a single summer rain event, a northern Wisconsin monitoring station received two thirds of its annual mercury load (L. Bruss, Section Chief, Wisconsin DNR–Bureau of Air Management, Personal communication, 2003).

2003). The propensity of atmospheric Hg^{II} to be depleted by rainfall, and the indication that vegetation may act as a sink for Hg^{II} species, suggests that elevated ecosystem exposure to Hg^{II} may be possible near a major mercury emitter (Lindberg and Stratton 1998). Table 1 lists mercury particle speciation profiles for a number of anthropogenic source categories.

While a number of studies have markedly increased our understanding of both total Hg and MeHg cycling within forested watersheds (Bishop et al. 1998; St. Louis et al. 2001; Hintelmann et al. 2002; Munthe and Hultberg 2004), few studies address the role of wildland fire in mercury cycling. One of the more spectacular examples of gaseous mercury transport within the plume of a large wildfire occurred during July 2002, when researchers using carbon monoxide (CO) as a tracer of a plume originating from a series of boreal wildfires in northern Quebec calculated a strong correlation between mercury levels and CO at Harvard Forest in western Massachusetts (Singler et al. 2003). Average flux rate for these boreal fires was determined to be 1.5 μg Hg per hectare, resulting in an annual Canadian wildfire emission rate of 3.5 metric tons Hg, equaling 30% of average Canadian anthropogenic emissions. Singler et al. estimated annual global boreal wildfire emissions to be 22.5 metric tons.

Table 1: Emission speciation profiles for various anthropogenic mercury source categories. Adapted from Round et al. 1998, with biomass fire data taken from Friedli et al. 2003.

	Speciation (%)[a] of Mercury Emissions		
Source Type	**Hg^0**	**Hg^{II}**	**Hg^P**
Electric utility fossil fuel boilers	50	30	20
Non-utility fossil fuel combustion	50	30	20
Municipal waste combustion	20	60	20
Medical waste incineration	20	60	20
Chlor-alkali factory	70	30	0
Other point sources[b]	80	10	10
Biomass fires[c]	>95	negligible	<5
Area sources[d]	100	0	0

[a] Hg^0 symbolizes elemental mercury; Hg^{II} symbolizes divalent, oxidized mercury; Hg^P symbolizes particulate mercury.

[b] Includes residential boilers, sewage sludge incinerators, wood-fired facilities, lime manufacturing, mercury compounds production, cement manufacturing, and secondary mercury production. However, a number of potentially important source categories (such as refineries) are not included because emissions estimates for these sources are currently lacking.

[c] From Friedli et al. 2003.

[d] Because most area sources do not involve combustion sources, emissions were assumed to be 100% Hg^0 for this source category. However, a small (but presently unknown) fraction of area source emissions may be in divalent or particulate forms.

Using fuels from across the United States, Friedli et al. (2003) demonstrated in the laboratory that nearly all mercury from biomass fires may be emitted as elemental mercury. Friedli et al. also sampled smoke from a small wildfire with a research aircraft, and determined that wildfires may emit a larger percentage of Hg^P than was determined from laboratory studies. This additional particulate mercury was likely released from fire-heated soils. Mercury concentrations ranged from 14 - 71 μg Hg/kg (dry mass) fuel for the laboratory burns and 112 μg Hg/kg for the wildfire. It is evident that forests act as sinks for atmospheric mercury, and wildland fire emissions contain mercury deposited on and incorporated in fuel, as well as that which may be released from fire-heated soil (Friedli et al. 2003). Forest Service researchers are currently researching mercury mobility and accumulation in fish responding to wildland fire in the Boundary Waters Canoe Area of northern Minnesota's Superior National Forest (Kolka 2003). There is also some evidence that mercury may be mobilized during soil disturbances from construction of logging roads or large fire breaks (Munthe and Hultberg 2004).

Environmental Dynamics

Sulfur reducing bacteria within aquatic sediments are ubiquitous, and are recognized as the primary agent of mercury methlyation within aquatic systems (Wetzel 1983; King et al. 2002; Bates et al. 2002). Benoit et al. (1999) postulate that the presence of mercury complexes such as cinnabar (HgS), the dominate neutral mercury complex in sulfidic sediment pore waters, mediates bacterial methylation of mercury by passively diffusing across bacterial membranes, and being used in sulfate reduction/mercury methylation reactions. Other researchers point to precipitation of relatively insoluble HgS, decreasing mercury availability, and inhibiting MeHg production (Gilmour et al. 1998; King et al. 2002). Gilmour et al. also determined that those areas with sediments exhibiting high sulfur reduction rates were characterized by lower relative sulfate levels, and thus lower levels of sulfide inhibiting methylation. Wetzel (1983) reported the conditions within aquatic sediments, relative to redox potential, supporting the presence of sulfur reducing bacteria, and therefore also mercury methylation (See Figure 1). Ultimately, translocation of easily-soluble MeHg out of the sediments

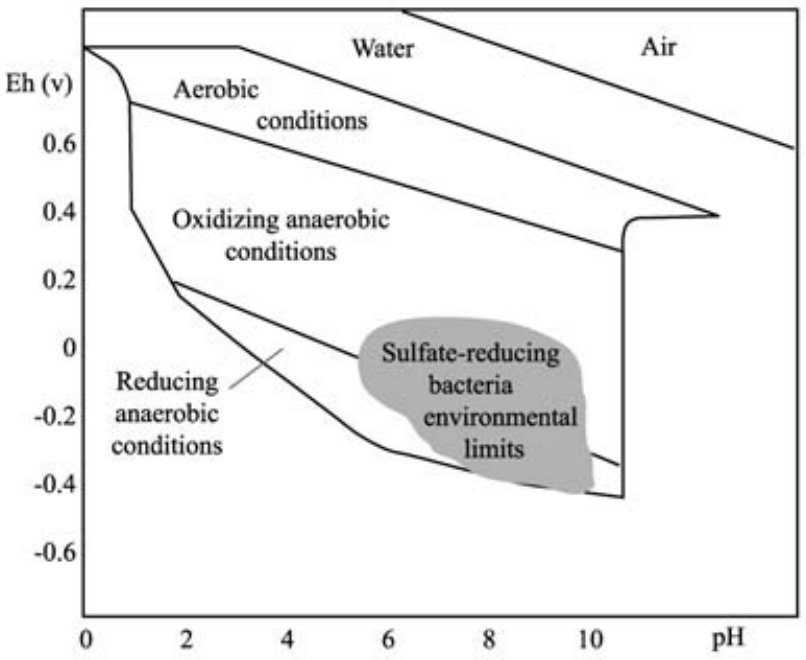


Figure 1: Environmental limits of sulfur reducing bacteria in aquatic sediments. Based on Wetzel (1983).

leads to its biomagnification within higher trophic levels (USEPA 1997d).

Due to the relative abundance of anaerobic sulfur reducing bacteria in associated sediments, wetlands and those lakes characterized by large shoal areas appear to generate methylmercury at greater rates than other freshwater systems (Sutton 1998; King et al. 2002). In addition, flooding appears to initially and significantly increase the production and export of MeHg (Kelly et al. 1997; Gerrard and St. Louis 2001) and its bioaccumulation (Paterson et al. 1998). Based on this evidence and Wetzel's (1983) indication of optimal redox conditions, the avoidance of flooding and the minimization of anthropogenic water level manipulations may offer a means to minimize MeHg production, even within existing lakes and wetlands.

Several factors independent of mercury depostion are associated with MeHg concentrations in fish. Abiotic factors include an increase in dissolved organic matter (Sorensen et al. 1990; Babiarz et al. 2001) as associated with increased leaf fall and subsequent algal blooms (Balogh et al. 2002), fluctuation of lake levels (Wiener et al. 2002), and higher sulfate-laden inflow to shallow waters (Gilmour et al. 1992, 1998; Sutton 1998; Harmon et al. 2003; Jeremiason et al. 2003; MPCA 2004). In addition, proximity to geothermal vents, land disturbance events, and major sewage treatment plants (Sutton 1998) and some mining operations (Wiener et al. 2002) are also associated with higher MeHg levels in fish.

It is unclear how pH within the water column affects MeHg levels. Sorensen et al. (1990) determined pH was negatively correlated with fish MeHg levels, contrary the Sorensen et al. literature review and that of Sutton (1998). This discrepancy could be related to the inclusion of deeper lakes in the Sorensen et al. study. HgS nodule precipitation occurs readily under reducing conditions within the deeper areas of hypolimnetic waters, decreasing the amount of mercury available for methylation. However, if pH is high within these hypolimnetic waters, Hg can become soluble and so available for methylation (Sutton 1998).

On her comprehensive website, Sutton (1998) reported that ideal lake conditions leading to high levels of mercury methylation include: high sulfate levels, shallow well-mixed lake waters, deep lakes with a high pH, or lakes with large shallow areas. Hurley et al. (1995), in their study of 39 river sites within Wisconsin, found MeHg generation rates were positively correlated with the percentage of wetlands within a hydrologic unit, and were highest within watersheds containing greater percentages of wetland/forest sites relative to agricultural/forest sites or agricultural only sites. In their study of 80 lakes in remote northern Minnesota, Sorensen et al. (1990) also found the significant ($|r| > 0.90$), water related and positively correlated predictor variables: Al (aluminum), low sediment acid neutralizing capacity (ANC), percent of watershed in forest, lake surface area, and watershed area. High Al and low ANC have also been associated with lakes sensitive to acid deposition (Adams et al. 1991).

As part of the comprehensive METAALICUS study, Hintelmann et al. (2002) found that in a boreal forest, the initial mobility, and so the ultimate bio-availability of mercury received through wet and dry deposition, decreased markedly in a short time through methylation relative to the larger pool of stored mercury, suggesting

that there may be rapid decline in rates of MeHg bioaccumulation in fish if mercury deposition is reduced. Hintelmann et al. further suggest that this decline could take less than 10 years, although WDNR (1999) suggests 15-20 years. Potential exists for land managers and air quality regulators to influence the abatement of mercury and sulfur deposition to aquatic systems, and so abate MeHg concentrations within these systems. However, the mercury isotope marker in the Hintelmann et al. study was bound to vegetation to a much higher degree than native mercury, suggesting there may be a time delay before atmospherically derived mercury enters the mercury soil pool, and therefore before that soil pool would respond to changes in deposition.

General knowledge of the factors that contribute to MeHg bioaccumulation would not be complete without noting that abiotic and biotic MeHg degradation pathways exist within natural systems, mitigating MeHg toxicity. In addition to the abiotic processes of MeHg photodegradation in lakes (Seller et al. 1996), these include production of HgS within soil pore water (Benoit et al. 1999), and dissolution of HgS in the presence of humic and fulvic acids (Ravichandran et al. 1998). Various aerobic and anaerobic microbial populations are known to possess enzyme degradation systems that react with mercury species. These systems impart to the host some resistance to the toxic effects of MeHg, and result in the cleaving of MeHg, forming CH4 and HgII. Some bacteria possessing a more "broad spectrum" resistance have the ability to further reduce HgII, forming volatile, elemental mercury (Marvin-Dipasquale et al. 2000). However, the evident widespread bioaccumulation and biomagnification of MeHg suggests that these degradation mechanisms do not dominate within aquatic sediments.

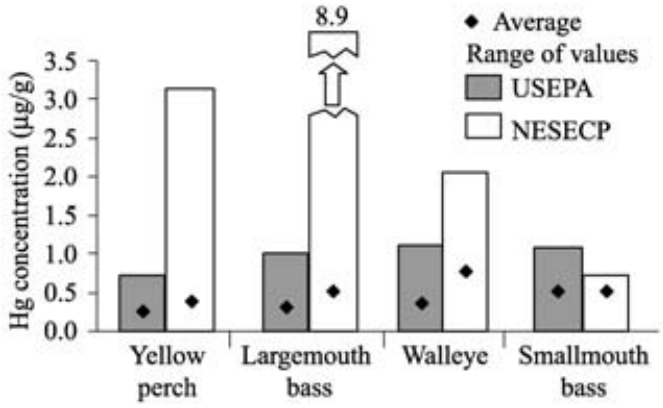
Of particular concern to the Air and Watershed Programs of the Forest Service is the correlation between the presence of sulfates and MeHg production within wetland systems. An example of note is the repeated and long-term applications of sulfur-rich agricultural fertilizers on the sugarcane fields of southern Florida, resulting in significant MeHg loadings to fish and birds downstream, within the Everglades wetland system (Bates et al. 2002). Conversely, in their study of total mercury bioaccumulation in fish, the United States Geological Survey (USGS 2001a) found a significant negative correlation of mercury bioaccumulation with sulfate in water within 20 river basins nationwide. However, nearly all collection sites were within larger streams, and it is unclear how these collection sites relate to their associated wetland systems or sulfate inputs. Preliminary results of an ongoing study within a two-hectare wetland by researchers on the Marcell Experimental Forest in northeastern Minnesota (Jeremiason et al. 2003; MPCA 2004) clearly demonstrate an increase in peat pore water MeHg concentrations following sulfate addition. While sulfate concentrations decreased following its addition, MeHg concentrations rose until pore water sulfate levels were depleted, corresponding to the findings of the USGS (2001a) that the presence of acid volatile sulfide within sediment pore water will signal the reduction of available sulfate, and thus the reduction in the production of MeHg. Most significantly for this review, further study is needed to quantify an abatement of mercury levels in fish which could stem from reductions in industrial sulfur dioxide emissions, and subsequent sulfate deposition.

Effects on Wildlife

MeHg concentrations generally increase with trophic level and with increased size and age of a given organism. Fish eventually sequestered MeHg in skeletal muscle, reducing exposure to the central nervous system (Wiener et al. 2002). Haines (1996) reported mercury concentrations in wild freshwater fish populations in 125 randomly selected lakes in Maine commonly exceeded 1 μg/g wet weight, the United States Food and Drug Administration's action level, or that level deemed unfit for human consumption (USDHHS and USEPA 2004). Half the samples from the Haines study exceeded 0.5 μg/g. USEPA's two-year, National Fish Tissue Study found concentrations exceeding 1 μg/g in only eight of 282 composite samples of predatory, freshwater game fish distributed across the United States, while the highest concentration in the 237 composite samples of bottom dwelling fish was 0.531 μg/g (USEPA 2002, 2003). However, more than 28% of the total samples exceeded 0.1 μg/g, with over 86% of predatory fish exceeding this level. Levels exceeding 1 μg/g were also common as reported in the Northeast States and Eastern Provinces' comprehensive mercury study (Tatsutani 1998), with largemouth bass (*Micropterus salmoides*) reaching 8.94 μg/g. As in all studies reviewed, predatory fish exhibited the greatest mean and maximum mercury values. Figure 2 compares data from the USEPA and Tatsutani studies.

Numerous laboratory studies have established a link between the ingestion of MeHg at sublethal levels and subtle visual, cognitive, and neurobehavioral deficits in small mammals (Wiener et al. 2002). In addition, controlled experiments with mink (*Mustela vison*) and otter (*Lutra canadensis*) have established that dietary MeHg concentrations of 1 μg/g lead to death in less than a year. In their critical review, Wiener et al. reported numerous reproductive and behavioral effects on wild avian and mammal populations associated with ingestion of realistic

Figure 2: MeHg concentrations in predatory fish: A comparison of the USEPA and NESECP studies



concentrations MeHg. For example, neurotoxic effects from sublethal exposure of eggs to MeHg can result in reduced prey capture efficiency and competitive ability of grayling (*Thymallus arcticus arcticus*) three years after exposure. MeHg content of eggs is strongly related to concentrations of the maternal fish. Tan (2003) attributes reproductive effects, based on gender, to disruption of endocrine systems by MeHg. Kamman and Burgess (2004) suggest that, in the northeastern United States, the widespread occurrence and mercury uptake characteristics of brook trout (*Salvelinus fontinalis*) and particularly yellow perch (*Perca flavescens*) may make them preferred subjects for monitoring of mercury impacts on natural systems.

While the scientific community has focused on affected salt and freshwater aquatic processes and species, wild piscivorous birds and mammals receive a greater exposure to mercury than any other receptor (USEPA 1997d). Few studies have addressed impacts on these species (Haines 1996; USEPA 1997d). Wiener et al. (2002) reported impaired reproduction in wild merlins (*Falco columbarius*), common loons (*Gavia immer*), wood storks (*Mycteria americana*), and common terns (*Sterna hirundo*) associated with ingestion of aquatic prey exhibiting elevated body burdens of MeHg. Eisler (1987) established a Lowest Observed Adverse Effect Concentration (LOAEC) of 0.1 µg/g wet weight for MeHg contaminated food fed to mallards (*Anas platyrhynchos*). Wiener et al. (2002) suggested that mercury in feathers is an indicator of mercury in other avian tissues, and Evers et al. (1998) indicated that common loons can reduce their body burden during the winter molt. Evers et al. (2003) found that common loon egg volume declined significantly as egg-Hg concentrations increased, while mercury levels in common loons were higher at eastern North American sites relative to western. In general, common loon eggs appear to be suitable indicators of MeHg availability on lakes with territorial pairs. Gerrard and St. Louis (2001) also reported adverse impacts on reproductive success of wild tree swallows (*Tachycineta bicolor*) associated with elevated aquatic MeHg levels.

Data reported for six terrestrial species rated relative rank of exposure as: Kingfisher > otter > common loon = osprey = mink ≥ bald eagle, setting reference doses for MeHg in avian and mammalian wildlife at 21 and 18 µg/ kg body weight per day, respectively (USEPA 1997d). Table 2 lists the percent of species range overlapping with regions of high mercury deposition and a generalized wildlife criterion, defined as the concentration in water that, if not exceeded, protects avian and mammalian wildlife taken from these waters. It should be noted that mercury in birds and mammals is considered to be almost exclusively in the form of MeHg.

Table 2. Impacts of methylmercury on selected bird and mammal species' ranges, with the wildlife criterion as measured in water and body tissue for each species. Data from USEPA (1997d).

Species	Percent of Range Affected	Wildlife Criterion in water (pg MeHg/L)	Kg body wt. / Kg ingested / day
Kingfisher *Ceryle alcyon*	29%	27	0.50
Mink *Mustela vison*	35%	57	0.22
Loon *Gavia immer*	40%	67	0.20
Osprey *Pandion haliaetus*	20%	67	0.20
River otter *Lutra canadensis*	38%	42	0.16
Bald eagle *Haliaeetus leucocephalus*	34%	82	0.11
Florida panther *Puma concolor coryi*	100%	NA	NA

Gnamus et al. (2000) linked mercury deposition on terrestrial plants to food intake by roe deer (*Capreolus capreolus*). A Florida panther (*Puma concolor coryi*), thought to have died of MeHg poisoning, was found to have a concentration of total mercury in its liver of 110 μg/g (Roelke 1990). Due to the numerous uncertainties involved in field experiments, more studies are needed for definitive determinations regarding effects on wild fish-eating birds and mammals.

Hopefully, the decrease in overall body burdens of mercury in Wisconsin's adult common loons from 1992-2000 (Fevold et al. 2003) represents the effectiveness of recent emission reductions associated with more stringent SO_2/acid rain regulations for coal-fired utilities.

Emission Controls

Mercury control strategies acceptable to the regulated community have been difficult to establish because of both the political issues involved and the uncertainties in the emission inventories of mercury species (Bruss 2003). However, as a result of more recent understanding of the sources and impacts of mercury deposition, USEPA, Canada, and several states have sought tighter controls on emission sources (WDNR 1999; EIA 2001). After a long and contentious review process, USEPA released its final Clean Air Mercury Rule on 15 March 2006, instituting a cap and trade program for coal and oil based power plants, over the protests of critics who sought the more stringent Maximum Achievable Control Technology standard for those sources.

As previously stated, mercury plume speciation varies greatly relative to source category (Round et al. 1998), and is an important factor in the control of mercury emissions (Laudal 2001). Coal plume mercury speciation at the inlet of particulate control devices was found to depend on the inlet temperature and the chlorine and calcium content of the coal burned (Senior 2001). For example, emissions of chlorinated HgII compounds (e.g., mercuric chloride) can be captured with particulate control devices at high efficiencies (Laudal 2001; Senior 2001), while calcium within coals can reduce the beneficial oxidizing effect of chlorine (Benson 2003). This is evident in tests performed on western coals that are low in both chlorine and calcium. However, Hg^0, representing the dominant species emitted, is not well controlled by scrubbers or other particulate control devices (UNEP 2002). Finally, Hg^p species are obviously well controlled by particulate controls.

A reading of EPRI (2004) and USEPA (1997e) suggests mercury control strategies for coal-fired sources can be divided into two general categories: (1) Fuel controls, including the burning of high ranking (high Btu) coal, burning low mercury coal, coal washing (which may reduce mercury levels by 50%), and use of alternative fuels such as natural gas; and (2) Flue gas controls, of which there are currently two leading contenders. Flue gas controls include activated carbon injection (ACI), followed by a particulate collection device, or a compact baghouse (fabric filters) added after use of an electrostatic precipitator (ESP) (EPRI 2004). A combination of these flue gas control technologies, employing ACI between the baghouse and the ESP, has been shown to be most effective under some circumstances. However, mercury removal efficiencies from the burning of lignite coal were shown to be poor (0-9%) for both ESPs and fabric filters (Sjostrom et al. 2004). As a general rule, traditional SO_2 controls also remove some Hg^{II}. The nature of mercury control strategies is too complex to be comprehensively reviewed here. For a more thorough review, inclusive of multiple source categories and technologies, see USEPA (1997e).

Conclusion and Future Research Needs

The impacts and dynamics of mercury within natural systems are still not fully understood. Recommended areas for future research that could productively contribute to this understanding include:

- Effects of soil disturbance and wildland fire on translocation of mercury relative to watershed conditions.
- Physiological and behavior effects of realistic levels of MeHg on wild populations of birds and mammals.
- Effects of sulfate deposition on in-situ mercury methylation rates under various watershed conditions.
- Relationship between acid deposition and mercury methylation rates.

For many years, comprehensive program integration has been a Forest Service goal, whether in the collection and management of data, as with recent developments within and linkages between multiple databases (e.g., the Natural Resource Information System, NRIS, and the Forest Service infrastructure inventory database, INFRA), or in the implementation of project-level management decisions. The avoidance or abatement of mercury levels in wildlife species offers an opportunity to more completely reach that goal. The following recommend actions, if implemented, could provide forest managers involved in the fields of air resources management, wildlife management, recreation, timber management, and watershed improvement, opportunities to better understand the impacts and dynamics of mercury within the natural systems they manage:

1. Monitor mercury levels in water and wildlife, as linked to implementation, effectiveness, and validation monitoring associated with various forest land management activities (e.g., management of sedimentation associated with timber harvest).

2. Rank wetlands and lakes as to their potential for elevated MeHg production rates.

3. Minimize water level manipulations of lakes and wetlands to minimize mercury methylation rates within aquatic sediments.

4. Minimize sedimentation associated with land disturbance activities.

5. Manage fish species relative to risk factors associated with proximity of mining operations, lake morphology, and landscape ecology (e.g., avoid managing for top predators in areas of high risk).

6. Comment to state and federal air regulatory officials to maximize controls on industrial mercury and sulfate emission rates near forest boundaries.

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Section 4. Valuing the Earth Sciences
Part 4. Water

Overleaf:
River on the Carson National Forest, northern New Mexico. Photo from USDA Forest Service.

Short History of Watershed Management in the Forest Service: 1897 to 2100

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Congressional direction for administration of the forest reserves, now called national forests, began in 1897 with passage of the Organic Administration Act. One of the defined purposes for which forest lands were set aside from settlement was "securing favorable conditions of water flow." Subsequent passage of over 25 other federal statutes further defined watershed management on these lands, and federal courts have interpreted these laws since 1908 in ways that sometimes expanded, sometimes contracted, delegated authorities. The Research Branch began watershed experiments in 1910 at Wagon Wheel Gap, Colorado, and has since expanded to 24 research watersheds. The contributions of certain individuals, the 1930s Civilian Conservation Corps, the barometer watershed program in the 1960s, and the State and Private Forestry suite of watershed technical assistance are discussed. Finally, possible future watershed management scenarios in the Forest Service in the years 2050 and 2100 are briefly discussed.

Keywords: *watershed management, barometer watersheds, research watersheds, history*

Beginnings: 1897-1911

When the first forest reserve (Yellowstone) was proclaimed in 1891, President Harrison was trying to stop exploitation and destruction of the forests adjacent to Yellowstone National Park – nothing more. No direction was provided to the General Land Office personnel responsible for administering this piece of the public domain, nor was much money appropriated for it. Other forest reserves established from 1892 to 1897 suffered from the same lack of consistent direction. Foresters in the federal Bureau of Forestry were fearful of the consequences and supported efforts in the Congress, led by Senators A. S. Paddock and R. Pettigrew and Congressman T. R. McRae, to obtain passage of a bill that would put the federal forest lands on a course of purposeful and professional management (Steen 1976). The answer was what is known today as the Forest Service Organic Administration Act of 1897.

Gifford Pinchot, then an employee of the Bureau of Forestry, was the first professional forester in the United States. He had studied in France and had read George Perkins Marsh's 1864 landmark monograph *Man and Nature: Or, Physical Geography as Modified by Human Action*. He was also greatly influenced by Marsh's conclusions that many civilizations had vanished as a result of abusing their watersheds to the point where severe erosion and polluted water supplies deprived them of necessary resources for their survival. Pinchot hired other college educated professionals able to put American forest conservation on a solid footing, and who were capable of persuading local settlers to accept wise use of forest resources and the need to obtain special use permits prior to removing timber, grazing livestock, building dams, and conducting other activities on the national forest reserves.

In 1898 the Department of the Interior's General Land Office (GLO) made its first timber sale on a forest reserve. The Homestake Mining Company purchased 15 million board feet (35396 m^3) of timber on the Black Hills reserve (South Dakota) at one dollar per thousand board feet (Fedkiw 1998). By 1901, the GLO and the USDA Division of Forestry were sharing the management of the forest reserves, with the GLO patrolling them for trespassers and the foresters providing technical advice. In 1902, Interior issued its Forest Reserve Manual. When the reserves were transferred to the Department of Agriculture in 1905, the Forest Service quickly issued its own Use Book which had stated objectives of the forest reserves as … "preserving a perpetual supply of timber for home industries, preventing the destruction of forest cover which regulates the flow of streams, and protecting local residents from unfair competition in the use of forest and range." (USDA Forest Service 1905)

Raphael Zon was one of Pinchot's hired professionals. Born in Russia and an immigrant into the United States in the 1890s, Zon was a key figure in establishing and continuing the watershed experiments on the Rio Grande National Forest at Wagon Wheel Gap, Colorado, from 1910 to 1926 (Schmaltz 1983). The experiment in clearcutting one small watershed while leaving an adjacent, similar watershed uncut, to test whether stream flows

Furniss, M.J., Clifton, C.F., Ronnenberg, K.L., eds., 2007. *Advancing the fundamental sciences: proceedings of the forest service national earth sciences conference, San Diego, CA, 18-22 October 2004*. PNW-GTR-689. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station.

were changed by the logging after seven years of baseline monitoring of both drainages was the first time in the world that such a scientific experiment was undertaken. The controversy derived from questions on the relationship between forests and rainfall, and the best way to control floods: reforestation of denuded watersheds, or building dams and levees? Pinchot and most foresters advocated reforestation, while Hiram Chittenden of the Army Corps of Engineers (CoE) strongly advocated a structural approach to flood control. To win this argument, in July of 1910 the Forest Service appointed C.R. Tillotson, while the Weather Bureau, then part of USDA, appointed B.F. Kadel to initiate the Wagon Wheel Gap experiments. After 16 years of careful measurements were completed, it took the personal involvement of Zon to work with Carlos Bates, in charge of the Wagon Wheel Gap work at the time, and his counterpart, A.J. Henry of the Weather Bureau, to produce the final report in 1928 on the results of the experiment, after disagreements arose between the two men as to the significance of the results (Bates and Henry 1928).

In 1908, President Theodore Roosevelt's Inland Waterways Commission reported on its survey of U.S. waterways for commercial navigation and other water resource uses and problems. Pinchot was a member of this commission. Modeled after the successful 1905 Forest Conference, Pinchot hoped this commission would lead to the establishment of a national, federal policy for managing water resources in the United States. Indeed, the commission recommended that both local and national benefits of a water policy be considered as well as costs; that plans for improving waterways should consider all of the uses of water including flood control, water power, irrigation and pollution control; and that a national waterways commission be created to coordinate the work of the Corps of Engineers, the Reclamation Service, USDA's Forest Service and Bureau of Soils, the Bureau of Corporations, and other concerned federal agencies in making multiple-purpose plans for waterways in cooperation with state and local governments. (USDA Economic Research Service 1972). However, the commission's report failed to spur creation of a national water policy largely because it would have usurped 50 years of western states' water laws, customs, and policies, and these states would have none of that! One other result of this commission and the National Conservation Commission of 1909 was increased discussions within the Congress that resulted in passage of the Weeks Act in 1911. This Act provided authority to the Forest Service to purchase lands in the eastern United States, in watersheds whose water supplies were needed to preserve river navigability. The Act also created the National Forest Reserve Commission and provided that the Secretary of Agriculture, in cooperation with Interior's U.S. Geological Survey, could recommend for purchase such lands in the watersheds of navigable streams needed to regulate water flow. This Act is responsible for the eventual acquisition of 25.3 million acres (10.2 million ha) in the East as national forests (USDA Forest Service 2003).

Custodial Era: 1911-1945

Between 1911 and 1945, the Forest Service was largely focused on the acquisition and reforestation of abandoned and abused watershed lands in the East and Midwest; establishment and expansion of the Research Branch in 1915; passage of a few new laws such as the Clarke-McNary Act of 1924; and the work of the Civilian Conservation Corps (CCC). Many Forest Service employees, including Chief Henry Graves, enlisted in the Army Expeditionary Force during World War I, where they served in Europe setting up sawmills and acquiring timber needed for trench walls, railroad ties and other purposes.

The National Waterways Commission was authorized in 1917 to coordinate the work of all federal agencies with water resource responsibilities on preparation of nationwide multiple purpose plans, either by the federal government alone, or in cooperation with states and localities. The commission members were never appointed due to World War I, and in 1920 the Federal Power Act expressly repealed the 1917 law that created the commission. A Forest Service engineer, O.C. Merrill, helped Congressional staffers write the Federal Water Act in a manner that served the public interest, rather than the many land speculators then buying many of the best hydropower sites on private lands.

The Research Branch did almost all of the watershed work for the Forest Service until the CCC was established in 1933. Even while Wagon Wheel Gap was still operating, other watershed and soil erosion research was begun in Utah, Arizona and California. Harold Croft, Charles Hursh, and others whose names are now lost, were some of the first soil or water scientists hired by the agency in the 1910s and 1920s. In 1917, Research produced one of the first soils reports, and in 1928, a well written report on the role of forests in watershed management was issued (Shepard 1928).

Edward Munns served in the Chief's Office from 1923 to 1951, as the modern equivalent of the director of watershed research, where he played a key role in maintaining the agency's focus on scientific research of many soil and water issues. He helped establish the experimental forests, watersheds and laboratories at Coweeta (NC), Fernow

(WV), H.J. Andrews (OR), Fraser (CO), South Umpqua (OR), San Dimas (CA), Teakettle (CA), Manitou (CO), Sierra Ancha (AZ), Calhoun (SC), Delta (MS), Koen (AR), Santee (SC) and Tallahatchie (MS), which have cumulatively contributed much knowledge about how mountain watersheds behave. He also recruited many of the research hydrologists and soil scientists who worked at these experimental areas, and insured their growth and survival when times got tough during the Great Depression and World War II. Munns was also successful in getting the CCC enrollees to help build the research laboratory infrastructure at many of these locations between 1933 and 1942, including access roads, measuring weirs, lab buildings, and telephone lines (Otis et al. 1986).

Chief Forester Pinchot created a separate State and Private Forestry Branch in 1908 to render assistance to private forest landowners, in cooperation with USDA's Bureau of Entomology for pest control work and with the Bureau of Plant Industry on forest tree diseases, among other tasks (Williams 2000). The 1911 Weeks Act expanded the scope of this work to include firefighting on all land ownerships. The Clarke-McNary Act of 1924 expanded the Weeks Act to improve conditions on private forest land, and modified taxation policy to favor retention of forests.

In 1939 the Chief established a Division of Watershed Management within the National Forest System (NFS) Branch with Gordon Salmond as Director. Mr. Salmond served in that position until he retired in 1961. None of the 13 subsequent directors of this staff have served as long as he.

In 1949, Congress passed the Federal Classification and Pay Act which authorized the Civil Service Commission to create the job classification system in use today in most federal agencies. Prior to this Act, it was very difficult to assess how qualified applicants were for many technical job series, such as hydrologists, geologists or soil scientists, and to keep track of how many people in each job series were employed by federal agencies.

Development Era: 1945-1969

Demand for timber to build homes and other needs for returning GIs skyrocketed after World War II. Clear-cutting became normal practice on many national forests, and access roads were built to move the logs to the mills. Forest Service watershed research was maintained, but not expanded, until the 1960s. The most significant watershed developments during these 25 years included establishment of the barometer watershed program starting in 1962, and greatly accelerated hiring of soil, water and geology specialists in many Forest Service Regions and Research Stations, as a result of the McIntire-Stennis Act in 1962 which greatly expanded university-based forestry research at land-grant institutions (Glazebrook 1969; Steen 1998).

Barometer watersheds were intended to apply results from small experimental watersheds to larger basins, where typically a fuller set of multiple uses of land and resources were in place, so that effects on water quantity and quality could be determined. Some 24 barometers, ranging in area from 24,000 to 189,000 acres (9,700 to 76,500 ha) and representing 24 hydrographic provinces in 18 states were selected, instrumented, and staffed by 1970. A few fulfilled their original intent, but most never did for a variety of reasons that are more fully covered in a paper by Larry Schmidt and Byron Beattie in this publication.

The barometers were successful in helping justify the need for more agency hydrologists and hydrologic technicians. Probably close to 50 of these professionals worked at some point in their career on a barometer watershed. I was one of them, and my experience on the Lake Creek barometer in Colorado in 1969 was a very valuable training opportunity.

The Forest Service also hired more soil scientists in the 1960s to do soil surveys in cooperation with the then-Soil Conservation Service, now Natural Resources Conservation Service (NRCS). The national Soil Survey program was initiated in 1961 under John Retzer's leadership in the Washington Office. Many Soil Conservation Service soil scientists transferred to the Forest Service in the 1960's, bringing their expertise with them.

The 1954 Small Watershed Program (P.L. 83-566) expanded Forest Service authority to include flood prevention on farmland watersheds less than 250,000 acres (101,000 ha) in size by means of structures, upstream protection measures, and livestock controls. The Forest Service has worked with USDA's NRCS and Agricultural Research Service, the Army Corps of Engineers, the states, and local entities to implement these projects on NFS lands. Funding for maintaining these structures has diminished over time and there is a growing need to repair, replace or de-commission some of these structures as they approach the end of their design life.

The 1960s also brought the seeds of the environmental movement, with passage of the Multiple-Use Sustained-Yield Act of 1960, the Wilderness Act of 1964, the Jobs Corps Act of 1964, the Wild and Scenic Rivers Act of 1968, and the grand-daddy of them all – the National Environmental Policy Act (NEPA). These statutes, plus U.S. Supreme Court decisions involving reserved water rights from 1908 through 1963, portended that watershed management of the national forests and grasslands was about to change in the 1970s.

Environmental Era: 1970-1990

The year 1970 saw the passage of NEPA, the Youth Conservation Corps Act, and creation of the U.S. Environmental Protection Agency (USEPA), all of which helped change watershed management in the Forest Service. NEPA certainly created many more specialist jobs in the Forest Service at all levels within the NFS Branch, and improved the quality of land use decisions in ways that have lessened adverse impacts on the environment. The Youth Conservation Corps program provided new opportunities to educate young people about the environment and for them to learn job and life skills that have served them well (Figure 1). Some valuable soil and water improvement work has been accomplished by this program.

The USEPA has certainly changed water and air quality management in the Forest Service through their many rules, regulations, requirements, and interactions. We in the Forest Service often underestimate the amount of change that USEPA has brought about in this nation, including how NFS lands and natural resources are actually managed. Both the Clean Water Act of 1972, as amended, and the Clean Air Act of 1977, as amended, have resulted in the hiring of more Forest Service hydrologists and air quality specialists to work on evaluating likely effects of proposed resource extraction activities upon water and air quality and identifying mitigating measures for those activities. For example, the number of hydrologists went from 76 in 1970 to 203 in 1980, and 225 in 1989, while the number of air quality specialists increased from none in 1970, to 10 in 1980, to 22 in 1989 (USDA Forest Service 1970, 1980, 1989). Improvements in both water and air quality have resulted from these specialists' efforts in local areas.

The Bitterroot National Forest clear-cutting and terracing controversy, together with the District and Appeals Courts' decisions in the Monongahela National Forest case, led to Congressional hearings, passage of the National Forest Management Act (NFMA), and greatly restricted the size of clear-cuts on NFS watersheds in the mid 1970s. They also caused a large expansion in water quality monitoring of logging and road construction activities by hydrologists. In the Northern Region, several forest hydrologists developed "Hydrologic Cutting Guides" as a tool to assess water yield changes; they were fairly effective and other regions adopted modified guides as well. A major report, An approach to water resources evaluation of non-point silvicultural sources (A procedural handbook), also known as WRENSS (USEPA 1980), was issued as a tool for controlling non-point sources of water pollution from silvicultural activities. It had limited utility, because the data input needs were too large and complex, the handbook itself was 861 pages long, and the computer had not yet matured as a usable tool at the forest level.

The first inter-disciplinary teams were formed in early 1971 as a mechanism for implementing NEPA at the project level scale; almost all of them included soil, water, and geology expertise, as well as forestry/silviculture, fire, engineering and landscape architecture skills. I was part of the first team formed in Region 2, the Rocky Mountain Region. The previous multiple use surveys gave way to unit planning by these teams. There was a large degree of freedom to develop data collection and analysis methods,

Figure 1. The Youth Conservation Corps doing stream stabilization work on a national forest in the 1980s. Photo from the Forest Service achives.

write reports, and participate as an equal or almost equal member of the team as long as the team leader and other members were willing to operate in that manner. By 1973, a few national forest teams were starting to develop forest-wide land use plans, some of which went beyond the forest boundaries and eventually led to at least one forest supervisor losing his job. These early teams broke the ground for later planning teams that were helping implement long-range planning requirements of the Resources Planning Act and NFMA. They also certainly showed many line officers the value of hiring soils, water, geological and air specialists.

The year 1978 saw passage of the Cooperative Forestry Assistance Act and issuance of the Mimbres water rights decision by the U.S. Supreme Court. This Act expanded the suite of technical and cost-sharing assistance programs that the Forest Service could deliver for private forest landowners and state foresters, including new soil and water stewardship programs. In addition, Title IV of the Agricultural Credit Act of 1978 authorized the Secretary of Agriculture to undertake emergency measures for runoff retardation and soil erosion prevention to safeguard lives and property from floods, drought, erosion after fire, or other natural occurrences that caused watershed impairment. The Mimbres decision restricted the scope of federal reserved water rights under the 1897 Organic Act to the minimum needed to secure favorable conditions of water flow, or for sustained timber supplies. In dicta, the Supreme Court dismissed reserved rights claims for recreation, grazing, and fisheries under the Multiple-Use Sustained-Yield Act of 1960.

To encourage technology transfer, agency hydrologists published an important summary of forest watershed management knowledge (Anderson et al. 1976) and convened national meetings at Grand Targhee in 1974, and Atlanta in 1978. These were the first meetings of mostly field based hydrologists, and contrasted markedly with the 1955 soil and water meeting in Denver which consisted entirely of 85 Washington Office and Regional Office based personnel. Some 83 hydrologists and hydrological technicians attended the Targhee meeting (82 men and 1 woman), while 130 attended the Atlanta meeting (119 men and 11 women). Both meetings were very successful in accomplishing their networking and technology transfer objectives. They helped set the stage for the following era and the 1992 FS National Hydrology Workshop in Phoenix.

Planning and Ecosystem Management: 1980-Present

Development of the initial round of Forest and Resource Plans based on the 1979 planning regulations that followed passage of NFMA engaged almost every physical scientist or practitioner during this period. As a result, very few new watershed initiatives were undertaken and some of those started in the 1960s, like the barometer watershed program and many water quality monitoring efforts, were terminated. There has also been a slow but steady decline in inflation-adjusted Forest Service watershed administration and research funds in this period.

Several important watershed events did occur. The Forest Service and USEPA cooperated in a massive water quality sampling effort in 1985 as part of the National Acid Precipitation Assessment Program. Over 2,000 remote lakes, often in wilderness areas, were sampled during their fall overturn period, under often difficult weather and logistical conditions, for their vulnerability to acidification from deposition of atmospheric pollutants. Limited, concurrent sampling by USEPA personnel in helicopters that landed on the lakes within minutes of the Forest Service ground-based crews that rafted out to the deepest part of the lakes proved that the Forest Service crews did a superb job of their sample collection, preservation, and transfer of samples to mobile labs set up at nearby airports within four hours of sample collection. This effort greatly increased the trust that USEPA had in Forest Service personnel.

Also in 1985, Data General mainframe computers were installed at almost all agency offices. This network allowed better communication among employees and sharing of ideas, methods, draft papers and data. They also allowed batch processing of large data sets using FORTRAN. Both were significant improvements over earlier dumb Typagraph terminals and tiny CPU processors.

The number of watershed councils and other ad hoc committees devoted to improving some aspect of watershed management has blossomed during this period. They are trying to accomplish what earlier federal river basin planning commissions and groups never could: application of real solutions to local problems of water quantity, quality, or both.

The year 1992 saw the New Perspectives and PACFISH initiatives, and the Appeals Reform Act. President Clinton's Northwest Forest Conference in 1993 and the Ecosystem Management Conference in 1994 also changed how watershed management is practiced by the agency by greatly expanding the number of stakeholders and the planning processes used to make a decision. In 1997, Chief Mike Dombeck introduced the "Collaborative Stewardship" term to describe his vision of working together with many partners to accomplish the "Taking care of the land and serving people" mission statement of the agency. Watershed management is embedded within the collaborative stewardship terminology. The late 1990s also

saw an interagency, inter-disciplinary team effort led by this author to develop agency policy, and technical and legal guidance for managing the ground water resources of the national forests and grasslands. This effort is expected to be completed in 2005.

The large wildfires of 2000 and 2002 led to creation of the National Fire Plan and passage in 2003 of the Healthy Forests Restoration Act (HFRA) by Congress. This Act could result in a shift of soil, water, geology and air resources expertise toward work on planning and execution of projects designed to reduce woody fuel accumulations in the wildland-urban interface zone. The Act also provides for small increases in watershed expertise in state forestry organizations.

Future Prognosis: Present to 2100

This section is based upon an evaluation of current demographic, societal and natural resource trends projected into the future. Since the future is really unknowable, these projections represent a mix of subjective and some objective views of the author and others. Only time will tell if any of these projections or views were correct; they are intended to stimulate discussion now.

The population of the United States in the 2000 Census was 283 million. The Population Reference Bureau projects that number to be 422 million in the year 2050 (Haub 2003). I estimate it could be 650-700 million in the year 2100. Not only will the absolute numbers be higher, but the average population is projected to grow steadily older, richer, healthier, and more ethnically diverse and urbanized (Cetron and Davies 2003). All of these factors, plus future legislation and court rulings, will affect the commodities and amenities Americans expect from their national forests and grasslands.

By the year 2040, the 1990 RPA Water Situation report (Guldin 1989) predicts water supply shortages in many parts of the southwestern U.S., depletion of groundwater in California, Nevada, Utah, and growing shortages in eastern and midwestern states. Projected changes in freshwater withdrawals for public and domestic uses from 2000 to 2050 could rise 85 percent, industrial and commercial uses could increase 71 percent, and irrigation could decline by nine percent in the west coast states of California, Oregon, Washington, and Idaho (Houston et al. 2003) The amount of cropland being irrigated in the East and South is growing rapidly (Hutson et al. 2004) and is likely to cause more rivers to become partially or totally dewatered in the future unless state water rights laws are changed to prevent it. Based on the rate of change in western states water rights laws, the chances of the eastern states upgrading their laws appear "iffy" at best in my opinion.

By 2050, water quality effects from non-point sources of pollution typically found on NFS lands are expected to approximate today's conditions. It is very difficult to make large improvements in what are often small amounts of pollutants resulting from current land uses in forested watersheds, compared to the large amounts of eroded sediment from colonial farming practices that still clogs many eastern waterways. Drinking water will become more costly to consumers and the amounts of reclaimed wastewater will also have to increase to partially solve local shortages of water for non-potable uses. Today's challenges arise from hardrock mining, oil and gas and coal-bed methane extraction, suburbanization of forested areas, and atmospheric deposition of acidic precipitation and other pollutants. Effective solutions have been difficult to implement for these types of land uses or sources; nevertheless, these parts of what has been dubbed the "Restoration Economy" (Cunningham 2003) will continue to grow rapidly. Forest Service soil scientists, geologists, hydrologists, and air resource specialists employed in 2050 will need to devote increasing shares of their time and attention to tackling these problems over future decades, and there will be fewer of these experts than at present.

By 2100, it is quite possible that the national forests and grasslands will be used primarily for recreation, other amenity values, and for water production. The amounts of timber harvesting, livestock grazing, and oil, gas, and mineral production could decrease greatly. The number of special use authorizations is expected to increase from today's 75,000. Unfortunately, as these numbers grow, the general public's access to their public lands continues to diminish since each of these authorizations essentially becomes a separate in-holding and more expensive and troublesome for the agency to administer. Water shortages will continue in the same basins as in 2050. A better water rights marketplace will develop by 2100 that will allow more transfers of agricultural water rights to ever-growing communities at lower unit transaction costs than in 2000.

Satellites will monitor air, soil, geological and water resources continuously by 2100. They will feed this data into large data warehouses where the few remaining agency specialists will use it to develop contracts for private sector firms of resource specialists to bid on to do the actual watershed analysis work for NFS lands. Since federal pay in 2100 could be much lower than the private sector for similar work, I think there will be fewer physical science practitioners in the Forest Service in 2100 than there were in 2000. It is also possible that there will be fewer NFS acres in 2100 than there were in 2000,

as land ownership consolidation continues unabated and Water and Conservation Fund monies dry up. There has been, and will continue to be, pressure from individuals, corporations, and perhaps states and the Congress to dispose of federal forest lands for various other needs or wants just as in the 1800s and in the 1930s, when federal forest land acreage actually declined. I certainly hope that I am wrong about this.

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The Marginal Economic Value of Streamflow From National Forests: Evidence From Western Water Markets

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Evidence from over 2,000 water market transactions that occurred in the western U.S. over the past 14 years (1990 through 2003) was examined to learn who is selling to whom and for what purpose, how much water is involved, and how much it is selling for. Roughly half of the transactions were sales of water rights; the rest were water leases. The transactions show that the price of water is highly variable both within and between western states, reflecting the localized nature of the factors that affect water prices. Ideally, if water market prices or valuation studies are to be used to help determine the marginal value of water from specific areas such as national forests, information from local markets or local studies should be used. Lacking site-specific value information, only rough estimates are possible.

Keywords: *water value, streamflow, economic value, water markets*

Introduction

The economic value of a good or service is indicated by a willingness to sacrifice other goods and services in order to obtain or retain it, and is typically measured in money terms, usually as willingness to pay (WTP). WTP may be determined for changes in the quantity, quality, or timing of water. This paper deals with the value associated with water quantity, specifically the quantity of streamflow.

The value of a small change is what economists call marginal value. Estimates of marginal value are useful in analyzing policies that cause relatively small changes, such as changes in streamflow resulting from vegetation management. Of course, even small changes in streamflow may have numerous additive downstream effects. For example, an acre-foot of streamflow increase may first be used by recreationists, next pass through a hydroelectric plant, then be diverted to a farm, and finally be diverted to a city, all the while helping to dilute wastes and enhance fish habitat. The aggregate value of a change in streamflow is equal to the sum of its values in the different instream and offstream uses to which the water is put during its journey to the sea (e.g., Brown et al. 1990). For the general case, the aggregate value of a small change in streamflow (V^*) is given by:

$$V^* = \sum_i \alpha_i \beta_i V_i$$

where i indicates a water diversion or instream use location; α_i is the proportion of the marginal acre-foot that reaches a use i (water that is not consumed upstream) ($\alpha \leq 1$); β_i is the proportion of the marginal acre-foot reaching use i that arrives when it actually can be of use ($\beta \leq 1$); and V_i is the value of the marginal acre-foot in use i assuming the water is put to use ($V \geq 0$).

The task of estimating the marginal value of streamflow from a national forest thus consists of estimating the V_s and their respective αs and βs. Our focus here is on V_i.

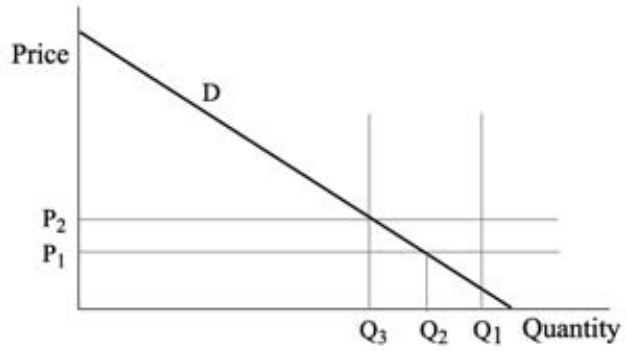
There are two basic approaches to estimating the marginal value of water: employing economic valuation methods and observing water market prices. The suite of valuation methods (Gibbons 1986; Young 1996) was developed because markets for goods like water were uncommon and, when present, rarely competitive. However, water market activity has increased in recent years, raising hopes that water markets can offer useful estimates of water value. This paper presents evidence from water market transactions in the western United States.

To review how price is related to marginal value, consider the case of offstream uses depicted in Figure 1. If demand (i.e., marginal WTP) for water at a point of use is represented by D, Q_1 is the total quantity of streamflow available, and P_1 is the cost of transporting (e.g., pumping) the diverted water to the point of use, then users desire to divert Q_2 units. Here the net marginal value of the diverted streamflow (V) is P_1-P_1 = 0 per unit. Alternatively, if water supply were constrained at Q_3, Q_3 units would be diverted. At a diversion of Q_3 units, the marginal value of delivered water is P_2, and $V = P_2$-P_1. If a competitive market for streamflow existed in this location, the market price would be P_1, and if a competitive market for delivered water existed its market price would be P_2.

Furniss, M.J., Clifton, C.F., Ronnenberg, K.L., eds., 2007. *Advancing the fundamental sciences: proceedings of the forest service national earth sciences conference, San Diego, CA, 18-22 October 2004*. PNW-GTR-689. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station.

This example thus illustrates two points: (1) streamflow has value at the margin only when there is not enough of it to meet all demands; and (2) if the price includes consideration for storage or delivery, it may overstate the marginal value of streamflow.

Figure 1. Marginal value of offstream diversion.



Water Markets

Water has become scarcer as population, economic growth, and changing values in the West have increased demand for water (Gillilan and Brown 1997). Where institutions allowed it and transaction costs were not excessive, the growing scarcity often brought willing buyers and sellers together in what is called a water market. The term "water market" lacks a precise definition, but once a few voluntary trades of water of relatively common physical and legal characteristics occur, it is said that a water market has developed.

Water markets require a well-administered system of transferable water rights. The doctrine of prior appropriation that underlies water law across the West allows for clearly defined and transferable water rights, and state agencies or the courts administer and enforce those rights, although the states differ in how they implement the doctrine and administer the water rights systems (National Research Council 1992).

Water market activity may be limited by physical and legal constraints. Physical constraints on water trades, such as uneven water availability and lack of access, are eased by such structures as diversion dams, canals, and storage reservoirs, which extend spatial and temporal control over water delivery. Legal constraints on water sales often exist, perhaps due to state law (e.g., constraints on moving water to another basin, or constraints on the availability of instream flow rights) or federal guidelines for specific water development projects. As scarcity has intensified, some constraints on water markets are being loosened (North 1990; Loomis 1992).

If water in a water short area were freely traded in an efficient market, water would be reallocated via trades to the point where each user was consuming at the point where the marginal values in all uses were identical (e.g., the marginal value in irrigation would be equal to the marginal value in municipal use or in instream recreation). In this ideal world, a single market price would emerge that would indicate the marginal value of raw water in that market area. However, in the real world, even in those locations where water markets exist, water rarely trades so easily or completely. Two reasons for this are lack of a homogeneous product and lack of market competitiveness.

Lack of homogeneity is a natural consequence of how the prior appropriation doctrine accommodates the stochastic nature of streamflow. The doctrine deals with shortage by assigning priorities to water rights and temporarily canceling permission to divert based on those priorities, beginning with the most junior right and moving as far up the list of priorities as needed to assure delivery to more senior rights. Each individual right may have a unique priority date. Senior rights are worth more than junior rights because senior rights face less risk of shortage. If each right is unique, homogeneity of product is compromised. However, within the overall structure of prior appropriation there exists a quite different approach know as fractional flow rights (Eheart and Lyon 1983). With such rights, all users have equal priority, and shortage is accommodated in a given time period by lowering the allowable diversion for all users. The use of fractional flow rights is common in mutual ditch companies and some water conservancy districts, wherein water is owned as shares of the total amount available (Hartman and Seastone 1970). Within such an organization all members essentially have the same priority, and the effect of a flow increase available to the organization is distributed to the members in proportion to the number of shares each owns, thus providing homogeneity of product. Many of the more active water markets deal in shares of such a company or district.

A fundamental tenet of neoclassical economic theory is that competitive markets yield prices that reflect the true marginal economic value of the good being traded. Competitive markets have many buyers and sellers, do not artificially restrict price or ability to trade, have low transaction costs, allow an easy flow of information about prices and potential trades, and internalize all relevant costs and benefits of the transaction. Water markets typically fall short on one or more of these requirements. Many markets areas are so small that sellers and buyers are few. In others, laws, regulations, or customs limit price. In many water markets transaction costs are substantial, involving

administrative and legal requirements. In many markets information is not readily available. And externalities (effects on individuals not party to the exchange) commonly exist, especially in the form of changes in water quality and instream flow (Howe et al. 1986; Saliba 1987). Some of these restrictions on the competitiveness of the market (e.g., a limited number of sellers) may elevate the price relative to the price that would be established in a purely competitive market, whereas others tend to depress the price (e.g., government subsidies, transaction costs, regulations or customs). Many of the restrictions, such as transaction costs, will also tend to limit the number of trades.

Studies of water markets have usually focused in detail on one or a few specific markets (e.g., Hartman and Seastone 1970; Saliba et al. 1987; Michelsen 1994; Howe and Goemans 2003). Only with a detailed examination can the numerous characteristics of the individual markets be given their due consideration. This study, in contrast, takes a broad look across the western United States, emphasizing geographical scope rather than in-depth focus (see also Brown 2006). This "big picture" approach offers a look at how water prices in general have changed over the past few years and how they differ across locations or across the purposes for which the water was purchased.

When water is sold in the West, either a water right changes hands or use of the right is essentially leased for a period of time. Ownership of a water right conveys access to a specified quantity of water in perpetuity, subject to particulars such as priority, timing, and location. With a water "lease" as used herein, the holder of the right agrees to deliver, or allow the buyer access to, a certain quantity of water over a stated time period, subject to conditions such as timing of access and location. One-time transfers of water (essentially short-term leases) are sometimes called "spot market" trades or "rental" transactions. This paper reports on both sales and leases of water rights.

Methods

The broad-scale examination of water prices reported here is made possible by the Water Strategist and its predecessor the Water Intelligence Monthly, published by Stratecon, Inc., of Claremont, California, which have summarized many of the available western water market transactions in reports released on a monthly or quarterly basis. Fourteen years of transactions reported by these publications (1990-2003) were tabulated to provide the estimates of the price of water described here. It is important to note that these publications did not report on all the transactions that occurred. Especially in the case of water leases, large numbers of trades were not summarized. Neither are the included transactions a random sample. Thus, the current report indicates the nature, but not the breadth or precise character of western water trades.

Each water transaction entry in the Water Strategist or Water Intelligence Monthly briefly summarizes one or more actual trades. The entries do not allow a full understanding of what influenced the price, and are not always consistent in how the transactions are described (perhaps because some information was not available). Nevertheless, most of the entries provide sufficient information for a rudimentary analysis of the factors influencing water market prices, and together they form the most comprehensive set of information available about water market trades in the western United States.

The entries typically include buyer, seller, purpose for which the water was purchased, type of transaction (whether purchase or lease of a water right), and the source of the water (surface water, ground water, effluent, or potable water). Buyers and sellers are categorized herein as one of the following: (1) municipality; (2) irrigator (farmer or rancher); (3) private environmental protection entity (e.g., public trust concern, or private entity such as the Nature Conservancy); (4) private entity providing water to many users, such as a water "district," "association," or "company," referred to here as a "water district"; (5) public agency (federal or state government agency, conservancy district, or other water "authority"); (6) other entity (e.g., power company, mining company, developer, investor, country club, feedlot, individual homeowner); or (7) several entities (when several buyers or sellers of different types were listed, such that the transaction could not be neatly assigned to one of the other categories.

The purpose of the transaction was characterized as one of the following: (1) municipal or domestic (including commercial and industrial if serviced by a municipality, and golf courses and other landscape irrigation); (2) agricultural irrigation; (3) environmental (e.g., instream flow augmentation); (4) other (e.g., thermoelectric cooling, recreation, mining, aquifer recharge, augmentation of flows leaving the state per court order, supply to individual businesses such as feedlot or manufacturing plant, an investment of undefined characteristics, unspecified); or (5) several (several purposes, such that the transaction could not be neatly assigned to one of the other categories).

Some entries covered several related transactions. For example, several sellers or several buyers, or both, may have been included in the entry. Or several transactions within the same market may have been listed together in the same entry. Such entries were broken down into separate cases for analysis if distinct prices were listed and different categories

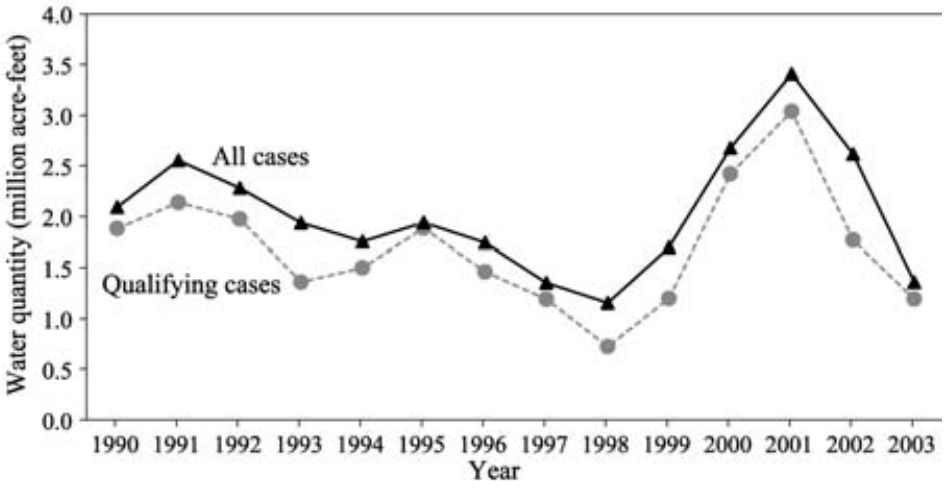


Figure 2. Trends in total number of acre-feet transferred .

of buyers, sellers, or purposes were involved. After this disaggregation process, a total of 2,447 transactions were available for the 1990-2003 period.

The Colorado Big Thompson (CBT) market is the most active market for water rights in the West, with up to 30 or more purchases per quarter by municipalities alone. It is also a market about which market information is readily available. The entries listed 949 CBT trades over the 14 years. Because the sale price for CBT shares differed little among trades completed during a given month, and because the volumes traded were typically small (averaging 40 acre-feet), all CBT transactions of a single purpose within a given month were tabulated as one case for analysis in order to avoid having CBT transactions overwhelm the summary statistics. This aggregation process left a total of 228 CBT cases for the 14-year period, and thus a total of 1,726 cases (2,447 - 721 CBT transactions consolidated) for analysis.

Of these 1,726 cases, 349 were omitted from further analysis because key information was missing (such as price or amount of water transferred), something other than raw water (i.e., effluent or treated water) was involved, the price included payment for things other than water (e.g., land), or the transaction was not a market sale (e.g., it was an exchange or a donation). Thus, 1,377 qualifying cases (1,726 - 349 missing information) were left for analysis. Figure 2 shows the total water volume by year of the qualifying cases and the full set of cases.

Prices, expressed on a per acre-foot basis, were adjusted to year 2003 dollars using the consumer price index. Prices for water rights were converted to an annual basis using a 3% interest rate, which is approximately the mean annual growth rate in real gross domestic product over the past 20 years in the U.S. Although mean prices are also reported, this analysis emphasizes median prices, which more accurately indicate the price of a typical water sale when the price distributions are skewed.

Prices paid for untreated water often include reimbursement for water management, including such services as storage and conveyance, in addition to the cost of the raw water in the stream. Such prices are analogous to P_2 in Figure 1 given supply at Q_3. Because our primary interest is in the value of streamflow, costs of water management were not included in the price when such costs could be separated out. However, storage and delivery services are so commonly a part of water transactions that such services were often not even mentioned in the entries. Most prices reported here probably include some consideration for the value of water management services.

Results

All results reported here are based on the 1,377 cases meeting the criteria for further analysis explained above. Figure 3 shows the number of cases by a convenient geographic breakdown, climatic division (*www.cdc.noaa.gov*). Fourteen states have qualifying cases (all states in Figure 3 except North Dakota, South Dakota, and Nebraska). Three climatic divisions within these states have over 75 cases: division 4 in northeast Colorado, including Denver, Fort Collins, and other cities along the northern Front Range; division 5 in California, capturing the southern (San Joaquin River) portion of the Central Valley and on down to the Bakersfield area; and division 10 at the southern tip of Texas, along the Rio Grande as it enters the Gulf near Brownsville. Nine climatic divisions had between 26 and 75 cases-three in California, two in Texas, and one each in Arizona, Colorado, Idaho, and Nevada. Thirteen climatic divisions had between 11 and 25 cases, and 43 had from 1 to 10 cases. Another 44 climatic divisions in the 14 states had no cases.

Figure 3. Number of cases meeting criteria for analysis of market prices, 1990-2003, by climatic division (divisions are numbered independently within each state).

Quantity of Water Sold

A median of 804 acre-feet was transferred per case (the mean is 17,234 acre-feet). Table 1 lists the volume transferred by state. Three states (Arizona, California, and Idaho) account for 75% of the water transferred.

In all years much more water has been transferred via leases than via rights (Figure 4), which reflects in part the fact that water transfers are easier to agree upon and arrange on a temporary than on a permanent basis. The median lease size over the 14 years is 6000 acre-feet per case, compared with 110 acre-feet for water rights cases. There is considerable annual variation in amount of water transferred for both types of transactions, but no apparent relation between the two trends (R = 0.13).

Ten percent (141) of the cases involve groundwater, with the remainder (1,236) being of surface water. However, only 4% of the water transferred in these trades has been ground water, as suggested by the fact that the average water volumes per case are 6,679 acre-feet for groundwater and 18,438 for surface water.

Table 1. Western water market activity and prices by state, 1990-2003 (both leases and rights, price in year 2003 dollars per acre-foot per year).

	Number of cases	Volume	Price			
	(N)	(1000 acre-feet)	Mean	Median	Min*	Max
Arizona	86	7,910	51	48	0	115
California	294	8,104	96	66	0	1,000
Colorado	427	443	133	81	1	630
Idaho	64	2,802	15	6	0	251
Kansas	16	11	40	48	13	54
Montana	5	15	20	6	2	56
New Mexico	59	525	77	55	1	607
Nevada	69	1,299	125	106	6	375
Oklahoma	3	81	246	118	46	575
Oregon	43	261	31	9	1	302
Texas	207	1,376	104	28	7	2,258
Utah	43	122	34	16	5	165
Washington	25	563	70	32	3	343
Wyoming	36	219	37	40	3	93
All	1,377	23,731	96	56	0	2,258

** Cases with a $0 price were not included. $0 indicates rounding of a very low price.*

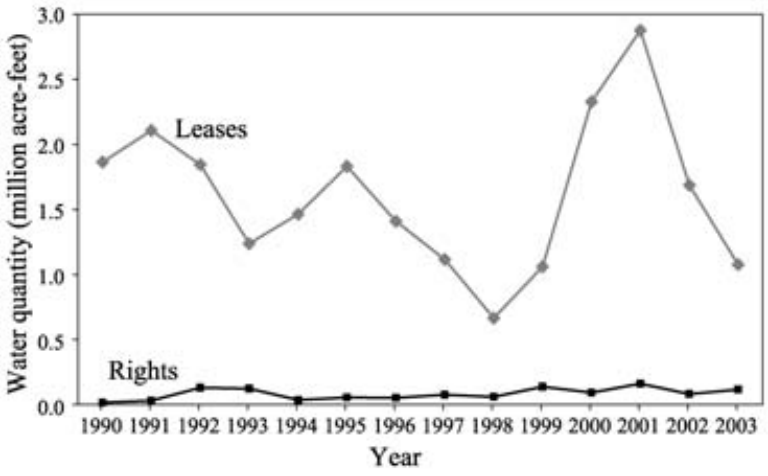


Figure 4. Trends in total quantity of water transferred (qualifying cases only).

Price of Water

A quick look at Table 1 reveals at least three findings of interest about water prices. First, mean prices exceed median prices for the complete set of cases (a mean of $96 per acre-foot per year versus a median of $56) and for all but two states. Second, the range in price is substantial for each state, with most minimums near $0 and maximums typically in the $100s (the maximum of $2,258 is for a lease by a mining company). Clearly, water changes hands at a variety of prices. Third, the median prices vary substantially among the states, ranging from below $10 in Idaho and Oregon to over $80 in Colorado and Nevada (ignoring Oklahoma and Montana because of their small numbers of cases). There is no apparent relation between number of cases and median price. Also of note is that water trades are much more common in some states (e.g., California and Colorado) than others (e.g., Montana and Oklahoma). Water scarcity no doubt plays some role in determining the number of trades, but institutional and legal differences are probably the most important factors affecting sale frequency among the western states.

To begin to understand the reasons for the range of median prices, consider Table 2, which summarizes the sales by type of transaction, either a lease or a perpetual right. Over all states, the median price for leases ($47 per acre-foot per year) is about two-thirds that of rights ($72) given the 3% interest rate for annualizing prices of rights. However, the median price of leases exceeds the median annualized price of rights in most states. The overall superiority of median water rights prices results largely from the fact that 56% of the water rights cases are for Colorado, a state where the median price of water rights far exceeded the median price of leases. Fully 216 (59%) of the 369 water rights cases for Colorado are of CBT shares, and another 129 (35%) are for other water rights along the northern Front Range within or near the area of the Northern Colorado Water Conservancy District where CBT shares trade (in climate division 4, Figure 3). Also of interest is that for 10 of the 14 states the number of lease cases exceeded the number of rights cases. The exceptionally high number of water rights transactions in Colorado reflects the relative ease with which such transactions can be accomplished and the strong demand for secure water supplies by the fast-growing cities along the Front Range.

Table 3 summarizes the cases by the purpose for which the water was purchased. Over half (739) of the purchases were for municipal purposes, another 23% (321) were for irrigation, and 11% (150) were for environmental purposes. The median price paid for municipal uses ($77)

Table 2. Western water market prices by state and type of transaction, 1990-2003 (year 2003 dollars per acre-foot per year).

	Leases		Rights	
	N	Median ($)	N	Median ($)
Arizona	48	58	38	40
California	250	68	44	37
Colorado	58	18	369	84
Idaho	49	8	15	3
Kansas	11	50	5	16
Montana	5	6	0	
New Mexico	29	55	30	76
Nevada	4	83	65	109
Oklahoma	2	347	1	46
Oregon	34	9	9	7
Texas	159	29	48	24
Utah	11	7	32	17
Washington	21	37	4	13
Wyoming	34	40	2	43
All	715	47	662	72

Table 3. Western water market prices by purpose of buyer, 1990-2003 (both leases and rights, year 2003 dollars per acre-foot per year).

Purpose	N	Mean ($)	Median ($)	Min ($)#	Max ($)
Municipal	739	118	77	0	1607
Irrigation	321	46	28	1	490
Environment	150	56	40	0	450
Other	105	180	62	2	2258
Several	62	51	56	2	190
All	1377	96	56	0	2258

 # Cases with a $0 price were not included. $0 indicates rounding of a very low price.

was nearly three times that paid for irrigation water ($28) and nearly twice that paid for environmental purposes ($40). Purchases for municipal purposes tended to be of water rights (453 cases involving rights versus 286 for leases), suggesting that municipalities desire-and are able to pay for-dependability of supply. Purchases for irrigation and environmental purposes tended to be of leases.

For the three principal purposes for which water was purchased (municipal supply, irrigation, and environmental protection), there is a wide range in median price across the states (Table 4). The overall median price paid for municipal water ($77 per acre-foot per year) is heavily influenced by sales in Colorado, where the median price of the 250 cases is $88. Other states with both high median prices for municipal purposes and a substantial number of cases are California (median of $96), Nevada ($110), and Wyoming ($77). Excepting Colorado, the median price of the remaining 489 sales for municipal purposes is $57. The overall median price paid for irrigation water ($28) is also heavily influenced by Colorado, which had over one-third of these cases and a median price of $72. Other states with a substantial number of cases include California (median of $45), Idaho ($4), and Texas ($24). Excepting Colorado, the median price of the remaining 211 cases for irrigation purposes is $16. Among purchases for environmental purposes, states with the highest median prices and with at least ten cases are California ($64), Colorado ($20), Idaho ($8), Oregon ($26), and Washington ($32).

Table 4. Western water market prices by state and purpose of buyer, 1990-2003 (both leases and rights, year 2003 dollars per acre-foot per year).

	Municipal		Irrigation		Environmental	
	N	Median ($)	N	Median ($)	N	Median ($)
Arizona	47	48	12	45	5	45
California	149	96	66	45	51	64
Colorado	250	88	110	72	19	20
Idaho	5	6	31	4	19	8
Kansas	14	48	2	51	0	
Montana	0		1	6	3	2
New Mexico	26	77	4	50	10	47
Nevada	59	110	0		7	43
Oklahoma	3	118	0		0	
Oregon	0		20	8	19	26
Texas	141	26	40	24	0	
Utah	28	20	13	7	2	40
Washington	3	40	5	17	15	32
Wyoming	14	77	17	5	0	
All	739	77	321	28	150	40

Who Sold to Whom, and for What Purpose?

Irrigators are the sellers in 38% (531) of the cases (Table 5), not counting when they might appear among the 222 cases involving several sellers. Public agencies are the sellers for another 16% (224) of the cases. These public agency sales include those involving State Water Project or Central Valley Project water in California, Central Arizona Project water in Arizona, and water managed by the U.S. Bureau of Reclamation in many states, including Colorado, Oregon, and Wyoming. Nearly all public agency sales were leases.

Municipalities were the most common buyers of water, accounting for 27% (375) of the cases (Table 5), not counting when they might appear among the 206 cases involving several buyers. Other active buyers were public agencies with 17% (234) of the cases, farmers with 15% (204) of the cases, and water districts with 13% (183) of the cases.

Trends in Occurrence and Price

The number of cases per year (across all states and purposes) ranges from a minimum of 77 in 1995 to a maximum of 142 in 1999 (Figure 5). Recent years show an increase in the number of cases (over the 14 year period, the four highest numbers of cases occurred in 1999, 2001, 2002, and 2003); the overall increasing trend is statistically significant at the 0.05 probability level based on the Mann-Kendall test for time trends (test statistic = k = 2.56). Examining sales of leases and rights separately reveals that the number of leases has increased substantially over the past 14 years (k = 3.60), whereas the numbers of sales of rights show no trend (k = -0.49).

The median price per year (across all states and purposes) ranges from $34 in 1998 to $76 in 1991 (Figure 5). No overall trend is evident (k = 0.24). However, looking

Table 5. Number of western water market trades from seller to buyer, 1990-2003 (both leases and rights).

Seller	Buyer							Total
	Municipality	Irrigation	Environmental	Water district	Public agency	Other	Several	
Municipality	26	8	0	7	18	6	4	69
Irrigator	175	96	10	60	95	40	55	531
Environmental	1	0	1	0	1	0	0	3
Water district	21	19	1	38	32	8	16	135
Public agency	39	48	1	32	46	18	40	224
Other	60	12	1	26	22	68	4	193
Several	53	21	0	20	20	21	87	222
Total	375	204	14	183	234	161	206	1377

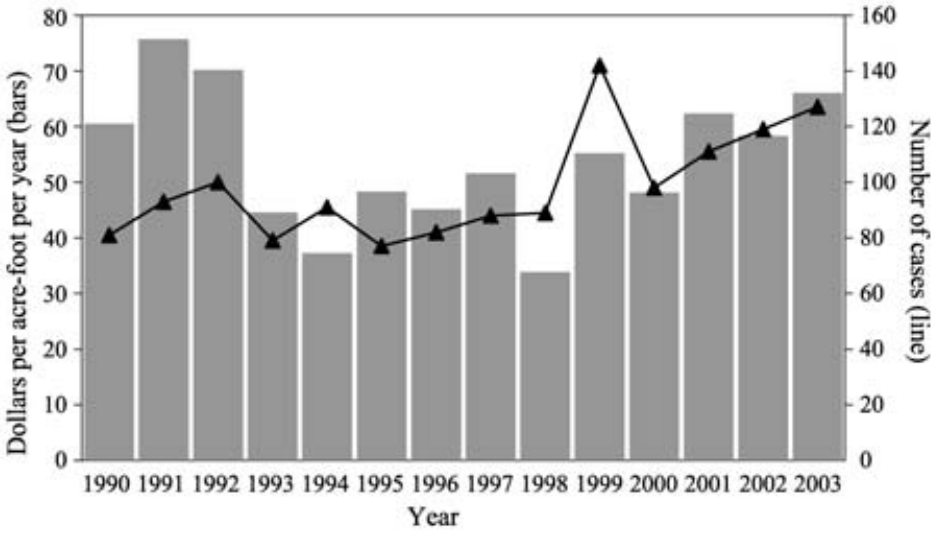


Figure 5. Trend in median price of water, all water uses (includes both leases and rights, year 2003 dollars).

separately at sales of leases and rights reveals that the median price of rights has increased significantly ($k = 2.07$), whereas the price of leases has not ($k = 0.00$). Colorado, especially the Front Range area, is largely responsible for the overall increase in the price of water rights.

Price Differences Across Markets

Space constraints preclude presenting details here about individual water markets. An analysis of separate markets revealed the following findings. First, prices at a given time can vary considerably even among markets located quite close to each other. Such markets often differ in local economic conditions, availability of alternative supplies (such as groundwater as a supplement for surface water), extent of water distribution infrastructure, and past decisions to obtain secure surface water rights. Second, prices in competitive markets can change dramatically over time in response to development pressures or weather cycles. Third, prices of leases in many markets are heavily influenced by administrative criteria, and thus not competitively set (exceptions to this observation include the Texas Rio Grande lease market). Fourth, water rights are typically sold in relatively competitive situations where the prices are determined by individual negotiations between buyer and seller.

Conclusions

Analysis of the trades reported by Stratecon allows the following general statements (which may not represent the full population of western trades):

1. The incidence of water market trades is geographically variable. Markets are very active in a few areas of the West, but most areas apparently had few trades over the past 14 years. Although three states (California, Colorado, and Texas) account for three-fourths of the qualifying sales, even in these states some areas had very few trades.

2. In a given year, at least ten times as much water changes hands via leases as changes hands via sales of water rights. The median size of leases is over 50 times that of water rights sales.

3. Across the western states, the median price of water is highly variable, with Colorado and Nevada having the highest medians, and Idaho and Oregon having the lowest medians, when sales of leases and rights are combined. However, the price of water is also highly variable within every state, reflecting the particular physical and legal characteristics of individual water markets. This variability makes it risky to transfer a value from one location to another, thus complicating the process of benefit transfer.

4. Among the major purposes for which water was purchased, purchases for municipal uses have the highest median price ($77) and account for over half of all trades. Purchases for agricultural irrigation and environmental protection have lower median prices (roughly $35).

5. Purchases for municipal purposes have tended to be of water rights, whereas purchases for irrigation, environmental, or other purposes have tended to be of leases.

6. Irrigators were the sellers in about 40% of the transactions. Public agencies, such as federal agencies managing large water storage and delivery projects, were the sellers in another 16% or so of the transactions. Municipalities were the most common buyers, accounting for about 30% of the transactions. Other common buyers were farmers, public agencies, and water districts.

7. Across all cases, the median price of leases in real terms showed no consistent trend over the past 14 years, whereas the median price of water rights showed an upward trend.

Water market activity in aggregate offers a broad and rich understanding of the value of water. Water values can be substantial, but because they also are highly variable both geographically and temporarily, care must be used in applying water market prices to analyze policies affecting streamflow.

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An Army of Watershed Specialists: Good Working Relationships Encourage Everyone to Value Watersheds

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By developing strong personal relationships, physical scientists can get the field-going people in their sphere of influence to do the best job possible for the sake of watershed health. In order to accomplish a large workload with limited resources, it is valuable to use the entire workforce to find, report, and improve unacceptable watershed conditions. When there is mutual respect among hydrologists, timber sale administrators, engineers, and other Forest Service disciplines, the watershed is the biggest winner, because those employees can act as recruits in the "watershed army". To recruit this army, hydrologists need to listen to the needs and challenges of their coworkers. This active listening promotes additional communication between watershed specialists and people who can help improve watershed conditions. When scientists participate in cooperative work to meet agency objectives, this proves their commitment to accomplishing the entire job, and fosters a cooperative spirit within the entire organization. Finally, after the army has been enlisted and beneficial watershed work has been accomplished, those employees need to feel appreciated, in order to encourage them to continue to fight for improved watershed conditions. When all Forest Service employees are interested in being good watershed stewards, the effectiveness of a single physical scientist can be multiplied.

Keywords: *resource management, partnership, restoration*

Introduction

Hydrologists are a relatively scarce resource in the Forest Service, with large areas of responsibility and huge workloads. In order to maximize their effectiveness, watershed specialists can enlist other employees to help them care for the land, and accomplish more resource improvement objectives in a time when personnel and funding are dwindling. Building strong personal relationships and working together are the way to get the entire job done.

This paper contains case studies from the North Zone of the Black Hills National Forest, South Dakota, and ideas on how physical scientists can work with their fellow employees to maximize watershed benefits. A hydrologist may think, "I'm the hydrologist, and that's all I do". However, by thinking more broadly, and doing everything possible to build solid relationships with the other people on a district, zone, or forest, scientists can be more effective. No one can do everything on his or her own. The Black Hills in an active forest that has many timber sales, fuels projects, recreation activities, land transactions, mineral operations, and grazing allotments. All of these actions have the potential to affect watershed resources. In order deal with this level of activity, and build good relationships, a watershed specialist should listen to the concerns and challenges facing their coworkers, demonstrate respect and understanding for other people's jobs and viewpoints, communicate watershed concerns while participating in work that is mutually beneficial to all, and appreciate work that is done in order to achieve a better outcome for watershed values.

Case Studies

Mud Bogging

Fresh out of graduate school, I was relatively new to the Forest Service, new to the job, and definitely new to the Black Hills. I didn't know what was happening on the ground, and didn't even really know what could happen out there.

For example, our Law Enforcement Officer (LEO) notified me of a situation where ATVs (all-terrain vehicles)

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Figure 1. ATV ruts in Johnston Gulch. Photo by Ken Boerman.

Figure 2. Johnston Gulch condition before signing and enforcement. Photo by Ken Boerman.

Figure 3. Johnston Gulch condition after signing and enforcement. Photo by Ken Boerman.

and 4X4s had been mud bogging in a Black Hills riparian area (Figure 1). He knew this was a problem, and because he and I had communicated with each other on occasion, he knew who to contact about it. We talked more and I listened to his past experience with this kind of activity and how to stop it. I expressed to him that this was a priority area to address, and he agreed to do some enforcement work at this site. During a stakeout on Easter weekend (11 April 2004), he caught someone in the act of destroying this meadow, and issued a citation. LEOs are very busy, with more enforcement work than they could ever handle, but because we talked, and because he felt that some enforcement could make a difference at this site, we put some time and effort into patrolling this area and posting some closure signs.

Before we took any signing or enforcement measures, this area did not meet riparian objectives (Figure 2). Upstream from the photographed area, a hand-excavated trench diverts water flow out of the natural drainage channel and onto the road surface. ATVs and full-size 4x4 vehicles have driven along this road, and through this wet meadow, intentionally looking for ways to make more tracks. Fortunately, after the LEO issued a few citations, and our Recreation Staff Officer talked to some of the local off-road clubs, people have left this spot alone, and conditions are improving. In this case, lots of eyes looking for problems found an area that was in trouble, and some cooperative work helped turn things around. As a new hydrologist in a new place, I could not know everything. However, with a little help from people in the field, we were able to improve conditions at this site (Figure 3).

Snowmobile Trail Erosion

In order to cover more ground, and accomplish more resource improvement, I enlisted the help of our engineers. They are looking at roads all the time. Since connected disturbed areas associated with roads are the main source of damage in all regions (USDA 2001), it makes sense to get more people to look at water/road interactions. By communicating my concerns and participating in joint field visits, I was able to understand the complete situation, and work cooperatively to find a solution.

After using GIS to find locations where roads overlap with perennial streamcourses, and conducting site visits to find evidence of direct sediment contributions, I contacted the engineers about rills in the fillslope of the road, and the resulting sediment plumes in the creek. Spearfish Canyon is one of the few major perennial streams on the Northern Hills District. It is a popular fishing destination with resident brook trout (*Salvelinus fontinalis*) and is one of the most visited canyons on the forest. Once I shared my concerns with the engineers, one of them brought some additional details to my attention.

Although the majority of the erosion and sedimentation problems in the Black Hills are the result of heavy summer thunderstorms, this problem was the result of snowmelt along the snowmobile trail. This road is closed in the winter, and groomed as a snowmobile trail. This grooming creates packed snow conditions on the surface of the road, and large snow berms along the sides of the road. In the spring, melting snow generates water that flows down the surface of the road, since the berms prevent water from flowing into the ditch or shedding off the road. This trapped flow gathers volume and energy as it continues downhill, forming small gullies in the road surface. Eventually, the water reaches the end of the melting snow berm, and cuts a deeper gully in the fillslope as it falls off the side of the road, and down to the creek, at the bottom of the fillslope. Because of our good working relationship, and because these conditions affect the integrity of the road as well as the stream, the engineers and I worked together with the recreation specialist to solve this problem.

The road is constructed with lead out ditches that route water and sediment through filter zones before it reaches the creek. To allow the snowmelt to access these lead out ditches, changes can be made to the snowplowing techniques used by the snowmobile trail grooming machines. The berms can be broken up by "snow ditches" or plowed openings in the berm. This allows snowmelt to escape the road surface, and flow into the filter strips, before it concentrates and generates enough volume and energy to start eroding the road surface and fillslope. Therefore, it reduces the amount of sediment reaching the creek. With this as an example of cooperative success between engineers and hydrologists, future work can be done, where hydrologists or watershed crews can report on road maintenance problems, and engineers can find and repair watershed problems at damaged sites.

Timber Sale Best Management Practices

Large timber sales can be difficult to survey with only one person. If other district personnel fail to look for the same problems that I look for, something will certainly be missed. That is why it is ideal to work with the other people on the districts to spot potential problems and take the necessary measures to avoid creating them in the first place.

Heavy mechanical vehicles dragging logs on a steep slope adjacent to a creek could result in excessive sediment delivery to the creek. However, to expedite emergency vegetation treatment, a special law passed by congress exempted 8,000 acres (3,240 ha) on the Black Hills National Forest from the environmental analysis requirements of the National Environmental Policy Act (NEPA). Because of this exemption, I didn't get the opportunity to identify a potential trouble spot on one of the timber sale areas. Fortunately, sale prep foresters and sale administrators – looking for the same kind of problems that I look for – brought this to my attention before the sale was even sold. They recognized the risks of operating within a few feet of a creek. The law also exempted this area from compliance with Forest Plan Standards and Guidelines, including those designed to protect soil and water quality. Despite this, the foresters and administrators still asked for my advice on how to reduce the risk to water quality.

After several site visits and weeks of proposals and counter proposals, we reached an agreement to reduce potential impacts on water quality. Logging operations were conducted over the snow and with frozen soil conditions, to reduce soil damage and loss of ground cover. Landings were designated and placed in locations away from the stream, or in places where potential runoff would be filtered through remnant riparian and streamside vegetation. Some steeper sections of the sale were dropped, since they could not be accessed in frozen soil conditions, and couldn't be operated on during dry conditions without causing unacceptable soil damage. Finally, temporary bridges were used at pre-selected locations to enable harvest operations on the far side of the creek without damaging streambanks or building new roads. By working together to put necessary mitigation measures in place, large problems can be avoided.

Listen, Communicate, Participate, Appreciate

Listen

In order to encourage other Forest Service employees to bring problems forward, it is important to listen and show interest in their work. Listening to people and the challenges that they face helps develop trust and fosters cooperative relationships. These relationships are further strengthened by a constructive, not antagonistic, expression of needs by all sides. By presenting watershed needs and concerns, instead of simply saying, "No, you can't do that", people are given a chance to come up with their own solutions. This solution-oriented mindset gives people incentive to work together to find the best fit for all.

Communicate

When we communicate, we realize that none of us want degraded watershed conditions. Excessive streambank erosion is something Range Conservationists should be willing to bring forward, whether it's caused by overgrazing or not. Communication is the key to this. When watershed specialists talk about why it is important to reduce streambank erosion, and range specialists talk about management techniques that can be implemented, a dialogue is maintained that can lead to tangible improvements. Without such dialogue, the effort to improve watershed conditions receives only a fraction of the attention necessary to create change.

Participate

One way to get people to work with each other is to participate with them on the task at hand. This includes engineering route reviews, timber sale unit inspections, grazing evaluations, and other types of projects. When hydrologists participate in reviews like these, they can learn more about what it takes to do each job in the Forest Service. This greater understanding can put their job into better perspective. Participation can also provide an interactive opportunity to explain the challenges of managing the watershed resource. It's another way to foster good relationships.

Hydrologists that participate in fire fighting or fuel reduction work may be able to motivate their local fire organization to help them for project work, like spreading mulch after a wildfire, or monitoring efforts, like looking for damaged or ineffective travel management structures. As engines are patrolling for fires, fire fighters can look for road closures that are not working, repair them when possible, or report them for later repair. In this way, employees can work together to improve road conditions, and reduce the impacts that damaged roads can have on watershed values.

Appreciate

The amount of cooperation I receive increases dramatically with the amount of appreciation I express. Once people demonstrate a willingness to help and take steps to protect or improve watershed conditions, it is important to show appreciation for that work. Constructive cooperation with people can encourage them to help more. Giving credit where credit is due, with a personal "thank you", or a public expression of gratitude, motivates people to be advocates for the watershed. Nominating employees for spot awards is another great way to express well-deserved appreciation.

Sometimes, there are outliers, and no matter how willing and cooperative a watershed specialist may be, some employees may not want to cooperate toward achieving watershed goals. It must be understood that there will always be people like this. However, these attitudes should not keep hydrologists from attempting to connect with people, build solid working relationships, and engage them in a constructive dialogue.

Conclusion

Watershed management in today's environment takes an army of watershed specialists. It is important to make a concerted effort to get to know the field-going personnel in an office. These are the people who can have the greatest impact on the ground. Listen to their points of view. Hear and understand their day-to-day concerns. Cooperate in helping them get their jobs done. When a watershed issue needs to be addressed, explain these concerns in a way that gives people incentive to help solve problems, instead of just shutting them down. Participate in the work that needs to be done, including any fieldwork that demonstrates an interest in working toward a common goal, not just a hydrology goal. Finally, make sure to appreciate the hard work that people put forth for the watershed resource. By following these steps, an army of many can be recruited to fight the watershed battle, instead of fighting it as an army of one.

Acknowledgements: I would like to thank Monte Williams for guiding me to conduct myself in a way that fosters cooperation. I would also like to thank the employees of the Black Hills National Forest, who work to improve watershed conditions every day.

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Section 5. Partnership and Collaboration

Overleaf:
Rafters floating the Middle Fork of the Salmon River, Salmon-Challis National Forest, east-central Idaho. Photo by Jay Craig, 1982.

Forest Sustainability Criteria and Indicators: A Common Language for the 20 States Served by the Northeastern Area

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The USDA Forest Service, Northeastern Area State and Private Forestry (NA) and the Northeastern Area Association of State Foresters (NAASF) are working collaboratively with the Northeastern Forest Resource Planners Association to integrate concepts of sustainable forest management into USDA Forest Service State and Private Forestry policies, monitoring and management programs, and technology transfer activities. A key component of this effort is built around a framework for measuring sustainability using sustainability indicators distributed among seven sustainability-related criteria. These criteria highlight important aspects of the conservation and management of biodiversity, forest productivity, forest health, forest soil and water resource quality, global carbon cycles, the social and economic benefits of forest use, and the status of the legal, institutional and economic framework that affects forest resource management. This framework was adopted from an international system referred to as the Montreal Process criteria and indicators (C&I). Components of the Northeastern Area effort to date include: (1) a C&I-based report on the status of forest health and sustainability in the 20-state region; (2) a sourcebook on C&I; and (3) selection of indicators to track at regional and state scales; and (4) a forest sustainability information clearinghouse. For more information, see the NA Sustainability Web Site: *http://www.na.fs.fed.us/sustainability*.

Keywords: *sustainability, indicator, biodiversity, forest productivity, forest health, forest use, forest policy, forest research, water quality, Northeastern Area*

Introduction

Physical scientists help manage forests in a sustainable manner. A sustainability challenge, not fully met, is to integrate the fundamental knowledge of physical systems and their management with knowledge and activities occurring in the biological, social, economic and political realms. The USDA Forest Service, Northeastern Area State and Private Forestry (NA) and the Northeastern Area Association of State Foresters (NAASF) are working collaboratively with the Northeastern Forest Resource Planners Association (NFRPA) to integrate concepts of sustainable forest management into forestry policies, monitoring, management, and technology transfer programs. One focal point for this effort is the use of a framework of criteria and indicators of forest sustainability within their jurisdictions. The Northeastern Area includes the 20 states from Maine to Minnesota, south to Missouri, and east to Maryland.

The Criteria and Indicators Framework (C&I)

A criterion is a broad goal or category that reflects public values and scientific principles. An indicator is a measure of a criterion. Indicators can be quantitative or qualitative variables that, over time, will indicate positive or negative trends toward sustainability.

The C&I framework was developed in an international forum (Montreal Process Working Group 2001) and used in the United States to prepare the recent National Report on Sustainable Forests 2003 (USDA Forest Service 2003). It consists of sustainability indicators distributed among seven criteria that highlight important aspects of forest conservation and management including: (1) the conservation and management of biodiversity; (2) forest productivity; (3) forest health; (4) forest soil and water resource quality; (5) global carbon cycles; (6) the social and economic benefits of forest use; and (7) the status of existing legal, institutional and economic systems.

Furniss, M.J., Clifton, C.F., Ronnenberg, K.L., eds., 2007. *Advancing the fundamental sciences: proceedings of the forest service national earth sciences conference, San Diego, CA, 18-22 October 2004*. PNW-GTR-689. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station.

NA, NAASF, and NFRPA are using this framework to build a common understanding and language of sustainability with stakeholders and the general public. C&I components of the sustainability effort to date include: (1) a C&I-based report on the status of forest health and sustainability in the 20-state region; (2) selection of indicators for on-going at regional and state sustainability monitoring; (3) development and maintenance of a forest sustainability information clearinghouse; and (4) a book that introduces the benefits and challenges associated with the use of C&I.

Forest Sustainability Assessment for the Northern United States

An indicator-based assessment can introduce the many facets of sustainability to the general public; contribute to informed discussions of the appropriate balance among ecological, social, and economic considerations; and provide a mechanism to track general information with regard to sustainability. To this end, NA and NAASF began work in 1999 on a Forest Sustainability Assessment for the northern United States that is being prepared for digital publication right now (will be available at *www.na.fs.fed.us/sustainability*). The effort was intended to build on the base of information provided through the USDA Forest Service's Forest Inventory and Analysis (FIA) and Forest Health Monitoring Programs (FHM), and to provide insight into which federal, state and private inventory and monitoring programs, technical reports, journals, and other publications were relevant to this effort.

The assessment provided hands-on experience working with the C&I on a regional scale. It involved compiling data across state borders with the associated issues of data gaps and inconsistencies in terminology, inventory methods, and data and cartographic resolution. To add to the FIA and FHM program data, USDA Forest Service Research, the Natural Resource Conservation Service and The Nature Conservancy mined organizational databases for information specific to our needs. Existing Resource Planning Act [RPA] assessments and information from the national report on sustainable forests (USDA Forest Service 2003) were all critical sources of information. Over the course of the assessment, indicator related information has become more accessible through the Internet.

The technical report is currently being prepared for digital publication (available at *www.na.fs.fed.us/sustainability*). Keys points derived from the technical report were published in 2003 in Sustainability Assessment Highlights for the Northern United States (Carpenter et al. 2003).

NA and NAASF Base Indicators.

NA and NAASF have agreed to provide historical and current information on 18 specific indicators that can provide a strong base for state, multistate and area sustainability assessments (Table 1). These base indicators are derived from those in the international C&I framework, to insure linkage with national and international efforts. They span all seven international criteria, but are intended for use at regional and state scales. They were chosen because of their perceived utility by a wide range of stakeholders. There are some data gaps associated with this set of indicators, and data inconsistencies across state boundaries that will be worked out over time. The process used to select the indicators is documented in a publication, NA/NAASF Base Indicators of Forest Sustainability: Metrics and Data Sources for State and Regional Monitoring (USDA Forest Service 2003).

NAASF recommended that the indicators be used as the core of NA-wide forest sustainability C&I assessment reports that are planned to occur every five years, at a minimum. The base indicator information will be posted online, and NA will be responsible for ensuring the currency of the information. Benefits of online indicator reporting include the ability to post new data as soon as it becomes available, rather than waiting a full reporting period; providing stakeholders with easy access to data; and the ability to query data sets to retrieve graphs, download data, and generate summary reports.

Sustainability Clearinghouse Activities

As part of the overall initiative, NA serves as a clearinghouse for information and inquiries regarding sustainability from state forestry agencies, the Forest Service, other public agencies, nongovernmental groups, and stakeholder groups. The clearinghouse helps raise awareness about sustainability and NA/NAASF sustainability efforts. It helps in uncovering opportunities to integrate regional, national, and state work. A key component of the clearinghouse is the Northeastern Area's Sustainability Program Web site (*http://www.na.fs.fed.us/sustainability*). The site provides information on national, regional, and local sustainability assessments, strategic and state forest resource planning, sources of ecological classification and mapping, forest certification, and up-to-date information on the status of the NA/NAASF sustainability efforts. For example, because the C&I framework spans the fields of physical, biological, social, economic and political, science, management, and policy, it can seem overwhelmingly complex on first introduction. To reduce the learning curve, a publication is available on the Website called Sourcebook

on Criteria and Indicators of Forest Sustainability in the Northeastern Area (USDA Forest Service 2002). This publication outlines the basic use of C&I to assess forest sustainability, summarizes information on the development and use of C&I by various organizations and agencies, provides a list of recommended resources, and presents information on the NA, NAASF, and NFRPA sustainability work. It is intended as a starting point for states and other organizations to help guide their efforts to use criteria and indicators for assessing forest sustainability. Up-to-date displays of the base indicator information will be a major feature of the clearinghouse Website.

Next Steps for C&I Effort

Over the next several years, the effort will focus on four areas: (1) focusing on data issues and gaps in information needed to address the 18 base indicators; (2) developing the base indicator on-line clearinghouse; (3) increasing awareness of the C&I framework and the base indicator web site through education and training; and (4) development of the first five-year assessment that incorporates the 18 base indicators.

The on-line clearinghouse is currently being developed to provide indicator reports with user-friendly graphs, maps, and tables at regional, state and other scales, where appropriate. The target audience includes state foresters, planners, policymakers, other natural resource professionals, and people doing strategic planning. Where possible, data will be displayed to show trends over time and users can download data tables. It will also have links to the data sources and to additional information and resources.

Summary

The USDA Forest Service, Northeastern Area, State and Private Forestry and the Northeastern Area Association of State Foresters share a commitment to the sustainable management of forests. They have determined that criteria and indicators provide relatively complete, accurate, and unbiased information on forest conditions, the factors that influence forest conditions, and the way changes in forest conditions affect the benefits derived from forests. Thus, a suite of 18 indicators consistent with the C&I framework have been adopted by the USDA Forest Service, Northeastern Area and the Northeastern Area Association of State Foresters. They are intended to provide a base of comparable information across state borders through state and regional assessments, and are a valuable means of tracking the effectiveness of agencies' programs and policies (USDA Forest Service 1999).

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Beyond Boundaries: Resource Stewardship in the Skagit River Basin–Communities and National Forests in Partnership

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This publication is about people, place, and partnerships – a story of relationships among the Forest Service, communities, and organizations in the Skagit River basin in western Washington. It's about the power of partnerships to help conserve and restore resources when people are inspired and motivated to push beyond boundaries and work together. The partnership story as it plays out in the Skagit involves many people, resources, and issues. A common thread to the stories in this document is the Pacific Northwest salmon, currently in decline. The large and relatively intact Skagit River watershed is widely recognized as a critical stronghold for wild salmon in Puget Sound and a key to salmon recovery efforts. The push to protect and restore salmon affects every aspect of life here, galvanizing local conservation efforts and fostering controversy. But every region has its own resource conflicts and its own opportunities to build the relationships that can lead to solutions. Partnerships can help accomplish work, but partnering is as much about building relationships as it is about outcomes. We explore what the Forest Service can bring to the partnership table, share some of what we've learned about partnerships through stories of and by our partners, and discuss some of the stewardship and partnership challenges that lie ahead. The overriding lesson that we want to share is that partnerships can work and can help provide a foundation for effective resource stewardship.

Keywords: *partnerships, stewardship, salmon, salmon recovery*

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Beyond Boundaries:

Resource Stewardship in the Skagit River Basin

COMMUNITIES AND NATIONAL FORESTS IN PARTNERSHIP

USDA

Mt. Baker-Snoqualmie
National Forest

OCTOBER 2001

Prologue

This publication is about people, place, and partnerships—a story of relationships among the Forest Service, communities, and organizations in the Skagit River basin in western Washington. It's about the power of partnerships to help conserve and restore resources when people are inspired and motivated to push beyond boundaries and work together.

The Mt. Baker-Snoqualmie National Forest is located in a unique and inspiring place, largely wild, yet within a stone's throw of major metropolitan areas. The convergence of abundant natural resources and 5.5 million people creates an environment that is on the one hand passionately prized, and on the other hand threatened by increasing pressures and conflicting demands on natural resources. This climate has fostered abundant opportunities for developing partnerships that push beyond geographical, legal, administrative, political, and personal boundaries to find effective solutions.

Partnerships can help accomplish work, but partnering is as much about building relationships as it is about outcomes. Working in partnership is a way of thinking and engaging with others. It is a way of building trust and facilitating the process of joint problem-solving. Partnerships take hard work, but the results usually outweigh the difficulties as long as partners share mutual interests and remain true to their own values and capabilities.

The partnership story as it plays out in the Skagit involves many people, resources, and issues. A common thread to the stories in this document is the Pacific Northwest salmon, currently in decline. The large and relatively intact Skagit River watershed is widely recognized as a critical stronghold for wild salmon in Puget Sound and a key to salmon recovery efforts. The push to protect and restore salmon affects every aspect of life here, galvanizing local conservation efforts and fostering controversy.

Every region has its own resource conflicts and its own opportunities to build the relationships that can lead to solutions. The lesson that we want to share is that partnerships can work and can help provide a foundation for effective resource stewardship. We hope that Forest Service staff and others will see similarities to their own situations and find our collective partnership experiences useful.

This is our story, on this landscape, but it is part of a bigger picture. Nurturing partnerships at all levels will become even more important as emerging issues reach across regional, national, and global boundaries. It will be essential not only to have partners but to be partners in the important work of caring for the land and serving people.

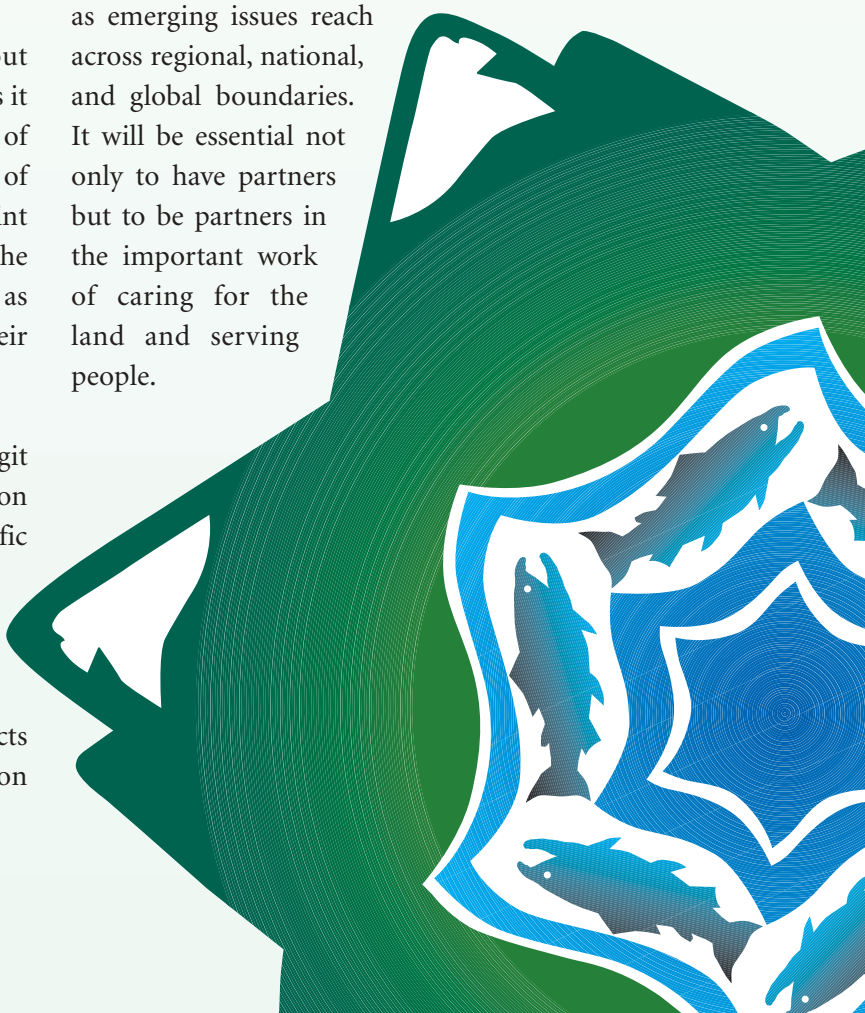


Table *of* Contents

Prologue

An Extraordinary Place 2-3
Sidebar: *Livelihoods and Lifestyles*
Sidebar: *Landscape and Resources*
Map: *The Skagit River Basin, Washington*

The Forest Service in the Skagit 4-5
Box: *How did we get here?*
Box: *Pacific Coast Watershed Partnership*
Sidebar: *What the Forest Service Brings to the Table*

A Web of Partnerships 6-7
Sidebars: *What We've Learned*

Partnership Activities–Watershed Restoration 8-9
Story: *Who Among Us Would Argue Against Working Together?*
Sidebar: *Sampler of Other Watershed Restoration Partnerships*

Partnership Activities–Habitat Protection 10-11
Story: *Skagit River Bald Eagle Natural Area*
Sidebar: *Sampler of Other Habitat Protection Partnerships*

Partnership Activities–Recreation 12-13
Story: *Wildcat Steelhead Club: For the King of All Sportfish*
Sidebar: *Sampler of Other Recreation Partnerships*

Partnership Activities–Education 14-15
Story: *Skagit Watershed Education Project*
Sidebar: *Sampler of Other Education Partnerships*

Partnership Activities–Community Support 16-17
Story: *Concrete, Washington: On the Road Again*
Sidebar: *Sampler of Other Community Support Partnerships*

Partnership Activities–Assessment, Monitoring, and Evaluation 18-19
Story: *Is Good Science Enough?*
Sidebar: *Sampler of Other Assessment and Monitoring Partnerships*

Looking Ahead: Stewardship Challenges 20-21
Story: *Crossing Management Boundaries in North Cascades National Park*
Sidebar: *Definitions*

Looking Ahead: Partnership Challenges 22-23
Story: *Expanding Partnership Boundaries on the Skagit Delta*
Sidebar: *Partnership Tips*

Partners and References 24-25
Sidebar: *Acknowledgements*

"Ecological understanding is a cultural imperative for each of us… And what better place to begin that deeper appreciation than in the place we live. From such appreciation can come wise decisions and actions to preserve and protect what is left of the Puget Sound basin's natural beauty and wild, self-sustaining life in variety."

– A.R. Kruckeberg, The Natural History of Puget Sound Country

An Extraordinary Place

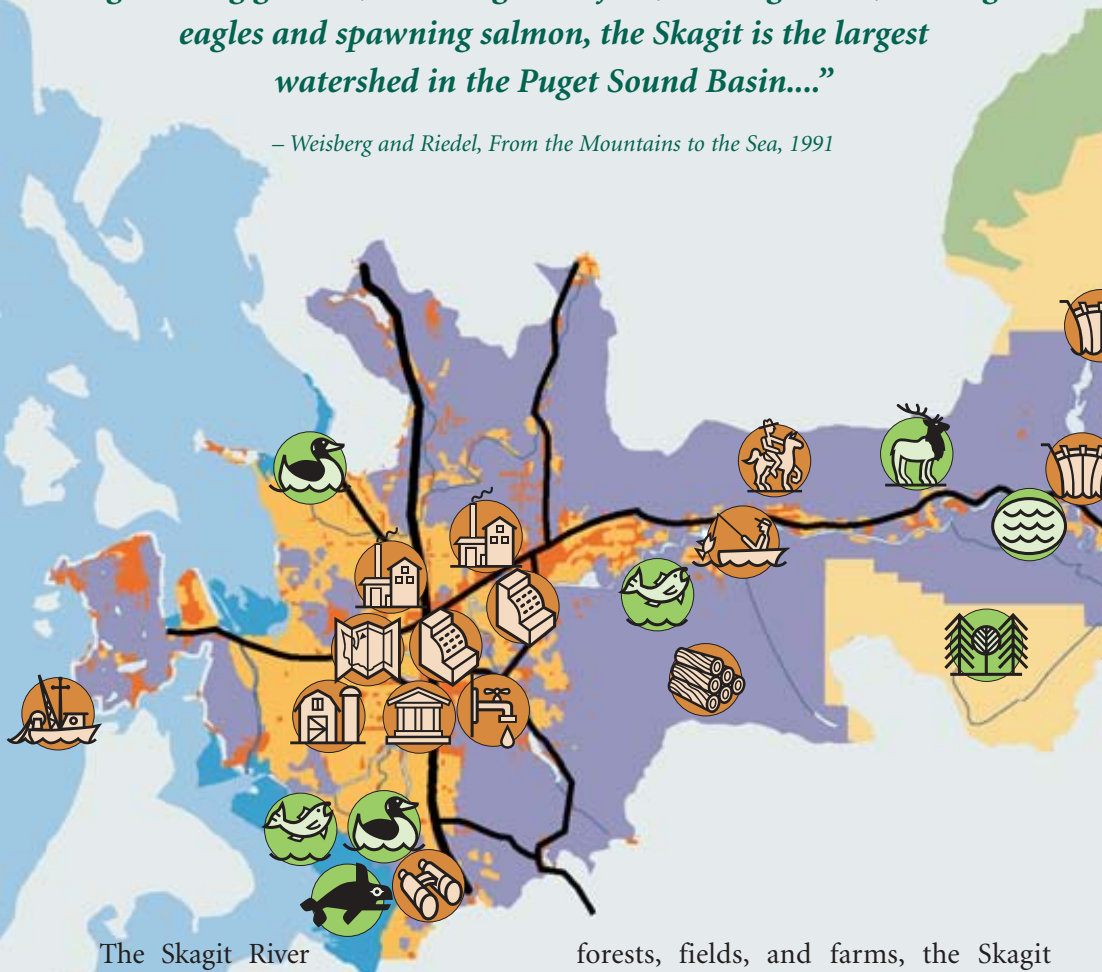
" The Skagit is one of the great rivers of North America. The river and its tributaries are the focus of life and energy for more than 1.7 million acres of the North Cascades - one of the most rugged mountain ranges in North America. Containing hundreds of glistening glaciers, tumbling waterfalls, rushing creeks, soaring eagles and spawning salmon, the Skagit is the largest watershed in the Puget Sound Basin...."

– Weisberg and Riedel, From the Mountains to the Sea, 1991

Livelihoods and Lifestyles

- Farming/Agriculture
- Logging/Wood Products
- Fisheries (commercial)
- Manufacturing & Construction
- Trades, Services, Schools
- Government
- Tourism-Related Businesses
- Camping
- Recreational Fishing, Hunting
- Watchable Wildlife
- Horseback Riding
- Water Use
- Power Generation

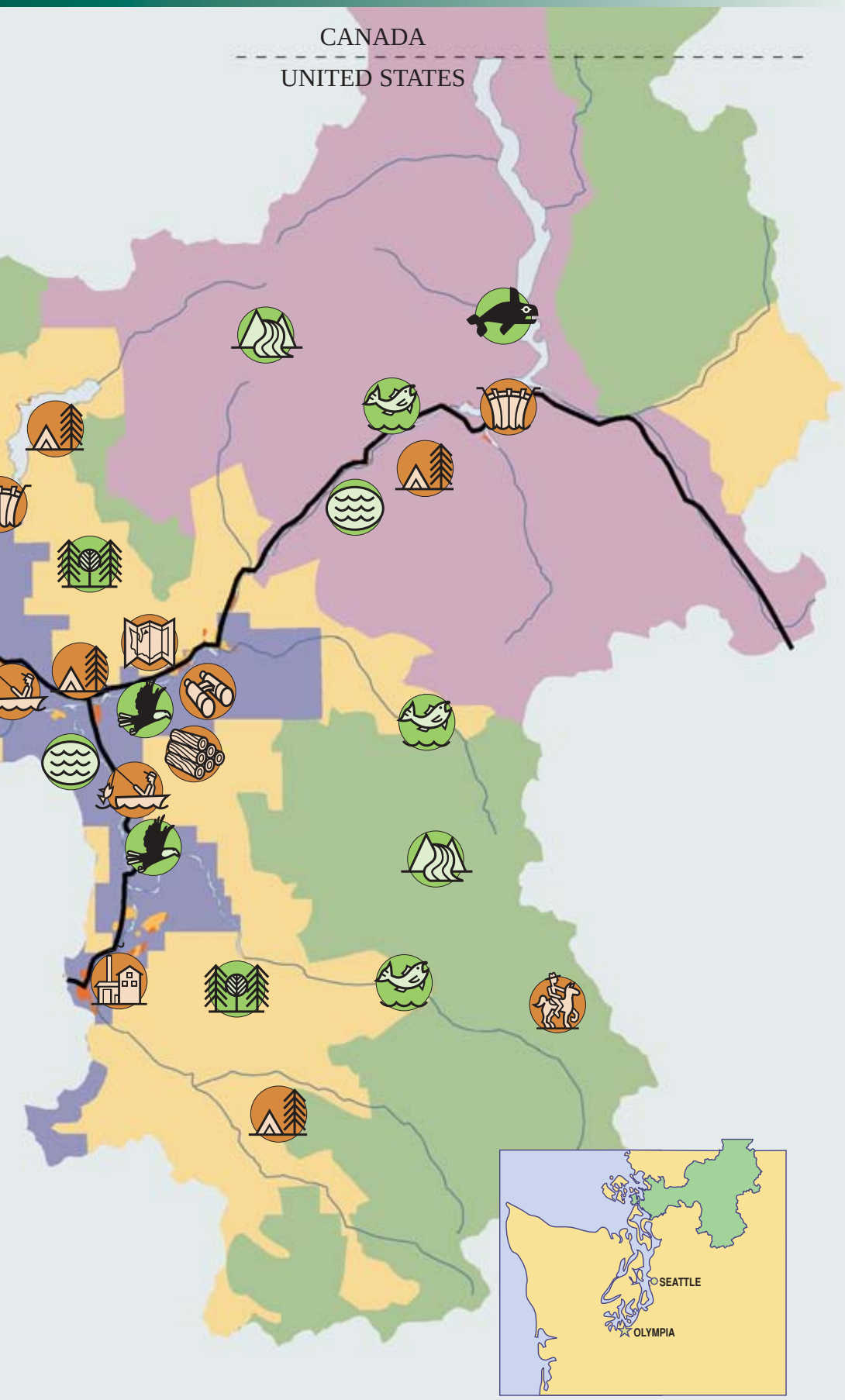
The symbols and graphics represent only a sampler of some of the major natural resources, human uses, and stewardship challenges in the Skagit River basin



The Skagit River basin provides the setting for the stories we are telling here. This extraordinary place has inspired and motivated an uncountable number of strong and diverse partnerships.

The Skagit appears largely natural and undeveloped in its sweep from the peaks of the North Cascades to the open waters of Puget Sound. The largest river in the region, the Skagit is one of the few rivers to support five types of salmon as well as seagoing trout. With its numerous tributary streams, high mountains, deep canyons, broad floodplains, estuaries, forests, fields, and farms, the Skagit retains a wealth of environments vital to fish, wildlife, and humans alike.

Over the past century, increasing human uses and competing demands on the Skagit's natural resources have presented a daunting challenge in the effort to maintain naturally functioning ecosystems. At stake are not only the survival of the region's salmon, forests, waters, wildlife, and wild places, but also the cultural identities, family heritages, lifestyles, and livelihoods of the people whose lives are so intimately linked with this landscape.



Landscape and Resources

Landscapes/ uses/ownership

- Farmland
- Wilderness
- Estuary/wetlands
- National Park
- National Forest
- State & Private Lands
- Towns/Urban Areas

Wild inhabitants and resources

- Fish
- Water
- Forest
- Waterfowl
- Eagles
- Elk
- Glaciers
- Human Cultural/ Historical Places

The symbols and graphics represent only a sampler of some of the major natural resources, human uses, and stewardship challenges in the Skagit River basin

The Forest Service in the Skagit

The Forest Service stewardship mission, Caring for the Land and Serving People, has long been served by formal and informal partnerships. Collaboration with others in firefighting, commodity production, conservation, and other resource management efforts has reinforced the notion that we are not just 'The Government'. Rather, the Forest Service is people—people who live in and build relationships within their communities to address shared resource management concerns.

The Forest Service mission is becoming ever more challenging as we strive to maintain functioning ecological systems in light of the accelerating and sometimes conflicting needs and demands of a diverse public. Our broadly defined role of resource steward increasingly relies on partnering. Successful resource stewardship requires: (1) working cross functionally within the agency, (2) coordinating programs with other federal agencies, and (3) going beyond geographical and administrative boundaries to develop partnerships of mutual interest with individuals, organizations, tribes, agencies, and communities.

The Skagit River basin has a long history of people working together, on a wide range of resource management issues. The Forest Service has a stake in the condition of the entire landscape, since the resources we manage both affect and are affected by activities outside national forest boundaries. Key management decisions and resource concerns have provided both opportunities and mandates to work cooperatively (see box below).

As a partner, the Forest Service is sometimes viewed as having capacity and resources unavailable to many grassroots organizations, nonprofits, or individuals. We do have specialties to offer (see sidebar), but our partners also contribute much that may be unavailable to us: different kinds of experience, expertise, and enthusiasm; established programs; or the ability to lobby Congress and fundraise. For the Forest Service in the Skagit, the process of partnering enables us to work together more effectively for the benefit of the resources we care for in common.

How did we get here?

Key resource management decisions and concerns have motivated the Forest Service to form resource-based partnerships. A few include:

- ***The Skagit Wild and Scenic River was designated—but left unfunded—in 1978. Because about half of the Wild and Scenic River is in non-federal ownership where the Forest Service has no regulatory authority, we had the opportunity early on to work cooperatively with other agencies and jurisdictions to protect the values for which the river was designated.***
- ***In the late 1980s, concern over the impact on fish habitat from increased sedimentation due to roads compelled the Forest Service to work with partners to develop a basin-wide approach to watershed restoration.***
- ***Implementation of the 1994 Northwest Forest Plan, along with current salmon recovery efforts, have created the need for the national forest to become more involved in basin-wide partnerships.***

"Watersheds are complicated biological systems. This fact, coupled with the diversity of ownerships, jurisdictions, social interactions and regulations, makes for highly complex problem solving. Success can be achieved only with collaboration and good communication at all levels of government and with key interests engaged and working together."

– John Phipps, Forest Supervisor, Mt. Baker-Snoqualmie National Forest

Pacific Coast Watershed Partnership

The Mt. Baker-Snoqualmie National Forest participates in the Pacific Coast Watershed Partnership (PCWP), one of 12 national Large-scale Watershed Restoration Demonstration Projects funded by the Forest Service. The purpose of the program is to change the way the Forest Service approaches watershed management—from concentrating watershed restoration efforts within national forest boundaries to exploring the use of holistic large-scale watershed restoration partnerships.

The PCWP and the other demonstration projects emphasize collaboration: with the people whose livelihoods depend on the watershed, with those who simply cherish the land, and with organizations striving to create a vigorous self-sustaining landscape. The partnership projects show how the Forest Service and communities can work together rather than in conflict, building connections between ecological and economic health. The projects highlight places where local and regional efforts, driven by common visions and goals, are: reflecting public values, integrating watershed restoration efforts, using science, fostering learning-by-doing (adaptive management), restoring and enhancing habitats of species at risk, and protecting and improving watershed conditions.

What The Forest Service Brings to the Partnership Table

Land and Resources, and their Management

- Land base
- Infrastructure (roads, trails)
- Facilities (campgrounds, buildings)
- Terrestrial and aquatic habitats
- Cultural and historical places
- Natural sites and settings
- Sustainable resource products
- Land management strategies, practices, and experience

People, Processes and Programs

- Familiarity with processes and procedures
- Experience with regulatory requirements
- Interdisciplinary and multi-resource perspectives
- Established outreach programs
- Staff with technical expertise and local ties
- Institutional longevity
- Regional, national, and international links and perspectives

Expertise and Technology

- Access to scientific research
- Place-based knowledge
- Ability to collect, store, analyze data
- Technology development and transfer
- Training opportunities
- Inventory and monitoring
- Clearinghouse for information

Asset Leveraging

- Grants and donations
- Community assistance
- Seed money and matching funds
- Challenge cost-share dollars

Services

- Recreation experiences
- Conservation education
- Visitor orientation and information
- Interpretive services
- Public safety efforts (e.g. fire, flood)

A Web of Partnerships

What We've Learned

Build partnerships smartly

We can neither do it alone nor do it all. Partners bring different strengths and contributions—know your strong points, so you can complement each other's skills and build a smart partnership that makes the most of what everyone has to offer to achieve mutual goals.

Partnerships are relationships

Partnerships that last and accomplish the most are built on personal relationships, trust, flexibility, and caring about common concerns and mutual interests. Each partner should be able to work toward both their own individual goals and the shared goal. While partnerships are about mutual interest they may not always be of direct or equal benefit to each.

Partnerships are place-based

People have a passion about their place—where they live, recreate, and work. The strongest partnerships are based in places people care about, reflecting their culture, heritage, livelihoods, and quality of life. Because each place is unique, each partnership is unique.

This section introduces just a few of the many different projects in which the Forest Service has partnered in the Skagit River basin. The stories are organized around six types of stewardship goals important here today–watershed restoration and salmon recovery, habitat protection, education, recreation, community development, and assessment and monitoring.

Our partnerships vary in form and size, from informal information sharing with a few constituents, to long-term, intensive programs. They are always in flux–some collaborations grow stronger over time, while others taper off or alter their form as needs and players change. The web of Skagit partnerships is wide and deep–some are individuals, agencies, or organizations, while others involve multiple agencies and groups under a larger umbrella, such as a watershed council. In many cases a single organization is involved in different types of projects, playing diverse roles and bringing varying contributions and needs to different endeavors.

Why Partnerships?

Partnerships make sense because ecological, social, and economic issues and concerns are impossible to tease apart or keep within boundaries, especially when working at a landscape scale. A partnership approach also is wise given the increasing pace of development, declining budgets, expanding agency mandates, changing societal values and expectations, increasing scientific information and awareness of the complexities of natural systems, and a broadening desire among national forest users and neighbors to participate meaningfully in forest management. Through their diversity and flexibility, partnerships can lead to more creative ideas, better decisions, and ultimately better conditions on the landscape.

"We cannot do it alone. The issues are too broad, the land base too large, and the resources too scarce."

– Mike Dombeck, former Chief of the Forest Service

What We've Learned

We can and must work across boundaries

All kinds of boundaries—geographical, legal, administrative, organizational—need to be crossed or bridged to see the bigger picture, work at a broader scale, take a longer-term perspective.

Partnerships aren't the easy way

Partnerships take a lot of time, effort, commitment, and energy, to be successful over the long term. Partnerships aren't always the right choice (e.g., where there is an apparent conflict of interest). Some partnerships just don't make it.

Monitoring and feedback are essential

Without monitoring our progress (both on the land and within our partnerships) we can't measure the benefits of our actions; we need frequent reporting, both formal and informal. We need to reward and recognize partners and their achievements, large or small.

Partnerships can benefit all aspects of Forest Service work

Good collaboration reaps good relationships and good will. We all get more work done, achieve more of our natural resource agenda, and jointly solve problems through partnerships.

Partnership Activities: Watershed

Watershed restoration is a cornerstone of Forest Service management direction in the Pacific Northwest, where declines in fisheries and water quality have resulted from the disruption of natural systems. We strive to understand and restore natural physical and biological processes, as well as places important to local communities, through such activities as unblocking fish passages, reducing sediment in streams, or revegetating riparian areas.

Until the 1990s, watershed and fish habitat improvement projects often focused on a single site or target species. But restoring whole watersheds and ensuring species recovery requires a broader approach. Since the mid 1990s, a watershed scale approach to restoration has been used in the Skagit, creating both incentive and opportunity for extensive partnership efforts.

Who Among Us Would Argue Against Working Together?

Salmon once swam the Skagit River by the millions, but today salmon and trout are found in only a fraction of those numbers. There are many causes for the decline and many opinions about potential solutions. However, few would argue that for restoration actions to be effective, they must be coordinated across landownership and jurisdictional boundaries, to involve all those who have a stake in healthy watersheds.

Early in the 1990s, several organizations in the Skagit began meeting informally on sub-basin and watershed scale issues. Over time, these groups evolved as people became familiar with each other and the interconnected nature of their interests and concerns. The Forest Service helped to coordinate informational meetings among agencies and organizations as part of the interim watershed assessment process under the Northwest Forest Plan. By 1997, these relationships were formalized as the Skagit Watershed Council, an umbrella organization of 38 members with disparate interests, missions, and philosophies but with one overriding common interest: the restoration of the Skagit River watershed and its resident salmon.

The Skagit River basin is recognized as supporting the best remaining habitat for wild salmon in Puget Sound. Council members feel strongly that protection and restoration of these salmon stocks are vital to recovery throughout the region. The council supports voluntary restoration and protection of salmon habitats and the natural processes that form and sustain them. Through collaboration, technical assistance and education, the council seeks to fulfill its mission, which is to understand, protect, and restore the

"We are together because we know that this inclusive approach is our only hope, the only way to ensure abundant salmon in this river system in the future."

– Shirley Solomon, Skagit Watershed Council Chairperson

production and productivity of the Skagit and Samish watersheds in order to support sustainable fisheries. The Forest Service supports the work of the council with contributions of staff time and financial assistance.

Among the tangible results of this partnership effort is the councils' highly regarded restoration strategy. The council has adopted the strategic approach of using the best science available to identify target areas for restoration and protection that are biologically important for salmon recovery and protect the best habitat first, and to complete those projects that are most cost-effective.

Less visible but equally important are the relationships and history of working together that have developed. Still, Council Chairperson Shirley Solomon suggests that building consensus around controversy among groups who might otherwise have little in common has been no easy task: "Who among us would argue against working together? But actually working together in a way that gets things done is not particularly easy, especially in a partnership of the big tent variety that this council represents. Interests and world views cannot but collide at times."

Buffering those collisions will be critical for future successes. "The council currently functions as the hub for coordinating watershed restoration and salmon recovery efforts in the basin," said Dave Pflug Seattle City Light Fisheries Biologist and council member. "But the history of watershed councils is that they have a five year life-span. The challenge is to keep the council alive so that we continue to have a mechanism for collaboration on these vital issues."

A Sampler of Other Watershed Restoration Partnerships

MAJOR PARTNER

Seattle City Light

The City of Seattle (which owns and operates 3 major hydroelectric dams on the Upper Skagit River) has developed an Early Action Plan to address Endangered Species Act concerns and help in species recovery. Implemented through the Skagit Watershed Council, SCL provides funding to protect and restore high quality habitat in watersheds where the city has an interest.

MAJOR PARTNER

Skagit Fisheries Enhancement Group

The SFEG has supported several restoration projects on National Forest System land and played a major role in the implementation of the Skagit Watershed Council Restoration and Protection Strategy.

MAJOR PARTNER

Skagit County

The national forest and Skagit County have partnered on several fish passage improvement and flood repair projects both on and off National Forest System land.

Partnership Activities: Habitat Pro

Protecting habitats for all living things, including people, is a key focus of resource stewardship. Forest Service management emphasis has shifted in recent decades from a focus on habitats for individual species, to protecting whole landscapes and their numerous habitats that support species native to the system.

Where resources are relatively intact, such as in the Skagit, it is less expensive and more feasible to protect high quality habitat than to fix problems in the future. We won't succeed through regulation alone, but rather through working together, having a commitment and ownership in the outcome. Land acquisition and habitat protection efforts throughout the Skagit River basin feature agencies and organizations sharing strategies, priorities, and funds. The Forest Service engages in partnerships to manage habitats in an ecosystem context, rather than piece by piece.

Skagit River Bald Eagle Natural Area

Each November, a remarkable interaction plays out on the forested riverbanks of the Upper Skagit River: the return of spawning runs of salmon and hundreds of hungry bald eagles. The primary setting for this natural drama is an 8,000-acre natural area created by a unique partnership between a private nonprofit conservation organization and several cooperating local, state, and federal agencies and organizations.

Since 1976, the Skagit River Bald Eagle Natural Area (SRBENA), under the management of The Nature Conservancy (TNC), has protected habitat for one of the largest wintering populations of bald eagles in the lower 48 states. This multi-partner conservation effort began with a focus on the preserve, but quickly expanded to work at the landscape or watershed scale.

"The aim of this approach—looking at the entire Skagit watershed and devising strategies to protect the areas of highest quality habitat—is to protect not only eagles, but salmon and all other species in the watershed," says TNC's Bob Carey. "That requires several things, including working closely with our partners."

In this case, the partners include the Forest Service, the Washington Department of Fish and Wildlife, the National Park Service, the Skagit Watershed Council, the U.S. Fish and Wildlife Service, the Skagit Land Trust, Seattle City Light, and The River Network.

The SRBENA not only provides protected land but also serves as a hub for conducting critical scientific and educational activities involving local communities. During the eagle

"What's noteworthy here is the way we're all building on each other's work. In an area where there are so many different landowners, it's essential that we work together and that we focus on what's most ecologically significant."

– Bob Carey, The Nature Conservancy

wintering period, TNC naturalists and other partners conduct a weekly bird census, give guided tours of the area, and make presentations to local school and community groups. The Forest Service, as Skagit Wild and Scenic River manager, helps manage human disturbance during eagle wintering season through voluntary timing restrictions on river use and volunteer Eagle Watchers who focus visitor use in designated areas.

Thanks to TNC and its partners, land is protected for eagle roosting in winter, participation of community members in volunteer programs is on the rise, and thousands of people attending the annual Upper Skagit Bald Eagle Festival are learning about bald eagle habitat and management needs. Bob Carey attributes much of SRBENA's success to its strong partnerships.

"The idea is not to buy large areas within the watershed," Bob explains. "We have neither the resources nor the desire to do so. Rather, the objective is to work cooperatively with both private landowners and public partners to protect the most ecologically important parts of the watershed and to ensure that natural processes still unfold and a functioning landscape is maintained."

Changing resource values and declining partnership funding are among the challenges facing SRBENA and other partnership efforts that seek to gain protection for large areas and natural processes. More landowners and stakeholders need to be involved if landscapes from ridgetops to estuary are to be connected and conserved.

A Sampler of Other Habitat Protection Partnerships

MAJOR PARTNER

Skagit Land Trust

The Skagit Land Trust has worked with the national forest to prioritize acquisition of high quality riparian habitat including a recent purchase of 15 acres at the confluence of Diobsud Creek and the Skagit River. This parcel has over 900 feet of forested shoreline, providing pristine habitat for bald eagles and 4 species of wild salmon.

MAJOR PARTNER

Seattle City Light

Seattle City Light's land acquisition program purchases land in the upper Skagit basin in an effort to improve connectivity and provide habitat as mitigation for the impacts of the Skagit Hydroelectric Project.

MAJOR PARTNER

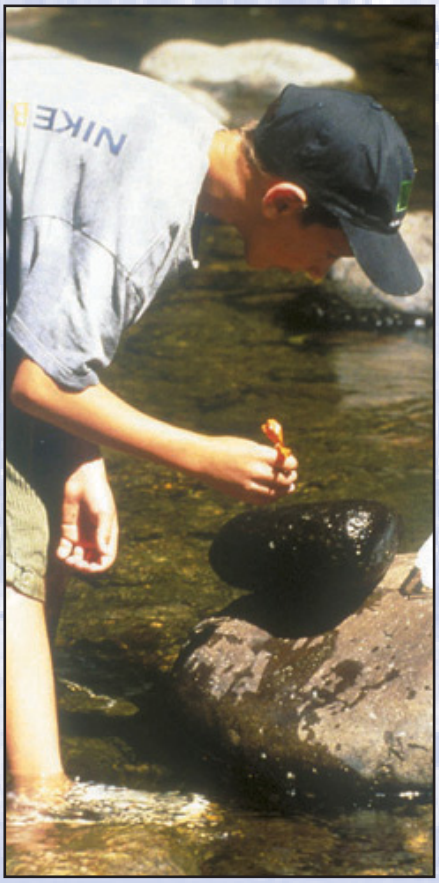
River Network

The River Network secures properties of interest in partnership with other organizations to achieve mutually agreed upon conservation goals. In the Skagit they have been instrumental in facilitating acquisitions that were later sold to the Forest Service.

Partnership Activities: Education

Effective conservation education helps people understand their environment and how it relates to their daily lives. Such education instills awareness and concern, especially among younger members of society, and provides people of all ages the tools they need to participate effectively in stewardship of natural and cultural resources.

The Forest Service embraces education both as an effective tool to achieve stewardship goals and as a way to learn from the unique knowledge, advice, and values of local people. An extensive partnership network has developed across the Skagit River basin, providing abundant opportunities for effective and comprehensive educational efforts. The national forest's contributions often center on: (1) providing a place in which outdoor education can occur, (2) translating and providing accurate and timely scientific and technical information, and (3) providing financial support to ongoing educational activities and programs.



Natalie Fobes

Skagit Watershed Education Project

The plea from local teachers was loud and clear: "It's easier to find out information about the Amazon than about the river outside our classroom windows!"

Their voices reached the ears of the North Cascades Institute (NCI), a non-profit educational organization committed to connecting people, nature, and community in the Pacific Northwest. Their response: creation of the Skagit Watershed Education Project, or SWEP.

All seven school districts signed on for the program, which focuses on creating a sense of stewardship for the Skagit River basin. Integrated classroom and field activities are designed around the entire watershed, with an emphasis on the relationship between a healthy watershed, a healthy fisheries population, and healthy communities.

SWEP began in 1990 as a partnership between the schools and NCI, but within a few years, as national forest management focus shifted more to the watershed level and to the growing need for conservation education, the Mt. Baker-Snoqualmie National Forest joined in. The partnership has since grown to encompass several other collaborations between the forest and NCI.

"It was great timing," says NCI's Tracie Johannessen. "We had been able to get the program off the ground and developed an ongoing relationship with the schools, but it

"We all learned that to be a good partner you don't go out to find someone to do what you need done. You go out and take a look around to see what's going on and how your message can fit in."

– Tracie Johannessen, North Cascades Institute

was hard for us to get enough staff to cover all the field trips. The Forest Service had a common interest and was able to provide funding and staff assistance. It's a great relationship."

What makes this partnership work? "It's all about flexibility," says Tracie. "It's about being cooperative, having a give and take, playing to each other's strengths."

Other reasons for success hinge on the program's inclusiveness—involving students, teachers, parents, landowners, natural resource managers, Skagit River Tribes, and business interests who recognize the value of education in ensuring the health of the Skagit basin.

The SWEP program reaches more than 750 elementary school students and their parents annually. Watershed education continues to gain momentum and attention as a vehicle for the integration of community and schools. The program has received national recognition and now has more than 40 partners.

A challenge for SWEP is to stay ahead of the curve, anticipating and aligning program objectives with changing community and partnership needs. Trying new approaches, organizing in new ways, learning, and adapting will continue to help this partnership thrive.

A Sampler of Other Education Partnerships

MAJOR PARTNER

Upper Skagit Bald Eagle Festival

The Forest Service helps the Eagle Festival organize and staff the Bald Eagle Interpretive Center. The annual Eagle Festival provides project leadership; the national forest assists with funding, materials, supplies, and River Rangers to lead interpretive programs.

MAJOR PARTNER

Local Schools

In 2001, 26 students of Ms. Korn's 6th grade class from Central Elementary School in Sedro-Woolley, Washington, monitored the survival of trees planted in newly acquired lands along the Skagit River. The children used their math and science skills collecting and analyzing data about tree growth and survival and shared their findings on the school website.

Partnership Activities: Recreation

A key element of resource stewardship is protecting and facilitating uses of natural and scenic sites, settings, and landscapes, which serve to nurture individual needs and values. But a dramatic increase in recreation, tourism, and travel in the Pacific Northwest, coupled with a continued decrease in regional recreation funding, has resulted in overcrowding, poor facility conditions, and degraded forest settings.

The outstanding natural environment of the Skagit River watershed supports a wide array of year-round recreational opportunities, from hiking, fishing, and boating, to snow sports, mountain climbing, and wilderness experiences. Most of these types of recreation are available on the Mt. Baker-Snoqualmie National Forest and adjacent public and private lands. The forest works with partners to ensure the integrity of the outdoor recreation experience while emphasizing watershed and wildlife habitat protection, restoration, and enhancement.

Wildcat Steelhead Club: For the King of All Sportfish

Fishing for certain sportfish often takes on mythic proportions when the stories are told. Recreational fishing has long been celebrated as an opportunity to relax in a natural setting while meeting the challenge of outsmarting the fish. The Skagit River steelhead is one of those mythic fish, and the Wildcat Steelhead Club was formed in 1936 to promote the enjoyment of fishing for all fish, but particularly the steelhead.

In its early days, club members focused on advancing the recreational activities of fishing and hunting in area rivers and in the high country. But in recent years as the numbers of fish have declined and the conflicts over dwindling stocks have risen, members have expanded their concerns to habitat protection and other issues vital to their form of recreation.

"Sadly, today with overall declines in local fish stocks, club members spend more time arguing over fisheries harvest issues and lobbying for the sport fisher's share of the catch, than they do out on the river," says club member Ron Tingley.

The club sponsors an annual river clean-up day, works for the betterment of local hatcheries, and disperses salmon carcasses in small streams to replenish natural nutrients. The Forest Service, the Steelhead Club, and others partnered on the development of eagle watching sites along the river to focus visitor use and help mitigate disturbance of eagles during winter. In these and other ways, club members work in partnership for the protection and enhancement of the river and its resources

"I grew up on the river, and fishing was part of daily life along the river. The funny thing is, my father, who ran tugboats up and down the river every day, never fished, he said it was too easy."

– Ron Tingley, Wildcat Steelhead Club

Sometimes the interests and needs of the partners don't quite align, straining the relationship. In its role as Skagit Wild and Scenic River manager, the Mt. Baker-Snoqualmie National Forest may make management decisions that conflict with the club's interests as river users. For example, when the Forest Service limited fishing on the Skagit during bald eagle winter feeding times, the fishing community and the club found themselves at odds with agency decisions.

But club members are hopeful that their concerns about habitat and fisheries can also be addressed through local collaborative processes embodied by the Skagit Watershed Council, of which both the Steelhead Club and the Forest Service are members. Keenly aware that habitat isn't the only factor affecting the sustainability of salmon stocks, club members feel strongly that in order to be effective they need to be involved in cooperative local efforts to restore the fisheries resource on the rivers they care about.

Speaking to the challenge of achieving salmon and steelhead recovery in the face of continuing fishing pressure, Ron says, "Politics is getting in the way of listening to what science is trying to tell us."

Challenges for recreational partnerships include not only addressing political realities, but also gaining awareness that although interests may diverge, resolving the conflicts can help build stronger partnerships, which in turn can help resolve future conflicts.

A Sampler of Other Recreation Partnerships

MAJOR PARTNER

Washington Trails Assn., Sierra Club, Audubon Society, Skagit Alpine Club, Mt. Baker Alpine Club

These organizations volunteer many hours to reduce the national forests' backlog of trail maintenance. With their assistance the forest accomplishes 20–30% more trail work annually.

MAJOR PARTNER

Skagit County Parks and Recreation

The Forest Service administers a county grant for the Snopark program and snowmobile trail grooming on Forest Service roads.

MAJOR PARTNER

Pacific Northwest Trail Association

The SKY (Service Knowledge Youth) program is a collaborative effort between school districts and private partners to provide high school students with an outdoor-based work experience blended with academic instruction. SKY is working with the Forest Service to develop a program for high school students to work on trails.

MAJOR PARTNER

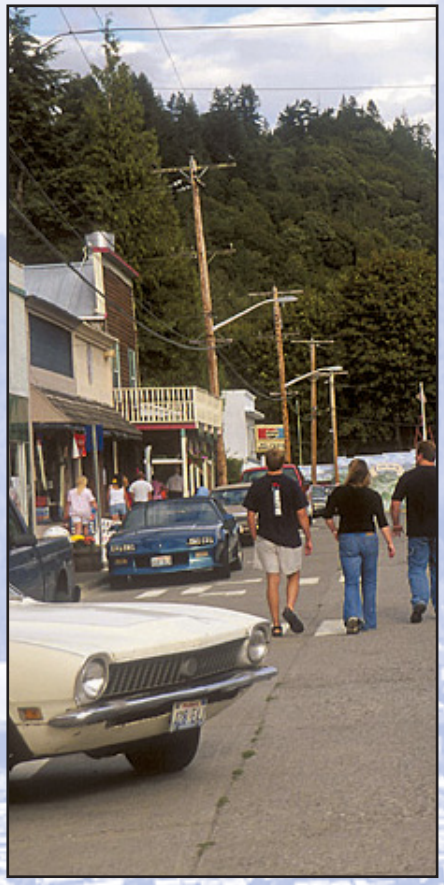
North Cascades Institute

In 1993, NCI and the Forest Service created the Eagle Watchers program to help manage the convergence of wintering bald eagles and the tourists who flock to watch the birds along the Skagit River. Volunteers inform thousands of visitors about bald eagles, salmon, and related habitat and management issues.

Partnership Activities: Community

Effective stewardship of the national forest supports—and depends on the support of the communities of which the Forest Service is a part. Rural communities can participate more meaningfully in the management of their national forests when they have the technology and the capability to do so. The Forest Service has both directives and incentives to encourage partnerships with our rural communities and tribes, especially those affected by declines in timber harvest and salmon populations in the Pacific Northwest.

The Mt. Baker-Snoqualmie National Forest is considered an 'urban forest' because of its proximity to the Seattle–Vancouver metropolitan area, but many of our staff live and work in rural communities. Our rural community partnership efforts focus on extending technology, expert assistance, professional knowledge, and resources to help small communities whose economies and lifestyles are tied to natural resources meet their economic, social, and environmental goals.



Concrete, Washington: On the Road Again

Sometimes it takes a couple of starts before you end up on the right road. When the upper Skagit Valley town of Concrete created its first Community Action Plan in 1994, the direction seemed to point toward tourism as the destination that would help them recover from economic downturns related to forest resource issues. Tourism was a logical choice given the town's scenic location at the gateway to the North Cascades.

Determined to get where they were going on their own, the town bypassed planning help from an outside nonprofit organization, Northwest Small Cities Services. Community leaders applied for Forest Service funds to begin downtown improvements to attract more tourists. They found themselves confronted by an unexpected roadblock—turned down for the grant in part because their action plan didn't address major water and sewer improvements, and in part because their reluctance to accept outside help or take on debt may have been interpreted as an inadequate level of local commitment.

After going back to the starting line, community leaders accepted a partnership with Northwest Small Cities Services. Members of the community formed a team with the Forest Service, the town council, and other state and federal agencies, to prepare for and work with others at the 1996 Northwest Timber and Salmon Communities Symposium to develop a new plan of action. This time the focus broadened to emphasize infrastructure

y Support

"Today, more than ever, we are committed to working in partnership with others, in the public and private sectors, who are trying to facilitate locally led changes that benefit both the land and rural communities."

– A Strategic Plan for the USDA Forest Economic Action Programs, September 2000

improvements, not only to meet their own residents' needs but also to increase the potential for development of all kinds and to meet newly emerging state regulations for water quality and growth management. This time around, tourism development was still identified as a goal, but one further in the future.

The most long-lasting impacts from this partnership effort have been the changes in community attitude—from a long tradition of independence to a willingness to work with partners, and from a feeling of uncertainty to an awareness of their own power to address problems that had seemed beyond their capacity to solve. In the process of accepting and nurturing relationships with others, the community has actually become more self-sufficient.

The Forest Service's role in Concrete's journey has evolved to focus more on helping with strategic planning and some design and engineering consulting. The town has numerous challenges ahead as they work toward a strengthened and more diverse economy enhanced by their proximity to abundant natural resources.

"The initial process did what it was supposed to do—launch the town onto its feet," says forest environmental coordinator Karen Nolan, who worked alongside Concrete throughout the initial planning process. "They're pretty much in control of their own future."

A Sampler of Other Community-Building Partnerships

MAJOR PARTNER

Town of Darrington

Forest Service employees initiated and helped plan and construct the Kids' Place Early Learning Center in Darrington, as well as a kiosk and restrooms for the community park.

MAJOR PARTNER

Economic Development Association of Skagit County

The Skagit Wood Products Project is a non-profit organization assisting small value-added wood product businesses in northwest Washington. Partnership funding helped with early feasibility studies and planning.

MAJOR PARTNERS

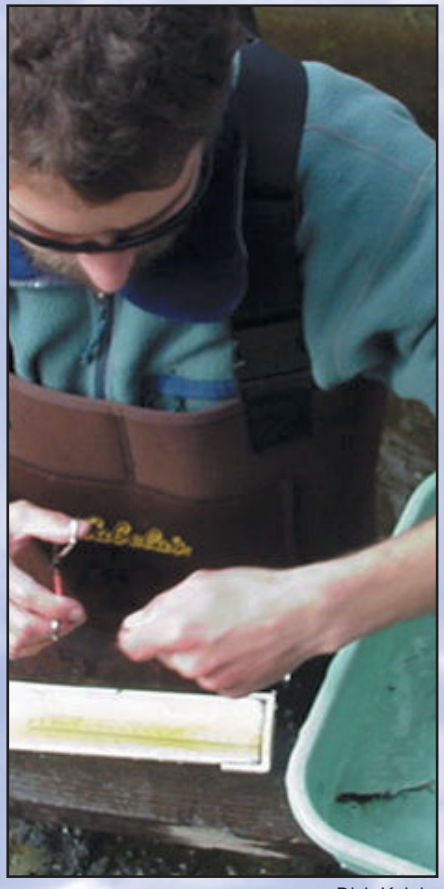
Samish Indian Nation, City of Burlington, Stillaguamish Tribe of Indians

Forest Service funds have helped with numerous community projects including: the production of the Samish Nation's five-year economic development plan, the development of the Burlington Farmers' Market, and the launching of the BankSavers Business Startup Project for the Stillaguamish Tribe of Indians.

Partnership Activities: Assessment

Monitoring and evaluation, with feedback to the assessment and planning processes, are key to the success of resource stewardship. Unless we learn from our efforts and become aware of what works and what doesn't, millions of dollars may be wasted on misguided attempts to manage multiple resources and improve resource conditions across the landscape.

Science can provide not only technical information but also a common language to start discussion among those with different viewpoints. Effectively engaging in such dialogue requires a long-term commitment of resources, technical expertise, and extensive local knowledge. The Forest Service has long been a storehouse of technical and scientific data about individual species as well as ecosystem functions and processes, while tribes, communities, and organizations are storehouses of local wisdom and experience on the land. Successful resource stewardship requires partners with complementary skills and capacities to maintain a commitment to assessment, monitoring, and evaluation.



Dick Knight

Is Good Science Enough?

In the Puget Sound region, local Indian tribes have not only a vested interest in the survival of salmon, but also a legal right to the assurance of the salmon's continued existence. Tribal scientists consequently have played a major role in salmon recovery efforts. The Skagit River basin is home to several treaty Indian tribes: the Swinomish, Upper Skagit, and Sauk-Suiattle. Together they formed a partnership known as the Skagit System Cooperative (SSC), a natural resources consortium that addresses fisheries management issues.

For the tribes, fisheries management is not merely a technical exercise concerning another creature or piece of real estate. It is about maintaining opportunities for the exercise of ceremonial, subsistence, and commercial rights to harvest fish. Under the Treaty of Point Elliot (1855) the Puget Sound Tribes retained the "right of taking fish at usual and accustomed grounds and stations," and they are making a concerted effort to restore sustainable fisheries for future generations.

SSC recognizes the need to use the best available science to evaluate the effects of human activities on salmon and their habitats and to develop strategies to reverse the decline of the species. The Research and Restoration Program of SSC has been involved in studies of historical habitat loss, current habitat condition assessment, stock status assessment, development of recovery strategies, restoration projects, and monitoring and evaluation. The Mt. Baker-Snoqualmie National Forest, the Skagit River Indian Tribes, and others have been working

, Monitoring, and Evaluation

"We are now entering a new era, in which science and scientists—along with managers and stakeholders—will be intimately and continuously involved with natural resource policy development.... However, we are still very much at the stage of learning how the scientific, the technical, and the social can be integrated".

– Jerry Franklin, biologist, in Science Findings May 2000

collaboratively on these issues for the past 15 years.

The SSC believes that good science should lead to good management decisions, particularly with regard to a strategic approach to implementation of restoration projects. Because SSC works for the benefit of the fisheries interests of the Skagit Tribes, their work is a contribution to cultural survival. "For the first time, all groups interested in salmon restoration in the Skagit River basin can sit down at the same table and begin to identify what needs to be done to bring our salmon back," says Lorraine Loomis, of the Swinomish Tribal Senate.

Inventory, assessment, monitoring, and research conducted by SSC and others, including the Forest Service, in the Skagit Basin have provided a working knowledge of the functions and processes of the Skagit River system. This knowledge forms the basis for the Skagit Watershed Council's Habitat Protection and Restoration Strategy and has guided development of procedures for its implementation.

The success of these collaborative efforts in restoring salmon will test the effectiveness of our scientific theories. "The public expects that there will be measurable benefits from expenditures for stewardship activities," says Dave Pflug, fisheries biologist with Seattle City Light, another partner in assessment activities. "We need to be able to measure these benefits, at the watershed scale, and provide information to the public and feedback to the planning process."

A Sampler of Other Assessment, Monitoring and Evaluation Partnerships

MAJOR PARTNER

North Cascades National Park

Skagit River Stewards is a volunteer monitoring program coordinated by the Forest Service and North Cascades Institute in partnership with North Cascades National Park and the Skagit Fisheries Enhancement Group (SFEG). Volunteers collect aquatic insects (which are indicators of stream health). Data are used by the national forest to monitor the conditions in the Skagit Wild and Scenic River, by the national park to develop a regional index of aquatic conditions, and by the SFEG to measure the success of stream restoration projects.

MAJOR PARTNER

Skagit Chinook Work Group

This coalition of agencies and organizations is developing a limiting factors analysis and recovery strategy for the six Skagit chinook salmon stocks.

MAJOR PARTNER

Washington Department of Fish and Wildlife (WDFW)

The WDFW has conducted assessments of off-channel habitat and fish-passage blocking culverts on streams throughout the Skagit Basin. In addition, the WDFW monitors the status of all fish stocks in the basin.

Looking Ahead: Stewardship Cha

"If we assume that biodiversity is worth conserving, it is far less clear how we go about actually conserving it. How do you take the whole world into account?"

– Science Findings, November 2000

The need to establish and nurture relationships with stakeholders in management issues will only expand in the future as the stewardship challenges developing in our local communities take on regional, national, and global proportions. Working beyond geographical and administrative boundaries will become critical to achieving resource goals at multiple scales. Monitoring our progress, both on the land and in our partnerships, will also be an essential element to achieve our mission over the long term.

Crossing Management Boundaries in North Cascades National Park

A national park that is also designated wilderness might seem an unbeatable way to protect a sensitive landscape and its inhabitants forever. But North Cascades National Park (NCNP), a gem at the mountainous headwaters of the Skagit River, illustrates that even undeveloped lands are closely connected to the world around them—that ecological challenges cross boundaries and so must their solutions.

"Administrative boundaries are invisible to the migratory species that travel through and to many other habitats, which may be degraded or threatened with development or alteration," notes Bruce Freet of the NCNP. " Air pollution also crosses boundaries, coming into the national park system, in the form of acid rain or persistent organic pollutants. These can affect the water quality of the park's lakes, streams, and glaciers, which are critical to the water budget for the entire Skagit River watershed."

Addressing such challenges at the NCNP involves broadening the boundaries to work at multiple scales and with various partners. NCNP and its national recreation areas are known together as the North Cascades NPS Complex (NOCA). The NOCA complex itself is part of a larger network of seven national park system areas known as the North Coast and Cascades Network, which facilitates work at the local level while linking the NCNP with other ecoregions including Southeast Alaska/British Columbia and north coast California/Oregon.

The national park system has the dual and sometimes conflicting mandate of providing for public enjoyment and protecting resources

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Challenging stewardship issues include:

- Habitat fragmentation
- Water quality and quantity
- Introduction and spread of exotic plants and animals
- Recreation demands
- Energy use
- Preservation of farmland and open space in the face of increasing urbanization
- Additional listings of endangered species, declining fisheries, and other species losses
- Ecological literacy for an engaged and knowledgeable public
- Maintaining a connection to the land and natural resources in our daily lives
- Lack of resources to complete needed plans: decreasing staff and funding levels
- Political influences in natural resource management, which may conflict with science and with biological or ecological needs
- Continued threats to sustainable populations.
- Implications beyond our boundaries: air pollution, loss of biodiversity, displacing our environmental problems to other parts of the world

for future generations. In the late 1990s as science and resource management co-evolved, the priority tipped more toward resource protection. The shift created new challenges, including funding and a need to monitor progress. In 2001, NCNP embarked on a long-term ecological monitoring program to evaluate the status and trends over time of the natural resources that the park is mandated to protect. Developing and implementing monitoring strategies and activities necessary to deal with cross-boundary issues has led to close partnerships with research institutions, agencies (including the Forest Service), and many others.

"Monitoring natural conditions at multiple scales and time frames can provide insight into the range of natural variability," says Freet. "The results provide reference conditions for more heavily developed or altered landscapes outside the park boundaries. Scientists can use conditions in the park to assess changes from historical conditions and set goals for restoration."

Ecological monitoring will provide valuable information that allows the NCNP to serve as a barometer of conditions within and beyond the Skagit watershed. This long-term monitoring, with occasional research, may provide a window into the complexity of local and global ecosystems and an opportunity to show the essential connection of our actions and intentions, beyond boundaries and over time.

Definitions

Society's evolving views of ecology, conservation, stewardship, and partnership have contributed to an emerging perspective on the vital role of partners in managing resources across boundaries, at landscape scales such as river basins.

Resource Stewardship ~ An approach to resource management that considers ecological, economic, and social/cultural factors in deciding appropriate protection and uses of natural resources. Guiding principles are:

* The **interconnectedness** of communities of living things and the physical environments in which they interact. *Effective stewardship requires reaching across political or jurisdictional boundaries to collaboratively achieve common goals in a particular place and time.*

* **Sustainability** of watersheds, forests, rangelands, and communities—taking no actions that would limit future land management options.

Partnership ~ A type of collaboration built on personal relationships and mutual interest, in which people, organizations, and/or institutions voluntarily work together toward common goals that are consistent with their individual values, objectives, and resources. *Effective partnerships are synergistic, allowing more to be accomplished than would be possible with everyone working alone.*

Looking Ahead: Partnership Chall

"That so many geese would crowd together on a single farm field indicates that wildlife friendly farming has worked. What is worrisome though, is the unrelenting development pressure that is turning agricultural expanses into slivers of property."

– Ducks Unlimited website

The partnership approach to problem solving will become increasingly important, yet ever more challenging in the future. As resource conflicts increase, it will take more and more effort to foster the trust and understanding that are critical to solving problems. It will take strong personal relationships to get past the inevitable stumbling blocks. And it will be important to be able to anticipate the changes that may affect our ability to do good work as partners.

In the long haul, partnership challenges for the Forest Service resemble those confronting all interpersonal relationships.

Ducks Unlimited

Expanding Partnership Boundaries on the Skagit Delta

While far downstream of national forest borders, estuary habitat has become part of the partnership story for the Mt. Baker-Snoqualmie National Forest because this habitat has been identified as a limiting factor in salmon recovery. The Skagit River delta is extremely important to juvenile salmon, which spend time there to feed and acclimate to salt water. The delta also provides habitat for 80 percent of the wintering waterfowl in western Washington, some of which also use habitat on National Forest System land.

In the Skagit, as in much of Puget Sound, most of the natural wetland habitat was diked and dredged at the turn of the last century, replaced by farm fields. Over time the waterfowl have adapted to the farmlands as a food source (salmon have not been as successful), but today farms are subject to increasing pressures. Loss of farmlands and remaining wetlands is threatening habitat for wintering waterfowl, migrating salmon, and the agrarian economy in the Skagit Valley.

"While restoration of Puget Sound's estuaries is essential for the survival of chinook and other wild salmon, it also provides myriad benefits for birds and wildlife as well as for human recreation and enjoyment of nature," according to People for Puget Sound, a conservation organization dedicated to renewal of the region's estuaries. Ducks Unlimited (DU), a major partner in the Pacific Coast Watershed Demonstration Project, is another key player in efforts to protect the estuary and ensure that sufficient habitat and food remain to support the life stages of migrating waterfowl and other wetland birds as well as salmon.

enges

Challenging partnership issues include:

- Communication and follow-through
- Maintaining real personal commitments to make partnerships work over time
- Keeping issues and relationships alive as conditions and expectations change and individual partners or staff move on
- Engaging diverse communities of place and interest
- Expectations and accountability
- Learning how to assess when conflicts are just not resolvable
- Having all people in the Forest Service trained and experienced in working as partners, both within and outside the agency
- Supporting people in developing and sustaining partnerships
- Competition among each other for resources and the need to be strategic with limited resources.

Biologist Lorna Ellestad, a third generation Skagitonian, formerly represented DU in the Skagit. Lorna has built strong relationships with the farming community, working to alter farming and drainage practices on marginal lands, creating higher crop yields and providing benefits to wildlife. "The value of these resources compels us to action," she says. "We couldn't do better work for the resource in any other place in Puget Sound."

Increasingly DU is attempting work salmon-friendly designs into its wetland and waterfowl improvement strategies, part of an effort to keep farm-friendly issues in the limelight while expanding awareness to embrace the challenge of salmon recovery. While not always in agreement with the single species focus, DU seeks to build agreement on the broader ecosystem stewardship issues including protection of rural areas from development and restoration of natural processes and functions that benefit all species.

Driven by her passion for this place, Lorna worked tirelessly to create win-win situations for the farmer and the resource. But farmers are increasingly overwhelmed by development pressure, growth management restrictions, high fuel prices, and low food prices. The inherent tug-of-war between natural resources and human needs is making it tougher to keep partnerships going.

Keeping partnerships alive into the future will require finding creative ways to support the goal of diverse and functional habitats in the Skagit River basin. For the Forest Service, moving beyond our boundaries to include partnerships in the Skagit River delta is one way we hope to address this key challenge.

Partnership Tips

Partnerships are:

Relationships—based on

- mutual trust
- honesty
- understanding
- flexibility
- open communication
- constructive conflict resolution

A way to achieve a common goal

- not a way to farm out your own work
- not just about your agenda, but about mutual interests

For the long term

- Be ready for change

Partnerships need:

Clearly defined goals, tasks, responsibilities

- be true to your own mission and values but…
- work toward the common goal

The right mix of partners

- skills
- resources
- stakeholders

Organizational support

- commitment
- accountability

A clear way to measure progress and success

- Reward the small achievements
- Monitor, learn, adapt

Partnerships must overcome:

Time and resource limitations

- be selective about how much to tackle
- avoid burnout

Barriers and Boundaries

- turf battles
- adversarial approach
- red tape
- negativity

Partners and References

Selected Partners in the Skagit

The following are a few of the major partners with whom the Forest Service has worked on substantial projects and programs over the past 15 years. Innumerable other individuals, organizations, and agencies have been partners in the Skagit, working together to conserve and restore natural resources.

Backcountry Horsemen

Crown Pacific
http://crownpacificpartners.com/

Ducks Unlimited
http://www.ducks.org/news/pacific_nw_part_2.asp

Economic Development Assoc. of Skagit Co.

National Marine Fisheries Service

Natural Resources Conservation Service
http://www.wa.nrcs.usda.gov/nrcs/

North Cascades Institute
http://www.ncascades.org/

North Cascades National Park
http://www.nps.gov/noca/

Pacific Northwest Trail Association
http://www.pnt.org/

Padilla Bay
National Estuarine Research Reserve

Puget Sound Energy
http://www.psechoice.com/index.html

River Network
http://www.rivernetwork.org/

Seattle City Light
http://www.ci.seattle.wa.us/light/environment/lightimpact/

Sierra Club
http://www.cascadechapter.org/

Skagit Audubon Society
http://wa.audubon.org/

Skagit Chinook Workgroup

Skagit Conservation District

Skagit County
http://www.skagitcounty.net/index.htm

Skagit Fisheries Enhancement Group
http://www.skagitfisheries.org/

Skagit Land Trust
http://www.skagitlandtrust.org/

Skagit System Cooperative (Skagit Tribes)

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Skagit Valley College
http://ww2.svc.ctc.edu/dept/Environ/index.htm

Skagit Watershed Council
http://www.skagitwatershed.org/

The Nature Conservancy
http://www.tnc-washington.org/preserves/skagit_river.html

Town of Concrete

Upper Skagit Bald Eagle Festival
http://www.skagiteagle.org/

WA Department of Ecology
http://www.ecy.wa.gov/

WA Department of Fish and Wildlife
http://www.wa.gov/wdfw/

WA Department of Natural Resources
http://www.wa.gov/dnr/base/dnrhome.html

WA State University Cooperative Extension
http://mtvernon.wsu.edu/

Washington Trails Association
http://www.wta.org/

Wildcat Steelhead Club

US Fish and Wildlife Service

USDA Forest Service. 2001. Toolkit: Promoting health and sustainability; a stewardship approach to ecosystem management—using existing authorities to improve the linkage between local social and economic needs and the management of our natural resources. Draft version 1.0. Available from USDA Forest Service, Region 6 Regional Office, Strategic Planning, Portland, Oregon.

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The Roger Rule for Restoration Partnerships

- We are all in this boat together, acting in good faith.
- We are engaged in developmental work so we don't always know exactly how to get where we want to go.
- We will undoubtedly encounter Class IV rapids.
- When we do, if we don't all pitch in and help, our boat will sink.

-Roger Nichols, Forest Service geologist

"Our goal of restoration and protection of salmon habitat in this basin will not come easy. It will take science and story, on-the ground progress, plus solid planning and evaluation. It will also take time and resources and the goodwill of the entire community.""

-Skagit Watershed Council Chairperson Shirley Solomon

"Stewardship of habitat [was then and] remains today divided among many landowners, each with a different perspective on risks and values associated with natural ecosystems. In addition, most of the habitat in the United States is privately owned and not subject to similar management goals and policies."

- Ross Kiester in Science Findings November 2000

"We recognize that some of our individual objectives will be met through the partnership, while other objectives will have to be met some other way."

-Tracie Johanessen, North Cascades Institute

USDA United States Department of Agriculture

Forest Service

Ecological Management Decision Support Model of the Applegate River Basin

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The Ecological Management Decision Support Analysis of the Applegate River sub-basin of the Rogue River basin in southwest Oregon resulted from an integrated effort to develop a watershed health assessment tool. The Rogue River Basin Technical Team, an interagency group formed with the cooperation of 25 federal and state agencies, assessed and identified priority restoration work needed across the 33 sub-watersheds in the Applegate sub-basin. The analysis relied primarily on the Ecosystem Management Decision Support model, which evaluated 11 indicators of watershed health. When fire risk was included in analyses, 29 of the 33 were rated in poor health. Excluding fire, 21 sub-watersheds were rated in poor health. Federally managed areas contained 9 of 12 healthy watersheds. Based on instream conditions (four indicators), 25 of 33 sub-watersheds received poor scores. Across the Applegate basin, all floodplains received poor health scores for function. Generally, the upper reaches of the watershed were in better health than the low gradient areas that have the highest potential for structural and biological diversity. Recommendations for restoration differed by elevation and ownership. Accomplishing restoration priorities in the low gradient areas may be complicated due to the predominance of private ownership in those areas. Although this report is directly applicable to the Applegate sub-basin, the ecosystem indicators evaluated, the relationship between indicators, cumulative effects, and rationale used to prioritize restoration health are appropriate throughout the Rogue River basin.

Keywords: *ecosystem modeling, GIS, watershed health, landscape planning, restoration, collaboration*

Introduction

The Applegate River sub-basin is a 4th-field watershed tributary to the Rogue River basin in southwest Oregon. Traditionally, assessments and restoration planning in the Rogue River and its tributaries have been fragmented, conducted by various agencies or watershed councils. While these assessments provide a useful tool for project level planning, they do not provide priorities at larger scales. Additionally, the disparate efforts have not engaged all land managers in the watershed or incorporated limiting conditions across the landscape, reducing the efficacy of restoration efforts. To coordinate watershed restoration efforts, the Southwest Oregon Provincial Interagency Executive Committee (PIEC) and the Southwest Interagency Group (SWIG) comprising 25 federal and state agencies in the Rogue River basin signed a Memorandum of Understanding (MOU) to develop a basin-scale approach to watershed restoration. To accomplish this task, the agencies formed the Rogue River Basin Technical Team (hereafter referred to as 'the team'; see acknowledgements for members), representing various agencies and skills, to identify and prioritize restoration work needed across the 33 sub-watersheds in the Applegate sub-basin.

A functioning, healthy watershed has the structure, products and resources needed to support productive natural systems (Kolb et al. 1994). Specifically, a healthy watershed is defined as one that has: the physical structure, biotic resources and trophic (energy) levels that support productive systems; the capacity to quickly recover from episodic disturbances at the landscape scale; and the presence of a diversity of habitats for native species.

Based on these definitions of watershed health, the team selected eleven indicators to evaluate conditions in the Applegate River sub-basin. The indicators represent upslope, riparian, and in-channel processes as well as current aquatic conditions. Seven indicators define key processes that directly and indirectly influence aquatic conditions; these are causal process indicators. Process evaluation facilitates the understanding of linkages between the upslope, riparian and aquatic systems and provides insights to cause and effect relationships. Four of the eleven indicators are response indicators and represent current aquatic conditions. Table 1 lists the processes, respective indicators and variables used to measure the indicators.

Furniss, M.J., Clifton, C.F., Ronnenberg, K.L., eds., 2007. *Advancing the fundamental sciences: proceedings of the forest service national earth sciences conference, San Diego, CA, 18-22 October 2004*. PNW-GTR-689. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station.

Table 1. Watershed processes and indicators (Whitall et al. 2004)

Process	Indicator(s)	Variables
	Causal Indicators	
Water delivery	Terrestrial Vegetation	• Diameter • Species • Crown closure • Canopy layers
Sediment yield	Terrestrial Vegetation	Same as above
	Erosion	• Roads in riparian areas • Roads on slopes >30% • Roads crossing streams with gradients 25%
Fire risk	Terrestrial Vegetation	• Diameter • Species • Crown closure • Canopy layers
Streamside shade	Riparian Vegetation (within 30 m of stream)	• Species • Diameter • Crown closure
Large wood delivery to streams	Riparian Vegetation (within 30 m of stream)	• Canopy layers • Species • Diameter • Crown closure
	Wood Removal	• Roads in riparian areas
Channel processes	Floodplain Connectivity	• Entrenchment of low gradient (<3%), with valley bottoms having a valley width index of greater than 2.2
	Bank Stability	• Roads in riparian areas
Aquatic community	Fish Passage	• Percent of watershed upstream of fish barrier
	Water Availability	• Undetermined
	Response Indicators	
Aquatic conditions	Water Temperature	• Water temperature
	Key Pieces of Large Wood	• Number of pieces of large wood per mile
	Fine Sediment Deposition	• % fine sediment in riffles
	Pool Habitat	• Pool frequency

Causal processes data used were derived from spatial GIS data sets including roads, streams, DEMs, and satellite imagery. For current aquatic conditions, Oregon Department of Fish and Wildlife and the USDA Forest Service aquatic habitat surveys provided data sets. Team members used their collective local experience to assign rating criteria, develop ecosystem relationships, and evaluate results.

Model

The Ecosystem Management Decision Support (EMDS) model (Reynolds 1999) was selected to evaluate conditions at multiple scales. EMDS integrates GIS, used to store and display data, with Netweaver. Netweaver is the knowledge base that reflects the team's understanding of indicators and their cumulative condition to define watershed health and is founded on a combination of thorough literature review and the team's collective professional experience. This data set provided the reasoning to assign condition ratings to each indicator, and to describe the relationships between indicators.

The Netweaver knowledge base contains two key design features to evaluate watershed health. First, evaluation curves assign condition ratings to each indicator. Secondly, the model establishes relationships between indicators used to synthesize individual scores to generate a watershed health score.

The knowledge base evaluates the condition of each indicator using a set of curves, known as evaluation curves. These curves evaluate the proposition: "This watershed is in good health". Indicator scores range from +1, the indicator supports the healthy watershed proposition, to -1, the indicator does not support the proposition. Figure

Table 2. Indicators and evaluation criteria.

Indicator	Variables	Determination*
Causal Indicators		
Terrestrial Vegetation	• Diameter	• 0" = -1; 10" = 0, 30"= +1
	• Species	• Hardwood = 0; Mixed and conifers = +1
	• Crown closure	• <10% = -1; 10-20% = 0; 50% = +1
	• Canopy layers	• 1 = 0; >1 = +1
Riparian Vegetation	• Species	• Hardwood and mix = 0; Conifer = +1
	• Diameter	• <5" = -1; 5-15"= 0; >30"= +1
	• Crown closure	• <5% = -1; 10-20% = 0; >60 = +1
LWD recruitment	• Ratio of mi. rd. to mile of stream	• 0 = +1; 0.4 = -1
Roads in Riparian Zone	• Mi. of rd. per sq mi on slopes 60+%	• 0 = +1; 1 = -1
Roads on Steep Slope	• # roads crossings/ sq. mi. over streams with slopes 25+%	• 2 = +1; 4 = -1
Road-stream Crossing	• Species	• Hardwoods= 0; Mixed and conifers= +1
Riparian Vegetation-Shade	• Diameter	• <5" = -1; 5-15"= 0; >30"= +1
	• Crown Closure	• <30% = -1; 70% = 0; 90% = +1
Floodplain Connectivity	• Canopy Layers	• Single = 0; Multiple = +1
	• % of low gradient valley bottom streams with an entrenchment ratio < 2.2	• 50% = -1; 10% = +1 • 0 = +1; >20%= -1
Fish Passage	• Percent of watershed upstream of fish barrier	• 0.25 = +1; 0.75 = -1
Water Availability	• Ratio of consumptive water use to natural august flows	• Range subdivided into thirds: Cooler 1/3 = +1; Middle 1/3 = 0; Warmer 1/3 = -1.
Response Indicators		
Water Temperature	• 7-day maximum water temperature in relation to range of recorded temperatures of similar watershed size	• 8 = -1; 18 = 0; 29 = +1
Key Pieces of Instream Wood	• Number of pieces of large wood/mi.	

** Rating: +1 represents full support of the proposition (the watershed is in good health); 0 represents moderate support, undetermined; -1 represents no support for the proposition. With score values along the Y-axis(from -1 to +1) and existing condition along the X-axis, the points are to be connected creating a graph depicting value/score relationship.*

1 displays an evaluation curve for the indicator pool frequency expressed as number of channel widths between pools. Table 2 lists all indicators and the values used to generate evaluation curves.

The ability to assign a range of values has a distinct advantage over procedures using a dichotomous choice, such as either good or bad. Threshold values that distinguish between healthy or unhealthy rarely exist in natural systems. Rather, there is a gradient of conditions existing between the two extremes; this gradient is captured in the rating curves. The curves provide a more accurate expression of our knowledge by expressing the full spectrum of conditions.

In this study, the EMDS model assesses causal processes health and instream response conditions independently, and uses a hierarchal evaluation. The framework for the model that expresses scoring and relationships is the

Figure 1. Pool frequency evaluation curve.

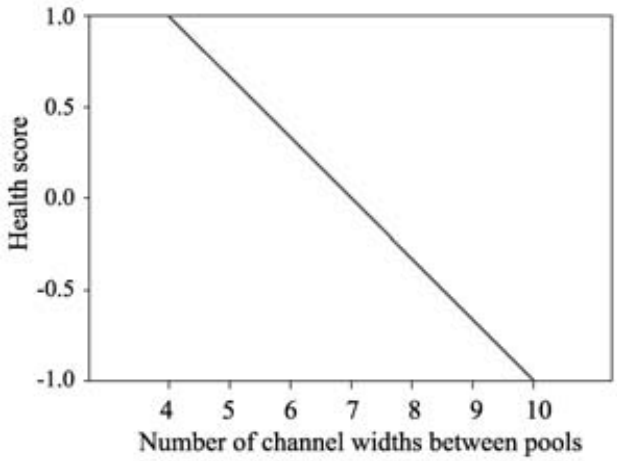
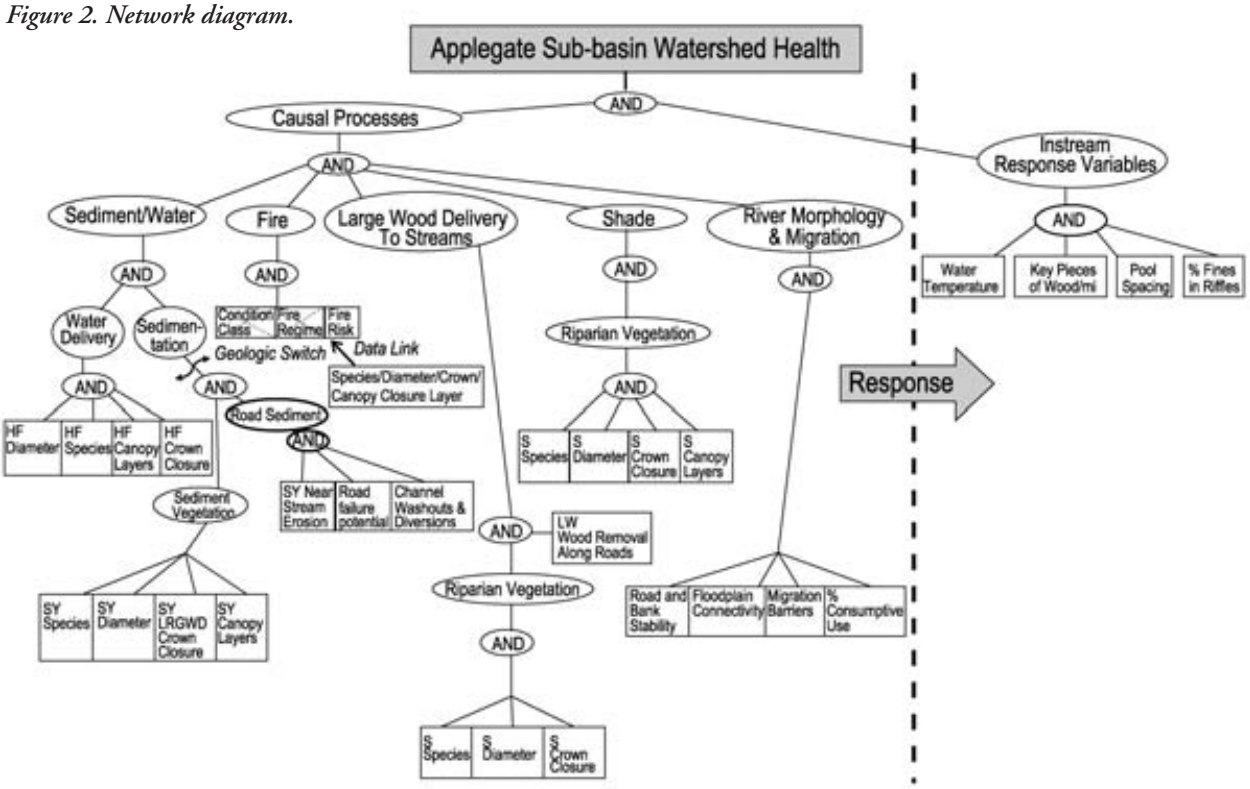


Figure 2. Network diagram.



network diagram (Figure 2). The lowest tier of information, represented by indicator scores, is synthesized providing an interpretation of a watershed process. Each watershed process is then integrated to establish watershed scale evaluation. For example, large wood delivery to streams is the combination of vegetative conditions (species, diameter, and crown closure) and wood removal along roads. The wood delivery to streams is synthesized with all related processes (water delivery, sediment yield, fire risk, streamside shade, large wood delivery, channel-floodplain connectivity, and aquatic connectivity) to generate causal processes health. Aquatic condition health is determined by combining indicators for instream large wood, water temperature, fine sediment, and pool frequency.

The separation of processes and response in the model offers the opportunity to substitute knowledge of process information for current instream condition and vice versa. Namely, if instream wood levels are not known, conditions can be inferred by the condition of wood recruitment and removal processes. Conversely, information on current instream wood levels reflects the process of wood recruitment. Thus, watershed health can be determined by either process-based or response-based conclusions.

Results

Due to the transparency of the model, as the evaluation curves, data input and network diagram were agreed upon prior to output results, outputs were deemed reasonable and defensible during peer review. Additionally, the Applegate River sub-basin maintains a strong collaborative monitoring program, providing a means to verify EMDS model output. When compared to monitoring data, model outputs accurately reflected observed conditions at the 6th-field sub-watershed level.

Recognizing that fire risk was high across the basin, influencing scores for all 33 sub-watersheds in the Applegate River watershed, results of causal processes were examined including and excluding fire. With the inclusion of fire risk, 29 of the 33 sub-watersheds rated in poor health. Excluding fire, the analysis rated 21 sub-watersheds in poor health. Of the 12 sub-watersheds rated healthy, nine are located above Applegate Reservoir where federal management predominates.

While the risk of fire influenced negative scores for watershed health, loss of floodplain connectivity and migration barriers led to poor health scores in all but three sub-watersheds below Applegate Reservoir. Other indicators lowering watershed processes health scores included high numbers of road/stream crossings and roads in riparian zones.

Similar to causal processes, instream conditions were generally in poor health, with 25 of the 33 sub-watersheds in the Applegate sub-basin receiving negative scores. Only five showed support for healthy watershed conditions. A lack of large wood and associated lack of pool habitat were

primarily responsible for poor aquatic conditions. Large woody debris functions to dissipate energy, store sediment, form pools, and provide cover and velocity refugia. In the absence of wood, channel processes become simplified, reducing channel complexity. Combined with a system-wide loss of floodplain connectivity, which provides off-channel habitat and pool formation, pool and rearing habitat has greatly decreased in both moderate gradient and low gradient channel reaches.

Cumulative Effects

At the Applegate River watershed scale, the results show that 100% of the 6th-field watersheds received a poor health score for floodplain connectivity. Seventy-five percent of the watersheds received a poor rating due to lack of large woody debris and pool frequency, while 60% received a negative score due to fish migration barriers.

A number of indicators, when examined together, can reveal cumulative effects that are integral to establishing restoration priorities. Whitall (2004) identified four particularly important process/condition interactions that greatly reduce watershed health and resiliency:

(1) ***Water temperatures and fish migration barriers.*** Flows in salmon spawning areas, typically in the lower gradient reaches, become low and warm during the summer months. Juvenile fish, with the presence of barriers, are unable to access cooler water, resulting in poor survival.

(2) ***Sediment yield and key pieces of wood per mile.*** Large roughness elements create complexity by sorting and storing sediment, as well as providing areas of quality habitat. In the absence of large wood, sediment deposits uniformly across the bed surface.

(3) ***Key pieces of wood per mile and floodplain connectivity.*** The principle mechanisms for pool formation are large wood in moderate gradient reaches and lateral channel movement, both of which create sinuosity in lower gradient reaches. Losing both large wood and meandering creates a lack of complex habitat throughout the length of the stream (i.e., longitudinal profile).

(4) ***Floodplain connectivity and water availability.*** Lowering channel bed and water surface elevations can drastically reduce the adjacent water table. Maintenance of the water table within riparian zones is necessary to preserve wetlands and diverse riparian vegetation.

A third of the Applegate sub-watersheds received a negative score for water temperature/migration barriers and floodplain connectivity/water availability indicator pairs. Negative scores for the indicator pairs of sediment yield/instream large wood, and instream wood/floodplain connectivity were found in 25% of the sub-watersheds.

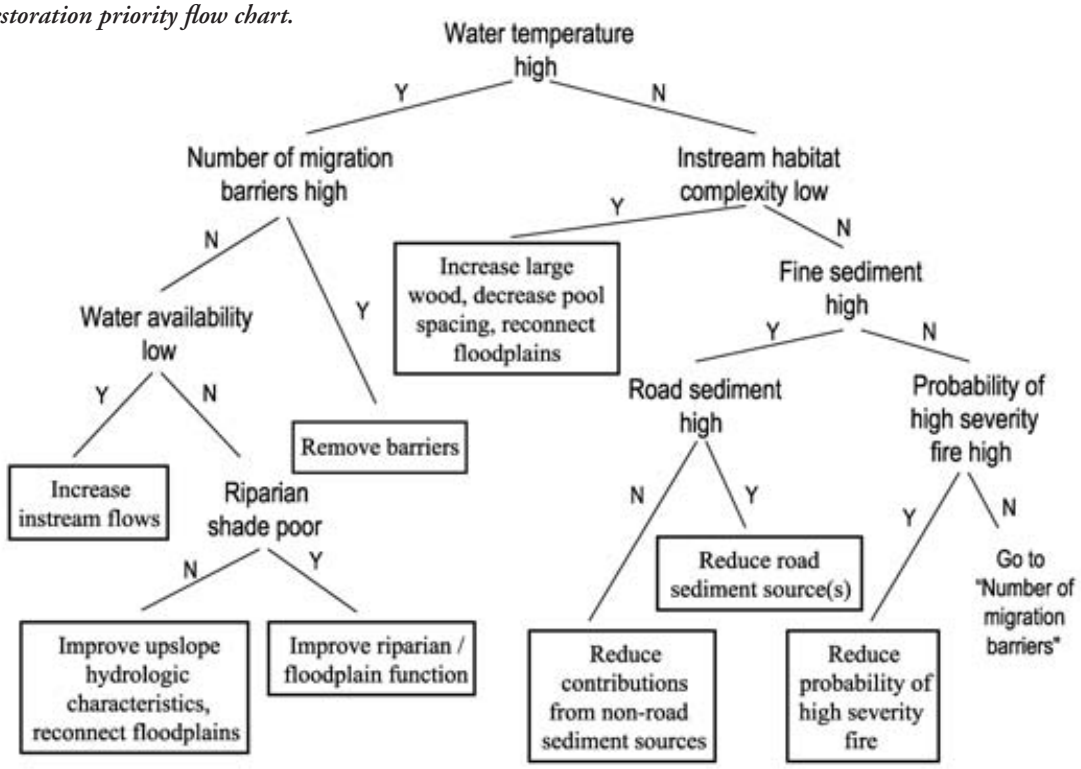
Across the Applegate River watershed, the upper reaches afford better watershed health conditions. The team determined that the lower gradient valley bottom reaches fail to support healthy watershed conditions. These low gradient valley bottoms provide the highest potential structural and biological diversity. Healthy stream channels in low gradient systems contain side channels, alcoves, pool-riffle sequences, undercut banks, off-channel wetlands, and gravel bars. Low gradient floodplain areas also provide conditions for diverse riparian plant and animal species. For a number of species, including coho salmon (*Oncorhynchus kisutch*) and steelhead (*O. mykiss*), unhealthy conditions of the valley bottoms contribute to population declines and inhibit the opportunity for recovery.

Recommendations

Based on the results of the analysis, the team developed a flow chart identifying restoration needs in the Applegate River sub-basin (Figure 3); this chart could apply equally to many watersheds in southwest Oregon. In sub-watersheds with poor water temperature, restoration actions should focus on removing barriers to allow free movement of cold-water aquatic organisms to thermal refuge areas and increasing base flows. Other restoration actions, though potentially needed, will provide little benefit until water temperature conditions are addressed. In those watersheds with reasonable or good water temperatures, restoration actions should be directed at providing high quality structural habitat (i.e., complex cover, pools, and off channel habitat) and reducing sediment where appropriate. A combination of road improvements and placement of large wood in channels in watersheds with significant increases in erosion is recommended. In the short term, wood provides flow velocity complexity, creating scour and sorting of gravel, partially mitigating high sedimentation rates. Long-term restoration may require road and culvert improvements or removal. Re-establishing healthy riparian vegetation, particularly conifers, and providing the stream access to its floodplain will reduce erosion and contribute to increased habitat complexity.

Final recommendations followed a trend with ownership and elevation. In the upper watershed areas, predominately managed by federal agencies, increasing large woody debris and reducing roads in the riparian zones were the top recommendations. Channel types in the federal land allocations typically have moderate to high gradients with little floodplain development and maintain full surface flows throughout the summer. However, wood removal practices combined with riparian harvest have left many channels lacking large instream wood. In the low gradient

Figure 3. Restoration priority flow chart.



reaches, improving water temperature, instream barriers and floodplain functions were the most frequently recommended actions. Consumptive uses and alteration of channel courses via direct modification have reduced both shade and streamflow volume, leading to increased water temperatures. When these effects are added to instream barriers that prevent migration, there is a basin-wide reduction in salmonid rearing habitat.

The EMDS analysis successfully identified restoration priorities for both moderate- to high-gradient and low-gradient areas of the Applegate River sub-basin. Accomplishing the restoration actions may be problematic, particularly in lower-gradient areas where private ownership predominates. Cooperation and collaboration among agency managers, watershed councils, and local landowners will be necessary to meet these objectives.

Acknowledgements. This manuscript summarizes the collaborative work conducted by the Rogue River Basin Technical Team. The team represents a wide range of expertise and skill profiles necessary to accomplish watershed scale planning. Cindy Ricks-Meyers, geomorphologist for the South Coast Watershed Council; Brian Barr, fisheries Biologist from the World Wildlife Fund; Dr. Tom Atzet, retired ecologist from the Rogue-Siskiyou National Forest; Debbie Whitall, policy analyst from the Washington Office of the Forest Service; and Mike Mathews, hydrologist from the Medford Bureau of Land Management developed the watershed health model and restoration strategies.

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Klamath Adjudication–Lessons Learned

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Beginning in 1990, the Forest Service and the U.S. Department of Agriculture, Office of General Counsel (OGC) became intensely engaged in developing federally reserved claims to be filed in the Klamath River basin water rights adjudication. With no data and no inventory of water uses on the three forests in two regions covered by the adjudication, the Forest Service and OGC began what looked at first to be a monumental task. Not only were claims developed, but also the underlying hydrologic information and analysis tools to support such claims. In addition, a unique instream flow protection claim pursuant to the Organic Act was developed. After claims were filed, the Forest Service, OGC, and U.S. Department of Justice (USDOJ) presented preliminary evidence to the Oregon Water Resources Department (OWRD) to assist in its preliminary determinations of the validity of the Forest Service water right claims. After the preliminary evaluations were issued by OWRD, various claimants and water rights holders in the Klamath River basin filed over 1000 objections to Forest Service claims. The Forest Service and OGC met with the various objectors and were able to resolve all objections without contested hearings. This paper discusses the steps taken to assure success in this most contentious of situations, and lessons learned in conducting such complex litigation.

Keywords: *water rights, adjudication, instream flow*

History

The Klamath Basin Adjudication was initiated in 1975 to quantify all federally reserved water rights and state law based rights prior to the date of the Oregon Water Code, 24 February 1909, on the waters of the Klamath River and its tributaries, located in the state of Oregon. Shortly thereafter, litigation between the State of Oregon and the Klamath Tribe (Tribe) was started over whether the Tribe retained a water right after sale of former reservations lands, and if so how much.

The Federal Courts, through the Adair decisions issued by the United States District Court for the District of Oregon and the 9th Circuit Court of Appeals, held that the Klamath Tribe retained a water right initially reserved under its treaty of 1868, but left to the State of Oregon adjudication proceedings the determination of the quantity of that right. (United States v. Adair, 478 FS 336 (Dist. OR 1979) aff'd 723 F.2d 1394 (9th Cir. 1983)).

The State of Oregon issued a notice to the federal government, requiring that federally reserved claims be filed by 1 February 1991. The United States then filed its own action against the State of Oregon, challenging the adequacy of the procedures in the Adjudication, arguing the procedures did not meet the requirements of the McCarran Amendment. The United States lost its challenge of procedural issues. However, the Court held that the United States could not be required to pay filing fees to the State of Oregon.

Challenges of the Adjudication

Pursuant to federal case law, when Congress reserves land from the public domain, such as for a national forest, a reservation of water to fulfill the purposes of the reservation is implied.

Obtaining federally reserved water rights for the Forest Service in the Klamath Basin Adjudication was a challenge. The State of Oregon had never before granted federally reserved water rights in any of its adjudications. The listing of fish species as threatened and endangered was just beginning in 1990. The public in the Klamath River basin was generally suspicious of the federal government, with some ranchers warning that the granting of instream reserved rights was just a veiled attempt to stop all irrigation in the basin.

Early on, the Forest Service arranged a meeting with the Director of the Oregon Water Resources Department (OWRD). In this meeting the Forest Service explained the benefits of instream rights that might be granted, including the benefit to maintaining and enhancing habitat of recently listed fish species. This meeting helped to

Furniss, M.J., Clifton, C.F., Ronnenberg, K.L., eds., 2007. *Advancing the fundamental sciences: proceedings of the forest service national earth sciences conference, San Diego, CA, 18-22 October 2004*. PNW-GTR-689. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station.

convince OWRD that Forest Service instream rights might help soften the impact of the listing of fish species under the Endangered Species Act, and gained the Forest Service considerable credibility.

Through the process, the Forest Service had to deal with this laundry list of challenges:

1. Determining what rights the Forest Service should file, and on what theories.
2. Hydrology – How much water is there in the Klamath River basin, how to calculate those flows, and what to do about the lack of flow data in the basin.
3. Klamath Tribal Claims – as outlined in the Adair decisions, discussed earlier.
4. Endangered Species Act and listed species in the Klamath River basin – How would the listing of fish species effect operation of Federal irrigation projects in the Klamath River basin?
5. Bureau of Reclamation/Klamath Irrigation Project – who owns the water right for lands in the project area: Bureau of Reclamation, the irrigation districts, or the private land owners.
6. Operation of the Klamath Irrigation Project and priorities among the irrigators.
7. Downstream fisheries.
8. Walton irrigation rights – claimed by individuals owing lands formerly owned and farmed by Tribal members.
9. The Klamath Compact, between the states of Oregon and California, governing management of this two-state basin.
10. Claim of the Klamath Tribe for return of former reservation lands.
11. Downstream Tribes – Hoopa and Yurok – They claim their treaty right to salmon harvest is not being met.
12. Dealing with the many differences of opinion and direction among the group members – Bureau of Reclamation, Fish and Wildlife Service, Bureau of Land Management, National Parks Service, Bureau of Indian Affairs, Klamath Tribe and the Forest Service, plus the U.S. Department of Justice.
13. Filing Claims – Based on these Acts of Congress; Organic (instream favorable conditions, instream fire, consumptive), Wild and Scenic Rivers, Wilderness, and Multiple Use Sustained Yield (MUSY).
14. Coordinating science and its application to the claims.
15. Working with the State on the actual mechanics of filing claims – compiling maps, land status documents, consumptive claims by sub-basin.
16. Alternative Dispute Resolution process – what could be gained in that forum.
17. Litigate or Settle

The above issues all had to be analyzed and addressed while developing the claims. Many times the team had to change or modify direction as analysis was evolving.

No other Forest Service region had yet been successful in an adjudication that could provide any guidance, though there were other adjudications at similar stages. Region 6 of the Forest Service (the Pacific Northwest Region) chose to use and develop its own expertise and responses to the challenges listed above.

Results

1. The Forest Service collected all data to support its claims. Now that data is relied upon by almost all other claimants and OWRD. This includes sediment data, flow and stage readings, and habitat rating curves.
2. The Forest Service developed a favorable conditions of flow claim theory and hydrograph that meshed with the hydrology and needs of the Forest Service in the Klamath River basin.
3. Over 1000 instream nonconsumptive and consumptive claims were filed by the Forest Service in a timely manner.
4. The Forest Service quantified fisheries flows. The results are used by the forests for planning purposes; however, MUSY Act-based claims were withdrawn because of prior unfavorable case law.
5. The Forest Service created fire suppression instream claims pursuant to the Organic Act, which were granted by OWRD, resulting in the awarding of almost the same flow amounts as the MUSY fisheries claims that were later withdrawn. This type of claim was first filed in Oregon, and exhibits the creativity of the team in claiming water for National Forest purposes.
6. Over 1000 objections to FS claims were filed by private parties. All objections were settled by the Forest Service without compromising legal and management objectives.

Lessons Learned

In going through this more than ten-year process, the Forest Service and OGC personnel working on the case came up with the following lessons and pearls of wisdom to share with anyone starting work a water rights adjudication:

1. Know your objectives – it keeps the team from being sidetracked, and wasting time and resources.

2. Listen for understanding – you may learn from so-called opponents and see you have more in common than you suspected.
3. Be truthful – it helps gain credibility when trying to resolve differences.
4. Share information – again, it illustrates that there are no ulterior motives.
4. Work towards common goals – understand other claimants' motivations.
6. Cooperate – again, helps gain credibility.
7. Be helpful – it helps to shorten the process.
8. Know your partners' objectives, policies, rules and regulations.
9. Know your opponents' objectives, policies, rules and regulations.
10. Don't lose sight of your agency's objectives.
11. Don't depend on others, i.e., tribal rights on FS lands.
12. Make sure your attorneys understand your science.
13. Don't be afraid to get the lawyers out of the room and talk about what is on the ground.
14. Expertise can and should be local – parties don't like persons outside the area telling them about their areas of expertise.
15. Don't be afraid to come up with your own science.
16. Again, know and keep sight of your objectives – this cannot be repeated enough.
17. Be realistic with your claims – claim just what is needed for forest purposes.
18. Don't be afraid to branch out and be creative when drafting water right claims.
19. Respect the opinions of others.
20. Don't panic; if you are moving forward you will compete the tasks – break down the tasks into smaller, achievable items.
21. Large negotiations don't necessarily solve all issues, but they can solve small issues.
22. The lawyers' objectives may not be the same as yours – keep them focused on the agency's goals.
23 Don't make assumptions.
24. Use time in meetings with the public to educate them on Forest Service goals, benefits to the public and the limits of Forest Service authorities.

Conclusion

Though the Klamath Adjudication is a few years from receiving a final order from the Director of OWRD because of the time needed to address the reserved claims of other federal agencies, the reserved claims filed by the Forest Service have been resolved, and the Director will be issuing virtually all reserved claims filed by the Forest Service. When the final order of the Director of OWRD is issued, it will grant to the Forest Service water rights reserved under the Organic Act for favorable conditions of flow, fire suppression flows and administrative consumptive uses; instream flows for Wilderness Act purposes; and instream flows for Wild and Scenic River Act purposes.

The effort in the Klamath Adjudication was successful because Region 6 Forest Service personnel did not try to solve all issues in the Klamath River basin. General stream adjudications can be successful in meeting Forest Service water needs if the agency concentrates on its specific objectives and direction, as well as mapping out a reasonable strategy. The key to resolving objections and issues with other claimants is being open to scrutiny and the sharing of information.

The Coastal Initiative: Innovative Partnerships to Restore Watersheds

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Siuslaw National Forest, Corvallis, Oregon

The Siuslaw National Forest watershed restoration program depends on partnerships, both programmatic and strategic: this paper highlights two of them. The Coastal Initiative, 1998-present, is a cooperative agreement between the Siuslaw National Forest and the local Resource Conservation and Development District. As of this writing, this holistic program has involved twenty-one projects encompassing all aspects of restoration including project planning and design, environmental education, monitoring, and implementation. The success of the Coastal Initiative lies not in isolated projects, but in its multi-faceted approach to implementing a program in which local groups identify local needs. The Karnowsky Creek Restoration began when the local watershed council introduced the concept of a "charette" or rapid restoration design involving graduate students, followed by a participatory bimonthly design review. The Forest Service provided paid staff time, but partnerships with the watershed council and Soil and Water Conservation District contributed private foundation monies and state funds toward completion of the project. Each partner was integral to the success of the project. An $81,000 commitment by the Forest Service leveraged $350,000 in contributions from partners – a 1:4 match. The partners are now implementing contracts on federal lands.

Keywords: *watershed restoration, collaboration, partnerships*

A new management philosophy, declining forest budgets, and the need to recover aquatic species, have encouraged a variety of partnerships to facilitate watershed recovery. This paper highlights several partnerships that helped us grow as a forest, as a program and as a community.

The Northwest Forest Plan (1994) and the Oregon Plan for Salmon and Watersheds (1997) were two important policy documents that initiated a change in the management philosophy of the Siuslaw National Forest, and organized community involvement in local watershed issues through watershed councils. Both of these policies emphasized the need to recognize that everything in the watershed is connected, and that understanding limiting factors throughout the whole watershed, from the ridges to the estuary, is a crucial component of land management. In response to both of these policies, watershed analyses were being done on both federal and private lands.

Watershed analysis on the central Oregon Coast documented, for the first time, that while about 85% of perennial stream miles were on national forest land, approximately 80% of coho salmon (*Oncorhynchus kisutch*) spawning and rearing habitat was on private lands below or adjacent to national forest boundaries. It was readily apparent that if the national forest system was going to be actively involved with salmon recovery, we needed to do two things: protect and restore uplands for water quality and quantity, and work with landowners throughout the watershed on stream habitat improvement on low gradient, unconfined stream systems. To accomplish the latter objective, the Siuslaw National Forest needed to work with those entities that already had local contacts, specifically local Soil and Water Conservation Districts, Resource Conservation and Development Districts, state agency personnel, and watershed councils, which were made up of local landowners.

Existing budgets were rapidly declining, as a result of reduced timber harvest activities on federal lands and a higher proportion of the remaining budget was covering salary and overhead costs, so it was clear that appropriated Forest Service funding would be insufficient for the amount of restoration work that needed to be done. Only about 20% of the forest's appropriated fisheries and watershed funding was available for restoration project implementation. We needed to seek supplemental funding elsewhere.

Watershed restoration is not a task that any one entity can take on by itself. There are many groups, both governmental and non-governmental, already actively working to restore conditions for a variety of natural resources, but particularly for coho salmon recovery in coastal watersheds. Many of these groups have common objectives; however, none of them individually has the funding or the technical ability to accomplish large watershed restoration projects. The Siuslaw Watershed Council convenes monthly meetings of many local groups interested in watershed restoration. Over the

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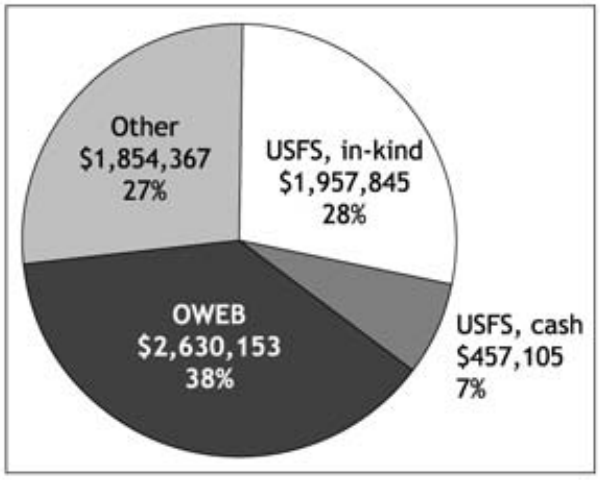
Figure 1: Six years of partnership funding on the Siuslaw National Forest.



years, considerable trust and respect has developed among participants. Two or more partners often work together, drawing on the skills of each organization to accomplish shared restoration goals. True collaboration exists not when we seek approval for work we already have planned, attempt to get someone else to do our work for us, or tell someone else what they should be doing, but when the funding, skills, and advice of each group present combine to complete restoration assessments and projects efficiently and in a technically sound manner.

The benefits of developing strong partnerships can easily be portrayed in economic terms. Through these collaborations, between 1999 and 2004, approximately $6.9 million was spent on restoration in the Siuslaw River basin (Figure 1). Direct USFS funding was only 7% of the total; another 28% was in USFS donated salary and supplies (usually large logs for in-stream structures). Partners provided 66% of the funds for restoration with the single largest contribution (38%) coming from the State of Oregon Watershed Enhancement Board.

Working with partners is a huge, long-term commitment, and it requires constant maintenance to succeed. For the Forest Service, internal commitment from the Forest Supervisor, the District Rangers, and the local district staff is essential for partnerships to succeed. And nothing can move forward without the involvement of the contracting and grants and agreement staff; their working knowledge of all the laws and regulations can either keep the process running smoothly or bring everything to a grinding halt. Often partners can apply pressure to ensure this internal support if you cannot obtain it yourself-don't hesitate to ask them for help.

A large variety of tools enable the Forest Service to work with the public and other agencies. First, natural resource specialists should have a working knowledge of all the internal authorities that allow the creation of various types of partnerships. Table 1 lists the agreements and authorities. It's worthwhile to take training about partnership mechanisms, as knowing the ins and outs of those tools will allow you to help guide possible partners through the potentially-daunting paperwork required to set up the agreements. Make it as easy as possible for them to become involved by taking on the burden of the application process yourself. Ask someone to tell you more about the programs on this list if you think they may be appropriate for the project you want to implement.

Second, there are many programs external to the Forest Service that are available for landowners, and often for federal lands if applied for through a partner, that can contribute funding for your projects. Table 2 lists some

Table 1: Agreements and authorities available to Forest Service employees to facilitate partnership development.

Partnership type	Mechanism
Exclusive benefit of the government	Procurements Cost-reimbursable agreements
Support someone else's program	Federal financial assistance Cooperative Agreement / Grant Joint Venture Agreement
Cooperative programs	Memorandum of Understanding Participating Agreement Collection Agreement Challenge Cost-share Agreement INTERagency agreement INTRAagency agreement
Authorities: Wyden Authority, Stewardship Authority	

Table 2: Programs providing potential external funding for watershed restoration projects.

Agency	Programs
USDA Natural Resources Conservation Service and the Farm Service Agency	Wetland Reserve Program Wildlife Habitat Incentive Program Conservation Reserve Program Conservation Reserve Enhancement Program Environmental Quality Incentive Program
US Fish and Wildife Service	Partners for Wildlife Coastal Wetland Reserve Program
National Oceanic and Atmospheric Administration	Community Restoration Programs
State Department of Forestry (Oregon)	Forest Land Enhancement Program Forest Resource Trust Forest Stewardship Plan
Non-profit groups (e.g, National Forest Foundation)	Community Assistance Program Matching Awards Program
Other	Easements Exchanges Acquisitions Tax incentives

of the programs, many nation-wide, some state-specific. Find out what is available in your own area. A third critical component of watershed restoration is obtaining funding through grants. Hundreds of organizations have funding available for environmental restoration. However, there are a few things to know about writing successful grants. You stand a better chance of success if you make an effort to participate on boards of local non-profit groups, or volunteer to be on grant review teams, to develop honest and reliable relationships with potential backers. Get to know the source of funds for which you are applying, make a personal contact, explain your idea, and find out whether your project is something they are interested in before you begin to fill out the grant application. Invite potential funders out to your project site, along with your partners. Let your partners do the talking - they make a bigger impression. Then, if you get the grant award, be sure you do what you said you were going to do, make sure your project is technically sound, market the results and always give credit to the funding organization.

Enough of the abstract: how about some real examples of successful watershed partnerships?

The Coastal Initiative and Karnowsky Creek projects are two partnerships developed by the Siuslaw National Forest to accomplish a complex of watershed restoration projects in the Oregon Coast Range.

The Coastal Initiative

The Coastal Initiative, a Cooperative Agreement between the Siuslaw National Forest and Cascade Pacific Resource Conservation & Development District, Inc. (CPRCD), has helped the forest develop outreach to existing local organizations and build capacity to further their on-going efforts. Through this agreement, the USFS supplied both analytical and technical project implementation skills while capitalizing on the contacts that already existed between landowners and these other local groups. The cooperative agreement and several amendments enabled us to have multiple on-the-ground restoration or outreach and monitoring projects active simultaneously. Twenty-one separate projects were included in the Coastal Initiative I 1998-2003. With the Coastal Initiative II 2004-present, fourteen projects are already authorized (Figure 2). The ability to amend the existing agreement on an on-going basis makes the initiative flexible and responsive to local community needs.

The Coastal Initiative pools financial, technical, and social resources to accomplish its objectives. The project is economical and cost effective: with only a 10 % overhead charge, the CPRCD is responsible for project recruitment, landowner agreements, contracts, fiscal management, monitoring and reporting.

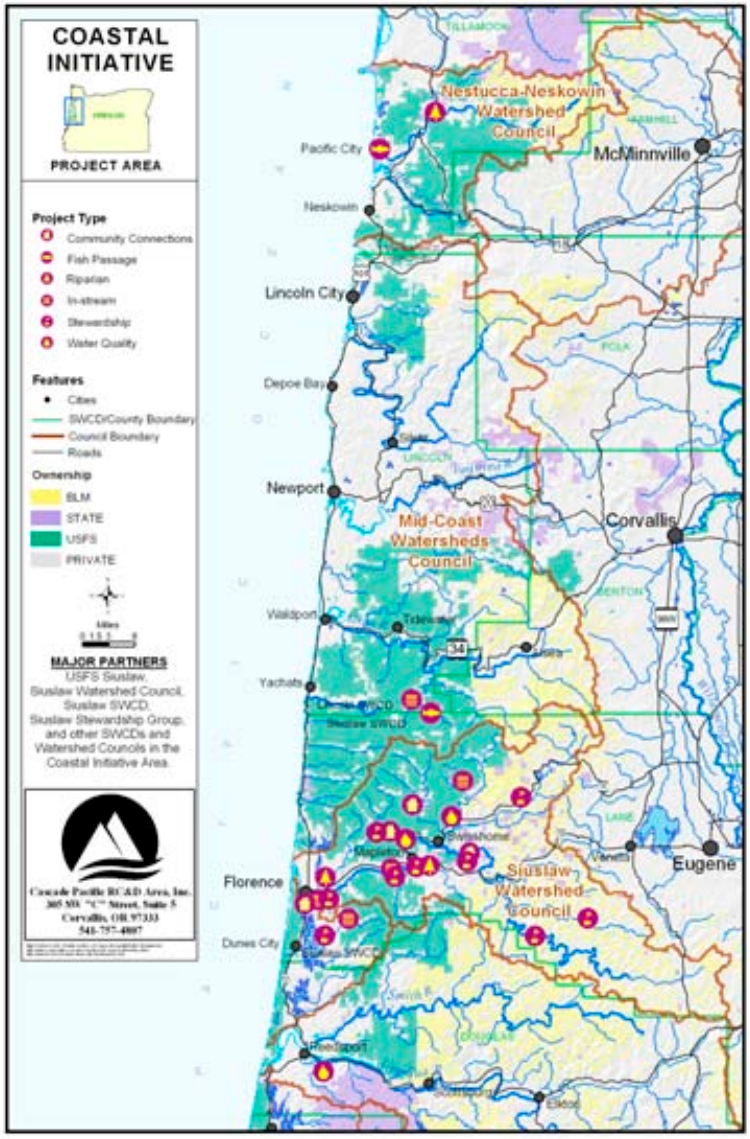


Figure 2. Coastal Initiative sites and types of projects.

Restoration of tidal flow onto an estuarine wetland that has been farmed for over 70 years improves salmonid rearing habitat.

When we first began soliciting outside funding for projects, we found that the single greatest limiting factor in applying for grants is the inability to fund project designs-no granting group will pay for the design, yet they want to see the design before they will approve the project. The Coastal Initiative employed two successful methods to design projects. The first method provided a competitive grant to a local contractor to design stream restoration projects. The grant required the contractor to submit the final design (approved by the local watershed council technical team) in the form of a grant application. The first project of this type designed eight stream restoration projects for $8,000, which in turn brought in additional implementation grants amounting to $250,000. This project was not only successful in obtaining implantation grants, but also in increasing the project design capability of the local community. Since that initial grant, two more projects of this type have been authorized and are on-going. One unexpected benefit of this method is that local contractors are known and trusted in the community and they can often work with landowners whom state and federal agency personnel cannot easily approach.

The second way the Coastal Initiative has found to accomplish project design is to hire an interdisciplinary team of graduate students for an eight-week internship managed by the local watershed council. This student-led project provided graduate students with the challenges of a real-life restoration design opportunity, working in cooperation with local community members and agency representatives (Figure 3). The students bring a freshness, enthusiasm, solid academic background, and phenomenal computer and graphic skills to the project. They respect local input, and through the interactive process of reporting back to an advisory committee every two weeks, they engage community interest and incorporate knowledge that agency staff might not have had time to gather. The

Figure 3. Students from the Mapleton Schools planting native plants from seeds they have collected and grown as part of the Natural Resources curriculum. Funding for the greenhouse came from the Coastal Initiative.

final restoration project design is an easy-to-read document emphasizing graphic design, which is used as a marketing tool to acquire grants. The document content exemplifies the value of stakeholder involvement and partnerships in formulating a successful project design that engages community participation from concept through implementation. Two projects of this type have been completed under the Coastal Initiative. One project was successful in bringing in $450,000 for implementation of the plan; the other, still in phase one, was granted $125,000 for implementation within three months of the final design.

In addition to the above-mentioned projects, the Coastal Initiative has included water quality monitoring, in-stream habitat improvement, education and outreach, fish passage improvement and riparian and tidal wetland restoration. All of these projects filled an important gap in funding to local communities, strengthened local programs, and accomplished technically sound watershed restoration. By being a part of these projects, the Forest Service has increased community trust and support, has been able to identify and propose local projects to restore watershed conditions, and has highlighted data gaps, particularly in the area of water quality.

The Karnowsky Creek Project

Karnowsky Creek was purchased by the Siuslaw National Forest from a private landowner in 1992. When the Northwest Forest Plan was signed, it was apparent to the district that grazing land use occurring in the valley was not in line with current management direction. With encouragement of the Siuslaw Watershed Council, a group of students were brought in to develop a restoration strategy for the area. With the student-generated Karnowsky Creek Restoration design in hand, the watershed council and the Forest Service collaborated to develop a grant proposal for its implementation. The watershed council submitted the grant to the National Forest Foundation to fund the riparian restoration portion of the project, but a watershed council executive board member unexpectedly blocked submittal of the application to the State of Oregon Watershed Enhancement Board (OWEB), stating that he did not support state funding being spent on federal land. However, because the community was integrally involved with the design of the project from the concept phase onward, they felt great ownership in the project and wanted to see it move forward. The local Soil and Water Conservation District then submitted the grant to OWEB. The Forest Service didn't even know these discussions were occurring, but the strength of community investment kept the project going. Both grants were successful in acquiring the funds needed to do the restoration work. Meanwhile the Forest Service completed the necessary environmental documentation. Each partner was integral to the success of the project: a true spirit of collaboration. In this project an $81,000 commitment by the FS leveraged $350,000 in contributions from partners for implementation - a 1:4 match.

Implementation of the Karnowsky Creek restoration continued the unique partnership developed in the initial phases of the project. The Forest Service facilitated the necessary working agreements with the Siuslaw Soil and Water Conservation District (SWCD) and the Siuslaw Watershed Council, resulting in a Memorandum of Understanding that set up a Karnowsky Creek Board of Directors to enhance communications and oversee all activities that occurred within the Karnowsky Creek Valley. Participating agreements with the Siuslaw Watershed Council, the Siuslaw SWCD, and the Siuslaw National Forest enabled the partners to do projects on national forest lands. As a result, the watershed council hired a contractor and facilitated development of the riparian planting design, site preparation, planting, maintenance and monitoring of all riparian species. In addition, the SWCD hired a local contractor to do all road access, stream reconstruction and ditch filling, and hired a monitoring coordinator to facilitate local school involvement in project monitoring. A Forest Service employee was on site to inspect work done by the contractor. The collaboration has been phenomenal, each organization feels ownership in the work that has been done to restore Karnowsky Creek,

and we all acknowledge that the project would not have been possible without the enormous contributions of all involved.

It takes innovation, enthusiasm and dedication to engage partners in a whole watershed restoration program. Personalities can be as varied as they are strong willed. Finding and working from common ground, forging alliances wherever necessary, and capitalizing on the skills and knowledge that each group and individual brings to the table is critical to success. The strong partnerships on the Siuslaw have been recognized internationally, receiving the 2004 Thiess International Riverprize for high quality river basin management. The Siuslaw National Forest will continue to be a part of the team that earned that recognition, in the interest of restoring watershed conditions, building strong communities, and fostering a positive relationship between local people and their environment.

The Pathfinder Project: A Collaborative Effort to Provide for Instream Flow Management

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Gary Shellhorn
Grand Mesa, Uncompahgre and Gunnison National Forest, Delta, Colorado

The Pathfinder Project was a pilot effort initiated by the USDA Forest Service Washington Office and hosted by the Grand Mesa, Uncompahgre and Gunnison National Forest (GMUG) from 2000 thru 2004. Water users, state water officials, local watershed coalitions and conservation organizations met and worked together with the forest to determine how best to provide for instream flow needs in the Forest Plan, while recognizing historic needs and existing laws. Technical work and field investigations involving examination of water rights, diversion points, basin hydrology and comparison of instream flow quantification models were key components and are addressed in this paper. The results of this collaborative effort produced a product different than that envisioned by the Forest Service, but provided a useful critical public perspective on instream flows early in the planning process. The Pathfinder Project has been used as an example of cooperation between the state of Colorado and the Forest Service, in an effort to find common ground on an issue of long standing conflict.

Keywords: *water rights, instream flow, stream diversions, R2Cross method, collaboration, GMUG*

Introduction

Conflicts over water, particularly in the arid western United States, have been and will continue to be a key resource allocation issue facing both elected officials and policy makers. There are many facets to this subject, with instream flows being just one. In states where water is controlled by the doctrine of prior appropriation, water use is considered to be a property right and falls primarily under the jurisdiction of the states. This situation presents huge challenges for federal land management agencies.

In Colorado, instream flow uses are generally looked upon as secondary to consumptive uses, or those uses which capture and control the stream in order to put it to beneficial use. Additionally, instream flows are often very junior to long established agricultural, industrial and municipal uses. The Forest Service must comply with a host of federal laws that direct it to protect the environment and sustain ecosystems. Therein lays the conflict, because without water in stream channels it is impossible to sustain ecosystems.

Colorado has been a real battleground over federal vs. state interests in water. In order to provide water for national forest purposes, the Washington Office was interested in exploring alternatives to litigation, which has historically been costly and less than fully successful. The Pathfinder Project was a Washington Office initiative intended to learn if collaboration could be used as a way to share ownership in water issues and perhaps cut through the contentious and entrenched positions that surround water issues in Colorado. Because the Grand Mesa, Uncompahgre and Gunnison National Forests (GMUG) were initiating a Forest Plan revision, which provides the framework for determining resource management objectives and authorized uses of the national forest, the GMUG was selected as an excellent candidate to test a collaborative process. Water users, state water officials, local watershed coalitions and conservation organizations were brought together for the purpose of assisting the forest in determining how best to provide for instream flow needs in the Forest Plan, while recognizing historic needs and existing laws.

The GMUG is located in western Colorado (Figure 1). These national forest lands are the headwaters for and control about 60% of the Gunnison River basin, which is the largest tributary to the Colorado River within the state. Annual water production is on the order of 2.9 million acre-feet (3,576 million cubic meters), which flows down 3500 miles (5,600 km) of streams. There are 162 reservoirs and 212 ditches authorized by special-use permits or easements on the forests. The Grand Mesa National Forest

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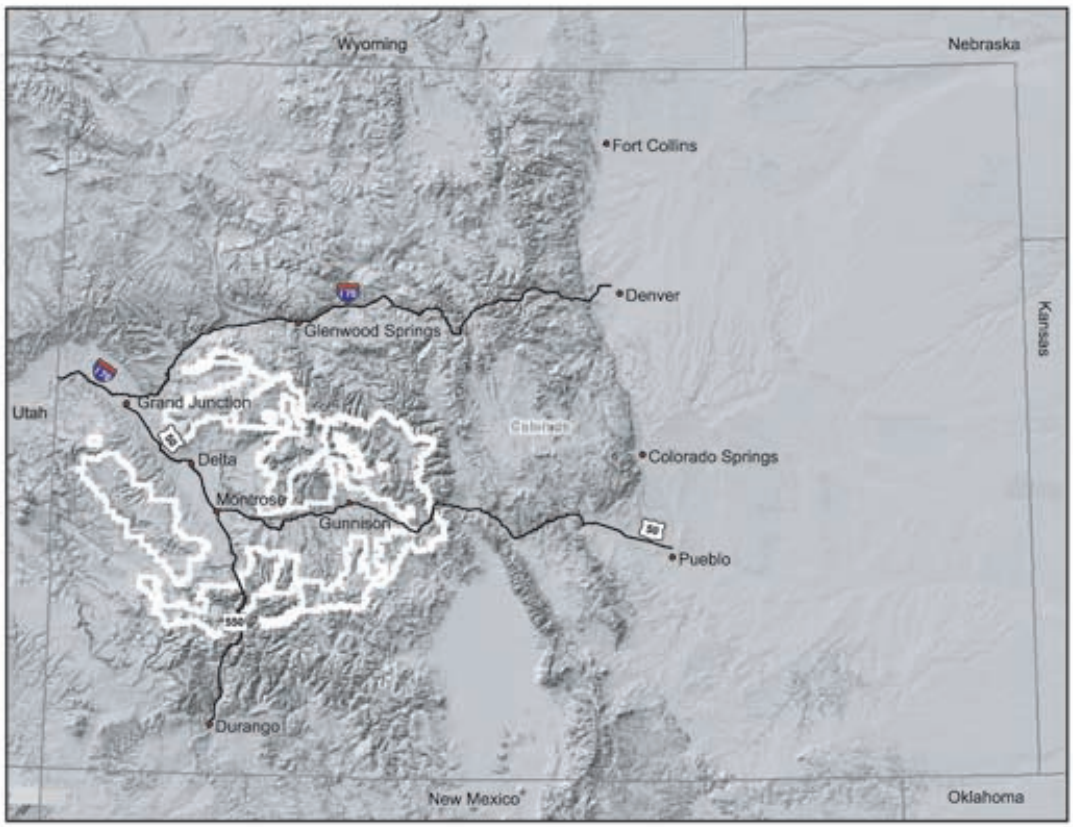


Figure 1. Location of the Grand Mesa, Uncompahgre, and Gunnison National Forests in Colorado.

has more water related facilities authorized than any other national forest in the nation.

Over an approximately three-year period the forest used the extra funding provided by the Pathfinder initiative to undertake a considerable effort to gather and analyze hydrologic data, conduct field investigations and develop both tabular and spatial databases needed to support the project. The efforts can be categorized into four groups. Components of these efforts occurred simultaneously and were often inter-connected. These were:

1) Characterization of flows and basin water yields for the forest;
2) Site investigations of diversion points on the forest;
3) Acquisition of private water right records for locations on the forest; and
4) Comparison of instream flow quantification methodologies and application to a study site on the forest.

A key component of our dialog centered on Colorado's existing instream flow program, which was first adopted by the state legislature in 1974. An issue, which surfaced repeatedly in our citizens work group, questioned whether the state's program, which is based upon protection of "minimum flows necessary to preserve the natural environment to a reasonable degree" (CWCB 1993), can or should be relied upon to meet the more stringent federal environmental legislative mandates of the national forest. The highlighted streams on the map indicate instream flow rights held by the state for streams on the GMUG (Figure 2). Instream flow rights established and held by the state are often very junior, and in some circumstances do not provide any water to the stream, particularly during periods of critical water shortage.

Characterization of Flows and Basin Water Yields for the Forest

In conjunction with the United States Geological Survey (USGS) Water Resources Division, we analyzed existing flow records so that we could better understand the hydrology of our streams. All USGS gage site records, both active and abandoned, were reviewed. Sites were selected that were located on the National Forest or within a few miles of the boundary. Sites with fewer than three years of record were discarded as were those where stream flows were regulated. A total of 60 stations were selected. For all stations with ten or more years of record, an instantaneous peak-flow frequency analysis was performed using the log-Pearson type-III distribution. To the standard set of return intervals, we added the 1.5-year flood, often used to approximate bankfull discharge. The daily mean low-flow and high-flow frequency analysis for 1, 3, 7, 15, 30, 60, 120 and 183 consecutive days was calculated. For all stations with three or more years of record, flow

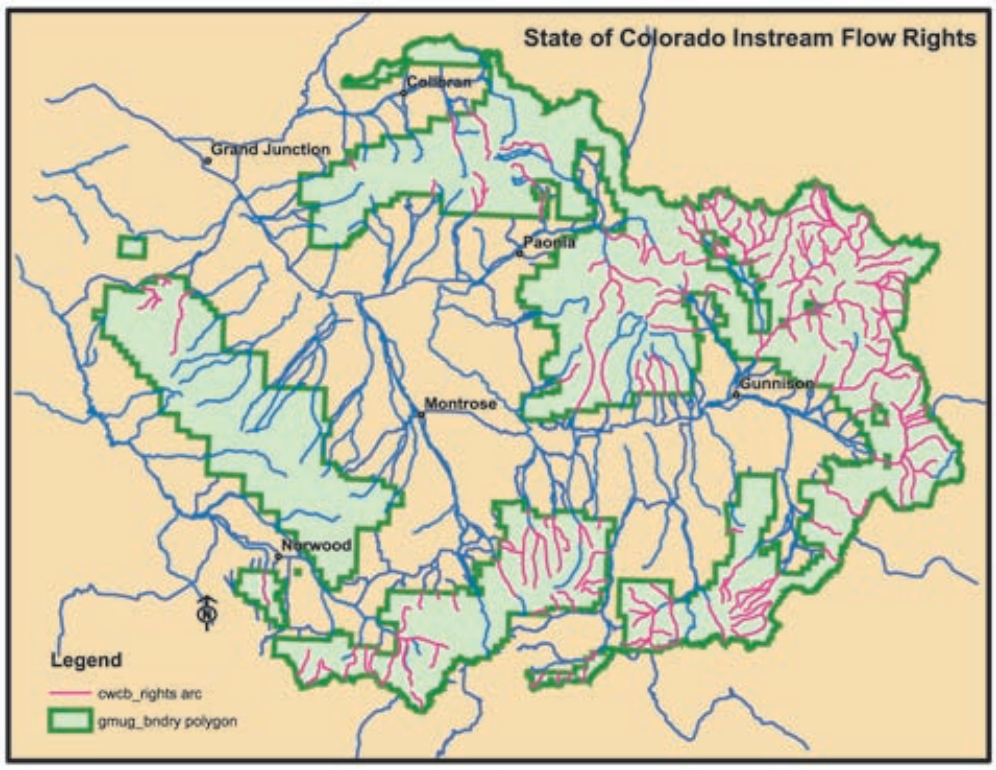


Figure 2. Colorado Water Conservation Board existing instream flow rights on the GMUG.

duration curves using daily means were generated for both an annual and monthly basis (Kuhn 2003).

It was recognized that a lack of long term flow data for headwater streams in the study area would be problematic. In an effort to address this information gap, we selected five sites distributed across the forest for pairing with one or more long-term USGS sites that share hydrologic similarities. Simultaneous discharge measurements taken at the paired sites over a minimum of one full hydrologic cycle were used to estimate monthly streamflow characteristics. In order to get a good representation for the range in flows, sampling was done more frequently during the rising and falling limbs of the hydrograph and less frequently during baseflow periods. At two of the sites, we established continuous water level recorders that allowed us to estimate mean daily flows. The alteration of flow pattern and inundation of the water level recorder due to repeated invasion by persistent beavers (*Castor canadensis*) resulted in the abandonment of one site.

For those basins with no gaging data, we estimated natural streamflow characteristics using published regression equations for western Colorado (Kircher et al. 1985)

Figure 3 is an example of one of the products that was developed from the analysis of flow data. Relative water yield was calculated using mean daily flows projected at the mouth of each watershed. While mean annual flow values are related to basin size, they are primarily influenced by annual precipitation, geology and basin morphology. This information was useful in helping to focus our efforts on watersheds where conflicts may occur with existing diversions or where future water development projects might be expected. In other words, where diversions exist in drier basins, the potential for diminished flow issues is more likely, and similarly, those basins that have greater water production are potentially better suited for future water development demands.

Site Investigations of Diversion Points on the Forest

The field inventory of physical diversions was an interesting and revealing exercise. Our diversion inventory sites were identified by compiling location and attribute information from both Forest Service permits and state water right records. Even though all the structures we visited were under some type of federal authorization, there was often only limited information in our files. We found that in some cases it had been 20 or more years since there was a documented site visit. Our inventory was not sophisticated and did not attempt to quantify flow impacts directly. We employed a two-person crew for three summers, and they inventoried 246 different diversions. The primary attributes recorded were: structure type; evidence of use; maintenance issues; appearance of fish in the stream at the point of diversion; notation of flow measurement devices and channel morphology characteristics, both above and below the diversion point. During the site visit, an estimate was made of the percentage of the stream that was diverted. The estimate of

Figure 3. Relative water yield of watersheds on the GMUG National Forest.

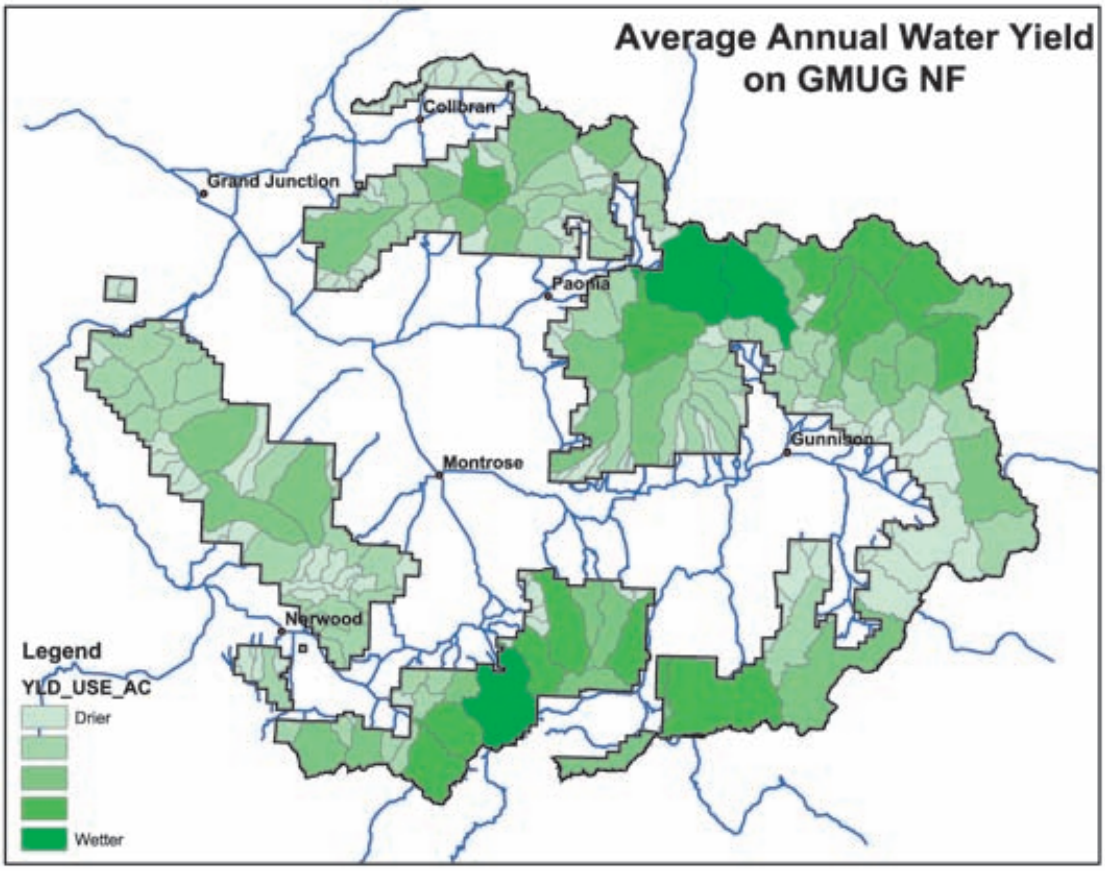
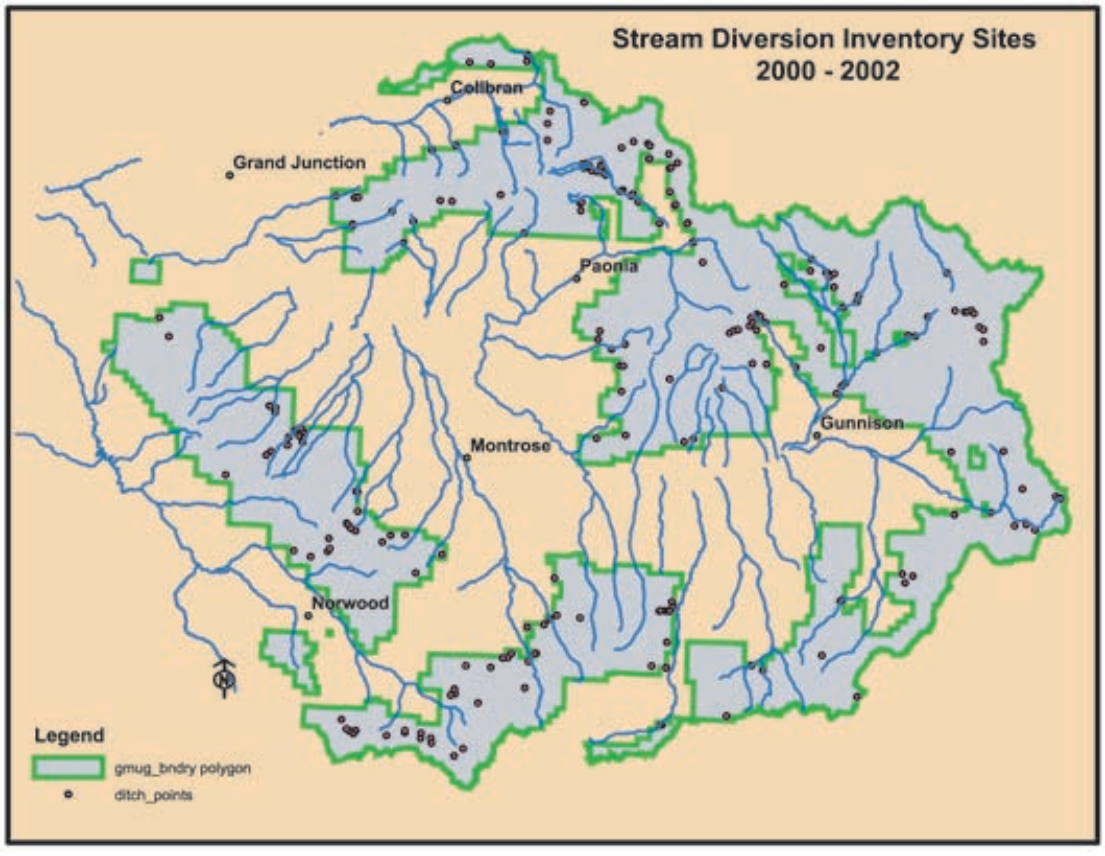


Figure 4. Stream diversion inventory sites on the GMUG NF, 2000-2002.



stream diversion was a key piece of data and was used later to prioritize diversions of concern. However, since our inventory was a one-time visit the estimate on diversion percentage and how it could be used was limited. Digital images were taken and Global Positioning System (GPS) coordinates obtained. This information was used to create a GIS point coverage of diversion sites on the forest with active hotlinks to the digital images (Figure 4). The data from field sheets was used to create a Microsoft Access™[1] data table, which enabled us to sort and query the data. We had enthusiastic support from our lands staff, who recognized that this inventory was going to be very beneficial in evaluating "Ditch Bill" easements and development of operation and maintenance plans. This work proved to be very useful in defining thresholds of concern when used in combination with assigned flow-dependent values and streamflow data for specific basins.

A number of the diversions were well-designed, permanent concrete structures, but most were primitive and made of wood, rock and plastic. Many structures were probably reconstructed, if not every year then every few years, either by hand or with equipment in the channel. Many were barriers to fish passage and virtually none prevented movement of fish into the ditch. While most would be considered small diversions, taking less than 25% of the flow, a few virtually dried up the stream. Most diversions were located within a mile of the forest boundary, but a few were located in the headwaters and were usually associated with a trans-basin diversions or private land inholdings. The farther up in the watershed the original point of diversion was located, the more likely the water transport facility consisted of a series of diversions, ditches and natural channels used to move water to the desired place of use.

Acquisition of Private Water Right Records for Locations on the Forest

The GMUG National Forest has been the source of water for use in surrounding communities and agricultural/industrial uses for more than 100 years. A significant number of water rights were established prior to the creation of the Forest Reserves. There are in excess of five hundred private water rights associated with diversion structures on the GMUG. Each point in Figure 5 represents the location of a private decreed water right.

Electronic water rights records where obtained from the state of Colorado Engineer's Office and used to extract information such as location, type of right (conditional or absolute), quantity and priority. In addition, we obtained records of actual diversions. This was extremely useful in separating a decreed water right flow amount, which is often inflated, from what has been historically diverted. Early in the process we experimented with an examination

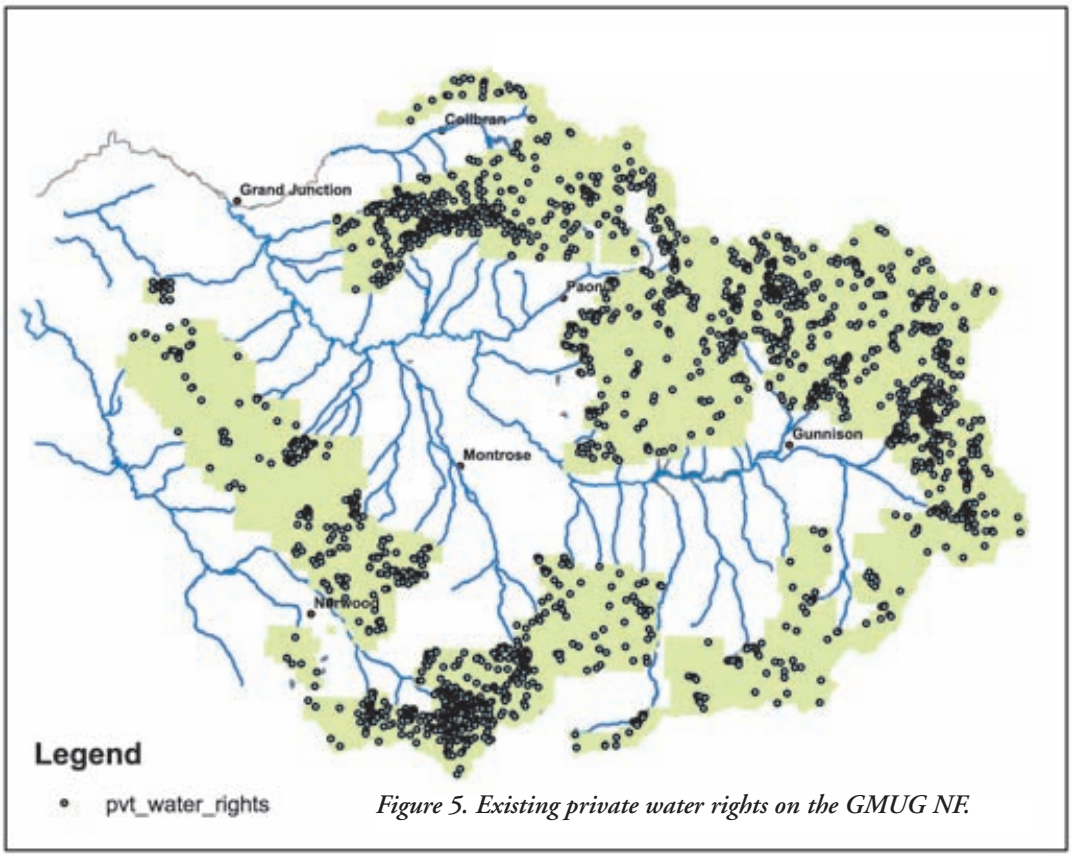


Figure 5. Existing private water rights on the GMUG NF.

[1]The use of trade or firm names in this publication is for reader information and does not imply endorsement by the U.S. Department of Agriculture of any product or service.

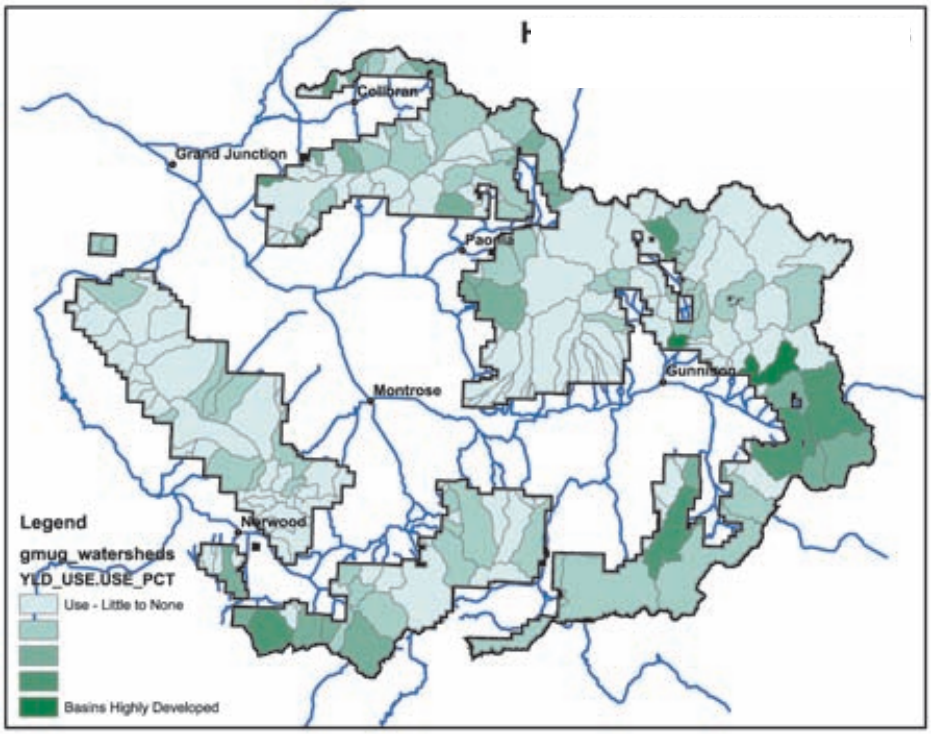


Figure 6. Historic water withdrawals on the GMUG NF.

of water storage and release records, but quickly learned that correlating reservoir operations with stream flows was a very a complicated accounting problem. As a result, we abandoned the idea of addressing the effects of storage facilities and focused primarily on historic stream diversions.

Given our ability to predict native stream flows and with some indication of how much water is being diverted off for human uses, we were able to estimate how much water is being left in the streams. A determination on whether or not that is enough water to fulfill national forest purposes and public expectations really depends upon the site-specific situation and was not something we could answer in the context of a forest-wide assessment.

Using the information gained from our evaluation of basin hydrology and gaging records, we were able to make projections of basin water yields. When combined with water diversion records associated with identified diversion points, we were able to portray the scale of water withdrawals on the forest as a percentage of yield. (Figure 6) This served as a good communication tool with our working group and the public, and indicated which of our basins are heavily impacted by water diversions. The effects of storage are not considered. The percent of basin yield that was captured and diverted was calculated, whether there were one or many points of diversion. Several basins on the forest have more than 50% of their annual yield captured and removed from the stream, with the largest proportion being 70% of annual yield.

Comparison of Instream Flow Quantification Methods

The West Willow Creek study was intended to look in detail at a representative forest stream and compare several popular instream flow estimation methods. West Willow Creek (Figure 7) is a stream with high flow dependent values, typical in size and morphology of many headwater streams and one with no existing diversions above the study site. The West Willow Creek Study was a joint effort between the Forest Service, Colorado Water Conservation Board and Colorado Division of Wildlife. The field work was done by our integrated team, the hydrology work was done by the Forest Service, and Miller Ecological Consultants did the PHABSIM modeling.

Five methods were examined in detail. The Colorado R2Cross Method (Nehring 1979; Espegren 1996) used by the Colorado Water Conservation Board is based on one or more cross sections and the hydraulic modeling and selection of established width, depth, and velocity criteria intended to provide for "reasonable" protection of aquatic resources. The modified Tennant Method (Tennant 1976), which is based on a percentage of mean monthly flows, is intended to mimic the form of a natural hydrograph. The Wetted Perimeter Method (Nelson 1980; Stalnaker et al. 1995) is obtained by graphing discharge versus wetted perimeter and selecting the inflection point. The Physical Habitat Simulation Method (PHABSIM) requires establishment of multiple cross sections and is resurveyed at different discharges. It results in a determination of the

Figure 7. Field work on the West Willow Creek study.

weighted usable area according to fish species and life stage (Milhous et al. 1989). These four methods are designed to estimate the flows necessary to sustain fish populations. The fifth method used was developed by the U.S. Forest Service with the objective of estimating flows necessary to move sediment and maintain channel morphology (Schmidt and Potyondy 2004). This method requires a determination of bankful discharge and the 25-year return interval flow. Table 1 (see next page) summarizes the characteristics of each method and their strengths and weaknesses.

Using our water level recorder and the 20 discharge measurements we made over a two-year period, a correlation was established between the West Willow site and a nearby USGS gage, and estimates of mean daily flow values were derived. The mean annual peak is approximately 22 cubic feet per second (cfs) (0.62 cubic meters per second [cms]) and the mean base flows are 3 to 4 cfs (0.085 to 1.13 cms). Bankful discharge is estimated at 17.5 cfs (0.5 cms).

Upon completion of fieldwork and analysis of the data, we compared the resulting protection flows that were determined from either application of standards or interpretation by staff. These results were overlaid on the mean annual hydrograph, which was synthesized by correlating short term mean daily flow records at our study site with long term records at a nearby USGS gaging site (Figure 8).

The Tennant method tracks the hydrograph well, as expected. Applying the standards used for R2Cross resulted in a 1.6 cfs (0.045 cms) winter flow and 2.6 cfs (0.074 cms) summer flow protection recommendation. Interestingly in this case, the Wetted Perimeter (5.7 cfs [0.16 cms]) and PHABSIM (5.0 cfs [0.14 cms]) flows were very similar. PHABSIM could be interpreted for seasonal variability but to date this has not been done for this study. In order to provide for sediment transport and periodic disturbance of sufficient magnitude to maintain fluvial processes, flows would need to be protected once they exceed 80% of

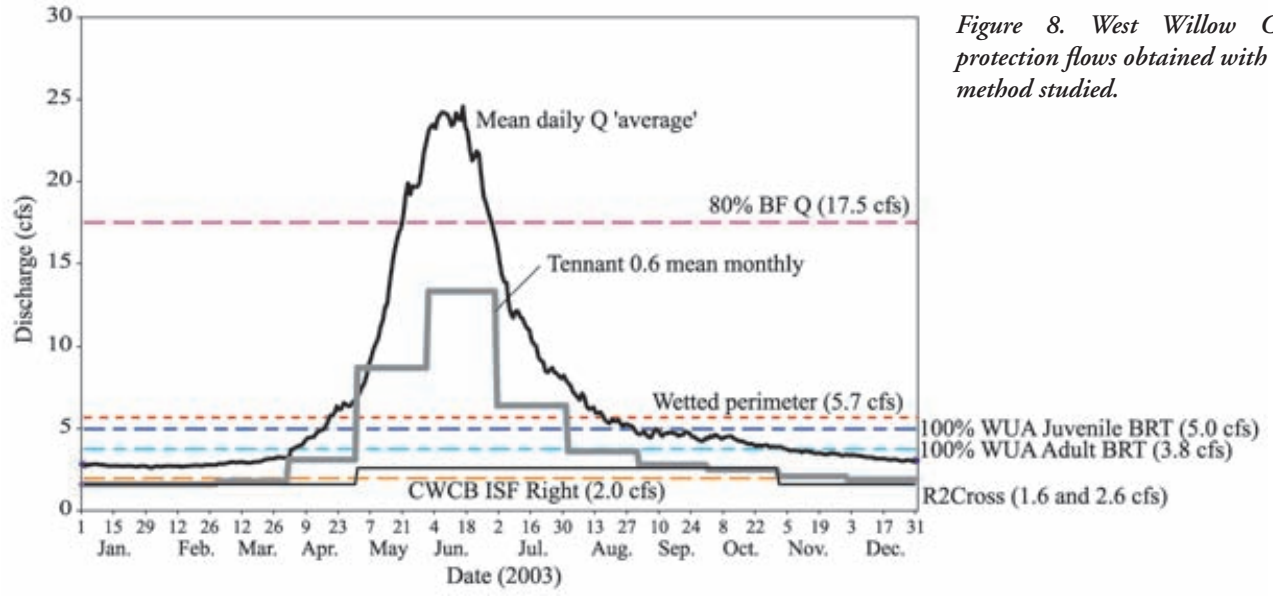


Figure 8. West Willow Creek protection flows obtained with each method studied.

Table 1 - Comparison of instream flow quantification methods.

A. General Characteristics of ISF Methods

	Hydrology Based	Field Based	Existing Standards	Time/Cost Efficiency
R2X	No	Yes	Yes	Moderate
PHABSIM	No	Yes	No	High
Tennant	Yes	No	Yes	Low
Wetted Perimeter	No	Yes	No	Moderate
Channel Maintenance	Yes	No	Yes	Moderate

B. Pros and Cons of Each Methodology

R2Cross

Pros	Cons
Data gathering in short period of time	Modeling limitations - Current version of R2X doesn't allow Manning "N" to vary with changes in modeled flows (modeling accuracy constrained to 0.4 to 2.5 times measured flow)
Inexpensive	Only addresses in-channel fishery needs, mostly used for trout
There are accepted standards	No flexibility of standards
Data and results are reproducible	Doesn't address out-of-channel needs or invertebrates
Looks at "reasonable protection" of trout	Doesn't' address pools w/in Manning's equation (assumes that maintaining riffle habitats will also maintain pool habitats)
Institutionally accepted by the State of Colorado	TU says amounts are too low
R2Cross-based ISF recommendations have been used by the state to "preserve the natural environment to a reasonable degree" since 1973.	Doesn't deal with flushing flow or channel maintenance
	Doesn't deal with impacts of changes of velocity on fish (is not an issue on Willow Creek, is an issue on the GMUG)
	Have we been able to calculate if R2X provides a "reasonable level of protection" since the 1979 standards setting?

PHABSIM

Pros	Cons
Very adaptable/more variables	Labor intensive/ expensive
Deals with habitat types other than riffles	"Illusion of technique"
Deals with life history of fish species	No relationship between WUA and fish
Facilitates looking at tradeoffs of different flows	Takes 1 year to develop data
Learn more about the stream	No standards - difficult to defend in legal arena
Useful where we need more detailed analysis (in a high conflict area, may be a useful tool)	Difficult to interpret results
	Difficult to apply across all of the GMUG
	Consistency of analytical technique--the different variables can lead to subjectivity

Tennant (Montana Model)

Pro	Con
Inexpensive	No clear standards
Don't have to go to field	Relies on professional judgement
Ball park answer	May not have records, rely on empirically derived estimates which may be inaccurate
Accounts for full range of flows	
Based on actual records, where they exist	
Commonly used/easily applied	

Table 1 continues on next page.

Table 1. (continued)

Wetted Perimeter

Pro	Con
Can be evaluated with data using several hydrologic models	Inflection pt. can be subjective based on channel type
	Requires fieldwork
	Is a single flow recommendation rather than a two stage one
	No biological component

USFS Channel Maintenance Method

Pro	Con
Looks at channels maintaining the system, moving the sediment, plus benefits to habitat	This process may not necessarily create a "healthy" stream
Has side benefits related to over bank flows and recharging banks/ground water	Difficult to administer
Simple model	If you have in system storage there is more difficulty in meeting flow requirements
Easy to calculate discharge requirments until bank full level level is exceeded	Not as applicable below dams for determining flow releases
Greater applicability to some stream types	Above bank full flows discharge levels difficult to determine
Has very specific standards	Some stream types not applicable
	Works best where sufficient flow data exists to conduct frequency analysis

QBF (bankfull discharge), which is 14 cfs (0.40 cms), and protection would continue until flows exceeded the 25-year flood event (61 cfs [1.7 cms]).

The consequences of instream flow protection on limitations to potential channel storage projects are presented in Table 2. This table displays West Willow Creek's total average basin water yield of 4,986 acre-feet (6,147,738 m^3) and the amounts and percentage of yield that would still be available above protection levels and therefore available for storage. The values range from a low of 21% of annual yield when the objective is to provide for both channel maintenance and adult brown trout (*Salmo trutta*) habitat needs, to a high of 69% of the annual yield when protection is based upon standards used in R2Cross.

Collaborative Process

The Pathfinder project involved a lengthy collaborative process. True collaboration involves meaningful dialogue between stakeholders and differing points of view provide for a broader approach to management options. While total agreement is rare, the outcome of collaboration is a function of many minds rather than a few. The "front loading" of stakeholder involvement is a departure from the traditional federal agency process where agency scientists and specialists work out a plan or system of strategies then release the results to the public for review. Collaboration early on, brings issues to the forefront sooner rather than later. It attempts to address a full array of concerns, build consensus, and have participants attain a level of ownership in the outcome. Key to any collaborative approach is a group of stakeholders committed to the process, the outcome, and representative of a large array of public perspectives.

The Pathfinder Steering Committee began meeting in May 2000. The Steering Committee was a diverse group of individuals representing the perspectives of organizations or entities concerned with water-resource use and management on national forest lands, private water users, local water purveyors and managers, state regulatory and management interests, and conservation and environmental perspectives. Individual participants and their organizations included: Reeves Brown (Club 20), Charlie Stockton (Ute Water), Peter Kasper (Overland Ditch and Reservoir Company), Steve Glazer (High Country Citizens Alliance), Stan Irby (rancher), John Trammell (Trout Unlimited), Nathan Fey (San Miguel Watershed Coalition), Dan Merriman (Colorado Water Conservation Board), Wayne Schieldt (Colorado Division of Water Resources), Ron Valvarde (Colorado Division of Wildlife), Bob Storch and Carmine Lockwood (U.S. Forest Service). This group held 45 meetings and conducted several public outreach efforts to address instream flow issues and management for the GMUG.

Over time, the interest of the Steering Committee became clear and they focused much of their work addressing two major perspectives on providing for instream flows: (1) Bypass flows, meaning a federal action that imposed regulatory control by administratively requiring a

Table 2. Water available for withdrawal in West Willow Creek.

	Flow Protection	Necessary for Instream Flows (AF and % of total)	Available for Development (AF and % of total)
Average Basin Yield = 4986 AF			
Existing CWCB ISF Claim	2.0 cfs Jan - December	1450 (29%)	3536 (71%)
R2X Method	1.6 cfs Nov - April 2.6 cfs May - Oct	1526 (31%)	3460 (69%)
Tennant Method	Jan. - 1.6 cfs July - 6.4 cfs Feb. - 1.6 cfs Aug. - 3.6 cfs March 1.8 cfs Sept. - 2.8 cfs Apr. - 3.1 cfs Oct. - 2.5 cfs May - 8.7 cfs Nov. - 2.1 cfs June - 13.3 cfs Dec. - 1.9 cfs	2977 (60%)	2009 (40%)
Wetted Perimeter	5.7 cfs, Jan - Dec	3118 (63%)	1868 (37%)
PhabSim (Juvenile) Method	5.0 cfs, Jan - Dec	2941 (59%)	2045 (41%)
PhabSim (Adult) Method	3.8 cfs, Jan - Dec	2526 (51%)	2460 (49%)
Channel Maintenance*	14 cfs, 21 May - 21 June	1687 (34%)	3299 (66%)
R2X + BF Method		3009 (60%)	1977 (40%)
PhabSim (Juvenile) + BF Method		4239 (85%)	747 (15%)
PhabSim (Adult) + BF Method		3917 (79%)	1069 (21%)

Time of flow protection varies in accordance with availability of flows exceeding 80% bankfull Q. During low flow years, no water would be allocated for channel maintenance.
Calculations are based upon a synthesized mean annual hydrograph correlated between the study site and adjacent long-term USGS gaging sites.

needed volume of water to by-pass the diversion structure or that require specific releases from storage facilities to provide downstream flows; and (2) Colorado instream flow rights that reserve a baseline flow rate to protect the environment to a "reasonable degree". The Steering Committee determined that an array of existing "tools" or mechanisms could be used to provide some level of instream flow protection or enhance stream flows in Colorado. (Table 3) They further found that in order to achieve cooperation and coordination between the various stakeholders involved in water use and water management, it was critical to implement these tools in a tiered approach, meaning that some tools are more acceptable and easier to implement if they follow an order of implementation.

Within the Steering Committee, the perspectives on these two procedures to provide for instream flow had varied acceptance. For example, the state of Colorado asserted that the Forest Service does not have the legal authority to impose bypass flows on a decreed water right. In contrast, some stakeholders held that bypass flows are the "price" of doing business on national forest land, or that imposing bypass flow requirements was the most effective means to protect instream flows on public lands.

The consensus of the Steering Committee was to use an array of options or strategies rather than focusing on one solution. First was to focus on cooperative efforts - voluntary actions that provide for better operations and management of water and then, if resource protection needs are not met, to move to more coordinated efforts - actions that involve multiple participants, call on differing authorities and institutional programs. A last resort would be to take unilateral federal action and impose bypass flow requirements or acquire water through condemnation. This process of tiered implementation is important, and if done in a progressive manner, a full array of opportunities to provide for instream flows would have been considered by the Forest Service before there was a need to move into the more regulatory actions where bypass flow requirements are imposed on water users.

Management Strategies

The tiered implementation of tools was captured in a management strategy matrix (Table 4, p. 524). This

Table 3. Tools for instream flow protection.

Forest Service Management Options	Cooperative or Partnership Approach Options	CWCB's Instream Flow Program Options
1. Inventory and consult with permittee on water rights, water uses, and permits.	11. Assist Colorado Water Conservation Board (CWCB) and State Engineer in monitoring and protecting existing ISF rights on GMUG National Forests (NF)	21. Pursue opportunities offered by CWCB ISF Program
2. Negotiate permit conditions for instream flow purposes on new water development.	12. Work with CWCB to recognize the NF land and resource management objectives and quantification methods for streams on the Forest may differ from the objectives and methods CWCB currently provides.	22. Seek CWCB agreement to appropriate or acquire needed flows on NF lands.
3. As a permit condition, limit diversions to decreed amounts when needed, seasonally.	13. Investigate voluntary re-operation alternatives with existing diversion permit holders to meet FS and permittee objectives.	23. Encourage CWCB to file on USFS flow recommendations the year they are made.
4. Implement channel and fish habitat improvements to compensate for lower flows when a determination has been made that such improvements have biologic merit.	14. Seek voluntary agreement with new applicants to develop operational plans to meet FS and applicant's objectives.	24. Establish legal, shared property ownership with the CWCB for acquired ISF rights on NFS lands.
5. Consider other forest practices that influence stream flows, such as vegetation management.	15. Consider new and expanded storage with participation by the USFS for instream flow purposes (which include the Forest Service appropriating or acquiring an interest in the water rights).	25. Encourage CWCB to file on peak spring flows and shoulder flows under ISF Program to allow for recharge of groundwater and to maintain riparian and off-channel habitat.
6. Use land and water acquisition programs and water right purchases to obtain water rights that could be converted to instream flow (ISF) rights.	16. Consider off-channel storage for later release.	26. Encourage the State Legislature to expand the CWCB ISF program to include recreational, scenic, and aesthetic uses.
7. Ensure that water rights acquired as part of an USFS acquisition or exchange are incorporated into the Forest water right inventory.	17. Provide State Engineer with documentation on water rights not being used.	27. Identify stream segments currently limited by availability of water for ISF protection and improvement.
8. Protect water rights held by USFS.	18. Initiate educational program for water conservation and promote/facilitate delivery and application efficiencies.	
9. Expand USFS efforts to inventory and assess the aquatic and riparian resources on GMUG NF.	19. Establish ISF management objectives for watersheds on the GMUG NF.	
10. Practice good watershed and streamside management to deliver sufficient quantity and quality of water to meet downstream and forest uses.	20. Work cooperatively with local governments to establish Recreational Instream Channel Diversion (RICD) on stream segment(s) located on NFS lands.	

matrix of strategies looks at implementation by working in two directions. First, streams were categorized into four diversion classes. These four categories are: no diversions; zero to 25% diverted; 25 to 50% diverted; and over 50% diverted. The tools or strategies were identified for implementation moving from top to bottom of the matrix in a tiered approach based on the resource or water use objectives. Those objectives and values included water rights (recognizing existing rights), flow regimes, future water development, recreation, restoration, and water quality.

Implementation strategies are progressive in their approach. As water use increases, the protection objectives become more intensive. The implementation strategies also vary depending upon the instream flow objectives or values being managed for.

To evaluate the effectiveness of the strategies outlined in the matrix, the Steering Committee conducted a paper exercise where we tested the process using some real-world hydrologic conditions and water use situations. Each time the test showed that there were at least one or two points along the implementation process where instream flow needs could be met provided there was some level of agreement between the entities involved to use the tools. If not, then the tool of last resort was the final tier of action and the Forest Service would have to take unilateral action (requiring bypass flows) to provide the necessary resource protection.

With the tests completed and input from the public and those agencies, entities, and organizations represented by the Steering Committee, a Steering Committee Report, Strategies for Instream Flow Management, was finalized in May 2004. This report is available at the Grande Mesa, Uncompahgre and Gunnison National Forests Website, *http://www.fs.fed.us/r2/gmug/policy*.

The Steering Committee Report is written from the stakeholders' perspective to detail strategies and processes that could be used by the Forest Service to protect or provide for instream flows on national forest lands. It relies on existing procedures, programs, regulations and laws to manage for instream flows. It focuses on cooperation and coordination before unilateral action by the Forest Service is suggested. It is intended to provide the Forest Service with a possible strategy or template to address instream flows in the Forest Plan revision.

This Steering Committee Report is not a Forest Service document, nor does it represent a final decision by the GMUG National Forests on instream flow management, but it is a workable strategic plan for instream flow management in Colorado.

The Pathfinder Project will provide forest planners with possible instream flow objectives, desired conditions for water development, and tools that may work as standards and guidelines for instream flow management.

Conclusions

The technical aspects of this project have afforded us an opportunity (funding and priority) to gather related hydrologic data and do a kind of analysis that is not typically done. This has proven to be beneficial for uses beyond our instream flow needs deliberations. It has allowed us to improve our understanding of the water resources that shape the local environment. That understanding may prove to be most the lasting benefit of what this project set out to accomplish. The analysis process was a challenging blend of field hydrology, statistical analysis and GIS work.

Did collaboration accomplish our goals? Yes and no. The key benefits of the process have proven to be the relationships we have developed with the stakeholders, and in particular with their representatives on the Steering Committee. The Pathfinder Project has developed a level of trust among the parties involved that has already carried over into other projects, and that can with trust, cooperation and coordination, continue into the future.

The Forest Service now has an approach and strategy that can be incorporated into the Forest Plan Revision process for instream flow management and water management that comes to the agency with a level of support from our stakeholders and the public that we could not have developed in the more traditional plan review process.

The Pathfinder Project was a major time commitment for the forest involving almost four years of effort. The results of the collaborative effort produced a product that wasn't exactly what was envisioned by the Forest Service when it embarked on this project. That is the nature of a collaborative efforts, and they frequently take on the focus and concerns of the stakeholders and participants rather than agency expectations. Collaboration however provides a critical public perspective early in the process rather than at the end of the planning cycle, which is most useful to any public agency.

Acknowledgements. The Pathfinder effort began in May 2000 and was intended to be a collaborative effort that was built upon technical and scientific information. The work that was accomplished would not have been possible without the efforts of the following individuals. Jonathan Ferree (USFS), Warren Young (USFS), Chris James (USFS), Matt Sutton (USFS), Heather Eckman (USFS), Eric Eckman (USFS), Matt Welsh (USFS), Kathy Pagano (USFS), Gerhard Kuhn (USGS), Jay Skinner (Colorado Division of Wildlife), Greg Espegrin (Colorado Water Conservation Board) and Bill Miller (Miller Ecological Consultants, Inc).

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Table 4. Instream flow management matrix for Grand Mesa, Uncompahgre and Gunnison National Forest watersheds.

	No Recorded Diversions		0 to 20% Diverted of Annual Yield	
	Species of Concern	No Species of Concern	Species of Concern	No Species of Concern
	GOAL I: Preserve existing natural flows for the benefit of species of concern, ecosystem integrity and reference conditions.	GOAL II: Protect hydrologic flow regimes needed to maintain baseline values.	GOAL III: Maintain existing flow conditions for the benefit of species of concern and ecosystem integrity.	GOAL IV: Establish and/or maintain a reasonable balance between consumptive and non-consumptive uses of water resources on the forest.
Water Rights	OBJECTIVE I. A: Preservation of these watersheds will be the Forest Service's top priority for the conservation of species of concern TOOLS: Tier I: 9, 10, 19, 21, 22, 23, 25 Tier II: 12 Tier III: none	OBJECTIVE II. A: Instream flow volumes, including peak flows and timing regimes shall not be reduced to the extent that existing baseline flow-related values are unacceptably impacted or degraded within a sixth level watershed (HUC) TOOLS: Tier I: 10, 19, 21, 22, 23, 25 Tier II: 6 Tier III: none	OBJECTIVE III. A: Recognize existing legal water uses TOOLS: Tier I: 1 Tier II: 7, 8, 17 Tier III: none	OBJECTIVE IV. A: Recognize existing legal water uses TOOLS: Tier I: 1 Tier II: 7, 8, 17 Tier III: none
	OBJECTIVE I. B: Recognize conditional water right TOOLS: Tier I: 1, 17 Tier II: none Tier III: none	OBJECTIVE II. B: Recognize conditional water rights TOOLS: Tier I: 1, 17 Tier II: none Tier III: none	OBJECTIVE III. B: Recognize conditional water rights TOOLS: Tier I: 1 Tier II: 7, 17 Tier III: none	OBJECTIVE IV. B: Recognize conditional water rights TOOLS: Tier I: 1 Tier II: 7, 17 Tier III: none
Stream Flows	OBJECTIVE I. C: Achieve flow regimes that maintain self-sustaining populations of species of concern TOOLS: Tier I: 9, 10, 21, 22, 23, 25 Tier II: 4, 6 Tier III: none	OBJECTIVE II. C: For those segments identified in cooperation with the DOW as potentially providing high value habitat for reintroduction of species of concern, pursue protection efforts TOOLS: Tier I: 10, 19, 21, 22, 23, 24, 25 Tier II: 4, 18 Tier III: none	OBJECTIVE III. C: Achieve flow regimes that maintain self-sustaining populations of species of concern TOOLS: Tier I: 9, 10, 21, 22, 23, 25 Tier II: 4, 5, 6, 13 Tier III: Unilateral federal actions	OBJECTIVE IV. C: Ensure instream flows necessary to sustain baseline ecological values TOOLS: Tier I: 9, 10, 21, 22, 23, 25 Tier II: 4, 5, 6 Tier III: Unilateral federal actions
Water Development	OBJECTIVE I. D: Entertain future water development only when the action can be determined to have an insignificant impact on flow regimes necessary for the conservation of species of concern TOOLS: Tier I: 2, 3, 10, 11, 19 Tier II: 18 Tier III: none	OBJECTIVE II. D: Accommodate future water development requests when a high level of ecosystem protection can be ensured TOOLS: Tier I: 3, 11, 21 Tier II: 2, 18 Tier III: none	OBJECTIVE III. D: Entertain future water development requests when a high level of population protection and habitat protection can be ensured TOOLS: Tier I: 2, 3, 4, 19 Tier II: 14, 15 Tier III: none	OBJECTIVE IV. D: Accommodate future water development so long as baseline recreational and ecological values are not precluded TOOLS: Tier I: 3, 15 Tier II: 2, 4 Tier III: none
Recreational	OBJECTIVE I. E: Protect appropriate instream flows so that recreational uses (high use areas/unique recreation attractions) are not precluded by future water development TOOLS: Tier I: 10, 11, 15, 20 Tier II: 12, 18, 25, 26 Tier III: none	OBJECTIVE II. E: Protect appropriate instream flows so that recreational uses (high use areas/ unique recreation attractions) are not precluded by future water development TOOLS: Tier I: 4, 10, 15, 20 Tier II: 12, 24, 25, 26 Tier III: none	OBJECTIVE III. E: Protect appropriate instream flows so that recreational uses (high use areas/ unique recreation attractions) are not precluded by future water development TOOLS: Tier I: 1, 4, 10, 15, 20, 26 Tier II: 12, 24, 25 Tier III: none	OBJECTIVE IV. E: Protect appropriate instream flows so that recreational uses (high use areas/ unique recreation attractions) are not precluded by future water development TOOLS: Tier I: 1, 4, 10, 15, 20, 26 Tier II: 12, 24, 25 Tier III: none
Restoration				
Water Quality	OBJECTIVE I. G: Recognize Forest Service obligation to comply with provisions of the Clean Water Act (303(d)) as it relates to instream flow TOOLS: Tier I: 10 Tier II: 2 Tier III: none	OBJECTIVE II. G: Recognize Forest Service obligation to comply with provisions of the Clean Water Act (303(d)) as it relates to instream flow TOOLS: Tier I: 10 Tier II: 2 Tier III: none	OBJECTIVE III. G: Recognize Forest Service obligation to comply with provisions of the Clean Water Act (303(d)) as it relates to instream flow TOOLS: Tier I: 10 Tier II: 2, 3 Tier III: none	OBJECTIVE IV. G: Recognize Forest Service obligation to comply with provisions of the Clean Water Act (303(d)) as it relates to instream flow TOOLS: Tier I: 10 Tier II: 2, 3 Tier III: none

Table 4. (continued)

20 to 50% Diverted of Annual Yield		Greater Than 50% Diverted of Annual Yield	
Species of Concern	No Species of Concern	Species of Concern	No Species of Concern
GOAL V: Maintain existing flow conditions for the benefit of species of concern and ecosystem integrity.	GOAL VI: Establish and/or maintain a reasonable balance between consumptive and non-consumptive uses of water resources on the forest.	GOAL VII: Maintain existing flow conditions for the benefit of species of concern and ecosystem integrity.	GOAL VIII: Establish and/or maintain a reasonable balance between consumptive and non-consumptive uses of water resources on the forest.
OBJECTIVE V. A: Recognize existing legal water uses TOOLS: Tier I: 1 Tier II: 7, 8, 17 Tier III: none	OBJECTIVE VI. A: Recognize existing legal water uses TOOLS: Tier I: 1 Tier II: 7, 8, 17 Tier III: none	OBJECTIVE VII. A: Recognize existing legal water uses TOOLS: Tier I: 1 Tier II: 7, 8, 17 Tier III: none	OBJECTIVE VIII. A: Recognize existing legal water uses TOOLS: Tier I: 1 Tier II: 7, 8, 17 Tier III: none
OBJECTIVE V. B: Recognize conditional water rights TOOLS: Tier I: 1 Tier II: 7, 17 Tier III: none	OBJECTIVE VI. B: Recognize conditional water rights TOOLS: Tier I: 1 Tier II: 7, 17 Tier III: none	OBJECTIVE VII. B: Recognize conditional water rights TOOLS: Tier I: 1 Tier II: 7, 17 Tier III: none	OBJECTIVE VIII. B: Recognize conditional water rights TOOLS: Tier I: 1 Tier II: 7, 17 Tier III: none
OBJECTIVE V. C: Achieve flow regimes that maintain self-sustaining populations of species of concern TOOLS: Tier I: 9, 10, 21, 22, 23, 25 Tier II: 4, 5, 13, 15, 17 Tier III: Unilateral federal actions	OBJECTIVE VI. C: Ensure instream flows necessary to sustain baseline ecological values TOOLS: Tier I: 9, 10, 21, 22, 23, 25 Tier II: 4, 5, 6, 13 Tier III: Unilateral federal actions	OBJECTIVE VII. C: Achieve flow regimes that maintain self-sustaining populations of species of concern TOOLS: Tier I: 9, 10, 21, 22, 23, 25 Tier II: 4, 5, 6, 13, 16 Tier III: Unilateral federal actions	OBJECTIVE VIII. C: Pursue instream flows necessary to sustain baseline ecological values TOOLS: Tier I: 9, 10, 21, 22, 23, 25 Tier II: 4, 5, 6, 13 Tier III: Unilateral federal actions
OBJECTIVE V. D: Entertain future water development requests when a high level of population protection and habitat protection can be ensured TOOLS: Tier I: 2, 3, 4, 19 Tier II: 14, 15 Tier III: none	OBJECTIVE VI. D: Accommodate future water development so long as baseline recreational and ecological values are not precluded TOOLS: Tier I: 3, 15 Tier II: 2, 4 Tier III: none	OBJECTIVE VII. D: Do not entertain future water development requests if it would contribute to degradation that causes loss of species viability TOOLS: Tier I: 2, 3,14 Tier II: 15, 16 Tier III: none	OBJECTIVE VIII. D: Scrutinize future water development to avoid unacceptable impairment of baseline recreational and ecological values TOOLS: Tier I: 3, 4, 15 Tier II: 2 Tier III: none
OBJECTIVE V. E: Protect and/or enhance appropriate instream flows so that recreational uses (high use areas/ unique recreation attractions) are not precluded by future water development TOOLS: Tier I: 1, 4, 10, 15, 20, 26 Tier II: 3, 6, 12, 16, 18, 24, 25 Tier III: none	OBJECTIVE VI. E: Protect and/or enhance appropriate instream flows so that recreational uses (high use areas/ unique recreation attractions) are not precluded by future water development TOOLS: Tier I: 1, 4, 10, 15, 20, 26 Tier II: 3, 6, 12, 16, 18, 24, 25 Tier III: none	OBJECTIVE VII. E: Protect and/or enhance appropriate instream flows so that recreational uses (high use areas/ unique recreation attractions) are not precluded by future water development TOOLS: Tier I: 1, 4, 10, 15, 20, 26 Tier II: 6, 12, 16, 18, 24, 25 Tier III: none	OBJECTIVE VIII. E: Protect and/or enhance appropriate instream flows so that recreational uses (high use areas/ unique recreation attractions) are not precluded by future water development TOOLS: Tier I: 1, 4, 10, 15, 20, 26 Tier II: 6, 12, 16, 18, 24, 25 Tier III: none
OBJECTIVE V. F: For those segments identified in cooperation with the DOW as potentially providing high value habitat and/or recovery sites pursue restoration efforts to improve flow and habitat conditions TOOLS: Tier I: 2, 3, 11, 13, 15, 21, 22, 23, 24, 25 Tier II: 4, 5, 6, 7, 12, 16, 18 Tier III: Unilateral federal actions	OBJECTIVE VI. F: Consider restoration of baseline values where evaluation has concluded that restoration is needed. TOOLS: Tier I: 1, 3, 5, 6, 10, 11, 13, 19, 21, 22, 23, 24, 25 Tier II: 4, 7, 18, 27 Tier III: Unilateral federal actions	OBJECTIVE VII. F: For those segments identified in cooperation with the DOW as potentially providing high value habitat and or recovery sites pursue restoration efforts to improve flow and habitat conditions TOOLS: Tier I: 2, 3, 6, 13, 15, 21, 22, 23, 24, 25 Tier II: 4, 5, 7, 12, 16, 18 Tier III: Unilateral federal actions	OBJECTIVE VIII. F: Seek restoration of baseline values where evaluation has concluded that restoration is needed. TOOLS: Tier I: 1, 3, 5, 6, 10, 11, 13, 19, 21, 22, 23, 24, 25 Tier II: 4, 7, 18, 27 Tier III: Unilateral federal actions
OBJECTIVE V. G: Recognize Forest Service obligation to comply with provisions of the Clean Water Act (303(d)) as it relates to instream flow TOOLS: Tier I: 10 Tier II: 2, 3, 5 Tier III: none	OBJECTIVE VI. G: Recognize Forest Service obligation to comply with provisions of the Clean Water Act (303(d)) as it relates to instream flow TOOLS: Tier I: 10 Tier II: 2, 3, 5 Tier III: none	OBJECTIVE VII. G: Recognize Forest Service obligation to comply with provisions of the Clean Water Act (303(d)) as it relates to instream flow TOOLS: Tier I: 10 Tier II: 2, 3, 5 Tier III: none	OBJECTIVE VIII. G: Recognize Forest Service obligation to comply with provisions of the Clean Water Act (303(d)) as it relates to instream flow TOOLS: Tier I: 10 Tier II: 2, 3, 5 Tier III: none

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Cooperative Forest Watershed Management in Maryland: Watershed Restoration Across Land Ownerships

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Maryland Department of Natural Resources, Forest Service, Annapolis, Maryland

The Maryland Department of Natural Resources Forest Service has worked cooperatively with USDA Forest Service Northeastern Area State and Private Forestry to develop a forest watershed management program that covers public and private land. Maryland has 41% forest cover state-wide, predominantly privately owned. The forest watershed program spans riparian forest buffer restoration, drinking water reservoir watershed management, forest harvesting Best Management Practices (BMP) assessment, and targeted watershed activities. Progress has included 1722 km of riparian forest buffers planted since 1996, statewide forest buffer survival estimates increasing from 60% of planted seedlings in 2000 to 78% in 2002, a comprehensive forest conservation plan for 7,225 ha of forest surrounding the Baltimore, Maryland, drinking water supply, developing the Potomac Watershed Partnership with five other major partners in the region, and assessing harvesting BMPs in the state in collaboration with the Northeast Area Regional BMP Assessment Protocol.

Keywords: *Aquatic/riparian; watershed restoration, watershed management, timber harvesting BMPs*

Introduction

The Maryland Department of Natural Resources Forest Service established a watershed forest management program in 2001 to better encourage the use of forests and forestry to improve watershed condition in the state. The USDA Forest Service State and Private Forestry has been an important resource for technical and financial assistance in developing an effective program. The design for a watershed program depends on conditions in the watershed. Some of the major resources and stressors in Maryland are covered briefly here as context for Maryland's watershed forestry efforts.

With 5 million people, Maryland is the fifth most densely populated state in the nation and has 41% forest cover. Maryland lacks any national forest land, although neighboring states to the south, west, and north have substantial national forests. Maryland does have state forests and parks, national park land, national wildlife refuge land, military bases, and state natural resource management areas that include significant forested areas and provide long-term forest conservation. Maryland also benefits from a close partnership with USDA Forest Service Northeastern Area State and Private Forestry, an important connection in a state where forestland is 76% privately owned. Maryland lies in the middle of the Chesapeake Bay watershed, and is heavily involved in the regional program to reduce nutrients and improve living resources in the Chesapeake.

The areas with the most extensive forests are in the mountains in the western portion of the state and on the coastal plain in southern Maryland and the lower Eastern Shore (Figure 1). Piedmont areas in the central portion of the state (Baltimore/Washington, DC, corridor and concentrations of agricultural lands) have the least forest cover. The forest products industry is the fifth largest in the state, and many small mills and secondary manufacturing facilities provide demand for wood. However, in many areas of central and southern Maryland, population density and small parcel sizes limit the likelihood of active management for any reason, even timber stand improvement, wildlife, or water quality (Figure 2).

Baltimore, Washington, DC, and several smaller communities draw substantially on surface water reservoirs for drinking water, which goes through water treatment facilities before delivery. Even outside of the reservoir systems, many areas rely on rivers and streams for drinking water sources. Many watersheds in central Maryland are substantially developed and bear the effects of land use changes in loss of function in streams.

In a recent study in Montgomery County in the Maryland Piedmont west of DC, Goetz et al. (2003) quantified the relationship between impervious surfaces, forest buffers, and forest cover (Figure 3). They found

Furniss, M.J., Clifton, C.F., Ronnenberg, K.L., eds., 2007. *Advancing the fundamental sciences: proceedings of the forest service national earth sciences conference, San Diego, CA, 18-22 October 2004*. PNW-GTR-689. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station.

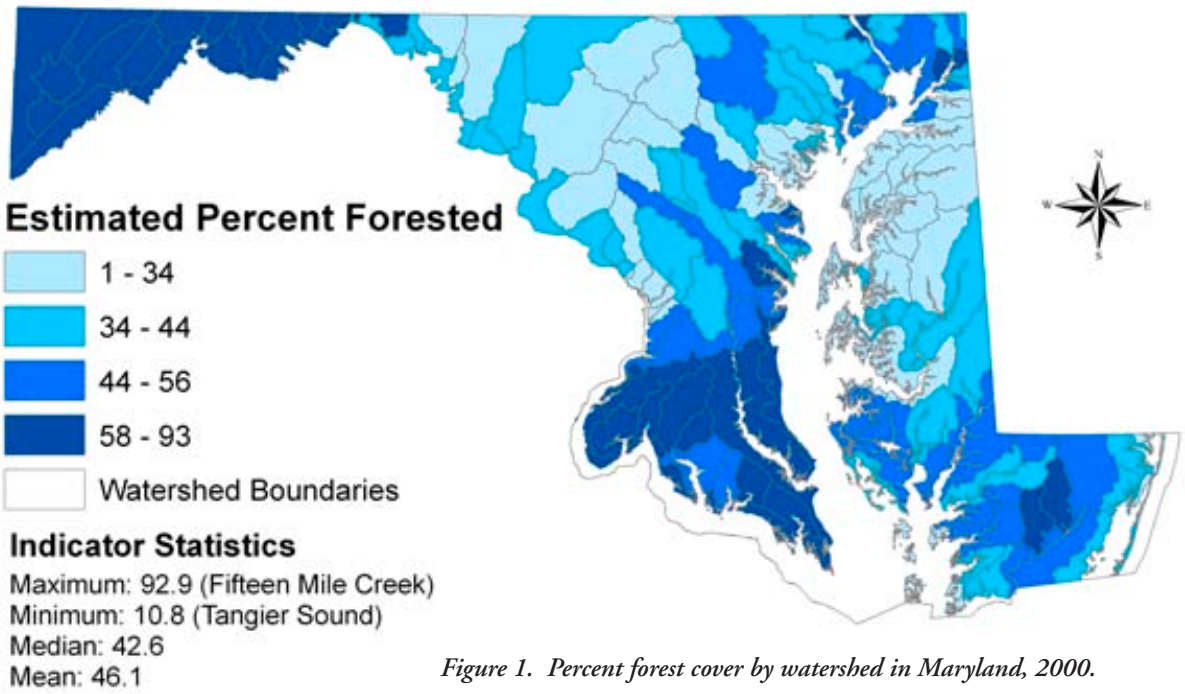
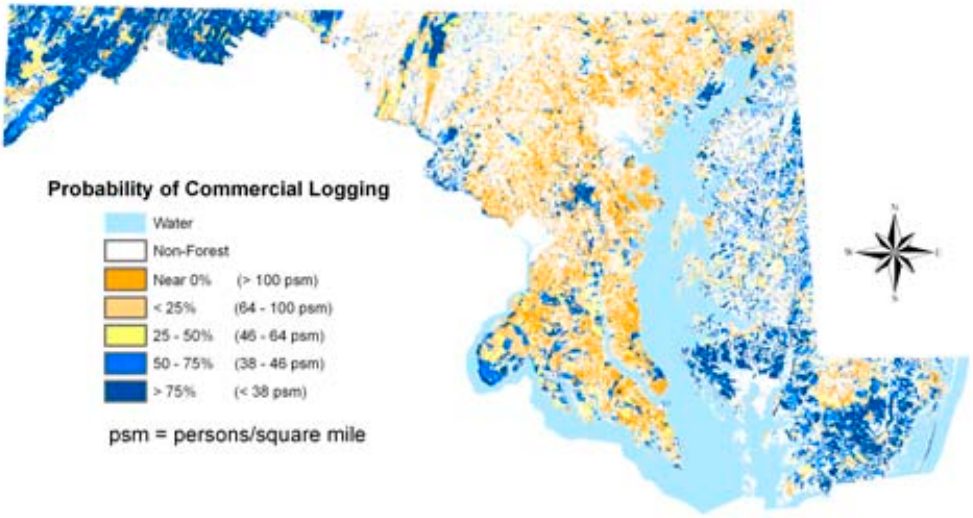


Figure 1. Percent forest cover by watershed in Maryland, 2000.

Figure 2. Probability of commercial logging of forests in Maryland as predicted from population density.



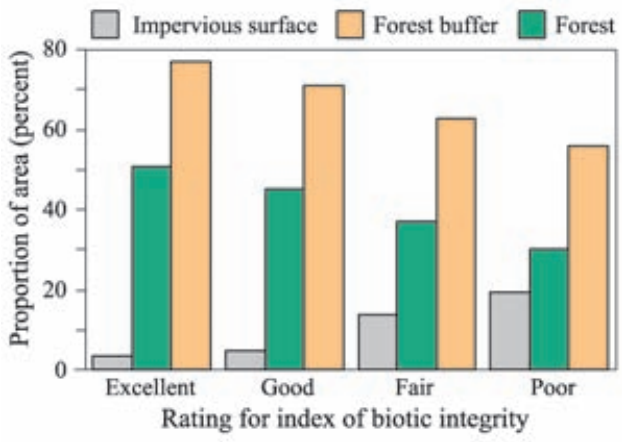


Figure 3. Percent of impervious surfaces, forest cover in watershed, and forest buffers for streams receiving excellent, good, fair, or poor ratings for an index of biotic integrity based on benthic macroinvertebrate composition.

the closest relationship to the Index of Biotic Integrity (IBI) for benthic macroinvertebrates was with impervious surface percentage, and the next closest with forest buffers. Forest cover in the entire watershed was the least closely linked but still important. In a range of watersheds from mostly rural to intensely urban, there were no streams with "excellent" IBI rankings except where watersheds had less than 6% impervious surface and more than 65% forest buffer. Even "good" IBI ratings were found only where impervious surfaces were less than 10% of the watershed and where more than 60% of the streams had forest buffers.

Within the context of extensive population and still significant forested areas, the Maryland Forest Watershed Program currently has four concentrations:

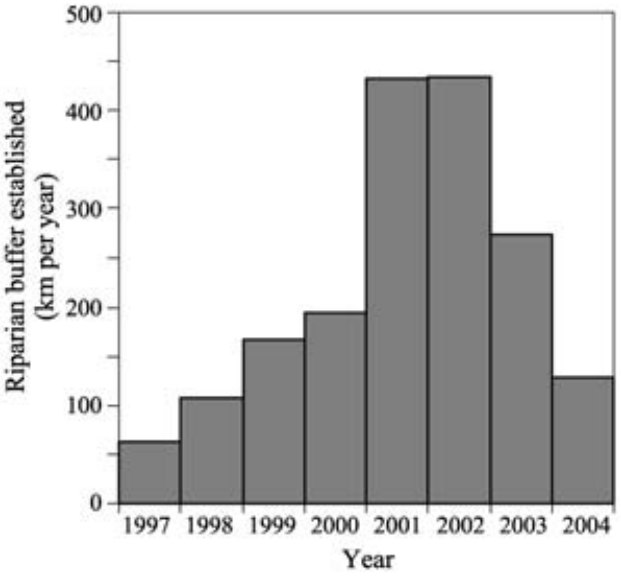
- Riparian forest buffers
- Forest management to protect drinking water reservoirs
- Watershed partnerships
- Forest harvesting Best Management Practices (BMP) assessments.

Riparian Forest Buffers

Streamside areas are an essential focus for watershed health because their influence on streams is great in comparison to their area. Forests are a preferred riparian land use because they help prevent nutrient input to streams and foster greater instream nutrient processing (Sweeney et al. 2004), in addition to providing riparian and aquatic habitat. Riparian forest buffers (RFBs) have been part of Maryland's forestry program since 1987. They became a focus in 1996, when the Chesapeake Bay goal of 3235 km (2010 miles) of new RFBs created by the year 2010 was adopted, recognizing the importance of buffers for improving water quality and habitat. Maryland committed to 965 km towards that goal. The Conservation Reserve Enhancement Program (CREP), authorized in the 1996 Farm Bill, became the major tool in expanding the rate of buffer creation. From an average of 19 km of buffer per year prior to 1996, buffer creation increased more than ten-fold (Figure 4). Expanded benefits under CREP stimulated even more increases, but later decreases in payment rates and eligibility saw rates fall off.

Maryland established 1,722 km (1,070 miles) of RFBs between 1996 and July 2004, about 2.6% of the state's riparian miles. The summaries sound simple, but the order-of-magnitude and greater increases required ramping up activities in a number of service arenas, including landowner assistance, training for resource professionals, supplying native hardwood seedlings, making planting machines available, and finding or training skilled contractors. Efforts

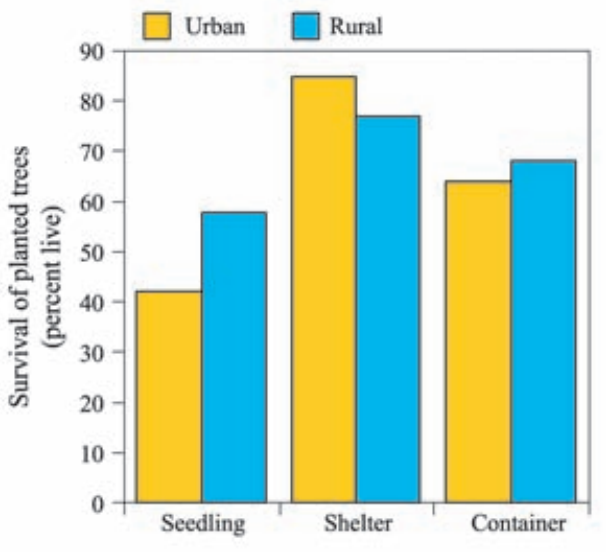
Figure 4. Kilometers per year of riparian forest buffers established in Maryland.



were also made to assess overall survival of seedlings, contribution of natural regeneration, and effect on stream and riparian functions. USDA Forest Service support was essential in expanding capabilities and funding training and buffer assessments through state grants, including the Potomac Watershed Partnership.

Seedling survival was assessed using a consistent statewide method in 2000 (Pannill et al. 2001) and 2002. Survival increased from an average of 60% in 2000 to 78% in 2002, attributed to increased maintenance efforts. Natural regeneration was not consistently present, but was significant on many sites, with one-third of trees being volunteers in the 2000 survey and one-quarter in 2002, even with increasing mowing and spraying to favor planted trees. Monitoring of riparian plantings as part of the Potomac Watershed Partnership found 87% average survival through 2003. The surveys were also used to assess stressors on survival. The top three factors affecting survival were weed competition, drought, and deer browse. Weed competition was by far the greatest, with noxious or invasive species being common, but not usually dominant, on newly planted sites. Deer damage is especially problematic in the middle portion of the state, where the proportion of a third forest, a third farm, and a third developed land proves to be the recipe for large deer herds with low hunting pressure. As a result, tree shelters were commonly recommended, and proved beneficial to survival (Figure 5). Other stress factors that were less common but problematic where present were insects, beavers, voles, and mice. Particularly on urban sites, mechanical damage from weedeaters and mowers took a toll on tree survival.

Figure 5. Percent survival of planted trees in riparian forest buffers in Maryland, 2000.



Forest Management for Protection of Drinking Water Reservoirs

Land management in watersheds draining into reservoirs used for public drinking water greatly affects water quality and treatment costs for water supply. Maryland DNR Forest Service has partnered with municipal water suppliers in developing forest management plans for lands immediately surrounding reservoirs. Baltimore City's reservoirs were established starting before the turn of the 20th century, and the landscape surrounding the water supply has changed dramatically in the 100+ years since (Figure 6). Urbanization now affects a major portion of the Loch Raven watershed. The reserved lands immediately adjacent to the watershed are now even more critical for appropriate management, as are buffer reforestation efforts along tributaries throughout the watersheds.

A comprehensive forest conservation and management system was developed for the 7,225 ha of forested lands owned by Baltimore City around its three reservoirs, based on the city's hierarchical goals of water quality, biodiversity and recreation, and emphasizing restoring forest resilience. Issues that emerged as significant for the City's primary goal of water quality included a dearth of regenerating seedlings for sustainable forests, extent of recreational use including mountain bikes and off-road vehicles (ORVs), excessive area in roads and damaged stream crossings, and forest stands currently susceptible to windthrow. The management approach includes deer exclosures on parts of regeneration cuts to demonstrate the effect of excessive deer browse, gradual stand conversion to more windfirm stand types, and management of shallow soils near nutrient sources to encourage rapid growth and nutrient uptake. A complementary watershed-wide analysis of land critical to reforest or conserve was completed, funded by USDA Forest Service. It developed better information on stream networks and forest distribution, and identified priority lands for conservation and restoration.

Watershed Partnerships

Maryland forestry watershed partnerships range in scale from the Chesapeake Bay Program, covering a good part of the Mid-Atlantic region, to the Potomac Watershed

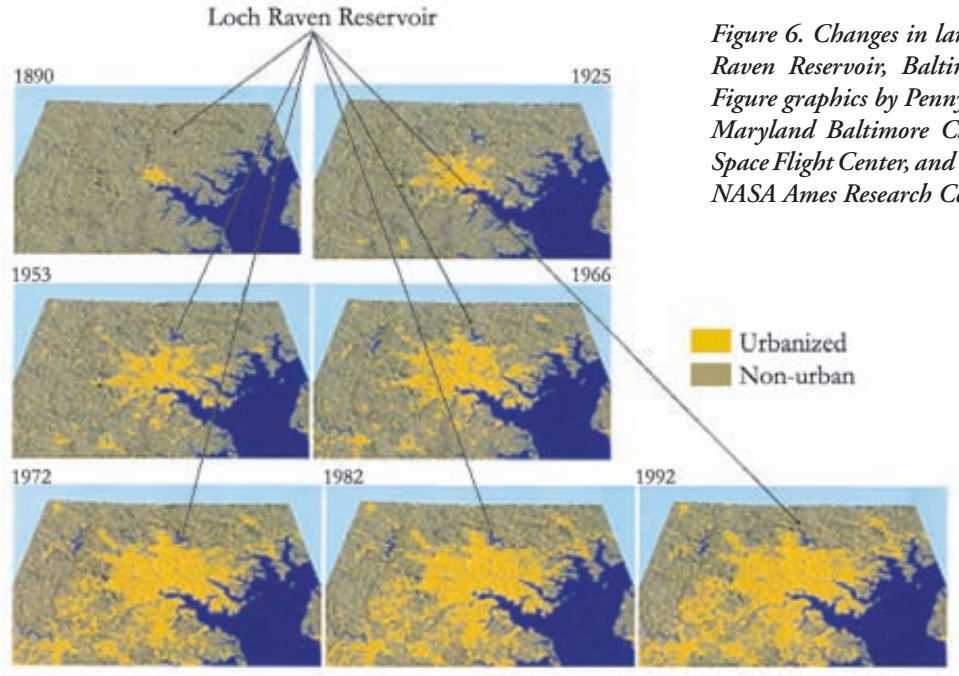


Figure 6. Changes in land use surrounding Loch Raven Reservoir, Baltimore, MD, 1890-1992. Figure graphics by Penny Masuoka, University of Maryland Baltimore Campus, NASA Goddard Space Flight Center, and William Acevedo, USGS, NASA Ames Research Center.

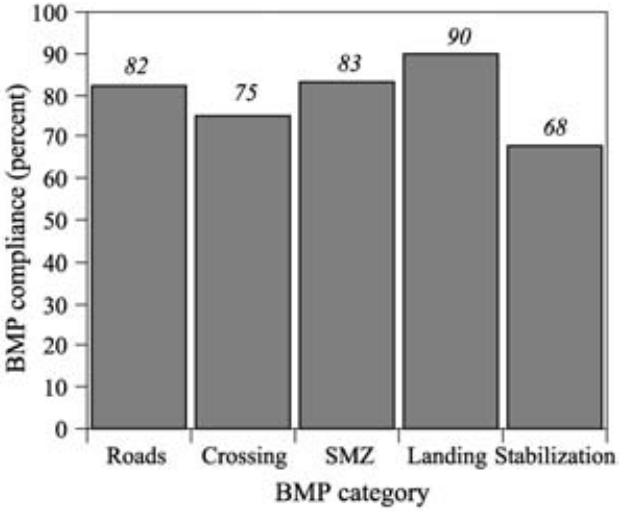
Partnership with surrounding states, and the Special Rivers Chesapeake Bay Implementation Grant, focusing on four areas within Maryland. The Potomac Watershed Partnership (PWP), used as an example here, is one of the large-scale, community-based watershed restoration efforts initiated with USDA Forest Service funding. PWP partners include Virginia Department of Forestry, Pennsylvania Department of Environmental Protection, Ducks Unlimited, George Washington/Jefferson National Forest, and Potomac Conservancy. The focus watersheds in Maryland were selected based on priority watersheds with the lowest proportion of forest buffers, using information from the state's Clean Water Action Plan. The PWP is our best effort at integrating the range of forestry services, including forest stewardship, forest fire risk reduction, monitoring of RFB survival and effectiveness, and urban forestry, on a watershed basis. It provides the focus and framework for expanding landowner services for forest stewardship and buffer restoration, coordinating monitoring of buffer restoration, minimizing risk from damaging wildfires, and increasing community forestry projects in an area of the state that has particular need for watershed improvement.

Examples of projects that draw on the synergy of multiple partners focused on mutual objectives, include the Growing Native project, a volunteer seed collection that also spreads the message about need for watershed restoration, and a recent conservation landscaping project that pulled together information on rain gardens (vegetated infiltration areas), native plants, and fire-resistant landscaping. The partnership helps expand horizons and focus resources on common goals.

Harvesting BMP Assessment

Forests provide one of the least-polluting land uses in the watershed, a circumstance that relies on appropriate use of BMPs during periodic harvesting. Maryland is cooperating with Northeastern Area State and Private Forestry on a regional assessment of harvesting BMPs developed by Maine Forest Service. The regional protocol allows comparison across state lines and focuses on sediment delivery pathways and quantifiable measures. Maryland will be doing 80 samples statewide, with the samples being defined from stream crossings as called for in the protocol. Maryland is particularly interested in this approach to harvesting BMP assessment because it could be used to support Total Maximum Daily Load development (rather than assigning disproportionately large sediment sources to poorly documented timber harvesting), and Chesapeake Bay Program nutrient reduction modeling and tracking.

Figure 7. Implementation rates for forest harvesting BMPs in Maryland, 1995.



Maryland has completed previous studies on BMP use, for effectiveness and implementation rates. A paired watershed study with a one-year calibration period was conducted from 1995 to 1999 in the Piedmont physiographic province (Pannill et al. 2000). It assessed effects of forest harvesting using standard state BMPs on stream benthos, temperature, and suspended sediment, none of which were found to differ significantly following harvest. For BMPs to work as intended to protect water quality, they have to be widely applied. Maryland did a statewide survey of BMP implementation in 1994, and found an average 82% application rate, with the steeper western portions of the state having greater difficulty in maintaining BMP compliance (Figure 7). The 2004-2005 assessment will update statewide BMP implementation rates.

Summary

Forests play an important role in watershed health throughout Maryland. The Maryland Department of Natural Resources Forest Service has worked cooperatively with USDA Forest Service State and Private Forestry to develop a forest watershed program that emphasizes using forests and forestry to improve watershed condition. The state has made significant advances in riparian forest buffer restoration and forest watershed management approaches for drinking water reservoirs. Maryland is using and assisting with the development of a regional harvesting BMP assessment protocol that may prove useful for state water quality modeling and Chesapeake Bay reporting. Watershed partnerships at several different scales are being used effectively to increase coordination and focus

attention on geographic areas and activity types that improve watershed health. These advances have occurred during a time of shrinking state budgets and staff. The leadership, technical assistance, training coordination, and financial support of Northeastern Area State and Private Forestry have been critical to expanding the state's program in watershed forestry and increasing the use of forestry as a solution to non-point source pollution.

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II. Poster Abstracts

Overleaf:
South Fork Clearwater River, just upstream of Cottonwood Creek, near Stites, Idaho. The Nez Perce National Forest manages approximately two-thirds of the upper South Fork subbasin, and has been actively involved in subbasin-wide monitoring, assessments and restoration plans, including the reach pictured. Photo by Nick Gerhardt.

Poster Abstracts From Advancing the Fundamental Sciences: the Forest Service National Earth Sciences Conference San Diego, CA, 18-22 October 2004

Excavator Subsoiling Applications: Integration of Subsoiling with Grapple Piling and Road Obliteration

J. Archuleta, and M. Karr

Erosion occurs from the exposure of soil to the effects of wind, water, and gravity. When soil is compacted, these forces may be exacerbated. By slowing or inhibiting vegetative growth, moisture infiltration and soil development, compaction can maintain erosion on gentle topography. Some land managers intend for nature to treat compaction, spending their limited watershed restoration funds on other treatments, while others choose the expensive proposition of subsoiling compaction. However, evidence of the longevity of compaction can be found in the unmanaged and abandoned portions of the historic Oregon Trail, a testament to the endurance of the problem. On the Umpqua National Forest, two implements were developed to combine the needs of multiple project objectives with subsoiling treatments. The implements are available for any make of excavator of suitable size for this type of heavy duty work. Combining grapple piling and subsoiling has been shown to produce results equivalent to any subsoiling operation, at a minor cost afforded through reduced piling production and minimal financial cost to the project. The primary benefit of this treatment is related to its use of available organic matter. Often by the time subsoiling is done, all available organic material has been disposed of during prior harvest slash disposal activities, leaving no material available for effective ground cover after subsoiling. By combining harvest slash disposal, road obliteration and subsoiling, use of these implements reduce the lag time between impact, restoration and restored soil productivity.

Application of Water and Sediment Models in Hydropower Relicensing

Margaret Beilharz

Hydropower Relicensing provides an opportunity for the Forest Service and other parties to make decisions about water storage and use at hydropower projects. Because these decisions are codified for a 30- to 50-year time frame in the License to Operate issued by the Federal Energy Regulatory Commission, they have major long-term consequences for the health of the watershed and rivers. The decisions must be based on "substantial evidence," which commonly includes the results of instream flow, reservoir and sediment transport models. The decisions are often arrived at by collaborative groups of the hydropower industry, federal, state, and county agencies, and NGOs, who learn to interpret the results of the models in order to discuss the environmental and other consequences of the projects. Standard and project-specific models are applied to a variety of project configurations, by a variety of consultants, resulting in evolutions of the models to fit the needs. These projects range in size from steep headwater streams with operating ranges as low as 100 cfs, to the Hells Canyon Complex on the Snake River, with an operating range of up to 30,000 cfs. An overview of the application of models, their benefits and pitfalls will be discussed. We include description of: Instream flow models - PHABSIM, River2D, Expert Habitat Mapping; Reservoir operation models - CHEOPS, HYDROPS, HEC-5, project specific models: Channel and sediment models - Mike11, Mike21, HEC-RAS, SAM, and others.

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Detecting Water Yield Increase in a Downstream Direction

Gregory S. Bevenger

Streamflow was measured at the mouth of two sub-watersheds of the North Fork Shoshone River drainage to monitor effects of the 1988 Clover-Mist Fire. The sub-watersheds were Jones Creek (19 mi^2), which was completely consumed by the fire, and Crow Creek (12 mi^2), which was not burned. Troendle and Bevenger (1996) analyzed the stream flow data and demonstrated that seasonal water yield in Jones Creek was, on average, 5.4 inches greater than Crow Creek. Though this was not a true paired watershed study, they concluded there was strong circumstantial evidence that the difference in yield can be attributed to fire effects. The Clover-Mist Fire, in total, resulted in a stand-replacement burn of 13% of the North Fork Shoshone River drainage (as measured from a USGS gage located near the mouth of the drainage and having a watershed area of 699 mi^2). In 2002, Shoshone National Forest staff conducted a watershed assessment of the North Fork Shoshone River drainage. One item they assessed was whether the apparent water yield increase resulting from the Clover-Mist Fire could be detected at the USGS gage, which is 35 miles downstream of the burn area. Analysis of pre- and post-fire streamflow indicates the water yield increase is not detectable ($p = 0.586$) at this scale. There is uncertainty whether this is due to distance from the burn or to the fact the gage was moved in 1988 to accommodate expansion of a reservoir that flooded the original gage location, which had a watershed area of 725 mi^2.

Land Type Associations of Weber County, Utah

Jeff Bruggink, DeVon Nelson

A land type association inventory of Weber County, Utah, was made primarily to support county planning and as an example of ecological land classification for county planners and others who could benefit from information gathered by this approach. The inventory was made by visually delineating, describing and interpreting 13 land type associations on satellite imagery using personal knowledge and field observations supplemented by existing resource reports. The inventory proved to have limited application to the present, residential level of planning in the county, but has considerable promise as the bridge between the current widespread use of land classification on national forest lands and its possible use on lands of other jurisdictions. We broke new ground by making a county level LTA inventory. This kind of survey is not uncommon on National Forest land nor are more general subsection maps new to the state. We know such inventories are widely used in other parts of the country. In Utah, detailed, individual resource maps, e.g., soils, vegetation and geology, cover much of the state and are essential for some uses, but their number, diversity, and detail can lead to confusion among planners and local officials if the need is for an overview of a large land area. This inventory was aimed at the gap between the generalizations of the subsection maps and the detailed, single resource inventories. It will take some time to determine the value of land type associations to local planning but we now have an example we can use to reach out to this vital level of government.

Forest Practice Changes in Response to Soil Protection Guidelines on the Umatilla National Forest

Craig R. Busskohl

Standards and guidelines for forest soil protection were established in the Pacific Northwest Region of the US Forest Service in the 1980s in response to site impacts of random, nonsystematic logging practices and site preparation. Extensive and intensive soil disturbance was common, with measurable effects on reforestation success, growth and erosion rates. The Umatilla NF adopted the regionally developed standards in the Forest Plan of 1990. Harvest systems and site preparation techniques used on the Umatilla NF have changed dramatically from the late 1980s to early 2000s. Monitoring results measuring soil impacts affecting soil productivity have changed concurrently. BMPs and other control measures have produced reductions in erosion potential due to exposed mineral soil. This poster illustrates changes in practices and monitoring data from 1990 to 2003 as they apply to standards and guidelines for detrimental soil conditions.

Low-water Crossings and Channel Functions: What Works and What Doesn't

Kim Clarkin, Suzan Hixson, Gordon Keller, Terry Warhol

A wide variety of low-water stream crossing structures have been built on low-volume forest roads throughout the country with the primary objectives of traffic access and cost efficiency. Fords and vented fords are low-profile structures that may not obstruct stream channels as completely as a standard culvert/road fill installation. Nonetheless, they are still rigid structures in a dynamic system. Depending on their design, they can have most of the same detrimental effects as traditional culverts, including promoting upstream aggradation, bank erosion, and downstream scour. In aquatic habitat, they often pose a barrier to aquatic species. This poster summarizes the results of a review of numerous low-water crossings,

including some low-water bridges, in national forests throughout the country. Many older structures do not meet the modern objective of maintaining channel functions, even though they may have been modified over time as problems became evident. Much can be learned from these structures about how not to locate and design a low-water crossing. Other structures incorporate design elements that go a long way toward achieving minimum interference with channel processes. Many are designed specifically to function in extremely dynamic conditions, such as in debris torrent or alluvial fan channels, desert and other flashy hydrologic regimes, or where debris jams, ice jams, or overbank flooding are frequent. The poster will illustrate some of the structural design elements - both successful and unsuccessful - that have been used to deal with these conditions in different valley and channel types.

Hemlock Dam Removal–The Issues and the Story So Far

Bengt Coffin

The Forest Service is working on an Environmental Impact Statement to evaluate options for improving fish passage and water quality at Hemlock Dam. The 22-foot high dam is located on Trout Creek, a tributary to the Wind River on the Gifford Pinchot National Forest in Washington state. Hemlock Dam is a USFS dam that was constructed to provide irrigation water to the Wind River Nursery. The nursery was closed in the mid 1990s, and since that time the only purpose of the dam is to provide a recreational lake behind it for summer use. The Forest Service is proposing to remove the dam, but is considering a range of alternatives at the site including leaving the dam in place and improving fish passage there.

Protecting and Restoring Riparian Area Structure and Function Along Forest Highways and Low-Volume Roads

James E. Doyle and Roy Jemison

Transportation corridors have had profound effects on riparian area structure and function in the United States as well as abroad. With over 600,000 km of system roads to manage across the United States, protecting and restoring habitat in riparian areas along these roads has become a priority long-term management need for the US Forest Service. Beginning in 1999, the US Forest Service, in partnership with other federal agencies and non-government natural resource organizations, initiated a multi-year project to evaluate efforts for protecting and restoring riparian area values affected by roads. Through field evaluations in various ecoregions of the United States, this interdisciplinary team of hydrologists, soil scientists, civil engineers, and fish and wildlife biologists identified and documented the most effective of these restoration efforts. In addition, the most effective road best management practices (BMPs) applied to protect riparian area values were documented. The team also conducted literature searches to augment these field reviews. Road-related restoration treatments reviewed included road outsloping, retaining walls, revegetation, soil bioengineering, landslide mitigation, invasive species control, low-water crossings and fords, culverts, bridges, wildlife crossings, fish passage, beaver pond maintenance, wetland maintenance, and channel modifications. Besides Forest Service funding, this project was supported by national funds from Department of Transportation-Federal Highway Administration, Department of Interior-Bureau of Land Management, and the Environmental Protection Agency. Other partners contributing professional services included the Department of the Interior-Fish and Wildlife Service, Department of Agriculture-National Resource Conservation Service, National Marine Fisheries Service, Army Corps of Engineers, Ducks Unlimited, and Trout Unlimited. Total cost of this project over a three year period was about $150,000. After two and a half years of field and literature reviews, the project identified and documented 24 treatments and techniques currently being used across the country to either protect or restore riparian areas associated with Forest Service highways and roads. This poster highlights the findings and results of this project.

Movement of Sediment Associated with Lowered Reservoir Levels in the Rio La Venta Arm of the Presa Netzahualcoyotl, Chiapas, Mexico

Juan de la Fuente, Bonnie Allison, Saul Bezares, Sue Hilton, Tom Lisle, Alisha Miller, Brenda Olson, Rebecca Quinones, Jose Velasquez

A joint sedimentation study is currently underway at Netzahualcoyotl reservoir in Chiapas, Mexico, involving the Comision Nacional de Areas Naturales Protegidas (CONANP) of the Secretaria de Medio Ambiente y Recursos Naturales and the US Forest Service. The reservoir is adjacent to Reserva de la Biosfera, Selva El Ocote, administered by CONANP. Study goals are to provide watershed managers with strategies to protect the resources of Rio La Venta canyon. The Rio La Venta arm of the reservoir is incised into karst terrain, with near-vertical limestone walls up to 300 meters high. The canyon is fed by two rivers, Rio La Venta and Rio Negro, and is surrounded by pristine tropical forest. The majority of the sand and fine gravel entering the reservoir originates in the headwaters of the two rivers, which are underlain

by granitic rock. Rapid sedimentation of the canyon poses a threat to the aquatic ecosystem. Longitudinal and transverse profiles were surveyed in March 2002, and repeated in April 2003 when the reservoir level was 15 meters lower, and again in February 2004. The 2002 longitudinal profile shows an inflection from a slope of 0.0017 to one of 0.0075 at 7.2 km downstream of the mouth of Rio Negro. In 2003, the two slopes remained the same, but the bed lowered 5 meters and the inflection point moved downstream 2.3 km. Data from 2004 are being processed. Initial findings suggest that by managing reservoir levels, sediment accumulation in the gorge can be controlled to meet specified goals.

Turbidity Threshold Sampling in Watershed Research

Rand Eads, Elizabeth Keppeler, Jack Lewis

When monitoring suspended sediment for watershed research, reliable and accurate results may be a higher priority than in other settings. The timing and frequency of data collection are the most important factors influencing the accuracy of suspended sediment load estimates, and, in most watersheds, suspended sediment transport is dominated by a few, large rainstorm events. Automated data collection is essential to effectively capture such events. Continuous turbidity measurements can reveal sediment pulses unrelated to discharge and can be used in real-time to govern the collection of pumped physical samples. While turbidity cannot replace suspended sediment concentration, it can be a tremendous asset as an auxiliary measurement. The turbidity threshold sampling method has been used since 1996 at the Caspar Creek Experimental Watershed in northern California where it is now being used at 21 gaging stations. Sample collection is distributed over the range of rising and falling turbidity values during each significant turbidity peak. A data logger records discharge and turbidity at frequent time intervals and activates a pumping sampler when specified turbidity conditions are met. The resulting set of samples can be used to accurately determine suspended sediment loads by establishing a relation between sediment concentration and turbidity for any sampled period with significant sediment transport, and applying the relation to the continuous turbidity data. The approach can be used in general for other target and surrogate variables and is thereby useful for a wide range of water quality issues.

Monitoring of Stream Channel Cross Sections on the Chequamegon-Nicolet NF

Sara Eckardt and Dale Higgins

Permanent cross-sections have been established on several streams in the Chequamegon-Nicolet National Forest to monitor the effects of channel restoration and culvert replacement over time. In recent years, Wisconsin trout stamp funds have been used to restore wide (20-30 ft), shallow, C type channels by narrowing (10-12 ft) and deepening the thalweg to create low width/depth E type channels that provide better habitat for adult trout. Following such work on three streams, 40 permanent cross-sections were established to determine if the new channel dimensions would remain stable over time. Five to eight years of data for these streams indicate most cross-sections have become 0.5-3.0 feet wider, the bed has aggraded 0.1-1.0 feet and the newly constructed floodplain, which is usually below the level of the adjacent floodplain, has aggraded 0.2-0.8 feet. Eleven permanent cross-sections have been established at three stream crossings and measured for 1-4 years. All had elevated or under-sized culverts that caused upstream aggradation mostly of sand. The cross-sections are helping to characterize and quantify the extent of channel adjustment and restoration associated with culvert replacements.

The 1997 Flood in Northern California: Applications to Refining Landslide Hazard Assessments in the Klamath Mountains North-Central California

Don Elder, Juan de la Fuente, Polly Haessig

The effect of human activities on landslide rates is a key issue in the management of western forests. In the Klamath Mountains of northern California, sedimentation has been identified as a key issue relative to anadromous fish habitat, and landslides contribute most of the sediment to the stream system (about 90% in the Salmon River sub-basin). On the Klamath National Forest, a simple empirical model is currently used for estimating future sediment delivery. It uses GIS coverages (bedrock, geomorphology, roads, and others) and a concept of geomorphic terranes, lands expressing similar slope processes and similar landslide rates. A landslide rate is assigned to each terrane for undisturbed, harvested or burned, and roaded conditions. These rates are based on air photo/field inventories of landslides that occurred in the Salmon River basin from 1965-1975. The model is used to predict future sediment delivery by geomorphic terrane under various roading and vegetation management scenarios, assuming a 1965-1975 type climatic episode. The 1997 flood was used to test the predictive ability of this model. It was found that undisturbed land produced 34% of the volume in 1997 compared to a model prediction of 39%. For road corridors, it was 40% versus the model prediction of 39%, and for harvested or burned lands, it was 27%, versus 21%. The model over-predicted total sediment volumes several fold for each of the land use categories. For undisturbed

land, modeled rates were 3.3 times higher, harvested land rates were 2.6 times higher, and road corridor rates were 3.0 times higher.

Monitoring in the Upper South Platte Watershed, Colorado: Before and After Wildfire

Deborah Entwistle, Lee MacDonald, Kevin Bayer, Ken Kanaan, Jennifer Hall

The Forest Service has long been in need of methods of watershed monitoring that are cost-effective and produce useful products in a timely manner. Various monitoring methods have been used in the Upper South Platte River watershed in conjunction with the Upper South Platte Watershed Protection and Restoration Project. In 2001, multiple small sub-watersheds were instrumented to collect erosion data at the hillslope scale, small catchment scale, and sub-watershed scale. Stream monitoring has included repeat cross section surveys, pebble counts, bank stability surveys, and monthly water quality sampling. This work has been conducted collaboratively by the US Forest Service and Dr. Lee MacDonald and his graduate students at Colorado State University. In late spring of 2002, the Schoonover and Hayman Fires burned approximately 140,000 acres in the Upper South Platte watershed, including a large percentage of the monitoring sub-watersheds. This presented a unique opportunity, as the erosion monitoring sites could now be used to monitor effectiveness of various Burned Area Emergency Response (BAER) treatments. The hillslope plots have been treated with a variety of BAER treatments, and the water sampling program was also expanded to include several streams within burned areas. New monitoring programs have also been added after the fires; these include the use of erosion bridges, ground-cover transect surveys, and photo point monitoring in BAER treatments and salvage timber sale units. The results of all of these monitoring projects will be used to evaluate the various management practices as well as the monitoring methods themselves.

Improving Project-Level Soil Interpretations With Geospatial Technologies

Don Fallon, Eric Winthers, Haans Fisk

Soil interpretations are arguably the most important information derived from a soil survey. However, the development of soil interpretations, through the traditional methods of observation, characterization, and interpretation generation based on map unit and component concepts, needs to be revised to include readily-available geospatial data. Since the majority of soil and ecological unit mapping on western national forests is at an order-three level (associations and complexes), component-level interpretations can, at best, only be represented at the map-unit level. Through the use of remote sensing and GIS technology, generation and display of soil interpretations at larger scales (project level) may be possible. Geospatial technologies have been used to depict individual components within map units and spatially refine specific interpretation ratings. For instance, fundamental interpretation criteria, based on slope or aspect, can be derived empirically from topographic data to increase the usefulness and precision of soil interpretations within map units. Once the process is established, a step-wise approach to derive interpretations geospatially could result, further reducing inventory analysis costs and enhancing soil interpretations at the project level.

A Simplified Nitrogen Deposition Collector: A Tool for Evaluating Ecological Impacts

Mark E. Fenn

Quantification of atmospheric nitrogen (N) inputs is needed to determine areas at risk from air pollution. In most areas adequate data on N deposition are lacking, largely because of the difficulty of measuring dry deposition fluxes of the array of nitrogenous pollutants. This problem can be circumvented by measuring nitrate and ammonium in throughfall. Throughfall is the hydrologic flux of compounds from vegetative canopies to the ground during precipitation events. Tree canopies function as natural and effective "filters" of atmospheric pollutants. Thus the transfer of N pollutants from the canopy to the forest floor is an important measure of N deposition and can be effectively used to evaluate air pollution loading to the ecosystem. We describe a greatly simplified method of collecting nitrate and ammonium in throughfall or precipitation. This approach uses ion exchange resin (IER) columns which adsorb N from throughfall solutions. We found that collectors can be employed in the field for as long as a year. Such infrequent sample collection reduces analytical and logistical costs. This method has made it possible to define N deposition gradients in the Sierra Nevada and in the San Bernardino Mountains and to determine thresholds of N deposition that elicit ecological changes such as N saturation conditions. Effects include increased nitrate in soil and streamwater, changes in nutrient cycling and carbon sequestration, increased N fertility, stand densification, and soil acidification. IER collectors provide a useful tool for monitoring N deposition in remote areas and will foster greater understanding of N deposition impacts.

FishXing 3.0: Software and Learning Systems for Fish Passage Through Culverts

Michael Furniss, Susan Firor, Antonio Llanos, Kathleen Moynan, Michel Love, Jeff Guntle, and Robert Gubernick

Culverts at road-stream crossings are traditionally designed for hydraulic efficiency, assuming this will yield a cost-effective design. However, this singular objective often produces adverse environmental effects. Poorly designed stream crossings frequently become barriers to fish and other aquatic organisms, resulting in the fragmentation of habitat essential for their viability and long-term survival. The scale of the problem is immense, with hundreds of thousands of culverts installed on fish-bearing streams in North America alone. Assessment and design of culverts for fish passage is a flow-dependant problem involving knowledge of both hydraulics and fisheries biology. FishXing is an interactive software package for use in culvert design and the assessment of fish passage conditions. FishXing identifies the types and locations of potential barriers across a range of flows by modeling fish swimming and leaping abilities against culvert hydraulics. The model has proven useful in identifying specific fish passage limitations, leading to the removal of numerous barriers. As a design tool, FishXing accommodates the iterative process of designing a new culvert to provide passage of fish and other aquatic species.

Managing Low-Water Crossings on Roads

Leslie S. Gonyer

This poster presentation will present work that is being done on the Black Hills National Forest to harden low water road/stream crossings with concrete mats. It will outline different alternatives that are available to address the problem, including closing the road and rebuilding the stream banks. Closing the road is not always an option and mitigation of the crossing is required to minimize the impact on the stream and watershed. The information will be presented through limited text and photographs display before and after pictures. Low water road-stream crossings can affect the stream and aquatic resources. Impacts include a continual supply of sediment to the stream and widening of the stream. The supply of sediment comes from erosion of the banks and stream channel each time a vehicle crosses. The widening of the stream provides for increased water surface area that allows for additional absorption of solar radiation during the summer, which can elevate stream temperature. One could argue that one crossing in itself is not very significant, but each crossing contributes to the cumulative impacts on the watershed and stream.

Abandoned Mine Inventory, Assessment, and Restoration: Case Studies on the Klamath National Forest, California

Polly A Haessig, Edward K. Rose, Don Elder, and William Snavely

The Klamath Mountains Province has a long mining history and many abandoned mines. National Forest abandoned mine land (AML) programs locate and identify mine hazards and restoration opportunities. Assessment of AML is also critical in property evaluations for land acquisitions and exchanges. Problems associated with AML on Forest lands include unsafe mine openings, erosion and mass wasting of mine waste materials, threatened failure of relict impoundment structures, acid mine drainage, abandoned drums containing hazardous materials, and unneeded or sediment-producing roads. Geologists, engineers, and other earth scientists work closely together in the process of field inventory, hazard assessments, ranking and prioritization of sites, site investigation, proposal development, NEPA analysis, and project implementation. Partnerships with other agencies are used to: expand the framework of knowledge; accomplish more restoration particularly on mixed-ownership sites; and increase opportunities for implementation funding. An interdisciplinary approach using other skills in related sciences of botany, fisheries, wildlife, and archeology is used to ensure long-term rehabilitation of sites and to protect resources. Case studies are presented on various Klamath National Forest AML sites including: (1) mine adit gating & wildlife habitat improvement; (2) sediment tailings dam removal and channel stabilization; (3) contaminant removal; (4) mine waste stabilization and containment; and (5) mine road repair and stormproofing.

Applying Hydrology to Forest Management–Examples Over a Career

William F. Hansen

Rainfall, streamflow and other hydrometeorologic records are available at various densities across most of the United States. Understanding and applying the hydrologic record is a valuable consideration when dealing with the variety of conditions and activities common to most national forests. This poster provides examples of how the hydrological record was applied to various scales from landscape planning to site-specific work. Understanding the frequency, risk, duration and extent of hydrologic events leads to a better understanding of how water functions as it moves from the hillslope to the stream, or is delayed in soils or wetlands. The tools available today make assembling and analyzing hydrologic records easier. Records need to help characterize changes with respect to

scale from hillslopes to valleys. However, an appreciation of the data may be lost when dealing with only the numbers. The goal is not amassing and compiling numbers for an answer. Learn to appreciate the data themselves, including the methods and other collecting specifics, their limits and conditions. Breathe data in, let it out. Does it make sense? Hydrologic field indicators such as channel measurements, flood deposits, soils, landforms, plants and land uses can help verify a record or provide as basis for adjusting estimates. Specific examples will be taken from experience in Missouri, Oregon, California, South Carolina, Georgia, Texas, and Puerto Rico. Hydrologic analysis was applied to specific but normal forest management decisions or activities such as culvert sizing and spacing, type of stream, stream crossings, landslide and gully treatments, water right needs, channel stabilization, wetland restoration, timber harvesting, pesticide applications, forest conversion to other uses, nutrient cycling, pollutant loading, emergency watershed protection, and burned area emergency rehabilitation projects. Management styles have changed over the last 33 years. Decision makers may be more receptive, but decisions still depend on the strength of the arguments. Some decision makers are easier to influence than others. Providing clear options with full disclosure of risk and effects should lead toward better management decisions. The question today is not always whether hydrology is a consideration, but to what degree and under what circumstances will it be an overriding consideration. Some activities do fine with default forest standards including best management practices. However, in impaired or unstable systems, or under unusual intensities of management, added consideration may be necessary.

Guidance for Intermountain Region Hydrology Specialist Reports–Field Review Notes, Technical Assessments, and NEPA Specialists Reports

Ronnie-Sue Helzner and Sherry Hazelhurst

As new professionals and technicians have entered our workforce, the Ashley National Forest (Utah and Wyoming) found a need to provide some guidance on information and data considerations for compiling various hydrology specialist reports. Region 4 adapted the Ashley's guidance with comments from other forests to create a general guidance document for all forests in the region. Many of the ideas, topics, and principles extend beyond our specialty and region. We would like to share our "living" document, available via website, with others. It may be useful to 1) new employees seeking guidance and examples, 2) supervisors and line officers responsible for training or mentoring new staff, and 3) experienced specialists looking for new ideas or ways to improve documents. The poster will summarize the document with an outline, example links, and business cards with an fsweb site for downloading (http://fsweb.ashley.r4.fs.fed.us/planningweb/templatesindex.shtml).

The Rebirth of a Stream–the Enchanted Valley Stream Restoration Project

Johan B. Hogervorst and Barbara Ellis-Sugai

The Enchanted Valley Stream Restoration Project was completed in summer 2002, and involved the reconstruction of over one mile of meandering stream channel in a low gradient valley on the Central Oregon Coast. The original stream channel had been moved to the side, straightened and diked to accommodate agricultural use over the last century. After the original relocation, the straightened channel cut down into the valley floor, increased in velocity and began eroding its banks, becoming a problem for both downstream water quality and fish habitat. The primary focus of the project was to restore wetland and floodplain function that once provided high quality rearing habitat for coho salmon (*Oncorhynchus kisutch*) in Enchanted Valley. To accomplish that goal, a new meandering channel was built in the middle of the valley. The new channel was constructed in 1999. The old ditches were plugged, and the water was diverted into the new channel in 2000, giving the willows and other vegetation planted on the banks a year to grow. Riparian and floodplain vegetation restoration continued in 2001 and 2002 with the planting of a variety of trees and shrub species. Large wood was placed in the new stream. Results: Spawning surveys from 2003 show a five-fold increase in returning adult coho salmon since the early 1990s. Last year was the first year that adults returned to the restored channel. Surveys in other local streams in 2003 did not show the same level of increase.

Mapping Air and Natural Gas Resources–the Management Value of Integrating Disparate Information

Melody R. Holm, Jeff Sorkin, and Janice Wilson

Rapidly expanding development of natural gas resources in the greater Rocky Mountain region is requiring more effective integration of the physical and biological sciences. With large areas of development come types and levels of effects not previously encountered with smaller, more confined development projects. Ironically, one of the reasons for growing demand for natural gas is its environmentally desirable clean-burning nature, while at the same time, effects of production and transportation of the resource on other resources are a growing concern. Of particular concern are effects on air quality,

specifically impairment of visibility in Federal Class I areas and atmospheric deposition in sensitive areas. A developing series of GIS maps (currently Wyoming and Colorado) depict the geographic relationship among existing production, permitted emission sites (gas compressors), areas of future production potential, sensitive areas (particularly Class I areas), and air monitoring sites. These maps provide for more informative and accurate prediction of effects of development activity on air quality. Initial maps of production, future potential, land ownership, Class I areas, and monitoring sites revealed some surprising relationships that will facilitate managing and planning for existing and future development. This poster presents representative GIS maps that illustrate the management value of integrating seemingly disparate information related to air resources and development of fossil energy resources.

The Effectiveness of Aerial Hydromulch on the Cedar Fire in Controlling Water Movement and Erosion

Ken Hubbert, Pete Wohlgemuth, and Pete Robichaud

The Cedar Fire consumed 272,318 acres, resulting in the loss of 14 lives and 1,483 residences burned. Aerial hydromulch treatments were prescribed by the BAER team in the upper Puetz Valley/Viejas Mountain area of southern California. Our objective was to monitor the effectiveness of aerial hydromulch, applied as a 100% treatment and as a 50% strip treatment, in controlling hillslope water movement and erosion. A total of 56 silt fences were installed and were divided between three units with adjacent untreated controls: 1) Capitan Grande Indian Reservation (100% treatment), 2) granitic parent material in the upper Puetz Valley (strip treatment), and 3) gabbroic rock in the upper Puetz Valley/Viejas Mountain area (strip treatment). Five plant cover quadrats were located at each silt fence to measure cover. Three channel check dams were also constructed to measure sediment yield and peak discharge in three small watersheds located on granitic parent material. Five rain gages were installed. The mean mid-March rainfall total was 165 mm. Rock cover in the gabbroic parent material was 25% as compared with less than 2% in the granitic. Hillslope sediment yields (on a tons/acre basis) were: control gabbroic = 1.20; strip gabbroic = 0.58; control granitic = 2.72; strip granitic = 0.67, and 100% granitic = 0.33. Sediment yields (tons/acre) within the channels were: control = 4.53, strip = 4.49, and 100% = 1.66. On both granitic and gabbroic parent materials, both the 50 and 100% hydromulch treatments were effective in reducing both channel and hillslope sediment yields.

Energy Development in the Eastern United States and Air Pollution Impacts on Aquatic and Terrestrial Resources

Cindy Huber, Chuck Sams, and Andrea Stacy

Energy development has increased dramatically in the eastern United States in recent years, in response to increasing energy demands by the public. Energy consumption is increasing at a faster rate than population growth in the US. One of the byproducts of supplying energy is air pollution. Nitrogen oxides, sulfur dioxide, volatile organic compounds and hazardous metals are some of the pollutants that enter the atmosphere. Whether energy development occurs on national forests or other public and private lands, resulting air pollution can affect forest resources as it disperses across the landscape. Coal-fired power plant development in the East will be used to demonstrate the air quality issues currently facing national forest managers. GIS products will be used to show the spatial relationship between projected development and emissions and national forest resources sensitive to air pollution. Linkages will be discussed between emissions of these pollutants and associated impacts on aquatic and terrestrial resources.

Using BARC for Fire Disturbance Analysis

Kevin Hyde

Severe erosion commonly follows intense wildfires throughout the Mountain West, altering stream channel morphologies and aquatic habitats, and threatening human life and property. These hazards can lead to large financial expenditures to assess and mitigate impacts. We therefore need to explicitly identify locations of highest post-fire erosion potential. Satellite-derived burn severity mapping, now referred to as Burned Area Reflectance Classifications (BARC), was used to quantitatively describe and explain post-fire gully rejuvenation triggered by intense rainfall following the Bitterroot, Montana fires of 2000. Vegetation disturbance was mapped in a GIS by means of an innovative metric, the Vegetation Disturbance Distribution Index (VDDI). Gully rejuvenation occurred in 66 of the 171 drainage basins examined. The mean VDDI value for gullied basins was very high compared to non-gullied basins. The degree and extent of vegetation disturbance was more important than any other landscape variable in predicting the incidence of gully rejuvenation. BARC mapping quantifies the difference in green before and after wildfires and thereby serves as a proxy for the magnitude of vegetation disturbance. Using BARC to generate VDDI values provides a rapid and repeatable means to assess the risk of severe erosion following wildfire. This model may prove to be useful for Burned Area Emergency Rehabilitation team assessment, and the

planning, implementation, and monitoring of burned area recovery treatments.

Lichen Air Quality Biomonitoring Partnership on the Salmon-Challis National Forest

Gary L. Jackson and Larry St. Clair

The Salmon-Challis National Forest occupies approximately 4.3 million acres in east-central Idaho. The forest lies in a transition zone between the maritime climate of western Idaho and the continental climate of southeastern Idaho. During the spring and summer seasons, precipitation results from convectional storms moving up from the Gulf of Mexico and the California coast; during the winter, weather patterns develop from the Pacific Northwest. A lichen air quality biomonitoring program was initiated in 1988 in conjunction with Brigham Young University, Provo, Utah. In 1993 a Challenge-Cost Share agreement was put in place to sustain a long-term lichen air quality biomonitoring program. Since 1988 more than 300 lichen species have been identified from 85 sites. This project represents one of the largest and most comprehensive lichen air monitoring programs in North America. Lichen species were first collected for elemental analysis in 1988. Initially, two sites were established, one at Golden Trout Lake (8153 feet) and one at Garden Creek (3400 feet). Both sites were re-sampled in 1993. Between the sampling periods, Golden Trout Lake showed a 32% decrease in sulfur; 70% decrease in copper; and 26% decrease in lead. Likewise, Garden Creek showed a 42% decrease in copper; a 28% decrease in lead with a slight increase in sulfur. The 1988 samples were analyzed using "atomic absorption" methods and the 1993 samples by "PIXIE" methods. The sulfur value at Garden Creek was 0.039%, a concentration well below background levels (0.2 percent).

Restoration of Bluewater Creek Riparian Rangeland Meadow in the Zuni Mountains of Western New Mexico

Roy Jemison

Riparian areas within rangelands of the southwestern United States are centers of high biodiversity. Despite the small size of these areas, when compared to surrounding uplands, they can support greater diversities of plant and animal species. Stands of willow and other woody vegetation in high elevation riparian areas play important roles in maintaining healthy watersheds. Such vegetation stabilizes bank and channel structures of streams, slows water movement downstream, and helps maintain good water quality. Riparian systems provide crucial habitat for native species of birds, fish, amphibians and small mammals. Historically, large numbers of cattle and sheep grazing in these areas eliminated many of these habitats. Although grazing is controlled now, it is felt that current grazing pressures may be keeping native vegetation from re-establishing. The Cibola National Forest in western New Mexico successfully restored riparian vegetation to a stretch of Bluewater Creek (south of Bluewater Lake) over a 10- to 15-year period. Activities that contributed to the success included replanting of native willows (*Salix* spp.), fencing to control cattle, and beavers (*Castor canadensis*). The restored area has increased use by birds, mammals, and people. In 2003, forest personnel began restoration work along Bluewater Creek in the area upstream and adjacent to the area restored earlier. Lessons learned during the first restoration project are being used. Modified and new techniques will also be incorporated as appropriate. A monitoring program is also being conducted with the current restoration activities to document changes in environmental factors as a result of restoration activities.

Relationships Between Hydrology, Exotic Plants, and Woody Fuel Loads in the Middle Rio Grande of New Mexico

Roy Jemison

Management options to reduce the risk of wild fires in the Bosque (riparian zone) of the Middle Rio Grande in New Mexico are being investigated. The Bosque, one of the longest and most contiguous riparian zones in the western US, developed under a much different river flow regime and land uses than exist today. River regulation and flood control, with diversion dams, levees, and fire suppression, have decoupled the self-perpetuating and self-sustaining terrestrial biotic community from the water on which it depends. Elimination of flooding, lowered water tables, and lack of naturally occurring cool fires have allowed exotic plants to establish and thrive in monotypic vegetation types as well as beneath cottonwood (*Populus* spp.) overstories. Salt cedar (*Tamarix ramosissima*) and Russian olive (*Elaeagnus angustifolia*) have formed thickets that are almost impassable without the use of mechanized equipment. The presence of exotic woody plants increases the risk of fire near the river communities of Albuquerque, Socorro, Bernalillo and several Pueblos, reduces opportunities for recreational use of river woodlands, and contributes to the loss of native plants. For example, woodlands dominated by a cottonwood overstory and exotic understory, when burned, typically return as exotics only. In collaboration with landowners and managers, Forest Service scientists are testing methods to reduce and control the build up of exotic fuels in the understory. Relationships between water management, exotic plant

distributions, and fuel loads on the middle Rio Grande will be described in this poster along with the current management and research practices that address the identified problems.

Beyond Statistics: Landscape Controls That Mask Apparent Effects of Harvest Activities on Soil Saturation

Adelaide Johnson, Kellie Vache, and Rick Edwards

Observations of peak water table heights in 56 groundwater-monitoring wells at two study locations (Hanus and Portage, southeast Alaska) suggest that soil saturation levels on hillslopes differed significantly with harvest intensity only at Portage Bay following 25, 75, and 100% harvest. For example, before the forest at Portage Bay was cut by 100%, the average rainfall needed for 50% saturation of the soil was 54 mm, but after clearcutting soils reached 50% saturation with only 21 mm. We hypothesize that Hanus Bay sites lacked statistically significant differences in levels of saturation following harvest due to several factors: 1) location, size, and landform of areas contributing to wells, and 2) number, species, size, and density of trees in relationship to wells for pre- and post-harvesting conditions. To test these hypotheses, we developed a simple hydrologic model to predict saturation. Model results were tested with existing records of saturation for various levels of rainfall.

Modern Stromatolites and Benthic Phototrophs in Ultra-Oligotrophic Waldo Lake, Oregon

Al Johnson

Waldo Lake is located in the Willamette National Forest near the crest of the Cascade Range. The 6,298-acre lake is 420 feet deep and is one of the largest natural lakes in Oregon. The lake is regarded as one of the most oligotrophic lakes in the world. Investigators have reported the water to be extremely dilute and chemically similar to distilled water, with reported values of phytoplankton primary production and concentrations of chlorophyll a among the lowest ever found in a freshwater lake. Previous studies have noted the importance of benthic primary production in the lake. Over the last several years, personnel from the Willamette National Forest have participated in investigations of areas < 20 m in depth including studies of the benthic microbial community. Cyanobacteria including many nitrogen fixing species were found to compose a large portion of the biomass of this zone. These cyanobacteria along with a variety of eukaryotic algae form microbial communities covering benthic surfaces. Primarily through the trapping and binding of sediment, these benthic microorganisms have formed modern stromatolite structures over extensive portions of the lake < 7 m in depth. Previous studies of other freshwater lakes have reported the formation of modern living stromatolites in calcareous lakes. Waldo Lake is likely a rare or unique example of modern stromatolite formation in a freshwater lake under ultra-oligotrophic conditions. Further studies of these stromatolite formations are in progress as part of an overall scientific study plan of this extraordinary lake.

Low-Volume Roads Engineering Best Management Practices Field Guide

Gordon Keller and James Sherar

Over the past several years the US Forest Service and US Agency for International Development (USAID) have been working with Virginia Tech on the publication of a roads "best practices" guide titled "Low-Volume Roads Engineering Best Management Practices Field Guide". This Roads BMP Guide was produced to provide an overview of the key planning, location, design, construction, and maintenance aspects of roads that can cause adverse environmental impacts and to list key ways to prevent those impacts. Best Management Practices are techniques or design practices that, when applied, will prevent or reduce pollution and maintain water quality. Roads often have major adverse impacts on water quality, and most of those impacts are preventable with good location, engineering and management practices. This Guide presents many of these desirable practices, with the use of many photos, drawings, and designer aids. Most of these BMPs are sound engineering practices, and are cost-effective because they prevent failures and reduce maintenance needs and repair costs. Key objectives of Roads Best Management Practices include the following:

- Protecting sensitive areas and water quality, and reducing sediment transport off roads;
- Maintaining natural channels and passage for aquatic organisms;
- Controlling surface water and stabilizing the roadbed driving surface;
- Controlling erosion, stabilizing slopes and reducing mass wasting; and
- Stormproofing and extending the useful life of the road.

This poster will include examples of practices in planning and design, roadway surface drainage, drainage crossings, slope stabilization and erosion control used to achieve the above objectives.

Lessons Learned Between BAER Assessment and Implementation on 2003 Southern California Fires

Allen King

The southern California fires of October 2003 burned 750,000 acres within a few weeks, including portions of four major fires on three national forests. Geologists and geotechnical engineers made significant contributions to BAER assessment teams evaluating geologic hazards, defining risks to humans, watersheds and infrastructure, and recommending treatments to reduce risks. Implementation of those treatments provided many challenges as BAER implementation teams installed some of the recommended treatments, modified others, and created new treatments. As winter storms hit burned areas, sixteen people were killed on the San Bernardino NF by the December 2003 Christmas storm. New in-channel debris dams on the Piru Fire were destroyed by the February 2004 storms. Roadwork in the Sespe Oil Field greatly improved traffic flow, but some construction practices caused additional drainage and sedimentation problems. "Before and after" photo monitoring provides many lessons learned, related especially to accurately understanding and interpreting current geomorphic processes, water flow dynamics, and climatic conditions specific to the burned area being studied. What works in New Mexico or Idaho doesn't automatically work in southern California. Many of the lessons learned raise questions about how many times we need to re-learn the same lessons and how can we change old practices that don't reflect BMPs. Some suggestions will be offered.

Modeling the Role of Evapotranspiration in the Unsteady State of the Groundwater Regime in Watershed-Scale Projects

Tom Koler

Forecasting the slope stability of hillslopes at a watershed scale has been successfully completed in industrial timberlands in northern California. The fundamental equations include the infinite slope equation for time-series evaluation and nested code for measuring changes in normal effective stresses in response to fluctuations within the hydrologic cycle. A focus was placed on the evapotranspiration loss from the harvest of redwood stands. Results from this study show the effectiveness of applying this science in the decision-making process for timberland watershed management.

Influence of Prescribed Fire on Fish and Streamwater Mercury Concentrations

Randy Kolka, Jason Butcher, and Trent Wickman

Because of its persistence and wide dispersal in the environment and its ability to bioaccumulate in organisms, mercury (Hg) is a contaminant of great concern. Although scientists are beginning to understand the Hg cycle in forested systems and the important Hg species that lead to bioaccumulation in the food chain, little is known about the role of fire in Hg cycling processes. The North Central Research Station and the Superior National Forest have started to fill these data gaps by establishing a plan to monitor mercury changes during fuel reduction efforts in northeast Minnesota. The Larch Lake watershed, part of which is located in the Boundary Waters Canoe Area Wilderness, is included within an area of the forest where fuel reduction efforts are taking place in response to a major blowdown event that occurred in 1999. The Larch Lake watershed is a 2100 ha headwater system; approximately 40% of the watershed has been recently managed with prescribed fire, with another 30% planned for similar fuel reduction treatments. Total and methyl-Hg in water were measured along with standard physicochemical variables both pre- and post-treatment. Tissue Hg concentrations in young-of-year smallmouth bass (*Micropterus dolomieu*) were also analyzed for the pre-burn (baseline) period; post-burn samples will be taken for a several-year period after treatment to understand any potential bioaccumulation timelines. These data will provide a better understanding of how prescribed fire in the Larch Lake Watershed affects the magnitude and timing of Hg delivery to streams, lakes and fish.

Influence of the Intensity of Silviculture on Soil Carbon

Randy Kolka, Rachel Tarpley, Marty Jurgenson, and Brian Palik

A primary goal of silviculture is manipulation of forests to produce fiber, while sustaining the ecological systems that drive this production. Unfortunately, we know little about tradeoff responses between fiber production and soil physical properties governing productivity, across gradients of silvicultural intensity. Maintenance or enhancement of soil carbon pools is one indicator of productivity. Moreover, the effect of silvicultural intensity on soil carbon has implications for the mitigation of greenhouse gases. In this study we assessed soil carbon pools across a gradient of red pine (*Pinus resinosa*) growing stock at the Cutfoot Experimental Forest in North Central Minnesota. The replicated study treatments include five levels of growing stock (60, 80, 100, 120, 140 ft^2/ac) maintained through repetitive commercial thinning in extended rotation stands.

Since study establishment in 1949, within 85-year-old stands, there have been seven commercial harvests. The experimental forest also contains old-growth stands (130+ years old) with no history of harvesting since initiation. Soil carbon was sampled across the gradient in 2003. In this poster we will present the result of our analyses.

Application of a LIDAR-Generated Digital Elevation Model to Active Landslide and Geomorphic Process Mapping and Interpretation

Benjamin R. Kozlowicz and Mark E. Smith

Six Rivers National Forest has acquired a 10-foot (3-meter) LIDAR generated digital elevation model (DEM) for most of the Willow Creek basin, Lower Trinity RD. Such dense, accurate topographic data can aid in the identification of landforms and surface process zones and can be used to quantify some geomorphic processes. We use this data to estimate the volumes and delivery rates of active, shallow debris slides mapped on sequential aerial photos for sediment budgeting. These volume estimates are then compared to estimates from field surveys using a laser rangefinder. The results of this and previous studies are used to develop area to volume ratios for shallow debris slides in different geologic and geomorphic units. These relationships are applied to the forest-wide active landslide inventory of over 11,000 features. In addition, we use the 3-meter LIDAR DEM to aid in interpreting 1:24,000-scale geomorphic processes and in assessing the relative activity of deep-seated landslides.

Native Plants and Fertilization Help to Improve Sites and Stabilize Gullies on the Sumter National Forest

Dennis L. Law and William F. Hansen

The Sumter National Forest (South Carolina) lands were acquired in the early 1930s under the Weeks Law to provide sustained timber and improve soil productivity. Most areas were severely eroded and depleted of nutrients due to past farming practices. Soil productivity was drastically lower and approximately 20,000 acres of actively eroding gullies and galled barrens dissected the area. Reforestation and active stabilization measures have been used to help restore the landscape. However, some gullies and galled barren areas continue to produce sediment at excessive rates. Trees and other vegetation present on severely eroded lands are often sparse and in poor health. Surface erosion and productivity problems have been reduced or eliminated on most of the treated areas. A variety of techniques have been used to treat gullies, such as soil ripping, disking, fertilizing, seeding and mulching, but this poster will focus on activities involved with using native plants and fertilization. A multi-agency agreement was developed with the South Carolina Native Plant Society, Tall Timbers, Clemson University, county, state and federal agencies to assist in providing cost and technical sharing of native plant information. The poster will highlight pictures of soil recovery efforts. Efforts have included increased cooperation among agencies with over 1,000 person days of volunteer time. The information will show how native plants are collected within the ecotypes and grown in both nursery and field conditions for use on gullies and other disturbed or barren areas.

Coordinated Interagency Response to the Aspen Fire

Robert E. Lefevre, Salek Shafiqullah

The Aspen Fire of June-July 2003 burned 84,750 acres including 330 residential and business structures in and adjacent to the Coronado National Forest in southeastern Arizona. A Burned Area Emergency Response team assessed the fire, prescribed treatments, and implemented them in the burned area. In addition, 7 federal agencies, 6 state agencies, 16 county agencies, and 7 local agencies and utilities began to plan and act before the fire was contained to minimize damage due to accelerated erosion and flooding that was expected across the multiple ownerships. The events leading up to the Aspen Fire that contributed to the exceptional coordination including seven large fires on the Coronado National Forest in 2002 and five large fires in 2003 prior to the Aspen Fire as well as the experience of state and federal agencies following the Rodeo-Chedeski Fire in 2002 are described. Values at risk and burn severity mapping are summarized. The coordinated response including on-the-ground treatments of seeding, mulching, channel clearing, and road drainage improvement are described, and the results of monitoring the efforts are reported. The continued efforts to keep the public aware of potential accelerated erosion and flooding are also reported.

Ecological Classification, Organic Layer, and Large-Scale Prescribed Fire Monitoring on the Superior National Forest

Barb Leuelling and Jeff Tepp

The Superior National Forest (Minnesota) was one of the first national forests to initiate an Ecological Classification System (ECS) in the early 1960s, now known as Terrestrial Ecological Unit Inventory (TEUI). It was pioneered by Don Prettyman in response to FS Manual Direction 2535 to provide baseline information for barometer watersheds. Located within the Boundary Waters Canoe Area Wilderness (BWCAW), this inventory was meant to be a "representative area" to identify changes over time in soil and water from management-caused activities

or natural events. From 1965-1990, landtype phases (LTPs) were mapped on national forest land based on combined factors such as climate, geology, landform, soils, vegetation, and hydrology. The Superior National Forest is now concentrating efforts on converting legacy data to electronic format, transferring mapping to GIS format, and developing a TEUI intranet website. TEUI information is being used to conduct monitoring of mechanical and burn treatments to salvage and restore a 500,000-acre blowdown event on the forest in 1999. The monitoring includes about 12,000 of 88,000 planned prescribed burn acres within the BWCAW. This may be the first "implementation prescribed burn monitoring" on a large natural event where lightning-ignited fires were a part of its history, and is designed to assess effects of prescribed burning on the organic layer of shallow to bedrock sites. Monitoring and mercury research on the forest may help answer questions concerning the role of the organic layer: oxidation of the organic layer during natural/prescribed fire events or its accumulation over time in the absence of fire.

Effects of Forest Management in the Caspar Creek Experimental Watersheds

Jack Lewis, Elizabeth Keppeler, and Tom Lisle

Caspar Creek Experimental Watersheds were established in 1962 as a cooperative effort between the California Department of Forestry and Fire Protection and the USDA Forest Service Pacific Southwest Research Station to research the effects of forest management on streamflow, sedimentation, and erosion in the rainfall-dominated, forested watersheds of north coastal California. The project has evolved from a simple paired watershed study into one of the most comprehensive and detailed investigations of its kind. In 1962, weirs were installed for measuring streamflow and sediment loads on the North and South Forks of Caspar Creek. From 1971 to 1973, 50% of the timber volume in the South Fork was selectively cut and tractor yarded, and the untreated North Fork was retained as a control. In 1986, thirteen new gaging stations were installed in the North Fork basin and three unlogged tributaries served as controls when 48% of the North Fork basin was clearcut and cable yarded between 1989 and 1991. Ten new gaging sites in the South Fork will be used to assess impacts of selective harvest and road rehabilitation on tractor-logged terrain. The scope of research in the watershed has expanded beyond hydrological studies to include geomorphological, ecological, silvicultural, and biological investigations.

Restoration of Cherry Creek–Lessons From a Southwestern Stream

Grant Loomis and Tom Moody

Large stream systems, composed of a small baseflow channel lined by a narrow greenline of riparian vegetation bordered by barren gravel and cobble bars are not uncommon in the Southwest. The elevation of the surfaces of the gravel and cobble bars above the water surface elevation of the baseflow channel makes natural recruitment of riparian vegetation on these surfaces difficult and leaves these systems vulnerable to scouring by even relatively frequent floods. In an effort to raise the level of stability of these systems, a demonstration channel restoration project was implemented on Cherry Creek on the Tonto National Forest in Arizona. The project attempts to create a channel that can transport the water and sediment of the watershed while at the same time maintaining the level of floodprone surfaces at an elevation that permits natural recovery of riparian vegetation. This poster will discuss some of the hydrologic challenges involved in design of the channel and some of the uncommon restoration methods used in the reconstruction.

Characteristics of Peak Flow Return Intervals for Small Drainage-Area Watersheds of the Southern Cascades of Eastern Oregon: Implications for Culvert Sizing

Walt Lucas

The equations for the magnitude and frequency of floods in Oregon used by the USGS have high standard errors for return interval values in two regions of Eastern Oregon. They assume that hydrologically similar sites were nested or adjacent, regardless of size. However, the large drainage area watersheds include diverse climatic zones where precipitation could vary from less than 20 inches year falling primarily as rain, to areas of over 60 inches of precipitation that is largely released as snowmelt. Consequently, the relative importance of the geomorphology, climate, and size could vary significantly, causing some of the large errors in the estimates. This work tries to reduce some of that error. Data from ten FS gages with over eight years of record is used to refine the magnitude-frequency relationships for a more uniform environment, where drainage area was between 4 and 50 square miles, minimum basin elevation was above 4200 ft and precipitation zones ranged from 25 to 60 in and were strongly influenced by snowmelt. Extending the relationships out to the 100-year return interval results in different discharge estimates, which have implications for culvert sizing.

Effects of Pine-Bluestem Restoration on Soil Quality on the Ouachita National Forest and Implications for Improved Air Quality and Watershed Condition

Ken Luckow and Hal Leichty

Thinning, midstory reduction and frequent (three- to four-year interval) prescribed fire have been used to restore the shortleaf pine-bluestem ecosystem. During 1997, 1998 and 1999, soil and foliar nutrient data were collected from three shortleaf pine-bluestem (*Pinus echinata*/*Andropogon* spp.) stands that have undergone restorative treatment for the past 18-20 years, and three untreated control stands. The analyses indicate soil quality has been improved in the pine-bluestem treatment stands as compared to the control stands. In the treatment stands soil pH has increased from 4.96 to 5.34; percent organic matter and cation exchange capacity have each increased by about 10%; percent base saturation by 15%; calcium by 60%; and total N and C by about 11% and 31%, respectively. In addition to improved soil quality, both air and water quality and watershed condition are indirectly benefiting from the pine-bluestem treatment stands by an increased soil buffering capacity and from added sequestration of C. The analysis indicate a net soil C increase of 0.20 tons ac^{-1} y^{-1} in the treatment stands, which equates to the removal of 1,500 pounds of atmospheric carbon dioxide ac^{-1} y^{-1}. Increased levels of Ca and organic matter in the treatment stands are beneficial in reducing the negative effects caused by atmospheric acid deposition on watershed condition and water quality, by providing a more effective soil buffering capacity to retain and neutralize acids.

How to Lighten Your NEPA Workload

Tom Mainwaring and Carl Leland

Forests today face ever-increasing NEPA workloads. Combined with staff and time limitations, it has become increasingly difficult for forests to meet project workload requirements and timelines with existing staff and budgets. Use of an enterprise team provides an "in-house" solution to meeting workload requirements within existing budgets, without the commitment to additional full-time personnel. An enterprise team is a group of Forest Service employees functioning as an established business within the agency, providing needed skills and services.

The Timber Experts and Measurements Services (T.E.A.M.S.) team specializes in providing project planning, project implementation, and quality control services to forests nation-wide. T.E.A.M.S. can provide full IDT NEPA contract services such as EAs, EISs, Landscape and Watershed Assessments, or it can provide staff on an individual resource basis, such as a soil scientist, hydrologist, geologist, or interdisciplinary team leader. Implementation services include project layout, quantity determination, contract preparation and appraisal, and BAER services. Quality control includes contract administration, checking cruising and scaling, and product accountability audits. T.E.AM.S. specializes in fire, wind storm, insect emergencies, and large complex projects that forests and other clients typically do not have the time or staff to complete. T.E.AM.S. ability to provide a full range of services, from a complete IDT to staff for a single resource, allows maximum flexibility to forests in determining how to best meet workload and budget requirements.

Quantifying Measurement Error for Accurate Testing of Channel Cross-Sectional Change

Daniel A. Marion

Channel change over time or between different locations is frequently assessed using cross-sectional variables like top width or hydraulic depth. For a given cross-sectional variable, the apparent difference between any two surveys is actually composed of two parts: that part representing the actual difference; and that part resulting from the combined errors associated with using different personnel to make measurements and the variation inherent in the measurement method itself. This latter part can be termed measurement error. To statistically test the actual change in cross-sectional variables between any two surveys, the measurement error must be determined. Measurement error is evaluated by doing repeat measurements (replicates) of randomly selected cross sections on the same day, but rotating survey personnel so that each performs a different job. It is quantified using the standard error of the mean. The standard error is computed for each variable of interest by determining the variable value for each replicate separately, computing the mean of the paired values, and then computing from multiple replicate surveys the standard error of mean. Using data from high-gradient streams in the Ouachita Mountains of Arkansas, I give an example showing how the standard error is computed and used to test changes in cross-sectional area, wetted perimeter, and hydraulic depth. I speculate that measurement errors would vary significantly between channels that differ substantially in substrate size and cross-sectional shape.

Ecosystem Mapping and Soil Survey in the Western Upper Peninsula of Michigan

Sarah E. Mase

The Ottawa National Forest was an early pioneer in ecosystem mapping using the nested hierarchy of ecoregions. Beginning in the 1980s, the Ottawa began mapping ecological landtype phases (LTP) at the 1:15840

scale, using the Land Type Association map to define mapping areas and legends. Components of LTP mapping include soil, landform, and potential natural vegetation. The Ottawa has used both LTA and LTP information in Forest Planning and project design over fifteen years. As a cooperator in the National Cooperative Soil Survey (NCSS), the Ottawa incorporated those standards into LTP mapping, including annual field reviews with oversight and correlation by a Natural Resource Conservation Service (NRCS) State Soil Specialist. In 1998, NRCS initiated soil surveys in Ontonagon and Gogebic Counties. The two counties comprise over 1.5 million acres; about a third of the area is National Forest System lands. Cooperation, technical advances, and databases such as NASIS (the National Soil Information System) and TERRA (the Forest Service's Natural Resource Information System [NRIS] application for soil data), and working relationships between the agencies enabled a vision of a seamless inventory to evolve. Working together on soil-site mapping in an atmosphere of mutual respect, concepts of both systems have been incorporated. Data and mapping from both agencies are contributing to a seamless inventory and added interpretive applications across the continuously forested landscape of the western Upper Peninsula of Michigan.

Geomorphic and Hydrologic Effects of High-Elevation Summer Storm Events

Alisha Miller, Tuli Tannaci, Juan de la Fuente, Abel Jasso, and Steve Bachmann

Two Northern California summer storm events during July and August 2003 resulted in high elevation debris flows on the slopes of Mount Shasta, Mount Eddy, and West Haight Mountain in Siskiyou County. The storm effects were exacerbated by glacial melt and significant snow pack above 8,000 feet on Mount Shasta, which experienced fourteen debris flows on its south and east flanks resulting in numerous plugged culverts and water quality degradation in the McCloud River, Lake McCloud, and McCloud Arm of Shasta Lake. Two debris flows occurred on Mount Eddy along with extensive rilling and gullying. Water quality concerns were raised for five alpine lakes on Mount Eddy due to the influx of sediment, with several of the lakes remaining discolored at least into September. Three stream crossings were damaged by a debris flow on the north side of West Haight Mountain. Because high elevation slopes are buffered with snow through much of the year, summer storm events are important for sediment production and transport processes and stream channel morphology. These events typically occur when rivers are at low flow and incapable of flushing sediment through the system. The occurrence of summer storm events needs to be considered during planning of land management activities, including road construction or maintenance, timber harvest, prescribed fire, and other ground disturbance activities. A better understanding of summer storm events, their temporal and spatial distribution, and their effects could be reached through improved cooperation between earth and atmospheric sciences and sharing of information between forests.

A Comparison of Northern California Sediment TMDLs

Alisha Miller and Juan de la Fuente

Many California rivers and streams have high sediment loads due to a combination of anthropogenic and natural factors. Sediment is one of the pollutants addressed with the Total Maximum Daily Loads (TMDL) Program established by the Clean Water Act and administered by the Environmental Protection Agency (EPA). A TMDL is a three step process of identifying water quality concerns, identifying pollution sources, and determining the load reductions and abatement actions necessary to restore the water body. For sediment-impaired rivers, an important part of the TMDL process is to determine natural sediment production and land management-related contributions through a sediment source analysis. Sediment source studies attempt to estimate the volume of sediment coming off of the hillslopes and being delivered to the river system. These studies typically use varying combinations of aerial photograph interpretation, extrapolation based on field sampling, and literature references. We compared sediment TMDLs completed for Northern California rivers and streams, along with several other sediment studies. The comparison was complicated by the wide variability in study methodologies, including sediment source categories (natural versus anthropogenic), data collection techniques, units of measure, and study time periods. Considering the implications TMDLs have for land management, the associated sediment analyses need to be standardized. Ideally standardization should be universal, but it would also be valuable for analyses of national forest watersheds. We offer suggestions on standardization of key elements of sediment source analyses to allow for a more concise evaluation of each TMDL and simplify comparisons of TMDL findings.

Stream Restoration at Road Crossings in Wisconsin

Jim Mineau and Dale Higgins

Poorly designed road-stream crossings can affect water quality, stream morphology and fish passage in northern Wisconsin. Sediment is the most significant water quality

impact, and frequent failures are the largest source of sediment, followed by road surface and embankment erosion. Aggradation is the most common morphological impact. Downstream aggradation is often associated with coarse sediments from frequent failures. Most upstream aggradation consists of muck, silt and fine sand that accumulate because culverts are set too high or are undersized. Since 1998, the Chequamegon-Nicolet NF has replaced over 90 stream crossings through the Ten Percent program. These crossings have been designed to restore channel morphology, provide fish passage, improve safety and reduce maintenance. A protocol for survey and design has been developed to accomplish these objectives. Culverts are sized to pass the 100-yr flood, which is estimated from USGS regional regression equations and occasionally checked with other techniques. The road, culvert, stream thalweg, and at least four channel-floodplain cross-sections (two up and two down) are surveyed in the field. The thalweg survey is used to identify channel morphology impacts and to specify the new culvert elevation. The remaining data are used in Hec-Ras to hydraulically model the existing and proposed culverts. Other key design and construction techniques include stream diversion during construction, compaction, road surfacing, riprap and locating the low point of the road profile to one or both sides of the culvert.

The 1997 Flooding in Two Northern California Klamath National Forest Streams: Geomorphic Effectiveness and Sediment and Large-Wood Budgets

Zackary J. Mondry

The 1997 "New Year's Day" flood produced a range of effects in valley bottoms across the Klamath National Forest in northern California. I assessed flood disturbance in two adjacent basins (drainage area ~35 km^2) having similar bedrock, geomorphic terrane, and land-use characteristics. I examined valley bottom forests and morphology with pre- and post-flood air photos, and with cross sections, and constructed flood sediment and large wood budgets. I then linked event disturbance to volumes of sediment and large wood input during the flood, at the reach scale. Major landsliding in one basin produced large debris flows and downstream debris floods that stripped riparian forests and mobilized floodplain deposits along the entire valley network (~10 km). Large headwater landslides and debris flows also affected the second basin, but disturbance was patchy and decreased downstream as sediment and large wood were deposited at valley bends, impingements, and on unmobilized floodplains. The degree of valley bottom disturbance increases with the volume of sediment delivered to reaches during flooding, and may also increase when greater volumes of large wood are input to reaches lacking valley bends or mature conifer trees that promote deposition. Intermediate-level disturbance increased valley system complexity. In managed Klamath Mountain basins, debris flows commonly originate by landsliding from roads or deforested hillslopes. Such debris flows may have insufficient mature conifers to moderate run-out distance or to promote complexity in receiving channels. These debris flows are more likely to simplify downstream valley forests and morphology and convey flood disturbance to larger systems.

Drought, Storms, and Streamflow and Stream Temperature Monitoring on the Coconino and Prescott National Forests, Northern Arizona

Zackary Mondry

Prolonged drought across the US Southwest has sharpened concerns regarding the availability of water for consumptive uses, and drought effects on forest health and wildfire potential. Of special concern to watershed managers are the impacts of drought on water availability to sustain aquatic and riparian habitats, and effects on associated fish and wildlife species. In support of instream flow water rights programs, the Coconino and Prescott National Forests are monitoring stream flow with instantaneous measurements at some 14 streams. Flow monitoring began in earnest in the summer of 1998, and most sites were previously ungaged. Additionally, I began collecting stream temperature data with Tidbit data loggers in the summer of 2002, and now have temperature data from nine streams across the Coconino NF. Many of these streams were also monitored for stream flow by the FS or USGS (continuous records) during this time. The period from September 2001 through May 2002 was the driest on record dating back to 1898 in northern Arizona. However, storms in September 2002 and February and March of 2003 produced overbank flows along many streams in northern Arizona. Stream flow and stream temperature data are presented, and some effects of weather patterns and storm events on flow rates and stream temperatures are illustrated. For example, temperature depressions can help constrain the onset and duration (but not magnitude) of spring run-off events in streams lacking continuous flow records. These data also provide a baseline to monitor future impacts on water resources from drought and consumptive uses.

Evaluation of Habitat Variability, Channel Changes, and the Effectiveness of Restoration Projects in an Eastern Washington Stream

Mark Muir, Susan Bolton, Robert Wissmar, and Pete Bisson

The purpose of this study was to evaluate habitat variability (1990-2001), channel changes (1994-2001) and the effectiveness of restoration projects (1986-2002) in the Little Naches river, Washington. An adjacent, relatively undisturbed river was used as a reference of natural conditions and processes. Response or pool-riffle reaches were surveyed in both study streams. Between 1990 and 2001, Little Naches response reaches showed an increase in pool habitat, large woody debris [LWD] and surface area comprised of spawning-sized gravels, while the percent of embedded stream length decreased. Cross-section surveys revealed localized channel migration, LWD recruitment and pool formation in the most altered and confined reach. The observed habitat and channel changes in the Little Naches River appear closely related to flood events, rather than management or restoration projects. The effectiveness of in-stream structures varied with structure type, location in the channel and channel type. In-stream structures were not effective at creating or maintaining habitat in the long term, particularly in active response reaches. Although habitat conditions in the Little Naches River appear to be improving, they are still quite different from reference reaches, which exhibited a more complex array of habitat for both juvenile and adult salmonids. Pool habitat, side channel habitat and LWD were all more abundant in reference reaches. Pools in reference reaches also had more total cover, deeper residual depths and were more often associated with meander bends. The observations and results of this study can help offer insight and guidance to future restoration efforts within the Little Naches watershed.

Tools to Evaluate the Effect of ATVs on Soil Physical Properties

Carolyn Napper

The US Forest Service started a study to determine the potential impacts of All Terrain Vehicles (ATVs) on National Forest Lands and Grasslands. The objective of the study is to look at different types of ATV equipment (different weights, tires, suspensions) and evaluate changes in soil physical properties on both existing ATV routes and uncompacted soils. The study is done in partnership with six national forests across the country and the Rocky Mountain Research Station. Key soil indicators used include soil bulk density, rut depth, soil moisture, trail width, soil displacement and erosion. ATV equipment types include sport and utility models with original equipment manufactured tires and after market tires. Data gathering methods include visual observations to define condition classes of low, moderate and high with actual soil measurements of rut depth, trail width, soil bulk density, soil moisture and erosion. Photographic documentation is used to help define condition classes and provide a reference for completing the condition class rating. The findings of the study will be released once the study is completed but the tools and methodology used can help physical scientists in their evaluation and management of ATV use.

Impacts of an Historical Wildfire on Hydrologic Processes: A Case Study in Arizona

Dan Neary

An opportunity to study the impacts of a watershed-scale fire on hydrologic processes in a ponderosa pine (*Pinus ponderosa*) forest ecosystem of the Southwest presented itself following the devastating Rodeo-Chediski fire of June-July 2002, which burned a total of 462,606 ac in north-central Arizona. Streamflow regimes, erosion-sedimentation processes, and other hydrologic and ecological characteristics are being measured on two watersheds to assess the short- and long-term impacts of this historical fire. Findings to date with respect to post-fire changes in soil and water resources are reported upon in this poster.

Regulatory Tools for Watershed Management

Karen Nelson

The U.S. Army Corps of Engineers has regulatory roles designed to help protect the biological, chemical, and physical integrity of waters of the United States. The activities requiring authorizations in the form of a permit include placement of fill, bioengineering streambank treatments, docks, piers, and other structures, in waters of the United States. Regional permits, developed by coordinating with federal, state, and local agencies, cover numerous relatively minor activities and are tailored to the geographic nuances of our regions. Information on nationwide, regional, and individual permits will be available. Permitting requires the balancing of environmental protection with economic development. Mitigation is permitted for losses of water resources when all practical efforts to avoid wet areas have been applied. Failure to seek or comply with a Department of Army permit may result in civil penalties. We will show the Army Corps of Engineers jurisdictional boundaries for both Section 404 of the Clean Water Act, and Section 10 of the Rivers and Harbors Act. Information on permit

processes and mitigation information associated with work in waters of the United States will be provided. The poster educates people about the Corps role, rules and laws, applicable for working in waters of the United States, and the resources used to monitor and verify permit compliance.

Spatial Data Analysis of Soils Within the Kisatchie National Forest Using Geographical Information Systems

John C. Novosad, Wayne H. Hudnall, and Jacqueline A. Prudente

The Kisatchie National Forest (KNF, Louisiana) maintains designated trails within the forest for off-road vehicle (ORV) use, but many ORV users create their own trails, causing soil erosion and rutting problems. To help guide the management of this use, a spatial data analysis of the soils within the KNF was performed using geographical information systems (GIS). The objectives were to summarize and present the spatial distribution and nature of the soil resource in a thematic format and to identify areas that are suitable and unsuitable for ORV use with the map overlay procedure in GIS. Results reveal that soils within the Kisatchie Ranger District (KRD) with potential for severe erosion are located on sloping areas, and soils that have the potential for severe rutting are located on upland flats and floodplains. Problem soils–soils with potential for severe erosion or rutting–were identified. These soils are loamy, poorly drained and very slowly permeable, or sandy and well-drained but located on sloping areas. Designated and user-created trails crossed streams and traversed problem soils. Based upon the results of the spatial data analyses of soil suitability, the entire KRD is unsuitable for ORV traffic. Traffic should be restricted on this district to allow damaged sites to recover from the damage that has occurred. The USFS has temporarily closed the KRD to ORV traffic during wet conditions based upon this recommendation.

Streamflow Analysis of the Little Popo Agie River Near Lander, Wyoming

Liz Oswald, Greg Bevenger, and Laurie Porth

The simplified water balance equation Q = P - ET, where stream flow discharge is equated to precipitation minus evapotranspiration, was evaluated to determine whether discharge from the 125-square-mile Little Popo Agie River watershed (central Wyoming) has changed over time. The analysis was made as part of the Little Popo Agie River (HUC 1008000301) Watershed Assessment conducted by Shoshone National Forest staff in 2003. The objective of the analysis was to determine whether forest management activities or the lack thereof (such as timber harvest and prescribed burning) or wildfire, are having an effect on the water balance. Double-mass analysis, following the methods of Anderson (1955), was used with local and regional data from the Natural Resource Conservation Service, the National Weather Service, and the United States Geological Survey. The analysis involved identification of stable snow survey, precipitation, and stream gaging stations that would be suitable as references for 1 April snow water equivalence, average annual precipitation, and seasonal (April through September) stream flow, respectively. The reference information was then compared with the Little Popo Agie River (USGS site 06233000) seasonal stream flow record. The results show no detectable change in stream flow for the period of record (late 1940s to 2003) leading to two possible conclusions: 1) management activities on the national forest have not had a significant effect on the water balance; or 2) if there has been an effect, it is not detectable at the Little Popo Agie stream gage.

Ground-Penetrating Radar and Seismic Refraction as Tools for Characterizing Aquifer Properties in Recently Active Glacial Moraine Settings, Tongass National Forest, Alaska

Noel S. Philip, Steven D. Sheriff, and Robert A. Gubernick

Ground penetrating radar (GPR) and seismic refraction surveys were conducted at a critical location on a glacial moraine near Yakutat, Alaska. Observations of the aquifer material on the moraine were made from exposures at the surface and from shallow excavation. The near-subsurface moraine material is composed of clean sand and poorly sorted gravel, with boulders having a major axis >1 m. Seismic data acquired at the moraine show a subsurface depth to refractor of ~10-16 meters at the moraine. GPR data show a strong reflection at ~25-30 m depth. The expected results from the surveys should allow a reasonable geometric model of the subsurface to be made within a 10% estimated resolution of depth. Further applications of the data set and extrapolated properties of the subsurface should lead to a reasonable conceptual model of hydrogeologic units and general flow regime. The subsurface model will prove valuable during the next cyclical closure of Russell Fjord by Hubbard Glacier, the water body bordering the glacial moraine to the north.

The Stream Systems Technology Center

John Potyondy

This poster will present information about the Stream Systems Technology Center, a national technical service

center of the Washington Office Watershed, Fisheries, and Wildlife Staff located at the Rocky Mountain Research Station. The poster highlights technology transfer products STREAM has produced to help the field do their job better. The STREAM charter, operating philosophy, and primary objectives are presented, and STREAM staff are introduced. Examples of resources available from STREAM designed to help physical scientist do their job better are given. This includes information about the STREAM Webpage (*www.stream.fs.fed.us*), the Stream Notes newsletter, technical information and training resources, videos, DVDs, publications, and new technology. The National Stream Systems Technology Center is a unique example of collaboration between the National Forest System and Research and Development to make research findings and other information readily available to field specialists.

Monitoring Soil Erosion Following Wildfires in North-Central Washington State

Kenneth J. Radek

Several large wildland fires, caused by lightning storms, occurred in the North Cascades of Washington, on the Okanogan National Forest, in 1992 and 1994. Concerns about the potential for soil erosion led to a monitoring project. Severely burned sites were identified and treated on two of the fires to reduce soil erosion. Soil erosion plots were established on three of the 1994 fires and the 1992 fire to evaluate the amount and duration of soil erosion. Two methods were used to estimate soil loss. One method used metal troughs on small plots to trap soil movement. The second method used erosion pins or stakes to measure soil loss or accumulation. Onsite erosion measurements were conducted for seven years after the wildfire. Erosion rates were highest in 1995, when high intensity storms occurred in the spring and early summer. Normal spring runoff did not appear to cause increases in erosion. Erosion diminished somewhat on most plots following the 1995 event. By the fall of 2000 most of the plots had an adequate vegetative ground cover where soil erosion had diminished or was non-existent. Natural vegetative recovery of groundcover species was key to reducing erosion as time progressed.

Climate Variability and Change in the Southern Appalachians

Mark S. Riedel

Global warming and climate change may cause significant potential impacts to all of life as we know it. While there has been a wealth of research documenting trends and patterns in global and regional climates, debate within the scientific community still rages as to the existence, magnitude, duration and potential causes of these phenomenon. For example, only recently have we recognized that, given historical global climate patterns, much of the global warming trend we are experiencing appears to be natural. Within this context, long-term climatologic records from Coweeta Hydrologic Laboratory (1934 to present) are presented. From these data it is evident that there is a significant amount of natural climatic variability in the southern Appalachians. The natural variability is closely linked to fluctuations in the North Atlantic Oscillation (NAO). For example, the record drought in the southeastern United States, while extreme, was not unusual given historical patterns of alternating wet and dry cycles. These cycles are characteristically preceeded by phase shifts in the NAO. The breaking of the drought by Hurricane Isidore and Tropical Storm Kyle (Sept. 2002) was also consistent with past drought cessation in this region. Apparent trends toward cooler and wetter conditions for this region are consistent with observed behavior in the NAO. While the highly variable nature of climate in this region makes it difficult to identify climate trends, nighttime temperatures (minimum daily) have increased over the past fifty years.

Estimating Impacts of Cattle Grazing on Stream Sediment Budgets

Mark S. Riedel, Kenneth N. Brooks, and Elon S. Verry

Streams in the Nemadji River Watershed of east-central Minnesota are deeply incised in lacustrine clay and glacial till. Due to "recent" glacial activity (~10,000 years before present) and resultant geologic uplift, this region is quite erosive. Indeed, the Nemadji River is the largest source of fluvial sediments to Lake Superior (on both mass and per unit area bases). While natural land cover was dominated by coniferous forests, riparian areas were commonly used for grazing by the late 1800s. To determine the impacts of grazing on sediment yield, we compared morphology and sediment budgets of streams having forested and grazed riparian areas. We surveyed numerous cross-sections on representative study streams over a three-year period. Grazed streams were generally larger, shallower (increased width depth ratio) and straighter (decreased sinuosity) than forested streams. The highly variable riffle-pool structure of forested riparian areas was lost to sedimentation and replaced by relatively uniform profiles in the grazed streams. Using watershed scale sediment budgets and channel morphology, we computed sediment budgets for each study reach. We then computed the minimum amount of erosion necessary to change the morphology of a "typical" forested stream to that of the grazed streams. We estimate

that grazing only 0.01% to 0.1% of the riparian areas increased annual sediment yields by 2% to 9%, over a relatively short period (the grazed streams appear to have stabilized) following the introduction of cattle. While significant locally, these values are orders of magnitude lower than sediment yields from prevalent mass wasting.

Gradient Analysis of Soil, Vegetation, and Climate on the Tonto National Forest

George T. Robertson and W.H. Moir

Ecological site description (ESD) plots contain approximately 150 data elements (mostly soil and vegetation data) that are used in gradient analysis on the Tonto National Forest, Arizona. These ecological data and climate data from NOAA weather stations characterize life zones along a climatic gradient that ranges from low elevation Sonoran desert to high elevation coniferous forests. Gradient analysis is the process used to integrate soil and vegetation with climate. To determine climatic relationships between soils and plant communities, weather station (WS) data are embedded within each life zone. This is accomplished by describing vegetation at or near acceptable weather stations. By including climate data in ordinations, we now see how climatic features, soils and vegetation are distributed within and among life zones. A robust ordering program known as Non-parametric Multivariate Analysis (NMS) in PC-ORD version 4.0, arranges or ordinates ESD and WS data into life zones. NMS is a standard gradient analysis technique developed for analysis of complex, multivariate ecological data. Computer ordination is not by itself definitive in arranging vegetation and soils data along a climatic gradient. Therefore, the final gradient will combine our field knowledge with ordination results.

Rehabilitation of the Left Hand Canyon Dispersed Recreation Area

Theresa Stevens Savery

This project is located on the Arapaho-Roosevelt National Forests, Boulder, Colorado. The Left Hand Canyon Dispersed Recreation Area is an area that has received heavy off-highway vehicle (OHV) recreation use for several decades. **Left Hand** Canyon is in the **Left Hand** Creek Watershed, which is part of the drinking water supply in the Northern Colorado Water Conservancy District, serving millions of people on the Front Range of Colorado. The OHV use had become unmanaged and users were developing new OHV trails weekly. The proliferation of trails caused substantial vegetation and soil loss. This use resulted in the development of several headcuts and gullies ranging from 5 ft to 30 ft deep in a meadow called the "playground" by the recreating public. These gullies had become a main source of sediment in the **Left Hand** Creek Watershed. In 2003 and 2004 the Arapaho-Roosevelt National Forests entered into a partnership with Trail Ridge Runners, Wildlands Restoration Volunteers, and Walsh Environmental to design a restoration project for the "playground" to reduce the amount of erosion and sedimentation occurring in the **Left Hand** Creek Watershed. In April of 2004 the restoration project was implemented through the leveraging of the grant money and the forest was able to restore approximately 14 acres with the help of over 100 volunteers. This poster presentation will show the condition of the recreation area before and the dramatic change after the restoration project and display the efforts of the partners involved. Without the partnerships this project would not have succeeded.

Long-Term Soil Productivity of Western Gulf Coast Loblolly Pine Stands

D. Andrew Scott, John Novosad, and Rodney Peters

Forest management operations have the greatest potential to reduce soil productivity through altered soil porosity and fertility, which are most affected by compaction and organic matter removal, respectively. The objectives of this study were to assess the 10-yr growth response to compaction and organic matter removal and the soil recovery from compaction. We measured tree volume and soil bulk density on four sites in the Kisatchie National Forest in Louisiana and three sites in the DeSoto National Forest in Mississippi as part of the USDA-FS Long Term Soil Productivity project. Three levels of compaction (none, moderate, severe) and three levels of organic matter removal (bole only, whole tree, whole tree and forest floor) were applied in a factorial design at each site, and half of each treatment plot was kept free from competition using herbicides. Soil compaction had no negative impacts on tree growth at ten years, partly due to the rapid recovery of the surface soil from the applied compaction. Removing more organic matter than the boles-only reduced stand volume on five of seven sites by 15 to 30%. This study indicates that harvesting operations that remove tree branches and foliage and site preparation operations that remove the forest floor can have negative impacts on long-term soil productivity.

The Dosewallips Washout: A Reach Analysis Case Study to Evaluate Road Management Solutions and Consistency With the Aquatic Conservation Strategy (ACS)

Bill Shelmerdine and Dan Cenderelli

During the flood of January 2002 approximately 95 meters of Forest Road 2610 on the Olympic National Forest, Washington, was washed out. The Dosewallips River is a key watershed and contains several species of Pacific salmon including the Endangered Species Act (ESA) listed Puget Sound Chinook salmon (*Oncorhynchus tshawytscha*). Over the following 15 months, an interdisciplinary analysis was conducted in order to determine the best solutions for providing access beyond the site. The preliminary assessment suggested that reconstructing the road in its original location, now within the channel of the river, was the preferred solution. Traditional bank hardening methods along with more contemporary structures such as log complexes would be employed. After the initial evaluation it was decided that a more detailed reach analysis was warranted. The analysis concluded that a number of physical and hydrologic processes would be altered if the original preferred alternative were implemented. Analyzing the site in more detail and expanding the scope of the analysis upstream and downstream of the site provided a much better understanding of watershed conditions, processes and potential impacts. Based on the new information, reconstructing the road in its former location was determined to be inconsistent with the Northwest Forest Plan Aquatic Conservation Strategy (ACS) and the alternative was dropped from further consideration. A significant conclusion of this analysis is that traditional approaches and cursory analysis may provide incomplete or misleading results if the scope of assessment is too narrow.

The Olympic National Forest Road Management Strategy–Aquatic Risk Assesment

Bill Shelmerdine, Robert Metzger, Scott Hagerty, and Robin Stoddard

Over the last couple of decades the Olympic National Forest (Washington) has completed numerous road maintenance, stabilization, and decommissioning projects to help restore aquatic conditions. Available funding for such work is far below what is required, resulting in the need to prioritize activities. In 2000 the forest completed a forest-wide Road Maintenance Strategy (RMS) to help us prioritize road treatments to meet multiple resource objectives. The RMS provides a forest-wide framework for integrating road management and watershed restoration. By rating each road based on access needs and potential resource risks, the RMS provides a science-based approach to resource management decisions. Aquatic risk is a critical component of the RMS. Aquatic risk assessment was based heavily on findings from many of our recent watershed analyses. Elements used to determine aquatic risk include: geologic hazard; proximity (delivery) to fish habitat; stream crossing density; riparian zone-stream proximity; and upslope hazard. Aquatic risk is GIS generated and is consistent across the forest. Experience indicates that the aquatic risk assessment is particularly accurate and useful and is a reliable predictor of conditions found on the landscape.

Keeping Water on the Land Longer

Janice Staats

The longer water remains on the land before running off, the more productive that land will be. There are many ways to keep water on the land longer in and near streams. One approach involves working with individuals, institutions and communities to create a common understanding of what riparian-wetland areas need to function properly, and what that means relative to how quickly water moves over and through the land. Through the Creeks and Communities strategy, the USDI Bureau of Land Management and USDA Forest Service, in partnership with the USDA Natural Resources Conservation Service, are helping to create this common understanding by bringing together people of diverse interests and backgrounds to explore the physical attributes and processes (i.e., the interaction of soil/landform, water, and vegetation) that produce values such as clean water, habitat, and other benefits. The concepts of physical function, as outlined in the Proper Functioning Condition (PFC) assessment method, provide this foundation. The PFC method also serves as a communication tool, providing common terms and definitions. By incorporating technical information into collaborative processes, the Creeks and Communities strategy works to ensure that elements of the fundamental sciences are not only incorporated, but help structure the dialogue. This enables diverse stakeholders to craft a common vision that supports the recovery and maintenance of the physical functions that produce important, but often conflicting, public values. As a result of this learning process, people are rediscovering that the largest fresh water storage area in the world is not a lake or reservoir, it is the soil.

Forests on the Edge: Projecting Housing Development on Private Forests Across America's Watersheds

Susan Stein, Mark D. Nelson, Dave Theobald, Ronald E. McRoberts, and Mike Eley

The private working land base of America's forests, farms and ranches is being lost at an increasing rate by conversion to suburban uses. These lands are being converted at the rate of nearly 800,000 acres per year or more than 4,000 acres per day. These trends are affecting the future of private working landscapes and the important habitat and ecological services that they provide. To better understand the contributions of America's private forests to timber, wildlife and water, as well as pressures from development and other ecological factors such as fire, air pollution and insects and disease, the USDA Forest Service has sponsored the "Forests on the Edge" project. This project uses GIS techniques to produce a series of maps of pressures and opportunities on America's private forests for the lower 48 states. Cooperators in this effort include the Forest Service North Central, Southern, and Pacific Northwest Research Stations of the USDA Forest Service, as well as American Farmland Trust and Colorado State University. Phase I of the project has identified watersheds containing substantial forest cover that are likely to experience development pressures, by integrating digital data layers depicting private forest cover and housing density projections out to 2030.

Automated Water Quality Monitoring in the Clackamas River Watershed, Mount Hood National Forest

Ivars Steinblums

The Clackamas River is a public water supply with its source on the Mt. Hood National Forest, serving approximately 175,000 people in the Lake Oswego, Oregon City, and Clackamas areas near Portland, Oregon. Municipal water suppliers expressed a need for real-time turbidity data for the Clackamas River near the Mt. Hood National Forest boundary so they could have early warning of high instream turbidity during storm events. There was also public concern about the potential effects on drinking water quality from the Eagle Creek Timber Sale located on a tributary of the Clackamas River. Automated YSI water quality monitoring sondes were installed on the Clackamas River (December 1999) and Eagle Creek (December 2001) to continuously monitor water temperature, turbidity, conductivity, and pH. Real time water quality data is available via telephone for the Clackamas River monitoring station, with an additional capability to provide early warning by telephone if a pre-set turbidity threshold is exceeded. Monitoring data at the Eagle Creek monitoring site is stored internally for later retrieval and analysis. This poster will display installation methods, operation, and monitoring results and analysis for Clackamas River and Eagle Creek continuous water quality monitoring stations on the Mt. Hood National Forest.

Soil Moisture Monitoring at SNOTEL Climate Stations on National Forest Lands in Oregon and Washington

Sheila Strachan

The Natural Resource Conservation Service Snow Survey program has traditionally monitored mountain snowpack and precipitation for streamflow forecasting. Soil moisture probes have been installed at 17 SNOTEL sites on national forest lands in Oregon and Washingotn. Data are transmitted in real time via the SNOTEL meteor burst telemetry network to the NRCS National Water and Climate Center in Portland and posted on the web for user access. NRCS hydrologists plan to use soil moisture monitoring data to improve their water supply forecasts. Soils that are extremely dry prior to fall snow accumulations are expected to absorb more spring snowmelt, reducing streamflows. The soil moisture profile varies greatly with site and soil type. The Lapine soil on the Winema National Forest (Oregon) is forming in deep air-fall tephra deposits from Mt. Mazama. Soils may never reach saturation and dry out very quickly following snowmelt. In the Wallowa Mountains of Eastern Oregon, the influence of groundwater is apparent at the Mt. Howard SNOTEL site. The Angelpeak soils at Mt. Howard have a deep, ashy over loamy skeletal particle size and are considered well drained. Soil moisture at the 20 inch and 40 inch sensors has been greater than expected since the August 2003 installation.

An Application of the Hillslope Erosion Model (HEM) to Determine Erosion Predictions and Interpretations for Terrestrial Ecosystem Survey (TES)

Steven Strenger, Steve Sebring, and Wayne A. Robbie

The Hillslope Erosion Model [HEM] is primarily designed to predict sediment yield in tons/acre or tonnes/hectare from a particular rainfall frequency such as a 2-year, 24-hour rainfall event. Erosion predictions and interpretations made in the US Forest Service, Southwest Region, however, are based upon temporal soil loss per unit area in tons ac^{-1} y^{-1} or tonnes ha^{-1} y^{-1}. The HEM input values are slope gradient, slope segment lengths, cover percentages and runoff volume. Average slope gradient and cover percentages are obtained from data summarized in Terrestrial Ecosystem Survey [TES] reports and databases. Slope segment length is obtained on-site or from topographic maps. The runoff volume value used in the HEM is derived from the SCS Curve Number

Method. For most curve numbers used in the Southwest, a rainfall of one inch or more is required to produce runoff and resulting erosion. NOAA weather stations provide data on the number of days per year rainfall is equal to or greater than one inch. Data is also provided on the maximum recorded rainfall for each day of the year. By knowing an average rainfall amount equal to or exceeding one inch, the number of days per year this occurs, average slope gradient, slope segment lengths and average cover percentages, average annual erosion rates can be estimated and interpretations made for TES map unit components using the HEM.

A Comparison and Evaluation of Stream Substrate Embeddedness Techniques

Traci L. Sylte

"Embeddedness" or "cobble embeddedness" are terms used to describe fine sediment deposition surrounding larger surface substrates, and have been used as an indicator of substrate habitat conditions. Despite considerable controversy in the early 1990s on its validity, embeddedness remains a measure employed in various studies across the nation and in some regulatory environs. Although descriptions and protocols have emerged in high profile publications, the meaning of embeddedness and its metric are commonly misunderstood, and most documentation necessary for field application of measured embeddedness methodology exists in gray literature or office files. Fundamental problems exist in one methodology and errors and inconsistencies occur between guidance documents. Although measures from the various techniques are typically accepted to accurately portray embeddedness, statistical variance between methods was significant, and was substantially larger than variance between controlled, similar sites. Embeddedness varied by method, calculation technique, streambed composition, and observer. Embeddedness was found to be only weakly correlated with other common bed surface measures. A combination of physical processes are likely responsible for conditions referred to as embeddedness, and predicting embeddedness with any one variable, or linking it directly to biological criteria, is unlikely and not feasible at this time given the current level of understanding and measurement methods. Although very worthy in concept, this study suggests that embeddedness determinations should be used only for general characterization purposes at this time. However, potential exists for methodology improvement, and suggestions for further research and application development are offered.

Dunham Creek Rehabilitation: Early-Day Riparian Harvest Gone Bad-The Consequences, the Remedy, and Highlight for Riparian Health Management First and Foremost

Traci L. Sylte

Photos help recollect the story of almost a mile of riparian harvest in the mid-1960s in Dunham Creek, a tributary of Montana's Blackfoot River basin. Then, a road and bridge bisected the area, where activities targeted large spruce trees and spanned the entire valley bottom. Shortly after removing all trees and understory, the high bedload, C4 stream unraveled. During the early 1970s, well-intentioned stabilization attempts channelized, bermed, and reshaped the channel into a trapezoidal character. In 1998, remnants of the berms existed, the bridge had washed out, bank erosion was magnitudes above natural levels, the channel was braided and 150 feet wide in many locations, and sediment loads threatened fisheries and downstream facilities. Although slowly recovering, projections of attaining natural stability were 50-100 years into the future, which was unacceptable to multi-entity bull trout (*Salvelinus confluentus*) recovery efforts in the basin. With funding, collaboration, or both from at least eight entities, Lolo National Forest water resource personnel designed and implemented a detailed rehabilitation plan that will stabilize the reach for at least 10-15 years until vegetation is re-established. To foster favorable stream values, the District Ranger decided to use an alternative travelway and abandon the existing road and bridge. Today, the project highlights the importance of considering riparian values first and foremost in all management activities and how trained personnel can successfully employ Rosgen's geomorphic and other environmental river mechanic design approaches in a very cost-effective manner. After several high flow events, the stream is functioning as intended and studies have already shown increased fish populations.

Analysis of Relationships of Stream Shading vs. Vegetation Density and Spectral Radiance

Bárbara Gutiérrez-Teira, Charles H. Luce, and David Nagel

Solar radiation is the dominant factor controlling stream temperatures. Attempts to evaluate or model stream temperature patterns and impairment over river basins require estimates of shade for extensive areas. It is generally not feasible to collect such information from the ground, and methods are needed to estimate shade from remotely sensed data. As a first step to develop a shade model, we analyzed the relationships between shade values in specific stream reaches and vegetation density, and between shade

and remotely sensed imagery values. Shade is evaluated through solar radiation, obtained with hemispherical canopy photos at each site. Reflectance values from Landsat Thematic Mapper imagery were obtained and different combinations of values from different bands, together with known vegetation indices, are correlated with total radiation. Although the main purpose of these relationships is to obtain an average that can be extrapolated to greater areas, the results are not as reliable as needed for the mapping, mainly due to the great ratio between the pixel size and the area sampled by the hemispherical photography. Other alternatives such as spectral unmixing are explored.

Sediment Transport and Production From Two Small Watersheds in Central Idaho

Robert Thomas, John King, Robert Kenworthy, and Nick Gerhardt

Sediment production from forested watersheds is useful to land managers in evaluating the effects of management activities or natural events, comparison of different watersheds, evaluating and refining existing models and tools, and determining channel maintenance streamflow requirements. Sixteen years of bedload and suspended sediment transport and seasonal (1 April to 30 September) streamflow data were used to estimate annual sediment production for two small watersheds in central Idaho on the Nez Perce National Forest. Missing streamflow records (1 October to 30 March) were estimated using regression relationships with a downstream USGS gaging station. A locally weighted regression technique (LOESS) was used to develop relationships between logarithms of sediment transport and logarithms of stream discharge. The LOESS relationships were used with the mean daily streamflow records to estimate annual sediment production. This approach resulted in relationships with less variance and smaller bias correction factors than more traditional techniques. We evaluate and discuss time trends in sediment production and compare our sediment production estimates with predictions from a sediment yield model (NEZSED) used as a planning tool by the Nez Perce National Forest.

Integrated Forest Plan Monitoring Program: Tongass National Forest Riparian and Aquatic Synthesis

Julianne Thompson and Emil Tucker

Since 1997 resource managers on the Tongass National Forest, southeast Alaska, have struggled to address at least nine separate forest plan monitoring questions through a dozen or more discrete protocols pertaining to watershed resources (soils, wetlands, riparian areas, streams, water quality, and fish). A few protocols have several years of data, some are still in pilot or development stages, and other protocols specifically listed or inferred in the Forest Plan have been ignored. This aquatic synthesis considers the forest plan monitoring questions as an integrated package of watershed monitoring that includes stream, riparian, and upland response indicators (both biological and physical). Stream, riparian, and upland attributes will be monitored in watersheds throughout the Tongass National Forest. These watersheds include a set of case-study watersheds that will be instrumented and intensively monitored as well as a subset of existing monitoring sites tracking physical and biological response indicators that will be periodically remeasured. By aggregating existing projects and focusing our sampling efforts, the riparian synthesis will allow us to tease apart anthropogenic effects on the proper functioning condition of small watersheds from the dynamic disturbance regime naturally present in these young post-glacial systems, and to evaluate ability of the standards and guidelines set out in the forest plan to insure the continued health of our watershed resources. Our presentation focuses on the development of the riparian and aquatic synthesis, the complexities of watershed monitoring in a remote and dynamic rainforest environment, and preliminary information after the first season of instrumentation.

Real-Time Smoke Monitoring–Current Instrument Evaluation and Telemetry Systems

Andy Trent

One mission of the USDA Forest Service, Missoula Technology and Development Center (MTDC) is to evaluate commercially available, real-time, particulate monitors. These monitors provide forest managers, fire and air quality specialists with information on smoke concentrations generated from burning biomass. Airborne particulates, especially those particles smaller than 2.5 microns in diameter ($PM_{2.5}$), pose potential health, visibility, safety and nuisance problems. Measurement of these airborne particulate concentrations is very important to the Forest Service and other land managers as the use of managed forest and rangeland burning increases. Recently, MTDC conducted an evaluation of several new real-time particulate monitors. Included were the E-BAM and E-Sampler manufactured by Met One Instruments, Inc. and the Dataram 4, manufactured by Thermo Electron Corp. The key items of the evaluation were determining the accuracy of each monitor when measuring or estimating smoke concentrations, comparing results from like instruments (inter-instrument comparison), reliability, operational characteristics such as portability, power

requirements, data collection, and cost. Additionally, a satellite telemetry system has been developed to transmit data from each instrument to display the smoke concentration data in near real-time on a Web page. The Interagency Real-Time Smoke Monitoring Web page displays the smoke concentration data, along with any other meteorological data associated with the monitor. The Web page also displays historical information for each monitor. The telemetry system uses the ORBCOM low-orbiting satellite system to transmit the data.

Effects of Prescribed Fire on Mercury Concentrations in Water and Fish in the Larch Lake Watershed, Superior National Forest, Minnesota

Trent R. Wickman

Because of its persistence and wide dispersal in the environment and its ability to bioaccumulate in organisms, mercury (Hg) is a contaminant of great concern worldwide. Although scientists are beginning to understand the Hg cycle in forested systems, little is known about the role of wildland and prescribed fire in the Hg cycling processes. The North Central Research Station and the Superior National Forest, Minnesota, have started to fill these data gaps by establishing a plan to monitor mercury changes during fuel reduction efforts in northeast Minnesota. The Larch Lake watershed, partially located in the Boundary Waters Canoe Area Wilderness, is in the process of fuel reduction efforts in response to a major blowdown event that occurred in 1999. The Larch Lake watershed is a headwater system of about 2100 hectares in size. Almost the entire watershed is planned to be, or has been, burned. Total and Methyl Hg in water were measured along with standard physicochemical variables both pre- and post-treatment. Stream sampling was also intensified during the spring snowmelt following the most recent treatment. Tissue Hg concentrations in young-of-year smallmouth bass (*Micropterus dolomieu*) were also analyzed for the pre-burn (baseline) period; post-burn samples will be taken for a several year period after treatment to understand any potential bioaccumulation timelines. These data will provide a better understanding of how Hg is delivered to streams and lakes, how long it takes Hg to accumulate and then decline in organisms within the watershed, and the management implications of these findings.

State Water Quality Exceedence: Fecal Coliform and *E. coli*

Kirk Wolff

Currently, within the US Forest Service Region 2 (Rocky Mountain Region) there are three stream segments in Wyoming listed on the State 303d list for exceedance of fecal coliform/*E. coli* bacteria. One stream is on the Big Horn NF. On the Medicine Bow NF within the Pole Mountain grazing area there are two stream segments which have exceeded state water quality standards for fecal coliform/*E. coli* for the last two years. On the Routt NF in northwestern Colorado we sampled water samples from three streams on three different grazing allotments for *E. coli* bacteria and analyzed them in-house. We sampled streams on the Routt because of public comments on our scoping documents during the NEPA phase of AMP revisions and because of the ongoing fecal coliform results on Pole Mountain. We had limited data or out-dated information on this water quality parameter, so we purchased the equipment to do our own analysis for the Routt based upon EPA guidelines. The results of this lab analysis have shown exceedence in *E. coli* on two of the streams. We have been in contact with the Colorado Water Quality Control Division since we became aware of the situation. A BMP monitoring field trip is planned in early June with the Colorado agency and the FS to review grazing and riparian BMPs within one of these allotments. Colorado has no interest in listing these streams on the state 303d list. Their perspective is different from the Wyoming Department of Environmental Quality (WYDEQ). On the Medicine Bow NF in Wyoming we have been working with grazing permittees, the WYDEQ, multiple Conservation Districts, and other interested stakeholders. We are in the process of developing a new monitoring plan based upon last summer's results with the stakeholder group. The dialogue has been started for doing a watershed management plan with the local conservation district. In the interim, a local environmental group, Biodiversity Conservation Alliance, has issued a Notice of Intent to sue. The forest has been working with Office of the General Council and Department of Justice lawyers. There is no definitive DNA test that can be performed to determine the source of *E. coli* bacteria. Potential candidates are all warm blooded organisms. We feel that this is an emerging issue that has the capability to adversely affect domestic livestock grazing on NFS land throughout the West.

Development of ELTP Layer for the Hoosier National Forest, Southern Indiana

Andrey V. Zhalnin, George R. Parker, and Patrick C. Merchant

One of the critical components of decision making in natural resource management is ecological information. The US Forest Service adopted a national ecological classification hierarchy in 1993 with the ELT (ecological land type) and ELTP (ecological land type phase) forming the lower levels of the hierarchy. This study examines the

potential of computer mapping ELTPs for the Hoosier National Forest (HNF) located in southern Indiana. An extensive ELTP sampling was performed in 2001 and 2002 within the four units of the HNF that are situated within the Brown County Hills and Crawford Upland subsections according to the eastern United States classification. We developed an ecological classification for the forest in 1993 that includes six ELTs and sixteen ELTPs total for both subsections. Another study mapped the forest ELT layer based on physiographic conditions using GIS tools. The most important factors affecting classification at ELTP level were soil A-horizon depth and vegetation composition. We hypothesized that ELTPs can change within a single ELT map unit, vary spatially from region to region, or both. We performed an extensive ELTP sampling to find possible correlations with landscape physiography as well as to refine classification, throughout all four units of HNF in 2001 and 2002. Analysis shows a correlation between soil survey mapping units and some ELTPs, which aids in prediction of spatial distribution of ELTPs. Results produced an ELTP map for the HNF as well as providing the basis for development of Land Type Associations (LTAs) using a "bottom-up" approach.

Section III. Index to Authors

Volume I comprises pages 1-288; Volume II comprises pages 289 and above.

Author	Pages
Allison, Bonnie	547
Almy, John M.	522
Amatya, Devendra	180
Archuleta, J.	545
Bachmann, Steve	559
Baichtal, J. F.	111
Bayer, Kevin	549
Beattie, Byron	173
Beilharz, Margaret	545
Bengeyfield, Pete	69, 85
Bennett, Karen	516
Bevenger, Gregory S.	546, 562
Bezares, Saul	547
Bian, Xindi	60
Bisson, Pete	561
Bolton, Susan	561
Brooks, Kenneth N.	563
Brown, Thomas C.	458
Bruggink, Jeff	20, 546
Busskohl, Craig R.	546
Butcher, Jason	555
Bytnerowicz, Andrzej	43
Cain, Thomas C.	94, 428
Carpenter, Constance A.	475
Carr, Mary A.	478
Cenderelli, Dan	565
Charney, Joseph J.	60
Cisneros, Ricardo	43
Clarkin, Kim	546
Clifton, Catherine F.	iii, 7
Clinton, Barton D.	197
Coffin, Bengt	547
Connolly, Stephanie J.	428
Cook, Carolyn	297
Cummins, Ken	118
de la Fuente, Juan	547, 548, 559
DeGraff, Jerome V.	352
Dolanc, Christopher R.	217
Doyle, James	291, 547
Dresser, Adam	297
Eads, Rand	548
Eagan, Sean M.	217
Eckardt, Sara	548
Edwards, Pamela J.	94, 428
Edwards, Rick	554
Eilers, Joseph	102
Elder, Don	548, 550
Eley, Mike	566
Ellis-Sugai, Barbara	279, 551
Entwistle, Deborah	549
Fallon, Don	549
Fedora, Mark A.	255
Fenn, Mark E.	549
Firor, Susan	550
Fisk, Haans	549
Franks, Earle	352
Fryxell, Jenny	232
Furniss, Michael J.	iii, 550
Gagen, Charles J.	94
Gerhardt, Nick	568
Glasser, Stephen P.	166, 451
Goldsmith, Gala	331
Gonyer, Leslie S.	550
Grant, Gordon E.	391
Gubernick, Robert	401, 550, 562
Guldin, James M.	341
Guntle, Jeff	550
Gutiérrez-Teira, Bárbara	567
Haessig, Polly	548, 550
Hagerty, Scott	565
Hairston-Strang, Anne	537
Hall, Jennifer	549
Hansen, William F.	76, 550, 556
Harris, Robin M.	7
Hazelhurst, Sherry	244, 551
Heffner, Ken	244
Heilman, Warren E.	60
Helvey, J. David	205
Helzner, Ronnie-Sue	551
Higgins, Dale	548, 559
Hilton, Sue	547
Hixson, Suzan	546
Hogervorst, Johan	279, 551
Holm, Melody R.	551
Hubbert, Ken	552
Huber, Cindy Mitchell	421, 552
Hudnall, Wayne H.	562
Hunsaker, Carolyn T.	217
Hyde, Kevin	552
Ilhardt, Bonnie	i, 261
Jackson, Gary L.	553
Jasso, Abel	559
Jefferson, Anne	391
Jemison, Roy	547, 553
Johnson, Adelaide	554
Johnson, Al	554
Johnson, Chad R.	217
Jones, Mikeal	102
Jurgenson, Marty	545
Kanaan, Ken	549
Kann, Jacob	102
Kaplan-Henry, Terry A.	27
Karr, M.	545
Keller, Gordon	546, 554
Kenworthy, Robert	568
Keppeler, Elizabeth	191, 548, 557
Ketcheson, Gary	291
King, Allen	555
King, John	568
Knopp, Chris	227
Koler, Tom	555
Kolka, Randy	555
Kozlowicz, Benjamin R.	556
Law, Dennis L.	76, 556
Lefevre, Robert E.	556
Leichty, Hal	558
Leland, Carl	558
Lentz, Rodney T.	368
Leuelling, Barb	556
Lewis, Jack	191, 548, 557
Lewis, Sarah L.	391
Lisle, Tom	118, 547, 557
Llanos, Antonio	550
Loomis, Grant	157, 557
Love, Michel	550
Lucas, Walt	133, 557
Luce, Charles H.	567
Luckow, Kenneth R.	341, 558
Lynch, Marie E.	217
MacDonald, Lee	549
Madej, Mary Ann	118
Mainwaring, Tom	558

Author	Pages
Marion, Daniel A.	558
Martin, Richard	157
Mase, Sarah E.	558
Mathews, Mike	507
McCammon, Bruce	i
McDonnell, Jeffrey J.	205
McLean, Holly R.	513
McNamara, Michael L.	145
McRoberts, Ronald E.	566
Merchant, Patrick C.	569
Metzger, Robert	565
Miller, Alisha	547, 559
Mineau, Jim	559
Moir, W.H.	564
Mondry, Zackary	560
Moody, Tom	557
Movassaghi, Greta	478
Moynan, Kathleen	550
Muir, Mark	561
Nagel, David	567
Napper, Carolyn	318, 561
Neary, Dan	561
Nelson, DeVon	546
Nelson, Karen	561
Nelson, Mark D.	566
Novosad, John C.	331, 562, 564
Olson, Brenda	547
Oswald, Liz	363, 562
Palik, Brian	555
Parker, George R.	569
Paustian, Steven	401
Peters, Rodney	564
Philip, Noel S.	562
Porth, Laurie	562
Post, Tim	237
Potter, Brian E.	60
Potter, Deborah Ulinski	421
Potyondy, John	136, 562
Procter, Trent	43, 50
Prudente, Jacqueline A.	562
Prussian, Katherine M.	111
Quayle, Brad	43
Quinones, Rebecca	547
Radek, Kenneth J.	563
Riedel, Mark S.	197, 563
Roath, Brent	352
Robbie, Wayne A.	566
Robertson, George T.	564
Robichaud, Peter R.	3, 36, 552
Robison, Tom	53
Ronnenberg, Kathryn L.	iii
Rose, Edward K.	550
Ryan, Sandra E.	383
Ryder, Roger	237
Sams, Charles E.	438, 552
Savery, Theresa Stephens	564
Schmidt, Larry J.	173
Scott, D. Andrew	331, 564
Sebring, Steve	566
Seibert, Jan	205
Shafiqullah, Salek	556
Shellhorn, Gary	522
Shelmerdine, Bill	310, 565
Sherar, James	554
Sheriff, Steven D.	562
Sims, Bruce	227
Smith, Kristine	261
Smith, Mark E.	556
Snavely, William	550
Sorkin, Jeff	551
St. Clair, Larry	553
Staats, Janice	565
Stacy, Andrea	552
Stein, Susan	566
Steinblums, Ivars	566
Stoddard, Robin	565
Strachan, Sheila	566
Strenger, Steven	566
Sullivan, Tim	133, 145
Swift, Lloyd W., Jr.	197
Sykes, Karen	237
Sylte, Traci L.	567
Tangenberg, Scott	467
Tannaci, Tuli	559
Tarpley, Rachel	555
Tepp, Jeff	556
Theobald, Dave	566
Thomas, Robert	568
Thompson, Julianne	232, 568
Trent, Andy	568
Trettin, Carl	180
Tucker, Emil	568
Ulinski Potter, Deborah	421
Vache, Kellie B.	205, 554
Velasquez, Jose	547
Verry, Elon S.	563
Vestal, Jeremy S.	428
Vose, James M.	197
Warhol, Terry	546
Weinhold, Mark	271
Welsch, Dave	237
Wickman, Trent	555, 569
Wilson, Janice	551
Winthers, Eric	549
Wissmar, Robert	561
Wohl, Ellen	363
Wohlgemuth, Peter M.	36, 552
Wolff, Kirk	569
Wondzell, Steven M.	7
Woodsmith, Richard D.	205
Wormstead, Sherri	475
Zhalnin, Andrey V.	569

Section IV. Conference Organizers and Producers

Advancing the Fundamental Sciences
A Conference for Forest Service Physical Sciences
October 18-22, 2004, San Diego, CA

Steering Committee: Bruce McCammon, Chair; Bonnie Ilhardt, Co-Chair; Steve Glasser, and Russell LaFayette

Registration: Sherry Hazelhurst, Chair; Connie Athman, Timothy Evans, and Lori Wilson

Website: Michael Furniss

Posters: Steve Howes, Chair; Joni Brazier, Connie Carpenter, Dave Dechane, Betsy Reifenberger, and Ruth Tracy

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Awards & Events: Trish Carroll, Chair; Courtney Cloyd, Michael Collette, Michael Furniss, Steve Glasser, Chris Knopp, Mike McNamara, John Rector, Ken Roby, Wes Smith, Robin Stoddard, John Thornton, and Mark Weinhold

Proceedings: Michael Furniss, Chair; Catherine Clifton, and Kathryn Ronnenberg; Jeff Guntle, CD-ROM

Pinchot Institute for Conservation: Stephanie Kavanaugh, Jennifer Becker, and YenieTran

"The Life and Times of Forrest Stump": Karen Bennett (Angry Citizen), Corrine Black (Sally Mander [ID Team Wildlife]), Jerry Boberg (Bob Dylan), Joni Brazier (Coffee Person), Trish Carroll (Thought Bubble Lady), Alan Clingenpeel (FS Employee & Bernie Stokes [ID Team Fire]), Carolyn Cook (ID Team Leader), Mike Derring (Clint Eastwood), Mark Fedora (Yogi Berra), Michael Furniss (Forrest Stump; writer; montage music), Bob Gubernick (Woody Grove [ID Team Forester]), Polly Hays (Flo), Roy Jemison (Dr. Uncertainty), Terry Kaplan-Henry (Mary Mayor), Chris Knopp (News Anchor & Smokey Bear; writer), Russel LaFayette (Venue Liason), Bruce McCammon (slideshow production), Mike McNamara (The Minstrel; writer), John Rector (shotgun mike), Ken Roby (writer; FloMo Commercial Announcer & video testimonials), Kathryn Ronnenberg (Director, scenic backdrops, photo montages, writer), David Salo (Chip Stone [ID Team Archeology] & Smokey Bear), Larry Schmidt (Frank Cyprinid), Wes Smith (Stage Manager), Adam Solt (Stage Manager), Brian Staab (Eddie), Robin Stoddard (Stranger at the Bus Stop, props and wardrobe) Traci Sylte (Ranger Jane), John Thornton (Walter Aware, Sleepy Pete, Spock), Al Todd (Hank Lakewood), Mark Weinhold (Ranger Dan; writer)

Section V. Manuscript Reviewers

The following people made significant contributions to the Proceedings as technical manuscript reviewers. Sixty-two manuscripts were each independently reviewed by two or more subject matter experts. Their time and expertise in providing careful review, critique, and constructive comments added greatly to the quality and credibility of the final proceedings.

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Section VI. Contents of Multimedia CD-ROM

About the Advancing the Fundamental Sciences Portable Electronic Presentation CD

The CD in the inside back cover is an interactive learning resource that presents many of the Conference plenary talks and two of the workshops in an electronic format. The format provides for interactive access: you may watch them start to finish, or just the parts that most interest you.

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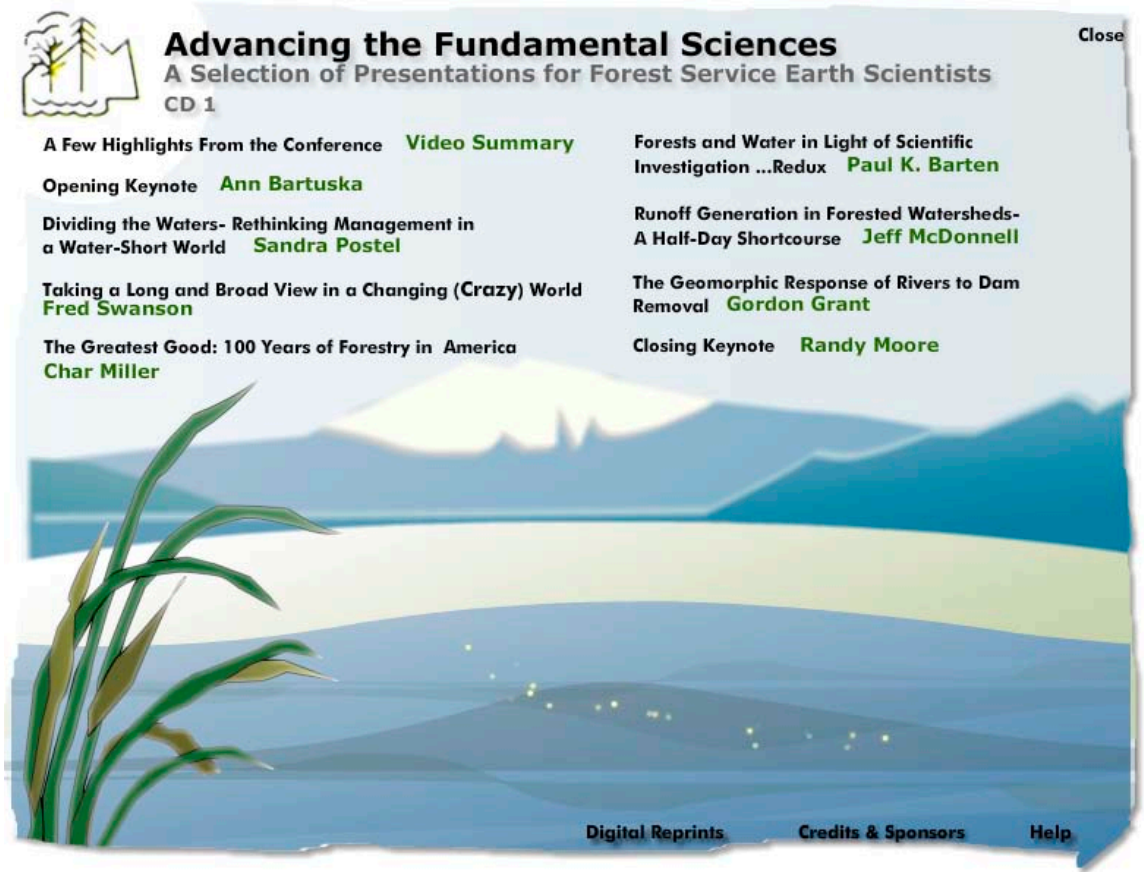

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