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Land Stewardship in the 21st Century: The Contributions of Watershed Management

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Abstract

The purpose of this conference was to increase awareness through exploration and evaluation of global, national, and regional perspectives about the potential contributions that watershed management can make to the conservation, sustainable development, and use of natural resources in ecosystem-based land stewardship in the 21st century. The conference consisted of 2 and a half days of synthesis papers. These papers were presented in plenary sessions and prepared by invited speakers from public and private research, management, and educational organizations. Over 50 poster papers complemented the synthesis papers to broaden the conference scope.

Keywords: land stewardship, watershed management, ecosystem-based management, natural resources, conservation, sustainable development, sustainable use

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Land Stewardship in the 21st Century: The Contributions of Watershed Management

Conference Proceedings **Tucson, Arizona** **March 13 – 16, 2000**

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Southern Arizona Chapter, Southwestern Section of the Society of American Foresters

IUFRO Working Party 8.04.04, Erosion Control by Watershed Management

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We thank Leonard DeBano, a member of the watershed resources faculty in the School of Renewable Natural Resources, who willingly accepted the task of soliciting and then organizing the poster sessions for the conference. These poster presentations were crucial in supplementing and expanding on the synthesis papers presented. We thank the authors of the synthesis papers for accepting our invitation to participate in this conference, and comprehensively covering their topics to provide a benchmark for land stewardship into the 21st century.

The timely publication of the conference proceedings is attributed to the exemplary efforts of Madelyn Dillon and Karen Mora of the Rocky Mountain Research Station, USDA Forest Service. Their efforts, and the long hours they spent helping to make these proceedings a quality publication will long be remembered. We are grateful to Carl Edminister for furnishing the necessary financial support for publication of these proceedings through the Borderlands Ecosystem Research Project of the Rocky Mountain Research Station. Thanks are also extended to Carol LoSapio of Beyond Words for timely and quality layout.

Financial, logistical, and other forms of support provided by the sponsors of the conference are gratefully acknowledged. This support ensured participation in the conference by the widest possible audience of interested people.

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Peter F. Ffolliott
Malchus B. Baker, Jr.

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CONFERENCE OPENING

Overview

Peter F. Ffolliott[1] and Malchus B. Baker, Jr.[2]

Abstract.—The purpose of this conference was to increase people's awareness of the potential contributions of watershed management to conservation, sustainable development, and use of natural resources to land stewardship in the 21st century. Through exploration of global, national, and regional perspectives, a review of issues likely to be confronted in the coming century, a retrospective viewpoint of watershed management entering the 21st century, anticipated watershed management contributions to future land stewardship, and future protocols necessary to attain these contributions, information was provided to accomplish the conference purpose. The conference included 2 and a half days of synthesis papers presented in plenary sessions by invited United States and international speakers from public and private research, management, and educational organizations. Two poster sessions complemented the synthesis papers to broaden the conference scope.

Introduction

To meet a growing population's need for conservation, sustainable development, and use of natural resources, land stewardship effectiveness must improve in the 21st century. Ecosystem-based, multiple-use land stewardship is necessary to present and potential future uses of natural resources on an operationally efficient scale. Holistically planned and carefully implemented watershed management practices, projects, and programs will always be needed to meet the increasing demand for commodities, amenities, clean water, open space, and uncluttered landscapes in the 21st century.

Watershed Management

Watershed management means different things to different people. Even watershed managers have different perspectives about what watershed management entails, and how it should be accomplished. It was important, therefore, that a perspective of watershed management be adopted before the conference to enable presenters of invited synthesis papers and contributed poster papers to focus their contributions. This adopted watershed management perspective is in the following definitions and concepts (Brooks et al. 1992, 1994, 1997).

Watershed - a topographically delineated area that is drained by a stream system; also a hydrologic-response, a physical-biological, and a socioeconomic-political unit for management planning and implementation purposes; a smaller upstream catchment that is part of a river basin.

River basin - similar to a watershed but larger in scale.

Watershed management - the process of organizing and guiding land and other resource use on a watershed-basis to provide the goods and services demanded by society while minimizing adverse impacts to soil and water resources. This concept recognizes the interrelationships among soil, water, and land use, and the linkages between uplands and downstream areas.

A common misconception is that watershed management is based only on physical interrelationships. Watershed management also involves economic and institutional interrelationships. Keeping this in mind helps to guide design practices and institutional mechanisms needed to implement more effective watershed management practices for better land stewardship.

Watershed management practices - changes in land use, vegetative cover, and other nonstructural and structural actions on a watershed that achieve ecosystem-based, multiple-use watershed management objectives. Integrated concepts and operational applications of watershed management provide a framework for the conservation, sustainable development, and use of natural resources. Watershed management practices are the tools that make the framework operational.

Synthesis Papers

The conference consisted of 2 and a half days of synthesis papers presented by invited speakers from the United States and international public and private research, management, and educational organizations. These papers were presented in plenary sessions on global, national, and regional perspectives of watershed management, a

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review of land-stewardship issues likely to be confronted in 21st century, a retrospective viewpoint of watershed management entering the 21st century, anticipated watershed management contributions to future land stewardship, and future protocols necessary to attain these contributions.

Watershed Management Perspectives

The role of watershed management in moving toward conservation, sustainable development, and use of natural resources was considered in a series of invited papers presenting global, national, and regional perspectives of watershed management. The regional paper focused on past, present, and future watershed perspectives in the Southwestern United States, which was the conference setting. Issues of concern, lessons learned, and future directions that might be followed to promote watershed management were also reviewed. It was thought that successful watershed management will advance because organizations responsible for its use as a land management strategy are highly adaptive, constantly seek new information sources, and effectively use processes that foster innovation.

Issues to be Confronted in the 21st Century

Global and national issues, and issues in the Southwestern United States that are likely to be confronted in the 21st century when implementing watershed management practices, projects, and programs were the topics of a second series of invited papers. Many issues discussed in this series concerned the current status and success and the future of the watershed management planning process. This planning process is complex and often difficult to understand due to physical, biological, and social interactions, which are the foundation of watershed management. The point was made that society has a responsibility to act together to conserve natural resources and to preserve their integrity for future generations. The outcome of this joint effort is sustainability.

Case Studies

Contributions of watershed management research to land stewardship in the United States and internationally were reviewed in a series of case studies that reinforced information presented in the earlier papers. Management-oriented research to learn more about the effects of natural and human-induced disturbances on the functioning, processes, and components of ecosystems in the regions of the United States and internationally was described in these synthesis papers. To this point in the conference, the papers presented provided background to presenting a retrospective viewpoint of watershed management.

A Retrospective Viewpoint

Evolving perceptions of watershed management from the ancient concept discussed in Indian texts dated from 1,000 B.C. to that expressed in 19th and late 20th century texts, permitted a comprehensive review of the watershed lesson learned in the past 100 years. Advances in computer technologies in recent years to facilitate storage, retrieval, and summarization of historical natural resource-based data sets for use by watershed researchers, managers, and decision makers were illustrated to the conference participants through computer demonstrations. Other emerging tools and technologies for the capture, storage, and use of spatial data sets for improving the scientific understanding of watershed processes were also demonstrated. The importance of socio-cultural perspectives regarding development of watershed management partnerships between public and private sectors in the 21st century were next examined.

Contribution to Future Land Stewardship

Securing clean water has been and will continue to be a significant watershed management contribution to land stewardship. Generally, agencies have taken a regulatory approach to meeting this goal; however, at this conference it was suggested that, in recent years, a government trend has been to move decision making and action taking to the local level. Another paper emphasized that watershed management will contribute to land stewardship by sustaining physical and economic flows of crucial natural resources into the coming century. Maintaining the future health and stability of sensitive riparian ecosystems through the watershed-riparian connection is another important contribution of watershed management. The historical adverse impact of people on riparian sites through their action on surrounding watersheds was examined. Maintaining landscape integrity through restoration of degraded riparian ecosystems was discussed in a case study on the White Mountain Apache Reservation in Arizona.

Future Protocols

Future watershed management protocols will probably focus on anticipating future watershed conditions, responding to increased demands for water and watershed resources, and then implementing the appropriate effective policies. The conference dealt broadly with watershed and natural resources management and with the multiple outputs from this management. However, the authors of one paper felt, like others, that water will be a key land stewardship issue in the 21st century. Furthermore, these authors believe that water will be a unifying theme drawing integrated watershed management elements together. However, new, effective policies that incorporate ecological understanding into their structure and promote democratic ideals will be necessary. Authors of the concluding synthesis paper identified guidelines to achieve this end. Guidelines included immediate integration of the political process, building bridges to citizens, reexamining laws, rights, and responsibilities, strengthening administrative capacity, and looking beyond the watershed to a broader scale.

Contributed Poster Papers

Fifty contributed poster papers supplemented and expanded on the synthesis papers. These poster papers reported on the results of watershed-related research projects, applied watershed management activities, and innovative technology transfer mechanisms for watershed-based information.

Watershed-Related Research Projects

Poster papers on watershed-related research projects included studies of vegetation relationships, the role of dendrochronology in natural resources management, erosion and sedimentation processes, riparian ecosystems and wetlands, fire effects on ecosystem processes, simulation techniques, and mathematical modeling. A poster paper on a research-support program for enhancing ecosystem management along the United States-Mexico border was also presented. A paper on the International Arid Lands Consortium, a partnership of organizations dedicated to research, education, and training activities relative to the development, management, and restoration of arid and semi-arid lands throughout the world, and programs the consortium has supported in water and watershed management was included in this group of poster papers.

Applied Watershed Management Activities

Applied watershed management activities were illustrated by poster papers on implementing watershed management practices to meet specified goals, the role of agroforestry interventions on watershed lands, erosion and sedimentation control, restoration of riparian ecosystems and wetlands, impacts of fire on the management of watershed resources, and a variety of operational watershed management programs in the United States and internationally. Included in these poster papers were examples of management programs and monitoring activities on a regional government's approach to natural resources management planning, challenges of coastal management in Baja California, and applications of remotely-controlled vehicles in Taiwan to monitor changes in watershed land-use. Other international programs on water and watershed management were also presented.

Technology Transfer Mechanisms

Applications of geographic information systems and the use of the World Wide Web in making watershed-related information more accessible to practitioners were the focus of a series of poster papers on technology transfer mechanisms. Demonstrations on accessing watershed management information from the World Wide Web were presented to conference participants, who were encouraged to interact with the systems illustrated.

Watershed management's need to have a central "voice" to gain the attention of political, agency, university, and business leaders was addressed in a poster paper about increasing the visibility of watershed management as a land management profession. As part of this presentation, a questionnaire was available to conference participants, soliciting their thoughts on the need to heighten the visibility of watershed management as a land stewardship discipline.

Conference Contributions

The conference provided a forum for researchers, resource specialists, managers and practitioners, decision makers, and other interested people to share their experiences, opinions, and knowledge about the contributions that watershed management can make to improve land stewardship in the 21st century. The conference presenters updated the state-of-knowledge on a wide range of watershed management and practices topics in the United States and internationally. This conference and the published proceedings represent a beginning for planning and implementing watershed management practices, projects, and programs leading to improved land stewardship in the 21st century.

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Contributions of the College of Agriculture, University of Arizona, to Education, Research, and Technology Transfer in Watershed Management

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Abstract.—The College of Agriculture, University of Arizona, has been heavily involved in providing research, education, and outreach concerning the management of watersheds. The Barr Report of 1956, a cooperative effort of the Salt River Project, the State Land Department and the University of Arizona, was a significant beginning that addressed the productivity of watersheds in the state and a plan of action to enhance water flows. Out of this initial effort came the formation of the Arizona Watershed Program, a state program that began to focus on watershed management activities in Arizona. Realizing the need for the university's involvement in the Arizona Watershed Program, the Arizona Board of Regents established the Department of Watershed Management at the University of Arizona, and a forestry program at Arizona State College (now Northern Arizona University) in 1958. The Department of Watershed Management became part of the School of Renewable Natural Resources in 1974, and now offers BS, MS and PhD degree programs in watershed management that are internationally recognized.

Introduction

The College of Agriculture, University of Arizona, has a long history of contributions to education, research, and technology transfer in watershed management. These contributions started with providing a leadership role in the preparation of the report that lead to formulation of the Arizona Watershed Program in the early 1960s and continue to the present by providing a diversity of educational opportunities, supporting needed research investigations, and fostering the transfer of watershed-related information. Much of this history is interwoven with the history of the Arizona Watershed Program and Arizona Water Resources Committee, a citizens group that was instrumental in moving the Arizona Watershed Program to fruition, presented in the publication that was included with the registration materials for this conference. I would like to extract and expand upon a few of the more notable contributions of the College of Agriculture, University of Arizona, reported upon in this publication, starting with the Barr Report of 40 years ago.

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Barr Report

A milestone study on the conditions of watershed lands in northern Arizona in the middle 1950s culminated in what became known as the Barr Report. This report was prepared in response to a call by the people of Arizona to explore potential productivities of these watersheds and outline a plan of action to improve on these conditions where necessary. The Salt River Project, responsible for storing and delivering water and producing and supplying hydropower to the people of central Arizona, financed the study; the Arizona State Land Department furnished much of support personnel and logistics; and the University of Arizona provided scientific leadership with Dr. George W. Barr, an agricultural economist and the founder of the University of Arizona's Department of Agricultural Economics. With the assistance of Bob Humphrey, a range management specialist in the College of Agriculture, other members of the University's faculty, and a group of watershed management experts within and outside of the region, Barr and his team began their study in the winter of 1955-56.

The products of this effort, a massive document (Volume II) and a shorter summary (Volume I), both going under the title of "Recovering Rainfall — More Water for Irrigation," confirmed that the "condition" of Arizona's watersheds could possibly be improved by more intensive management practices (Barr 1956a, 1956b). These two volumes, made public in the fall of 1956, represented the first formal announcement of what was to become known as the Arizona Watershed Program.

On October 26, 1956, in an address at the Westward Ho Hotel in Phoenix, George Barr stated "The day has passed when water can be considered a mere by-product of a watershed devoted chiefly to timber and forage. Water production is now the most important use of the land...."

In their report, Barr and his team recommended that an extensive, well-coordinated action program be initiated as quickly as possible to explore the possibilities of increasing the flow of water from these watersheds into downstream reservoirs. The team believed that the time had passed when water could be considered only a unchangeable and inexhaustible by-product of watershed lands devoted chiefly to growth of timber and livestock forage. They suggested that the proposed action program be initiated in areas where the greatest increase in water might be economically obtained, and where results of water-yield improvement treatments and costs of these treatments could be adequately evaluated. The team concluded that watershed research closely linked to the action program should lead the way to improved methods of achieving this goal — thus, the beginning of the Arizona Watershed Program.

Arizona Watershed Program

The Arizona Watershed Program was a joint initiative of the State Land Department, the Arizona Water Resources Committee (a citizens group formed to obtain public support for the Arizona Watershed Program), the USDA Forest Service (the major land management agency in Arizona), the University of Arizona, and other cooperators. The purpose of the program was to obtain and then extrapolate needed research findings on water-yield improvement potentials to operational-scale watershed management practices designed to increase water yields by manipulating vegetative cover.

Other aspects of the Arizona Watershed Program included determining the costs of water-yield improvement treatments; encouraging the development of improved methods and techniques for multiple use management practices on the state's watersheds; measuring both positive and negative effects of planned vegetative manipulations on all natural resources; making economic and social evaluations of these practices in assessing the feasibility of operational applications; and supporting watershed management research. The Arizona Watershed Program, therefore, became a focus of watershed management activities in Arizona from its inception in the early 1960s.

Arizona Board of Regents Actions

Eager to have the state's institutions of higher education become an active player in the Arizona Watershed Program, the Arizona Board of Regents took two actions in 1958 to involve these institutions in the program. Establishment of a Department of Watershed Management at the University of Arizona, Tucson, and a forestry program at Arizona State College, later to become Northern Arizona University, Flagstaff, were approved.

Department of Watershed Management

The Board of Regents accepted a gift of $120,549 from the Charles Lathrop Pack Foundation for the study of watershed management and authorized the University of Arizona, the state's land grant institution, to establish a Department of Watershed Management in the College of Agriculture. This gift helped the College tie into other proposed work in aridlands research that was contemplated through an earlier grant of $201,800 from the Rockefeller Foundation.

This action by the Board of Regents confirmed program authority in watershed management to the University of Arizona, with options in forest-watershed management and watershed hydrology. An existing program in Range Management, taught in the College of Agriculture since the 1920s, was also incorporated into the instructional and research structure of the Department of Watershed Management. When the new department was formed in 1958, the USDA Plant Materials Center was affiliated with the department under a grant from the U.S. Soil Conservation Service (SCS). This continued until 1962 when the Center reverted to the SCS.

The Department of Watershed Management was created largely in response to the growing public interest in managing vegetation of all types on the state's watersheds to increase water yields. The University of Arizona was directed, from the date of approval for establishing the Department of Watershed Management, to conduct instructional programs and supporting research in forestry and forestry-related subjects, and range management and other renewable natural resources fields. The University was also directed to develop the necessary information and professional capabilities for managing watersheds. In 1973, the Water Hydrology Unit of the Department of Watershed Management held the first symposium ever given on the topic of surface-mining reclamation in the West. This stimulated the funding of a number of major projects in the West by several federal agencies and the coal and copper mining industries.

School of Renewable Natural Resources

Organization of the Department of Watershed Management into a broader School of Renewable Natural Resources at the University of Arizona was approved by the Board of Regents in 1974. The purpose of the School of Renewable Natural Resources was, and continues to be, the integration of teaching and research programs primarily related to land management and to land use products. Changes brought about by the creation of the School of Renewable Natural Resources also brought together closely allied academic and public service interests. It was anticipated that this interdisciplinary approach to the problems of land management should be more productive with this new arrangement.

Instructional programs in the newly formed School of Renewable Natural Resources were expanded from those programs available in the Department of Watershed Management to include wildlife ecology, fisheries management, natural resources recreation, and landscape architecture, which has since moved to the College of Architecture. The Board of Regents authorized the School of Renewable Natural Resources to offer interdisciplinary degree programs in a Renewable Natural Resources Studies program in 1984. This academic orientation and emphasis remains the basic framework of the School of Renewable Natural Resources to the present time.

Water Resources Research Center

Another important component to the state's watershed-related research program is the Water Resources Research Center (WRRC). Currently housed in the Department of Soil, Water and Environmental Science Department of the College of Arizona, the Water Resources Research Center was established in 1964, as authorized by the federal Water Resources Research Act of 1964, to facilitate research at all three Arizona universities on water-related problems of critical importance to the state and region. The foundation for the WRRC was provided earlier by the establishment of the Institute of Water Utilization in the College of Agriculture in 1953. The Water Resources Research Center administers the federal grant program authorized by the Water Resources Research Act of 1964. Related missions include the communication of water-related research needs from researcher users to researchers, and to report research findings to potential users of that information. The Water Resources Research Center also works with public and private organizations and individuals, and provides information and services through a publications program including two newsletters, conferences and symposia, and through outreach.

Thorud-Ffolliott Report

Representatives of the Arizona Water Resources Committee approached the (then) Department of Watershed Management in 1973 to discuss a project of vital importance to the Committee. About 15 years had passed since George Barr had completed the historic report that had made his name a byword in the annals of the Arizona Watershed Program. Since that time, millions of dollars had been spent on watershed education and research in the state. Thousands of hours had gone into the collection of extensive, and often unique, data sets depicting hydrologic conditions throughout Arizona. The Committee felt that it was time to assemble, collate, refine, and analyze all the information obtained by watershed researchers over the decade-and-a-half that the Committee and the Arizona Watershed Program had been in business, and present this collated information and its interpretation to the public. The Department of Watershed Management was asked to do the job. Thus, what became known as the Thorud-Ffolliott Report, more formally titled, "Vegetation Modification for Increased Water Yields in Arizona," was initiated.

It took Thorud, Ffolliott, and their collaborators about 18 months to prepare the report, a massive document exceeding 1,000 pages (Ffolliott and Thorud 1975). A shorter version of the report, published by the Arizona Agricultural Experiment Station, College of Agriculture, had been made available to the public earlier (Ffolliott and Thorud 1974). The report contained a detailed summary of the status-of-knowledge obtained from the Arizona Watershed Program to that time and a statement of a "theoretical maximum" water-yield improvement potential that might be obtained through implementation of hypothetical vegetation management practices. This latter statement became part of the Thorud-Ffolliott Report at the request of the Arizona Water Resources Committee, who felt such an estimate might be helpful in placing the water-yield improvement potentials of the state's watersheds into perspective.

Arizona Water Resources Committee

The College of Agriculture remains proud of its close, long-standing relationships with the Arizona Water Resources Committee throughout the existence of the latter. These mutually beneficial collaborations helped the Committee to establish working relationships with important interest groups and governmental entities in the state, region, and nation. These relationships afforded the Committee opportunities to broaden its political base and secure endorsements from decision-making influential individuals in the community.

College of Agriculture faculty members also assumed responsible roles with the Committee. The Director of the School of Renewable Natural Resources served as an Associate Member of the Committee throughout the 1970s, participating in the Committee's regularly scheduled monthly meetings. Other faculty members were also frequent guests of the Committee at these meetings, where they presented invited inputs to the Committee's agenda. The Director of the Office of Arid Lands Studies, College of Agriculture, was Vice President at the time that the Committee voluntarily terminated its existence in 1992.

Several Committee members held public office at one time or another. All of its members were civic and professional leaders in the state. Several members received national, state, professional, or academic honors and awards. One noteworthy award was the presentation of an honorary degree of Doctor of Science to Kel Fox, a founding leader of both the Arizona Watershed Program and the Arizona Water Resources Committee, by the University of Arizona. Fox, whose contributions to the Arizona Watershed Program are well chronicled (Ffolliott et al. 1998), was nominated for this honor by the School of Renewable Natural Resources, formerly the Department of Watershed Management which, in 1958, he and the Committee were instrumental in forming.

In presenting this honorary degree at the University of Arizona's commencement ceremony on May 19, 1973, Harold Myers, the (then) Dean of the College of Agriculture, remarked that Fox had "rendered outstanding service to the people of Arizona in advancing research, policies, and practices for the wise use and conservation of the state's natural resources." Furthermore, as a lawmaker, Fox helped pass legislation that promoted soil and water conservation and improved the management of Arizona's wildlife resources.

Continuing Involvement in Watershed Management

Nearly 40 years have passed since George Barr and his team of experts recommended the testing and implementation of improved methods and techniques for multiple-use management practices on Arizona's watershed lands. One result of this action has been to provide today's managers with a better, more holistic, and perhaps more realistic basis for management of the state's water and other watershed-based natural resources. In this regard, the School of Renewable Natural Resources and other faculties in the College of Agriculture continue to play an active, often catalytic role in offering and fostering watershed-related educational, research, and technology transfer programs to the benefit of people in Arizona and elsewhere.

Educational Programs

The School of Renewable Natural Resources continues to offer educational programs in watershed management and, more generally, integrated natural resources management. These programs have gained regional, national, and international recognition through the years (Tejwani 1985, Ffolliott et al. 1990). Degree programs are available at the BS, MS, and PhD levels in the School of Renewable Natural Resources.

The BS program curricula present basic knowledge of principles and techniques for a wide range of watershed-related subjects. BS programs also outline approaches to integrating these "building blocks" into technically-sound packages for practical applications of watershed management. MS programs present, in greater depth, available knowledge of principles, methodologies, and techniques in a watershed management field of interest. Additionally, students acquire conceptual and technical skills to develop new technologies in watershed management. PhD programs, consisting largely of research orientations, aim at finding solutions to fundamental problems. Basic knowledge that permits development of "path-breaking" techniques in watershed management is also expanded through these programs.

The School of Renewable Natural Resources, together with other faculties in the College of Agriculture and faculties from other universities, has also offered short-term technical training courses focusing on watershed management to targeted professionals regionally, nationally, and globally. These training courses are structured more toward imparting technical knowledge and "here's how" information. A body of proven and locally adapted methods and techniques for integrated land management systems involving hydrology, forestry and rangeland management, and agriculture is presented in these courses.

The capability of the School of Renewable Natural Resources to offer a breadth of training and education in watershed-related areas was very much enhanced during the period from 1969 to 1976, when the Department of Watershed Management, and then the School, received an annual 211d institutional grant from the U.S. Agency for International Development to strengthen university watershed management competency.

Such institutional building provided the underpinning for a six-week technical training course that the School of Renewable Natural Resources conducted for nearly 15 years that was titled "Resource Development of Watershed Lands," offered in cooperation with the Office of

International Cooperation and Development, U.S. Department of Agriculture to mid- and upper-level professionals from largely developing countries throughout the world. A theme of this course was "training of trainers," a concept that resulted in a cadre of nearly 300 professionals who subsequently trained people in watershed management in home-country settings.

Shorter, largely *ad hoc* training courses on a variety of watershed-related topics have also been, and continue to be, offered by faculty of the School of Renewable Natural Resources to professionals in the United States and internationally, with the assistance of faculties in the College of Agriculture and other universities in many instances. Titles of these training courses, structured largely to meet in-country needs include "Watershed Management and Environmental Monitoring," "Integrated Watershed Management," "Watershed Instrumentation and Measurements," and "Forest Hydrology Modeling." In addition to offerings on campus, venues for the courses have included the Philippines, Thailand, Indonesia, India, China, Mexico, Honduras, Panama, Zimbabwe, Jordan, and Israel. Among collaborating sponsors have been the U.S. Agency for International Development, CARE International, the Farmer-to-Farmer Program, Partners of the Americans, and other non-governmental agencies; UNESCO's Man and the Biosphere Program, the Food and Agriculture Organization (FAO) of the United Nations, the United Nations Development Programme, and the World and Asian Develop Bank; and numerous regional and national governmental agencies in this country and abroad. These training courses are often offered for continuing-education credit from in-country educational institutions.

Research Programs

One of the more valuable outcomes of the watershed research programs in the state has been the opportunities for long-term monitoring and continuing evaluations of the resulting databases describing vegetative manipulations on watershed lands. A more responsive, more holistic management-framework for conservation and the sustainable use of natural resources on the state's watersheds has often evolved from these evaluations. These databases are unique in their "multi-resource character" by describing the dynamics of the diverse ecosystems studied. Information of this kind has, and continues to, become increasingly important in attaining a better understanding of how ecosystems on the state's watersheds function through time — information that today is at a "high premium" in planning to accommodate people's demands for better long-term ecosystem management.

Many of the databases are available today for additional analyses because of efforts made by researchers to protect the original maps and aerial photos, inventory sheets, and file copies of summaries. Faculty and students in the School of Renewable Natural Resources have helped to computerize many of these databases, making them easier to store, retrieve, and analyze as a basis for future studies of hydrologic processes and land management on watershed lands.

Research sites comprising the framework for the Arizona Watershed Program continue to be "outdoor laboratories" for faculty and students in the School of Renewable Natural Resources and elsewhere in the College of Agriculture to further investigate how land management practices impact forage, wildlife, water, and wood resources, and amenity values such as the scenic beauty of the state's landscapes. As the mixture of these benefits and values changes through time, the emphasis placed on the newly formulated studies can also change.

The College of Agriculture has recently added the V Bar V Ranch, located in north-central Arizona within the Beaver Creek watershed drainage, to the list of outdoor laboratories for education, research, and extension activities. Studies focusing on water and range restoration, riparian ecology, soil-vegetation relationships, livestock grazing practices, and wildlife habitat improvement are found on the V Bar V Ranch, a working ranch typical of those operating in north-central Arizona. The USDA Forest Service is responsible for managing the land, while users in the private sector share the responsibility for keeping the land healthy.

Technology Transfer Activities

One of the more lasting contributions of the Arizona Watershed Program is the large number of technical publications that resulted from the research efforts and following action programs; many of these publications have been authored or jointly authored by faculty and students in the College of Agriculture. An annotated bibliography of research on the Beaver Creek watersheds, compiled by a USDA Forest Service researcher and a member of the School of Renewable Natural Resources faculty, represents one example of the lasting value of the Arizona Watershed Program (Baker and Ffolliott 1998). This bibliography, consisting of nearly 670 citations of publications processed between 1956 and 1996, furnishes a valuable informational-base for the formulation of future research projects by faculty and students in the School of Renewable Natural Resources, College of Agriculture, and elsewhere.

Another major technology transfer effort was initiated by the College of Agriculture and USDA Forest Service in 1997 to deliver information generated by the Arizona Watershed Program, and more specifically the Beaver Creek Project, to a broader audience than previously possible (Young and Baker 1998). One phase of this project consists of bringing this information to the public through the World Wide Web. A Web site entitled the "Sustainable Management of Semi-Arid Watersheds" features the Beaver Creek references included in the recently compiled bibliography as real-life examples of what works and what does not work. The home page, titled "Watershed Management in the Southwest," includes topics on watershed management practices; order forms to obtain technical references on watershed management practices; and an interactive learning package on watershed management practices. Other technology transfer mechanisms with ties to the Web site are also available. A telephone system provides students, teachers, and others with recorded two-minute messages on sustainable management practices for watershed lands in arid and semi-arid environments. Field days to watershed sites are also scheduled to introduce the general public, including students and teachers, to forest management, wildlife habitat management, rangeland management and monitoring, and watershed condition and function, and to initiate future educational workshops.

This three-pronged technology transfer project provides a unique opportunity to combine the strengths of three units — the University of Arizona Cooperative Extension with its commitment to information dissemination and training; the USDA Forest Service as a major repository of watershed management information; and the University of Arizona Arid Lands Information Center for the necessary Web site management and expertise.

A Final Comment

Water is the lifeblood of Arizona. The appropriate management of watersheds is imperative to our future for water management and for important ecological and environmental concerns that contribute to the quality of life in our state. The University of Arizona, as the state's land-grant university, has been heavily involved in watershed management via its School of Renewable Natural Resources. The school's tripartite mission of education, research, and outreach has served the state well in the past. We look forward to continuing to better understand and manage Arizona's watershed in the future.

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SYNTHESIS PAPERS

Watershed Management Perspectives

Global Perspective of Watershed Management

Kenneth N. Brooks[1] and Karlyn Eckman[2]

Abstract.—This paper discusses the role of watershed management in moving towards sustainable natural resource and agricultural development. Examples from 30 field projects and six training projects involving over 25 countries are presented to illustrate watershed management initiatives that have been implemented over the last half of the 20th century. The level of success has varied from project to project. Means of achieving greater success are discussed, including the need for institutionalizing watershed management, that take into account the workings of people, governmental agencies and organizations, and their use of resources at local and national levels.

Introduction

Watersheds have been viewed as useful systems for planning and implementing natural resource and agricultural development for many centuries. Recognition of the importance of watersheds can be traced back to some of the earliest civilizations; ancient Chinese proverbs state that "Whoever rules the mountain also rules the river," and "Green mountains yield clean and steady water." The Polynesians who settled Hawaii organized their economic and political systems on the basis of watersheds, realizing that their livelihood depended on the sound management of land and water together, from the ridge tops to the lowlands and the productive coral reefs that received runoff from the land (Morgan 1986).

Expanding human populations and their increasing demands for natural resources have led to exploitation and degradation of land and water resources. Revenga et al. (1998), in an assessment of 145 watersheds globally, emphasized that expanding human demands for resources have intensified watershed degradation, with the result that some of the watersheds with the greatest biological production are becoming the most seriously degraded. Development projects and programs by all types of organizations (national governments, multinational and bilateral agencies, nongovernmental organizations (NGOs), etc.) have proliferated in response to these problems. Previous reviews of watershed projects throughout the world, indicate that inadequate diffusion of technology and an absence of continuity of project benefits have hindered many countries from achieving sustainable development (Brooks et al. 1992). If watershed management is deemed an essential underpinning of sustainable natural resource and agricultural development, then what needs to be accomplished so that we can move from short-term projects to sustainable programs? To address this question, we will highlight selected countries and projects, examining the successes and failures, and look ahead at the key issues in the coming century.

The Issues

Current and expanding scarcities of land and water resources, and the human response to these scarcities, threaten sustainable development and represent paramount environmental issues for the 21st century (Rosegrant 1997; Scherr and Yadav 1996; Rosegrant and Meinzen-Dick 1996). An added concern is developing means of coping with the extremes and uncertainty of weather patterns, such as the 1997- 1998 El Nino effect that resulted in severe droughts in some parts of the world and record flooding elsewhere. We suggest that watershed management provides both a framework and a pragmatic approach for applying technologies to cope with these issues, which are discussed below.

Water scarcity has been widely called the *top global issue* of concern in the coming century in developed and developing countries alike (Kundzewicz 1997; Meinzen-Dick and Rosegrant 1997; Rosegrant 1997; Rosegrant and Meinzen-Dick 1996). By 2025, it is estimated that between 46 and 52 countries, with an aggregate population of about 3 billion people, will suffer from water scarcity. Coping with water scarcity is compounded by soil degradation, groundwater depletion, water pollution, and the high costs of developing new water supplies or transferring water from water rich to water poor areas (Rosegrant 1997). Through watershed management we can recognize

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both the opportunities and limitations of water yield enhancement through vegetative and structural measures.

Floods, landslides and torrents result in billions of dollars being spent each year globally for flood prevention, flood forecasting, and hillslope stabilization. Yet the cost of lives and property damage due to floods, landslides and debris flows are staggering. The impacts of these naturally occurring phenomena are exacerbated by human encroachment on flood plains and other hazardous areas, which is often the result of land scarcity discussed below. In many parts of the world there has been an over reliance on structural solutions (dams, levees, channel structures, etc.) in river basins, along flood plains, and in areas susceptible to debris torrents, all of which impart a false sense of security to those living in hazardous areas. In addition, the replacement of natural wetlands, riparian systems, and flood plains with urban and agricultural systems can cumulatively add to downstream problems, a point emphasized in post flood assessments of the 1993 Mississippi River flood by Leopold (1994). A watershed perspective brings these cumulative effects and linkages into focus, but the ability to develop solutions requires that we have the appropriate policy and institutional support.

Point and nonpoint water pollution continue to plague many parts of the world, threatening the health of humans, compounding water scarcity issues noted above, and adversely impacting aquatic ecosystems, with subsequent implications for fish and wildlife. Best Management Practices (BMPs) and related technologies of watershed management have the advantage of stopping non point pollution at its source.

Scarcity of land and natural resources results from a shrinking arable land base due to expanding populations of humans and livestock. Land degradation resulting from cultivation, grazing, and deforestation of marginally productive lands compounds the effects of land scarcity. These are often steep areas with shallow soils that experience accelerated surface and gully erosion, soil mass movement, and increased sediment and storm flow damage to downstream communities. In the tropics, it is estimated that about 0.5 ha of farmland is needed to feed one person (Pimental et al. 1995). Lal (1997) indicates that by the year 2025, 45 countries in the tropics will have less than 0.1 ha of arable land per capita. Globally, of the 8.7 billion ha of agricultural land, forest, woodland and rangelands, over 22% has been degraded since mid-century, with 3.5% being severely degraded (Scherr and Yadav 1996). Deforestation continues to gain worldwide attention with most of the concern expressed in terms of lost biodiversity; of equal importance are the implications of deforestation on watershed functions.

Watershed management efforts have been directed towards one or more of these issues in countries around the world, as illustrated with the following examples.

Watershed Management Projects: Some Examples

Projects aimed at soil and water conservation and watershed rehabilitation date back to the colonial period, particularly in the former British colonies. After independence, large-scale afforestation, hydropower, and other water resource projects were enthusiastically promoted by government leaders in an effort to demonstrate rapid progress toward development. In the 1960s — 1980s, watershed management in many developing countries focused on restoring land and water systems that had become degraded and protecting earlier water resource development investments. Much work was accomplished under the umbrella of soil and water conservation without the spatial and temporal view of watershed management. Unfortunately, such projects tended to be narrowly focused and sometimes were considered to be quick fix solutions, but in fact, they often dealt with the symptoms (e.g., soil erosion) and not the causes (human demands for food, fuel wood, etc.) of the problem. In recent years, interdisciplinary and participatory methods have been promoted in watershed management as a more sustainable approach to overcome these problems.

After a half century of implementation, what can we learn from past experience? Has there been any transition from technically oriented, operational projects (e.g., erosion control) to sustainable watershed management? To what degree are communities involved in identifying problems and proposing solutions? What can be learned from our past successes and failures?

Projects on Watersheds

Thirty operational watershed management projects in 20 countries were reviewed, spanning the period from 1967 to 1999 (table 1). Although some of these involved training, six international training projects were reviewed separately (table 2). In selecting projects, we included those described in terms such as *integrated rural development, soil and water conservation,* and *upland conservation,* because they often have a major focus on watershed management. Any such review must be aware of the changing terminology that is prevalent in the interna-

Table 1. List of projects reviewed.

Number	Project Title	Countries Involved	Reference
1	Interregional Project for Participatory Upland Conservation and Development	Bolivia, Nepal, Tunisia	Urquizo 1999; fe D'Ostiani 1999
2	Watershed program in Andhra Pradesh	India	Turton et al 1998
3	Watershed program in Orissa	India	Turton et al 1998
4	Watershed program in Madhya Pradesh	India	Turton et al 1998
5	Integrated Rural Environmental Program	Java Indonesia	McCauley in Easter et al 1991
6	Peum Perhutani Project	Java Indonesia	McCauley in Easter et al 1991
7	Watershed Management Through People's Participation and Income Generation	Java Indonesia	McCauley in Easter et al 1991
8	Yallah's Valley Land Authority Programme	Jamaica	Edwards 1995
9	Farm Development Scheme	Jamaica	Edwards 1995
10	Integrated Rural Development Project	Jamaica	Edwards 1995
11	Hillside Agricultural Programme	Jamaica	Edwards 1995
12	Agroforestry Development in NE Jamaica	Jamaica	Eckman 1997
13	Agricultural Production and Support Systems for Achieving Food Security	Grenada	Eckman 1998
14	Maissade Integrated Watershed Management Project	Haiti	White and Quinn 1992; White July 1992; White October 1992; White November 1994
15	Pilot Project in Watershed Management on the Nahal Shikma	Israel	UNDP/FAO 1967
16	Mae Se Integrated Watershed and Forest Use Project	Thailand	FAO/UNDP 1982
17	Salto Grande Hydroelectric Project	Argentina and Uruguay	IADB[1] (unpublished)
18	Abary Water Control Project	Guyana	IADB (unpublished)
19	Cauca River Regulation Project	Colombia	IADB (unpublished)
20	La Fortuna Hydroelectric Project	Panama	IADB (unpublished)
21	Pueblo-Viejo-Quixal Hydroelectric Project	Guatemala	IADB (unpublished)
22	Tavera-Bao-Lopez Multipurpose Hydro Project	Dominican Republic	IADB (unpublished)
23	Kandi Watershed and Area Development Project	Punjab India	Gupta 1988
24	Integrated Watershed Development Project	Himachal Pradesh India	Development Alternatives 1989
25	Loess Plateau Watershed Rehabilitation Project	China	World Bank 1994
26	Integrated Rural Development Through Communes	Rwanda	Eckman 1987
27	Women's Development in Sustainable Watershed Management	Myanmar	van Leeuwen 1995
28	Sustainable Agriculture Development and Environmental Rehabilitation in the Dry Zone	Myanmar	Eckman 1995
29	Watershed Management for Three Critical Areas	Myanmar	UNDP 1994
30	Konto River Watershed Project Phase III	Indonesia	de Graaff 1987; DVH Consultants 1990

[1] *InterAmerican Development Bank*

tional development arena. The projects range from those that are relatively small, with low budgets implemented by nongovernmental organizations (NGOs), to those with a large regional focus implemented by international agencies with budgets in excess of US $250 million.

A comprehensive and detailed case study analysis of all of these projects is beyond the scope of this study. Our approach was more of a synthesis of various projects and project components to help understand key factors that contribute to success and those that present barriers in the transition towards sustainable use of land, water and other natural resources. In reviewing project documents, we attempted to identify factors that contribute to positive and sustainable impacts. We also looked for elements that seem to foster undesirable and unsustainable project outcomes. Published literature, unpublished official agency reports, reports from evaluation missions and consultant visits, baseline survey reports, feasibility studies, and other fugitive materials were reviewed. We should note that for some of these projects we had access to limited, unpublished reports from various agencies; complete documentation of many such projects reside in agency files and were not available for scrutiny.

Training in Watershed Management

Six international watershed management training projects (table 2) that have been undertaken in the past few decades were examined, representing a small sample of projects that were specifically targeted for training and education. Some of the projects listed in table 1 also contained training components, but their focus was more field implementation.

To paraphrase an old saying, “give a man a fish and he eats for a day, teach him to fish and he eats forever,”

Table 2. Examples of international training and educational programs in watershed management.

Project title and sponsor	Country	Training components and outcomes	Duration and reference
ASEAN Watershed Project / US Agency for International Development	Regional: Indonesia, Malaysia, Philippines, Singapore, Thailand, Brunei	Symposia, seminars, workshops, short courses, study tours, manuals, networking (465 participants)	1983-1990 (Cortes and Saplaco, 1984)
FAO/Finland Training Course in Forestry and Watershed Management	Regional: Asia-Pacific Region (Nepal), and Southern Africa Region (Lesotho)	Training courses with field trips:43 participants from 18 countries	1985-1986 (Food and Agricultural Organization 1985, 1986)
Eastern Anatolia Watershed Rehabilitation Project (World Bank)	Turkey	Extension training; short term study tours and long term (3 month) training	1993-1998 (Ministry of Forestry, 1997)
Water and Soil Conservation and Environmental Protection; Upper and Middle Reaches of the Changjiang River Basin (Asian Development Bank)	People’s Republic of China	Seminars for 67 provincial and county leaders; training course for 32 middle managers/technicians Training manuals in English and Chinese	1995-1996 (Brooks et al. 1995)
Resource Development of Watershed Lands; (OICD - USDA and University of Arizona)	Global (participants from 27 countries)	Six-week training courses with field trips; over 350 mid-level managers trained	1978-1991 (personal commun., P.F. Ffolliott, 1999)
Watershed Resources Management and Environmental Monitoring in Humid Tropical Ecosystems (UNESCO - MAB)	Regional Training held in Honduras, Panama, the Philippines, and Thailand	Five 2-week training courses; 115 mid-level managers trained	1979-1982 (personal commun., P.F. Ffolliott, 1999)

underlies the importance of training and educational programs. Although it is sometimes difficult to evaluate the success of training, or any educational program, making people aware of the importance of watershed management and its role in meeting production and environmental goals, cannot be minimized. In many instances, regional training programs have brought people together with common problems and have facilitated networks that last long after the formal training ends. As many of the participants of workshops, seminars and training courses move into positions of upper management, policy makers and political leaders, their ability to implement watershed management becomes enhanced. Such outcomes of training programs may far outweigh the benefits of learning a particular technology at some point in time.

Lessons Learned

The outcomes of projects ranged from those with significant benefits, to failures that had unwanted environmental and socioeconomic consequences. Examination of the 30 watershed projects suggests that while there have been some notable successes, there is considerable need for changes in planning and implementation strategies to foster more sustainable outcomes. Because few of the projects had documented ex post evaluations, we could not provide a comprehensive analysis of individual projects, and therefore, have summarized our observations in an overview context.

Planning Aspects

The reviewed watershed projects were largely planned in a top-down manner with specific, technically oriented objectives, such as erosion control, reforestation, and so forth. Most projects are planned by outside experts on short-term contracts who have limited responsibility for implementation, or accountability for long-term outcomes and consequences.

The importance of participatory planning methods was emphasized by many, but D'Ostiani (1999) notes that participatory methods are not ends in themselves, and, if used alone, are insufficient. The importance of local involvement and input in the planning process is stressed to help ensure that the most basic cultural and socioeconomic dimensions, such as land use, are fully considered. Projects that are more technically oriented tend to focus more on outputs, whereas projects planned with participatory methods tend to focus on outcomes. A case can be made that *neither* technical nor participatory approaches are sufficient in watershed management. Close collaboration with local resource users tends to promote more sustainable outcomes, both environmentally and socioeconomically.

Only five of the projects reviewed (table 1) attempted to study socioeconomic factors, such as land use, farming systems or land tenure, prior to project implementation. In most other cases, socioeconomic studies were conducted after project planning was already completed, often years after the project was operational, and then only when problems surfaced. Three projects were planned in consultation with local communities in which the project was sited. Several larger-scale projects called upon nongovernmental organizations (NGOs) once project implementation was well underway, either to diagnose socioeconomic problems associated with the project or to assist with project management.

Management and Administrative Aspects

Project management and planning are interrelated with other factors that affect project success. For example, the smaller projects in our modest survey seemed to experience better coordination, integration, communication, and local participation than the larger, more complex projects. Smaller, more focused projects seemed to be more successful in achieving project objectives. Projects with less complex institutional and administrative structures had more flexibility and seemed to have greater success in monitoring benefits attributed to project measures. Several larger projects lacked a mechanism for equitable sharing of project benefits, and some did not monitor such benefits.

Subsidies, cash-for-work, and other payments were components of many of the projects. As incentives, such measures are intended to facilitate direct project benefits. In reality, however, whether they contribute to voluntary, long-term local participation is questionable. For example, maintenance of soil conservation structures, or planting of trees in degraded areas often cease when subsidies or cash payments end. Clearly projects should carefully consider using appropriate incentives that will motivate local people to carry out and sustain those practices needed to achieve watershed management objectives.

As mentioned earlier, few of the projects reported ex post evaluations. One explanation, we hypothesize, is an absence of comprehensive monitoring of costs and benefits throughout and beyond the project life. Monitoring is an essential management tool that allows managers to track projects and make needed adjustments to achieve objectives, and furthermore, allows donor agencies to determine project success. Too often, monitoring is underutilized and underappreciated (Eckman 1994). One-third of the projects routinely monitored for technical environmental data; four projects also monitored socioeconomic aspects, and one project successfully employed participatory monitoring techniques. As a result, formal and informal evaluations of projects were not complete, nor as comprehensive as they should be to determine success or failure of project components. Participatory monitoring and evaluation techniques, with direct involvement of local resource users and other watershed residents, would have facilitated more effective project management.

Scale and Topography

Scale and topography appear to be interrelated in influencing project success. As discussed earlier, less ambitious projects in smaller watersheds seem to be more successful in achieving project objectives than larger more complex projects. Positive impacts of such projects are often reported in terms of improved farm incomes, improved fisheries, etc. rather than an emphasis on such components as number of gully plugs constructed, miles of roads improved, etc. While this is a tentative finding, we noted that the very large and administratively complex projects, encompassing numerous watersheds, were also reporting more complex outputs that were more difficult to translate into impacts at the local level. We also observed that projects that focused on mountainous uplands and island systems had some unique characteristics.

The hydrologic response of montane watersheds to land use can be direct and severe to both upland and downstream inhabitants. On one hand, such areas are prone to extreme events associated with excessive rainfall resulting in landslides and debris flows, but on the other hand, land and water scarcity are also prevalent as well (Brooks 1998). The capacity of these often fragile lands to support growing populations is limited. Yet, upland areas are commonly seen as the last remaining living areas for rural poor, resulting in the upland migration of growing populations of humans and livestock. The resulting differences in socioeconomic well being between upland and lowland inhabitants becomes an issue that must be dealt with in watershed management projects.

Projects in the mountainous areas of Nepal, India and Myanmar suggest that watershed management projects require special considerations and planning must incorporate practical interdisciplinary approaches. In many tropical areas that are both island and montane, extreme meteorological events associated with monsoons exacerbates watershed problems. Under these conditions, the potential cumulative effects are severe, with local communities experiencing more direct and immediate consequences.

Montane and small island ecosystems with densely inhabited watersheds pose acute challenges to watershed management. The close proximity of uplands to productive lowlands and estuaries highlight upstream-downstream linkages. Island case studies from Grenada, Jamaica and Java suggest that natural conditions make hillsides particularly vulnerable to serious erosion and runoff problems (Edwards 1995). Given the inherent scarcity of land and natural resources with dense populations, small island watersheds seem more prone to conflicts over land use and resource rights in coping with upstream-downstream impacts (Eckman 1997; Eckman 1998). Financial constraints to natural resources programs on small islands are also a problem (Lugo and Brown 1985). Attempts in Jamaica since the 1950s to introduce effective engineering structures for soil and water conservation have not been successful, and none were sustained by farmers after termination of four major watershed projects. It is now widely accepted that such structures are not feasible for general use in Jamaica, as they are not compatible with farmers' patterns of resource use and labor allocation (Edwards 1995).

Tenure Issues

Land and resource tenure and rights of access issues were noted in about one-fourth of the project documents reviewed. In most projects, the right of access to land was of concern in carrying out projects, although in four cases water tenure was an important issue. Too often land and natural resource tenure are neglected in project planning. To achieve sustainable programs in watershed management, and ultimately sustainable development, projects need to fully recognize the tenure arrangements in any country. To understand these arrangements, appropriate socioeconomic studies need to be conducted early in project planning. Specifically, projects should examine pre-existing land use and tenure, thereby avoiding problems of the past. For example, in some countries trees and forests are owned by national governments; projects promoting reforestation on watershed, therefore need to understand how such activities would affect local people and how such people may respond. Who has rights to water and what are the methods of resolving conflicts? In some instances tenure arrangements may be seen as barriers to achieving project objectives, and may require institutional and policy changes.

Role of Training

The types of training activities in table 2 are far ranging and represent innovative ways of delivering information to international audiences. Some of these training projects had a regional focus, such as the UNESCO-MAB and the

ASEAN Watershed Project, which utilized a variety of seminars, workshops, and training courses that were held in the respective ASEAN countries but also included study tours to other countries. Similarly, the FAO/Finland training courses held in Nepal (Asia-Pacific focus) and Lesotho (Southern Africa focus) brought together mid-level managers and professionals who were facing common land and water management issues and problems. In the Lesotho training, there was direct support for the Southern African Development Community (SADC), with goals of promoting regional development cooperation between South Africa, Lesotho, Angola, Botswana, Malawi, Mozambique, Swaziland, Tanzania, Zambia and Zimbabwe. SADC has formed a regional watershed network, called the SADC Environment and Land Management Sector (SADC-ELMS), and publishes a watershed management newsletter called *Splash*. SADC-ELMS has developed a joint policy and strategy, as well as a sustainable development program based upon watershed management principles. These types of projects built networks of professionals who continue to collaborate on research, training and development activities today.

The Eastern Anatolia and the Water and Soil Conservation and Environmental Protection projects of Turkey and China, respectively, represent efforts to build national expertise to deal with a particular region with serious watershed problems. The Chinese project developed specific training activities for different groups, including county and local government officials, and middle and upper level resource managers. In all cases, training objectives were to improve watershed capabilities and ultimately watershed conditions above the major Three Gorges Dam project on the Changjiang (Yangtze) River.

The Resource Development of Watershed Lands was a series of courses held at the University of Arizona as part of the U.S. Department of Agriculture's support of U.S. Agency for International Development (USAID) programs in the field. The six week courses provided intensive training in technical subjects and included field applications. Participants had the option of receiving formal university graduate credit. Participants were selected from countries in which USAID had missions. The outcome of such training is difficult to track, given the dispersion of people who are trained. Even so, the experience of instructors in these courses suggests that many of the participants have emerged as country, regional and international leaders in watershed management.

Institutional and Policy Implications

Policy and institutional support is essential for watershed management projects to become integrated into long-term programs that have lasting impacts on people and their use of land and water resources. Institutional issues are many and involve all aspects of land and resource use. In the context of projects reviewed, policies and institutional considerations need to include not only those of national governments, but also those of donor agencies. In the initial development of projects, better coordination and communication between national governments and external donors and agencies would facilitate success. In smaller countries, such as Jamaica, Lesotho, Nepal, and Rwanda, the myriad of large projects with many donors and implementing agencies can overwhelm the institutional capacity of the government. Projects initiated by outside donors should consider national development goals of the host country and the assimilation capacity of the respective governmental agencies and institutions.

An observation with respect to both donor and national agencies is a lack of institutional memory concerning the lessons of past watershed management projects, and an over reliance to repeat the same techniques and approaches without adapting to changing circumstances. This problem prevails at several levels, including the policy level, and is particularly troublesome within agencies that are funding projects and training programs. Policy makers must become aware of what has happened in the past and with changing leadership, there is need to frequently update and increase the understanding of policy makers about watershed management. The issue is one of developing mechanisms for maintaining continuity of projects and programs so that knowledge from past projects are passed on for future reference.

Effective institutional support is necessary for project outcomes to become implemented into sustainable watershed management programs. This support can be at various levels, local, regional or national. Two observations can be made in this regard. First, institutional arrangements are needed so that natural resources are managed in a way that recognizes watershed boundaries, even though those organizations responsible for management are often organized around politically determined boundaries. Second, interdisciplinary approaches are needed to manage soil and water resources in a watershed framework. These two points are interrelated. Governmental organizations usually have specific mandates for a particular natural resource component, for example, forests, irrigation water, or hydropower, and are staffed with professionals in a particular discipline, i.e., foresters and engineers. They usually lack the ability and authority to cope with the myriad of watershed-level issues and they are not organized around watersheds, leading to both duplication of efforts and/or voids in responsibilities from a watershed perspective. Interestingly, this problem has been recognized by community based groups who have organized around watersheds; these groups have proliferated in the United States (Lant 1999) and in other countries as well, such as Australia (Ewing 1999) and Brazil (Porto et al. 1999). It is clear that institutional arrangements are needed that facilitate the management of land and water in concert with one another.

Strategies For Sustainable Watershed Management: Some Conclusions

Given the experience over the past few decades there is little evidence that watershed management is becoming woven into the fabric of natural resource and agricultural development. In the past, water resource, forestry, and agricultural projects were often developed with little regard to watershed management and upstream-downstream linkages. Furthermore, the role of local people and the importance of changing land use practices by those people are critical factors in achieving successful programs. Common sense tells us that to develop sustainable programs, land and water must be managed together and that an interdisciplinary approach is needed. Are we moving in that direction? There are some indicators that this may be happening. People who are trained and educated in watershed management are assuming leadership positions in many countries. Furthermore, the emergence of citizen-based watershed organizations in the United States and other countries recognizes on one hand, that a watershed management approach is relevant, but on the other hand, existing governmental institutions are not fulfilling the role of watershed management. Such movements indicate that policies and institutions that support integrated watershed management are emerging. Based on our observations and experience, the following are also noted:

- Interdisciplinary approaches to project design are needed that integrate the technical and human dimensions of watershed management. This requires an understanding of cultures and traditional land use practices. Watershed planning has historically relied upon engineering and technical expertise, but has been deficient in socioeconomic aspects, resulting in less than optimal outcomes and a diminished flow of benefits beyond the termination of projects.
- Socioeconomic research and participatory techniques need to be incorporated early in the conceptual design and planning stages of projects. Without coincident local participation, top-down approaches alone often have inconsistent and unpredicted results, even though they may be technologically sound. Bringing in local participation, and socioeconomic specialists later on when problems arise may be too late, and places undue responsibility on those not responsible for original project design. Participatory monitoring and evaluation methods should be used throughout the project cycle.
- Before utilizing subsidies or cash-for-work incentives, other means of providing incentives should be considered. Negative externalities can result when projects rely on subsidies; such economic strategies that may not fit because of cultural and economic differences between donor agencies and receptor countries.
- *Both* environmental and socioeconomic monitoring are needed throughout implementation and following project completion to assist in informed decision making.
- Project design and planning should consider scale and topography aspects in coping with upstream-downstream interactions and cumulative watershed effects (Reid 1993). Small scale projects with clearly defined watershed management objectives have a greater chance of demonstrating positive outcomes that can lead to long-term programs in contrast to large, ambitious, and complex projects that are difficult to manage and administer.
- Administrative and institutional structures should be developed that recognize watershed boundaries, without becoming overly complex. Flexibility in planning and management is essential.
- Regional training and networking programs at all levels should be promoted, building upon existing networks. Long-term funding support for technical professionals, managers, and policy makers should receive the same attention as operational field projects. Through expanded training programs, including training of trainers, diffusion of technology occurs and the continuity of positive project outcomes can be enhanced.

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Watershed Management in the 21st Century: National Perspectives

Carolyn Adams[1], Tom Noonan[2], and Bruce Newton[3]

Abstract.—Watersheds will continue to be planning management units of choice during the 21st century. Historic precedent, contemporary beliefs, regulation, and broad institutional support have insured their future. Whether their use will result in more sustainable systems depends on keeping natural resource issues a high national priority, balancing competition for consumptive resource use, advancing technology, developing strong public policies, and continuing appropriate research and supportive governmental policies. Further, it appears that successful watershed management will advance because organizations promoting its use tend to be highly adaptive, constantly seek new sources of information, and strategically use processes that foster innovation.

Introduction

As Americans look ahead to the 21st century, we recognize that we are in a position rarely matched in our nation's history. Our country has incredible prosperity and unparalleled technology, while experiencing dramatic and rapid changes. We view with pride some changes, such as medical advances, but other changes, such as the continuing degradation of our Nation's natural resources, especially our water, must be viewed with alarm. How can this nation continue to prosper without depleting its resource base? We need to enter the next century with our attention turned to how best to prevent, manage, or cope with the problems of gaining wealth at the cost of continued damage to our ecological systems (Killeen, 1999). Natural resource decisions, either by individuals or society, need to be framed in a meaningful context. Many believe that a watershed context provides this powerful basis for assessing environmental conditions and tracking the effectiveness of resource interventions. A watershed focus also provides a mechanism to bridge barriers between management agencies, a logical geographic unit for technical analysis, and perhaps most importantly, an understandable and tangible landscape unit for engaging the public.

In this paper we explore the following questions: will the use of watersheds as the framework for natural resource management increase as we move into the next century; and will that provide a reasonable structure for successful coping mechanisms to deal with the predictable and unforeseen challenges?

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A Brief Retrospective: How We Got Here

The United States has a long history of water management. In the first half of the 19th century, water management was strictly a local concern. Private citizens petitioned their town for permission to build structures to power a mill or to develop a private water supply system. Abuse of rivers was constrained primarily by public nuisance provisions from English common law. Late in the same century, Eastern and Midwestern cities with political power and financial resources condemned expanses of land for the development of water supply reservoirs. They acted unilaterally because no other level of government or segment of society claimed authority over water resources. In the West, water rights became the provenance of state government, which enacted laws to define water rights and settle disputes. The scarcity of water in Western states led to water rights laws based on codes of behavior originating with prospecting miners. Foremost was the concept that first in time was first in right. Toward the end of the 19th century, a series of disastrous floods in the East prompted calls for flood control. The U.S. Army Corps of Engineers (the Corps) was directed to build projects that "harnessed rivers" to protect life and property from floods. The Federal government also expanded its authority over water resources with the Rivers and Harbors Act of 1899. This Act extended federal authority to all navigable waters and prohibited the construction of any structure or the modification of any waterway without the expressed recommendation of the Corps' Chief Engineer and the authorization of the Secretary of War.

The early 20th century saw considerable activity at the municipal level. City Public Works departments constructed drinking water systems, built supply reservoirs, and installed sanitary sewage treatment works. Private power companies constructed hydroelectric dams. In 1902, under the Reclamation Act, the Federal government began the business of water development for irrigation supply in the West, primarily carried out by the Department of Interior's Bureau of Reclamation (BOR). The 1927 Rivers and Harbors Act significantly expanded water resource programs of the Corps and authorized the agency to develop comprehensive multipurpose plans for every river basin in the United States. By mid-1930 the Corps had prepared more than 200 plans, which became the basis for much of that decade's dam construction boom. The Corps and the BOR guarded their jurisdiction and actively opposed the establishment of other federal or regional entities. Even so, the 1930s saw the entry of several new players. The U.S. Department of Agriculture (USDA) was directed to reduce flood damages through watershed studies and land-based measures. The Tennessee Valley Authority (TVA) was established in 1933 with authorization to build dams (USDA, 1972; NRC, 1992). Largely motivated to stimulate the economy, the Federal government began a large program of dam construction in the 1930s. This era of large public expenditures for water structures continued until the 1960s. After World War II, USDA became a major player when the Soil Conservation Service (now the Natural Resources Conservation Service or NRCS) began building projects in upper watershed areas.

Throughout this period, concern about cost efficiency and interagency battles led to the establishment of several commissions charged with coordinating the federal agencies involved in water resources; the Corps, the BOR, the Public Health Service, and SCS. Those commissions failed largely because the politics of deciding which projects would be built where became very important to Congress. They resisted any attempt to interfere with the "pork barrel politics" that could benefit a Congressional representative so significantly (Riley, 1993).

After decades of failed attempts to coordinate water policy, the Water Resources Planning Act was enacted in 1965 to establish a National Water Resources Council (WRC) and several regional river basin commissions. The Act provided for the Council to develop water policy and to provide financial assistance to the states to support state-level water planning. Interstate basin commissions could be established to coordinate water supply, sewage and flood-control districts, state water resource agencies, the Corps, BOR, SCS, and the Environmental Protection Agency (EPA). Interstate commissions were to prepare and update coordinated plans and conduct data collection and studies (Fairchild, 1993). In 1972, the Clean Water Act was passed and it too had a major planning component; section 208 provided for a national program of "area wide" or regional water quality plans. Also in 1972, the Coastal Zone Management Act was enacted encouraging comprehensive planning for coastal areas.

By 1980 all of these programs, to some degree, had failed to fulfill their original promises. The main reason for widespread failure of the regional component of the 1965 and 1972 acts was that the major players refused to acknowledge the authority of the regional entities (commissions) that had been established. The Corps considered itself the nation's water planner and saw no benefit in cooperating with them. The Office of Management and Budget (OMB) saw its role of deciding which projects would go into the President's budget as threatened by the commissions (Fairchild, 1993). Congressional committees were opposed to what they interpreted as the WRC advancing the President's role in deciding project priorities. President Carter's "water project hit list" epitomized this belief when the WRC identified a multitude of water projects as inadequate in providing regional or national benefits (Riley, 1998).

Finally, the states saw these efforts as attempts to undercut their role in water planning and saw little reason to work with the commissions when they could get their projects funded directly from Congress. The states' perception was not unfounded since the Clean Water Act was, in fact, based on the belief that the states were unwilling or unable to control water pollution. The Act empowered the EPA to regulate cites and industries, run the permit programs, and manage the construction programs. The Act's 208 planning process and several other grant programs intentionally circumvented the states and provided funds to regional planning entities. As the states developed stronger programs through the 1970s and 1980s in order to win "delegation" of the Clean Water Act programs from the EPA, they increasingly opposed the efforts of regional planning commissions. The 208 plans had no buy-in from either state or local governments, and the EPA had no authority or funding to ensure that local governments followed plan recommendations. Thus, the plans developed reputations as bonanzas for consultants and unused documents. In 1981, the WRC was abolished by the Reagan administration and the Federal government largely abandoned basin planning. In the early 1990s, the EPA renewed the call for a "watershed approach" to environmental planning. The EPA was motivated by the need to engage local entities in nonpoint source control and ecological restoration efforts for which federal authority is inadequate (USEPA, 1991).

What lessons can be learned from the history of watershed planning? First, the public mind-set and state / local laws about water resources varied historically and continue to do so from east to west and from cities to small towns based on scarcity of water and community wealth. Second, the fragmented nature of the local-state-federal governing structure in the U.S. and the decentralized authority of agencies at all levels of government create barriers and challenges to integrated, comprehensive watershed or basin management. Third, the top-down model in which federal agencies act as the primary decision-maker draws strong resistance from state and local entities. Finally, planning agencies at any level of government must have adequate authority through either financial resources or policy-making authority.

Contemporary Predicament: Where Are We Now?

Given the lack of clear success historically in the managing the nation's water resources, what is our contemporary situation? To understand the present, the authors examine the primary influences on resource management at the watershed scale in this decade: the drivers, enablers, and state / federal support for watershed use.

Drivers: External Forces

Public Health and Expected Levels of Livability

Many institutions are revisiting or establishing new commitments to their constituents regarding environmental legacy; i.e., creating a vision of what kind of landscape should be passed on to descendants. For example, the Commonwealth of Pennsylvania's Constitution states in Article 2, Section 27, "The people have a right to clean air, pure water, and to the preservation of the natural, scenic, historic and esthetic values of the environment. Pennsylvania's public natural resources are the common property of all the people, including generations to come." This constitutional right became the basis of the state's 1998 Report of the 21st Century Environment Commission that recommends a comprehensive framework to conserve natural resources for sustainable use and make a healthy environment for healthy people. The framework depends in large part on comprehensive watershed management as an implementing mechanism. Other institutions and governments have similar initiatives and activities.

Pervasive Focus on the Essential Need for Clean Water

Arguably, water is the most necessary and recognized public natural resource. Concern for clean (drinkable, swimable, and usable) water is a major influence on the increase in watershed activities. In the 1990s, there have been outbreaks of microbiological contaminants (including such bacteria as *Cryptosporidium*, protozoa, and viruses) in drinking water, increased issuance of "boil water" notices, beach closures, fish kills, and elevated levels of nitrate in drinking water that pose immediate threat to young children. These situations fuel public and government concern about watershed functions and how the processes relate to the quality of potable water.

Regulatory Shifts

Since the 1970s, control of point-source discharges within our watersheds has been hugely successful due to the installation and upgrading of treatment facilities by units of government and industry. With these severe problems largely under control, nonpoint source runoff and aquatic habitat degradation are now considered the most significant impacts on water resources. Millions of individuals own nearly 70 percent of the land base in our Nation and each is responsible for generating some nonpoint pollution and habitat degradation. As a result, recognition that regulation of nonpoint sources is not culturally acceptable, cost effective, or practical to implement is increasing.

In response to this recognition, governments at nearly all levels are committing to more locally based systems of regulation and citizen-based actions involving communities. Many believe that these multitiered, citizen based processes may be the most effective ways of institutionalizing the underlying values necessary for lasting resource management efforts (Lee, 1996).

Belief in an Environmental/Economic/Community Equilibrium

Leadership in the U.S. believes that Americans can "have it all." "All" broadly defined means sustainable development; i.e., environmental health, economic prosperity, and social equity and well-being (President's Council, 1996). Some ecologists refer to this belief as the "Nature Balanced" view or a belief system based on the notion of logical growth and the challenge of navigating through demographic, economic, social, and environmental shifts to reach a plateau of sustainability (Gunderson, et al., 1995). Much scholarship and many policy changes are being driven by this belief. This equilibrium concept is a clear, intellectually appealing force, but as yet, its attainability is unknown.

Strong Feelings about Environmental Values, Community, and Future Generations

The American public has valued the environment, community, and responsibility to future generations since the early 1960s (Kempton, 1995). Some of these values now are evolving into the use of watersheds as spatial units for planning. In part, this comes from widespread public and political recognition that ecological identity or one's "watershed address," relates water resource concerns to one's nearby environment. Thus, environmental health for one's descendants is more likely to be perceived as a product of individual efforts in local communities rather than by centralized regional or national institutions. As U.S. Senator Kit Bond from Missouri stated in a recent press release, "I believe that a 'one size fits all' approach no longer works. I believe that states and localities, instead of Washington bureaucrats, are best able to make environmental decisions and set priorities." While this statement rings of political rhetoric, it was followed by the Senator's acquisition of $3 million in funds for the Missouri Watershed Initiative.

Enablers: Supportive Forces

Increasing Quantities of Resource Data at Large Spatial Scales

Satellites, aircraft, and ground-based instruments constantly collect data. At least 30 earth observation satellites and sensors were on observational missions in June 1999 using optical and near-infrared radiation and radar (active microwave) to generate visible images. The World Wide Web's remote sensing virtual library lists hundreds of sites for satellite data and remote sensing conferences, societies, documents, journals, news groups, and resources. An explosion of natural resource data is available as is the proliferation of regional and watershed scale assessments and plans. Paradoxically, even though remote sensing data has exploded in quantity, we still lack basic information on the status of resources that cannot be assessed using remote sensing such as the ecological condition of aquatic resources or status and trends in water quality (Paulson, 1998).

Increased Cooperation Between Organizations

Historically, myths, paradigms, and ideologies that represent special viewpoints drove institutions and organizations. When fewer paradigms exist and organizations work toward shared viewpoints, the flow of information and resources increases, learning occurs, and people coalesce toward action (Westley, 1995). In the 1990s, collaboration between natural resource agencies is being provoked, to a large degree, by downsizing and associated fund reductions and personnel. Whether stimulated by scarcity or perceived benefits, experienced watershed practitioners know that finding common ground through cooperation and building partnerships is leading to wider acceptance and quicker implementation of actions that benefit natural resources.

State and Federal Watershed Leadership

State Supported Strategies

State governments are now taking active roles in encouraging and requiring watershed management approaches, particularly for the reduction and elimination of nonpoint discharges to water. Kentucky, South Dakota, and Texas promote the use of statewide approaches; California and Oregon have assembled watershed-based project inventories and river information systems, while Massachusetts and Wisconsin have reorganized state agency structures to coincide with watershed or basin boundaries. The general trend is for states to take an active leadership role in resource management and to use watersheds as the basic planning unit.

Federal Strategies

Federal agencies, led by the authority and persuasiveness of the White House and the Clean Water Action Plan, are strongly supporting and advocating the use of watersheds (CWAP, 1998). The greatest federal emphasis is from the EPA's Office of Water. This office provides massive quantities of resource information related to watershed management in the form of publications, web sites, videos, training, and educational material. The monitoring aspect of watershed work is strongest from the U.S. Geological Survey's Water Resources Division and their NAQWA program, and on land technical assistance is the primary focus of the USDA's Natural Resources Conservation Service. The 1996 "Farm Bill" statute redirected financial support for conservation toward priority areas to better align resources with watershed planning efforts. The trend is clearly toward federal leadership in using watersheds as a basic planning unit.

Prospects for the 21st Century: A Potpourri of Opinions

The world is not run by thought, nor by imagination, but by opinion (Drew, 1926).

If indeed the world is run by opinion, what are our opinions with regard to how natural resources will be managed in the U.S. of the 21st century? Will a focus on watersheds influence scenarios for management? The authors used an informal query of opinions to gain some insights into these issues by asking knowledgeable professionals where they thought the nation might be and where it might go with regard to watershed management. Four questions were directed toward these professionals:

- How will people's attitudes toward natural resource issues change in the 21st century?
- What factors will cause those changes in attitudes?
- What do you think should be the primary role for the Federal government in watershed-based resource management in the 21st century?
- What motivations will encourage people to use a watershed approach in the 21st century?
- What will be the top three research needs for watershed management in the 21st century?

This was not a scientific study, thus no sampling techniques were applied. The authors received responses from 22 people from different areas of natural resource management. The individuals contacted work for a variety of governments and organizations including the Audubon Society, the Charles River Watershed Association, the Chesapeake Bay Commission, the South Florida Water Management District, Texas Natural Resources Conservation Commission, The Watershed Coalition, the University of Maryland, and the EPA among others. Many regions of the country are represented as well as job positions including policy makers, researchers, land managers, administrators, and natural resource managers. The synthesis of these conversations provides a compelling story about attitudes and societal direction for natural resource and watershed based activity for the 21st century.

Attitudes toward Natural Resource Issues in the 21st Century

In general, respondents described a strengthening in attitudes for natural resource awareness in the 21st century. Few consistent responses emerged about possible changes in citizen attitudes. Some believed that there will be a broadened focus on natural resources and an increasingly educated population will have a growing positive awareness of resource values. Some, but not all, thought these changes could relate to watersheds rather than political boundaries. A thread throughout the responses suggests that people will become possessive about natural resources and more demanding about their preservation and protection. This sense of urgency is countered by others who stated that environmental concerns will be lessened and more localized—a continuation of a current trend where people are now more interested in their backyards, less globally aware, and somewhat complacent. On the other hand, some thought that environmental awareness is now growing again in the late 1990s, after a strong beginning in the 1970s and a waning in the 1980s and early 1990s. Several said that natural resource issues might rise to a top priority.

Various rationales were given as to why people will become more involved, more focused and increasingly linked on natural resource issues. Changed attitudes and behavior will be the product of personal experiences, environmental education, media activity about ecological problems, and a result of technological advances that permit instant connections among a concerned citizenry. Respondents overwhelmingly believe that these changes will be driven by three primary factors: degradation of the environment, accompanied with associated declines in the quality of life; potential shortages of natural resources as commodities; and technological innovations that will keep decisionmakers and the public better informed.

Degradation of the Environment

Respondents felt that the public's witness of ecological degradation will help sharpen their viewpoints, especially degradation that results in decline of quality of life and increased costs of pollution control. Citizen attitudes will be influenced by personally experienced environmental degradation and impacts resulting from increased development, flooding, increased fragility of resources, more urban sprawl, loss of habitat, and more pollution problems moving from the city to rural areas, such as air pollution and poor water quality. Additionally, an increasing population will direct more and more pressure on natural resources. Some conjectured that these conditions would push people to seek solutions, such as more emphasis on protection of green space and natural habitat. People will become more informed about environmental issues and less tolerant of pollution. Attitudes in the 21st century may be further influenced by an expected clarification of the connection between degraded environmental conditions and negative human health.

Competition for Resources

Several respondents commented that people would view natural resources as commodities, with an increased eye to their extraction. Some stated that natural resources will simply become more limited, thus more expensive, and this scarcity will play an important role in a sharpened focus on them. One respondent thought a growing recognition that the "world is no longer empty" will be a major driving force, and that technology will be redirected toward conserving natural capital. In fact natural capital may be increasingly recognized as the limiting factor instead of more traditional measures of economic capital.

A number of respondents mentioned the increasing view of natural resources, especially water, as a commodity, and suggested that future debates will argue their true economic value. Expected population increases will demand more of these already stressed resources, and water scarcity will become a more crucial and controversial issue, especially in the more arid areas. The true costs for having abundant and clear water will sharpen the issue in the public's mind. Arid areas will seek more water, and those "areas of plenty" will view it more protectively, thus intensifying public debate and making a key natural resource the subject of intense economic concern. With increasing scarcity people may be willing to pay more for their consumptive use, but at the same time, more to protect them. Unfortunately, this protection could come mainly from an impetus to control resources rather than from an educated understanding of ecosystems.

Technological Contributions to Informed Decisionmakers and Citizens

Several respondents believed that the rapid availability of information to decisionmakers and citizens via new technology (i.e., the Internet) could affect what they know and understand and thus, influence their attitudes about natural resources. Computers and web sites will continue to provide increasing amounts of information on watershed issues, the overall environment, and environmentally induced illnesses. The availability of digital data should enhance availability and management of information for scientific evaluation and information sharing.

One professional suggested that technology breakthroughs might increase general knowledge and understanding of ecological impacts from different stressors on humans and other biota. This would result in greater abilities to intervene in ways that will achieve watershed management goals with a higher level of predictability. This broad and hopeful thought, one full of promise and challenge, might prove to be the most prophetic.

Future Role of the Federal Government in Watershed Management

Respondents thought that state and regional entities are best equipped to handle local issues and problems, but believed that the Federal government has several significant roles. The roles suggested are not necessarily new, rather the respondents' opinions of roles for which the national government is best suited. The majority of resource professionals contacted believed appropriate federal roles should be: a) providing funds and incentives while giving authorization to the states and regional entities; b) providing guidance and oversight, especially setting and regulating minimum standards; and c) facilitating complex, multiparty, integrated resource management plans. There were also minority opinions expressed that the Federal government should provide baseline information, inventory and disperse data, and be a "patron" for small watershed efforts.

Funds, Incentives, and Authorizations

Overwhelmingly, the respondents stated that the national government has a substantial role in funding the efforts of states and regional entities. One comment was "Many of the solutions are simply beyond the funding ability of many states in which the key natural resource issues are located." The general sense was that the government is going in the right direction with environmental mandates accompanied by funding. Support was also given for incentives and increased authorization to the states and regional entities to pursue local solutions to local problems. The respondents believed that these approaches should continue and be enhanced.

Provision of Guidance and Oversight

Contributors think that the Federal government should provide methods, protocols, and education, and in general, serve as a communication link for providing information across political boundaries. The government should also lead regional, state, and local governments to work cooperatively along watershed lines. Some respondents thought an essential role is providing oversight through establishing and enforcing broad-based standards, such as TMDL's (total maximum daily loads). Reasonable standards should be set by the national government, but a primary role should also be to bring constituents together to identify, analyze and solve natural resource problems. This is especially important for large basin issues with implications for regional and interstate water resource management.

Facilitation for Complex, Multiparty, Integrated Resource Management Plans

One respondent noted that a "forgotten" role of the national government is to provide focus on regional scale or interstate resource management issues. It was further emphasized that the government should be "emphasizing, encouraging, and insisting on integrated resource management." Integrated management was described as going beyond traditional concepts of watershed management as surface water control. The federal level should clearly understand and promote an ecological systems approach that integrates the interactions between all systems—physical, biological, and atmospheric.

Motivations to Use a Watershed Approach

Respondents thought that motivations to use a watershed approach will be strikingly similar to the factors cited as those most likely to change citizen attitudes about natural resource management in the next century. They believed appropriate motivations should be crafted around economic incentives, education, and regulation.

Economic Incentives

Clearly, the use of money as economic incentive was a recurring theme among the responses. Mini-grants and financial incentives for planning and watershed coordinators were discussed. Several respondents replied that economic logic is also an appropriate motivator. For example, watershed approaches have been demonstrated to be cost effective when the cost for not dealing with watershed issues is computed (i.e., pollution abatement, treatment facilities, remediation, and restoration costs).

Education

The most pervasive response to the issue of motivations was that education, in its broadest concept, was necessary. Citizens need to understand what watersheds are, how they can be used as a framework to balance differing resource concerns, and how their use would be beneficial to encourage collaboration and sharing of limited resources. Perhaps most importantly is the understanding that watershed system-based approaches could replace piecemeal, quick fix solutions that often generate worse conditions than originally present. Education could reduce lack of understanding about how total watershed systems react to intervention.

Regulation

A few respondents expressed strong belief that voluntary watershed management is limited in its ability to produce results. One person noted that "people are set in their ways; the Federal government must mandate—then the voluntary part will happen after that." Another noted that, "Many aspects of natural resources and the environment are essentially nonrenewable and must be proactively managed by those who are looking out for the long-term well-being of humans and other creatures."

Perhaps the most blunt, but true, response about motivations to encourage the use of watershed approaches was that, "Everything else that has been tried has failed; it is the only way to deal with cumulative effects. Watershed approaches will be successful when governments realize they are very effective tools to gather citizens toward action."

Research Needs for Watershed Management

The contributors provided a rich river of ideas about what watershed managers need under the general umbrella of "research," though most used a liberal interpretation of the term. There was little to no duplication of ideas, so clearly a great deal about the field and practice of watershed management is still to be learned. Respondents stated that more knowledge is needed in the inquiry areas of planning (tools, methods and protocols), basic research, and applied research.

Planning (Tools, Methods, and Protocols)

Several of the ideas involved planning tools to deal with the human elements of watershed work including how to change behavior and how to use communication techniques for effectively working with communities. Others focused on tools for more abstract processes such as developing ways to preserve natural resources along with quality of life and determining the effectiveness of controlled growth and land use planning.

Basic Research

Identified basic research needs included: (1) improved understanding of surface water and ground water interactions and their effect on stream ecology, and (2) improved understanding of the effects of low concentrations and mixtures of potentially toxic compounds interspersed with seasonal pulses of higher concentrations on aquatic organisms. Others focused on nutrient management from a watershed perspective: (1) transport, fate and effects of nutrients on stream ecology, (2) source and control of nonpoint bacteria and true relative risk, and (3) prediction of loadings of phosphorus and metals, and (4) better information on sources and controls of agricultural runoff.

Applied Research

Most responses dealt with application and the need for action-oriented guidance. One respondent stated emphatically, "We are a research happy nation—need to start applying the research we have." The applied research needs included: (1) cost effective water treatment technologies prior to discharge into natural systems, (2) decision tools that allow integration of natural resources with other activities so that system linkages can be portrayed, and (3) system tools for understanding urban ecosystems.

Predictions: A Summary

Does anyone have a crystal ball that will truly allow us to gaze into the next century with accurate predictability? Practically speaking, it is a great accomplishment if one can anticipate trends of the next 5 to 10 years. If current trends continue, it seems reasonable that the following will occur:

1. For privately owned lands, states will continue to support watershed organizational efforts, provide some financial incentives, coordinate with federal agencies, and orchestrate instate watershed management activities. Federal agencies will serve primarily in a technical support and facilitation role, provide some financial incentives, and continue to be active leaders in interstate and international efforts. On public lands, federal agencies will lead the planning and management activities, but with increased partnership from private land managers in the watershed.

2. States will increasingly adopt strong state statutes to require watershed planning and analyses, especially as it relates to the management of water resources. The Federal government will establish incentives for states to adopt strong statutes to support and provide oversight and guidance to watershed planning efforts.

3. The concept and practice of adaptive management will be increasingly critical and more frequently used in watershed management. Adaptive management starts with the recognition that the knowledge to predict the results of a resource management decision is often lacking. Major resource management decisions are approached similar to an experiment with monitoring and a process to evaluate results and modify the resource management plan in response to new knowledge.

4. Ecological sciences important to watershed management will continue to evolve at the same time as public agencies struggle with adaptive actions / reactions. Agencies will most likely still remain bogged down in inflexible policies and regulations; generally several steps behind leading edge of ecological knowledge.

5. Watershed planning processes will increasingly be bottom-up, locally based efforts that rely on strong citizen leadership and activism. Public dialog, ownership, and education will be critical. Nongovernmental organizations will increasingly build bridges to the public and be effective moderators between adversarial parties.

6. Interdisciplinary work will be absolutely essential in watershed management, and more 'nontraditional' and arcane disciplines will be needed to address increasingly complex issues.

7. Effective watershed management will require that scientists agree on definitions for "success" and "failure" and establish thresholds for tolerance. Monitoring and evaluation will become essential components of all watershed projects that involve ecosystem protection, modification, or restoration.

8. Scientists need to find more effective methods of explaining their work to reduce confusion and the fog factor for the public and decisionmakers using watershed approaches.

9. Ecological changes in watersheds and basins caused by cumulative, seemingly insignificant, human actions will continue to cause surprises and sometimes disasters.

10. Analysis tools, such as geographic information systems and remote sensing, will become more affordable, sophisticated, and commonly used in decisionmaking processes. At the same time these tools will become increasingly mobile and accessible to the public. The availability of data will increase exponentially as dependence on the information highway (Internet) grows. Watershed planning will be confounded by the vast amount of data available and practitioners will struggle with how to manage it effectively and in a timely manner.

The 21st century in the United States will be an ever changing ecological, economic, and social environment. If watershed management succeeds as a viable tool for managing natural resources, it will be because visionaries are attracted to the challenge and because organizations involved are highly adaptive, encourage shared collaboration, are constantly open to new sources of information, and strategically concentrate on processes that foster innovation and learning.

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Watershed Management Perspectives in the Southwest: Past, Present, and Future

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Abstract.—Watershed management perspectives in the Southwest have been, are, and will be reflected by the nature of watershed management practices. Past perspectives evolved from considerations of increasing water yields and water quality concerns. Present perspectives are centered on minimizing adverse impacts to soil and water resources, sustaining high-quality water flows, and rehabilitating watershed in poor condition. Future perspectives will likely focus on an increase in demand for watershed resources, more efficient use of limited watershed resources, and more efficient management of available watershed resources. These perspectives are more specific than global and national perspectives, which is expected when focusing on a specific biogeographic and socioeconomic setting.

Introduction

Watershed management perspectives presented at global and national levels also apply to the Southwestern region of the United States. Issues identified by Brooks and Eckman (this publication) at the global level, and Adams et al. (this publication) at the national level, such as water scarcity, water pollution, and a scarcity of land and natural resources, enhance consideration of past, present, and future watershed management perspectives in the Southwest.

At all levels of perspectives, watersheds are effective planning units for ecosystem-based, multiple use natural resources management practices, projects, and programs (Adams et al. this publication, Brooks et al. 1992, Lopes et al. 1993, and others). However, as pointed out by Adams et al., continued use of watersheds in a planning capacity will depend on whether natural resources management issues are prioritized by decisionmakers. In addition, the ability of competition for consumptive natural resource use, advancing appropriate technologies, and developing effective land-use policies to be adequately balanced will affect the continued planning use of watersheds. These are certainly relevant to the Southwest.

Past, present, and future perspectives of watershed management in the Southwest, reflected by the nature of watershed management practices, are considered in this paper. These perspectives of watershed management are more specific than global and national perspectives, which is expected when focusing on a specific biogeographic and socioeconomic setting.

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The Southwest Setting

The Southwest, which includes Arizona and New Mexico, and portions of Nevada and California, has broken and diverse topography. Isolated mountain ranges are separated by valleys, plains, or desert floors. Forest and woodlands cover the mountains, while mostly shrubland ecosystems and a diversity of floristic communities common to the warm-temperature Chihuhuan and Sonoran Deserts are found at low elevations. Soil parent materials are volcanic basalts, sedimentary rocks, and granitic in complex layers. These soils are shallow, often infertile, and moderately erodible.

The region receives an average of 330 mm of annual precipitation, mostly in 2 seasons. About 60% of the annual precipitation occurs in the winter, often as snow at the higher elevations. Winter precipitation is associated with frontal storms from the Pacific Northwest. The major source of moisture for summer rains is the Gulf of Mexico. As it moves into the region, this moisture passes over mountainous terrain, which causes it to rise, cool, and condense into intense, localized convectional rainstorms.

Mixed conifer forests of Douglas fir, ponderosa and southwestern white pine, white and corkbark fir, Engelmann and blue spruce, occupy 160,000 ha of wet, cool sites at the highest elevations in the region (2,100 to 3,000 m). Precipitation at these elevations averages 630 to 760 mm, of which more than half is snow. Streams originating above 2,900 m are often perennial, while those beginning at lower elevations are mostly intermittent. Preferring warmer and drier sites than mixed conifer forests, lower-elevation ponderosa pine forests occupy 2.4 million ha between 1,800 and 2,700 m. Annual precipitation on these sites averages 500 to 630 mm, equally divided between rain and snow. The mostly ephemeral streamflows originate largely from snowmelt.

Pinyon-juniper and evergreen oak woodlands occupy 8.2 million ha of intermediate-elevation lands between the higher forest types and lower desert ecosystems. Summer rains account for about half of the 300 to 450 mm of annual precipitation. Streamflows are generally less than 25 mm, although it can approach 75 mm on better water-yielding sites.

Interior chaparral shrublands cover about 1.4 million ha of discontinuous mountainous terrain south of the Mogollon Rim in Arizona; chaparral shrublands are limited in extent elsewhere in the Southwest. Average annual precipitation ranges from about 380 mm at the lower elevations to 630 mm at the higher elevations. Streamflows from these sclerophyllous shrublands average 25 mm, but varies greatly with precipitation, elevations, and soils.

Desert shrublands of numerous shrub species and cacti are delineated into northern and southern types. The northern desert shrub type is largely confined to elevations between 750 and 1,500 m, while the southern type is found mainly at elevations of 90 to 900 m. Annual precipitation ranges from 125 to 350 mm for the northern shrub type and 75 to 300 mm for the southern shrub type. Streamflow is negligible. Desert shrublands are adjacent to and often intermingle with desert grassland types at almost all elevations.

Riparian ecosystems (narrow bands of trees, shrubs, and herbaceous species along stream systems) are found throughout the region (Baker 1999, Baker et al. 1998). These ecosystems are often of special interest to the public because they consume large amounts of water (thereby reducing streamflows), represent conveyance systems for streams originating on upland watersheds, possess high scenic value, and provide critical wildlife habitats and recreational opportunities. Restoration of degraded riparian ecosystems is a high priority watershed management activity.

The Southwestern United States is one of the fastest growing regions in terms of human populations. Much of this continuing growth is due to the substantial migration of people into the region from the Midwest, the South, and elsewhere in the West. Although the population is concentrated in the larger metropolitan areas of Albuquerque, Phoenix, and Tucson, city dwellers escape the summer heat by traveling to higher, cooler forests. The Southwest enjoys relatively high incomes, low unemployment, and increasing amounts of leisure time. These conditions serve to accelerate the demand on the region's natural resources.

Past Watershed Management Perspectives

By the middle of the 20st century, when intensive management of watershed lands began in the Southwest, watershed management perspectives closely paralleled those at the national level (Neary this publication). It was thought, for example, that watershed management of forests, woodlands, shrublands, and untilled grasslands could be accomplished to improve water supplies. An early emphasis of watershed management was the importance of water as a commodity. Therefore, practices were largely centered on increasing water yields to downstream users through forestry-related and other vegetation management interventions. Intensive research efforts followed by operational programs began at this time and, to some extent, are still conducted on these important watershed-management topics.

Increasing Water Yields

Watershed management practices from the early 1940s through the beginning of the 1980s focused largely on increasing water yields through vegetation management on upland watersheds. Water-yield improvement tests were conducted on experimental watersheds located mostly in Arizona. If the experiments proved successful in increasing water yields, they were implemented operationally. Clearcutting, other silvicultural treatments, and conversions from high water-consuming vegetation to low-consuming vegetation were tested (figure 1). These experiments demonstrated that water yields originating on upland watersheds could be increased (to varying magnitudes and duration) by changing the structure and compositions of the vegetative cover on a watershed (Baker 1999, Baker and Ffolliott this publication). Additional water yields, when obtained, were attributed largely to decreases in transpiration rates.

An analysis by Hibbert (1979) showed that vegetative manipulations could increase water yields only on watersheds receiving more than 480 mm of annual precipitation. He reasoned that precipitation below this amount is effectively used by any residual overstory vegetation and subsequent increases in herbaceous plant cover on the watersheds. This finding, along with other analyses of water-yield improvement potentials, suggested that in the Southwest, high-elevation mixed conifer and ponderosa pine forests and portions of low-elevation chaparral shrublands have the best theoretical potentials for increasing water yields through vegetation management.

Figure 1. Heavy thinning of a ponderosa pine forest to increase water yields and enhance other multiple-use values.

However, beginning in the late 1970s, increasing environmental concerns have curtailed large-scale implementation of many of the vegetation management practices proposed for water-yield improvement.

Water Quality Concerns

Emphasis shifted by the late 1970s from strictly considering water-yield improvement to concerns about the quality of the water originating on upland watersheds; this remains the focus today (Ffolliott et al. 1997). Part of this concern evolved from the increased public awareness of environmental quality issues in natural resources management. This heightened level of concern is exemplified by passage of the National Environmental Policy Act, the Clean Water Act, and creation of the Environmental Protection Agency in the early 1970s. Watershed management took on the added dimension of ensuring that whatever practices were implemented considered physical, chemical, and biological qualities of water in steams from upland watersheds.

Present Watershed Management Perspectives

Watershed management perspectives in the Southwest are now largely framed by the watershed management approach to land stewardship, which recognizes the importance of land productivity as an integral part of watershed management. This approach incorporates soil and water conservation and land-use planning into a broad, logical framework by focusing on the influences of people; recognizing that the effects of these influences often follow watershed, not political, boundaries; and appreciating that actions taken on upland sites often impact downstream areas (Brooks et al. 1992, and others). Watershed management now recognizes the interrelationships among land use, soil and water, and the linkages between uplands and downstream areas.

Presently, watershed management practices are grouped into 3 general categories. These categories are practices that minimize any adverse impacts to the soil and water resources (thereby sustaining the status of watersheds in good condition), sustain high-quality water flows originating on upland watershed lands, and rehabilitate watersheds to increase productivity (Baker 1999, Baker et al. 1995, Lopes and Ffolliott 1992).

Minimizing Adverse Impacts

Because of fragile soils and limited water, it is important to protect the watershed lands in the Southwest from further deterioration of soil and water resources. Past degradation, often widespread, has been attributed to overgrazing, fire suppression, and both high intensity rains and prolonged droughts. Watershed management practices, similar to those used to prevent excessive rates of initial erosion, are implemented to reduce further degradation of watershed resources.

Road construction is prohibited in or near stream channels. When roads are closed to public travel, the roadways are seeded with herbaceous plant species to protect against erosion. Timber harvesting in the Southwest has recently been sharply curtailed, largely in response to environmental concerns. The limited logging that occurs is often restricted to periods of excessive rainfall. Livestock grazing and recreational use is continually monitored to determine if and when remedial actions should be taken to minimize the impacts of these land uses on stream channels, riparian ecosystems, and water quality. Prescribed burning and a variety of mechanical control treatments are imposed to reduce excessive fuel accumulations on sites prone to wildfire (Edminster et al. this publication). These actions are essential components of integrated watershed management to maintain watersheds in a good condition; accommodate ecosystem-based, multiple-use management programs; and address the increasing public concern about threatened and endangered plant and animal species.

Sustaining High-Quality Water Flows

Sustaining high-quality water flows from upland watersheds is a major focus of watershed management. Water shortages, always present in the Southwest, will likely become even more limited in the future as human populations increase. While large-scale manipulations of vegetative cover to specifically meet past water-yield improvement objectives are not planned, a custodial management strategy to maintain the health of the forests, woodlands, and shrublands in the region is paramount (Baker 1999). These management practices, once again, are consistent with sound land stewardship.

Best Management Practices (BMP) are often selected as the approach to sustaining high-quality water flows. The BMP approach involves identification and implementation of watershed management practices to reduce or prevent nonpoint pollution (Brown et al. 1993). Many of these practices are well known for erosion-sedimentation processes concerning agricultural, forestry, and road construction activities (Brooks et al. 1997). The BMP for mitigating some types of pollutants, however, are not known.

Watershed Rehabilitation

Concern for the declining health of watershed lands has led to implementation of management practices to restore the proper hydrologic functioning of degraded watershed lands. Management practices to rehabilitate watersheds in poor condition include controlling gullies and mass wasting with properly constructed check dams and other mechanical controls; protecting unstable stream channel from further damage (figure 2); establishing protective tree, shrub, or herbaceous covers on degraded sites; and further curtailment of timber harvesting, livestock grazing, and other exploitative land-use practices. Presently, restoring riparian ecosystems to retain their hydrologic equilibrium is a major focus of watershed management (Baker 1999, Baker et al. 1998).

In the Southwest, artificial seeding of herbaceous plant species on degraded watershed sites has been studied for nearly a century. Thames (1977), Cox et al. (1984), Oechel (1988), Roundy (1995), and others found that a variety of perennial grasses and forbs can be successfully established on sites needing rehabilitation. The results of these studies provide managers with information necessary to restore severely degraded watershed lands to more productive conditions by establishing a protective vegetative cover. Even though revegetation is difficult and costly, it is possible. However, frequent drought and continual human abuse of some lands continues to cause the deterioration of fragile watersheds through accelerated erosion, invasion of noxious plants, and reduction of plant growth in general.

Many sensitive ecosystems in the Southwest are delicately balanced within an environment having limited water and a highly variable climate. This balance has frequently been overwhelmed by past land-use practices, resulting in severe and widespread watershed degradation. Careful implementation of watershed and hydrologic information has successfully restored some highly

Figure 2. Protecting unstable stream channels by placing rocks on channels walls.

degraded sites. However, more intensive applications of known technologies will depend largely on a more thorough understanding of the fundamental hydrologic processes operating in this unique environment.

Future Watershed Management Perspectives

Future watershed management perspectives in the Southwest, and elsewhere in the nation, will likely represent a more holistic approach to managing the biological, physical, and social elements on a landscape delineated by watershed boundaries. Watershed management practices must be based on the art and science of managing natural resources on a watershed-basis to provide goods and services to society without adversely affecting the basic soil and watershed resources. Watershed management in the Southwest must broaden its traditional focus on wildlands to include the urban fringe and urbanized areas to content with anticipated population needs.

Continuing Emphasis on Watershed Improvement Practices

Future watershed management practices will continue to minimize adverse impacts, sustain high-quality water flows, and rehabilitate watersheds in poor conditions. It is likely that these practices will be intensified as continuing monitoring activities indicate that additional watershed lands require remedial actions to restore properly functioning hydrologic processes (Baker et al. 1998). Implementation of BMP should help achieve these objectives.

Increasing Emphasis on Demands for Watershed Resources

Much of the watershed-research effort in the past and, to some extent, in the present has focused on the supply-side of watershed management; for example, attempting to increase high-quality water flows from watershed lands. Other approaches to increasing water supplies have also been explored including water harvesting and spreading, gaining access to deep aquifers, increasing storage reservoir capacities, and changing storage techniques to reduce evaporation (Gregersen et al. this publication). These supply-side efforts will continue to be a focus of watershed management where realistic opportunities are present. However, watershed management practices must also emphasize the demand-side of the resource-availability equation.

Efficient Use of Limited Watershed Resources

The benefits of watershed management will become evident through increased efficient use of the limited watershed resources in the Southwest. To paraphrase Gregersen et al. (this publication), greater efficiency in watershed resources use is likely to be attained by changing technologies to those that more efficiently and effectively use these resources. Providing people with greater responsibility over their use of limited watershed resources to encourage conservation is also needed. Increasing the prices of watershed resources (water, timber, livestock forage, wildlife habitats, and recreational opportunities) to reflect their true scarcity-value and the costs of supplying them, is also necessary.

Efficient Management of Available Watershed Resources

Focusing on improving management of available (existing) supplies of water and other watershed resources despite progress made to increase the supply or reduce the demands for these resources will be necessary. More effective applications of known technologies should be encouraged; watershed-management technologies must be improved; effective technology transfer mechanisms should be developed; and increased public awareness of the need to balance the economic and environmental values of available watershed resources will be required.

Summary

Past perspectives of watershed management in the Southwest evolved from a desire to increase water yields to addressing water quality concerns. Present perspectives are centered on minimizing adverse impacts to soil and water resources, sustaining high-quality water flows, and rehabilitating watersheds in poor condition. Future watershed management will likely become more holistic than what presently exists. This will occur through increased emphasis on the demands for watershed resources and more efficient use of limited watershed resources and management of available watershed resources. With broad public participation, this integrated vision must be the future focus of watershed management to effectively respond to people's concerns about improved land stewardship in the 21st century.

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Watershed Management and Sustainable Development: Lessons Learned and Future Directions

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Abstract.—A fundamental belief underlying the direction and content of this paper is that the paradigms of land and water management evolving into the 21st century increasingly favor a watershed focused approach. Underlying that approach is an appreciation of the processes of sustainable development and resource use. The increasing recognition that sustainable development and sustainable ecosystem management are processes rather than end states, is coupled with an increasing awareness that these processes are fraught with uncertainty, and that cumulative effects matter. This recognition opens a number of new doors in terms of participatory adaptive management. Practical strategies for dealing with uncertainty and avoiding unsustainable development include more coordinated policies and programs that link distinct political entities; greater flexibility in planning and management; complementing technical appraisals with socioeconomic assessments; using interdisciplinary and participatory planning approaches at all levels; and precautionary monitoring with early warning signs.

Where Are We Going?

General Trends in Watershed Management

A recent USDA Forest Service report stated:

> "Throughout their history, conservation science and sustainable-yield management have failed to maintain the productivity of living resources. Repeated overexploitation of economic species, loss of biological diversity, and degradation of regional environments now call into question the economic ideas and values that have formed the foundation of scientific management of natural resources. In particular, management efforts intended to maximize production and ensure efficient use of economic "resources" have consistently degraded the larger support systems upon which these and all other species ultimately depend." (Bottom et al. 1996).

We learn from our past mistakes and move forward, hopefully, with greater wisdom and experience. A fundamental belief underlying the direction and content of this paper is that the paradigms of land and water management evolving into the 21st century increasingly favor a watershed focused approach. The logic of using a watershed management approach as the unit of management has been well documented, and encompasses multiple technical and socioeconomic dimensions. Underlying that approach is an appreciation of the processes of sustainable development and resource use. While all is not rosy and nice in the world, we see some fundamental trends that are leading toward a more sustainable management of our natural resources and ecosystems.

Greater emphasis also is being given to decentralized, participatory approaches to land use planning and management, ones that (1) are sensitive to the interests of a wider range of stakeholders, (2) recognize the need to deal in an open way with the tradeoffs that inevitably exist between maximizing production and environmental conservation, (3) introduce novel and more effective conflict management approaches from a sustainability perspective, and (4) recognize the right of future generations to inherit a landscape that is still productive, both in terms of producing goods and in terms of supplying needed environmental services. There is now much greater sensitivity to the positive "externalities" associated with proper natural resources use: clean and adequate water supplies, ecosystem protection from adequate instream water flows, access to biodiversity, carbon sequestration and so forth.

Lant (1999) points out that there are now more than 1,500 locally-led watershed management initiatives in the United States, almost all established since 1990. These types of initiatives focus on (1) a watershed or landscape level rather than small area or plot level planning and management, (2) interactions between resources and their uses and the impacts of such uses, including downstream, and (3) the nonmarket costs and benefits (particularly the environmental services) associated with land use.

These evolving approaches recognize that sustainable land and water management is a process and not an end state that can be defined. This recognition opens a number of new doors in terms of *participatory adaptive management (PAM)*, including those associated with the model forest program introduced in Canada and now spreading to other countries, participatory approaches used in developing countries, various integrated natural resources management programs in the U.S., and the ecoregional

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approaches introduced by a number of groups around the globe. The increasing recognition that sustainable development and sustainable ecosystem management are processes rather than end states, is coupled with an increasing awareness that these processes are fraught with uncertainty, that cumulative effects matter, and that there is need for flexibility in planning and management. The sum of these merging themes leads land and water managers to a fundamental conclusion: "Sustainable development" is a useful term in political and high-level policy discussions, and participatory adaptive management is a useful operational counterpart for management. In the sections that follow we attempt to weave these basic concepts together into a view of where we should be going, based on the lessons from the past.

Principles of Sustainable Development

Sustainable development can be defined as using watersheds and forests to produce goods and environmental services that increase or maintain the welfare of people today, while protecting the environment and natural resource base, on which future production will depend, for future generations (Gregersen et al. 1998). This concept of natural resource sustainability is not new. It has its roots in concerns during the 1800s about perpetuating the forest resource base of countries in Europe, and a growing concern about the dwindling timber supply in this country. In his presidential message of December 2, 1901, Theodore Roosevelt asserted: "The fundamental idea of forestry is the perpetuation of forests by use. Forest protection is not an end in itself; it is a means to increase and sustain the resources of our country and the industries which depend upon them." (Pinchot 1947, p.190). The president also emphasized the importance of protecting water supplies. This early vision recognized the need to sustain natural resources in order to be able to meet the present and future needs of people dependent upon them. Gifford Pinchot, first Chief of the U.S. Forest Service, became an influential advocate of this conservation philosophy: "The conservation of natural resources is the key to the future. It is the key to the safety and prosperity of the American people, and all the people of the world, for all time to come. The very existence of our Nation, and of all the rest, depends on conserving the resources which are the foundations of its life." (Pinchot 1947, p. 324). This conservation philosophy, rooted in concerns about perpetuating natural resources to meet basic needs of people, guided much of the early science and practice of forestry and watershed management. Today it has evolved into the wider concerns of sustainable development.

Our past work has uncovered some basic principles of sustainable development:

An interdisciplinary approach is essential. The sustainable management and use of natural resources involves the interaction of human society with the biophysical environment. A wide range of scientific disciplines is required to understand and address the problems involved in anticipating and solving sustainability problems.

Sustainability is a process, not an end state. Developing sustainable natural resource management and use requires viewing sustainability as a process, not as an end result. Policies and programs designed to promote sustainability are faced with continuing changes in physical, biological and social conditions over time, and must adapt to such changing conditions.

Sustainability has spatial and temporal dimensions. Sustainability policies and programs typically have distinct spatial boundaries within which they are to be applied — a watershed, a village, a state. Yet exchanges and movements of materials, energy, people, goods, and services, take place across any arbitrary boundaries that may be established. Further, although policies and programs have fixed spans of activity, their direct results and indirect or second-order consequences are likely to continue far into the future. Both spatial and temporal externalities and indirect consequences should be anticipated and taken into consideration in designing sustainability policies and programs. In doing so, physical, biological, cultural, and political realities must be recognized.

Distributional consequences must be considered. Changes in natural resource management and use to better address sustainability issues inevitably involve changes in who benefits and who bears costs in society, both now and in the future. Such changes in the distribution of costs and benefits among individuals and groups in society should be anticipated and evaluated before decisions are made about proposed policies and programs.

Consistency and stability of policies and programs are necessary. Some degree of consistency and stability in the external and internal operating environment is necessary. This includes consistency and stability in policies and programs, and in the availability of funding and capital resources, natural resources, and knowledgeable and skilled people. Some change is tolerable, and perhaps beneficial if you can adapt to it, but major unexpected changes may inhibit continued functioning of the existing system, or even lead to its eventual failure. Repeated shifts of missions, goals, and operating environment in response to changes in key managers and policy makers, may make it difficult if not impossible to achieve sustainable development.

Because outcomes of policies and programs are uncertain, *monitoring is essential.* It is difficult to know with any degree of certainty just what will be the outcome of various policies and programs designed to support sustainable development, particularly the farther we get into the future. Because of this inherent uncertainty, an effective program of monitoring must be established to provide the information needed to guide changes in policies and programs.

Learning and adapting must be continuous. Some form of adaptive management, an integrated system of identifying and responding to change (Holling 1978; Walters 1986), is needed. Attempts are being made to incorporate this new approach into public land management (e.g., Bormann et al. 1994).

Policy and practice must be compatible. Too often policies are designed at a level far removed from those who will carry out the intended practices, disregarding the realities faced by those who must actually carry out the work on the ground.

Coordination among governmental levels and responsible agencies is essential. Policies and programs among governments and agencies with related responsibilities must be coordinated. Jurisdictional and other conflicts must be resolved promptly.

How Do We Get There?

Processes and Practices for Implementation

Moving toward sustainable development requires us to first conceptualize some general principles of sustainability, as we have done above. Then, we need to put into place some practical processes and mechanisms to implement policies and programs that foster sustainable outcomes. In this section, we suggest some strategies, processes and practices for implementation (appendix 1).

All of us are accustomed to dealing with the technical aspects of watershed management, but less so with socioeconomic aspects. In our experience, we have found that the more successful policies and programs in terms of sustainable outcomes are those that consider both the technical and human dimensions of watersheds. First, *identifying stakeholder and natural resource user groups is essential.* We cannot assume that all people living in a watershed will benefit equally from our actions, or that they have the same land use practices, needs and priorities.

It isn't only those living within a watershed that are affected by particular policies and programs. Some who live outside may be affected too, and need to be consulted. Also, some policies, programs and activities outside of the boundaries of the watershed affect people living within the watershed, and may affect their activities as well. In other words, it is well to recognize that when we discuss watersheds, we are talking about an open system, not a closed one — one that is open to physical, biological and social interchange with the exterior world.

Consequently, *a baseline socioeconomic and technical assessment should be a fundamental step in the planning process,* so that we can identify various stakeholder groups, understand the overall policy context, estimate possible distributional effects, and ultimately compare outcomes with pre-existing conditions for various watershed users. Such baseline studies do not need to be costly or complicated. Many newer rapid socioeconomic assessment techniques now exist that integrate both quantitative and qualitative data, and that can complement other technical and economic assessments for more informed decision making.

Second, *forward-thinking and creative planning enables us to visualize what a sustainable outcome would look like.* We can use adaptive, participatory planning techniques to think in an integrated, multidisciplinary way about outcomes. Ideally, how should this watershed look in another generation or two? What are unacceptable outcomes for agencies, watershed users and residents? Local communities can help us to set broad goals and objectives, and to understand local issues and conditions that outside planners and experts may not anticipate. New approaches to joint planning of natural resources projects have been developed and tested, and can be applied to watershed management. Once we have a future vision and broad goals and objectives that are defined jointly by agency planners and communities, we can work backwards through time to set a work plan and timetable.

Third, we tend to think of decision making and management at discrete levels of responsibility. However, *watershed management can most effectively play a role if there are effective measures and decisions being taken at all levels in an integrated fashion.* Policies and institutional arrangements are needed at the highest levels of government, yet local governmental levels and citizen participation are also essential. Both ends of the spectrum are necessary, but coordination and mechanisms for joint decision-making and management are often the critical missing links. A watershed perspective that overarches individual land uses and landscapes has long been needed to deal with watershed dimensions that extend beyond local communities, such as cumulative watershed effects, externalities, and inequities between upstream and downstream users.

Fourth, while managing for sustainable development provides a proactive and positive policy perspective in watershed management and natural resources programs, in fact, from an operational perspective, *the focus should be on managing to avoid unsustainable development as we move along the path of development.* We can avoid unsustainable development by thinking about what might go wrong, and anticipating unplanned consequences. Sometimes problems and issues arise that the project planners did not anticipate years after a watershed project is implemented.

Fifth, to minimize possible externalities, *consider the law of unexpected consequences:* any human action will result in unexpected consequences (Lundgren 1976). Given that unexpected impacts will almost certainly be felt, have a process with clear procedures in place to deal with problems (Lundgren 1983). *Establish a precautionary monitoring system for both technical and socioeconomic aspects*, that looks for changes in both positive and negative directions (Eckman 1994). We can identify early warning signs and indicators of unsustainability that will inform us if project impacts and outcomes are moving in an unacceptable direction (Eckman 1994). Finally, *conduct an ex post evaluation* when the project is terminated so that we can benefit from accumulated professional and technical knowledge and experience.

Who Does It And Why?

An important lesson from past projects and policies is that resource managers now have a far greater appreciation for the socioeconomic and cultural aspects of watershed management. In particular, we now know that the range of stakeholders in a watershed is far from homogeneous, and impacts are felt differently by various stakeholder groups at different locations on the watershed. We also have a greater appreciation for the importance of involving those various stakeholders in planning and management decisions, no matter how difficult or contentious that process may be.

There is a need for civil society to be involved in watershed management to capture a wide array of values, needs and opportunities. In the United States, there has been an explosion of new partnerships between local citizen groups and agencies to manage natural resources. One such approach, participatory adaptive management, stresses monitoring, evaluation and adjustment (Shindler et al. 1999), with citizen groups playing a major role in monitoring various ecosystem and watershed components.

Many watershed projects now emphasize citizen science and participatory monitoring with the involvement of local groups. However, this process needs to be guided by watershed professionals through an educational component. Effective participatory monitoring means that people understand what they are measuring and why, how to correctly monitor for different purposes (e.g., compliance, cause and effect relationships, background monitoring, etc.), and how to analyze, use, and apply the monitoring information. When properly done, participatory monitoring can greatly assist watershed professionals, and serve to educate the public about watershed management and water quality issues. Citizen science can never replace professional watershed monitoring, but can complement and reinforce the work of watershed professionals if done under expert guidance.

In Minnesota, for example, such partnerships between public agencies, scientists, and communities have resulted in successful watershed and wetland projects at Lake Phalen in St. Paul, and Cedar Lake in Minneapolis. Volunteer groups monitor water quality at Bassett Creek and Kasota Pond under the guidance of scientists, and are compiling a quaternary history of Bridal Veil Creek. In Canada, innovative model forests integrate agency and private expertise.

These partnering arrangements bring educational, recreational and aesthetic benefits to local communities. They enable public agencies to reduce some human resources costs, while gaining additional information including rigorous quantitative data. Informed and active public citizens lobby legislatures and other policymaking bodies for funds to conserve and protect water resources. At least 768 volunteer monitoring programs exist in the United States, and data from these efforts are used for research, watershed planning, land use decisions, enforcement, education, and other purposes (Volunteer Monitor 1998). New publications such as *The Volunteer Monitor* and the *Conservation Volunteer* have evolved to meet the joint information needs of local groups conducting citizen science, and of technical experts wanting to partner with community members.

In developing countries, there is increased recognition that significant numbers of the rural poor continue to live in poverty, and that the impacts of natural resource and watershed management programs have not been beneficial or sustainable in many cases. In addition, there is increased realization of the negative impacts of conflict on watersheds, and that such conflict leads to unsustainable land use and degradation. In response, donors and nongovernmental organizations (NGOs) have evolved new participatory strategies to improve the positive impacts and sustainability of policies and programs. There has been a clear trend toward decentralization of natural resources planning and management in many countries for at least two decades. Such methods are at least in theory more democratic than conventional top-down, logical framework planning methods. Partnering arrangements between NGOs and local community groups are now very common, with the NGOs playing a major facilitative role at the program level, and a strong intermediary role at the international and national policy levels.

There is an array of facilitative approaches and methods that have been developed and tested by NGOs in the tropics. For example, participatory assessment, monitoring and evaluation (PAME) developed by the United Nations Food and Agriculture Organization has been widely tested and successfully used (see, for example, FAO 1989 and 1990). There is much that western scientists and public agencies can learn from the experience of our colleagues in the tropics about participatory approaches to watershed and natural resources management.

Creating a Policy Environment

Political boundaries and operational decisions seldom respect watersheds, yet good watershed management focuses on the whole system, not just part of it. Thus, management decisions to ensure sustainable development (or avoidance of unsustainable development, in an operational sense) need to be framed within institutional and policy arrangements that link watersheds with distinct political units. In practice, arrangements that have been used successfully in the past include user associations, river basin commissions, and farmers' irrigation associations.

It goes without saying that the integrated watershed management approaches discussed at this conference need to function in a policy environment that support their effective implementation. Participatory adaptive management approaches, ones that involve greater decentralized input from a broader segment of civil society, require some changes in the public policy environments that frame what can and cannot be done and what kinds of incentives exist to encourage participation.

Governments have three basic sets of policy instruments or mechanisms that they can use. They can: (1) introduce regulations and laws that specify what can and cannot be done and what has to be done by citizens and private organizations, (2) introduce financial and fiscal incentive mechanisms that motivate private action (subsidies and taxes are common examples); and (3) invest in public management and facilities (provision of information, e.g., through research and education, management of public lands, investment in infrastructure, and protection of citizens and their property). These three types of instruments commonly are used throughout the market economies of the world.

So what needs to change? How does the policy environment have to adjust if the new participatory adaptive watershed management approaches to sustainable development are to succeed? The following bullets just touch the surface of the complex interwoven policy changes that are needed:

- Encouraging effective participation of citizens in resources management requires good, relevant information that is accessible equitably to a wide variety of stakeholders. Investment in public research and information dissemination are key public policy elements.

- Innovative public financing mechanisms are needed for some key activities within the broader context of integrated watershed management, particularly those that involve public goods and common property management. Governments have bonding authority, and the ability to divert tax revenues into key sustainable development activities and watershed management programs. There are many other ways in which financial and fiscal policies can be used to ensure effectively funded PAM.

- PAM involves a lot of different people with different views. Public sector policies can contribute to improving facilitation of consensus building among the participants by providing incentives for groups to reach consensus on key issues.[1]

- Because sustainable development has both temporal and spatial implications, public policies have to be sensitive to both dimensions. Further, public policies should be designed to ensure safeguarding of resources for future generations. The use of best management practices (BMPs) in timber harvesting accomplish this objective, as do a number of other possible policy instruments.

- Means are needed to pay landowners and others for the positive environmental services they provide through various forms of resource management. (Note that this is a different concept than providing "subsidies" for private landowners who contribute to the social good through improved management). Tax rebates and low interest loans are merely two ways in which the public sector can transfer some of the costs of management from private to public sectors.

- Finally, and related to several of the points above, public policies need to provide appropriate regulation and guidance for activities involving common property resources and production of public goods. Such policies, including ones that involve co-management between public and private sectors, should attempt to turn open access resources into common property resources or lead to privatization where such makes sense from a public good perspective.

[1] *The Consultative Group on International Agricultural Research (CGIAR) with its 16 centers worldwide operates entirely on the basis of consensus. Dr. Ismail Serageldin, Vice President of the World Bank and chair of the CGIAR, likes to point out to the members of the Group that consensus means "I can live with the decision," not necessarily that "I like the decision."*

Summing Up

There are often many positive aspects and complementarities between socioeconomic and environmental goals and actions. The United States with its strong, growing economy has actually improved its natural resource base and the sustainability of its resources. This has been achieved through a mix of policies, incentives, and the organized and innovative efforts of water users at the local, state and national levels.

Traditional watershed management depended upon top-down planning methods by technical experts. We now know that technical expertise is necessary but not sufficient; we also need citizen participation in planning, decision-making and implementation. We now know that sound decision-making needs input at multiple levels: from policymakers, technical experts, *and* local users. To move towards sustainable development, watershed management can most effectively play a role if there are effective measures and good communication at all levels.

Finally, we have observed that sustainable development is a process, not an end state. As such, policies and programs must be flexible, and adjust to changing conditions. We also recognize a need to shift our goals and objectives from *outputs* to *outcomes* in order to achieve sustainable development. A key operational guideline is to avoid unsustainable outcomes, and to monitor closely for both technical and socioeconomic impacts and trends throughout the life of a project and beyond.

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Appendix 1. Dimensions of Sustainable Development in Watershed Management

Nature of the Watershed Policy or Program Impact

- Who/what specific groups are affected (e.g., us/them, poor/wealthy, etc.)
- How does the impact affect us? (Of what importance are the impacts?) Is the scale of impact beyond our control?
- Trend (What is the general direction of change?) Is there a general negative or positive trend in human well-being, or in the condition of natural resources? Is the impact positive or negative in terms of its contribution to sustainable development or its contribution toward avoiding unsustainability?

Spatial Scale of the Impact

- Level (Are the impacts felt globally, nationally, or locally?)
- Location (Where are the impacts felt, e.g. upstream/downstream?)
- Extent (How widespread are the impacts; do they occur beyond the project domain?)
- Intensity of the impacts (how strong are the impacts per unit area and time?) It is also important to determine whether the impacts are direct or indirect, primary or secondary. It is under this heading that the concept of externalities comes in, or the idea that a project has impacts that are external to the decision framework of the project manager.

Temporal Dimensions

- When are the impacts felt (e.g., right now or next generation)
- Incidence (pace or rate of change) of the impacts (How quickly are they disseminated?)
- Duration of the impacts (How long do they last?)
- Frequency (periodicity) (How often they occur?)

Source: Adapted from Gregersen and Lundgren 1993; and Eckman 1994

SYNTHESIS PAPERS

Issues to be Confronted in the 21st Century

Watershed Challenges for the 21st Century: A Global Perspective for Mountainous Terrain

Roy C. Sidle[1]

Abstract.—Three global challenges for watershed researchers in the 21st century are examined in this paper. These challenges are obtaining better assessments of terrain stability; understanding hydrologic responses at different watershed scales; and developing better methods for analyzing and assessing cumulative watershed effects. These topics are only a subset of the pressing issues facing watershed management in the coming century. However, they are important examples in the continuum from contributing processes (landslides), driving mechanisms (hydrologic response), and integrated watershed behavior (cumulative watershed effects). Emphasis will be placed on examples and needs in steep forested watersheds in considering these challenges.

Introduction

Watershed management is a highly interdisciplinary field. Hydrologic behavior in watersheds is complex, and is controlled by interactions among physical, geomorphical, biological, and geochemical processes. Planning and decision making in watersheds must also consider socio-economic and political objectives in the broader context of land use practices, allocation, and regulation. Within such an integrated perspective, it is important to remember that the primary driver in watershed systems is *hydrologic response*. Especially when considered from the viewpoint of small watersheds, such response controls the timing, amounts, and fluxes of water, nutrients, sediments, organic material, and pollutants to larger watersheds and drainage basins; as such it is the driver. Without understanding the controls on these materials, it is difficult to formulate prudent long-term management decisions and policies in watersheds. An outline of this simple conceptual model of integrated watershed management is presented in figure 1.

Both spatial and temporal distribution of land uses must be considered in watershed management. The concept of *cumulative watershed effects* (Sidle and Hornbeck 1991) addresses these spatial and temporal dynamics in the context of natural ecosystem processes. While empirical approaches have been developed by land management agencies and private sector organizations in response to legislation that requires assessment of cumulative effects, a sound approach to analyzing cumulative watershed impacts based on hydrologic response at different scales is lacking. Certainly, many of the cumulative effects issues are site-specific and, thus, need to be addressed in a local context; however, more general approaches can be taken for certain processes-based cumulative effects.

Three global challenges for watershed researchers in the 21st century are examined in this paper; this examination is based on the integrated watershed model in figure 1. These challenges are obtaining better assessments of terrain stability; understanding hydrologic response at different watershed scales; and developing better methods for analyzing and assessing cumulative watershed effects. These three topics are only a small subset of the pressing issues facing watershed management; however,

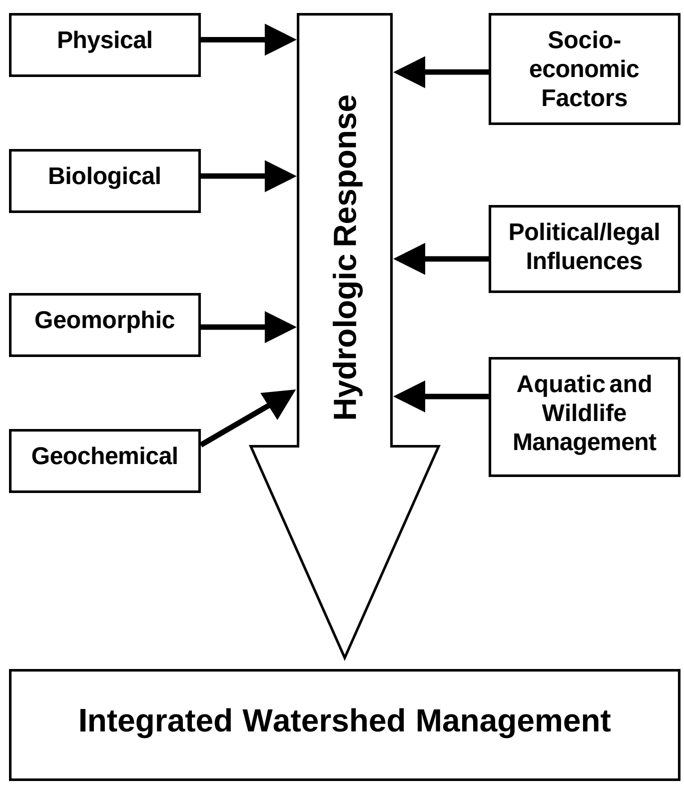

Figure 1. A conceptual model of integrated watershed management.

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they do represent important examples in the continuum from contributing processes (landslides), driving mechanisms (hydrologic response), and integrated watershed behavior (cumulative watershed effects). Emphasis will be placed on examples and needs in steep forested watersheds.

Terrain Stability

Timber harvesting, road construction, and certain types of vegetation conversion practices have been empirically demonstrated to increase landslide occurrence. Processes that influence this increase in landslide activity are known to vary with disturbance type. Increases in shallow landslide occurrence and volumes have been observed 3 to 15 years after timber harvesting in many areas worldwide (Bishop and Stevens 1964, Fujiwara 1970, Swanson and Dryness 1975, O'Loughlin and Pearce 1976, Megahan et al. 1978). The timing of landslide initiation corresponds to the period of significantly reduced root strength after logging and the occurrence of a major storm or snowmelt event. The conversion of forest and brushland vegetation to pasture or grassland has been shown to significantly reduce rooting strength in the soil and, in steep terrain such as parts of New Zealand (O'Loughlin and Pearce 1976) and southern California (Rice et al. 1969), has substantially increased landslide frequency and volume. Similarly, slash and burn agriculture practices used in developing regions of Asia and Latin America reduce site stability when steep forest lands are converted to temporary cropland with weak root strength characteristics (Wright and Mella 1963, Starkel 1972). Road systems in steep forest terrain are the largest contributors of landslide erosion on a unit area basis and, in many cases, the primary contributor overall (O'Loughlin and Pearce 1976, Sidle et al. 1985). Stability problems associated with forest roads include overloading effects on the embankment fill material, placement of unstable fill material on steep slopes, undercutting the hillslope, and redirecting road drainage water onto unstable portions of the hillslope or fill material. The later problem, road drainage, is commonly blamed for many road-related failures but is quite difficult to predict due to the complex nature of drainage systems, imperfect knowledge of road hydrology, and problems associated with drainage system failure (clogged cross drains) during runoff events.

Predicting Slope Failures

Given our knowledge of these management effects on slope stability, we have not been particularly successful at predicting where slope failures will occur, what the downslope or downstream impacts will be, or even estimating the increase in overall probability of slope failure related to various management activities. At the landscape or large watershed level, terrain evaluation procedures have been developed that utilize topographic and geologic information to provide broad categories of landslide hazard related to potential harvesting, road building, and other management activities (Gage and Black 1979, Howes and Kenk 1988). In regions where good site data and landslide records are available, the effect of land use can be evaluated by weighted multi-factor overlays (Nielsen et al. 1979, Hicks and Smith 1981). Both of these terrain assessment methods are qualitative and successful application relies heavily on expert knowledge.

Potentials exist for improving qualitative terrain assessment procedures. One possibility would be to include weighted factors into the terrain stability assessment that reflect not only terrain attributes associated with landslides, but also that emulate the underlying processes that contribute to slope failure. Such causative factors as rainfall intensity and duration, seismicity, and snowmelt, and other parameters influencing landslide potential (root strength, slope gradient, topographic expression, groundwater concentration zones) may need to be incorporated into terrain hazard analysis. Another needed improvement is the application of stability assessment methods to larger geographic areas or to areas that experience multiple failure types (slump-earthflows, debris avalanches, etc.).

An example of a simple GIS-based terrain hazard analysis applied in the Ramganga Catchment of the Lower Himalayas (Gupta and Joshi 1990) is shown in figure 2. Weightings for various factors used in the analysis are shown in parentheses, with larger weights representing more unstable conditions. In this region, earthquakes and rainfall trigger landslides. However, because of the paucity of spatially distributed data (particularly in steep mountain regions), causative factors were not included in the analysis of landslide hazard potential. Also, the assessment only incorporated recent and older failures, that is, not potential failures; thus, slope gradient was not included. This important parameter together with information related to vegetation, topographic expression, and causative factors would obviously improve the GIS hazard zonation especially if inferences on future land use changes are desired. Suggestions for improving the terrain hazard analysis are incorporated in figure 2 in the stippled boxes. As better remotely sensed data for some of the causative and related factors become available, such improvements for remote regions and developing nations can be feasible.

The U.S. Geological Survey developed an advanced, real-time forecasting system for shallow landslides in the

San Francisco Bay area. This method uses terrain attributes together with established rainfall intensity and duration thresholds for initiation of debris flows on susceptible slopes in the region. These thresholds were then linked with real-time rainfall data to develop a warning system for landslides during major storms in the region (Keefer et al. 1987). While such an advanced warning system is dependent on spatially distributed, accurate, and timely dissemination of triggering data (rainfall, snowmelt, seismic activity), it is possible that similar applications could be successful in densely populated regions where local governments made commitments to support regional networks of remotely accessed triggering and antecedent moisture data. Real time rainfall forecasts using Doppler radar are improving and may have future application in such hazard warning systems. Additionally, continuing advancements in microwave remote sensing (Verhoest et al. 1998) can be helpful in assessing antecedent soil moisture in potentially unstable terrain.

Distributed landslide analysis has recently been employed to predict landslide potential in larger watersheds and to design appropriate land management strategies. When distributed, physically-based modeling is applied to landslide analysis, not only are the distributed properties of the parameters of concern, but also the model output represents a spatial problem, because we need to know the locations of landslides. Although GIS

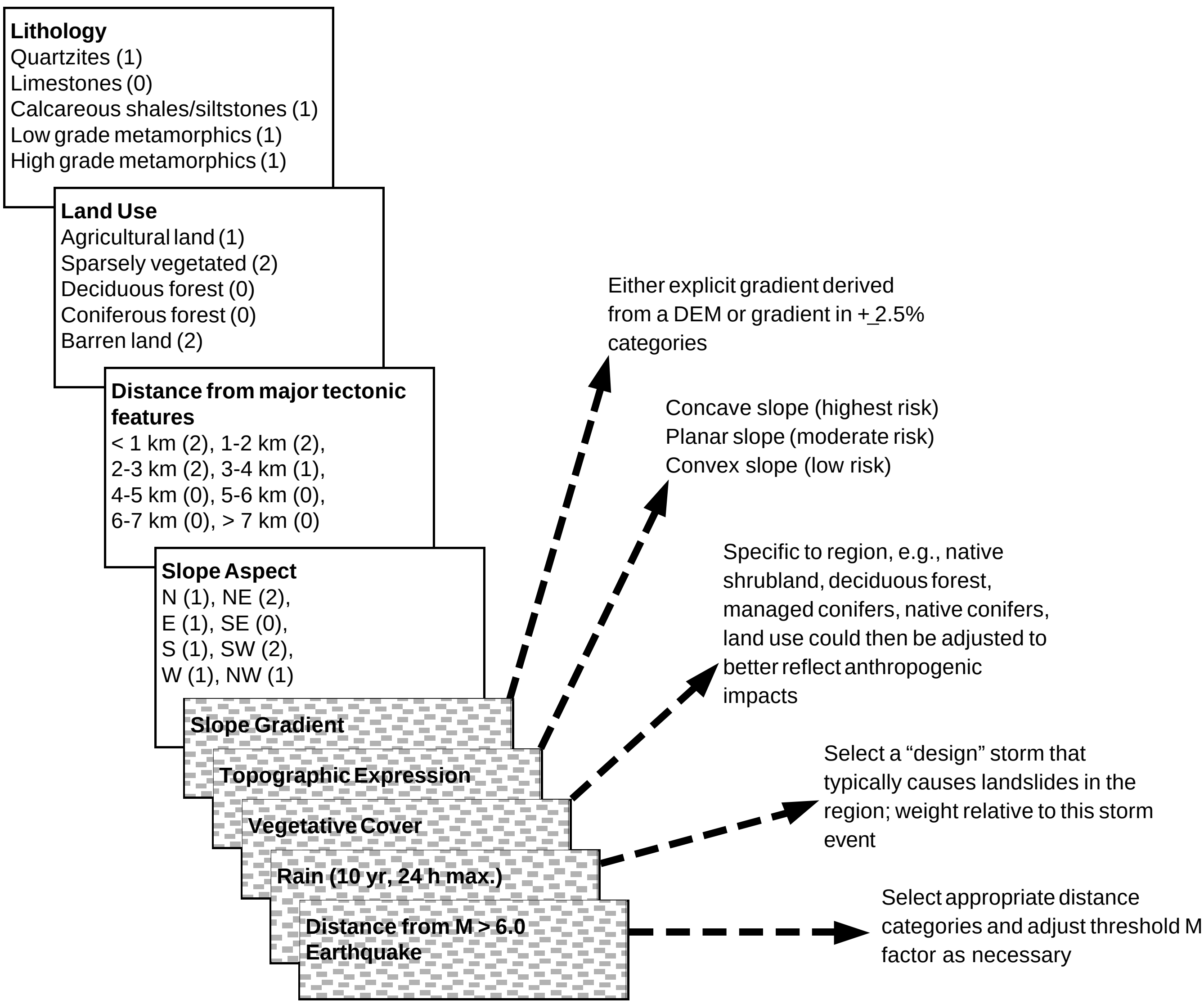

Figure 2. A weighted, multi-factor analysis for assessing terrain stability based on methodology of Gupta and Joshi (1990) for the Ramganga Catchment in the Lower Himalayas. Weightings for factors in the analysis are shown in parentheses, with larger weights representing more unstable conditions. The stippled boxes represent suggestions for improving the GIS-based terrain hazard analysis.

technology is highly regarded as a tool for landslide analysis in terms of spatial data extraction and display (Shasko and Keller 1991), little progress has been made to incorporate distributed, physically-based slope stability modeling with GIS. A recent physically based model (SHALSTAB) for shallow landslide analysis developed by Montgomery and Dietrich (1994) couples digital terrain data with near surface through flow (TOPOG, O'Loughlin 1986) and slope stability models. Recent versions of SHALSTAB assume that soils are cohesion-less and ignore the effects of vegetation root strength. Another distributed landslide (dSLAM) is based on an infinite slope model, a kinematic wave groundwater model, and a continuous change vegetation root strength model (Wu and Sidle 1995). This model has the advantage of predicting the effects of actual or hypothetical forest management scenarios, including clear-cuts, shelterwood cuts, alternate thinnings and clear-cuts, and partial cuts. The model has the flexibility to utilize either actual storm records or synthesize a random Monte Carlo series of storms. Two successful applications of dSLAM in managed forested basins in coastal Oregon (Wu and Sidle 1995, 1997) suggest this to be a promising tool that can be applied to unstable, intensively managed forest sites. Both SHALSTAB and dSLAM predict only shallow, rapid failures (debris slides, debris avalanches) triggered by rainstorms.

Some of the challenges that currently limit the successful prediction of landslide hazards using distributed, physically-based models include data limitations; inaccuracies in the groundwater model component; need to incorporate effects of low volume roads; need to simulate snowmelt processes as a trigger mechanism; inclusion of multiple failure types; and better simple routing models for debris flows. Limitations of data range from lack of spatially distributed data on soil depth, soil physical and engineering properties, and vegetation parameters (including rooting strength) to the need for better digital elevation models (DEMs) to characterize topography. In some cases, algorithms for parameters like soil depth and cohesion can be developed from more easily obtainable attributes such as topographic index and soil texture. Currently, such tested algorithms are not available. By the nature of the desired spatial application of distributed landslide models, hydrologic models that are more detailed than the stream-tube model (Moore et al. 1988) incorporated in dSLAM will be difficult to implement. However, with improved knowledge of fundamental stormflow pathways (see next section), some modification of existing subsurface flow models can be possible. Progress is currently underway to incorporate the effects of road systems into dSLAM. Issues related to the redistribution of surface and subsurface water by roads are critical to our understanding of managed watershed behavior. Such information is needed not only to assess landslide hazard but also to evaluate effects of roads on peak flows. Snowmelt has been successfully simulated in the context of other distributed hydrology models (DHSVM, Wigmosta et al. 1994), but no such applications have been incorporated into landslide models to emulate this important trigger mechanism. Little progress has been made in incorporating multiple landslide types into physically based models due to the differences in processes, movement rates, and periods of activity. Because theoretical models for debris flow routing require excessive parameterization, it is likely that simple empirical models will need to be developed and tested on a regional basis (Benda and Cundy 1990).

Linkage Between Processes

Another topic related to terrain stability that is poorly understood is the linkage between hillslope processes (debris avalanches, earthflows, etc.) and headwater and main channel processes (debris flows, bedload transport, suspended sediment transport, channel scour and fill). Knowledge of this linked behavior is important for predicting long-term effects of forest management on aquatic habitat, fluvial geomorphology, and water quality. While low gradient downstream reaches have been studied in terms of sediment movement, hydrologic response, and aquatic productivity, headwater systems have been largely ignored. In steep terrain, headwaters are subject to active erosion processes such as shallow landslides, debris flows, bank failures, and surface erosion. Woody debris in headwater channels provides temporary storage sites for this sediment. The dynamics of sediment storage and release related to woody debris is largely unknown. Management of riparian zones in headwaters has recently come under intense scrutiny. Issues, such as the width of buffer-leave strips necessary to protect channels and supply a sustainable level of large woody debris to streams, have been intensively debated (Streeby 1971, Murphy and Koski 1989) with little long-term data to support various economic, environmental, and political objectives. Furthermore, the effects of changes in inputs of woody debris over entire forest rotation cycles (40 to 100 years) on the overall attributes of headwater systems, particularly with respect to sediment movement, channel condition, and aquatic habitat, are virtually unknown. Such interactions will be briefly discussed in the context of cumulative watershed effects.

Control Methods

Given the current state of knowledge about landslide mechanisms and related effects of land management practices, there are some practical applications that need to be greatly improved. A notable example is the use of surface erosion control methods to attempt to ameliorate active landslide sites. Because landslides involve the mass displacement of the entire soil mantle and possibly some of the weathered regolith, grasses with shallow and weak roots offer almost no protection against landslide movement. However, grass seeding on active landslide sites remains a common "remediation" practice on private and public lands. True, establishment of grass cover will offer short-term protection against surface erosion; however, this benefit is negated if mass wasting remains active. Such phenomena can be observed on unstable over-steepened road cuts that have been reseeded: clumps of sod-covered soil often lay in the ditch-line as the result of bank sloughing. This case is an example of where improvements in technology transfer information are needed.

Hazard Assessment

Hazard assessment on colluvial and alluvial fans is a related area where advancements are needed in both technology transfer and scientific understanding. Such sites are conspicuously mismanaged in terms of residential development, water supplies, road construction, and other infrastructures. In steep forested watersheds, these sites are superficially attractive to developers since they represent some of the gentlest terrain. In arid and semi-arid environments, fans are much easier to delineate due to the paucity of vegetation, while in humid forested environments it is often difficult to detect evidence of older fan surfaces. Channels in fans are subject to avulsions and, thus, engineering methods commonly applied in flood control are typically doomed to fail since these avulsion channels have no defined floodplain, and it is nearly impossible to predict the direction of new avulsion channels. However, important features of channels on fans can be identified that provide insights into the susceptibility of channels to avulsions (channel depth, number of channels, degree of vegetation establishment). It is also important to distinguish between the causation factors related to fan development. Colluvial or debris fans are formed by debris flows and are directly linked to upslope landslide activity. Thus, geomorphic linkages among upslope landslides, debris flow initiation, and fan formation must be considered in hazard assessments for colluvial fans. In contrast, alluvial fans are formed by flood events and related sediment transport. They tend to have a gentler gradient and materials are better sorted compared to colluvial fans. In this case of hazard analysis for alluvial fans, stormflow generation mechanisms, flood magnitude and frequency, and bedload transport are major factors to be considered. In some cases, both processes can occur together, although one process usually dominates. Additionally, individual fans can be composed of both alluvial and colluvial components that are temporally separated. Most current hazard analysis conducted on fans does not distinguish between hydrogeomorphic formation characteristics.

Hydrologic Response in Forested Headwaters

Several features of headwater forested catchments result in different hydrologic response compared to similar sized agricultural and urbanized watersheds and larger scale basins with mixed land use. First of all, most forest soils have high infiltration capacities; thus, infiltration excess (that is, Hortonian) overland flow rarely occurs. This is particularly true in temperate, sub-tropical, and tropical forests where substantial accumulations of soil organic matter occur. It is the general consensus that subsurface flow either plays an active role in stormflow generation in these headwaters or a more passive role in recharging wet riparian areas. Of course, such sites are susceptible to disturbance and compaction from various land use activities. Additionally, certain types of artificial forests can promote overland flow due to exclusion of understory species and lack of organic litter. Because this paper focuses on steep forest terrain, slope gradients and the related incised topography influence hydrologic processes. As such subsurface flow pathways to channels have a high elevation head and riparian corridors are typically narrow with little storage capacity for subsurface water (Sidle et al. 1995).

Streamflow Generation

From the mid-1960s until recently, the variable source area concept of streamflow generation has been accepted as a working paradigm for forested hydrology (Tsukamoto 1963, Hewlett and Hibbert 1967, Kirkby and Chorley 1967). This concept invokes a dynamic riparian source area that shrinks and expands in response to rainfall or snowmelt and fluctuating water tables. However, the model does not specify flow mechanisms or pathways functioning at different spatial scales within the watershed. Although the original research behind the variable source area concept was conducted in the steep, forested Coweeta Experimental Watershed in the southeastern United States, later insights into hydrologic mechanisms were derived from work in a mixture of agricultural and forested catchments with gentle slopes and broad riparian corridors. These later investigations cited saturation overland flow and return flow within broad, flat riparian areas as the dominant stormflow generation mechanisms (Dunne and Black 1970, Eshleman et al. 1993, Fujieda et al. 1997). Alternatively, Sklash and Farvolden (1979) attributed stormflow generation in such gently sloping basins to a groundwater "ridging" effect. Many such inferences have been incorrectly applied to steep, incised forested terrain in attempts to explain stormflow response.

In steep forested catchments, specific stormflow mechanisms have been cited, such as capillary fringe response (Gillham 1984), pressure wave effect (Yasuhara and Marui 1994), and preferential flow associated with macropores (Mosley 1979; Tsukamoto and Ohta 1988), soil pipes (Jones 1971; Kitahara and Nakai 1992), deflection over bedrock (McDonnell et al. 1996, Noguchi et al. 1999), and channeling through surface bedrock discontinuities (Montgomery et al. 1997, Noguchi et al. 1999). These studies in steep forested terrain typically ignore Hortonian overland flow because of the high infiltration capacity of soils. Thus, lateral subsurface runoff is at least partly caused by the presence of a hydrologic impeding layer (bedrock, till) below the soil profile (Harr 1977).

Although subsurface flow is generally regarded as a significant process in steep forested hillslopes, the importance of preferential flow pathways as direct links to stormflow production is still questioned. Large discharges from soil macropores and pipes during natural and simulated storms have been measured or inferred at steep forest hillslope sites (Mosley 1979, Tsukamoto and Ohta 1988, Kitahara and Nakai 1991). Studies with applied conservative tracers have shown that macropore systems increase in importance (Chen and Wagenet 1992) and can expand during wetter conditions by interacting with surrounding mesopores (Tsuboyama et al. 1994). Such expansion can also include a lateral expansion of preferential flow networks by developing a complex linked network in the upslope direction (Tsuboyama et al. 1994, Sidle et al. 1999).

Macropore Flow

The issue of the relative importance of macropore flow was clouded by a series of potentially conflicting findings from the same catchments in New Zealand. Although Mosley (1979) measured high macropore discharges during storms, later oxygen isotope tracer studies questioned the importance of macropore flow because of proportionally high measured discharges of "old" water during storm runoff (Pearce et al. 1986, Sklash et al. 1986). These later investigations that associated "old" water discharge with matrix flow and "new" water discharge with macropore flow can be misleading because of the potential for inter-compartmental mixing in the hydrologically active regolith (DeWalle et al. 1988, Sidle et al. 1995, 1999, Buttle and Peters 1997, Tsuboyama et al. 1998). Later investigations at the New Zealand study site noted predominantly "old" water discharging from macropores and hypothesized that continuous macropores in the soil purge stored "old" water when shallow groundwater tables rise during storms and intersect these flow paths (McDonnell 1990). However, the upslope connectivity of such macropore systems was not confirmed and results from other forest sites suggest that such long distance spatial connections rarely exist (Noguchi et al. 1997, 1999). Thus, although these studies in New Zealand advanced certain understanding of specific hydrological methods and processes, many of the inferences related to flow pathways were misleading.

Hydrogeomorphic Linkages

Insights into hydrogeomorphic linkages are needed to elucidate spatial and temporal attributes of flow paths that affect both headwater and downstream systems, including cumulative impacts of land use (Sidle and Hornbeck 1991, Burgess et al. 1998, Sidle et al. 1999). With increasing computational capabilities, it will be possible to simulate the behavior of more and more complex flow systems that deviate from the treatment of hillslope soils as isotropic and that only consider matrix flow (Freeze 1974). As such, priorities should be placed on understanding the dynamics of flow pathways in headwater systems related to changing antecedent moisture conditions, topographic attributes, and management impacts. Linkages between hydrologic and geomorphic attributes need further investigation, as do the factors influencing nonlinear or threshold responses on such hydrologic functions as runoff from hillslope hollows, expansion of preferential flow networks, and redistribution of subsurface water storage (Sidle et al. 1999, Tsuboyama et al. 1998, 1999). There is evidence that these thresholds can have different scale dependencies even within the range of relatively small zero-order through second-order basins. Improvements in microwave remote sensing can offer future possibilities for analyzing basin scale soil moisture, an important parameter controlling hydrologic thresholds and linkages, and even variable hydrologic source areas (Verhoest et al. 1998). However, such methodology is still plagued by backscatter problems attributed to vegetation cover and surface roughness (Cognard et al. 1995). Additionally, potential problems can arise if catchment hydrologic response is inferred in the context of simplistic or even incorrect conceptual models (Van De Griend and Engman 1985, Verhoest et al. 1998).

Routing of Water

Another important issue related to hydrologic response is the routing of water from headwater channels to lower gradient channels. Roughness elements, such as woody debris and boulders, more significantly influence water routing in headwater channels compared to large stream systems (Abbe and Montgomery 1996, Gomi et al. 1999). Dynamics of woody debris and hillslope processes that are related to various forest management practices can influence hydrologic routing. This issue is discussed in the context of cumulative watershed effects.

Cumulative Watershed Effects

In larger watersheds, a variety of land uses are typically distributed according to ownership, zoning restrictions, site productivity, and resource availability. The spatial distribution of such land uses can change through time depending on changing economic conditions, environmental issues, land ownership, technology, and regulatory constraints. These spatially and temporally distributed anthropogenic effects can interact with natural ecosystem processes to produce cumulative effects on watershed resources (Sidle and Hornbeck 1991). Additionally, larger scale anthropogenic factors, such as global change and changing demographics, contribute to cumulative effects. Affected resources can be both on site or occur downstream of the impact (figure 3). On-site cumulative effects can include increased landslide susceptibility due to repeated timber harvesting (Sidle 1991), progressive gully development in response to forest clearing (Prosser and Soufi 1998), and increases in soil

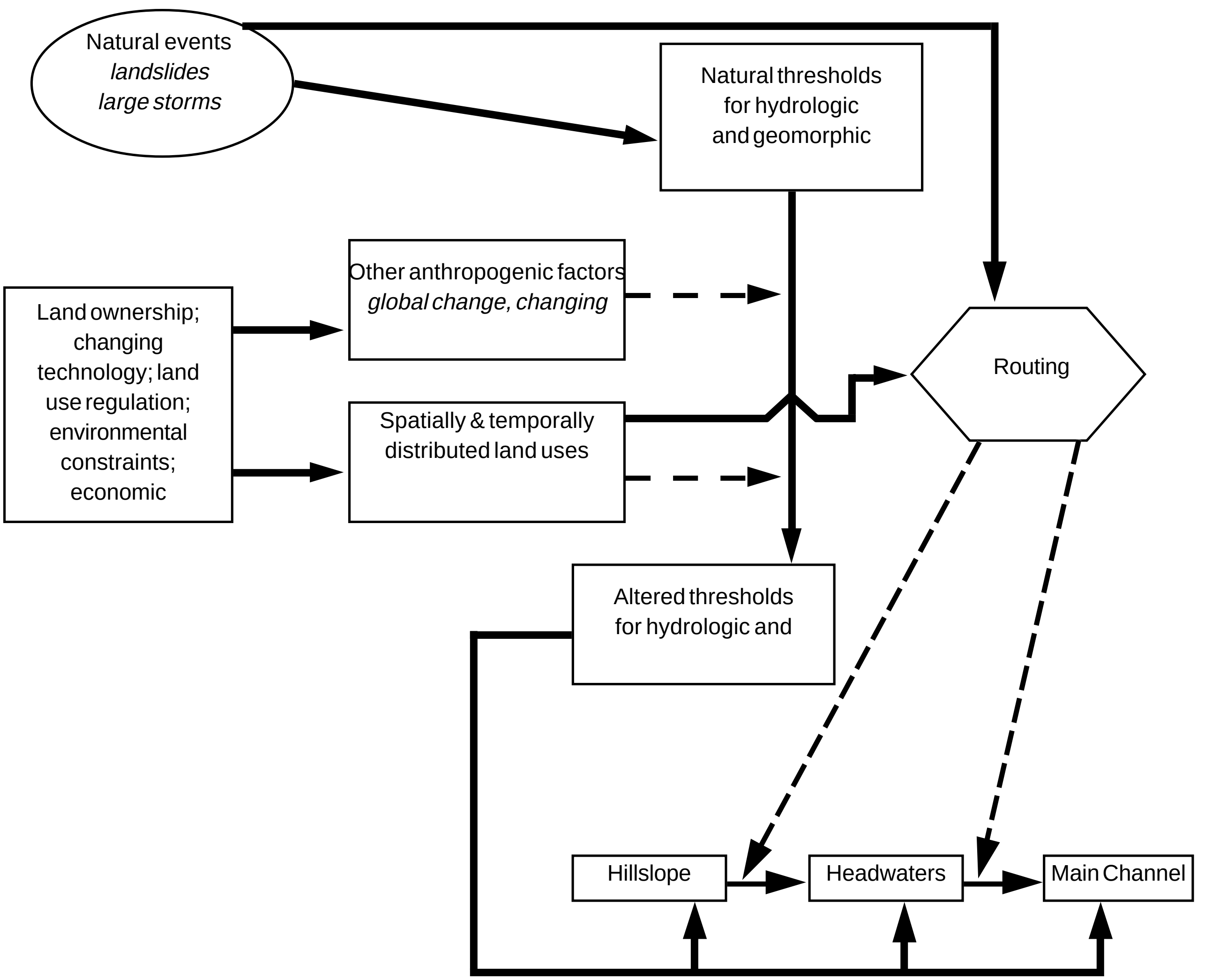

Figure 3. A linked system analysis for assessing cumulative effects of land uses on hydrologic and geomorphic processes in the watershed. Green denotes natural ecosystem processes; yellow external factors; pink ecosystem thresholds; orange routing functions; and blue affected system components. Solid black arrows represent compartmental connections; broken orange arrows represent process transfer or routing links.

compaction and surface runoff (Warren et al. 1986). Off-site or downstream cumulative effects include alteration of channel morphology and sedimentation regime (Lyons and Beschta 1983, Sidle and Sharma 1996), changes in water quality (Boyer and Perry 1987, Sidle and Amacher 1990), riparian vegetation response (Kauffman and Kreuger 1984), and stormflow changes (Jones and Grant 1996, Thomas and Megahan 1998).

Critical to the assessment of cumulative watershed effects is an improved understanding of how water and related materials (sediment, nutrients, pollutants, organic material) are routed through complex landscapes and what changes, if any, occur along the way. Understanding these routing processes requires careful consideration of spatial and temporal scaling issues such as hydrologic thresholds that trigger stormflow (Sidle et al. 1999, Tsuboyama et al. 1999), process linkages (Sidle et al. 1995, Tsuboyama et al. 1998, Brown et al. 1999), spatial variability in landscape properties (Sinowski and Auerswald 1999, Bierkens et al. 1999), "coarse-graining" in hydrologic observations (Kavvas 1999), disaggregation and aggregation criteria for hydrologic behavior (Becker and Braun 1999), and self-organization patterns and processes related to hydrologic behavior (Sidle 1999). Details of chemical and biological transformations, and the sinks and sources for these components will not be discussed. These issues are important to our understanding of cumulative effects on water quality.

The role of episodic natural events is particularly important in assessing cumulative effects. Episodic events can define thresholds of concern for certain ecosystem processes. Thus, if the occurrence of events above such thresholds should increase, the related effects on ecosystems would be much greater than if increases in events below the threshold occurred. Similarly, lowering of thresholds due to cumulative impacts of land use is also of concern. Geomorphic consequences of large storms vary not only by region but also by location in the catchment. Storm return periods of as large as 100 yr can be necessary to trigger major landsliding in some areas (Selby 1976), whereas events of much lower magnitudes (return intervals of about 5 yr) are believed to shape the course of large streams and rivers (Wolman and Miller 1960). Headwater channels can be influenced by intermediate sized events. Within such a continuum we need to focus on multiple hydrologic and geomorphic thresholds to adequately define the conditions and susceptibility of watersheds for analysis of cumulative effects (figure 3).

Examples of Cumulative Effects of Forest Management on Water and Sediment

Timber harvesting or vegetation conversion on steep slopes would potentially lower the threshold for a landslide-producing storm. Thus, the net effect would be a short-term (in a regenerating forest) or long-term (in a permanent vegetation conversion) increase in the probability of failure. Such effects could be simulated with distributed models like dSLAM (Wu and Sidle 1995). Thresholds for surface erosion would likely be lower and focused almost entirely on rainfall intensity. Changes in surface erosion response would depend greatly on the level of disturbance and site conditions. In most cases, we need to improve our understanding of what constitutes a significant geomorphic threshold – such as total storm rainfall, short-term rainfall intensity, antecedent moisture conditions, or a combination of these factors. For example, Prosser and Sofi (1998) attributed extensive gully development in Australia to ground disturbances caused by vegetation conversion and related these geomorphic changes to daily rainfall thresholds. However, many other investigations (Sidle et al. 1993) have shown that surface erosion is closely related to short-term rainfall intensities; thus, the thresholds proposed by Prosser and Sofi (1998) are potentially misleading.

Routing of sediment and water from hillslopes to main channels is an important and poorly understood linkage (figure 3). In landslide-prone terrain, the transition and timing from hillslope failures (debris slides, debris avalanches) to channel failures (debris flows) must be known to assess cumulative impacts. Questions such as - Do landslides convert directly to debris flows during an initiation event? or, Does a threshold of material need to accumulate in headwater channels prior to debris flow initiation? - must be answered. Such questions can require extensive field investigations; however, generalizations should be possible at local or even regional scales.

Once in the channel, routing of sediment and water needs to be considered in cumulative impact assessment. This becomes a complex issue that depends on the topographic characteristics of the channel and the interaction with riparian vegetation and related management effects. For sediment, both the storage capacity and longevity of storage related to hydrologic events and timber management are important. In the case of water routing, channel roughness due to boulders and dynamic inputs of woody debris can potentially influence the timing of runoff to larger streams. For both sediment and water routing, the influence of episodic debris flows on channel conditions must be considered. Factors influencing the more chronic transport of suspended sediment and bedload material need to be elucidated for headwater systems, particularly the supply of sediment available for transport during various peak flow conditions and changes in such supplies for different management scenarios. At this time, we are only able to identify important processes, construct sediment budgets, and develop crude models of water and sediment routing in complex headwater systems.

For lower gradient channels in the catchment, thresholds need to be established for bedload transport (Sidle 1988) and related channel changes (Lisle 1982), particularly in response to changes in woody debris volumes (Smith et al. 1993a, 1993b). The relationship between discharge and suspended sediment transport is better understood in managed forested catchments (Beschta 1978). However, for both bedload and suspended sediment transport in supply-limited streams, we need to develop better models that predict changes in sediment sources within the linked main channel system. Recent findings on "fingerprinting" techniques (radionuclide, magnetic properties, nutrients, carbon, heavy metals, etc.) for sediment samples are useful for identifying source areas (Walling et al. 1999). Response of peak flows in larger forest streams to management activities is a controversial topic (Jones and Grant 1996, Thomas and Megahan 1998). To progress, we need to investigate specific processes and conditions that can cause increases in discharge and determine over what range of discharges or storms such increases occur. Additionally, we need to establish links related to such increases with fluvial geomorphic effects and upslope conditions. Distributed hydrologic models such as DHSVM (Wigmosta et al. 1994) hold promise for evaluating cumulative impacts of land uses on peak flows, although better representation of certain hydrologic functions (road hydrology) can be necessary.

Although lower gradient channels serve as "integrators" for hillslope and headwater processes and have received the bulk of the attention to date, we need to now focus on linkages among all of these complex system components and related management practices to adequately address cumulative watershed effects. Such a simplified linked system analysis of the cumulative effects of land use on water and sediment is outlined in figure 3.

Practical Issues Related to Cumulative Watershed Assessments

From a practical perspective, it is reasonable to expect that empirical cumulative watershed effects procedures will continue to be used by land management agencies and industrial landholders. Such procedures like the Watershed Assessment Procedure (WAP) used by the Ministry of Forests in British Columbia offer an "all inclusive package" to address important cumulative effects issues such as water quality, slope stability, peak flows and aquatic habitat changes. These methods are based on local managers and scientists best knowledge of sensitivities to various watershed parameters and their response to management practices. The effective implementation of WAPs and similar cumulative effects procedures is contingent largely on user expertise. We now need to move beyond the point where cumulative watershed analysis is merely a regulatory compliance exercise to where it is representative of realistic long-term, spatially distributed processes in the watershed. Certainly, new research findings on watershed system responses and management effects need to be incorporated into the existing framework of empirical cumulative assessment procedures. Additionally, with advances in modeling technology and increased computing power, it appears possible to develop distributed, process-based models that have application directly to management, rather than just research tools. However, as with any model application, the most important consideration is ensuring that the underlying natural systems processes are adequately depicted. For cumulative effects analysis this implies both accurate temporal and spatial representation; thus, considerable basic field research will be necessary to define relevant processes.

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Watershed Management in the United States in the 21st Century

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Abstract.—Views of watershed management in the 21st Century are presented in terms of concept, status, progress and future of watershed planning. The watershed as a unit will increasingly be the basis of planning because the concept is widely understood, many state and federal laws require such a focus, and watersheds are a logical entity for monitoring purposes. Impediments to watershed planning remain, but progressive and effective policies are evolving in response to public demand that diverse land uses and users protect the watershed resources. Watershed management will be improved by new computer technology tools, more effective integration of social sciences capabilities, and advanced legal and institutional incentives for landowners and users. Research needs identified include better integration of computational capabilities with spatial and temporal information, watershed monitoring capabilities, mechanisms for evaluating watershed policies and programs, and better understanding of basic hydrology and the effects of multiple land user disturbances on water resources on a large scale.

Introduction

Watershed management policies and practices in the United States 21st century will be largely driven by a growing human population and the associated commodity and non-commodity demands placed on natural resource systems. The U.S. population now exceeds 270 million. A "medium" projection estimate for the year 2050 is 348 million people (Gardner-Outlaw and Engelman, 1997). Whether this projection is proven correct or not, the certainty is that the U.S. will have a much larger population in the 21st century than at present. The concentration of population in and around urban settings will also influence future watershed management policies and practices. Settlement patterns in the U.S. are concentrated around coastal areas including the Great Lakes, with the east and west coast being the most densely populated. Interior spaces of the U.S. are also under the influence of population expansion as exemplified by Denver and Phoenix. In addition, other urban areas are sprawling outward from city centers, as illustrated by Seattle and Portland.

This mix of concentrated settlement patterns and sprawl, in combination with overall population growth, is putting stress on natural systems. However, these demographic patterns describe only part of the issue. Increasing rates of land and water consumption in areas of low renewable water resources, especially in the western states, adds to the complexity of our national problem. The competitive demands for wildlife and fish habitat, clean water, food and fiber production, living space, transportation and utility corridors, scenic and recreational environments, and other natural resource-based attributes are growing dramatically. A major challenge for natural resource managers of the next century will be how to address these intensely competing demands imposed by a growing and increasingly consuming population, and at the same time protect and preserve natural systems on a sustainable basis.

One of the most central issues in the management of natural systems in the 21st century will be the demand for water, for endangered species, such as fish and other species, and for human consumption and use. The availability, characteristics, and behavior of water in natural systems are largely a cumulative function of the basin or watershed from which the water is derived (in addition to climate, of course), and land use practices. Thus, watershed management will become increasingly significant as a means to ensure adequate supplies of appropriate quality water for a variety of uses. High quality water in adequate quantity for human use will increasingly become a prominent and, in some cases, a dominant consideration in land management, and will be viewed as a human health and security issue. This will precipitate more national conflicts over water "rights" as opposed to water "privileges".

Through examination of the concept, status, progress, and future of watershed planning, we present here our views of watershed management in the U.S. in the 21st century. This is followed by discussion of a number of research issues that will impact efforts to plan and manage on a watershed basis.

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Watershed as a Planning Unit

As competition for natural resources, including water, intensifies to unprecedented levels, careful planning will become increasingly important. Watersheds are a logical unit for unifying the planning process and for producing the desired outcomes such as improved water quality and habitat for fish and other species. Several factors—the concept itself, evolution of federal and state laws, and monitoring issues—support the watershed concept as the basis for planning.

Concept

First, people can understand the concept of a watershed. For example, they understand the physiography in which the ridge lines of a watershed can be defined, as well as the downward cumulative flow of streams, rivers and ground water, and the general relationship between precipitation and high and low streamflows. This widespread understanding may be greatest where topographic relief is well defined as in the West, but even elsewhere the concept is appreciated.

Federal and State Laws

Second, federal and state laws are both forcing and encouraging watershed planning. The Endangered Species Act (ESA) requires adequate habitat conditions to ensure the survival of endangered and threatened species such as certain salmonids on the west coast. The survival of such species is dependent on many factors including ocean and near ocean conditions (National Research Council, 1996), but clearly habitat conditions in watersheds play a major role. Another federal direction is The Federal Guide to Watershed Analysis under the President's Northwest Forest Plan (Regional Ecosystem Offices, 1995).

The Clean Water Act (CWA) is another powerful federal law that has resulted in standards for permissible water quality variation. An overarching goal of the CWA is to maintain or improve the physical, biological and chemical integrity of the nation's waters. For example, the total maximum daily load (TMDL) of sediment in streams may be controlled by regulations resulting from this law. The sediment load at any particular point in the stream is a function of everything that influences sediment dynamics above the point of measurement, including up-stream land uses and practices. The many land uses in the watershed, and their individual and collective influence, will have to be addressed to meet water quality standards resulting from the CWA. But TMDL regulations only correct the problem after it occurs. Management practices are increasingly being stipulated in regulation, in the few states that have been aggressive, and other states are seeking either regulatory or voluntary Best Management Practices.

Protection and mitigation for threatened and endangered species will require that land users, including those in forestry, agriculture, utilities, range management, and urban and exurban development, deal with their own and their combined impacts within the watershed. If planning is not coordinated across ownerships and land uses, protection efforts by one land use or ownership group could easily be defeated by activities or practices in other parts of the watershed. Even disturbances on small areas of the watershed can have adverse downstream consequences for water quality and quantity. Desired outcomes cannot be achieved if the major factors influencing water quality or species survival within the watershed are not addressed. Obviously, improving and coordinating management practices across watersheds with multiple and fragmented ownerships will present a major challenge.

State laws and regulations that support watershed planning are also emerging. In 1998 the Washington State legislature passed Engrossed Substitute House Bill 2514, with overwhelming bipartisan support. The law establishes a watershed management planning process to develop standards for in-stream flow levels, water quality, and habitat plans for defined watersheds. A primary purpose of the bill is to address fish listings under the ESA and the needs of those who rely on out-of-stream uses of water. The provisions of the bill are voluntary and call for pluralistic representation from state agencies, local government entities, general citizenry and representatives of major interests in the area. The goal is to collaboratively develop integrated watershed management plans for the planning areas. Up to 500,000 dollars in grants per defined watershed can be provided by the state to support the process. A companion bill, Substitute House Bill 2496, instituted a "systems" approach for salmon recovery, and stipulated that a local planning process must occur in order to obtain state grants. A subsequent 1999 bill stipulated that a new planning entity, appointed by the Governor, should direct the flow of money to projects for salmon recovery.

Of course, all of these more recent watershed planning efforts were preceded by earlier efforts such as the old river basin studies of the 1960s, the Tahoe Regional Planning Agency (TRPA) and the Tennessee Valley Authority (TVA), for example.

Monitoring

A third reason that watersheds are a logical basis for planning is that monitoring for compliance with federal and state laws may be more easily achieved at the watershed level, if appropriate coordination mechanisms are in place. Runoff and water quality, traditionally monitored at gaging stations on rivers and tributaries, provide measures of compliance with regulations and serve as an indicator of responses to policy changes if measured carefully and over long time periods. Information from gaging stations provides an integration of all land use practices upstream and an indication of cumulative effects of these practices within the watershed. More sophisticated technologies are being developed to track movement and changes of particulates, pathogens, fish, and other elements of the watershed that in turn are indicators of overall environmental health.

Challenges related to monitoring remain, however. The watershed has been described as the "canary in the coal mine" since the 1960s, when river cleanup programs were begun. Monitoring may be able to pinpoint sources of pollution, with newer technologies, but it is more important perhaps that watershed monitoring will help individuals and communities understand the ambient health of their environment and the impacts of their own growth patterns. If monitoring is conducted, there is great variability in the types of biological, physical and chemical measures currently used to monitor, as well as uncertainty surrounding which indicators are appropriate. Questions also remain as to whether monitoring data is actually used by resource managers and policy makers to evaluate and adapt programs and policies. There is also variability in who monitors what variables and for what purpose. Further, monitoring may be resisted by those who may not wish to grapple with the findings that result.

Status of Planning on a Watershed Basis

Watershed planning in which the cumulative influence of all land uses and practices can be assessed and managed will require the involvement of all land ownerships and resource users in the watershed. The legal demands in the 21st century will not allow single landowner planning, or planning that assumes landowners will voluntarily participate on their own to achieve watershed objectives. Rather, landowners will be compelled by a combination of regulations and public sentiment regarding expectations for the watershed, as was the case for air quality management in airsheds in the 1970s. The laws (ESA and CWA), standards (TMDLs), and expectations (adequate quantity and quality of water) are clear. Further, the results of planning and implementation of plans can be continuously monitored to assess success or failure. We might argue that the state of the art of assessing success or failure has advanced far more rapidly than planning. Public access to information and consequent usage of information to coalesce public sentiment is almost unlimited, as the world wide web allows almost universal access to GIS and other information. Ultimately, successful planning and implementation will require public processes transparent to all and data bases that can be integrated. However, quality of access is a function of bandwidth, a phenomenon that was virtually unheard of five years ago. This means that rural and less wealthy areas will be more challenged for information, until bandwidth access is provided.

As early as 1992, Washington's Forest Practices Board provided an option in its regulations for watershed planning by landowners, which was generally supported in theory, but not implemented in any meaningful way. We believe that landowners initially waited for one another to lead the way with these "alternate plans," and no one led. Then the concept was supplanted by ESA-driven Habitat Conservation Plans.

Although the Washington policy was not implemented as intended, some forest landowners have begun to quietly address watershed planning, either as part of their habitat conservation plans to conform to ESA requirements, or for setting ISO (International Standards Organization) 14000 standards for their land management. These efforts have not deliberately attempted to achieve the cross-boundary, cross-ownership goals that watershed management contemplates, however.

In Oregon, Governor John Kitzhaber appointed a Willamette Restoration Initiative board, to follow a long-standing citizen-driven effort to focus on planning for the Willamette River Basin. Clearly, the Willamette, the major "gathering place" of water and people in Oregon, will be a model for planning and perhaps successful social engagement around a critical set of natural resources.

However, impediments to successful watershed planning remain, including: landowners with different objectives that may conflict with public watershed goals; years of regulatory behavior that has not rewarded collaborative planning; overlapping state and federal agency responsibilities; incoherent and disparate data collection; multiple political jurisdictions; undirected funding; distrust of data sets not one's own; models that have not been validated or linked; funding cycles that are too short to address the problem or long-term monitoring needs; and incomplete understanding of watershed processes.

Progress in the 21st Century

Notwithstanding the challenges described above, the 21st century will bring progress in watershed planning. The changes in policy and practice will not be revolutionary, but rather evolutionary and increasingly progressive and effective. We further posit that the trend of the last 200 years, of pushing one use or user aside as a new and presumably more valued land use emerges, will become more rare in the next century. Public sentiment is demanding that more uses coexist, and that users find ways to adjust to one another's needs in a more pluralistic way. Forestry is a case in point. Although not without difficulty and cost, forestry, as a watershed practice, is adjusting its ways of management around urban boundaries, as agriculture has done. Forest companies and some other large land users, like utilities, manufacturing industries, airports, municipalities, and in some cases, agriculture, have donated land, provided streamside buffers of consequence, invested millions of dollars in fish habitat restoration, and otherwise mitigated practices to gain wider public acceptance of their activities. None of these individual acts should be construed as watershed planning, even though they might be consistent with a plan.

Role of Technology

The expected improvements in watershed planning in the 21st century will be aided by significant new technical tools. GIS, highly sophisticated remote sensing capabilities such as hyper-spectral and laser imaging, large scale computer modeling, visualization technologies, and no doubt other developments, will make it easier for watershed managers to characterize, predict and assess watershed conditions and behavior. Perhaps more importantly, these tools will help both the public and landowners to better understand what proposed policy changes may look like on the ground and what the costs and benefits are likely to be. As information sophistication increases, the application of that information will increase as well. Sharing data across agencies and land ownerships will be essential, and organizational impediments to shared data and shared decisional tools will need to be overcome. The institutional and cultural shifts that are being surmounted in many technological industries will need to be addressed by resource managers and regulators.

The World Wide Web and internet are sources of vast information that nearly anyone can access. These tools and associated technologies have already revolutionized watershed planning in the 21st century by providing data and information to a wide audience. For example, U.S. EPA's "Surf Your Watershed" site (*http://www.epa.gov/surf/*) is a Web-based service designed to help users locate, use and share environmental information for their watershed. The state of Washington has a "Watershed Home Page" (http://www.wa.gov/ecology) that focuses on issues specific to the state. Oregon's state agency (http://waterquality.deq.state.or.us/wq/default.htm) provides information as well, as do many other state water quality agencies. The Web can help level the playing field by conveniently providing information in interactive form, and assisting all users to gain a better understanding of trade-offs and alternatives, possible courses of action and consequences, and what is known and is not known. These advances should make it more difficult for the selective use of information in achieving policy goals by any sector. An informed and involved public is necessary for a democracy to succeed and thrive, and this is no less true for the watershed planning process.

However, we must also observe that the usefulness of the Web for collaborative watershed planning may be limited by the lowest common denominator among the collaborators, as inequalities in Web access will dictate. Band width problems in rural areas, underfunded agencies or Indian tribes, or under-trained staff will inhibit mutual access to information. Applying advanced technologies to watershed planning will be a great challenge to social scientists and planners, as they work to obtain access for groups who might be left behind. Information management decisions will be critical, as government agency funding is always subject to funding cutbacks that might imperil a well-developed data system. Keeping systems updated, as new information is developed, will require strategic decisions about long term funding and maintenance capabilities.

Regardless of these complications, for natural resource land and watershed planning, the organizations that recognize the empowerment value of the internet will be most successful. They will create constituencies for their plans and goals, and they will experience, we believe, much more stability in their external relations as a result.

Role of Social Sciences

We posit that social science and natural science research will have to more closely integrate their emphases including interdisciplinary approaches in order to provide the comprehensive tools necessary for effectively understanding and managing watersheds well into the next century. This integration is critically important, as humans influence resource systems, decisions about resource planning and management, and the means to engage in both the planning and the evaluation of its consequences.

Social science research will bolster not only process, but behavioral, regulatory, and policy improvements in watershed management planning well into the 21st century. The 21st century will also bring more refined social mechanisms for the interchange of ideas in watershed planning. In addition, there is likely to be broader understanding and acceptance of landowner responsibility for environmental outcomes of land use. We believe this development will not only be national in scale but international as well. A companion development will be well-established technical capabilities within landowner communities and more sophisticated and well-informed local agencies and publics.

Impressive progress has already occurred. As long as 15 years ago, natural resource managers were stimulated to negotiate settlements of disputes and regulatory standards. Now watershed interests have been advancing similar processes, starting with vigor less than 10 years ago. The collision of economic and social interests with the requirements of the ESA and the CWA is accelerating the number and types of collaborative processes. People are becoming increasingly adept at these efforts, and agencies are adopting facilitative processes all over the country at all levels of planning. The negotiations have not been all successful, nor are they without challenges, but some have succeeded, and people at least have begun to better understand the multiple viewpoints on a number of different issues.

As we move ahead, everyone will have to develop a greater understanding of the role of the social and natural sciences in policy-making. Although today's resource managers are often involved in research, and scientists are helping design management techniques and prescriptions for social action (a significant change from traditional roles), policy processes and scientific processes are, in fact, very separate. There is considerable disappointment and disillusionment when science-intensive policies "fail" to "solve" problems.

One reason for this disappointment can be traced to the fact that there is a vast "culture gap" between "policy" people and scientists. Simply providing managers with results from scientific studies is inadequate for policy development and implementation. This is a two-way problem: lack of scientific training for policy-makers, plus inability, and occasionally unwillingness, of scientists to understand policy processes and pressures, or to explain their science in terms usable by policy-makers. Science is incomplete, fragmentary, and hard for non-scientists to understand and use. A major problem is the high level of uncertainty in much of the science needed for policy-making. Unlike scientists, most policy makers are not trained to deal with and act upon fragmentary knowledge and high degrees of uncertainty.

Often, scientific information is in greatest demand when cause and effect relationships are most obscure. It is difficult to identify the scientific information needed to make good policy: if the information does not yet exist, it is routinely impossible to do the research to produce it on policy-makers' time-scales. As a consequence, many resource management decisions are made in the face of fundamental uncertainty. Science, which cannot predict a "specific" outcome, needs to relate to the need to predict the range of possible consequences.

Another challenge we face is that science-based solutions to environmental problems often fail primarily because the policy is not implemented appropriately or effectively, if at all. In fact, because of the failure of science-policy communication, policy decisions often are not implementable. Examples include (1) federal mandates on water quality that require analysis of contaminants far beyond scientific capabilities, and (2) the federal listing of west coast salmon runs as endangered, which will force local and state governments to design and implement costly remediation plans of unknown utility.

Incentives for Landowners and Water Users

Legal and institutional incentives for encouraging landowner and water—user involvement in a watershed planning process are relatively undeveloped. Our society is still largely focused on command and control intervention and penalties. Further, agencies arguably are still advised by risk-averse legal counsel, and many interest groups capitalize on risk-averse publics to advance single-purpose causes. This is a litigious society, and the natural resources sector is no exception. Legal challenge continues to be a course of action for many people. While not a useful device for solving complex, natural resource problems, litigation has been used effectively for halting actions within watersheds that plaintiffs wished stopped. There is a large amount of current litigation based on federal environmental laws, suggesting that the courts are believed by some to be the most effective redress for their convictions and values. This reality results in risk and uncertainty for the regulators and the regulated alike, and it constitutes a challenge to the effectiveness of consensus forums for resolving differences and gaining understanding of physical and biological relationships on watersheds. Nonetheless, within our democracy there is no avoiding the use of multiple forums, consensus processes or the courts. However, we note the continuing gridlock in national forest planning as a result of various opportunities for vetoing any proposed action through litigation. If the same pattern should carry over into watershed planning, all the possibilities for planning across multiple ownerships and land uses could come to naught.

All of these legal realities can be a significant impediment to advancement in collaborative watershed planning. Several newer approaches include Habitat Conservation Plans between landowners, utilities, municipalities, and the federal government, conservation easements purchased with public funds, and conservation purchases with private funding in which owners or operators are compensated for alternative or modified uses of their land. In addition, proposals for tax concessions or credits to provide incentives for watershed and habitat improvements made by owners and users are being considered more seriously. We believe that incentives will gain a much stronger standing in the 21st century. Sequestration of carbon will likely be a major focus for forestry policy in the next century, and landowner and utility incentives for climate enhancing management should be on the agenda as part of watershed planning science and economic tradeoff analysis. Debate about how much owner/users should be compensated for costs they absorb in implementing watershed measures desired by the public, versus how much they should be willing to absorb under the mantle of environmental stewardship will move into the more sophisticated arena where people will confront compromises between the command and control approach and an incentive-centered approach. If we could wish our way into the 21st century, we would advance multi-resource, multi-ownership cooperation on watersheds that would accrue to the advantage of the public and owner/users alike. Arguably, the Forest and Fish Module, which was recently approved in Washington State and is described below, is a step in this direction, and may be an approach that other states would find useful.

Forest and Fish Module: An Experiment in Watershed Planning at the State Level

A 1997-1998 Washington State land use planning process involving diverse and sometimes adversarial interests in a consensus forum is called the Forest and Fish module. This effort was intended to set the stage for the next generation of forest practices on non-federal land in the State and involved 15 months of intense negotiations between industrial and non-industrial forest land owners, the State Department of Ecology and Department of Fish and Wildlife, the U.S. EPA, Fish and Wildlife Service, and National Marine Fisheries Service, counties, and treaty tribes. Although environmental interests participated in the early negotiations, they ultimately left the process and are extremely critical of the agreement. The process continued nonetheless and eventually resulted in a "Forest and Fish Plan" that was submitted to the legislature as Engrossed Substitute House Bill 2091. The proponents of the plan expect to provide functioning fish and wildlife habitat, and flexibility for landowners to sustain economic competitiveness for the life of the plan, which is expected to be on the order of 50 years. The plan includes only one principal watershed use, namely forest management.

Complexities ahead notwithstanding, the 1999 Washington State Legislature passed and the Governor signed into law the Forest and Fish Plan with bipartisan support, and included financial provisions for landowners to help meet conservation objectives. The principle of negotiated solutions between many widely diverse interests has been demonstrated and reinforced by the process, but one must ask whether there will be a newer model of engagement that replaces this often drawn-out and exhausting procedure. Environmental critics are particularly exercised at the science underlying the agreements. We posit that science must be transparent and even more integrated into the process in the next model, in order to both keep the parties at the table, and to help create a structure within the agreement that can be readily evaluated and monitored over time.

Research Needs

It is apparent that watershed planning is in its infancy, in part because it is complex owing to the interaction of physical, biological and social factors. Our knowledge base is limited in each of these areas, largely because of the scale at which planning in the coming century needs to be done. The stakes are high for our society and having good information will be an important key for successful policies and watershed plans. Societal investment in research is badly needed.

Clearly, we need more sophisticated and transparent systems for monitoring variables of interest to policy makers and the public, including runoff, water quality, fish populations and watershed condition, along with the data archiving, processing, and visualization capabilities that arguably can make these data useful and accessible for many critical groups.

We need to reinvest in basic hydrologic research that will improve our understanding of the linkages between various land uses and the variables of interest at the watershed scale. Understanding the complex pathways by which subsurface water moves on steep hillsides and its interactions with soil strength, erosion and landslide frequency is badly needed. We need to be able to trace the origins of non-point sources of pollution to sub-basins in watersheds and the practices causing them, as well as the incentives (educational, financial, technical, regulatory) that will encourage sources to control them.

Previous watershed studies focused on processes at the small catchment scale (usually less than a few hundred acres). While such studies are still needed, we also need to understand how multiple land uses interact to affect water resources on much larger scales. We need to understand and predict how large scale disturbances or long-term management policies are likely to affect water resources in larger basins. In the West, perhaps the most important such disturbance is wildfire. Increasing fuel loads as a result of long-term management practices, particularly on federal forest lands, makes this an especially critical issue.

Sensor technology, that measures nutrient demand and stress, should play a much larger role in forestry, as it will in agriculture, for detection and rapid response to disease, insects, fire, and even marketability. Incentive based management and more widespread public acknowledgement of resource goals will help make these investments usable.

Our "watershed" research must be extended to include coastal estuaries and the near shore portion of the ocean that is so important to anadromous fish. In the West, one of the major drivers for managing and regulating land use practices in watersheds, including the urban portions, is the ESA restrictions associated with threatened or endangered runs of anadromous fish. Throughout the world's coasts, the ocean and estuarine conditions that affect fish populations must be better understood in terms of their relationships to other terrestrial conditions. Without this sorting out of knowledge and relative contribution to habitat quality or decline, socio-political decisions about how and where to best apply money for protection and mitigation of environmental conditions will continue to be haphazard and likely unsuccessful exercises. Further, it will be impossible to ascertain whether and how much changes in watershed practices are effective in helping to restore these threatened or endangered populations. Having said this, we also recognize that improved watershed habitat conditions and management practices are essential to the healthy restoration of these fish populations.

We provided examples of watershed planning that involved multiple property owners, operators, and resource users with multiple land uses. Successful watershed planning of this type is currently rare, but such efforts are growing, partly as a result of endangered species issues. We believe the model needs to advance a step, with a more transparent basis in the scientific and other inputs that go into policy decisions. For this to occur, information structures and decision tools must be shared by groups that are not used to sharing. Research can help bridge organizational barriers to information and prevent jurisdictional and institutional boundaries between and within various levels of government from hindering effective watershed management. In the West, for example, it is common to have large blocks of federal land juxtaposed with state and private land in a basin, each with different policies and regulations and limitations on the role of public participation in planning and decision making. These need to be coordinated, and sharing science and knowledge may be the most sure way to span those boundaries.

More research is needed to develop mechanisms for evaluating watershed policies and programs. The evaluation mechanisms must include more than a measure of simplistic outcomes (e.g., "bean counting" the number of enforcement notices, numbers of species listed, and so on). At present, evaluation efforts often result in a determination that policies have "failed" simply because we do not know how to comprehensively evaluate and measure the impacts of those policies and programs. If "adaptive" management principles are to be properly implemented, then a new generation of evaluation technologies must be developed and implemented as a part of policy. Without such evaluation capabilities, the promise of adaptive management as a formal, systematic, and rigorous approach for learning from the outcomes of management actions will not be fully realized. Since many watershed practices and policies are essentially experiments, the reliable feedback that adaptive management is intended to provide is critical for improving subsequent actions and objectives, and accommodating change.

Lastly, we need to increase the public investment in both natural and social science research related to watershed management and water resources. Given the magnitude of the water resources problems we face and the growing value of water as our population grows, the current level of investment at state and federal levels is inappropriately low. If we commit to incentive packages that reward effective planning behavior, devote energy to collaboration, rather than strife, and take advantage of technological advances that will help understand and monitor our natural systems, we may achieve both a more coherent watershed management policy and more effective regulation to boot. But it will take a concerted devotion to research, effective funding, and a new collaboration model to pull it off.

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Watershed Management: A Concept Evolving to Meet New Needs

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Abstract.—Watershed management is attracting increased attention, not only among persons involved in natural resource management, but even among those with a less specialized interest in such issues. Watershed management is reviewed as a movement with historical, social and political implications, in the past and the present.

Introduction

At first glance, the term watershed management appears to be self explanatory, its meaning apparent. Watershed management is the managing of a watershed. At best, however, this definition is merely the starting point and might appropriately be compared to the initial upland flow of a watershed itself, before becoming part of a complex system covering a broad area. Variously interpreted and applied, watershed management, as public policy or field of study, also covers a broad area, to include consideration of social, cultural, and economic affairs as well as natural resource and environmental issues.

A concept well known to natural resource managers, watershed management is gaining wider recognition, with references to it now appearing in the popular press. Its recent and wide application ensures that thoughtful coverage of environmental issues having to do with water will likely refer to watersheds and watershed management. For example, a front-page article in the Sunday "New York Times" discusses an environmental strategy to ensure the overall quality of watersheds. Also, President Clinton's Clean Water Initiative relies on watershed management principles to achieve its goals. An understanding of watershed management is key to comprehending much developing water-related public policy.

Watershed management's relatively recent rise to prominence is due to the interest and support of researchers, policy makers, politicians at various levels of government, community groups and the private sector. Many people from these groups believe that watershed management, with its coordinated, voluntary and consensus-based solutions, helps them first recognize and then address problems and areas of mutual concern. Advocates of watershed management emphasize that its workings do not represent a new program, but rather is a new approach to solving natural resource problems. Present operations are redirected to better accomplish watershed goals.

Several watershed management initiatives are underway in Arizona. Projects along the Verde and Gila rivers have attracted national attention, and the San Pedro River is the site of varied watershed activities. Meanwhile the Arizona Department of Environmental Quality (ADENQ) is in the process of adopting a statewide watershed management framework, to expand the application of watershed principles and to institutionalize the approach in state government. A review of watershed management, its meaning and application, would be timely and help promote a better understanding of its potential to resolve present and future natural resource problems within the state. An understanding of watershed management begins with an understanding of a watershed.

Watersheds as Geography

In watershed management, a watershed is an administrative unit as well as a geographic designation. Considered either way, administratively or geographically, watershed needs defining. What is this structure or natural feature that conveniently serves this dual purpose?

A watershed is a geographic area defined by the flow and movement of surface water. In a watershed, because of the elevation and contours of the land, all water flows to the same location or water body, such as a stream, pond, lake, wetland or, although not in landlocked Arizona, estuary. An aquifer also might be the common destination for water within a watershed. The flow of water might carry sediment and dissolved minerals. In its flow to a common destination, water sets the boundaries of a watershed. Hydrologists sometimes refer to watersheds as catchments or drainage basins. The term river basin sometimes is used synonymously with watershed.

Some watershed-related terminology, e.g., catchments or drainage basins, conveys an image of plumbing, as if human intent were involved. Watersheds, however, are natural systems of flowing water. Much of the water coursing through a riverbed is the result of runoff and

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flow from the surrounding land, its hills, mountains, mesas and other surfaces that slope toward the river. In higher elevations snow falls, accumulates and melts. Rain also occurs. The runoff from melting snow and rain flows over the land, guided by its varied surfaces and forms, possibly through canyons and arroyos, into a system of tributary streams. Streams merge and in turn merge again, until the cumulative flow enters a larger body of water.

The above describes a watershed in a state of nature. To understand the conditions of a watershed, however, more than a natural flow of water needs to be examined. Various human activities also may occur within a watershed, and these may affect its natural conditions. For example, cattle may graze in certain areas. Waters within a watershed may be used for irrigation, and the return flow may carry fertilizers and salts. Lands may be set aside for various other human activities, from logging to recreational uses, each with a possible effect on water quality. Also the watershed may include urban areas. Centers of diverse and varied human activities, urban centers may be the source of runoff with varied kinds of pollutants that enters the watershed.

Sometimes more than just natural drainage features determine a watershed. In defining watersheds within the state, ADENQ also considered such factors as constructed boundaries (e.g., Painted Rock Dam, Granite Reef Diversion Dam and their associated canal systems.), common cultural and economic bases and location of population centers. For example, ADEQ combined Willcox Playa and Rio Yanqui with San Pedro River.

Watersheds exist at different scales or levels, depending upon a particular point of reference. For example, if the Colorado River is the point of reference then almost the entire state of Arizona consists of a single watershed. This is because almost all of Arizona's land eventually drains to the Colorado River. The only exceptions are certain areas draining through Mexico into the Gulf of California and a few closed basins such as the Wilcox Playa.

(Arizona shares the Colorado River watershed with six other states. The Seven Colorado Basin states' cooperative effort at negotiating and then signing the 1922 Colorado River Compact might be viewed as an early example of watershed or river basin management. The compact apportioned Colorado River water between Upper and Lower Basin states. Basin-wide agreements were not common at that time.)

On its way to the Colorado River, water in Arizona flows through various other drainage systems that are in themselves watersheds. In other words, there are watersheds within watersheds, with smaller watersheds nested within larger ones. For example, in Arizona, the Gila and Little Colorado rivers, each fed by their own watersheds, both eventually drain into the Colorado River. Their watersheds in turn are fed by others watersheds. Watersheds, therefore, range widely in size and scale, from the local to statewide.

(If flow along the Continental Divide is considered then water also divides the continent. Also known as the Great Divide, the Continental Divide is located at the watershed formed by the Rocky Mountain ranges or tablelands. This watershed marks the dividing of the waters in the United States. On one side water drains eastward into the Atlantic Ocean and on the other side water drains west, into the Pacific Ocean. Most water flowing east drains into the Gulf of Mexico before entering the Atlantic Ocean. Most of the western flows enters the Columbia or Colorado rivers before reaching the Pacific Ocean.)

Watersheds as Administrative Units

That watersheds can be subdivided into various sized segments enhances their value as an appropriate and workable management unit. A hydrologic system unto itself, a watershed provides a more comprehensive and rational setting to resolve water or natural resource problems than areas defined by political boundaries, whether national, state, tribal or local. For example, problems having to do with water quality or quantity or wildlife habitat are not likely to be confined to areas enclosed within political boundaries. Watersheds are more likely to match the geographic scale of such problems.

In developing its statewide watershed framework, ADEQ has identified ten watersheds as management units. The watersheds are ten interlocking sections that together cover the entire state.

The flow of water can determine borders between states and nations as well as the shape and extent of a watershed. The Colorado River is the border between the states of California and Arizona, and the Rio Grande divides Texas and Mexico. The use of rivers to define political borders, however, is profoundly different than their use as watershed boundaries. Water and its flow is the internal logic of a watershed, its prescribed area determined by the movement of water within it. When used as political boundaries, a river is merely a convenient point of reference. The watersheds of the Colorado River and the Rio Grande extend far beyond the political boundaries set by those two rivers.

Watershed management is not the only strategy for defining an area or spatial unit for the purpose of managing its natural resources. Ecosystem management also considers the broad regional context as the appropriate framework for addressing natural resource issues. Definitions of ecosystem management vary, but the approach generally is based on the occurrence of biota in an area.

The focus of ecosystem management ranges from specific sites to global regions. Debate is ongoing about whether watershed or ecosystem management better provides a framework for managing natural resources. Both, however, share a commitment to move beyond single-issue problems viewed on a micro scale to a holistic consideration of broader regional patterns, along with a consideration of the complex interaction of humans with the environment.

More is involved in a watershed management approach, however, than establishing administrative or organizational units along watershed lines. Topographical ridge lines may define the physical boundaries of a watershed, but the application of various principles, practices and theories within those boundaries determines whether a watershed management approach is in fact in place.

Watersheds in History

The historic roots of watershed management are evident in the Depression Era (1929-1942). This was a time of crisis that called forth new institutional arrangements to meet the ongoing economic emergency. In response to the perilous times, the Tennessee Valley Authority was established, its creation an effort to improve regional water development and management. The TVA reflects the premise that river basins should be managed as a unit and that institutional arrangements are needed for integrating the management of land and water resources.

Also at this time, the establishment of conservation districts, part of a national program administered by the U.S. Soil Conservation Service (renamed in 1994 the Natural Resources Conservation Service), encouraged land-water integration at the regional level. Partnerships among public, private and government interests to control erosion at the watershed level gained prominence during the depression. The influence of these developments is evident in the modern watershed movement.

In serving various needs, watershed management evolved over time, absorbing new ideas and concepts and reflecting shifts in thinking. In Arizona and the West, a version of watershed management that prevailed at one time has colored perceptions of its meaning even into the present. Watershed management was once viewed as primarily a means of increasing water supplies. It thus served the land use ethic that was dominant in the 1950s. Watersheds were valued as sources of various commodities–water, timber, minerals, etc.–and management practices were adapted to increase the supply of those prized commodities. Thus, a watershed was best managed that delivered a maximum amount of water.

A 1940 government publication on dam construction stresses managing watersheds as a water augmentation strategy. The author complains that dam builders often concentrate on the dam site itself, paying slight, if any attention, to the watershed. In this context the watershed is defined as the surface and subsurface flow that occurs upstream of the dam. The aim of watershed management is to maximize the amount of water available for storage behind the dam while minimizing the amount of sediment carried to the impoundment.

A prime strategy for increasing the supply of water, whether to a dam or to water users, was to manage the vegetation within a watershed. What this in effect meant was destroying or severely reducing vegetative growth within the watershed. This strategy was based on the fact that vegetation, to survive, uses water that otherwise could be put to human uses. Removing the vegetation is a way of redressing this perceived imbalance. Thin out or remove water-using vegetation within a watershed or replace it with a less consumptive species, and a net gain will result; i.e. more water for humans. Chains, cables and chemicals were the means of removing chaparral and pinon-juniper forests; ponderosa and mixed conifer forests were harvested.

In the mid-1950s, studies were done that showed if mixed conifer and ponderosa pine were cleared or thinned in certain areas grasses that use less water then would grow. Clearing of chaparral shrubs also was seen to have water augmentation promise. Since these shrubs readily reseed, however, burning and chemical treatment was the prescribed method of eliminating them. Additional water savings were anticipated by replacing vegetation along riparian areas with more shallow rooted types.

As might be expected this strategy did not go over well with some people. Environmentalists called it “tin roof watershed.” Although some experiments were conducted in Arizona, managing vegetation within watersheds for water augmentation was not done to any great extent within the state, for logistical as well as environmental reasons.

This version of watershed management, which was common in the semiarid West at that time, still lingers in some people’s minds as its dominant rationale. To them water augmentation is so closely linked to watershed management that the terms are more or less synonymous. This at times has worked to discourage a wider acceptance of today’s much different watershed management practices.

Contemporary Watershed Management

Defining watershed management as preached and practiced today is not an easy task. Increased references to watershed management in the natural resource field, in contexts ranging from environmental to regulatory, do not ensure a common understanding of the term. Even among those who advocate its use, who believe watershed management is the wave of the future, may not totally agree on its meaning and application.

Watershed management has been described as a "catch-all phrase," in its accommodation of different activities. EPA literature refers to it in a more positive light as "an evolving approach with many variations." Some people take comfort from this lack of precision, claiming that it is an advantage that watershed management does not fit a particular cubbyhole and instead can be creatively applied to serve different needs. Yet, sufficient agreement exists among watershed management advocates to provide a description of some basic working premises that underlie the concept and its application today.

More than just a policy-making strategy, watershed management also advocates a particular way of thinking, an integrated and holistic view of the world that also is influencing thought in a range of other fields. We now tend to be suspicious of any single cause-and-effect explanation for phenomena, especially natural phenomena. We urge taking the wider perspective, to look at various contributing factors and the way they interact, rather than focusing on a single component. Examples of this thinking are evident in various areas, from interdisciplinary studies to integrated pest management. Environmentalists lay special claim to the wisdom of such an approach, often citing John Muir's remark, "When we try to pick out anything by itself, we find it hitched to everything else in the Universe."

Today's understanding of watershed management reflects this view. For example, its literature includes such polysyllabic words as interconnectedness, integrated, interrelationship, multidisciplinary and multi-jurisdictional. What these words have in common, besides an abundance of syllables, is that they go beyond single categories. The phenomena they refer to are not cut from a single piece, but consist of several pieces that fit together creating a more complex whole.

More specifically, watershed management involves recognizing the complex workings of a watershed, its principles based on an awareness that land use, soil and water are all connected, and this land-water connection is an essential factor to consider when managing watersheds. Further, the strategy acknowledges that issues overlap, that streams are to be studied along with lakes and wetlands; that land uses and community activities are tied to water quality; that groundwater is connected to surface water; that wildlife habitats depend on the condition of water and land; that upstream is linked to downstream; etc.

Recognizing the complexity of the natural world begets awareness that human affairs are not conducted in isolation, nor do they play out as separate and independent acts, but often have implications beyond the immediate situation, to affect other actions and in turn to be affected by them. Human involvement in a watershed, therefore, can have far-reaching implications. As a result, watershed management is concerned with such human-related activities as agricultural practices, urban runoff, private property interests, beneficial uses, sustained economic vitality, net environmental benefit and water quality concerns, especially nonpoint source pollution.

In sum, managing a watershed is a strategy to promote its cooperative use among various, even competing interests, while as the same time protecting the watershed's natural or environmental values as well as public health. Despite the ambitious goal, practicing watershed management principles should not be viewed as a daunting task. Successful application is really based on a simple premise. Clayton Creager of the CADMUS Group describes the process: "By acknowledging a need to work together, problems are addressed more directly. So what we are basically talking about with watershed management is people cooperating—like in kindergarten."

People Working Together

Watershed management involves the participation of stakeholders. As defined in Arizona's watershed framework document, stakeholders are "individuals, organizations, and agencies that are involved in or affected by water resource management decisions for a watershed management zone." Stakeholders' interests in watersheds involve political, social and economic considerations. Assembling a watershed management team to speak to these varied interests can involve representatives of all levels of government, public interest groups, industry, academic institutions, private landowners and concerned citizens.

Broad stakeholder involvement has various implications. With power shared at different levels, new types of governance can be established. The previous reliance on specialized agencies too often resulted in inconsistent and fragmented efforts that often conflicted, overlapped or otherwise were insufficient. The result frequently was a form of institutional paralysis known as decisionmaking gridlock.

By working together and sharing information, stakeholders agree on ground rules to guide their participation in management activities. They come to an understanding about their particular roles and mutually agree on adopted priorities and shared responsibilities. With such broad and varied participation, the focus on environmental issues is thus broadened to also include consideration of social and cultural goals such as economic stability and quality of life issues.

Watershed management often partakes of the tenets of conflict resolution. The consequences of personal confrontations and legal entanglements have been shown to be damaging and costly. Collaboration now is generally viewed as the best way to resolve conflict, especially with regards to environmental issues.

Further, watershed management accommodates the interest of local stakeholders who often have complained of being left out of the policymaking process. The involvement of local and even community interests, however, should not be interpreted to mean that watershed management is a bottom-up approach in contrast to the federal top-down strategy. Instead, all stakeholders are partners in adopting watershed management goals.

Not the least of the benefits derived from having local people–those depending on the natural resources within the watershed–meeting and making decisions is that they become well informed about the issues. If, as is often said, knowledge is power, local individuals and groups become empowered by their participation in the watershed management process. Not only do they learn about the issues, but they also develop communication and leadership skills as well.

Arizona and Watershed Management

Watershed programs are being worked out at the state level throughout the United States, with mixed results. Such efforts are often undertaken with federal support. About one-third of the states either have adopted a statewide watershed management program or are in the process of adopting such a program.

Arizona's official commitment to watershed management began in 1994 when Brian Munson, then head of ADEQ's Water Quality Division, directed staff to explore what implications watershed management would have on ADEQ operations. At the time, watershed management was attracting national attention as an effective strategy for managing water quality.

Supported by EPA funding and technical assistance, an ADEQ work group was formed to look into watershed management possibilities for the state. Membership was limited to ADEQ staff, specifically those involved in water division programs. The intent was first to work out within the agency an understanding of watershed management and its implications, before involving other individuals and groups. A central task of the work group was to develop a statewide watershed framework to guide the state in adopting watershed concepts. In preparing this document, the work group consulted with various outside agencies such as the U.S. Environmental Protection Agency, U.S. Corps of Engineers, U.S. Bureau of Reclamation, Arizona Department of Water Resources and especially local councils of government.

In May 1997, the ADEQ work group issued a draft version of a document titled, "The Arizona Statewide Watershed Framework." The document is a blueprint, the theoretical underpinnings, of an Arizona watershed management program. It is intended to be an adaptive management document, to be adjusted and modified to best meet Arizona conditions and situations.

Along with defining watershed management, both as philosophy and public policy, the document also provides a specific work plan. As previously noted, the document organizes the state into ten management zones. A six-step method is identified for developing and implementing a successful regional watershed plan within the management zones.

- Initiate stakeholder outreach and involvement
- Collect and evaluate watershed data
- List and target environmental concerns
- Develop management strategies and measures of success
- Compile the watershed plan
- Implement and evaluate watershed plan

Along with identifying six essential steps the document also lists various ADEQ operations or activities that are to be performed as part of the watershed framework. Including these activities as part of the framework is consistent with the document's directive that "ADEQ will use the watershed approach as a practical means to consolidate and fulfill many of the department's objectives and activities."

In many ways the framework is a strategy for managing ADEQ programs. For example, the document outlines a schedule of when ADEQ programs and activities will occur within particular watersheds. They are scheduled as part of a sequenced and iterative pattern. For example, detailed monitoring would be scheduled during a particular year at an individual watershed, to be performed at different watersheds in future years. Other ADEQ programs would be worked out in a similar fashion. As a result, ADEQ operations would be taking place on a rotating basis in different regions of the state. The intent of this cyclical watershed approach is to better budget and allocate ADEQ resources and to enable the agency to perform its duties in a more thorough and consistent manner.

The framework represents the state's most far-reaching and organized effort to adopt watershed management concepts. Related issues that lend momentum to Arizona's consideration of watershed management are control of nonpoint source pollution and determining total maximum daily loads (TMDLs). Both are addressed by the state's watershed framework document.

Nonpoint Source Pollution Program

Watershed management, as generally understood and practiced today, is linked to efforts to control nonpoint source pollution (NPS). Background to the NPS issue therefore sheds light on the current interest in watershed management. More specifically, examining Arizona's operation of a NPS program also shows how experience in managing such a program has benefitted the state in efforts to apply watershed management principles.

The increased interest in watershed management is partly the result of a shifting regulatory focus from point to nonpoint source pollution. At one time, the control of point source pollution was a water quality priority. Point source pollution comes from an identifiable source; e.g., a factory or a mine. Controlling point source pollution involves identifying the source, whether mine, factory or other, with state or federal agencies then enforcing specific requirements on polluters. This is considered a "top-down" approach, with a source of authority enforcing directives on those subject to, or under its authority.

Efforts at controlling point source pollution eventually paid off, with sufficient progress demonstrated to enable regulators to focus on other sources of pollution. Officials then turned their attention to the control of nonpoint source pollution.

In 1986, when NPS pollution problems were attracting special notice, an EPA report stated that nonpoint sources account for 45 percent of the pollution remaining in estuaries, 76 percent of the pollution in lakes and 65 percent of pollution in rivers. Further, 165,000 miles of rivers and 8.1 million acres of lakes in the United States had been assessed to be impacted by various categories of NPS pollution. Clearly NPS pollution was a problem to be reckoned with.

Controlling non-point source pollution presents regulators with a different set of circumstances than point sources of pollution. Unlike point source pollution, NPS is less readily identified with a particular source or a single source of pollution. Frequently associated with urban or agricultural runoff, NPS pollution develops from many human activities, usually related land uses. Relatively diffuse in its points of entry into the environment, NPS pollution can originate anywhere on the land surface or within a watershed. NPS pollution might then flow with runoff to streams, rivers lakes, and aquifers.

Managing NPS pollution usually involves identifying a land area with a common drainage system and joining forces with other interested and concerned parties within the area to develop a strategy for solving problems. Many different interests need to work together, from the various levels of government–local, state, and federal–to the private sector and individual members of the public. The community needs to be involved because nonpoint source solutions often are voluntary. Consensus-building then becomes important, with an informed and concerned public participating in solving problems. Education and involvement of the public are therefore major concerns in the management of various NPS pollution.

In response to the rising concern about NPS pollution, ADEQ's Division of Water Quality adopted an NPS control program. The stated object of the program is: "To improve the health of the watershed through the development of community-based programs that minimize pollution from nonpoint sources to surface waters." Central to this effort is the Nonpoint Source Management Zone Program (NPSMZ) which divides Arizona into 15 Nonpoint Source Management Areas. These represent areas with certain community and hydrologic consistencies.

ADEQ's later efforts to establish a statewide watershed framework benefitted from the agency's experiences in administering its nonpoint source pollution program. Through its involvement with the NPS program, ADEQ gained familiarity with watershed-based environmental management. Further, managing the NPS program involved working with community groups since NPSMZ was instrumental in establishing local advisory groups in the Verde River Valley and the Upper Gila River Valley.

A task when designing the current state watershed framework was to broaden the focus beyond traditional NPS program concerns, such as impacts of farming, ranching, and urban runoff, to include a greater array of water quality programs. As previously discussed, watershed management is intended as a more comprehensive natural resource strategy.

Total Maximum Daily Load

TMDLs have attracted wide attention lately, even featured on a front page article in a Sunday "New York Times." TMDLs represent a new approach for evaluating water quality and protecting waters, with EPA heralding their use as "a defining moment." Enforcement of TMDLs earned EPA's accolade because it represents a commitment to control water quality on a watershed basis, rather than relying on technological strategies.

In brief, a TMDL is a measure or "budget" of the amount of a specific pollutant that a body of water can receive before it exceeds water quality standards for a designated use. TMDLs generally are set for individual pollutants within specific watersheds. TMDLs owe their prominence to the Clean Water Act and its requirement that loading estimates be set for those watersheds with water quality insufficient to meet designated uses. For example, TMDLs would need to be established for a stream segment that is designated for contact recreation but has high levels of fecal coliform bacteria.

Setting TDML standards means considering both nonpoint sources and point sources of pollution. As a result, efforts to set TDML standards require coordination among various regulatory agencies on a watershed basis. ADEQ is planning to establish about 92 TMDLs during the next eight to 13 years.

TMDLs have taken on a special importance lately for several reasons. EPA is viewing the process as an effective tool to improve water quality on a watershed basis. Also, the TMDL issue–or more specifically various states' failure to develop TMDLs–is providing an opportunity for environmental groups and others to sue EPA for its failure to enforce Clean Water Act directives in some states. In effect, TMDL is an issue for rethinking water quality on a watershed basis.

Critics Question Arizona's Watershed Commitment

Arizona has undoubtedly made a start in adopting a watershed approach for managing various state water quality programs. The work that went into developing "The Arizona Statewide Watershed Framework" demonstrates a commitment to applying watershed principles within the state. Many observers, however, view progress accomplished thus far as only the beginning, faulting ADEQ for not more actively promoting watershed management initiatives. Critics often refer to watershed work being done in other western states, especially Utah, California, Oregon and Washington, to demonstrate that Arizona could and should be making greater progress.

For example, Utah appears to be making impressive progress in adopting watershed management. The state is divided into ten watershed management units. A coordinator is assigned to each unit, and each unit also has a local steering committee and a technical advisory group. Unit coordinators act as a liaison between state government and local communities. At the state level, the statewide watershed management coordinator is part of a team consisting of representatives from various sections within the Utah water quality division. Chaired by the water quality division director, the team works to align various operations with watershed principles.

Critics claim that part of the problem in Arizona has been the administrative instability within ADEQ. An excessive number of personnel changes, especially at senior management levels, has left the state without effective leadership to promote watershed management initiatives. For example, in the last four years, four different directors have headed the Water Quality Division within ADEQ. This is a key position to ensure state commitment to watershed policy. This rapid turnover does not bode well for consistent and long-term attention to watershed affairs; not to mention other water quality matters.

In contrast, others believe Arizona already has demonstrated a leadership role among states in watershed management by organizing and implementing its NPSMZ program. They don't necessarily view NPSMZ as a precursor to a watershed management program, but a watershed program unto itself, embodying its essential principles. Those disagreeing with this view argue that watershed management involves much more than controlling nonpoint source pollution; that it operates with a broader focus, guided by a holistic, synergistic interpretation of watersheds and their workings. This is the approach they advocate for Arizona.

Some critics identify various characteristics of what they call the state's political culture as working against statewide watershed management. For example, they claim Arizona has an inordinate devotion to control at the local level, to the extent that it is the defining political philosophy of the state. This position often is interpreted to mean that not only is federal involvement resented, but even directives from state government are unwelcome. Applying such principles to efforts at cooperative governance, such as watershed management, can present problems.

For example, locals who grapple with complex watershed issues likely lack the scientific and technical expertise to make appropriate decisions. If government, which can be a source of such expertise, is suspect, where can local community members turn for help? If even state officials are reluctant to take action lest they impose upon local communities, citizen groups may be left to their own limited resources. Some critics fault ADEQ for not having worked out suitable procedures for building bridges to local communities to enable the agency to better work with advisory groups and respond to their needs.

Some people view Arizona's commitment to the property rights movement as hampering efforts to work out watershed initiatives. Property rights is an expression of local control, with individual property owners claiming certain inviolable rights to determine the use of their land, regardless of government policies. Whether viewed as a social, cultural or political movement, a property rights position often is at odds with the collective planning and negotiating of watershed management.

Finally, some people claim that Arizona is lukewarm in its commitment to watershed management for hydrological or water supply reasons. Tucson, which is Arizona's second largest city, relies on groundwater, with the Central Arizona Project supplying the city's only surface water supply. Without a direct vested interest, Tucson officials may not be overly concerned with the condition of adjacent watersheds. In Phoenix, the Salt River Project claims the watersheds of the Salt and Verde rivers. Its involvement with these watersheds, which are managed by the U.S. Forest Service, is said to discourage extensive watershed management activity.

If Arizona has in fact been slow to adopt principles of watershed management, the situation may be changing. Arizona, along with other Western states, is confronting change, some say it faces a transformation, the effects of which will become more evident in the future. Ranching, mining, agriculture and timber, once the economic mainstays of the west, are being replaced by recreation, exploitation of scenic resources and a concern for urban affairs. The effects of this shift undoubtedly will be evident in debates about the best strategy to deal with publicly owned land and water. Watershed organizations may be the pressure point to deal with these issues and as result may gain in importance in the future.

Federal Watershed Support

Various federal agencies are committed to watershed management as a strategy to further U.S. natural resource management objectives. Agencies such as the U.S. Army Corps of Engineers, the U.S. Department of Interior and especially the U.S. Environmental Protection Agency provide both financial and technical support to encourage watershed management planning and implementation.

Other federal agencies have adopted various aspects of the watershed approach, but often without the community involvement component. For example, the U.S. Bureau of Land Management and the U.S. Forest Service are using watershed analysis, but often without community participation. (The question then arises whether this in fact is watershed management. The watershed approach is multifaceted, involving a range of activities. Some proponents feel sufficiently protective about watershed management principles to be wary of agencies claiming to use the strategy, but without adopting what they consider to be a key component; i.e., community involvement. Supporters are quick to point out that more is involved in watershed management than organizing activities within watershed boundaries and government agencies are increasing their commitment to collaboration with local communities as mandated by the new draft rule for National Forest Management Act planning.)

When considering the federal role in watershed management, the Natural Resources Conservation Service merits special mention. Founded in 1935 as the U.S. Soil and Conservation District, this agency actively promoted regional federal-state-local partnerships. It was instrumental in establishing about 3,000 soil conservation districts that almost cover the entire nation. The agency's adoption of a "small watershed program" and its development of a "natural resource management" framework promoted regional cooperation in erosion and flood control issues. In 1994, the agency became the Natural Resources Conservation Service. The NRCS is a lead agency in the promotion of watershed management, its conservation districts providing the framework for many current watershed initiatives.

Various pieces of federal legislation refer to watershed management. For example, the Clean Water Act (CWA) mentions watershed management and includes options for watershed-based activities. The 1996 amendments to the Safe Drinking Water Act include new requirements for source water protection activities; in effect, this means watershed and associate groundwater basin protection. Also, in 1991, EPA released plans for a new watershed protection approach to confront nonpoint pollution problems. In 1994, EPA Region 9 came up with a watershed strategy plan, with various goals including setting clear watershed target priorities, supporting local, state, and federal watershed efforts, and tracking and evaluating the success of watershed management initiatives.

More recent federal action further promoted watershed management. On October 18, 1997, the 25th anniversary of the passage of the CWA, Vice President Al Gore issued a directive to various federal administrators in honor of the special occasion. He directed EPA administrator Carol Browner and Secretary of the Department of Agriculture Dan Glickman to work with other federal agencies and the public to develop a plan toward fulfilling the CWA's original goal of "fishable and swimmable" waters. A Clean Water Action Plan was duly prepared and forms the core of President Clinton's Clean Water Initiative which he announced in his 1998 State of the Union Address. The plan relies heavily on the watershed approach, referring to it as the "key to the future." Watershed assessments are to be used to identify watersheds to be targeted for FY99 funding, and watershed restoration action strategies will identify causes of water pollution and the actions needed to remedy those problems. In brief, the watershed approach is to be the guiding light for setting priorities and taking action to clean up the nation's rivers, lakes and coastal waters.

As is appropriate to a watershed approach, the plan calls for a collaborative effort, with federal, state, tribal, and local governments working together as a team, along with the private sector and members of the public. This broad partnership is to ensure public participation in restoration and protection efforts and to promote productive coordination among all levels of government as the preferred strategy for cleaning and protecting the nation's water.

As part of the Clean Water Action Plan, state environmental agencies and conservationists are directed to take the lead in conducting unified watershed assessments. The process also is to involve federal and local agencies, watershed-based organizations and the public. The assessment is to define watershed priorities for those watersheds most in need of restoration. These watersheds would be eligible for priority funding from the FY 1999 budget.

The assessment also calls for developing and implementing watershed restoration action strategies to restore those watersheds most in need of attention. Further, a preliminary schedule is to be set for working on the remaining watersheds. In Arizona, the U.S. Natural Resource Conservation Service and ADEQ are working together to assess and prioritize the state's watersheds.

The President's FY 99 budget proposes $500 million to implement the action plan. Further, the President said that over the next five years he will set aside $2.3 billion, in addition to current spending levels. Among other objectives, the federal money is to be spent to "increase direct support to the states and tribes to carry out a watershed approach to clean water, and fund watershed assistance and partnership programs and grants to help local communities and citizens take leadership roles in restoring watersheds."

Some people are skeptical of the initiative, claiming it is politically motivated, its goal to promote Vice President Gore's presidential aspirations. They say much of the funding of the initiative is uncertain, with some of the support depending upon future congressional appropriations. Not taking any chances, the Western Governors Association is actively promoting federal funding for watershed improvement and restoration.

Conclusion

That watersheds provide a framework for managing natural resources seems appropriate for a number of reasons. The most obvious reason is that watersheds are naturally defined surface areas and provide a focus for observing the effects of human activities on land and water. Managing a watershed often means managing human activities to lessen any damaging effects on natural processes.

Also, however, an acceptance of watersheds as managing units implies less reliance on bureaucratic techniques; instead, the workings of a watershed determine what decisions are made and what actions are taken, at least in theory. Natural watershed processes, rather than bureaucratic structures, provide the rationale for management plans. This is an appealing concept at a time when many people profess belief in an environmental ethic.

This mode of thinking also might lead us to consider what is basic to watersheds, i.e., water, the flow, drip, swirl and rush of water. Although obvious, this still might bear mentioning. Too often theory rules, its interpretation and application of primary importance. Even watershed management, although striving to be user-friendly, can at times seem rather abstract. Those wary of theories and abstractions can derive some comfort knowing that their involvement with watershed management is essentially an involvement with water, in its various states and conditions.

Watershed management, therefore, is more than just an effective management plan, to be studied, interpreted and applied. Part of its appeal extends beyond its use as policy to an awareness that watersheds are in fact systems of flowing water, and that an effective application of watershed management principles begins with an appreciation of river flow. In a memoir of his boyhood Richard Selzer describes the effect rivers have on him, "From each river, there is given off a personal drift that is the confusion of its numberless currents, the curves and recurves of its long traipse, the strew of its bed." In his feel for rivers, Selzer is effectively expressing one of the first principles of watershed management.

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Resource Integration and Shared Outcomes at the Watershed Scale

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Abstract.— Shared resources are universal resources that are vital for sustaining communities, enhancing our quality of life and preserving ecosystem health. We have a shared responsibility to conserve shared resources and preserve their integrity for future generations. Resource integration is accomplished through ecosystem management, often at a watershed scale. The shared outcome of resource integration is sustainability, which can be measured with the appropriate criteria and indicators. Using a watershed approach to land stewardship, we can identify priority problems, obtain stakeholder involvement, integrate the support and participation of multiple agencies, and measure success through monitoring.

Introduction

What do we mean by the term shared resources? Shared resources can be viewed as common resources that are essential for community economic growth, enhancing the quality of our lives and preserving ecosystem health. Shared resources cross ownership boundaries to reach a variety of users — the public (e.g., ranchers, farmers, industry, urban and rural communities, etc.), states, tribes, local governments and federal agencies. Air, oceans and watersheds are natural resources that are shared among many users who affect their quality. For example, if atmospheric emissions are reduced, many downwind ecosystems and watersheds may benefit. Shared resources can also mean migratory species such as birds or mammals, the variety of life and ecological processes (biodiversity), shared financial resources and shared knowledge among resource specialists.

The Southwestern Region of the United States Department of Agriculture Forest Service maintains an ecological basis for ecosystem management (Kaufmann *et al.*, 1994). By definition, ecosystem management crosses ownership boundaries and is practiced at various scales or hierarchical units, including the watershed level (U.S. Environmental Protection Agency, Environmental Monitoring and Assessment Program, 1997; USDA Forest Service, 1993; United States Department of Defense, Department of Agriculture and Department of the Interior, 1998). It is through ecosystem management that the various resource areas are integrated and sustainability is ensured.

Shared outcomes are when the benefits of watershed management and watershed health are shared among many resources and sectors. These benefits include improved watershed condition; species and habitat conservation; sustainability of renewable resources; and social, cultural and economic benefits. For example, well-planned activities, as demonstrated by the Verde Watershed Association, can benefit streamflows, riparian species such as cottonwood trees, and landowners within the watershed (Verde Natural Resource Conservation District, 1999). Therefore, the benefits of watershed management are shared among communities, water resources, soils, wildlife, etc. The measure of success for resource integration and shared outcomes is sustainability.

Watersheds are natural ecological units. They provide an appropriate spatial scale for assessments and management activities such as restoration. The Environmental Protection Agency defines a watershed-scale approach to resource management as "a strategy for effectively protecting and restoring aquatic ecosystems and protecting human health" (United States Environmental Protection Agency, 1999a, b). Healthy watersheds are important because they can provide the timing, quality and quantity of water needed for designated uses such as domestic water supply, contact recreation and fisheries. Terrestrial ecosystems and the health of many organisms benefit from well-managed watersheds. Thus, a watershed approach to resource management can be an umbrella that allows many disciplines to focus on identifying priority problems, obtaining stakeholder involvement, integrating support and participation of multiple agencies and measuring success through monitoring.

Focusing on Watersheds

The Forest Service emphasizes watershed management. Existing guidelines include the President's Clean Water Action Plan (United States Environmental Protection Agency, 1999), the Natural Resource Agenda (United States Department of Agriculture Forest Service, 1998) and the Southwestern Region's ecology-based approach

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to ecosystem management (Kaufmann et al., 1994). The Southwestern Region is also a partner in the Southwest Strategy that is designed to ensure continuing collaboration with other federal agencies and the public (United States Department of Defense, Department of Agriculture and Department of the Interior, 1998). In addition, large-scale watershed restoration projects are being identified nation-wide by the Forest Service.

Clean Water Initiative

In January 1998, President Clinton announced his Clean Water Initiative to meet national clean water goals (United States Environmental Protection Agency, 1999). A key element of the initiative is *community-based watershed protection efforts at high priority areas*. Focusing on whole watersheds is one of four key elements for setting priorities and restoring and protecting the quality of our nation's rivers, lakes and coastal waters.

In order to revitalize the national commitment to shared water resources, nine federal agencies were directed to develop a comprehensive plan for watershed protection i.e., the Clean Water Action Plan). The goal of this document is to accelerate the rate of progress in the improvement of America's water quality. The Action Plan is designed to provide cleaner water, public health protection, watershed protection at high priority areas, and stable water resources for communities. The nine agencies are working with tribal, state, and local partners to implement the Clean Water Action Plan.

Federal land management agencies are also developing a unified federal policy for ensuring a "watershed approach" to federal land and resource management (United States Environmental Protection Agency, 1999a). The proposed national policy is designed to improve water quality and aquatic ecosystems on Federal lands. The Unified Federal Policy emphasizes:

- assessing the function and conditions of watersheds;
- incorporating watershed goals in planning;
- enhancing pollution prevention;
- monitoring and restoring watersheds;
- recognizing waters of exceptional value; and
- expanding collaboration with others.

The draft policy outlines specific federal commitments that can achieve consistent watershed assessments; improve watershed management; comply with water quality requirements; and enhance collaboration with states, tribes and others. It also provides a schedule to meet those commitments. According to the policy, watershed management priorities will be based on the geographic extent of the watershed under federal management, the magnitude of the existing impairment, vulnerability to degradation, the amount of public interest, and concerns that arise from state and tribal assessments.

Natural Resource Agenda

On March 2, 1998, USDA Forest Service Chief Mike Dombeck announced a Natural Resource Agenda for the 21st Century (United States Department of Agriculture Forest Service, 1998). The first priority of the Natural Resource Agenda is to maintain and restore the health of ecosystems and watersheds. The agenda focuses on four key areas: watershed health and restoration; sustainable forest ecosystem management; forest roads; and recreation. Chief Dombeck challenged the agency to lead by example, saying "We can lead by using the best available scientific information based on principles of ecosystem management that the Forest Service pioneered. And we can use the laws that guide our management to advance a new agenda." This effort echoes the emphasis placed on watershed conservation by other federal policies and mandates.

According to the Natural Resource Agenda (United States Department of Agriculture, Forest Service, 1998) goals for healthy watersheds on the national forests will be achieved when:

- healthy, diverse, and resilient aquatic systems support a variety of conditions and benefits;
- forest and grassland systems support all biological and physical components, functions, and interrelationships and their capability for self-renewal;
- rangeland systems include robust riparian systems and a variety of conditions and benefits;
- populations of threatened, endangered, and sensitive species are abundant and thriving;
- watersheds provide the timing, quality, and quantity of water needed for beneficial uses and to sustain desired conditions; and
- soil is productive enough in the long term to support healthy, diverse, and resilient terrestrial and aquatic ecosystems.

Southwest Strategy

On December 16, 1997, nine federal agencies in Arizona and New Mexico began a cooperative program called the "Southwest Strategy." The strategy encourages close work with the public to develop a natural resource conservation and community development strategy for management activities under their jurisdiction (United States Department of Defense, Department of Agriculture and Department of the Interior, 1998). The Southwest Strategy recognizes that federal agencies need to be consistent and collaborate to most effectively serve communities and the public. As a federal family, agencies must reshape and strengthen relationships with other governments—tribal, state and local authorities. Only collaboration between researchers and scientists, public land managers and members of the public can lead to public land conservation that meets the needs of the land as well as people.

Large-Scale Assessments

The Forest Service is in a nation-wide process of identifying large-scale watershed restoration projects. Each project is intended to provide significant results over about 80,000 - 200,000 hectares. These restoration projects are being designed to enhance water quality, wetlands, migratory bird habitats, fisheries, riparian areas and watersheds. A key component of these projects is continuing partnerships with conservation organizations, state and tribal governments, other federal agencies, communities, private corporations and others.

Global Efforts Toward Sustainability

The federal government has international commitments to sustainable ecosystems. In 1995, the United States participated in an international agreement for Conservation and Sustainable Management of Temperate and Boreal Forests, known as the *Santiago Declaration* (Congressional Research Service, 1995; United Nations, 1995). Seven criteria (conditions or processes) and corresponding indicators (measures) for conservation and sustainability were identified. The seven criteria are:

- conservation of biological diversity;
- maintenance of productive capacity of forest ecosystems;
- maintenance of forest ecosystem health and vitality;
- conservation and maintenance of soil and water;
- maintenance of forest contribution to global carbon cycles;
- maintenance and enhancement of long-term multiple socioeconomic benefits to meet the needs of societies; and
- legal, institutional and economic framework for forest conservation and sustainable management.

Indicators are provided for each criterion in the *Santiago Declaration*. Examples include:

- ecosystem diversity addresses fragmentation, succession, etc.), species diversity, genetic diversity for *conservation of biological diversity*;
- production and consumption; recreation and tourism; investment in the forest sector; cultural, social and spiritual needs and values; and
- employment and community needs for *socioeconomic benefits*.

The participating countries of Australia, Canada, Chile, China, Japan, the Republic of Korea, Mexico, New Zealand, the Russian Federation and the United States represent about 90 percent of the world's temperate and boreal forests (Congressional Research Service, 1995). Other international efforts are targeting the sustainability of water resources. For example, the Israel Academy of Sciences and Humanities, Palestine Academy for Science and Technology, Royal Scientific Society, Jordan, and the U.S. National Academy of Sciences are collaborating on programs that can provide sustainable water supplies in the Middle East while preserving environmental quality (Committee on Sustainable Water Supplies for the Middle East, 1999).

Grey Towers Protocol

A land conservation strategy known as the Grey Towers Protocol was established in a summit sponsored by the Pinchot Institute for Conservation. Results are contained in a subsequent publication entitled "Land Stewardship in the Next Era of Conservation." The Protocol defined stewardship as *"passing the land and resources — including intact, functioning forest ecosystems — to the next generation in better condition than they were found"* (Sample, 1991). The Protocol also states that "*management activities must be within the physical and biological capabilities of the land, based upon comprehensive up-to-date resource information and a thorough scientific understanding of the ecosystem's functioning and response*." This implies that Forest planning and land management activities need to allow for climatic extremes, like drought associated with the El Nino Southern Oscillation (ENSO) climatic cycle. Therefore, stewardship means maintaining future options. Like physicians, land managers should strive to "do no harm" to ecosystem integrity.

Further National Efforts Toward Sustainability

Additional assistance in moving the agency toward sustainability may come from the United States Environmental Protection Agency's Environmental Monitoring and Assessment Program (EMAP). The research program will develop new technological tools to monitor and assess the status and trends of national ecological resources (United States Environmental Protection Agency, 1997). The goal of EMAP is "to develop the scientific understanding for translating environmental monitoring data from multiple spatial and temporal scales into assessments of ecological condition and forecasts of the future risks to the sustainability of our natural resources."

The Forest Service maintains strict Standards and Guidelines during project planning and implementation. Forest Plans are constrained by the standards and guidelines to protect and improve soil and water quality. In December 1997 the Secretary of Agriculture appointed a distinguished panel of natural resource scientists and professionals to review and evaluate our current land management planning process. The 13-member committee provided scientific and technical advice for improving the planning process for resource management on National Forest System Land. In their report, the Committee of Scientists said that sustainability — the preservation of plants, animals and habitats— should be the first priority in managing Forest Service natural resources (United States Department of Agriculture Forest Service, 1999). They also recommended more partnerships in making management decisions, including outside groups such as industry, recreation, environmental proponents and other government agencies. The report supports a Forest Service mission of providing multiple benefits to people within the capabilities of ecosystems. The Committee of Scientists recognized that in the past the agency focused more on timber and forage resources, but that today emphasis is placed on water and recreation resources.

Methods for Watershed Management of Shared Resources in the Southwestern Region

Watershed management is directed toward specific geographic areas that cross boundaries of ownership and management responsibility. Although watersheds such as the Rio Grande Basin cross international boundaries, smaller watershed scales are appropriate for local actions. The Forest Service uses a variety of methods to protect shared resources within watersheds. These include Best Management Practices (BMPs) for water quality protection, soil condition objectives, ecological-unit inventories and monitoring protocols to determine stream health and riparian function. Potential risks to water resources are also assessed through erosion modeling.

Best Management Practices emphasize controlling nonpoint source pollution. For example:

- minimizing impacts of roads at stream crossings;
- maintaining buffer zones of inactivity along riparian areas;
- protecting water quality within developed recreation sites;
- revegetation of disturbed areas; and
- mined-land reclamation.

Best Management Practices used in the Southwestern Region are described in the Region's Soil and Water Conservation Practices Handbook. They are designed to meet federal, state and tribal water quality requirements. The effectiveness of BMPs is determined by monitoring, and adjustments are made if monitoring results indicate that the BMPs do not adequately protect water quality.

The Southwestern Region of the Forest Service has implemented soil condition guidelines as a measure of changes in long-term soil productivity. The ability of the soil to function properly and retain its productivity is categorized as either satisfactory, impaired or unsatisfactory based on a soil condition-rating guide. Three soil functions that are rated to indicate soil condition are hydrologic function, stability against mass movement or erosion, and nutrient cycling. The soil condition-rating system incorporates indicators for each soil function, and the range of conditions is described for each indicator. Examples of soil condition indicators include infiltration, erosion, litter, and vegetative community composition.

The Southwestern Region of the Forest Service has an ecological inventory and classification system, the Terrestrial Ecosystem Survey (TES). The TES delineates ecological units based on climate, soil and vegetation. It contains a description of soil and vegetation type by map unit. A TES map unit is a collection of areas delineated by soil taxonomy; climate class; soil particle size, depth, texture, temperature class, mineralogy class; vegetation association (taxonomic abbreviation) and climax vegetation class (United States Department of Agriculture Forest Service, 1986). Preliminary map units are drawn from aerial photos then surveyed using transects and plots. Final TES map units incorporate the field observations and are recorded and displayed using a Geographic Information System. The results of TES inventory and mapping are available to all managers. This information is used to identify special use limitations, hazards and improvement opportunities for management units in the Southwestern Region.

The Water Erosion Prediction Project (WEPP) is a computer model that analyses how land use affects soil erosion and sediment delivery. This assessment tool contributes to making knowledgeable predictions prior to enacting a management practice that could influence sediment transport. Since it is not practical to monitor the effect of management practices in all ecosystems under all weather conditions, erosion predictions can be used to rank alternative practices based on potential impacts on erosion rates (Laflen et al., 1991).

The Forest Service also has a protocol to assess stream health called T-Walk for *Thalweg - Watershed Area LinK.* (Thalweg is the term for the deepest part of a stream channel.) These assessments evaluate: a 200 meter stream reach for diversity, productivity, stability (factors like pool depth, substrate, habitat, bank stability); and 16 ha of land for land-use effects on erosion, sediment transport and concentration of pollutants (Ohlander, 1998). This information can be used to help develop restoration plans.

Riparian areas can be described as stream-side transition zones between terrestrial and aquatic ecosystems. They are also corridors within landscapes that facilitate the flow of energy and species, and the cycling of materials. Many small birds require or utilize riparian nesting habitats (United States Department of Agriculture Forest Service, Riparian / Terrestrial Research). In the Southwest, a large percentage of birds utilize riparian areas, especially at low and mid elevations (Johnson et al., 1977, 1987; Cartron et al., 1999). One assessment method for riparian areas is called Proper Functioning Condition (PFC), a joint effort by the Bureau of Land Management and the Forest Service. It requires interdisciplinary teams to assess stability and determine whether riparian areas are either functioning properly, functional-at-risk, or nonfunctional (Rosenlieb et al., 1998). Accelerated wetlands losses are also a concern.

Discussion

At the dawn of the new millennium rests the promise and uncertainty of the global future. Exponential population growth, climate change and other global concerns are evident. In response, many efforts are coming together that can lead toward the sustainability of shared resources. These struggles to achieve sustainability are occurring from the global level to local levels. The watershed approach to resource integration is an important reflection of our agency's long-held commitment to stewardship.

The standards, guidelines, mandates and tools mentioned above are used in the Southwestern Region for watershed management and restoration activities. Watershed improvement projects help restore areas that have been damaged. Improvements are designed to reduce sediment transport to streams, reduce erosion from runoff, or improve soil condition. Watershed improvement treatments include large-scale treatments such as prescribed burning, and forest or woodland thinning and seeding. Other treatments are site-specific measures such as the installation of channel structures, road obliteration or relocation, and abandoned mine restoration. Assessment and prescriptions are also made for natural disasters that affect watershed condition like large wildfires, floods or windstorms. About 4,050 hectares are currently treated each year in the Southwestern Region.

At this time the Forest Service is entering into a new fiscal management and accounting process. The ability of the new system to integrate funding from various resource functions is currently being studied. When in effect, it will facilitate the implementation and monitoring of regional watershed management projects, the storage and retrieval of watershed management data, and data analysis. The results of these analyses will improve our ability to move toward adaptive resource management that utilizes new data as a feedback loop for updating management decisions.

What Lies Ahead?

Financial investors and gamblers can testify that predictions can be both precarious and dangerous! Given this disclaimer, here are some potential futures for watershed-scale management in the Southwest.

- Control of Southwestern water resources will be the biggest management issue during the next several decades.
- Watershed management will be a standard protocol to protect water quality, reduce contamination, and support healthy ecosystems.
- Watershed management partnerships will thrive and provide unique solutions to local problems.
- The role of National Forests in protecting shared resources will be more evident, as mandated through the Organic Act.
- The public will be more aware that preventing contaminants from reaching drinking water sup-

plies reduces the need and costs for treatment and ensures a sustainable water supply.

- Water for wildlife and plant species (vs. water for human needs) will require urban, community, and multi-agency collaborative negotiations.
- Water conservation efforts will accelerate in response to increasing demands on water supplies.
- The Forest Service will be a conservation leader by using the best available scientific information and ecology-based principles of ecosystem management.
- Restoration of Southwestern riparian areas will present a challenge for decades to come.
- There will be increased international coordination to reflect concerns for the global economy and the global environment.

Summary and Conclusions

Shared resources such as soil, water, air and biological diversity demand efficient use, prudent management, and protection from degradation. Everyone shares in the benefits of healthy, communal resources and depends upon them for survival. Watersheds link our shared natural resources and provide large-scale units on which conservation efforts can be focused.

Resource integration and shared outcomes are important at the international, national, regional and local levels. The Santiago Agreement signifies international cooperation for achieving sustainable water resources. The President's Clean Water Action Plan provides the foundation for accomplishing our watershed management goals at the national level. The Natural Resource Agenda provides parallel agency direction to maintain and restore the health of our ecosystems and watersheds. The Southwest Strategy provides the framework for interagency and public collaborations. A watershed emphasis in land stewardship results in sharing knowledge, working together to find and apply solutions to problems, and exploring a wider array of management options.

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SYNTHESIS PAPERS

Case Studies

Watershed Research and Management in the Lake States and Northeastern United States

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Abstract.—We present a brief synopsis of the beginnings of watershed management research and practice in the Lake States and Northeastern United States, followed by a summary of significant research findings on many aspects of watershed management, and finally, a review of four examples of how watershed management research has been incorporated into national forest management plans, state best management practices, state river basin projects, and the large, multi state Chesapeake Bay Program.

Introduction

George Perkins Marsh was concerned about changes in the land and streams of Massachusetts, New Hampshire and Maine in the 1860s. He was the first to write about land and water conservation in 1864 when he published *Man and Nature.* In 1902, J. T. Rothrock, Pennsylvania's first Director in the Department of Forestry also expressed concern about how land and water interact:

> "In all our alluvial valleys the frequent freshets work greater or less damage to the farm land. In fact, it can hardly be said that the beds of any of our rivers, which flow through wide valleys, are constant. They not only have entirely deserted the ancient water courses, leaving them off as back channels to one side or the other, but they are changing them from year to year before our eyes. . . Whilst it is true that a large quantity of valuable soil is sometimes deposited by these freshets on the surface of the land, it is also equally true that this same soil has come from the margin or river bank of somebody else's holding. (Rothrock 1902)"

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The concept that land-use change (or more precisely, how land was managed) could change river flow dynamics and result in erosion of channel banks was readily accepted by Rothrock. Twenty six years later, Raphael Zon, Director of the Lake States Forest Experiment Station, published his treatise: "Forests and Water in the Light of Scientific Investigation" (1927), and set down his conclusions of land and water interactions based primarily on case studies.

In the mid 1950s, watershed research focused on statistically valid, paired-watershed experiments and on replicated plot studies of hydrological processes. Bob Dills at Michigan State University detailed watershed management research needs in the forests of the Lake States in a cooperative agreement with the Lake States Forest Experiment Station in 1956. Sidney Weitzman, Assistant Director at the Experiment Station, had recently moved from West Virginia and new studies on watershed management at the Fernow Experimental Forest. Weitzman and Dills called for research on the impacts of forest management on water resources, and on the science of water. Weitzman and Forest Service colleagues decided to establish a network of experimental watersheds and they were careful to assign Forest Service watershed research stations on the basis of broad geologic regions: the central Appalachians of West Virginia (the Fernow Experimental Forest), the flat lands of New Jersey (Pequannock municipal watersheds), the White Mountains of New Hampshire (the Hubbard Brook Ecosystem Studies), the Driftless Area of SW Wisconsin (the Coulee Experimental Forest), the sandy outwash areas of central Michigan (the Udell Experimental Forest), and the moraine and peatland areas of Minnesota (the Marcell Experimental Forest). Studies on these Forest Service research watersheds, early USGS work in New York by Schneider and Ayer (1961), and university watershed research by Penn State University at the Leading Ridge Experimental Forest formed the nucleus of a mid-century push to bring rigorous evaluation to Rhaphael Zon's treatise. In 1965, Sopper and Lull edited the International Symposium on Forest Hydrology held at Penn State University and summarized much of what was known then about watershed management world-wide.

Much of the Forest Service work was born out of the forest influences work of Zon, Hardy, Kitteridge, and Stoeckler, but their mid-century effort focused new research knowledge on small watersheds. In the 1960s, the

U.S. Army Corps of Engineers approached large river basin management through a series of compendiums on river basin assessments throughout the United States. In agricultural areas, the Soil Conservation Service began the task of using soil conservation measures to manage water on the land and in streams. Carlos Bates' examination of the impact of large scale agricultural development in Wisconsin in the 1950s is an example and, later, both Stanley Trimble (1977, 1982, 1993), and James Knox (1971, 1987, 1989) did evaluations of exceptional extent and detail on agriculture's impact on stream and river geomorphology in southwestern Wisconsin's Driftless Area.

We cannot explore all of the watershed research and watershed management efforts that have occurred in the last half century, but we will summarize some of the knowledge gained from watershed research, and survey examples of how research findings have been incorporated into watershed management approaches. These examples include national forest management plans (the White Mountain National Forest in New Hampshire), incorporation of research into state forestry Best Management Practices (three versions of Minnesota's Department of Natural Resources and other NRCS-led, River Basin Projects), and large area, multi state, and multi agency watershed management plans (the Chesapeake Bay Plan).

Nutrient Cycling and Water Chemistry Research

Studies of forest nutrient cycles have been incorporated with watershed studies in the northeast since the mid 1960s (Hornbeck and Swank 1992). The studies have resulted in documentation of processes, pools, and fluxes in forest nutrient cycles (Likens and Bormann 1995); long-term data sets for chemistry of precipitation and streamflow (Likens et al. 1998, Edwards and Helvey 1991); and a general understanding of relationships between nutrient cycling and forest health and productivity (Bormann and Likens 1979).

These baseline data have been used extensively for evaluating the impacts of disturbances, especially harvesting and atmospheric deposition, on soil water leaching losses and stream chemistry. At most locations in the northeast, cutting the forest will result in increased leaching and thus higher streamwater concentrations of nitrogen (as nitrate), hydrogen, and base cations. This is true in the Sault Ste. Marie, Ontario hardwood area also, but clearcutting does not increase nitrate concentrations in other areas of the Lake States. The magnitude and timing of the increases are related to the intensity of cutting and stem from changes in a number of processes including:

- reduced uptake;
- movement of elements into and out of microbial pools;
- accelerated nitrification;
- accelerated decomposition of organic matter; and
- accelerated weathering of inorganic matter (Hornbeck et al. 1987).

Phosphorous is apparently not affected by these changes in processes and remains tightly bound in forest soils, even after harvests (Wood et al. 1984) and moderate fires, but can be released from severe fires that consume the forest floor above bedrock.

Northern hardwood forests are the most susceptible to increased soil water leaching and increases in streamwater ion concentrations. For example, intensive, even-aged harvests in New England have caused streamwater nitrate to rise from <5 mg/L before harvest to 25 mg/L by the second year after harvest, and calcium to rise from 1-2 mg/L before to 4-5 mg/L after (Martin et al. 1984, Hornbeck et al 1987). In comparison, maximum increases in streamwater nitrate after intensive harvests in other forest types have been 4 mg/L in spruce-fir (Hornbeck et al. 1986), 6 mg/L in central hardwoods of Connecticut, (Hornbeck et al. 1986), and <1 mg/L for central hardwoods in Pennsylvania (Lynch and Corbett 1990) and West Virginia (Patric 1980), and aspen in Minnesota (Verry 1972). The increases in nitrate and base cation concentrations are short lived, returning to pre harvest levels in 3-4 years.

The importance of changing ion concentrations to the aquatic biota has had only minimal study. Noel et al. (1986) and Likens et al. (1970) reported increases in stream periphyton and macroinvertebrates after clearcutting northern hardwoods, but they did not separate effects of stream chemistry from those of light and temperature. Studies at Hubbard Brook indicate that changes in streamwater ions due to harvest can be moderated by leaving a riparian buffer strip or by extending the harvest over several years (Hornbeck et al. 1987). None of the experiments involving commercial harvests resulted in nutrient ion increases that exceeded drinking water standards.

When translated to nutrient outputs, the increased ion concentrations in streamwater represent small proportions (<1%) of total site capitals and do not appear to reduce nutrient availability or forest productivity (Hornbeck et al. 1987). Nutrients removed in forest biomass, coupled with leaching losses induced by acidic deposition, are much more important in terms of losses from nutrient capitals of forest soils in the northeast. Federer et al. (1989), Grigal and Bates (1992), and Grigal (in press) reviewed results from several watershed studies in the Lake States and Eastern United States and pointed out the potential for significant depletion of base cations, especially calcium, due to harvesting and acidic deposition. Bailey et al. (1996) used strontium isotopes to show that rock weathering rates can not compensate for current rates of calcium depletion occurring in the northeast, even from watersheds that are not being harvested. The depletion of calcium and the accompanying mobilization of aluminum have been linked to declining tree health in some areas of the northeast (Shortle and Smith 1988, Lawrence and Huntington 1999).

The long term data on precipitation and streamflow chemistry collected as part of watershed studies are proving useful in studying trends and watershed responses. Driscoll et al. (1989) used the Hubbard Brook data to show that regional controls of sulfur emissions have resulted in decreasing concentrations of sulfate in precipitation and streamwater. Edwards and Helvey (1991) reported that since 1971, nitrate and calcium in streams at the Fernow have been gradually increasing, possibly due to nitrogen saturation from high anthropogenic inputs of nitrogen (Aber et al. 1998). This is the only reported incidence in the northeast of increasing nitrate in streams draining forests free of recent disturbance. Paired watershed studies are in progress at the Fernow in West VA and at Bear Brook in ME to determine effects and recovery from artificial acidification (Adams et al. 1993, Rustad et al. 1996), and a Hubbard Brook watershed will soon receive applications of calcium as part of an effort to learn more about calcium depletion.

Precipitation chemistry studies at the Marcell Experimental Forest in Minnesota first highlighted the interaction of upland and wetland nutrient cycling (Verry and Timmons 1975). Acid rain concerns in Europe and Canada soon brought the recognition that the chemistry of the atmosphere played a significant role in watershed response measured in stream and lake chemistry and their biota. The first operating station for the National Atmospheric Deposition Program (NADP) starting July 3, 1978, was located at the Marcell Experimental Forest. It was quickly followed by stations at the Fernow Experimental Forest in West Virginia and the Leading Ridge Experimental Forest in Pennsylvania. Today, more than 200 sites nationwide provide this necessary watershed input data for acidification, nutrient cycling, eutrophication, mercury, and, on occasion, pesticides and radio isotopes.

Realization that precipitation acidity had increased over much of the Northeastern United States spawned hundreds of studies that viewed watersheds as the important integrating unit to evaluate impacts to streams and lakes (Charles 1991). Of primary concern was the reaction of acidic inputs (sulfuric and nitric acid) with base cations (primarily calcium, magnesium) in the watershed soils. Three models of watershed chemistry ILWAS (itegraed lake watershed acidification study), MAGIC (model of acidification of groundwater in catchments), and ETD (enhanced trickle down) were developed at USGS, National Park Service, TVA, and U. S. Forest Service watersheds in the East (Munson and Gherini 1991). Assessments of lake and stream chemistry revealed that 14% of the lakes in the Adirondacks, 16% of the streams in the Catskills, 10% of the streams in West Virginia, and 14,000 lakes in Southeastern Canada were acidic (Charles 1991). The acidic condition of most of these lakes and streams was caused by acidic precipitation, but acid mine drainage, and high concentrations of organic acids also caused water acidification.

Effects of Forest Disturbance on Water Yield

Paired watersheds have been used to study the hydrologic cycle of forests in northeastern United States since the early 1950s. These studies have provided a good understanding of how both abrupt and gradual changes in forest cover affect water yield over time periods on the order of decades. Hornbeck et al (1993) summarized results from 11 separate, treated watersheds at 4 locations in the northeast, including the Marcell, Fernow, and Hubbard Brook Experimental Forests and the Leading Ridge Watershed Research Unit. He determined 3 generalizations regarding changes in water yield:

1. Initial increases in water yield occur promptly after forest cutting, with the magnitude being roughly proportional to percentage reduction in basal area.
2. The increases can be prolonged for an undetermined length of time by controlling natural regrowth; otherwise they diminish rapidly, nearly disappearing within 3-10 years.
3. Small increases or decreases in water yield may persist for at least a decade, and probably much longer, in response to changes in species composition.

Increases in annual water yield for the first year after each of the 11 watershed treatments ranged from <10 to 347 mm. As found in previous summaries (Douglass and Swank 1972, Bosch and Hewlett 1982), the increases were related to reductions in stand basal area. A comparison for all 11 watersheds suggests that reductions in basal area must approach 25% to obtain measurable responses in annual, water-yield. Above this threshold there is some variability in first-year responses among watersheds with similar basal areas cut, but the differences usually can be explained by factors such as configuration and timing of cutting, location of cutting in relation to the stream channel or source area, and whether regrowth was controlled with herbicides.

Flow-duration curves for post-treatment periods at each of the 4 locations show that nearly all changes in water yield result from increases at low flow levels (Hornbeck et al. 1997, Patric and Reinhart 1971, Verry 1972, Lynch et al. 1980). Further, the increases occur primarily in the growing season. Only Hubbard Brook and Marcell Experimental Forests normally have continuous winter snow packs. The timing of snowmelt runoff was advanced by forest treatments at both sites, but total volume of snowmelt runoff was not changed (Hornbeck et al. 1997, Verry et al. 1983).

Some watershed treatments at the Fernow and Hubbard Brook Experimental Forests eventually resulted in decreases in water yield. The decreases at the Fernow resulted from converting hardwoods to conifers, and were not unexpected based on studies showing that evapotranspiration is greater for conifers than hardwoods (Swank et al. 1988). Persistent decreases in water yield starting around the tenth year of natural revegetation on cleared watersheds at Hubbard Brook were unexpected. The decreases are due to pioneer and early successional species that dominate the regeneration during years 10 to 30 and beyond having significantly lower leaf resistances and thus greater transpiration than the trees comprising the mature forest (Hornbeck et al. 1997).

Implications for Municipal Water Supplies

Results from the 4 study sites indicate that various sizes of clearcuts, without control of regrowth, can provide immediate increases in annual water yield ranging from 100 to 250 mm. However, such increases diminish fairly rapidly, more so in some areas (Hubbard Brook and Leading Ridge) than others (Fernow and Marcell) (Hornbeck et al. 1993). When cutting forests with an objective of increasing water yields, consideration must be given to the possible impacts of a change in species composition during regrowth. The long-term results from Fernow and Hubbard Brook show that the desired increases in water yield occurring immediately after water yield may be compensated in later years if hardwoods are converted to softwoods, or if there is a major shift in composition of hardwood species.

The prolonged increases in water yield that occur after cutting in other regions of the USA, such as from deeper soils of the southeast (Swank et al. 1988) or from slowly regenerating forests of the west (Troendle and King 1985), cannot be expected in the northeast. Shallow soils and rooting depths, shorter growing seasons, lower evapotranspiration, rapid root occupancy and leaf area development by natural regeneration, and complete recharge of soil moisture during every dormant season all act to limit the magnitude and duration of increases in water yield in the northeast.

Bankfull and Flood Peak Flows

Bankfull discharge is considered the channel-forming discharge (Leopold 1994), thus, changes in this discharge (about the 1.5 year recurrence interval discharge) are necessarily accompanied by a change in channel cross section area, channel form, sinuosity, or roughness. Dramatic and stark examples of this have been documented by the SCS in Wisconsin and Minnesota's Driftless Area and by Trimble and Lund (1984) for Wisconsin's Coon Creek Watershed. Evaluation of land use changes from forest to agriculture in northern Wisconsin and Minnesota indicates that bankfull flows double when agriculture land use makes up more than half the basin (Verry 1999). Drainage of wetland and conversion to crops in the Minnesota River Basin more than doubles the average annual peak flow (Prof. K. N. Brooks, personal communication). In 1961, Schneider and Ayer showed that reforesting 58% of a cleared basin in New York decreased dormant season peak flows (both snow and rain) by 47%. The combination of a process-based hydrologic model developed at the Marcell Experimental Forest in Minnesota with long-term weather data also shows that clearcutting aspen forests can increase bankfull flows from snowmelt by 150%, with lesser increases for recurrence intervals up to 25 years (Lu 1994). No changes in peak flows were seen for flows with greater than a 25-year recurrence interval.

Watershed Condition

Sediment Control from Roads and Stream Crossings

Protecting watershed and channel conditions by minimizing erosion and sediment from logging roads and skid trails has always been a major objective of watershed studies in the northeast. The bulk of these studies have been conducted on the Fernow Experimental Forest and have focused on constucting and evaluating minimum-standard roads. Such roads are defined as roads built to the lowest standard that will provide a desirable level of utility and environmental protection at an acceptable cost.

Studies at the Fernow have resulted in guides for all phases of road construction including planning, layout, construction, care after logging (Kochenderfer et al. undated, Kochenderfer 1970), use of gravel to protect against erosion (Kochenderfer and Helvey 1987), sizing of culverts (Helvey and Kochenderfer 1988), and drainage structures (Kochenderfer 1995).

Studies at Hubbard Brook have focused on measuring sediment yields from uncut and cut watersheds (Martin and Hornbeck 1994). Sediment yields collected over several decades averaged 40 kg/ha/yr, which is among the lowest values in the nation (Megahan 1972), but were highly variable from year to year, depending largely upon occurrence of unusually large storm events within any given year. Disturbances from cutting and logging increased sediment yields by as much as 10- to 30-fold in the years immediately after cutting and skidding. However, total yields from harvested watersheds remained relatively small and there was minimal impact on stream turbidity.

Results from erosion and sediment studies in the northeast have been extensively tested and widely incorporated in best management practices used throughout the region (Eagan et al. 1998, Briggs et al 1998, Lynch and Corbett 1990, Kochenderfer et al. 1997, Kochenderfer and Hornbeck 1999). A general concensus is that terrestrial and aquatic ecosystems in the northeast can be adequately protected by following known precautions and guidelines for constructing and maintaining roads and skidtrails.

Many studies of culvert sizing for streams have previously provided for the passing of a 25 or 50 year event without overtopping of the road and loss of the culvert. Recently Baker and Votapka (1990) have emphasized the inclusion of fish passage criteria along with road integrity criteria for culvert sizing and placement. Round culverts selected with a diameter equal to the bankfull stream width will provide fish passage during bankfull spawning runs by keeping water velocities inside the culvert low enough for fish to pass through in most eastern streams (Verry 1999). Bridges are best able to pass flows without channel impairment. Temporary bridges, and other temporary stream and wetland crossing options can be used effectively to protect stream and wetland sites (Blinn et al. 1998).

Desirable Stream Conditions and Controlling Bankfull Flow Changes

Changes in bankfull, channel-forming, flows cause channels to change their type (Rosgen 1996, Verry 1999). When channels change their Natural Stream Type, they are unstable and unable to carry the water and debris from their watershed without excessive erosion and sedimentation (Rosgen 1996). Channels within plus or minus 30% of their modal values for entrenchement, width/depth ratio, and sinuosity are normal and constitute a desirable stream habitat condition (Verry 1999). Permanent land use changes from forests to agriculture cause channels to change their type; a process that can take from 1 year to 1 century (see the works of Trimble, and Knox for examples).

Even rapid rates of forest clear cutting without conversion to agriculture can change peak flows. The rate of change is dependent on the range of slopes within the watershed, the amount of land cleared over a period of 15 years, and on the size of the watershed evaluated. Bankfull flow rate increases of 100% can occur on flat land watersheds (with slopes generally less than 3%), when 2/3 of their basin is harvested in the span of 15 years on watersheds that are at least 10 square miles in size. Similar increases occur on moraine watersheds (with slopes up to 30%), when 2/3 of their basin is harvested in the span of 15 years on basins that are at least 1 square mile in size (Verry 1999). Mountain watersheds (with slopes up to 60%) can experience bankfull flow changes in basins of at least 3 square miles and with only 1/4 of their basin harvested (or permanently cleared) in the span of 15 years (personal observation (ESV)on the Allegheny National Forest, PA).

Case Studies: Integrating Watershed Research and Watershed Management

White Mountain National Forest

Primary audiences for watershed research in the northeast are managers and consultants working with private, state, and national forests, municipal watersheds, and aquatic resources. National Forests have been especially quick to implement results from watershed research directly onto the landscape and into the planning process. Some examples of implementation on the White Mountain National Forest (WMNF), which spans 750,000 acres in New Hampshire and Maine, are:

Long-term site productivity. National Forests have a responsibility to estimate the effects of their activities, including timber harvest, on long-term site productivity. The Northeastern Research Station and WMNF jointly constructed nutrient depletion tables for base cations, and a variety of forest disturbances, and harvest methods. The tables are used to select silvicultural practices that will provide optimum protection of site nutrient capitals and forest productivity.

Weathering Inputs for Calcium and magnesium. The primary uncertainty in estimating nutrient depletion is the rate at which base cations are supplied to the soil by weathering of minerals. WMNF is the study area for testing a glacial till-nutrient source model that estimates contributions from mineral weathering. The Northeastern Research Station devised the model and is compiling bedrock geology maps to support its use. The project is leading to maps of the WMNF showing weathering rates for calcium and magnesium. These maps are being combined with other factors, such as land use history, to develop standards and guides based on risks for soil nutrient depletion.

Nitrogen cycling and land use history. Nitrogen saturation is a concern because of base cation losses that reduce tree productivity, and elevated, but not dangerous levels of nitrate in streamwater (Aber et al. 1998). Susceptibility to nitrogen saturation is dependent upon past disturbances such as agriculture, forest harvest, and fire. The WMNF is cooperating with the Northeastern Research Station to determine past disturbances, susceptibility to nitrogen saturation, and possible restrictions to harvest and other silvicultural practices that accelerate cation loss.

Hydrology of alpine ski areas. Alpine ski areas existing on WMNF are heavily dependent upon surface waters for making artificial snow. In turn, there is controversy over impacts of extracting water, and again when it melts, on water yield, peak and flood flows, and water quality. Legal challenges regarding these impacts led to a need to better understand the impacts of ski area construction and snowmaking on hydrology, erosion and sedimentation, and water quality. Research on water quality and snow hydrology at the Hubbard Brook Experimental Forest has helped meet this need. Implementation of Hubbard Brook results at several ski areas helped to significantly improve their impacts analysis, and to provide background for the legal challenges regarding environmental impacts.

Best Management Practices and River Basin Projects: Minnesota Experience

Like many states, Minnesota responded to the 1987 Amendments to the Clean Water Act, Section 319 by developing their 1989, Water Quality in Forest Management guide as the "Best Management Practices in Minnesota" (MNDNR 1989). In 1995, the Best Management Practices in Minnesota was expanded and published as Protecting Water Quality and Wetlands in Forest Management (MNDNR 1995). In 1999, a much expanded effort produced Sustaining Minnesota Forest Resources: Voluntary Site-level Forest Management Guidelines (MFRC 1999). This progression of effort attests to the strong leadership at the State Department of Natural Resources to continually review, test, and improve forest management guides. It has witnessed major changes in the social climate, the inclusion of new watershed research, and the continual effort to monitor implementation on the ground.

The initial 1989 guide (104 pages) was produced over two years using a committee of forest managers from county, state, and federal agencies, forest industries, and the University of Minnesota. It was strictly limited to water quality issues and used recommendations for filter strips between roads and streams and for road construction derived from research at the Hubbard Brook Experimental Forests in New Hampshire published three decades earlier. Other recommendations used standard forestry guides for fire, petroleum, and pesticide use. Its implementation set the stage for voluntary guides in Minnesota and for the annual monitoring of their implementation.

The 1995 guide (140 pages) was produced over three years by committee members from the first effort plus members from other federal agencies, loggers, environmental organizations, and fisheries and water divisions of MNDNR. The guide was upgraded with newer road data from the Fernow Experimental Forest in West Virginia and the Coweeta Hydrologic Laboratory in North Carolina, and an extensive section dealing with wetlands relied heavily on research from the Marcell Experimental Forest in Minnesota using the preservation of hydrologic function as a guiding principle.

The 1999 guide (329 pages) was produced with four committees: riparian areas, wildlife habitat, cultural resources, and forest soil productivity. The previous water quality and wetland effort was included as well as a DNR effort on visual quality. This effort was administered by the Department of Natural Resources for the Minnesota Forest Resources Council created by the state Legislature in 1995. Additional organizations represented on the committees included Native Americans, archaeology agencies, other University departments, recreation, landowner, watershed, lake, resort and land management organizations. Unique to this effort was the initiation by the Forest Resource Council of several research projects on watersheds in the state.

Mike Phillips with the Minnesota Department of Natural Resources has shepherded all three of these efforts and is responsible for their monitoring programs. He recently offered this advice: "The involvement of stakeholder groups in the development of BMPs and other forest practice guidelines requires more patience and time. Once agreement is reached, however, implementation will likely be more rapid and effective since there is a greater probability that the interest groups have bought into the product produced. The BMPs or other forest practice guidelines developed by consensus are more likely to reflect a balance of science, practicality, and economics. There is also greater likelihood that trust will develop among the many stakeholders involved in BMP development, which is necessary for successful program implementation (Phillips et al. 1999)."

State BMPs have come a long way and have routinely incorporated watershed research, however, even the last effort in Minnesota was restricted by the Legislature to consider only site-specific guides. A newly constituted Minnesota Forest Resource Council has now begun the task of considering landscape-level guides for forest management. At each step forestry has come closer to incorporating the concepts of watershed management.

Many other units of county, state and federal governments have already addressed watershed-wide management through the establishment of 43 Watershed Districts in Minnesota administered by the state Board of Water and Soil Resources, 75 Clean Water Partnerships, county water management plans, and River Basin projects coordinated by the Natural Resources Conservation Service and the U. S. Forest Service, State and Private Forestry Division. Just one example of the latter is the Nemadji River Basin Project that spans parts of northern Wisconsin and Minnesota, incorporates 12 advisory subcommittees and seeks administrative implementation from local county boards (NRCS 1998). Forest Service and University of Minnesota research has been incorporated into basin-wide, landscape-scale recommendations that address the amount of harvested and cleared agricultural land with sub-basins of the watershed.

Chesapeake Bay Program

The Chesapeake Bay is the nation's largest and, because of its shallowness, the nation's most productive estuary. It is this shallowness that causes its amazing productivity and its sensitivity to what goes on in the watershed. Land use largely determines the quality of the water, the vitality of aquatic habitats, and ultimately, the health and resilience of the Chesapeake Bay itself. The Bay helps define the landscape as well as the culture and economy of the region.

A Bay in Trouble

Since the 1970s, there has been a consensus among scientists, government agencies, and concerned citizens that the Chesapeake Bay was in trouble. Drastic declines in fisheries, shellfish, waterfowl, and bay grasses were the effects of more than two centuries of steady development, loss of forests, increasing pollution and runoff, and accumulation of sediment, nutrients, and industrial wastes. Eutrophication and hypoxia are the primary problems. Runoff carrying sediment, fertilizers, manure, and pesticides from agricultural lands, point sources of municipal treated sewage, increasing runoff from urban areas, and atmospheric deposition all contribute to the problem. To restore the Bay, all of these nutrient sources were addressed when the Environmental Protection Agency (EPA) published a major study of the Bay in 1983.

Coordination at the Watershed Scale

The 1983 study brought the states of Pennsylvania, Maryland, Virginia, and the District of Columbia together with the Chesapeake Bay Commission (and federal agencies) in a partnership. Each agreed to work together to develop and implement a coordinated effort to improve and protect water quality and the living resources of the Chesapeake Bay. This action marked a turning point in watershed restoration because it sought to manage the Bay ecosystem as a whole. Subsequent agreements in 1987 and 1992, added a strategy to target efforts in each of the major tributaries basins. Locally-led "tributary strategies", tailored to individual sub-watersheds, built connections between local conditions, issues, and approaches and larger-scale Bay restoration goals for pollution reduction and habitat restoration. The Chesapeake Bay Program has grown into a unique regional institution, guiding and coordinating the Bay-related activities of literally hundreds of federal, state, local and intergovernmental agencies, and working with dozens of private business, civic, and environmental organizations.

Forests and the Bay

In the 1600s, 95% of the watershed was forested. The forests served as a continuous living filter and regulator of the Bay's environment. In the mid 1800s, 50% of the Bay's watershed was converted to farms, pastures, cities, and industry. Reforestation of abandoned agricultural land gradually raised forest land to 60% of the basin; however, for the first time in nearly a century, the percent of forest lands is once again declining. Although some forest land is still cleared for agriculture, as much as 100 acres per day have been converted to urban lands during the last 20 years. It is clear that the long term stewardship of the Chesapeake Bay depends in part on the health and stewardship of forests in the watershed.

The USDA Forest Service, Northeastern Area State and Private Forestry, joined the Bay Program partnership in 1989. Using a foundation of basic watershed management and forest stewardship principles, new technology and research, and the flexibility of cooperative forestry programs, the Forest Service is demonstrating how forests are part of the long-term solution to managing the Bay's watershed. Working across mixed ownerships, a Forestry Work Group serves as a catalyst to bring together federal, state, local and private resources to implement this approach. "Forest solutions" are developed in three areas:

- *Forest Protection* - Our activities demonstrate that forests have high social values for water supply, recreation, preservation of watershed functions. We show they are critical for aquatic and terrestrial habitat health, and that they and are storehouses of future benefits and uses. We seek to help communities assess their watersheds, educate citizens and design strategies to reduce fragmentation and forest loss where forest lands are threatened by conversion to other land uses.

- *Forest Restoration* - Restoring forests on erodible lands, wetlands, and along streams and shorelines, integrating forests into pollution control for farm runoff and storm water management, and promoting community "green infrastructure" projects in urban areas are the focus.

- *Forest Stewardship* - Properly managed forests retain land in a beneficial land use while supporting local economies. Working with partners in the states and through the Forest Stewardship Program, ecological concepts are integrated into forest management on private lands, and loggers and landowners are educated about BMP application and their benefits to the Chesapeake Bay.

This collaborative effort produced a Chesapeake Bay Riparian Forest Buffer Initiative in 1994. Endorsed by the Bay Program's Executive Council, this effort has resulted in a watershed-wide policy of stewardship to protect and restore riparian forests in the watershed. The Chesapeake Bay Partners have made commitments to improve communication and coordination, build new partnerships, provide additional incentives and funding, and develop education programs for citizens, schools, and practitioners. The Riparian Initiative has restored forests along nearly 500 miles of stream channel.

Managing a Watershed: Lessons Learned

What began as a water quality program has now grown to involve integrated management of land, air, water, and living resources. This integration of knowledge and goals into the institutions of daily life is essential for watershed efforts at both small and large-scale. This is true whether related to forest conservation or pollution prevention. The following ten lessons learned from the Chesapeake Bay Program are sound advice for watershed management approaches everywhere.

1. *Begin by establishing a sound scientific foundation*. Sound watershed management must be based on the best available science and basic data on natural resources. Focus on linkages between land, water, living resources, and people. Admittedly, policy decisions will not always be based on science or a complete watershed assessment, but if basic information is made available in an easily-understandable format, the chances are high that it will be integrated into the decision-making process. Facilitating a meaningful exchange of information between academic and government research and the local management community is essential. Assemble the best existing information first and establish ongoing monitoring to measure progress and test models in the future.

2. *Involve the highest and broadest levels of leadership possible.* There is enormous strength in strong leadership. The direct involvement of State Governors and high federal officials in setting goals and sharing in accomplishments is prerequisite. Only high-ranking officials have the authority to endorse and implement policies and provide the resources needed for program implementation. They should be involved in visible ways. However, just as strong government leaders are important, watershed leaders that emerge from the community must also be embraced and empowered. Seeking out and involving leaders in the watershed is a critical factor in making the watershed approach work.

3. *Embrace clear, strong, and measurable goals*. There is great strength in clear goals and accountability. At the Chesapake Bay Program, highly specific goals include: 40% reductions in nitrogen and phosphorus pollution, eliminating fish blockages in major tributaries, and restoration of bay grasses, wetlands and riparian forests. Goals are that are quantifiable make progress measurable and leaders accountable. Citizens should participate in setting and achieving goals that extend beyond the tenure of elected officials or agency managers.

4. *Invite a broad diversity of participants.* Watersheds and their problems and solutions are complex. Likewise, any watershed management framework should involve a diversity of participants. Watershed management should be inclusive and invite a variety of government, non-profit and private players to contribute unique skills, resources and perspectives. Together, a multitude of players also bring greater political leadership and financial support. At the Bay Program, members of government

work side by side with others from industry, local, and public groups, brought together by common issues and a commitment to a common set of resource goals. Although it requires strong communications efforts, this inclusive process has become a signature of the Bay Program.

5. *Establish incentives and methods for continual cooperation*. The principle incentives are money and public pressure. The active financial involvement of the EPA and other agencies has leveraged millions of state and local dollars. Cost share and assistance programs to meet Bay goals have allowed much of the restoration work to remain voluntary. The commitment to succeed voluntarily (rather than with more regulation) is an incentive in itself. Emerging issues or new strategic approaches and goals are brought to the Executive Council, and "Directives" are signed to renew commitments or define new actions. These high level directives take on the weight of an executive order to participating agencies. The Bay Program has also established more than 50 subcommittees and workgroups to ensure that all interests are represented and that there is continual interaction between participants.

6. *Inform and involve the public*. Keeping the citizenry of the Bay watershed informed is a top priority. Use extensive educational and technology transfer efforts. Management of resources in a watershed like the Chesapeake Bay requires complex political decisions. An informed and vocal public has proven to be the Bay's greatest ally. Honesty, even when findings or progress is disheartening, is critical to maintaining trust and stakeholder commitment.

7. *Choose prevention before restoration or mitigation*. Although it is often more politically appealing to fund many restoration projects, a watershed approach must focus first on ensuring that a solid foundation of preventive conservation measures are in place to ensure that restoration progress does not lose ground. A balanced set of management tools should be developed allowing individual jurisdictions to customize or adapt tools for their application.

8. *Test theories and management approaches on a small scale*. Our scientific knowledge and technologies for watershed management and restoration are continually growing. By studying the effectiveness of strategies in small watersheds through demonstration or pilot projects, we can increase success when these concepts are applied more broadly. These demonstration projects help develop public support, attract partnerships and funding, and build the confidence of political leaders to expand their application.

9. *Regularly reassess goals and progress*. The Bay Program is supported by a strong monitoring effort and has a strong commitment to reassess goals, monitor trends, and measure progress. The health and vitality of living resources serve as an important indicator. Keeping the public informed of findings and maintaining flexibility has helped maintain the integrity of the Program.

10. *Demonstrate results.* Progress in watershed restoration is incremental. Celebrating successes along the way is critical to maintaining momentum. Since the Bay Program began in 1983, phosphorus inputs to the Bay have been reduced by over 30%, nitrogen concentrations are down and total loads are not increasing in spite of an increasing population. Practices for pollution prevention from farm runoff and urban stormwater have improved dramatically. The striped bass fishery has recovered, bay grasses are returning in many areas, oysters are making slow progress, 1000s of miles of stream have been opened to migratory fish, and over 10,000 acres of riparian area and wetland have been restored. Local governments are also taking action to protect stream corridors and open space and adopt smart growth policies. Volunteer efforts are expanding and the increased environmental awareness of the citizenry is easy to observe.

Application of watershed management principles, whether at the site or landscape scale, must use competent watershed analysis of conditions on the ground as a base for action. Learn to read the land (Leopold 1949) and read the river (Leopold 1994), and when you do we have no fear of what you will do, indeed we are excited about what you will do for them.. For a detailed examination of management options for riparian areas in the Lake States, and Northeastern United States see Verry, Hornbeck, and Dolloff (1999).

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Watershed Management Contributions to Land Stewardship: Case Studies in the Southeast

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Abstract.—We describe three examples of watershed management studies, at different spatial scales, that provide approaches and information useful in enhancing natural resource stewardship in the southern Appalachians. A multiple use "pilot" study, initiated 35 years ago at the Coweeta Hydrologic Laboratory, demonstrates that southern Appalachian forests can be successfully managed for water, timber, wildlife, and recreation. Added benefits of this small scale (144 ha) watershed study are the education and on-the-ground demonstration values. A demonstration project of ecosystem management, initiated in the early 1990s on a 1820 ha watershed provides an integrated, interdisciplinary ecosystem approach to research, planning, and management. Organized around themes of ecosystem restoration, forest sustainability, human and economic values, and ecosystem structure and function, the multifaceted studies are providing new knowledge and management benefits. More recently, regional scale watershed research was initiated on two river basins within a 70,000 km^2 area of western North Carolina. The goal is to develop a predictive understanding of the social, economic, and environmental factors that drive land use cover changes and to evaluate the consequences of change for terrestrial and aquatic biodiversity, water quality, and regional carbon cycles. E'm'ergy, a tool for synthesizing the multiple values of watersheds, is applied to the ecosystem management study.

Introduction

As with much of the nation, the mix of forest uses and benefits in the southern U.S. has greatly accelerated in the past several decades. The rapidly changing faces and voices of the South (Cordell et al. 1998) provide exciting opportunities to address complex issues related to planning, policy, and science for the region's natural resources. Interdisciplinary watershed management provides a useful analytical framework for structuring and assessing alternative mixes of forest uses across multiple scales of time and space.

Our objectives in this paper are 1) to illustrate, through case studies in the southeast U.S., the utility of watershed management as a framework for evaluating the conservation and sustainable development and use of resources at several spatial scales and 2) to implement a methodology, emergy analysis, for synthesizing commodity and noncommodity values of watershed values and functions.

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The Regional Setting

The region is characterized by three physiographic divisions: the coastal plain, piedmont, and mountains. Abundant resources, highly diverse and attractive ecosystems, demographic shifts, job opportunities, and other socioeconomic factors contribute to a dynamic changing South. During the past three decades the population has increased 54% and the region (13 southern states) was the only one within the U.S. with net growth from domestic in-migration (Cordell et al. 1998). Forests cover 87 million ha in the region and the 81 million ha classified as timberland (Sheffield & Dickson 1998) accounts for an estimated 40% of the productive timberland in the U.S. Nearly 70% is in nonindustrial private forest ownership. Other timberland ownerships are comprised of national forests (5.7%), other public agencies (4.8%), and the remainder in forest industry (≈ 20%). About 52% of the timberland is classed as a hardwood type and upland hardwoods comprise 37% of the total timberland. The pine forest type occupies about 33% of the timberland with 15% in pine plantations and 18% in natural pine plantations (Sheffield and Dickson 1998). In the past decade the region has emerged as a leader in the world's forest products industry, accounting for about 25 % of world paper production and 35% of solid wood products manufacturing. nationwide, the region provided 50% of the softwood and 42% of the hardwood timber produced in the country in 1992 and the South is expected to supply major future increases in the national timber market (Wear et al. 1998).

The region also encompasses an abundance of water, recreation, and wildlife as illustrated in a comprehensive assessment of the Southern Appalachians, a sub-region of 15 million ha within seven southeastern states (Southern Appalachian Assessment Summary Report 1996). The area contains parts of 73 major watersheds, and nine major rivers that arise in the southern Appalachians provide drinking water to the major cities of the Southeast. The mean main stream and river density is 12 m / ha and when all perennial streams are included, ranges from 48 in the piedmont to 87 m / ha in the mountains. Natural lakes and reservoirs represent about 1.5% of the total area. The southern Appalachians are well known for their scenic beauty and the recreation opportunities they provide. In the past 15 years, there has been a significant increase in the number and diversity of recreationists in the region. Concurrently, demand has increased for specific recreation opportunities such as hiking and white water rafting / kayaking. The southern Appalachians is home to an estimated 80 species of amphibians and reptiles, 175 species of birds, 65 species of mammals and more than 25,000 species of invertebrates. Populations of major game species such as deer, turkey, and bear have increased in the past 25 years while populations of birds such as ruffed grouse and bobwhite quail have declined.

Clearly, the south is a region with a rapidly growing range of public interest and changing views of land and natural resources. This situation is probably most evident and complex in the Appalachians where mixed ownerships, diverse resources, and increasing population pressures offer challenging planning and policy decisions for multiple uses on the landscape. Fortunately, past and current watershed research in the region provides information relevant to decision making processes. The Coweeta Hydrologic Laboratory, a 2185 ha USDA Forest Service research facility located in the Appalachian Mountains of western North Carolina, has a long history of interdisciplinary watershed research. It is this cooperative research program from which we draw our case studies.

Multiple Use Management: A Pilot Program

One of the earliest and most practical demonstrations of the multiple use concept in a watershed context in the eastern U.S. was implemented at Coweeta in 1962 (Hewlett and Douglass 1968). At the time, there was substantial controversy over the Multiple Use Act passed earlier in 1960 because on-the-ground examples of the concept were lacking. The concept was pilot-tested on a 144 ha hardwood-forested watershed (WS 28) in the Coweeta basin for the uses it was judged to be best suited for; water, timber production, hunting, fishing, and hiking. Scientists delineated objectives and prescriptions to evaluate conflicts among uses and to demonstrate potential management practices for the future (Hewlett and Douglass 1968).

Prescriptions

One of the highest priorities was to provide access on the catchment without impairing other resources. Properly planned access is a basic component of watershed management that is essential in achieving other goals and access should be designed to meet current and anticipated future needs. Four classes of roads were specified and included forest engineered roads to specified standards and a network of climbing roads, contour roads, and skid trails using criteria developed from previous research at Coweeta and from some new ideas for design criteria.

Silvicultural conditions of existing stands dictated even-aged management (clearcutting) on the slopes and ridges to regenerate the degraded forest from the previous selective logging in 1923-24 and to produce the maximum yield of water and deer browse. In the cove forest, a thinning was prescribed along with removal of residual poor quality overstory trees remaining after earlier logging, to increase growth of the residual yellow-poplar stand. To enhance the visual appeal of the cove in winter and spring, eastern hemlock (*Tsuga canadensis*) and dogwood (*Cornus florida* L.) were not cut.

The Appalachian Trail, which traverses the higher elevations of the watershed, was improved and interpretative signs were placed at strategic locations to enhance recreation. Improvement of trout habitat consisted of removing old logging debris from the lower portion of the main stream and construction of small logs dams to create more riffles and pools.

Responses to Management

Previous papers provide detailed analysis of responses to prescriptions (Douglass and Swank 1976; Swank 1998) and only a review of findings are provided in this paper. An overall summary of resource / use responses is provided in table 1. Based on the paired watershed method of analysis, streamflow on WS28 increased 22 cm the first year after harvest and then declined exponentially over the next 9 years before returning to baseline levels. The cumulative effects of cutting on total flow was an increase > one million m^3 of water. Much of this increased discharge occurred in the autumn season when flows are lowest and both human and aquatic water demands are highest. Analysis of the storm hydrograph showed that, during storm periods, quick-flow volume (direct runoff) increased an average of 17% (Douglass and Swank 1976). During the height of logging activity, peak discharge increased an average of 33% and then declined rapidly following road stabilization and recovery of evapotranspiration.

Table 1. Summary of Watershed Responses to Multiple-Use Management Prescriptions on WS28, Coweeta Hydrologic Laboratory (0 = Minimal Response, + = Positive Response, - = Negative Response)

Resource/Use	Response
Water Yield	+
Storm Discharge	0/-
Sediment	0/-
Nutrient Loss	0
Vegetation	+
Wildlife	+
Recreation (Hunting, Hiking)	+

Sediment delivery to streams was minimal due to proper road locations and construction features. However, increased frequency of cleaning the weir ponding basin clearly indicated an acceleration of bedload movement. Much of the bedload scouring occurred in the stream section where fish dams were constructed and reflects readjustment of the stream energy gradient. Apparently, the impact of management on aquatic resources was minimal because the stream still supported a good native brook trout fishery several years after treatment. Stream chemistry was not measured in the early years but about 10 years after disturbance, net nutrient budgets (compared to adjacent control watersheds) suggested small losses of nutrients from the watershed (Douglass and Swank 1976).

Vegetation responses to cutting are rapid in the southern Appalachians due to both sprout and seedling regeneration. Thirty years after harvesting in the 73 ha of clearcutting prescription, basal area exceeds that of the forest prior to cutting (30 m^2 ha^{-1}). Moreover, the species composition is greatly improved with and abundance of *Quercus, Prunus, Betula, Tilia,* and *Lirodendron* species (Swank 1998). Stand conditions present an array of future management options. Objectives of thinning the cove forest were equally successful. Growth rates of residual yellow poplar were increased about 40% and by age 30, stand basal area had increased to 46 m^2 ha^{-1}. Advanced regeneration and understory diversity has increased over time and there is also a diverse herbaceous layer (Parr 1992).

Responses of other resources and uses to management have also been evaluated or observed. The variety of habitats produced by silvicultural and prescriptions increased species diversity of breeding birds (Tramer 1969; Tramer 1994) and the variety of shrews and mice (Gentry et al. 1968). The varied habitat has been a strong attractant for turkey foraging and the area supports a large turkey population. Other wildlife such as deer and ruffed grouse have benefitted from management and the watershed, with improved access, is still a favorite area of hunters. The road network over the watershed also provides a favorite area for the day hiker. Wild flame azaleas that became established on the edge of roadway clearing and an abundance of flowering dogwood provide outstanding aesthetic value.

Summary

This 35-year-old watershed based study has demonstrated that southern Appalachian forests can be successfully managed for a variety of uses. Although there may be some conflicts among uses, it is important to recognize that ecosystem changes are not irreversible and opportunities are available to meet future goals. Many of the findings from this pilot project have been factored into forest management planing and practice. Moreover, we suggest that another important long-term contribution of the study lies in its demonstration and education values. The watershed provides a setting where management decisions are made, applied, and evaluated. It provides an on-the-ground framework where managers, conservation and environmental groups, policy makers, and students can view and discuss resource issues. This benefit from watershed research has been repeatedly observed from interaction with numerous groups who tour Coweeta and this catchment each year.

Integrated Watershed Ecosystem Management

The Wine Spring Creek Ecosystem Management Project is a recent example of integrated research where the watershed is the basic unit for evaluating management and land stewardship. Ecosystem management is currently an operating philosophy of the USDA Forest Service with the objective of using an ecological approach to achieve broader multiple use objectives (Kessler et al. 1992; Thomas 1996). Similar to when the concept of multiple use management emerged in 1960, there are a wide range of views and opinions about the concept of ecosystem management (Swank and Van Lear 1992; Ecological Applications 1996). We suggest there is no blueprint for implementing ecosystem management; indeed, different approaches will be needed to address the array of issues inherent to varied regions of the country. The real need is for tailored, on-the-ground examples of ecosystem management.

Compared to the earlier demonstration of multiple use at Coweeta, ecosystem management encompasses a broader perspective. Specifically, there is a mixed partnership where scientists, managers, the public, and other groups have a role in the decision making process. As a result, the planning approach is more comprehensive, the science is more interdisciplinary, and tools for synthesis such as modeling and decision support systems are required to facilitate interpretations. However, a common thread of past and present approaches is that the watershed still provides the fundamental framework for evaluating land use issues and alternatives for management.

The Setting and Approach

In 1992 we developed and initiated the ecosystem management project in the 1820-ha Wine Spring Creek Basin which is located in the Nantahala mountains of western North Carolina, about 50 km from Coweeta (Swank et al. 1994). The objective of the project is to use / and or develop ecologically based concepts and technology to achieve desired natural resource conditions. The watershed is comprised of steep slopes with elevations ranging from 918 to 1660 m. Annual precipitation averages 1800 mm and mean monthly temperatures range from 0.5° in January to 21.3° in July. A mix of hardwood forest types, dominated by oak, cover the watershed and McNab et al. (1999) have classified five ecosystem units for the area based on vegetation, soil, and topographic variables. First-through third-order streams drain the basin and Wine Spring Creek flows to Nantahala Lake, an important reservoir in the region. Most of the basin is managed by the Wayah Ranger District, national Forests in North Carolina, but a portion is in private ownership at the base of the watershed near Nantahala Lake. The area supports a diverse fauna and variety of uses, with primary access provided by a paved Forest Service road through the middle of the basin.

The existing forest and resource management plan was utilized as the basic framework in an innovative approach for defining desired future resource conditions and specifying prescriptions to achieve conditions (figure 1). The plan identified 8 management areas in the basin, including about 40% of the total area as suitable for timber supply and other traditional forest uses (Swank 1995). Emphases on the remaining area includes animal habitat, recreational uses, scenery, protection of a national scenic trail, and special ecosystems such as high elevation mountain “balds” and riparian areas. Desired future conditions for resources were derived over an 18 month period from a consensus building process entailing a series of workshops comprised of interested stakeholders including managers, user groups, scientists, and the public. A product of this process was the specification of 35 desired resource conditions. Another outcome of the process was enhanced understanding among participants of each others viewpoint in considering the complex trade-offs in-

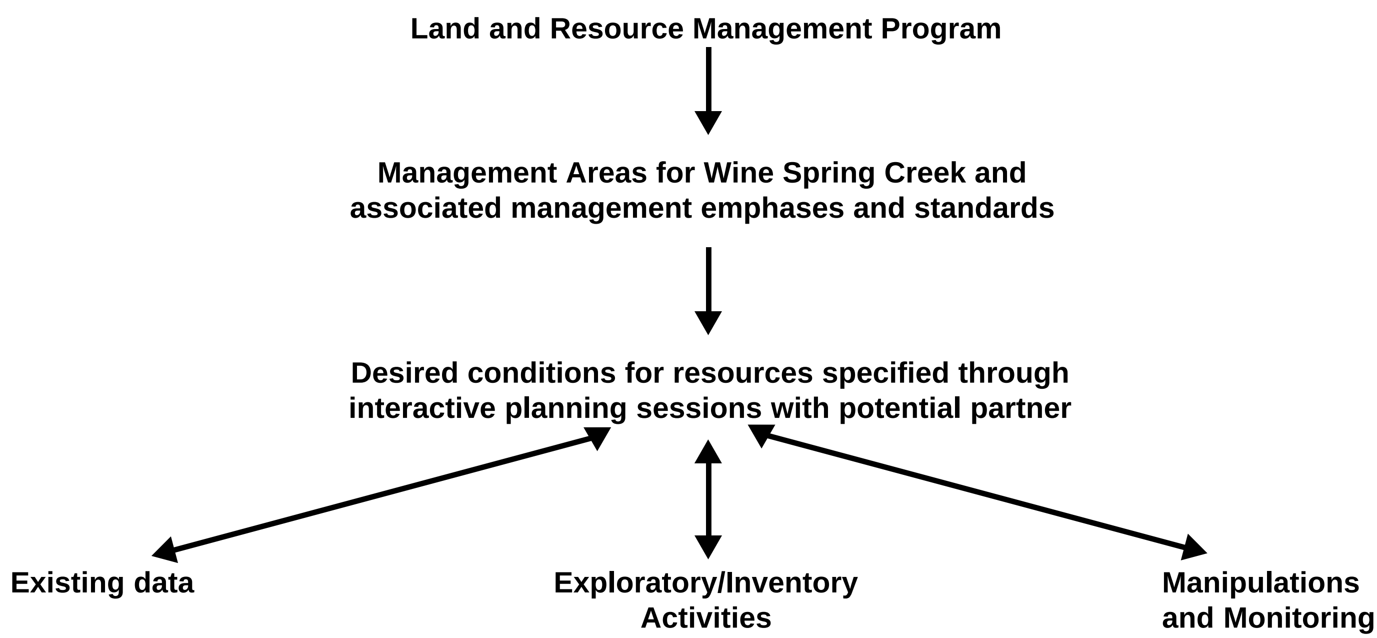

Figure 1. Outline of planning approach for ecosystem management on the Wine Spring Creek Watershed in western North Carolina. Existing forest plans were combined with stakeholders workshops to define desired conditions of resources and subsequent research and management prescriptions.

volved in ecosystem management (Meyer and Swank 1996).

Research

Over the past 5 years a cadre of more than 60 scientists and land managers in 6 research units in the Southern Research Station, National Forest Systems, and 8 universities along with conservation and environmental groups, state agencies, and the public have participated in the study. The 35 desired resource conditions span 8 primary research and management themes (table 2) which thus far, have entailed more than 40 studies. The research process entails the identification of existing data, exploratory and inventory activities, and manipulations / monitoring needed to test hypotheses or achieve goals (figure 1). In Phase I of the project three prescriptions are centered on various habitat manipulations to move the watershed toward desired conditions:

1. Stand replacement fire was prescribed on about 300 ha to restore a degraded pine / hardwood community and to stimulate forage production and promote oak regeneration along a hillslope gradient (Elliott et al. 1999). An interdisciplinary research team assessed initial responses of both terrestrial and aquatic ecosystems to management (table 3) and research continues to determine if desired conditions will be achieved;
2. Four silvicultural prescriptions (three replicates) were applied to the mixed oak stands to regenerate oak and increase biodiversity. Research is evaluating effects on vegetation, soil nutrients, water quality, small mammals and herpetofauna, ruffed grouse, soil invertebrates, stream invertebrates, and fish production;
3. Stream habitat improvement on an impoverished aquatic habitat section of Wine Spring Creek has been implemented through woody debris additions based on research on trout use of woody debris and habitat in Wine Spring the basin (Flebbe 1999).

An example of how research is integrated with management is illustrated in figure 2 where measured effects on resources are linked with adaptive management to provide a continuing process for achieving desired resource conditions. A major strength of the research is simultaneous studies in time and space which facilitates the detection of cause and effect relationships and provides a firmer basis for management decisions. Opportunities for incorporating findings into management are greatly enhanced because of the close planning and on-the-ground partnership between managers, scientists, and other participants in the project.

Additional research in the project also provides valuable information and tools for management. For example, soil erosion and stream sedimentation research are showing the benefits of best management practices associated with forest roads and other management prescriptions. Results have been used to develop a user-friendly, modular based, Geographic Information System for predicting soil erosion and transport to streams (Sun et al. In Press; Swank et al. 1994). This simulation model provides forest managers with a risk-assessment tool for evaluating the impacts of alternative management practices on water quality (Sun and McNulty 1998). An improved basis for management planning was also gained through socioeconomic research. Recreation studies identified human uses of the watershed and customer preferences for future uses (Cordell et al. 1996). A larger scale study of national forests in western North Carolina showed how economic tools can be extended to quantify complex social and biological

Table 2. Major research and management themes derived from enumeration of desired future conditions for resources on the Wine Spring Creek basin.

Ecological Classification
Riparian Zone Management
Aquatic Productivity/Water Quality/Habitat Alternation
Sustainable Productivity (Regeneration, Biodiversity, and Biogeochemical Cycles)
Social Value Assessment
Economic Analyses
Mammal and Bird Population Dynamics
Special Ecosystems ("Balds")

Table 3. Summary of resources examined and related documentation for stand replacement/habitat improvement burning on the Wine Spring Creek Ecosystem Management Project in western North Carolina

Resource	Reference
Vegetation	Elliott et al. 1999
Nutrient pools, soil and stream chemistry, stream sediment	Vose et al. 1999
Small mammals and herpetofauna	Ford et al. 1999
Soil macroarthropods	Crossley and Lamoncha, In Press

values associated with ecological processes (Schaberg et al. 1999). An extensive survey of citizen and special interest group preferences for a variety of goods and services associated with the forest lands showed that water and other ecological services and processes ranked highest across most groups. Other studies are focused on the riparian zone which is dominated by *Rhododendron maximum*, an understory species which is found over much of the stream system (Baker and Van Lear 1999; Laerm et al. In Press). Findings suggest opportunities for additional research in conjunction with management prescriptions to improve the structure, composition, and functional diversity of the riparian zone.

In the short-term, results from this research are reviewed, evaluated and incorporated into management using traditional approaches. However, our approach to ecosystem management includes the development of models that are spatially and temporarily explicit, synthesize and formalize knowledge, and provide an opportunity to view outcomes of proposed management. For example, some research findings from this project (soil erosion model, nutrient cycling, forest productivity) are planned for incorporation into a Decision Support System (Twery et al. In Press). Emergy, is a potentially powerful tool for synthesizing the value of multiple ecosystem components, functions, and outputs. It represents a novel approach to placing value on vastly differing resources (e.g., water, recreation, timber). In the following section, we provide a detailed description of an emergy analysis of WSC and its' potential management applications.

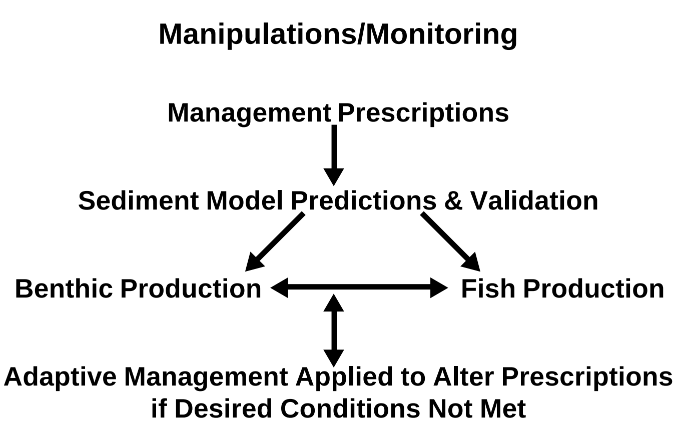

Figure 2. An example of linkages and feedback between management prescriptions, modeling, and stream research to identify the necessity for adaptive management. Wine Spring Creek Watershed, western North Carolina.

Emergy Analysis of the Wine Spring Creek Ecosystem Management Demonstration Project

Evaluation tools must be able to synthesize understanding of an ecosystems' multiple forcing factors, and components and outputs to integrate change across multiple geographic scales, and to predict future conditions. The ecosystem management philosophy adopted by the U.S. Forest Service requires such tools for measuring success in its effort to harmonize the needs of society, economy and ecosystem.

Emergy evaluation, a general methodology for assessing the functional and structural properties of any system, combines systems analysis with energy, material flow, economic and ecosystem analyses for holistic understanding (Odum 1996). For ecosystem management it offers a way of objectively comparing ecological benefits with economic and social benefits (Tilley 1999). It does so by expressing the varied benefits in a common metric, namely solar emergy. Solar emergy is the total sum of solar energy that was used previously in other system processes both directly, and more importantly indirectly, to make a product or deliver a service. It is the memory of energy used in the past. Ecosystem drivers (e.g., sunlight, wind, vapor deficit and rainfall), internal components (e.g., standing biomass, soil moisture, bedrock nutrition and species abundance) and products of an ecosystem (e.g., streamflow, recreated visitors, scientific knowledge and timber) can be quantified in terms of solar emergy for direct comparison of their relative importance to each other and to the larger economic system. The solar emergy per unit of available energy is defined as solar transformity (Odum 1996).

To contrast ecological processes with economic ones in a manner both meaningful and easily comprehended, the units of solar emergy (solar emjoules) for all products and services were translated to an equivalent amount of money. This was accomplished by converting solar emjoules to solar "emdollars" based on the ratio of money flow to emergy flow for the encompassing economy. Emdollars represent the amount of currency (e.g., dollars) being driven by a flow of emergy. In the case of the Wine Spring Creek (WSC) emergy evaluation, the emergy flow to dollar flow ratio was determined from North Carolina's economic activity of 1992.

Emergy evaluation has evolved over the last three decades (Odum 1996). It was applied to evaluate the interactions of man and nature in several river basins, including the Mississippi (Odum et al., 1987), Mekong

(Brown and McClanahan 1996), Amazon (Odum et al. 1986) and Maracaibo of Columbia and Venezuela (Howington 1999). Small watersheds have also been evaluated with emergy, including ones of the southern Brazilian coast (Romitelli 1997), the Coweeta Hydrologic Lab (Romitelli and Odum 1996) and most recently Wine Spring Creek of the Southern Appalachians (Tilley 1999).

We describe the methodology and demonstrate its application in evaluating the ecological-economic system of the Wine Spring Creek Ecosystem Management Demonstration Project (WSC). The multiple benefits of the forested watershed, such as wood, water, tourism and biogeochemical cycling, are compared in terms of solar emergy and emdollars.

Methods of Emergy Evaluation

Applying the emergy evaluation methodology to the WSC involved four steps:

1. identifying the system,
2. creating an emergy evaluation table,
3. determining the energy value of forcing factors and components and
4. converting energy values to solar emergy and emdollars.

The energy systems language (figure 3a) was used to conceptualize the system of the WSC. The diagrams provided a holistic picture of the ecosystem and identified the important forcing factors, internal components and exported products, along with their interactions. The process of developing each energy systems diagram was as follows:

1. The spatial boundary was defined as the watershed,
2. The temporal boundary was defined as a year,
3. A list of the forcing factors and internal units, thought to be important, was developed with input from the project team and other experts,
4. Preliminary, complex diagrams of the system were drawn with the energy systems language, arranging forcing factors and internal components in order of their solar transformity,
5. Rough values of the solar emergy of the forcing factors and state variables were calculated as a means of filtering out unessential parameters and aggregating others,
6. A final systems diagram was drawn, including only those forcing factors and state variables which represented greater than 5% of total emergy flow or stocked, respectively.

Figure 3b explains how the solar emergy values of the forcing factors, internal processes and multiple products of a system were calculated. First, the energy flow of each forcing factor was determined. The energy was transformed to solar emergy by multiplying by the appropriate solar transformity. Unless calculated within this work or otherwise noted, solar transformities used were from Odum (1996). In figure 3b the solar emergy value of the internal pathway Z equaled the solar emergy input Y. The solar emergy of product V was the sum of the two inputs to sector B, Z and U. The solar transformity of input U was determined based on its external transformation (i.e., Y' / U'). The solar transformity of internal pathway Z and the product V were calculated by dividing solar emergy by energy. The emdollars of each flow were found by dividing solar emergy by the average solar emergy-to-dollar ratio of the regional economy. In the case of WSC it was 1.12 E12 sej / $.

Results and Discussion of Emergy Evaluation

Figure 4a is the systems diagram of the ecosystem of Wine Spring Creek watershed. The diagram demonstrates how the energies of the meteorological system—sunlight, wind, vapor saturation deficit and rain—interacted with the mountain geology to create a mixed-hardwood forest with organically rich soils, deep saprolite and plentiful water reserves.

Figure 4b shows the systems diagram of the ecological economic system of the Wine Spring Creek watershed. The details of the ecosystem, which were shown in figure 4a, were aggregated and economic forcing functions were added. The diagram revealed how the capture of environmental energies by forest and mountain supported the ecosystem, which in turn, formed the basis for the human economy.

The diagrams and the process of developing them provide an instrument for focusing the attention of managers, policy makers and other environmental decision makers on the whole system. They help build consensus by identifying the system. If the practice of organizing forcing functions and components from left to right, according to their solar transformity, is followed, then holistic overview prevails and the diagrams clarify understanding.

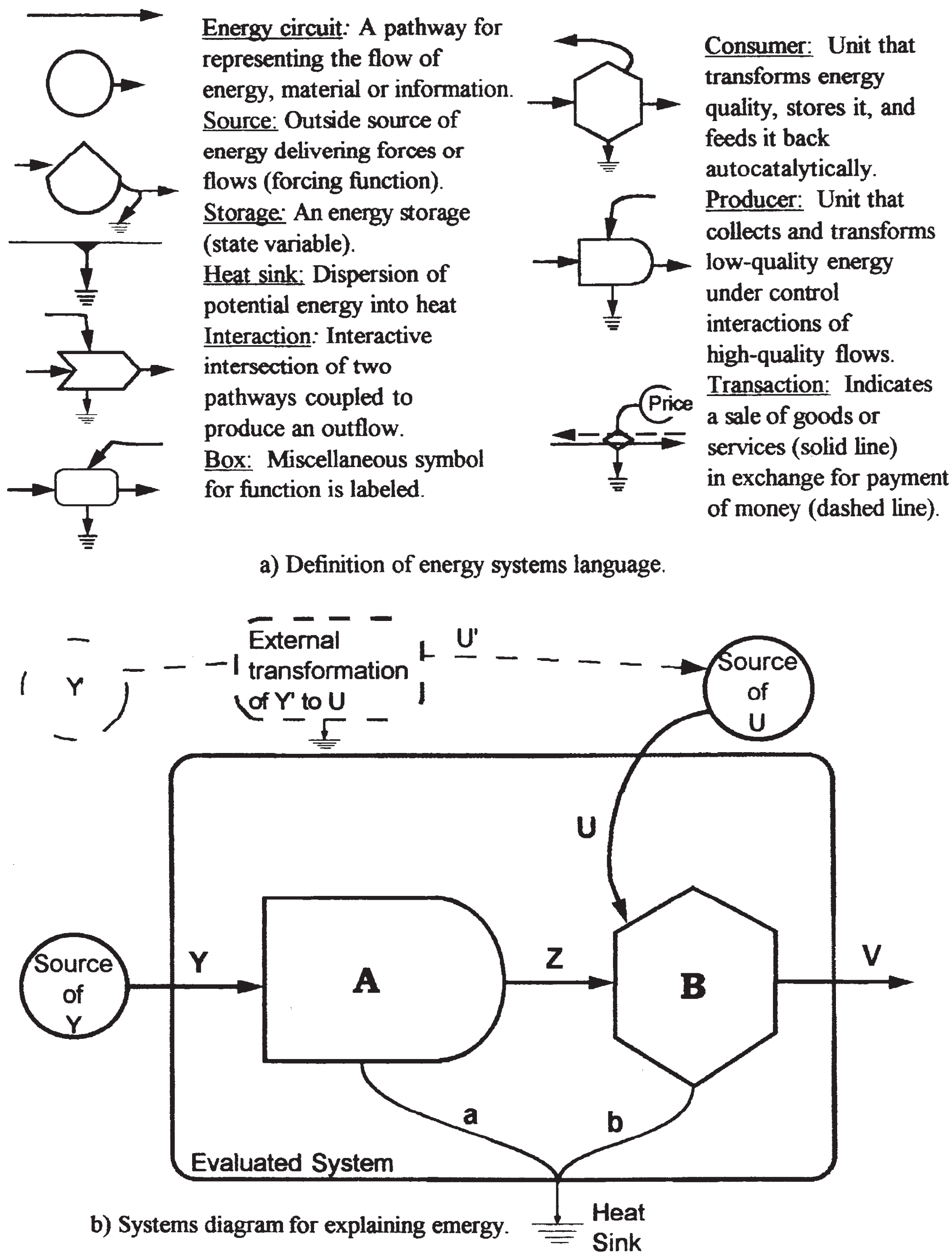

Figure 3. Energy systems language with definitions (a) and an energy systems diagram explaining how emergy flows are calculated (b). Abbreviations: e(X) = energy of X; M(X) = emergy of X; T(X) = transformity of X. The first step is to determine energy values of inputs, Y & U, internal pathway, Z and exported product, V. Next, emergy is assigned based on the total emergy required to make a product. Thus, M(Y)=T(Y)*e(Y), M(Z)=M(Y), M(U)=T(U)*e(U), M(V)=M(Z)+M(U). The waste heat [e(a)+e(b)] does not possess emergy since it is the energy lost in the energy transformation process. Finally, the transformities of the internal pathway and exported product are determined, T(Z)=M(Z)/e(Z) and T(V)=M(V)/e(V). In this example, T(U) is needed in terms of the base energy source, Y. Therefore, T(U) would need to be calculated, T(U)=M(Y')/e(U').

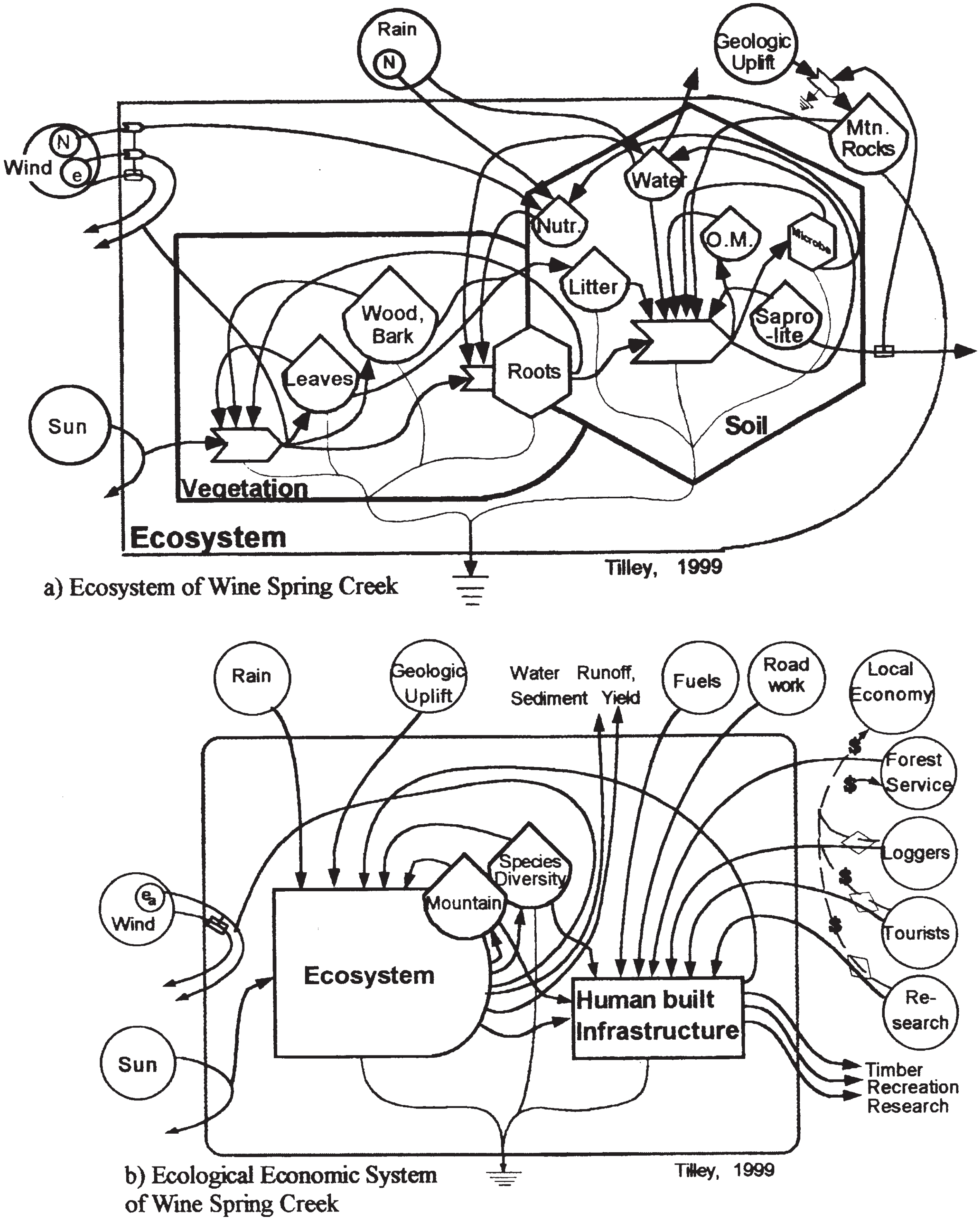

Figure 4. Systems diagram of the ecosystem of Wine Spring Creek watershed (a) and systems diagram of the ecological economic system of Wine Spring Creek watershed (b). Abbreviations: N-nutrients, e-water vapor, O.M.-organic matter.

Table 4 shows the emergy evaluation of the environmental energies used, the economic energies imported, the main internal processes and four important products exported for the WSC watershed.

The chemical energy of precipitation provided the largest input of solar emergy (1603 Em$ / ha / y), environmental or economic. Remarkably, four of the environmental sources (geopotential of rain, chemical potential of water used in transpiration, water vapor saturation deficit and land cycle) contributed a similar amount of solar emergy– between 385 and 525 Em$ / ha / y. The solar emergy of sunlight and atmospheric deposition were the two smallest environmental contributors (<46 Em$ / ha / y). The total incoming solar emergy derived from renewable environmental sources (2055 Em$ / ha / y) was the sum of three independent sources: chemical potential of precipitation, land cycle and atmospheric deposition. Other environmental sources are not added to avoid double counting (see Tilley 1999 for further explanation).

Comparison of the solar emergy contributed by the various ecosystem drivers demonstrated that water was the most important factor and indicates that properly managing water is critical to ecosystem health. The large amount of solar emergy in the land cycle confirms the fact that soil management is also important for a vibrant forest.

Listed next in table 4 (items 9-16) are the non-renewable sources of solar emergy that were imported by humans. The watershed received over 15,000 visitors annually (Cordell et al.1996). Tourists used various energies (automotive fuel and their own services) to enjoy free recreational resources. In one year, visitors utilized 12 Em$ / ha / y of automobile fuel while in the WSC watershed. An additional 124 Em$j / ha / y of auto-fuels were consumed by local through-traffic. The value of the tourists' time, worth 699 Em$ / ha / y, was a major imported resource. The Forest Service, over the last 25 years was paid an average of $9 / ha / y (12 Em$ / ha / y) by loggers. This was an order of magnitude less than the Forest Service expended (121 Em$ / ha / y) to maintain 32 km of paved and unpaved roads, but nearly equal to the value paid for management services (18 Em$ / ha / y). The largest imported source of solar emergy was from scientist's participating in the WSC Ecosystem Demonstration Project (1252 Em$ / ha / y).

If ecological sustainability is defined as the condition at which ecosystem benefits are acquired at a rate that does not hinder ability to provide future goods and services, then the ecological sustainability of the WSC system can be measured with the environmental loading ratio (ELR). The ELR was defined as the total imported solar emergy per unit of indigenous, environmental solar emergy (Brown and Ulgiati 1997). The WSC had an ELR of 1.1 indicating that economic activity evenly matched the ecological capacity of the forest. If the WSC was pristine and not used in any way for economic purposes, then there would be no imported solar emergy and the ELR would be zero. Multipurpose ecosystems with ELR's lower than the WSC include the Luquillo National Forest in Puerto Rico (ELR = 0.15; Doherty et al. 1997), where visitation was much higher but spread over a greater area, and the Everglades National Park (ELR = 0.82; Gunderson 1992). Odum and Odum (1980) found the ELR of a New Zealand pine plantation to be 1.4. At this rate of economic activity the ecological sustainability of the pine plantation cannot be assessed with definitiveness, but the ecological sources did provide less solar emergy than economic sources. For further perspective on how the ELR relates to ecological sustainable, consider that the ELR of Charlotte (N.C.), a modern American city, was 134 (Tilley 1999). Increasing the amount of imported solar emergy to the WSC will make the economic "load" much greater and the ecosystem less sustainable.

From a management perspective, the ELR could used for regional forest planning. Multi-purpose lands such as the WSC, could be targeted to maintain an ELR of one (i.e., an even match between economy and ecology), while wilderness lands could be selected to have much lower ELR's, possibly less than 0.10.

In table 4 the solar emergy value of wood growth and forest production (NPP) were each 892 Em$ / ha / y, which was the sum of the solar emergy of transpiration, land cycle and atmospheric deposition. The geologic work that weathered bedrock was the most valuable internal process (2055 Em$ / ha / y).

Water yield, harvested timber, recreationists and scientific data were the exports determined to posses large amounts of solar emergy (table 4). Total solar emergy of all exports was 4292 Em$ / ha / y. Based on this rate, the 1128 ha WSC watershed contributed wealth to the region at the annual rate of 4.8 million Em$.

A goal of ecosystem management is to maintain a balance between the ecological, economic and sociological goods and services provided by the ecosystem. With the emergy model, the balance (i.e., all outputs contribute equal solar emergy) of an ecosystem as well as its total output can be determined for alternative management plans. The WSC is fairly well balanced because it is contributing multiple benefits (water, recreation and information), valued in terms of solar emergy, at similar rates (table 4). If perfect balance is the goal, then timber harvest, which represented only 6% of total solar emergy output, needs to be increased or the other benefits need to be decreased. With all flows (input, internal and output) in the same unit (solar emergy), a sensitivity analysis can easily be performed to determine what happens to the balance of watershed products and ecosystem sustainability (i.e., environmental loading ratio ~=1.0) under various management plans.

Table 4. Emergy evaluation of Wine Spring Creek watershed (

Item	Physical Unit		Solar Transform (sej/unit)
ENVIRONMENTAL ENERGY INPUTS:			
[a] Sunlight	5.0E+13	J	
[b] Vapor saturation deficit	7.2E+11	J	5.9E+
[c] Wind, kinetic (annual)	1.9E+11	J	1.5E+
[d] Precipitation, geopotential	5.6E+10	J	1.0E+
[e] Precipitation, chemical	9.7E+10	J	1.8E+
[f] Transpiration	2.7E+10	J	1.8E+
[g] Land cycle	1.4E+10	J	3.4E+
[h] Atmospheric deposition	3.0E+04	g	1.0E+
Sum of c, g, & h			
IMPORTED ENERGY SOURCES:			
[I] Auto-fuel, visitors within	2.1E+08	J	6.6E+
[j] Auto-fuel, thru traffic	2.1E+09	J	6.6E+
[k] Visitors, length of stay	8.6E+07	J	8.9E+
[l] Timbering, services	9	$	1.5E+
[m] Timbering, fuels	1.6E+07	J	6.6E+
[n] Road maintenance	88	$	1.5E+
[o] Forest Service mgmt.	13	$	1.5E+
[p] Scientist's time	4.0E+06	J	3.4E+
Sum of imports (i - p)			

footnotes follow

Footnotes to Table 4

[a] Solar insolation @ ground 5.02E+13 J/m^2/yr (taken from Coweeta, Swift et al., 1988)

[b] Energy of vapor saturation deficit used, J/y = 7.17E+11 (see Tilley 1999)

[c] Wind energy, J/y = 1.88E+11 (complex function, see Tilley 1999 for details)

[d] Potential energy @ mean elev. (J) = (area)(runoff)(mean elev - min elev)(density)(gravity)
= (10,000 m^2)*(1.423 m/y)*(1318-920 m)*(1000 kg/m^3)*(9.8m/s^2)
Energy, geopotential (J) = 55.5E+9

[e] Precipitation @ 1330 m = 1,961 mm/yr Forest Service (1995-1997)
Gibb's free energy of rainfall (10ppm vs 35ppt), J = (area)(rainfall)(Gibbs no.)
= (10,000 m^2)*(1.960m)*(4.94E6 J/m^3)
Gibb's free energy (J) = 9.69E+10

[f] Mean rate of transpiration 538 mm/y CS301t (pers. comm. L. Swift, Coweeta)
Gibb's free energy of rainfall (10ppm vs 35ppt), J = (area)(transpiration)(Gibbs no.)
= (10,000 m^2)*(0.538m)*(4.94E6 J/m^3)
Total energy (J) = 2.66E+10

[g] Emergy of land cycle calculated as eart
Heat flow / Area = 1.36E+06 J/m^2/y, @ Bryson City, NC
Energy (J) = 1.36E+10 (Smith et al., 1981; in Pollack et al., 1991).
Transformity, 34,400 sej/J was the mean calculated for the continents by Odum, 1996.

[h] Deposition rate, kg/ha/y = 30 estimate based on Coweeta Hydrologic Lab

[i] Gas within WSC = 3.70E+01 (bbl/yr; see Tilley 1999)
Energy(J) = (____bbl/yr)*(6.28e9 J/bbl)
Energy(J/ha) = 2.06E+08

[j] Gas within WSC = 3.70E+02 (bbl/yr; see Tilley 1999)
Energy(J) = (____bbl/yr)*(6.28e9 J/bbl)
Energy(J/ha) = 2.06E+09

[k] no. of groups/yr = 4,361 Cordell et al., 1996.
mean group size = 2.7 people
mean length of stay = 19.0 hours
Energy(J) = (_____people-hrs/yr)*(104 Cal/hr)*(4186 J/Cal)
Energy(J/ha) = 8.63E+07
Transformity of 8,900,000 sej/J is the avg. for a U.S. citizen during avg. day.

[l] Revenue from timber sales from 1973-1999 (26y) was $250,000 (Wayah Ranger District).
Revenue, $/ha/y = 8.5

[m] U.S. National average fuel use: 23 E15 J/y to harvest 648 E6 m^3 of wood
Fuel use in WSC timbering, J/ha/y = 1.56E+07

[n] Length of unpaved roads = 24 km (GIS database)
Length of paved roads = 9 km (GIS database, FS 711)
Cost to maintain roads 5,000 $/mile/y (B. Culpepper, Wayah Ranger District)
Cost of rd, $/ha/y = (length of rds, km)x($5000/mile/y)x(1 mile/1.609 km)/(1128 ha)
Cost of rd, $/y = 8.84E+01

[o] Expenditures, $/ha/y = 13

[p] At least 52 forest scientist, forest managers, university scientists and graduate students worked on the WSC Ecosystem Project from 1992-99. Assume they devoted 10% of their total work per year to gathering, analyzing, publishing and sharing their research

Effort, people-hr/y = 1.04E+04

Energy (J/ha) = (____people-hrs/yr)*(104 Cal/hr)*(4186 J/Cal)/(1128 ha)

Energy (J/ha) = 4.01E+06

Transformity: post-college educated person (Odum 1996)

[q] Roots+wood+leaves 14390 kg/ha/y; Day and Monk, 1977.

Energy(J) = (NPP,kg/ha/y)x(area, ha)(1000 g/kg)(3.5 kcal/g-dry wt)(4186 J/kcal)

= 2.11E+11

Transformity = (empower of evapotranspiration + deep heat + atmos. dep.) / (net production)

[r] Wood growth 4.20E+03 kg/ha/y; Monk and Day, 1977.

Energy(J) = (accum.,kg/ha/y)x(area, ha)(1000 g/kg)(3.5 kcal/g-dry wt)(4186 J/kc

= 6.15E+10

Transformity = (empower of evapotranspiration + deep heat + atmos. dep.) / (wood accumulation

[s] Erosion rate, g/m^2/y = 60 Velbel, 1985.

Sediment lost, g/ha/y 6.00E+05

Empower-to-flux (sej/g) = (empower of rain+deep heat+atmos. dep.) / (weathering rate)

[t] From the species-area curve, there were 30 species found within the first ha sampled. See Tilley 1999 for details

[u] Stream discharge

Runoff = 1.42 m/y mean 1995-96. Source: Coweeta Hydro. Lab

Chemical Energy(J) = (10,000 m^2)*(1.42 m/y)*(4.94E6 J/m^3)

Chemical Energy(J) = 7.03E+10

Transformity: [empower of rain + deep heat] / energy

[v] Since 1973 (26 y), timber harvest from WSC watershed was 8623 m^3 sawtimber and 4259 m^3 of roundwood, valued at $251,000 (Wayah Ranger District, courtesy of Bill

Timber harvest rate, m^3/ha/y = 0.44

Energy(J) = (m^3)*(5 E5 g/m^3)*(4.5 Kcal/g)*(4186 J/Cal)

Energy(J) = 4.14E+09

Transformity of timber = (emergy of wood + road maintenance + FS management + timbering fuels + timbering services)/energy of timber

[w] Same energy as visitor's length of stay above (#24)

Transformity = [sum of env. & econ. empower inputs /[metabolism of visitors during

Environmental inputs were taken as half the annual flow of rain+deepheat+atmospheric deposition since the main road is only opened from Apr. to Nov.

Economic inputs were sum of auto-fuel use, visiting time, road maintenance, and FS managemen

[x] From 1992 to 1998, 47 publications and 10 reports were produced (Swank 1999)

Publication rate over the six years was 57 / 6 = 9.5 pubs/yr. Publications average 10 pages in len

Grams of research articles published, g/y = 9.5 articles/y x 10 pages x 1 g/page = 95 g/y

Energy of articles, J/y = grams x 3.5 kcal/g x 4186 J/kcal = 1.39E6 J/y

Energy of articles, J/ha/y = 1,232

Transformity = [sum of empower inputs (rain, deepheat, atmospheric deposition, road maintenance, FS management, and research effort)]/[energy of publications, annual rate]

[y] Total Export was rain + deep heat + atmos. deposition + all imported sources (items 10-18)

Regional Scale Analyses in Progress

Watersheds also provide a useful framework for evaluating land stewardship at larger landscape scales; i.e., river basins. However, the complexities of planning and assessment increase substantially at a regional scale with mixed ownerships and multiple land uses.

As part of the Long-Term Ecological Research program at Coweeta, regional scale research was initiated to assess the effects of human caused disturbances on ecological processes. The effort encompasses a 15,000 km^2 area of western North Carolina with a focus on the Little Tennessee and French Broad river basins. Interdisciplinary research is being conducted by more than 30 co-principal investigators including social and economic scientists, as well as aquatic and terrestrial ecologists. The overall research goal is to develop a predictive understanding of the social, economic and environmental factors that drive land use cover changes and to assess the ecological consequences of changes for terrestrial and aquatic biodiversity, water quality, and regional carbon cycles (Swank 1998). Regional land use change models (Wear and Bolstad 1998) will be linked to socioeconomic and environmental models to forecast the consequences of future land use practices and policy. Initial research shows that whole watershed land use in the 1950s (compared to 1990s) is the best predictor of present day diversity of stream invertebrates and fish (Harding et al. 1998). Findings indicate that past land use, particularly agriculture, may result in long-term reductions in aquatic diversity, that persist even with reforestation of the watershed.

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Watershed Management in the Pacific Northwest: The Historical Legacy

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Abstract.—The last 100 years marks a period of accelerating land use and consequent effects upon the water resources of the Pacific Northwest. In contrast, federal and state efforts to reduce land use impacts to water resources have largely emerged only during the last 35 years. While university courses in watershed management were generally available in the 1950s, the number of courses increased greatly through the late 1970s. Research productivity (i.e., published results) in watershed management was relatively low until the 1970s. Educational programs and research efforts that provide a better understanding of land use effects to the region's water resources is needed for the 21st century.

Introduction

A watershed can be simply defined as a portion of the landscape that drains to a common point. Hence the Columbia River Basin, perhaps the largest of the Pacific Northwest (PNW) watersheds, encompasses all area upriver of the Columbia estuary, including a significant portion that extends well into Canada. Within the various biophysical regions of the Columbia Basin are a multitude of subwatersheds of various sizes.

While watersheds are also areas within a landscape that cycle water, energy, nutrients, sediment and organic matter over time and under the influence of gravity, the predominant characteristics, functions, and processes associated with a given watershed may be similar to adjacent watersheds or be highly varied relative to those located elsewhere across the PNW. The degree to which various ecosystem functions and processes operate often provide an important perspective regarding the overall integrity of a particular watershed (i.e., the quality or state of being unimpaired, sound) (Committee of Scientists 1999).

The phrase "watershed management" is often used to recognize a broad array of land use activities that might occur across a landscape. However, in the context of this paper I will use a somewhat narrower scope. The focus herein will be primarily on management practices that influence the water resources of the Pacific Northwest, with some emphasis regarding forest and range lands. Within this context there exists an array of activities employed by society to obtain, distribute, use, regulate, treat, and dispose of water (Satterlund and Adams 1992). In some instances, water resources impacts or changes are simply a byproduct of land use, in others the protection, alteration, or use of the water resource may be the primary management target.

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Watershed Management in the 20th Century

The management of Pacific Northwest (PNW) watersheds over the last 100 years, and longer, is a checkered history. Unfortunately, our understanding of past practices, their occurrence in time, their spatial distribution, and their relative importance to water resources is often incomplete. While we may know that millions of board feet of old-growth timber were removed from forests of the PNW to meet economic and social demands or that hundreds of thousands of domestic ungulates foraged across rangeland watersheds of the region, our understanding of the ecological and environmental consequences of these widespread practices are imperfect. Similarly, the effects of urbanization and industrial activities of an emerging society upon the water resources of the PNW have not always been chronicled or evaluated. Nevertheless, it is important to look backward in time, albeit briefly, if we are to move forward into the next century with a heightened awareness and reasonable expectations of societal wants and needs regarding the region's water and other natural resources.

Historical Land Uses

Prior to 1800, native peoples of the PNW utilized the vast resources of the region to meet their social, cultural, and day-to-day needs for living (Ontko 1998). Their use of the land was predominantly nonagricultural. However, the expanding wants and needs of an EuroAmerican culture were soon destined to alter the long-term development of this area. While fur traders roamed the PNW in the late 1700s, the westward expedition of Meriwether Lewis and William Clark in the early 1800s provided additional impetus for increased exploration and immigration into the region by EuroAmericans. The bountiful natural resources of the PNW and a strong desire by the prevailing EuroAmerican culture to extensively utilize these resources were precursors to the widespread development and use of the region's forests, forage, water, wildlife, fisheries, minerals, and other resources. By 1900, the EuroAmerican culture was well entrenched in the PNW with a population of approximately one million people.

During the last 100 years, EuroAmerican influences upon the natural resources of the PNW have been extensive. While a detailed listing of EuroAmerican effects is not the purpose of this paper, it is important to at least consider some of the changes that have occurred so that future generations can better judge the appropriateness of both historical and projected water resources decisions. Excluding the direct effects of a burgeoning EuroAmerican population and culture upon the indigenous tribal cultures and peoples, perhaps one of the first impacts to the region was the general decimation of beaver populations. Today, we realize that beavers have an important role in a wide array of hydrologic and ecological functions for many headwater streams and associated floodplains. The full extent to which beaver were a factor in the long-term development of floodplains, riparian areas, and aquatic habitats not known, but it was likely significant in many areas of the PNW.

Utilization of the region's anadromous fish stocks by EuroAmericans began in earnest with establishment of canneries along the Columbia River in the late 1800s. These canneries continued through the 1940s when they were largely replaced by ocean harvests. In combination, various harvesting approaches have removed millions of pounds of fish annually from anadromous runs in the PNW. Once thought to be a limitless resource, fisheries stocks today are much reduced; many stocks have recently been listed as threatened or endangered under the Endangered Species Act. While the potential extirpation of these stocks is a major concern, perhaps just as importantly is their role as an indicator status regarding the impacts of land uses on instream habitats and water quality that continue to occur across many PNW watersheds.

Other natural resources also felt the development pressures of an EuroAmerican culture. As ranchers and settlers entered the PNW, livestock numbers rapidly increased. Although total numbers of livestock ranging public lands have decreased since the 1900s, increased grazing of private lands has occurred. The riparian and aquatic impacts from grazing have been significant and have often occurred over many decades (Meehan 1991).

Timber harvesting along lowland rivers and streams, which began prior to 1900, quickly spread upriver with the use of splash dams and railroad logging in the early part of the 20th century. The advent of improved cable logging systems, including the relatively recent availability of helicopters and other aerial systems, essentially made accessible to timber harvest most of the mountain terrain in the PNW (except areas specifically reserved for other purposes). From 1940 to 1990, approximately 14 billion board feet of timber from the forests of Oregon and Washington were removed annually (National Research Council 1996); tens of thousands of logging roads were constructed to access mountain lands.

Perhaps one of the most significant changes to occur in the PNW during the 1900s was the construction of dams. It is soon apparent to anyone who has traveled the western United States that PNW rivers represent an important resource of the region. With the advent of an engineering technology that made the construction of large dams possible and an increasing demand to regulate rivers for navigation, irrigation water, hydropower, and flood control, many of the major rivers and tributary streams of the PNW were to be rapidly transformed. From 1900 to 1920, the total volume of water impounded behind dams in northern California, Idaho, Oregon, and Washington went from essentially zero to 15 million acre feet. By 1975, this total had increased to approximately 65 million acre feet and included 14 mainstem Columbia River and 13 Snake River dams. While the economic benefits to the region from an extensive system of dams have been substantial, they have not been without significant effects and impacts. For example, 55% of the area and 31% of the stream miles of the original anadromous fish habitat in the Columbia Basin have been eliminated by dam construction; access to all Canadian Habitats has been eliminated (National Research Council 1996). Much of the mainstem Columbia "River" is now represented by a series of connected impoundments.

Looking back, there can be little doubt that a prominent social policy of the United States throughout the 1900s was one of "winning the west". In the beginning this policy was directed at suppressing and controlling the native populations. Once accomplished, the development and use of the region's natural resources became a high priority. To a major extent, society was successful in these endeavors. But the impacts to water resources have been significant. Loss of aquatic productivity, loss of riparian and wetland functions, degraded water quality, depleted instream flows, and other adverse effects have been all too prevalent.

Watershed Protection and Regulations

The general exploration, development, and use of the PNW's resources over the last 100 years have caused numerous adverse consequences to water and aquatic habitats. For example, agricultural users could essentially "dry-up" a stream since the maintenance of an instream flow for purposes of protecting water quality or aquatic habitats was not an acknowledged beneficial use. The "use it or lose it" approach to water resource management is well embodied in western water law *via* the doctrine of prior appropriation. In other situations, the "tragedy of the commons" occurred repeatedly as stock growers competed for a decreasing forage base with increasingly larger herds. Whereas early railroad logging efforts often chose "easy" terrain for tree harvesting, the widespread availability of construction equipment (e.g., bulldozer) after World War II saw the expansion of road systems into steep and often unstable terrain. Changing technologies eventually allowed access to timber on even the steepest of mountain slopes. In yet other instances, the conversion of lands from forest to agricultural or urban uses contributed to the loss of wetlands (National Research Council 1995). Separately and cumulatively, the wide variety of land uses in the PNW, and elsewhere across the United States, sufficiently provoked society such that a series of laws and regulations have been promulgated over the last 35 years for the protection of water quality and wetlands. While some of the legislative approaches have been national in scope, they have influenced state regulations and regional approaches to a variety of water resources issues.

In 1965, the federal Clean Water Act (CWA) required states to submit, for federal approval, water quality standards for all interstate waters and estuaries. This legislation essentially acknowledged that the nation's waters had experienced significant change and impairment from the demands of an agricultural/industrial economy. In 1967, Oregon was the first state to adopt water quality standards: the Oregon regulations were directed at both <u>interstate</u> and <u>intrastate</u> water quality standards for bacteria, dissolved oxygen, pH, turbidity, temperature, dissolved chemical substances, and others. While these standards theoretically pertained to all waters of the State, in reality they were more focused on water quality problems associated with "point-sources".

Passage of the 1972 amendments to the Federal Water Pollution Control Act (FWPCA) indicated an important need to improve the treatment of sewage, industrial effluents, and other point-source pollutants being discharged into the nation's waters. Two important goals of the 1972 FWPCA were to:

- By 1983, have water quality sufficient to promote fish life and be of general high quality (i.e., fishable and swimable)
- By 1985, eliminate the discharge of all pollutants (i.e., zero pollution)

This legislation not only gave the U.S. Army Corps of Engineers and the Environmental Protection Agency authority to regulate polluted waters of the United States, but expanded their authority into non-point sources of pollution, included those generated from forestry, range, and agriculture, and the status of wetlands. With regard to wetlands, coverage of the 1972 act was narrowly construed at first and extended to only 15% of the total wetland acreage in the United States. However, judicial decisions between 1972 and 1977 greatly broadened the coverage of the statute. Section 404 of the 1977 Clean Water Act amendments confirmed the national commitment to regulation of wetlands and broad federal application of the 1977 act to wetlands was upheld judicially in 1985 (National Research Council 1995).

Most of the mountainous areas in the PNW and elsewhere in the western United States are covered with predominantly forest vegetation types. It is these same mountain watersheds from which most of the region's streamflow is generated. For much of the 20th century, the forest industry in the PNW has been a major component of many local and state economies. Forest harvesting, site preparation, and roading have been widespread. Hence, there has been considerable interest in forest practices from a regulatory perspective. In addition, a significant amount of published research became available late in the 20th century that addressed basic ecological processes associated with forested watersheds (e.g., natural fires and disturbances) and the effects of forest operations (e.g., road construction, harvest systems, site preparation).

An important consequence of the 1972 FWPCA regarding non-point source pollution is that many western states began to look more closely at various land use activities and their potential impact upon water quality. In particular, forestry activities came under scrutiny. While water quality standards have been widely and often successfully used for addressing a wide range of point-source water quality problems, their application in the non-point water quality arena is often more difficult. Because of the often unpredictable nature of some non-point source occurrences, an "after-the-fact" use of water quality standards may not always be effective. For example, possible adverse consequences to water quality from road construction and logging on an erosion prone site might not become evident until major rainfall events occur the following winter or even several years later. Because of the challenges often associated with using water quality standards to control non-point sources of pollution, an alternative philosophical and regulatory approach to water quality issues associated with forestry was formulated. This alternative approach culminated in the promulgation of Forest Practices Acts by individual states. These regulations have been largely used to specify forest practices (sometimes referred to as best management practices) that are intended to prevent significant adverse impacts to water resources and water quality. In 1972, Oregon enacted into law the nation's first Forest Practices

Act; since then California, Idaho, Washington, and other states have also done so. Forest practices acts undergo periodic revisions to incorporate new knowledge or to address specific concerns. For example, in 1994 the Oregon Forest Practices Act was substantially modified to provide for substantially increased stream protection. In contrast, land use practices for rangelands, agricultural areas, estuaries, and urban areas practices have remained outside a similar regulatory framework.

The 1987 federal Water Quality Act continued to emphasize Congressional intent for controlling point and non-point sources of pollution to the nation's waters. This legislation introduced additional concepts related to such issues as water quality limited streams, total maximum daily loads (TMDLs), and non-degradation. Currently, the State of Oregon has undertaken several basin-wide assessments in an attempt to better understand the extent of water quality limited streams and the use of TMDLs for pollution prevention. Furthermore, in 1992, as required under Section 303 of the federal Clean Water Act, the Oregon Department of Environmental Quality initiated a water quality standards review of temperature, dissolved oxygen, and bacteria; these efforts resulted in new standards being issued in 1994. Thus, the pathways of regulatory development during the last 35 years have continued to evolve at both federal and state levels, and there is little indication that this evolution has yet run its full course.

Education and Research

Formal education in wildland watershed management in North America began around 1932 when a course entitled "forest influences" was first taught by Dr. Joseph Kittredge at the University of California (Ponce 1979). The course focused on the effects of woody vegetation on microclimates, soils, and water resources. By 1953, 17 of 36 forestry schools in the United States were offering one or more courses in forest influences and watershed management (Dils 1954). By the late 1970s, seven universities in California, Idaho, Oregon, Washington, and British Columbia were teaching 39 courses in watershed management, forest hydrology, range hydrology, and related subjects; there were over 180 such courses at 50 colleges and universities across North America (Ponce 1979). While it is likely that the relative educational effort of various colleges and universities has shifted somewhat in the last two decades, there is no doubt that educational programs in the PNW regarding the influence of management practices upon the region's water resources continue to be a high priority.

Similar to the general mushrooming of formal education in wildland hydrology that occurred in the last half of the 20th century, much of the published understanding of water resources management associated with forested and rangeland watersheds began to emerge in the last half of the 20th century, and most of that in the last 30 years. In 1994, Adams and Ringer compiled an annotated bibliography on the effects of timber harvesting and roading upon water quantity and quality in the PNW; they emphasized original reports of field research in their selection of published studies with a priority for peer reviewed publications. While their annotated bibliography was not intended to be fully comprehensive, it does provide an overview of research emphasis related to forestry and water resources in the published literature and when it occurred. The earliest cited publication was a study by Anderson and Hobba (1959) which analyzed streamflow data for streams in the Willamette Basin of western Oregon. From that early start, the knowledge base, as indicated by relative numbers of publications in Table 1, has expanded greatly. The vast majority of the early publications reported results from paired watershed studies. These types of studies involved monitoring water quantity/quality from two or more adjacent watersheds over a period of several years, imposing a treatment on one or more watersheds while retaining one watershed in an untreated condition (i.e., control), monitoring them for several more years, and finally analyzing for watershed responses due to treatment.

Table 1. Number of publications by topic and date that address the effects of timber harvesting and forest roads on water quantity and quality in the Pacific Northwest, for the period 1950-1989 (from Adams & Ringer 1994). [a]

	Decades			
Topics	**1950-59**	**1960-69**	**1970-79**	**1980-89**
Water quantity				
Timber harvest	1	2	11	16
Forest roads	0	2	3	7
Water quality				
Timber harvest	0	3	18	12
Forest roads	0	0	9	12
Totals	**1**	**7**	**39**	**47**

[a] *Publications cited by Adams and Ringer after 1990 are not included in the above table.*

The experimental watershed studies that occurred primarily in the 1950s, 60s, and 70s, and their inclusion of an untreated control watershed for separating treatment effects from natural variations in watershed outputs, was of fundamental importance in providing an improved understanding regarding the potential for forest practices to influence water resources. Results provided and continue to provide important sideboards on possible changes in quantity or quality of water following specific forest practices, or combinations of forest practices. Although paired watershed results often indicated the direction and magnitude of a hydrologic response, they seldom provided confirming information as to the processes that might have caused such a change. Thus, much of the hydrologic research on forested watersheds in the PNW since approximately the mid-1970s has attempted to address specific processes and functions occurring at various spatial and temporal scales (Adams and Ringer 1994). These studies have considered such processes or topics as snow accumulation and melt, interception, infiltration, subsurface flow, channel morphology, stream temperatures, nutrient dynamics, hyporheic flow, and others.

A general listing of some of the symposium and workshop proceedings related to land use and water resources that have occurred over the last several decades is shown in Table 2. While the tabulation does not provide a complete listing of all symposia and workshops associated

Table 2. Listing of selected symposia, workshops, and related publications that address some aspect of natural resources management and water in the Western United States, with emphasis on forests and rangelands of the Pacific Northwest.

Date	Title	Publisher	Number of pages
1956	**Snow hydrology**	Corps of Eng., Portland, OR	437 pp.
1966	**Practical aspects of watershed management**	School of Forestry, Oreg. State Univ., Corvallis, OR	135 pp.
1967	**International symposium on forest hydrology**	Permagon Press; Oxford, UK	813 pp.
1970	**Interdisciplinary aspects of watershed management**	Amer. Soc. Civil Eng, New York	411 pp.
1971	**Forest land uses and stream environment**	School of Forestry, Oreg. State Univ., Corvallis, OR	252 pp.
1975	**Watershed management**	Amer. Soc. Civil Eng., New York	781 pp.
1976	**Symposium and specialty conference on instream flow needs: Voumes 1 & 2**	Amer. Fish. Soc., Bethesda, MD	551 & 657 pp., respectively
1979	**Livestock grazing management and water quality protection**	USEPA, #910/9-79-67, Region 10, Seattle, WA	147 pp.
1980	**Symposium on Watershed Management: Volumes 1 & 2**	Amer. Soc. Civil Eng, New York;	1100 pp.
1981	**Cumulative effects of forest management on California watersheds: an assessment of status and need for information**	Special pub. 3268, Univ. Calif., Berkeley, CA	109 pp.
1982	**Sediment budgets and routing in forested drainage basins**	USDA Forest Service, Gen. Tech. Report PNW-141, Portland, OR	165 pp.
1983	**The potential for water yield augmentation through forest and range management**	American Water Resources Association, Reprint of Water Resour. Bull.	19 (3): 359-402.
1984	**Range watersheds, riparian zones, and economics: interrelationships in management and use**	Proceedings of Pacific Northwest Range Management Short Course, Dept. Rangeland Resour., Oreg. State Univ., Corvallis, OR	98 pp.
1984	**Symposium on effects of forest land use on erosion and slope stability**	Environment and Policy Institute, Univ. Hawaii, Honolulu, HA	310 pp.
1985	**Forest riparian habitat study: phase I report**	Dept. of Ecology, Olympia, WA	203 pp.
1985	**Riparian ecosystems and their management: reconciling conflicting uses**	First North American Riparian Conference, USDA Forest Service, Gen. Tech. Report RM-120, Fort Collins, CO	523 pp.
1986	**Wetland functions, rehabilitation, and creation in the**	Wash. Dept. of Ecology, Olympia, WA	184 pp.

Table 2. Cont'd.

Date	Title	Publisher	Number of pages
	Pacific Northwest: the state of our understanding		
1987	**Erosion and sedimentation in the Pacific Rim**	Internat. Assoc. Hydrol. Sciences, Pub. No. 165, Wallingford, Oxon, UK	510 pp.
1987	**Methods for evaluating riparian habitats with applications to management**	USDA Forest Service, Gen. Tech. Report INT-221	177 pp.
1987	**Proceedings of the workshop: applying 15 years of Carnation Creek results**	Pacific Biological Station, Nanaimo, British Columbia	239 pp.
1987	**Streamside management: forestry and fisheries interactions**	College of Forest Resources, Univ. Wash., Seattle, WA	471 pp.
1987	**Wetland and riparian ecosystems of the American West**	Proceedings of Society of Wetland Scientists, Wilmington, NC	349 pp.
1988	**Proceedings of California riparian systems conference**	USDA Forest Service, Gen. Tech. Report PSW-110, Berkeley, CA	544 pp.
1989	**Proceedings of symposium on headwaters hydrology**	Amer. Water Resour. Assoc., Bethesda, MD	708 pp.
1989	**Riparian resource management**	USDI, Bureau of Land Mgmt., Billings, MT	193 pp.
1990	**Case studies and catalog of watershed projects in western provinces and states**	Wildland Resources Center, Univ. Calif., Berkeley, CA	188 pp.
1991	**Monitoring guidelines to evaluate effects of forestry activities on streams in the Pacific Northwest and Alaska**	USEPA, #910/9-91-001, Seattle, WA	166 pp.
1992	**Interdisciplinary approaches in hydrology and hydrogeology**	Amer. Instit. Hydrol., Minneapolis, MN	618 pp.
1992	**National hydrology workshop proceedings**	USDA Forest Service, Gen. Tech. Report RM-GTR-279, Fort Collins, CO	210 pp.
1993	**Management impacts on water quality of forests and rangelands**	USDA Forest Service, Gen. Tech. Report RM-239, Fort Collins, CO	114 pp.
1993	**Monitoring protocols to evaluate water quality effects of grazing management on western rangeland streams**	USEPA, #910/R-93-017, Seattle, WA	179 pp. plus appendices.
1993	**Riparian management: common threads and shared interests**	USDA Forest Service, Gen. Tech. Report RM-226, Fort Collins, CO	419 pp.
1993	**Symposia proceedings on water resources education: a lifetime of learning & changing roles in water resources policy management**	Amer. Water Resour. Assoc., Bethesda, MD	715 pp.
1994	**Effects of human-induced changes on hydrologic systems**	Amer. Water Resour. Assoc., Bethesda, MD	1182 pp.
1994	**National symposium on water quality**	Amer. Water Resour. Assoc., Bethesda, MD	322 pp.
1995	**North American workshop on monitoring for ecological assessment of terrestrial and aquatic ecosystems**	USDA Forest Service, Gen. Tech. Report RM-GTR-284, Fort Collins, CO	305 pp.
1998	**Specialty conference on rangeland management and water resources**	Amer. Water Resour. Assoc., Bethesda, MD;	474 pp.

with the hydrology of forest and rangeland areas, it does provide an overview of research direction and emphasis that emerged in the 1970s, 1980s, and early 1990s. Hydrologic and water quality responses to management practices, and the measurement and monitoring of such responses, are some of the common themes. Also important are topics related to riparian and wetland functions, processes, and management. Increasingly, these technical symposia and workshops integrate research results across a variety of social, economic, and environmental themes.

Watershed Management in the 21st Century

As we are about to embark on a new century, we need to recognize that the historical effects of land use upon the water resources of the Pacific Northwest during the last 100 years have been relatively extensive. A social philosophy of "winning the west" has accumulated numerous changes in the forests and rangelands, in the streams, rivers, and estuaries, and in the economies and cultures of the region. While the forests, rangelands, and rivers are still present, they have often been altered or transformed in ways that would have been unimaginable only decades ago. It is from this "inherited" landscape that the region's current population of ten million people will forge their legacy for the generations that follow.

With increasing population and economic pressures, the need for PNW watersheds to help satisfy the various social, economic, and environmental demands of a modern society will become increasingly important. Thus, perhaps this is an appropriate time to ask how society in the PNW will view water and other natural resources during the coming years? For example, will society embody and implement "sustainability" as an overarching objective in land and resource stewardship? The 1987 Brundtland Commission Report (The World Commission on Environment and Development, *Our Common Future*) indicates that sustainability involves meeting "the needs of the present without compromising the ability of future generations to meet their own needs." More recently a Committee of Scientists (1999), commissioned to provide technical and scientific advice on land and resource planning on the national forests and grasslands, commented on the ecological, economic, and social aspects of sustainability:

"These different aspects of sustainability are interrelated: the sustainability of ecological systems is a necessary prerequisite for strong, productive economies; enduring human communities; and the values people seek from wildlands. Most basically, we compromise human welfare if we fail to sustain vital, functioning ecological systems. It is also true that strong economies and communities are often a prerequisite to societies possessing the will and patience needed to sustain ecological systems." (Committee of Scientists, 1999, p. 13)

Whatever future goals society elects to pursue in the PNW, and nationally, there is no doubt that demands upon the scientific and research community will continue to increase. Our understandings of how watersheds process incoming precipitation, where the water goes and when, who uses it, and the effects of land use on quantitative outflows (e.g., annual yields, peakflows, low flows, timing of runoff) and water quality (e.g., sediment, nutrients, water temperature, dissolved oxygen, introduced chemicals) will intensify. Researchers will need to have a much better grasp of hydrologic processes; modeling will be increasingly be needed to fill information gaps and to project the consequences of activities at multiple spatial scales.

Much of the PNW land base is in federal ownership. Policies and management practices on these ownerships are often quite different from the intermingled and adjacent private lands. These mixed ownerships create special challenges for attempting to satisfy multiple demands and perspectives of a changing society. Perhaps nowhere is this more apparent in the PNW than with regard to pacific salmon. These anadromous fish have been a cultural and ecological hallmark of the region for thousands of years during which they have repeatedly migrated through thousands of miles of streams and rivers, through estuaries and oceans, and back. They have not only been important culturally and economically, but they have provided a valuable indication of environmental conditions of riparian and aquatic habitats. While in the region's freshwater environments, these fish essentially synthesize information on a complex of management, political, social, and biological factors influencing the sustainability of aquatic biodiversity (Stouder et al. 1997).

Other indicators of the status of water resources in the PNW might include systematic evaluations of water temperatures, sediment levels, flow alterations, and others. Because of the high spatial and temporal variability often associated with many of these naturally occurring water characteristics or phenomena, there is an increasing need to better understand "background" conditions. Without a firm grasp of natural variations and disturbance regimes, it is often difficult to decipher the hydrologic effects of individual or cumulative management practices. With increasing regional interest directed at improving or restoring streams, riparian areas, and overall watershed conditions, there is a corresponding increasing need to better understand how relatively undisturbed watersheds function and the extent to which they can provide reference conditions for comparison against current responses. Concurrent with this need to better comprehend natural disturbance regimes at local and landscape scales is an improved understanding of the historical trajectories of resource development and land use at local and landscape scales, particularly as they pertain to water resources. Such historical information is essential before undertaking actions to "improve" or "restore" aquatic habitats or watershed functions (Natural Research Council 1992; 1996). Unfortunately, the large number of watershed councils that have recently emerged throughout much of the PNW are often faced with trying to project future watershed management needs based upon an imperfect understanding of natural watershed functioning and the effects of historical land uses.

Today's water resources issues and problems in the PNW increasingly involve multiple objectives and perspectives. Thus, in the coming years researchers may no longer have the luxury of working in isolation on narrowly defined water resources topics. Instead, interdisciplinary efforts that cross physical, biological, economic, and social subjects will be needed that involve more collaborative efforts in the scientific and research community. An important goal of such collaborative efforts will be the synthesis of research results and conclusions across disciplines for policy analysts and the general public. To be successful, a wide range of educational programs and research efforts will be needed to help society understand, manage, and conserve water resources of the PNW during the 21st century.

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Contributions of Watershed Management Research to Ecosystem-Based Management in the Colorado River Basin

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Abstract.—The Rocky Mountains and Southwestern United States, essentially the Colorado River Basin, have been the focus of a wide range of research efforts to learn more about the effects of natural and human induced disturbances on the functioning, processes, and components of the regions's ecosystems. Watershed research, spearheaded by the USDA Forest Service and its cooperators, leads to a better understanding of the regions's ecology, and to the formulation of management guidelines to meet the increasing needs of people living in these regions and throughout the Western United States. This paper presents pertinent details of watershed research that has been accomplished in the Colorado River Basin two regions and to provides highlights of the research results.

Introduction

People's behavior throughout the West, particularly the Southwestern United States, was conditioned and circumscribed by the perennial shortage of water. The expected, but variable, supplies of surface water were quickly appropriated. Electricity and electric pumps enabled access to previously unavailable groundwater sources, while the favorable climate resulted in an increase in agriculture and urbanization. As a consequence, nearly all of the water supplied to this rapidly growing area was pumped from underground basins. This has caused a steady decline in regional water tables, which, in turn, has affected local economies. Many hectares that formerly supported agriculture have been abandoned, converted to housing developments, or switched to an alternate water source such as the Central Arizona Project, which became available in the late 1980s. However, the water situation, especially in heavily populated areas, has had little affect on people's water consumption, except for the farmer. As the cost of water increases, the farmer's income decreases. Eventually, the farmer is forced to stop farming, and either abandons or sells the land. The profit margin for the urban home owner is much higher. Consequently, Arizona has many human-made lakes, golf courses, and green lawns, and residents continue to demand more. Conversion of water previously used for agriculture, however, has the potential to sustain the growth of municipalities and industry into the future.

The combined surface and ground water supplies in the Colorado River Basin are generally adequate for current needs. However, growing demands and uses of water in this basin could soon result in a widespread water shortage. Local shortages already exist (Hibbert 1979). Barring conversion of saline water, additional importation of outside water, advancements in rainmaking, and rigorous conservation measures, residents must rely on the variable surface and diminishing groundwater supplies. In response, the initial direction of the research in the Colorado River Basin focused on investigating the potentials for increasing water yields from the region's forests, woodlands, and shrublands through vegetative manipulations (Baker 1999, Gary 1975, Leaf 1975, Martinelli 1975, and Sturges 1975). Numerous watersheds were instrumented with climatic and hydrologic measuring devices by the USDA Forest Service and its cooperators in the late 1950s and throughout the 1960s to study the effects of vegetative clearings, thinnings, and conversion of vegetation on water yields under controlled, experimental conditions.

Theoretically, the surface water supply in the Colorado River Basin could be increased by as much as 1/3 (0.7 million ha-m annually) if vegetation and snow on 16% (10.5 million ha) of the basin were manipulated solely to increase water yield (Hibbert 1979). However, other forest resources, economics, and social and environmental concerns would greatly reduce the treatment area and effectiveness of the increasing water yield.

Water-yield increases are greatest where large reductions can be made in water transpired by plants and evaporated from snow. Clearcutting and conversion of vegetation usually increase water yield significantly. These practices can be appropriate in several vegetation types, such as chaparral and mountain brush, where the commercial value of the vegetation is low. However, where clearcuts and type conversions are unacceptable management practices, the potential for increasing the water yield is less, although it can still be substantial.

Hibbert (1979) reports that water yield in the Upper Colorado River Basin could be increased by 61,650 ha-m per year, or 3.5%, by treating up to 22% of each vegetation type, except aspen (*Populus tremuloides*) where 40% would

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be treated. About half of the increase would come from subalpine forests including Douglas fir (*Pseudotsuga menziesii*). More extensive treatments in the Lower Colorado River Basin would be necessary to obtain an additional 30,825 ha-m annually, an 8% increase in water yield. About 92% of the total increase would be generated by treating about 20% of the chaparral and 33% of the ponderosa pine (*Pinus ponderosa*).

While information on the cost of producing extra water is incomplete, it is believed that the cheapest water (based on cost to produce the additional water) would come from commercial forests, where timber yields would pay for part of the treatment costs (Hibbert 1979). Water would be more expensive from vegetation conversion treatments, because most of the treatment costs would be levied against water production. Regardless, most of the water is expected to cost less than imported water, and some of the water from commercial forests would supplement and be in the price range of water produced by weather modification.

Colorado River Basin

The Colorado River drains nearly 650,000 km^2 (65 million ha) in 7 Western states before entering the Gulf of California in Mexico (Hibbert 1979). The basin includes virtually all of Arizona and portions of New Mexico, Colorado, Wyoming, Utah, Nevada, and California. The drainage area is divided into Upper and Lower Basins at Lee Ferry, about 16 km south of the Utah-Arizona border. The Upper Basin contains 28.3 million ha and the Lower Basin contains 36.4 million ha.

Upper Basin

Precipitation averages 400 mm annually in the Upper Basin, where it is concentrated in the mountains (Hibbert 1979). The proportion of precipitation yielded as streamflow is nearly 6 times greater in the Upper Basin (16% or 64 mm) than in the Lower Basin (3% or 10 mm). Precipitation and streamflow vary greatly from year to year. Annual yields from the Upper Basin at Lee Ferry have varied from 37% to 163% of the 83-year mean flow of 1.8 million ha-m (Hibbert 1997). Seasonally, flow is concentrated in a few months of each year when the snow melts.

Conifer forests, including spruce fir (*Picea-Abies*), lodgepole pine (*Pinus contorta*), Douglas fir, mixed conifer, and ponderosa pine, cover nearly 6 million ha of the Colorado River Basin (Hibbert 1979). Subalpine forests of spruce fir, lodgepole pine, and Douglas fir occupy some 2.8 million ha in the Upper Basin. The elevations of these forests varies from 2,100 to 3,500 m, just below the alpine zone. The climate is cool and moist; mean temperature is near freezing. Precipitation is about 2/3 snow and averages from 500 to 1,400 mm/year. Water yield, largely from snowmelt, varies from 130 to 1,000 mm/year. Basin-wide, average precipitation in the subalpine forest is estimated at 700 to 760 mm and streamflow at 300 to 380 mm.

Ponderosa pine occupies about 0.6 million ha in the Upper Basin. The elevation range for ponderosa pine is between 1,850 and 2,750 ft, where the type grows best on sites that are warmer and drier than those occupied by mixed conifer and subalpine forests. Gambel oak and chaparral species are common understory plants in the lower fringe area of the pine. Annual precipitation is about half snow and averages from 380 to 635 mm. Water yield is mostly from snowmelt and averages 50 to 150 mm annually, depending on precipitation, elevation, and soils.

Quaking aspen occupies approximately 1.3 million ha in the Colorado River Basin, nearly all of it in the Colorado and Utah portions of the Upper Basin (Hibbert 1979). The aspen type is recognized for its multiple values of wood, livestock forage, wildlife habitat, watershed protection, recreation, and esthetics. Aspen is commonly found between 2,100 and 3,000 m in elevation in clumps to extensive stands interspersed among conifers of the subalpine, mixed conifer, and cooler portions of the ponderosa pine type. Precipitation averages 500 to 1,000 mm, half or more of it is snow. Water yield averages 70 to 130 mm in the Lower Basin but can reach 500 mm in the Upper Basin.

Mountain brush lands are extensive only in the Upper Basin, where they are found on about 1.3 million ha (Hibbert 1979). Gambel oak (*Quercus gambelii*), mostly in brush form, growing 0.6 to 3.7 m high in clumps or thickets, is the predominant species. Associated shrubs that sometimes dominate the site are chokecherry (*Prunus* spp.), serviceberry (*Amelanchier* spp.), snowberry (*Symphoricarpos* spp.), big sagebrush (*Artemisia tridentata*), mountainmahogany (*Cercocarpus* spp.), and other woody species. Though sometimes classified as chaparral, and similar in appearance, the mountain brush type differs in that most of the species are deciduous and, therefore, are active only in the summer. Mountain brush is commonly found at 1,500 to 3,000 m in elevation on relatively warm, dry exposures. Average annual precipitation ranges from 400 to 600 mm, less than half of it falling as snow. Water yield of 25 to 150 mm is expected.

Big sagebrush, found on some 10.5 million ha in the Colorado River drainage area (Hibbert 1979, Sturgis 1975) thrives over a broad range in elevation and climate. Big sagebrush is found at elevations up to 3,000 m and is well adapted to warm, dry growing seasons at lower elevations. Precipitation varies from 200 to 500 mm. Water yield is less than 25 mm on most sagebrush lands. However, where precipitation exceeds 350 mm, yield can reach 75 to 100 mm on the wettest sites. The relocation of snow by winter winds and the resulting water loss by sublimation are important features of this type.

The pinyon-juniper ecosystem occupies some 13 million ha in the Colorado River Basin (Hibbert 1979). Principal species are Utah (*Juniperus osteosperma*), Rocky Mountain (*J. scopulorum*), one seed (*J. monosperma*), and alligator juniper (*J. deppeana*) , and Colorado and single leaf pinyon pine (*P. edulis* and *P. monophylla*) The type is most commonly found in the foothills, low mountains, and low plateaus between 1,200 and 2,300 m in elevation. Though normally considered low in commercial value, the pinyon-juniper type is an important source of forage for livestock, food and cover for wildlife, and for various products such as fence posts, firewood, pinyon nuts, and Christmas trees. Extensive pinyon-juniper control programs have been conducted in the Lower Basin.

Pinyon juniper occupies 5.1 million ha in the Upper Basin. Precipitation averages 300 to 460 mm, with local areas receiving up to 500 mm. Winter rains and snow provide the bulk of the moisture. Water yield is generally less than 25 mm, although some of the better watered sites can approach 75 mm.

Lower Basin

The Lower Basin receives an average of 330 mm of annual precipitation; the Upper Basin receives 400 mm annually (Hibbert 1979). The proportion of precipitation yielded as streamflow is 3% or 10 mm, nearly 6 times less than streamflow in the Upper Basin.

The Lower Basin is characterized by a cyclic climatic regime of winter precipitation, spring drought, summer precipitation, and fall drought (Baker 1999). Winter precipitation, often snow at higher elevations, is associated with frontal storms moving into the region from the Pacific Northwest. Surface thermal heating in the winter is less pronounced than in the summer, upslope air movement is relatively slow, cloudiness is common, and precipitation tends to be widespread and relatively low in intensity.

The major source of moisture for summer rains is the Gulf of Mexico. This moisture moves into the region from the southeast and passes over highly heated and mountainous terrain, where it rises rapidly, cools, and condenses. Summer storms, therefore, are primarily convectional, often intense, and usually local rather than widespread. Summer rains typically begin in early July, breaking the prolonged spring drought and providing relief to the hot weather of June and July.

Mixed conifer forests in the Lower Basin occupy sites that are wetter and cooler than those usually occupied by pure stands of ponderosa pine. These sites are warmer, but not necessarily drier, than subalpine forest sites to the north. The most common overstory species are Douglas fir, ponderosa pine, white fir (*Abies concolor*), Engelmann spruce (*Picea engelmannii*), aspen, southwestern white pine (*P. strobiformis*), blue spruce (*P. pungens*), and corkbark fir (*A. lasiocarpa var. arizonica*). Most of the mixed conifer stands are found between 2,100 and 3,000 m elevation. These mixed conifer forest occupy nearly 160,000 ha. Precipitation averages 630 to more than 760 mm / year and is usually in excess of potential evapotranspiration; half or more of the precipitation falls as snow (Hibbert 1979). Streams originating in this area above 2,900 m in elevation are often perennial, while those originating in low elevation mixed conifer forests (2,400 to 2,900 m) are mostly intermittent. Water yield averages 75 to 130 mm, sometimes more on the wettest sites; 3/4 or more of it is from snowmelt.

Ponderosa pine occupies 2.4 million ha in the Lower Basin (Hibbert 1979). Elevation range for ponderosa pine forests is between 1,800 and 2,700 m, where the type grows best on sites that are warmer and drier than those occupied by mixed conifer and subalpine forests. Gambel oak and chaparral species are common understory plants in the lower fringe areas of the pine. Annual precipitation is about half snow and averages from 500 to 630 mm in the Lower Basin. Water yield is mostly from snowmelt and averages 50 to 150 mm annually, depending on precipitation, elevation, and soils. The overall average water yield from ponderosa pine in the Colorado River Basin is 75 to 100 mm.

Pinyon-juniper vegetation occupies 8.1 million ha in the Lower Basin. Summer rains account for half or more of the precipitation. Evapotranspiration rates are relatively high in the growing season and only during the coldest months of December through February is precipitation greater than evapotranspiration. Water yield is generally less than 25 mm, although on some of the wetter sites it can approach 75 mm.

The chaparral type is restricted almost entirely to the Lower Basin, where it covers about 1.4 million ha, nearly all in Arizona (Hibbert 1979). Unlike the mountain brush in Colorado and Utah, chaparral species tend to be low-growing shrubs with thick, evergreen leaves well adapted to heat and drought. The type is common on rugged terrain from 900 to 2,000 m in elevation. Shrub live oak (*Q. turbinella*) is most abundant, followed by mountainmahogany. Other common shrubs are manzanita (*Arctostaphylos* spp.), Emory oak (*Q. emoryi*), silktassel (*Garrya wrightii*), desert ceanothus (*Ceanothus greggii*), and sugar sumac (*Rhus ovata*). Most species sprout prolifically from root crowns after burning or cutting and are difficult to eradicate.

Chaparral shrublands occur on rough, discontinuous, mountainous, terrain south of the Mogollon Rim in central Arizona. Average annual precipitation varies from about

380 mm at the lower limits to over 630 mm at the higher elevations (Hibbert 1979). Approximately 60% of the annual precipitation occurs as rain or snow between November and April. The summer rains fall in July and August, which are the wettest months of the year. Annual potential evaporation rates can approach 900 mm. Water yield varies greatly depending on precipitation, elevation, and soils. The overall average is 25 mm or more; the lower, drier sites produce little, while the wettest sites can yield 75 or 100 mm.

The desert shrub zone in Arizona, an area of about 14.5 million ha, includes the northern and southern desert shrub type (Ffolliott and Thorud 1975). The delineation between desert shrub and the adjacent grassland vegetation is indistinct on many sites due to the invasion of the grasslands by the desert shrubs. The northern desert shrub type (see the sagebrush type description in the Upper Basin section) is largely confined to elevations between 750 and 1,500 m north of the Colorado and Little Colorado Rivers. The southern desert shrub type occurs mainly in southwestern third of Arizona, at elevations from about 50 to 900 m. This type extends upward into the desert grassland type, often invading these grassland ranges, possibly as the result of the exclusion of fire and depletion of grass stands.

Overstory species of the desert shrub type include numerous shrubs and cacti. The composition and density of these overstories are dependent upon climatic patterns, edaphic factors, and imposed land management practices. Pure stands of big sagebrush are common throughout the northern desert shrub type (Ffolliott and Thorud 1975). Another characteristic shrub of this type is blackbrush (*Coleogyne ramosissima),* fourwing saltbrush (*Atriplex canescens*), and winterfat (*Eurotia lanata*). The most common dominant shrubs in the southern shrub type include creosote (*Larrea tridentata)*, paloverde (*Cereidium* spp), and cacti (*Carnegiea gigantea* and *Opuntia* spp). The occurrence of these shrubs and cacti is often controlled by soil texture, permeability, presence of alkali, caliche, and other influences. Other shrubs found within this type are catclaw acacias (*Acacia greggii*), bur-sage (*Franseria deltoidea*), mesquite (*Prosopis juliflora*), tarbrush (*Flourensia cernue*), and ocotillo (*Fouquieria spendens*).

Average precipitation in the northern desert shrub type is about 250 mm annually, with a general range of 125 to 350 mm (Ffolliott and Thorud 1975). Depending upon the exact location, precipitation between June and September can approach, or slightly exceed, 50% of the annual amount. Annual precipitation in the southern desert shrub type varies from 75 to 300 mm, but averages about 150 mm. On the Santa Rita Experimental Range in south central Arizona, about 60% of the annual precipitation amount commonly comes between July and the end of September, with no effective precipitation expected in April, May, and June.

Upstream riparian areas consist of vegetation along streams that drain to the Colorado River, and its major tributaries. Total area occupied by these bands of vegetation exceeds 40,500 ha in the Lower Basin (Hibbert 1979). No acreage figure is available for the Upper Basin. Common riparian trees and shrubs are cottonwood (*P. fremontii*), willow (*Salix* spp.), sycamore (*Platanus wrightii*), and alders (*Alnus tenuifolia*). Native herbaceous species include sedges (*Carex* spp.), spike rushes (*Eleocharis* spp.), rushes (*Juncus* spp.), and bulrushes (*Scirpus* spp.) (Medina 1996). Elevations range from about 300 to over 3,000 m. Estimates of potential evapotranspiration for the lowest elevations are as high as 1.8 m / year. These upstream riparian areas are of special interest because they are areas of heavy water consumption, conveyance systems for water yield generated on upstream watersheds, areas of high scenic value, and high value areas for wildlife and recreation.

Multiple Use Research

Water has historically affected populations occupying this region. Water related activities have been documented since about 200 B.C., when Hohokam Indians settled the Salt River Valley in central Arizona and constructed canals to irrigate their fields (Baker 1999). European settlers in the Phoenix, AZ area in the late 1860s depended on irrigation water from the Salt River for agriculture. However, water supplies fluctuated greatly because the river often flooded in the winter and dried up during the summer. There were no impoundments to store water for the dry seasons. Therefore, the Salt River Water Users' Association, the largest irrigation district in Arizona, signed an agreement in 1904 with the United States government under the National Reclamation Act, to build a dam on the Salt River below the confluence with Tonto Creek. The Roosevelt Dam, the first of 6 dams on the Salt and Verde Rivers, was completed in 1911. Watershed managers in the early 20th century became concerned that erosion on the adjacent and headwater watersheds of the Salt River would move sediment into the newly constructed Roosevelt Reservoir, which would decrease its capacity. Measurements indicated that 12,450 ha-m of coarse granitic sediments accumulated behind Roosevelt Dam between 1909 and 1925 (Baker 1999). Because of the concern about these sediment accumulation, the Summit Plots were established in 1925 by the USDA Forest Service 24 km upstream from Roosevelt Dam to study the effects of vegetation recovery from livestock grazing (the dominate land use at the time), mechanical stabilization of disturbed soil, and reseeding on stormflow and sediment yields from the lower chaparral zone (Rich 1961).

The early research on the Summit Plots was expanded to consider the effects of watershed management practices on all the region's natural resource products and uses of the forests, woodlands, and shrublands. The USDA Forest Service and its cooperators began to thoroughly evaluate the effects of vegetative manipulations on the array of multiple uses from the ecosystems studied. Results from this research show that vegetation can often be managed to increase water yields, while still providing timber, forage, wildlife, and amenity values required by society in some optimal combination. This finding was not surprising, as many of the vegetation management practices studied to improve water yield were common in principle and application to other management programs often implemented to benefit other natural resources.

Research Findings

Summaries of important findings about the contributions of watershed research to multiple-use, ecosystem-based management in the Colorado River Basin follow. Additional details are in the cited literature.

Subalpine Forests

The original water-balance study in the United States was done on 2 watersheds at Wagon Wheel Gap on the headwaters of the Rio Grande in southwestern Colorado (Bates and Henry 1928). Streamflow was measured from 1911 to 1919, and then one watershed was clearcut. Of 530 mm of annual precipitation falling on these watersheds, about 150 mm was returned as streamflow, with almost 380 mm lost to evapotranspiration. Following the clearcut treatment, evapotranspiration was reduced and flow increased an average of about 25 mm. Bates and Henry concluded that much of the observed increases in flow came from net reduction in winter losses, and that reduction in overstory transpiration was offset by increased understory transpiration and ground evaporation.

A status-of-knowledge publication presented a discussion of the forest hydrology and an in-depth discussion and review of studies about the effects of watershed management practices on snow accumulation, melt, and subsequent runoff in subalpine forests (Leaf 1975). Many of the water-balance studies in the spruce fir and lodgepole pine forest were done on the Fraser Experiment Forest in north central Colorado. Simulation models designed to predict the hydrologic impacts of timber harvesting and weather modification on water yields were also addressed. Information presented in this publication was later updated by Troendle et al. (1987). Important finding for the subalpine-fir type included:

- The potential is good for increasing water yield in the subalpine type by managing for snow redistribution and transpiration reduction in small forest openings (Hibbert 1979, Leaf 1975). Increases in water yield of from 25 to 75 mm can be expected, depending on site factors and management strategies.
- Suggested harvest procedures in lodgepole pine is a series of patch cuts, 5 to 8 tree heights in diameter, each covering about 1/3 of the planning unit. The cuts would be made at 30-year intervals over a planning period of 120 years with periodic thinning in the regenerated stands.
- The harvest procedures for spruce fir is similar to lodgepole pine, except that the patch cuts would be made at 50-year intervals. Patch cutting in much of the Rocky Mountain area is considered ecologically sound if the management objective is to maintain the spruce-fir ecosystem (Alexander 1974).

Mountain Brush

There has been an insufficient amount of research in the mountain brush type to accurately predict how treatment will affect water yield (Hibbert 1979). However, results from plot studies in Utah (Johnson et al. 1969) suggested that responses to brush conversion might be less than in the chaparral type of the Lower Basin. A rough estimate is 25 to 75 mm of additional water from type conversion. If shrub regrowth is not controlled, the increase will be short-lived; probably about 3 to 5 years. It is also difficult to estimate the amount of mountain brush that would be converted to grass, in view of other resource values and social and economic factors that should be considered in resource management decisions.

Big Sagebrush

The potential for increasing water yield in big sagebrush is poorly defined, although type conversion on favorable sites might increase yield by 15% or up to 13 mm (Hibbert 1979, Sturges 1975). Additional increases of 25 mm or more might be possible by trapping blowing snow behind snow fences in areas where the winter snow water equivalent is at least 200 mm (Tabler 1975).

Mixed Conifer Forests

Research on mixed conifer watersheds at Workman Creek on the Sierra Ancha Experimental Forest in central Arizona (Lower Basin) demonstrated that increases in stream flow could be obtained by replacing the trees with a grass cover on large and strategically located parts of a watershed or by greatly reducing overstory densities (Baker 1999). However, many of these treatments compromised other resource sustainability. Additional research by the USDA Forest Service expanded its watershed program in mixed conifer and high elevation ponderosa pine forests to the White Mountains of eastern Arizona in the late 1950s and early 1960s. Major experiments in the White Mountains were designed to confirm results from Workman Creek experiments and to test multiple-use forest management treatments.

A status-of-knowledge publication presented the early results of water-yield improvement experiments and other research conducted on the watersheds in the mixed conifer forests through the early 1970s (Rich and Thompson 1974). This publication reported on the opportunities for increasing water yields and other multiple use values in mixed conifer forests. Many of these results were later refined and, in some cases, expanded upon and subsequently reported in other publications (Baker 1999). For example:

- Treatment of mixed conifer vegetation can result in water yield increases that have remained constant for 13 years on Workman Creek (Baker 1999). Treatments included both moist-and-dry-site clearcuts and single-tree selection prescriptions.
- There were minor changes in sediment yields, but a wildfire on the South Fork of Workman Creek had a greater effect on soil movement than the timber harvesting treatments.
- Using management strategies similar to those described for subalpine forests, the potential for increasing water yield in the mixed conifer forests is estimated to be about 25% less than in the subalpine, although large clearcuts appear to give greater increases in the mixed conifer (Hibbert 1979). In the drier, warmer climate of the mixed conifer forests, more of the response is attributed to reduction in transpiration and less to redistribution of snow. Increases in water yield of 75 to 100 mm are possible from clearcutting (Rich and Thompson 1974). However, without type conversion to an herbaceous cover, the increases would decline as the forest regrows. The overall estimate is a 40 mm average increase from maintaining about 1/3 of the area in small openings on sites where streamflow normally averages 100 to 125 mm.

Ponderosa Pine Forests

A status-of-knowledge publication presented the early results of water-yield improvement experiments and other research conducted on the pilot watersheds in ponderosa pine forests on the Beaver Creek Watershed (Brown et al. 1974). These results were refined and expanded upon in subsequent publications listed in an annotated bibliography of 40 years of investigations on the Beaver Creek watershed (Baker and Ffolliott 1998). Watershed management problems and opportunities for the Colorado Front Range ponderosa pine were also addressed by Gary (1975). Results of findings for the ponderosa pine forest type include:

- The potential for increasing water yield in ponderosa pine is less than from other commercial forest types, presumably because the pine forests are drier. Short-term (3 to 10 yr) increases of 25 to 75 mm can be expected from clearcutting ponderosa pine with basal area in excess of 23 m^2/ha.
- Under a multiple use management framework, where timber, range, wildlife, recreation, and water are all considered in the product mix, the long-term increases of 2 to 25 mm are a more realistic expectation (Brown et al. 1974). Low to intermediate stocking levels on approximately 2/3 of the ponderosa pine sites (Schubert 1974) can preclude water increases from these areas regardless of the management emphasis, except for clearcutting.
- No meaningful changes in total sediment production or water quality occurred as a result of the treatments applied in ponderosa pine forests. Average sediment production from untreated pine areas was 45 kg/ha and increased to 225 kg/ha after the clearing treatment (Brown et al. 1974). Relationships between the amount of sediment in suspension and streamflow discharge differed among the treated watersheds (Lopes et al. 1996). The highest sediment concentrations occurred after clearcutting, followed by stripcutting, thinning by group selection, and the combined shelterwood-seed tree silvicultural treatment. While changes in suspended sediment concentration are significantly different following treatment, these concentration are relatively low (generally less than 100 mg/l).

- Repeated inventories of the pine timber resource indicate that volume production has often been sustained, although at generally lower levels than those represented by pretreatment conditions (Baker 1999). Exceptions to this finding were found on a watershed that was totally clearcut in 1966 and 1967, and on a watershed that had been converted from ponderosa pine forest to grass in 1958 and subsequently subjected to livestock grazing in the spring and fall starting in 1968. While these 2 watersheds, particularly the watershed cleared in 1966 and 1967, have Gambel oak and alligator juniper growing on them, the areas have been withdrawn from pine production.

- Reductions in the density of ponderosa pine forest overstories have generally resulted in increases in the production of herbaceous plants (Baker 1999) and vice versa. These increases can approach 560 kg/ha after complete overstory removal including forage and non-forage plants. The untreated pine areas produced 225 kg /ha.

- Reducing densities of ponderosa pine forests have increased food for deer and elk, while retaining protective cover (Larson et al. 1986). Total clearcutting is detrimental to big game and Abert squirrel, although cottontail habitat can be enhanced when slash and Gambel oak thickets are retained.

- Fire can be prescribed to consume portions of the accumulation of dead organic material on mineral soil, impacting the hydrologic behavior of the burned site (Ffolliott and Guertin 1990). Burning the *L* layer (unaltered organic material), the *F* layer (partly decomposed organic material), and into the *H* layer (well decomposed organic material) affects postfire infiltration rates and erosion potentials. Other effects of fire can include thinning forest overstories from below, increasing seedling establishment, increasing production of herbaceous plants, and temporarily reducing fire hazard. Wildfire of moderate severity can have similar effects as observed with prescribed fire. However, wildfire of high severity often burns the forest floor to the mineral soil and induces a water-repellent layer in sandy soils (Campbell at el. 1977). The reduced infiltration rates can increase surface runoff from the burned site, causing soils to erode and removal of nutrients that have been mineralized. All small trees and many large trees can be killed, resulting in large increases in herbage.

- Public responses to vegetative treatments applied to the Beaver Creek watersheds were variable. Through applications of Scenic Beauty Estimation (SBE), which provides quantitative measures of esthetics preferences for alternative landscapes , the more natural-appearing watersheds were preferred by most publics (Baker 1999). This conclusion adds weight to the often heard, but seldom substantiated, claim that "naturalness" is a desirable forest landscape characteristic.

- Information obtained on resources in the ponderosa pine forests provided a framework for developing models to simulate the responses of natural resources to the treatments applied to the Beaver Creek watersheds, and production functions describing the trade offs among the affected natural resources. This work resulted in a variety of publications related to hydrology, vegetation, and wildlife responses (Baker 1975, Bojorquez-Tapia et al. 1990, Brown and Daniel 1984, Ffolliott 1985, Ffolliott and Guertin 1988, Larson 1975, Larson et al. 1979, Li et al. 1976, O'Connell 1971, Rogers 1973, Rogers et al. 1982). A complete listing of publications on modeling and simulation techniques is found in Baker and Ffolliott (1998).

- Results from the Beaver Creek Watershed project were obtained on watersheds located on volcanic soils along the Mogollon Rim. The literature suggests that similar results might be obtained on volcanic soils elsewhere in the Southwest. However, extrapolation of the results from Beaver Creek to sites on sedimentary soils requires prior validation (Ffolliott and Baker 1977).

Additional watershed-related research in the ponderosa pine forests of the Colorado River Basin were obtained from Castle Creek in eastern Arizona (Baker 1999) and from the Colorado Front Range (Gary 1975). The Colorado Front Range, generally regarded as the eastern foothills of the Rocky Mountains, extends from southern Wyoming to Canon City, Colorado. Results from an irregular, block, harvesting treatment on a predominately ponderosa pine watersheds were:

- An average water yield increase of 30% (13 mm) remained stable for 20 years after the treatment. The initial increase in water yield was attributed to reduced evapotranspiration and increased snow accumulations in the openings. This posttreatment water regime was probably because new tree roots had not fully occupied the soil mantle, and the height differences between the residual trees surrounding the openings and the regeneration continued to provide aerodynamics that favored increased snow accumulations in the openings (Baker 1999).

- No increase in water yields occurred after a prescribed burn. This was expected because the fire did not affect the forest overstory conditions or consume much of the forest floor.

For the Colorado Front Range pine type:

- Clearcut openings are necessary to significantly increase water yields (Gary 1975).
- Minimal water increases can be expected on grazed lands with adequate soil cover and highly permeable soil.
- Problems with the chemical and bacteriological quality of water due to expanding foothill communities, indicates a need for careful land use planning and wise use of the forest and forage resources.

Pinyon-Juniper Woodlands

Another state-of-the-art paper from research from the Beaver Creek Watershed described the effects of removing pinyon-juniper woodlands on natural resource products and uses (Clary et al. 1974). These results are listed in an annotated bibliography of 40 years of investigations on the Beaver Creek watershed (Baker and Ffolliott 1998). Finding include:

- The potential for increasing water yield in the pinyon-juniper type is negligible on most sites (any sites receiving less that 450 mm of precipitation/year), although small increases (less than 13 mm) are possible by type conversion on the wettest sites (Hibbert 1979). Overall, the potential for increasing water yield is considered poor for pinyon-juniper sites.
- Cabling resulted in increased suspended sediment concentrations at specified streamflow discharges, while the herbicide treatment did not cause a change (Lopes et al. 1996). Soil disturbances during the uprooting of trees by cabling was believed responsible for the increased sediment concentration. While sediment concentrations are significantly different following treatment, they are relatively low (generally less than 5 mg/l). Average sediment production in untreated areas was 225 kg/ha. Water quality (nutrients) remained unchanged following conversion.
- Herbage production, generally lower in the pinyon-juniper woodlands than in the ponderosa pine forests, increased several-fold as a result of the conversion treatments (Baker 1999). The value of this increase for livestock or wildlife is variable, however. It is likely that the levels of increased herbage production will slowly decline as the pinyon-juniper overstory becomes reestablished.
- Big and small game species dependent on pinyon-juniper trees for forage and cover generally decline as a consequence of conversion treatments. However, cottontails can increase, providing that a sufficient canopy cover remains (Ffolliott 1990). Overstory-dependent, non-game birds leave after treatment. These species are replaced by ground-feeding species.

Chaparral Shrublands

An earlier status-of-knowledge publication presented the results of increasing water yields and other multiple use values in chaparral shrublands through the early 1970s (Hibbert et al. 1974). These results were refined and expanded upon in subsequent publications (Baker 1999):

- The potential for increasing streamflow by type conversion of chaparral is good on favorable sites where precipitation averages 500 mm or more (Hibbert 1979). The key to increasing water yield is the replacement of deep-rooted shrubs with shallow-rooted grasses and forbs that use less water. The average is 100 mm increase in water yield in areas receiving 560 mm of average precipitation.
- Some discounting or reduction in potential water yield increases is necessary before extrapolating results to larger areas where conversions may not be as intensive, continuous, or as well maintained as on experimental watersheds. Some of the increased flow will also be lost to riparian vegetation downstream before it reaches storage or points of use. Therefore, the average increase expected downstream from type conversion is estimated to be about 2/3 of the on-site increase or 60 mm (considered average for treatable chaparral).
- Further discounting of potential water-yield increases is necessary for the exclusion of wilderness areas, sites too dry and open (cover density less than 30%), slope steepness, and operational restrictions or geographic location (chaparral on slopes of isolated mountain ranges). These factors

would reduce treatable acreage to 1 ha in 5. Therefore, use of 20% of the acreage (146,000 ha) and the 60-mm increase in water yield is probably the most optimistic potential attainable by large-scale management efforts in chaparral (Hibbert 1979).

Semi-Desert Shrublands

Owing to the relatively low precipitation input and high evaporation potential of the desert shrub type, it is the least important water-yielding area in the Colorado River Basin. In evaluating water-yield potential for this vegetation type as an entity in the lower basin (both the northern and southern desert areas) water-yield averages of between 1 and 8 mm have been reported, but these amounts are highly variable from year to year (Ffolliott and Thorud 1975).

The USDA Agricultural Research Service has maintained the Walnut Gulch Experimental Watershed in southeastern Arizona as a research facility to quantify the influence of upland conservation practices on downslope water supplies since the middle 1950s (Goodrich et al. 1994). Situated in the transition between the Chihuahuan and Sonoran Deserts, the Walnut Gulch Experimental Watershed is part of a national effort to establish highly instrumented watersheds in the primary hydro-climatic regions of the United States. The extensive hydrologic network and the data- and knowledge-bases from Walnut Gulch have had far-reaching impacts on development of semidesert shrubland water management and technology (Goodrich and Simanton 1995). Some of the contributions from the research efforts at Walnut Gulch to the general knowledge of watershed management in semidesert shrubland environments include:

- Quantification of the spatial and temporal variability of precipitation and development of design-storm characteristics used for design and construction purposes throughout the Southwest.
- Quantifying the role of stream-channel transmission losses in water balance relationships of semidesert shrubland watersheds.
- Development of flood-frequency relations for ephemeral streams used for design and construction purposes in the Southwest.
- Quantifying the impacts of ephemeral streams on sedimentation and groundwater recharge.
- Determining the consequences of possible climatic change on soil, water, and plant resources characterizing semiarid environments.

Research in recent years has included natural resource models developed from Walnut Gulch data bases into user-friendly decision-support systems to analyze alternative watershed management practices for the efficient and sustainable use of water and soil resources in semiarid environments (Renard et al. 1993). These decision-support systems facilitate selection and analysis of watershed management practices designed to optimize resource use while maintaining the integrity of the fragile ecosystems in these environments.

Riparian Ecosystems

The potential for increasing water yield in the upstream riparian areas can be greater per unit area than for any other vegetation type in the Colorado River Basin (Hibbert 1979). That is:

- Water-yield increases from 150 to 610 mm appear possible when riparian vegetation is eradicated along permanently flowing streams (Horton and Campbell 1974). However, extensive removal of trees and shrubs from these areas would impair scenic and recreation values, adversely affect channel stability, and destroy some of the most productive wildlife habitat in the river basin.
- Less than complete removal of trees and shrubs would reduce the water savings potential. Thus. it appears unlikely that upstream riparian areas can be counted on for significant augmentation of the water supply.
- Although there is a public perception that riparian areas are fragile, current information indicates, that riparian ecosystems can be resilient. Although much of our Southwestern riparian areas were destroyed around the turn of the century (1890), these areas had been exposed to thousands of head of cattle for years (1880s to 1900s), severe logging practices, and characteristic periods of drought and flooding (Cooperrider and Hendricks 1937).
- Many riparian areas are functioning “at risk” because of external stresses (overgrazing, drought, and flooding) that have caused the system to loose its dynamic equilibrium (Baker and Medina 1997). However, once this stress is relieved, many riparian systems regain their equilibrium within a few years because of the resiliency of the native riparian plants.
- Although expensive, engineering activities, such as use of instream structures, channelization, bank

modification, and rip-rap, can be used to provide flood control, irrigation development, and wetland conversion, many restoration projects have actually resulted in further site degradation and reduction in the condition of the affected streams (Baker 1999). Often, the importance of the interactions between the riparian and aquatic systems are not recognized as an integral factor in maintaining productivity of the system. Channel systems are continually adjusting to varying flows and sediment loads, which is not always compatible with placement of fixed structures.

- Aquatic vegetation allows the stream to function naturally and provides resiliency to a variety of environmental conditions.
- Restoration of a degrading channel system often only requires the reestablishment or placement of riffle bars and grazing control for a few years (Baker 1999). Riffle bars slow down the water velocities, reduce or terminate channel downcutting, and provide spawning habitat. Removal of the grazing stress allows the aquatic plants to regain vigor, and their functioning ability to detain flood flows and trap sediments and nutrients.

Management Implications

Watershed-research in the vegetation types of the Colorado River Basin has mostly evolved from single resource evaluations (e. g., increased water yield) to evaluations that consider the multiple benefits of from vegetation management treatments. Research has determined that vegetation can often be managed to increase water yields, while providing timber, forage, recreation, wildlife, and other amenities. However, one question should be answered: To what extent can the established research framework and available data bases be used to meet future management-oriented informational needs in the Colorado River Basin? Long-term monitoring and evaluations, based on reinventories of permanently-located sampling units on the study sites, represent a valuable use of the cumulative research efforts. A better framework for conservation and the sustainable use of the region's natural resources should evolve from the evaluations obtained.

Repeated measurements of permanent inventory locations provide a basis for long-term monitoring and evaluations, which are central to almost every important ecological concept and environmental issue (Franklin 1989). Information from these measurements allows a look at the "big picture" of how ecosystems might respond to disturbances resulting from climatic change, habitat fragmentation, or invasions of exotic species. Information of this kind is becoming increasingly important in developing a holistic, more coherent view of how ecosystems function (Baskin 1997).

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Basin of Mexico: A History of Watershed Mismanagement

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Abstract.— Mexico City Metropolitan Zone (MCMZ) is located within the Basin of Mexico. Because of its large population and demand for natural resources, several authors have questioned the viability of the city, especially in terms of water resources. These are reviewed at the regional and the local scales. It is concluded that a multi-basin management approach is necessary to integrate a water management strategy capable to meet near future challenges in water demand by the MCMZ.

Introduction

Humans have occupied the Basin of Mexico for about 2,000 years. The long-term history of the basin is one of growth, collapse, and cultural rebirth and reorganization. The causes of such changes are rooted on depletion of local supplies of natural resources and dependance on resources imported from other regions (Aguilar et al. 1995).

At present, the Mexico City Metropolitan Zone (MCMZ) is one of the largest megalopolis on Earth. It extends over the Federal District, and neighboring municipalities in the state of Mexico (figure 1); it concentrates 25% of the population in the country, and a 40% of the national gross product. Widespread land cover transformation is occurring at a rapid rate due to urban growth, deforestation, agriculture, and ranching. Competition for available land and water resources is likely to generate environmental conflicts (*sensu* Crowfoot and Wondolleck 1990) among the different stakeholders of the MCMZ and neighboring river basins.

Perhaps, water will be the limiting natural resource for a sustainable development of Basin of Mexico. According to Downs et al. (in press), existing water resources will be insufficient for the needs in the year 2015, so additional sources will have to be developed. On the other hand, other threats to the MCMZ are silting up of the drainage system, and citywide flooding resulting from deforestation (Ezcurra and Mazari-Hiriart 1996).

In this paper, we examine water management issues in the MCMZ at two scales: (1) regional, encompassing the Basin of Mexico and neighboring watersheds; and (2) local, focusing in the mountain ranges located within the conservation land of the Federal District. The two scales are needed for devising the needed sensible strategies towards integrated assessment and management of water resources.

MCMZ is in one sense an ongoing experiment. Clearly, a watershed management approach is needed for a more sensible use of the natural resources and to avoid an environmental crisis in the Basin of Mexico and neighboring river basins. Nonetheless, the problems of the MCMZ are not unique. The combination of natural resource constraints, environmental impacts, and the incapacity of governments to respond and solve rather complex problems can be found in both developed and developing countries.

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Basin of Mexico

Natural Setting

The Basin of Mexico is located at the southern end of the Mexican *Meseta Central*, along the Transverse Neo-volcanic Axis. It covers an area of 7,500 km^2 and encompasses the Federal District and parts of the states of Mexico, Hidalgo, Tlaxcala, and Puebla (figure 1).

The basin originated from late volcanic activity and upland formation. As lava and ash deposits closed the natural drainage outlets to the south, volcanic ridges built up around the eastern, southern, and western margins of a central lacustrine depression (Sanders 1979). At present, the basin is an elevated plain (2,240 m above sea level) bounded by high mountain ranges: Sierra Nevada to the east, which is formed by Popocateptl and Iztaccihuatl, the highest volcanoes of the basin (5,465 m and 5,230 m, respectively); Sierra de Las Cruces (4,000 m) to the west; Sierra Chichinautzin (4,500 m) and Sierra del Ajusco (4,000 m) to the south; and a series of low discontinuous ranges and to the north (Los Pitos, Tepotzotlan, Patlachique, Sierra Guadalupe and Sierra Santa Catarina).

The location of the Basin of Mexico along the Transverse Neo-volcanic Axis constitutes a boundary fringe between the Neartic and Neotropical biogeographic regions. Addi-

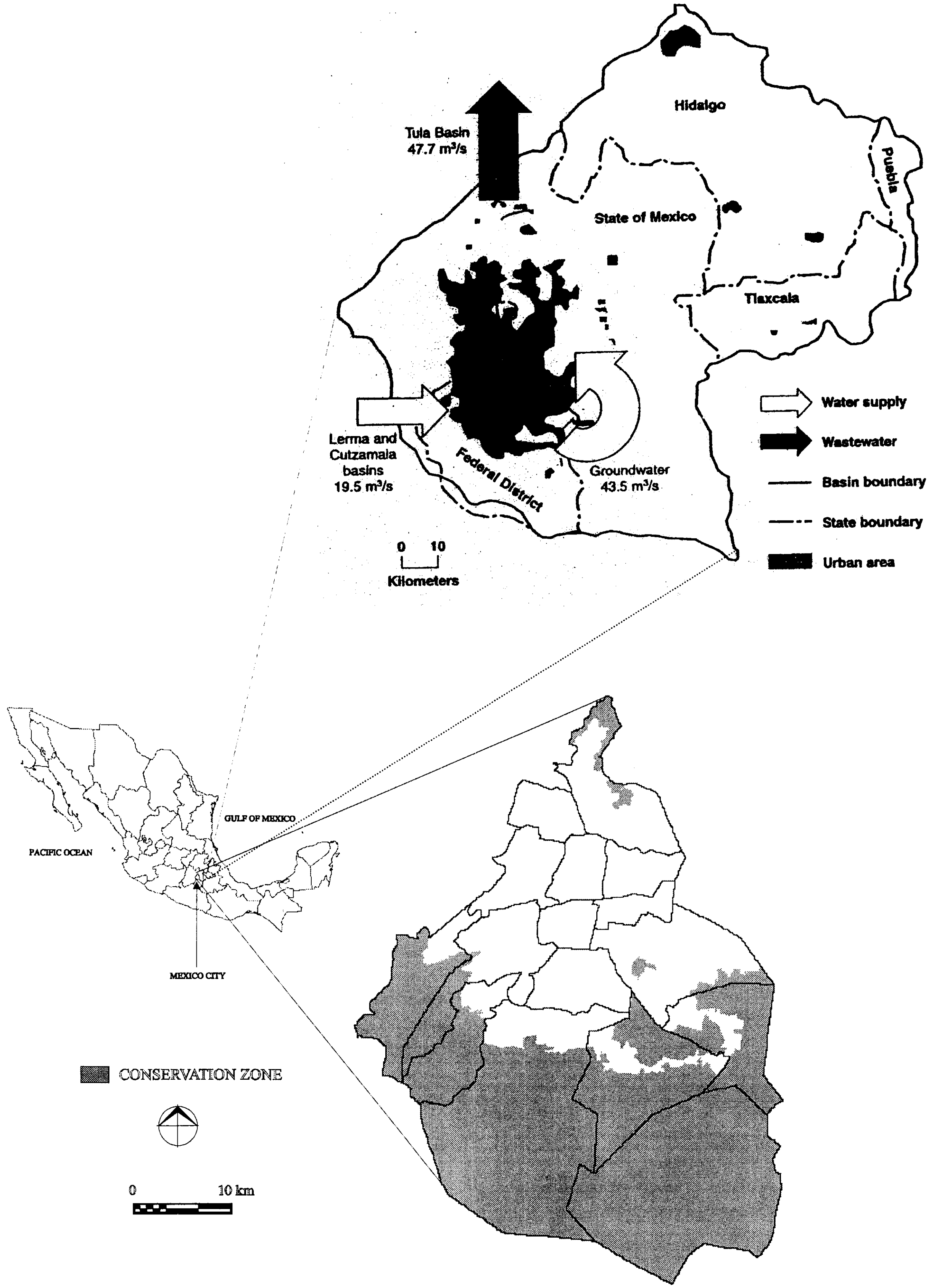

Figure 1. Study area and water management flows in the Mexico City Metropolitan Zone.

tionally, the tropical location of the Basin of Mexico, its internal geologic discontinuities, and the high altitude sierras, and isolated valley bottoms are covered create different patches originally covered with distinct vegetation types. Indeed, the lacustrine, transition, and mountain zones are correlated with a diverse flora and fauna.

Hence, three major environmental zones exist within the basin (Aguilar et al 1995, Ezcurra and Mazari-Hiriart 1996, Mazari-Hiriart and Mackay 1993): lacustrine, transition, and mountain. The lacustrine zone can be divided in three subzones: (1) lake system, an important resting habitat for migratory waterfowl; (2) saline lakeshore, characterized by halophyllous plants; (3) deep-soil alluvium, covered by sedges and swamp cypress. Clay deposits characterize the parental material of the lacustrine zone. These deposits are divided in upper and lower formations (30 to 70 m thick) by a hard layer (Capa Dura) of silt and sand. Furthermore, the clay layers are considered an aquitard because it is considerably less permeable that the Capa Dura or underlying sediments

The original lacustrine system covered 1,500 km^2. It comprised a sequence of five shallow lakes with a north south alignment: Zumpango, Xaltocan, Texcoco, Xochimilco, and Chalco. The lacustrine system was interconnected and drained to the Texcoco lake, but during extreme droughts, the lakes may have been separated by desiccation. The northern lakes (Zumpango, Xaltocan, and Texcoco) were saline, while the southern ones (Xochimilco, and Chalco) of fresh water, owing to the greater precipitation and springs located in that area of the basin.

The transition zone corresponds to the area between the lacustrine clays and the mountains. It encompasses five subsystems: (1) thin-soil alluvium, dominated by grasses and agaves; (2) upland alluvium, occupied by oaks and acacias; (3) lower piedmont, cloaked by low oak forests; (4) middle piedmont; covered by broadleaf oaks; (5) upper piedmont, covered by oaks and oak-pine woodlands.

The boundary between the lacustrine and the transition zones is generally defined as the edge of the upper clay formation. If present, clays are imbedded with silts and sands in the transition zone; closer to the mountains, the transition zone consists of fractured basalt. Groundwater recharge happens in the transition zone because of its high relative to the other two zones.

The mountain zone is composed of the area above 2,700 m above sea level in the major sierras. Temperate plant communities of pine, fir, and juniper cover this zone. Snow melt from the volcanoes of the Sierra Nevada, as well as springs and runoff from summer rains from all the sierras are the main source of water to the lakes at the center of the basin.

Mean annual precipitation in the Basin of Mexico is $744.2 \times 10^6 m^3$ ($23.6 m^3/s$). Rainfall in the Basin of Mexico is monsoonal and presents a NE SW gradient. Also, precipitation in the sierras is about 50% higher than that of the Basin floor. Accordingly, Sierra de Las Cruces receive the highest mean annual precipitation (1200 mm/yr) , followed by Sierra del Ajusco (900 mm/yr), and Sierra Nevada and Sierra Chichinautzin (800 mm/yr). Approximately 50% of the precipitation infiltrates to the groundwater. In spite of the differences in precipitation, Sierra Nevada and Sierra Chichinautzin are as important as the other sierras because of their area.

Land Use

High population has been an always present determinant of environmental change in the Basin of Mexico. In pre-Hispanic times, at the peak of the Teotihuacan Culture (A.D. 300-750), the basin had a population of 300,000. At the time of the Spanish Conquest (A.D. 1519), the basin's population was above 1,000,000; inhabitants were distributed over 100 settlements. At that time, the region was perhaps the largest and densest urban area in the world (Ezcurra and Mazari-Hiriart 1993).

From the 1300s to the 1500s, the Aztecs altered the hydraulic characteristics of the lacustrine zone to protect the city of Tenochtitlan, which was founded on an island at the western section of the Texcoco Lake in 1325 A.D. Tenochtitlan water supply was satisfied by artesian wells. To protect the city, the Aztecs achieved an efficient water management system in the lakes of Xochimilco, Chalco and Texcoco by means of dykes, canals and floodgates (Aguilar et al. 1995). Likewise, their settlements expanded with the establishment agricultural crops on raised parcels of land above water, known as *Chinampas* (Downs et al., in press).

The Spanish conquest launched further alterations to the lacustrine system. The basin was opened artificially in the early 1600s. The canals were converted into roads and water was drained out from the city. The alluvial plains and the piedmonts were deforested and overgrazed. Ultimately, the lakes were drained as modern MCMZ expanded and land uses throughout the basin changed during the colonial and independence periods.

Until 1930, the spatial development of the MCMZ was characterized by a pattern of concentration in the downtown area. Between 1930 and 1950, peripheral expansion of took place as household were built in the south and west sections, and industrial developments in the north section. Accelerated growth occurred from 1950 to 1980, as the city grew northwards into several municipalities in the state of Mexico, and the population soared with access to cheaper land, recently built infrastructure and basic services. Low-income housing concentrated on dry lacustrine areas on the east and northeast, while the middle class and industry settled along a major highway on the north. On the south and southwest, residential subdivisions were established on mountain slopes without control or regulations.

In 1940, urban settlements covered 90 km^2 (0.9% of the basin). By 1990, the MCMZ encompassed about 1,161 km^2 or 12% of the Basin of Mexico. Population of the MCMZ was estimated to be 15 million in 1995, although the growth rate is decreasing (Ezcurra and Mazari-Hiriart 1996). Nowadays, however, flows of people and materials between the MCMZ and other major cities (Toluca at the west and Cuernavaca at the south) have created a megalopolis that extends beyond the boundaries of the basin. From 1953 to 1980, the average growth rate of MCMZ was 5.2%.

Water Management

Water Supply

The main aquifers in the Basin of Mexico are composed of alluvial and volcanic materials of variable thickness (100 to 500 m). Due to artesian pressure, the aquifer's original hydraulic gradient and water flow was upward, through the overlaying clay aquitard. However, groundwater utilization has changed the hydraulic regime and the gradients and flow in the upper deposits are downward, toward heavily pumped zones (Mazari and Mackay 1993).

Groundwater pumping in the MCMZ started in 1847. By 1925, groundwater extraction had generated a 1.25 m subsidence in some sections of Mexico City. This phenomenon was accelerated by 150 deep production wells that were drilled in 1940. A ban on new wells in the city area was issued in 1954, and some existing wells were relocated to the north and south of the basin (respectively, the well fields of Teoloyucan-Tizayuca-Los Reyes-Chiconautla, and Xochimilco-Tláhuac-Chalco). Although these changes reduced subsidence in the central MCMZ, they have increased subsidence in the Chalco-Xochimilco area (Mazari and Mackay 1993). The subsidence rates have stabilized at about 6 cm/yr in the downtown area. Nevertheless, sinking is occurring at a higher velocity (15 to 40 cm/yr) along the limits of the urban area. Some areas in downtown Mexico City have sunk 9 m since the early 1900s.

Groundwater extraction supplied enough water for the population of Mexico City until the mid-1960. Nowadays, groundwater is insufficient to meet the demand. In addition, the extraction rate is higher than the natural recharge rate of the aquifer (25 m^3/s during the rainy season). Although there are 1,200 registered wells (of depths from 70 to 300 m), about 40% of them are used only occasionally during droughts. External river basins complement the supply of water in Mexico City.

Current water demand is about 63 m^3/s in MCMZ. Groundwater is still the main supply with 42 m^3/s (extraction rates are as follows: Xochimilco, 26.0 m^3/s; metropolitan zone, 7.0 m^3/s; Texcoco 5 m^3/s; and Chiconautla 4 m^3/s). Aqueducts supply water from the external river basins of the Lerma and the Cutzamala (6 m^3/s and 13.5 m^3/s, respectively). The remainder 1.5 m^3/s is produced by surface systems within the basin (Ezcurra and Mazari 1996).

Wastewater

Storm runoff, industrial wastewater, and domestic sewage are carried out of the Basin of Mexico by a combination of sewers, open canals, reservoirs, lagoons, pumping stations, and a deep drainage system. About 75% of the population in the basin have access to this system; the rest disposes sewage through septic tanks and absorption wells. It is conceivable that a significant amount of contaminants are released by the sewage system. Additionally, there are 24 wastewater treatment plants, whose capacity totals 4 m^3/s (7% of the water used in the basin).

Wastewater flows northward to the Tula Basin through an open canal (called *Gran Canal*) that has been in operation since the early 1900s, and the deep drainage system (called *Drenaje Profundo*), built in the 1970s. As the city has subsided, the open canal has lost its designed downgrade so auxiliary pumping stations are needed to discharge wastewater out of the Basin of Mexico to the Tula River. The closed drainage system consists of a network of tunnels that have a depth of 30 to 300 m. this system operates mostly during the rainy season and does not require auxiliary pumping. Wastewater is discharged to the Tula-Moctezuma-Pánuco River, which flows to the Gulf of Mexico. In the Tula Basin, the wastewater is used for irrigation and to generate electricity in the Zimapán Dam.

Groundwater Pollution

Contaminants released at surface can migrate or be carried down by infiltrating water towards the aquifer. Contamination sources include landfills, petroleum refining, transport, and storage, gasoline stations, electronic industries, other industrial and commercial sources, wastewater disposal.

Therefore, risk of groundwater contamination is higher in the transition zone because of its permeability and wells now draw water from zones within or near it. The main aquifer is considered hydrogeologically closed to contamination that originates in the lacustrine area, because the clays that overlie the aquifer are an effective barrier to downward migration of water and surface pollution.

The reliance on the lacustrine clays to act as an efficient barrier to contamination is based on the assumption that they are a relative homogeneous, impervious unit. However, human activities (drilling wells, excavations, abandoned wells, deep drainage system, and the subway transportation system), and natural cracks and fractures may have breached the integrity of clays. Surface cracking is known to result from subsidence.

Importantly, Mazari-Hiriart et al. (in press) have demonstrated the presence of viral pathogen indicators, as well as fecal associated bacteria populations, in drinking water supply of Mexico City. This is an evidence of groundwater contamination with serious implication for human health.

Conservation Land of the Federal District

The conservation land of the Federal District, officially known as *Suelo de Conservación Ecológica* (SCE; figure 1), was established by a presidential decree in 1930s, along with a series of natural parks. The SCE extends over 89,000 ha (58% of the Federal District), mostly on the south and southwestern mountain ranges. It includes 25 watersheds and encompasses the main groundwater recharge areas in the Federal District, and about 50,000 ha of natural cover (fir, pine, oak, scrub, and grasslands). It is located within the boundaries of nine of administrative units, or political delegations, of the Federal District (Cuajimalpa, Alvaro Obregón, Magdalena Contreras, Tlalpan, Milpa Alta, Xochimilco, Tlahuac, Iztapalapa, and Gustavo A. Madero; see figure 2).

The Natural Resources Commission of the Federal District (Comisión of Natural Resources or CORENA) is the governmental agency responsible for managing the SCE. CORENA is currently formulating a strategy to set land-use policy for natural resource management and conservation of natural resources, to delineate a land-use pattern that maximizes consensus and minimizes environmental conflict, and to protect the natural cover, natural habitats, a and groundwater recharge areas.

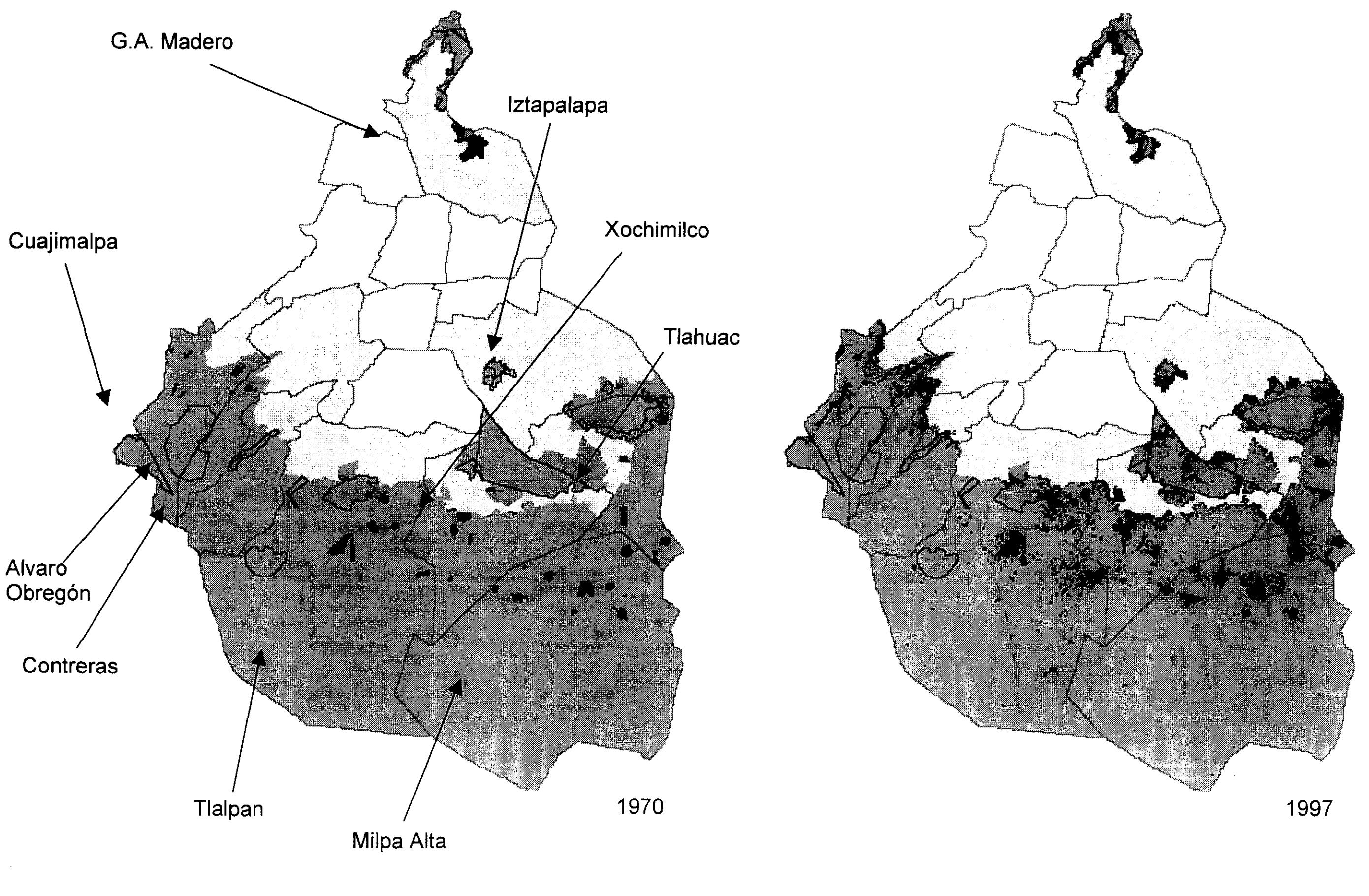

Figure 2. Land-cover transformation in the conservation zone of the Federal District (black). The names in the figure are those of the political delegations.

Water Balance

A water budget analysis shows that about 50% of the SCE present water surplus. When the SCE is divided according to water surplus categories, it is evident that the largest proportion of the SCE is either moderate (12,380 ha) or high (15,540 ha), while the categories low and very high occupy a smaller area (8,610 ha and 7,720 ha, respectively).

The relative importance of the vegetation for the hydrological cycle of the basin is related to their area and relative amount of water surplus. Practically, the total area covered with fir forests, alpine grassland, and riparian forests, as well as half of the area covered with grasslands. About 50% of the area covered with pine forest have average water surplus, while a similar percentage of oak forests have lower than average water surplus (figure 3a). Thus, pine and fir forests are the most important vegetation types, followed by alpine grasslands and riparian forests, grasslands, and oak (figure 3b).

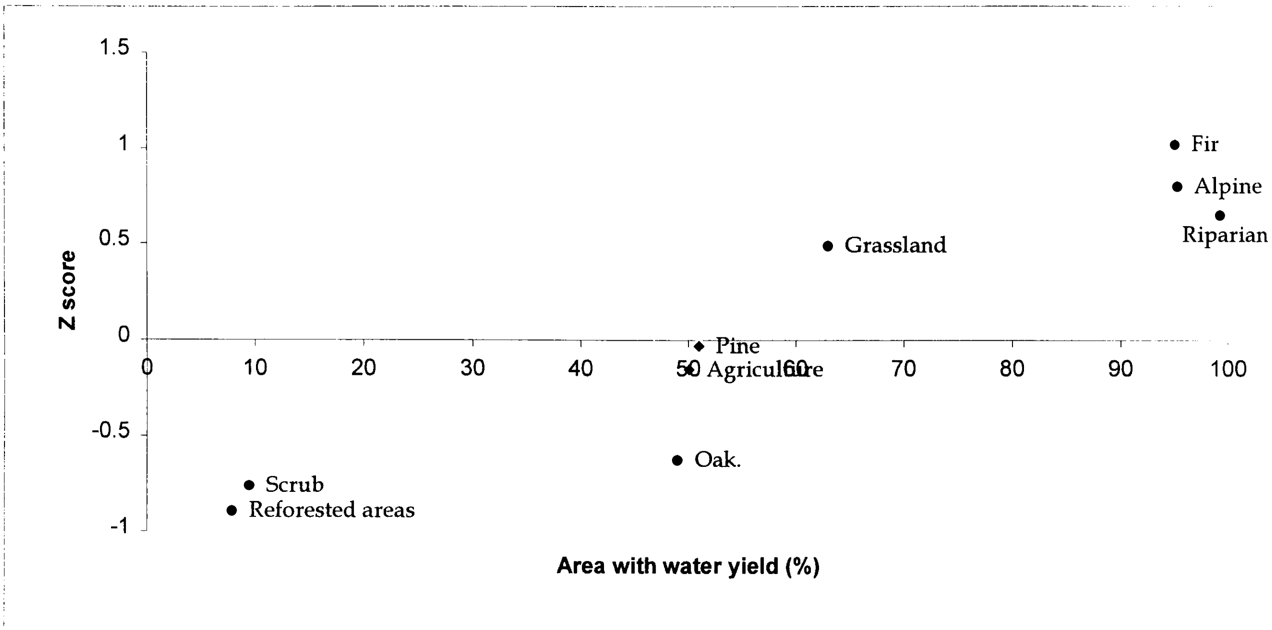

Figure 3a. Importance of vegetation types with respect to average water surplus in the conservation land of the Federal District.

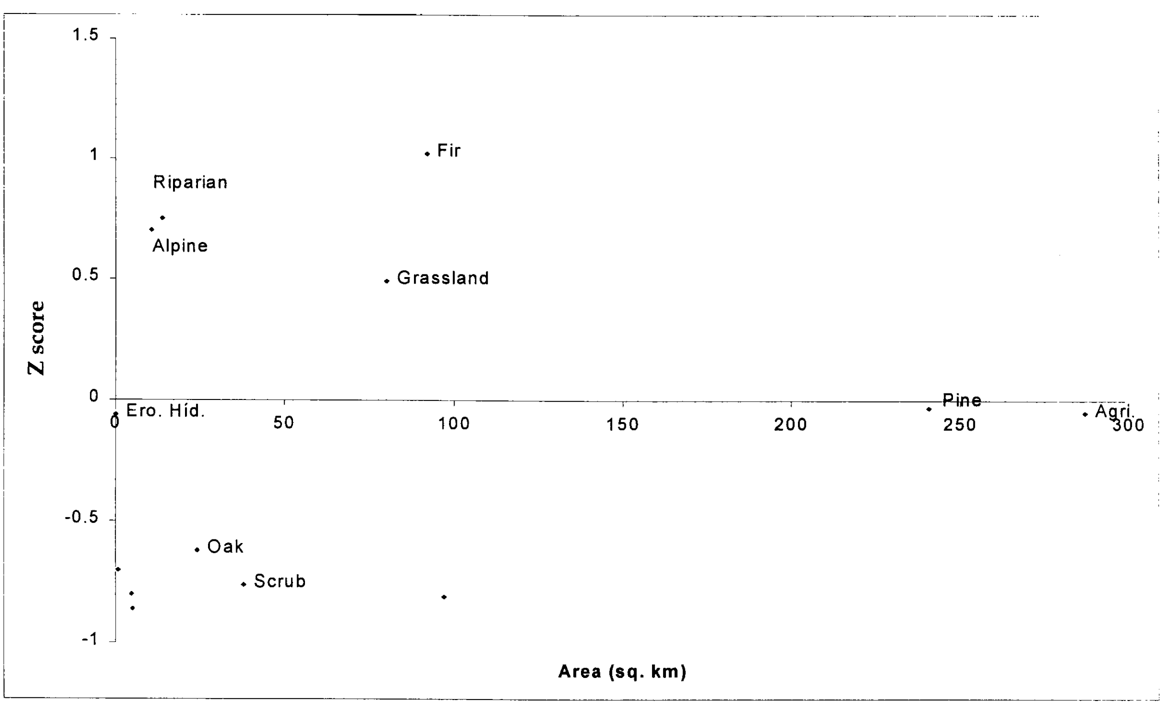

Figure 3b. Importance of vegetation types with respect to average water surplus in the conservation land of the Federal District.

Land Use and Land Cover Change

In general, ranching, uncontrolled recreation activities, and illegal logging have affected the forested areas, while ranching, agriculture, and urban growth have reduced grassland and scrub lands. Nonetheless, the economic importance of agriculture and ranching is decreasing; indeed, the rural population working in the metropolitan area is increasing. As an aftermath, agricultural fields and ranching areas have been abandoned, and have been replaced by urban developments. In fact, urban development is occurring at a rapid rate and is occupying natural and agricultural areas. Land cover transformation, however, is not occurring at the same rate in all the political delegations of the SCE and land cover types (figure 3; table 1).

Table 1. Land cover change in the Conservation Land of the federal District (SCE).

Land cover type	Land cover (ha) 1970	Land cover (ha) 1993	Change (ha)	Rate (%)
Forest	38,610	32,160	-6,450	-0.7
Urban	1,870	9,680	7,810	6.1
Grassland	11,090	14,400	3,310	1.0
Agriculture	35,910	31,230	-4,680	-0.5
Scrub	1,110	1,830	720	1.9

The political delegations can be grouped with respect to the proportion of SCE within their boundaries, remaining natural cover, and annual rate of land cover transformation (estimated for the period 1970 to 1997; figure 3; tables 1 and 2). Milpa Alta and Tlalpan form the first group. They included the larger proportions of SCE, both have extensive natural cover (> 50 km^2), and present low annual transformation rates (< 1%). The area decreed as SCE is smaller in the rest of the political delegations.

Gustavo A. Madero and Iztapalapa form a second group. The extent of SCE in the two is small and is virtually devoid of natural vegetation (< 2 km^2), while their annual rate of land cover transformation are low (this indicates that land cover transformation in occurred before 1970). Natural cover is equally small in Tlahuac, in spite of including a larger proportion of SCE. Its annual transformation rate is extremely high (5%).

The third group, formed by Alvaro Obregón, Magdalena Contreras, and Cuajimalpa, have low annual transformation rates (> 1%). The areas of natural cover included in these political delegations are moderate (between 3 and 29 km^2). Finally, Xochimilco stands alone because of the extension of natural cover (50 km^2) and a rather high annual transformation rate is high in Xochimilco (< 3%).

Land transformation trends can be inferred from preliminary results of a suitability analysis performed for the SCE. Figure 4 shows the criteria used for zoning, and Table 2 shows the capability of the political delegations for a land use set. Hence, considering only the political delegations within water surplus, Cuajimalpa, Magdalena Contreras, and Alvaro Obregón are threatened by forestry and urban growth; Xochimilco by agriculture, ranching, and urban growth; and Tlalpan and Milpa Alta by forestry, agriculture.

Table 2. Land suitability in the Conservation Land of the Federal District (SCE).

Delegación	SCE (ha)	Agriculture (%)	Conservation (%)	Logging (%)	Ranching (%)	Urban (%)
G.A. Madero	1,600	19	70	3	65	15
Cuajimalpa	6,600	13	61	52	35	11
A. Obregón	2,700	18	66	37	31	6
Iztapalapa	1,200	53	55	0	34	24
M. Contreras	5,100	3	79	62	39	2
Tlalpan	26,000	9	53	45	60	6
Xochimilco	10,400	61	23	6	77	14
Tlahuac	6.700	50	13	0	73	16
Milpa Alta	28,400	19	55	47	49	4
SCE	89,000	22	50	38	55	8

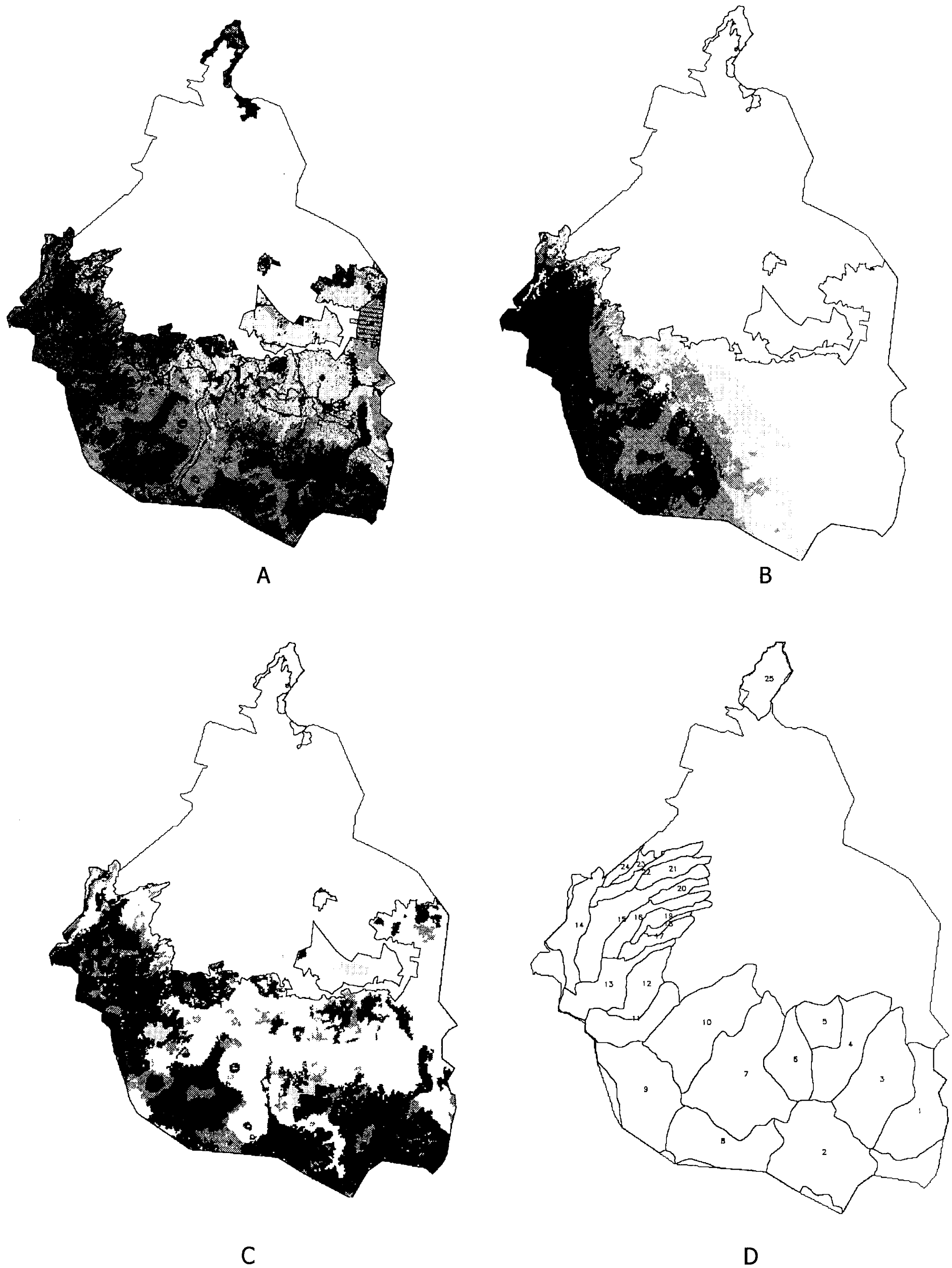

Figure 4. Zoning criteria used in the conservation land of the Federal District. A) land suitability groups (light gray=agriculture and ranching; dark gray=conservation and forestry; black=urban development; B) water surplus categories (white=null; light gray=low; dark gray=moderate; black=high); C) biodiversity importance categories (white=null; light gray=low; dark gray=moderate; black=high); D) watersheds.

Discussion and Conclusions

Large metropolitan areas have always exerted considerable pressure on its regional environment. However, megalopolises are a 20th century phenomenon: concentrated urban growth concentrated urban growth is affecting regions at a level never seen before. It is obvious to assert that megalopolises require scrupulous allocation of available natural resources to meet the demands of rising populations. Yet, it is not yet clear how environmental sustainable these cities will prove to be.

Arguably, the biggest challenge for the sustainability of megalopolises is water supply and wastewater disposal. The MCMZ is an excellent example on a serious case of what could be called "watershed mismanagement." Nowadays, a multi-basin level approach is necessary to face the challenges in the immediate future. According with Downs et al. (in press), existing water resources will not meet the demands by the year 2015, and groundwater substitution is needed to reduce the current subsidence problems in the MCMZ. Exploitation of external hydrologic basins to supply water to MCMZ is unavoidable even with recycling of wastewaters and detection and repair of leaks in the distribution systems (losses are estimated as high as 40% of the total volume).

At the regional level, overexploitation is the major groundwater management problem, although it is important to recognize that the problem is compounded by the threat of groundwater contamination. Also, the external basin of Alto Lerma appears to be over exploited perhaps by as much as 100%, while the other, Cutzmala, is being used under its potential.

At the local scale, observed land-cover transformation rates in the SCE (table 1) seem to contradict pervious assertions that deforestation is a major threat to groundwater recharge areas in the SCE (Ezcurra and Mazari-Hiriart 1996). This apparent contradiction results from the consideration of all vegetation types in the SCE for the calculations. However, deforestation rates differ among watersheds in the SCE. It is evident that the political delegations of Cuajimalpa, Magdalena Contreras, and Alvaro Obregón are being pressured by urban growth (table 2). Therefore, it can be concluded that the watersheds with the highest water surpluses (figure 4) are threatened by urban growth. At present, most of the impacts are occurring on the oak forests in the transition zone; the area with the highest permeability in the basin. On the other hand, the political delegations of Tlalpan and Milpa Alta present lower transformation rates, generated by illegal logging, agriculture, and cattle ranching (figure 4; table 2).

Therefore, integrated water resources management plans must include the following: (1) protection and enhancement of aquifer recharge areas, (2) control of deforestation, (3) reforestation of the mountain slopes, and (4) development of additional external water resources. Importantly, as new water sources will have to be developed, research will be necessary to evaluate the withdrawal limits and environmental impacts in external basins.

The evidence presented in this paper reinforces current efforts to promote a more sensible management of water resources and the implementation of a watershed approach in the Basin of Mexico and neighboring river basins.

Acknowledgments

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Watershed Management for Disaster Mitigation and Sustainable Development in Taiwan

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Abstract.—Heavy torrential rains during the typhoon season, steep topography, young and weak geologic formations, erodible soils and improper land uses are factors contributing to disasters associated with erosion, landslides, debris flows, and floods in Taiwan. With steady public and government support over the past 5 decades, Taiwan's watershed management program in which soil and water conservation is a dominant component has helped to alleviate impacts of disasters and enhance sustainable management of land and water resources. The program is periodically evaluated and revised according to scientific and technical advances, and rapid political and social-economic changes on the island to meet the rising diverse needs and expectations of the people. To help resolve conflicts and gain consensus related to watershed management policy and issues, public input can be solicited through properly designed and implemented public education and involvement initiatives.

Introduction

Few places in the world experience the watershed management problems and challenges resulting from combined hydro-meteorological extremes, and political, social-economical and cultural complexities like Taiwan. Heavy torrential rains during the May-October typhoon season, young and weak geological formation, erodible soils, frequent earthquakes, and improper land uses are factors contributing to disasters associated problems related to severe erosion, landslides, debris flows, and floods.

Watershed management and soil conservation programs have received continuous and growing public and government support since the early 1950s, due to clearly demonstrated increasing needs. However, political, social-economical and cultural conditions in Taiwan are changing rapidly in recent years, and the mission and program planning of watershed management should be timely revised accordingly to meet rising new needs and aspirations of people. Proper land uses are essential to a successful watershed management program for disaster mitigation and sustainable development. But dense population, land scarcity, and other political, social-economic conditions, and traditional ideas are not very favorable to strict implementation of a land use planning and regulation system. Therefore, there are tough and rewarding challenges in Taiwan's future watershed management program. This paper examines the problems, issues, and roles and challenges for watershed management in Taiwan in terms of its mission to foster stewardship of land and water resources for disaster mitigation, sustainable development, and integrations with other government service to meet diversed needs and expectations of the people.

Physical Environments, Land Uses and Watershed Problems

Physical Environments

Two-thirds of Taiwan are rugged mountains and hills (table 1). Most mountainous areas are very steep, with slopes usually exceeding 45%. The average annual rainfall is 2,500 mm, with more than 3,000 mm in some high mountain regions. About 80% of the rainfall is concentrated in the May-October typhoon season. Approximately

Table 1. Land Resources in Taiwan.

	Area (ha.)	Percent (%)
Plains	**948,797**	**26.4**
Slopelands	**2,653,899**	**27.2**
Hillslopes	*980,819*	*27.2*
Mountain forest lands	*1,673,080*	*46.4*
Total	**3,602,698**	**100**

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3 typhoons pass through the island annually, and often bring more than 100 mm/hr or as much as 1,000 mm/day of rainfall. For example, 1,987 mm of rainfall was measured over a 48-hour period during Typhoon Herb in 1986 at one high elevation climate station in central Taiwan (figure 1). Other important environmental characteristics include young and weak geological formations, erodible soils and frequent occurrence of earthquakes.

Land Uses

According to the third forest resources and land use inventory in 1995 (table 2), about 59 % of the land area are covered with forests. Comparison of slopeland uses in Taiwan for different time periods is given in table 3. Fifty percent of slopeland crops grow on slopes steeper than 30%. According to slopeland inventory in 1998, there were still 110,000 ha of cultivated land requiring conservation treatments. Nearly all the slopeland soils are subject to serious erosion when exposed. This problem is aggravated by cultivation on steep slopes.

Table 2. Land Use Inventory in Taiwan of 1995 (Taiwan Forestry Bureau, 1995).

Land use	Area (in I,000 ha.)		Percent (%)	
Forested lands	2,102.4		58.5	
Conifers		*438.5*		*12.2*
Conifer-hardwoods		*391.2*		*10.9*
Hardwoods		*1,120.4*		*31.2*
Bamboo		*152.3*		*4.2*
Agricultural lands	831.9		23.2	
Peddy		*264.8*		*7.4*
Upland-farming		*235.0*		*6.5*
Others		*332.1*		*9.2*
Other lands	657.2		18.3	
Grassland		*143.5*		*4.0*
Urban and industrial		*217.8*		*6.1*
Water area		*201.3*		*5.6*
Others		*94.6*		*2.6*
Total	**3,591.5**		**100.0**	

Landslides and Water Quality Degradation – Major Watershed Problems

Very few areas in the world experience landslide problems of the magnitude and extent of those in Taiwan (Dils 1978). Watershed field investigations throughout the island have indicated a close relationship between the presence of extensive landslides and the serious siltation problems of reservoirs (table 4) and streams. Landslides contribute large amounts of sediment and debris to water courses, which create many problems downstream such as raised streambeds, damaged hydropower generating facilities, reduced carrying capacities of irrigation canals, and rapid siltation of reservoirs. Therefore, a major goal of watershed management is to help reduce the heavy siltation in streams and reservoirs. Agricultural uses of hillslopes in reservoir watersheds with heavy application of fertilizers and pesticides also contribute to serious water degradation (table 5).

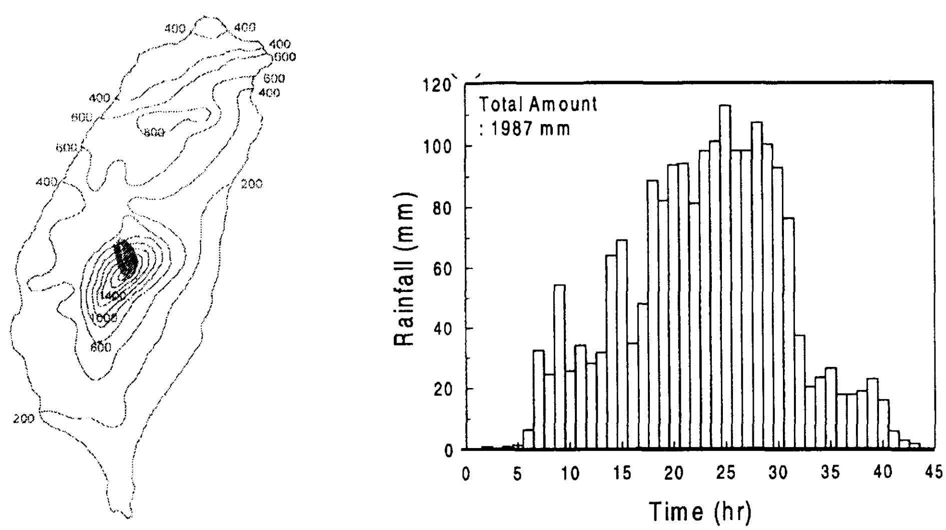

Figure 1. (a) Spatial distribution of total rainfall amount and (b) hourly rainfall at Alishan Climate Station during Typhoon Herb in Taiwan, July 31 - Aug 1, 1996.

Table 3. Comparison of Slopeland Uses for Different Periods in Taiwan.

Land Use		1974~1977 Inventory (1)		1985~1988 Inventory (2)		1997~1999 Inventory (3)		Land Use Change (3)-(2)	
		Area (ha)	%	Area (ha)	%	Area (ha)	%	Area (ha)	%
Cultivated	Fruit Trees	115,716	11.9	154,356	15.5	136,363	15.0	- 17,993	- 0.5
	Peddy Rice	72,081	7.4	37,504	3.8	17,156	1.9	- 20,348	- 1.9
	Upland Crops	147,899	15.2	79,801	8.0	49,384	5.4	- 30,417	- 2.6
	Others	2,489	0.3	1,885	0.2	64	0.0	- 1,821	- 0.2
	Subtotal	338,185	34.7	273,546	27.6	202,967	22.4	- 70,579	- 5.1
Forest and Grassland	Forest	406,779	41.8	458,970	46.2	465,052	51.3	6,082	6.1
	Bamboo	95,268	9.8	111,910	11.3	71,127	7.8	- 40,783	- 3.5
	Grasslands	41,028	4.2	43,013	4.3	32,961	3.6	- 10,052	- 0.7
	Subtotal	543,075	55.7	613,893	61.8	569,140	62.8	- 44,753	- 1.0
Others		92,934	9.5	105,272	10.6	134,118	14.8	28,846	4.2
Total		974,194	100.0	992,711	100.0	906,225	100	- 86,486	

Table 4. Mean Annual Sediment Data for Major Reservoirs in Taiwan.

Reservoir Name	Watershed Area (km^2)	Mean Annual Sedimentation (m^3/km^2)	Erosion Depth (mm)	Observation Period (Year-Month)
Shimen	763	2773	2.77	1963.5-1987.11
Techi	582	1971	1.99	1973.9-1987.11
Wushe	205	5937	5.93	1955.12-1988.2
Ming-Te	61	4118	4.12	1970.6-1975.6
Sun Moon Lake	334	522	0.52	1934-1984.5
Tsen-Wen	481	7830	7.83	1974.5-1987.12
Pai-Ho	27	14882	14.9	1965-1984.8
Ah-Kung-Tien	32	13350	13.4	1953-1971
Wu-Shan-Tou	60	26660	26.7	1920-1984.12

Review of Watershed Management Program in Taiwan

The physiographic, geologic, and climatic conditions make the mountain slopes of Taiwan extremely sensitive to disturbance (Koh et al. 1988; Wu et al. 1995). Road construction and forest clearing followed by improper land uses on hillslopes often accelerate the occurrence of landslides and debris flows (table 6, Cheng et al. 1997).

To combat landslides and other watershed problems, the government has, for 50 years, implemented a gradually expanding watershed management program, starting with two selected reservoir watersheds, Wushe and Akundien. Components of the watershed management program normally include forest management, soil conservation on cultivated hillslopes, road stability maintenance, land use regulation, landslide prevention and treatment, and stream channel stabilization work. Landslide control and stream channel stabilization generally account for the largest proportion of the watershed protection and restoration budgets. In recent years, watershed management has been extended beyond reservoir watersheds to other drainages, particularly those areas with a recorded history of disastrous damages caused by sediment-carrying floods. The total expenditure increased steadily as the program expanded over the years (figure 2).

Table 5. Calson's Eutrophication Index (TSI) for Major Reservoirs in Taiwan.

Reservoir Name	1993	1994	1995
Fetsui		40.85	36.0
Shimen	45.56	55.76	42.75
Te-chi		47.90	40.75
Wushe	45.44	40.42	41
Tseng-Wen	51.0	49.81	40.75
Wu-Shan-Tou	45.06	50.88	44.50
Pai-Ho	51.36	56.20	49.00
Ah-Kung-Tien	75.08	80.79	69.50
Feng-Shan	77.53	74.56	75

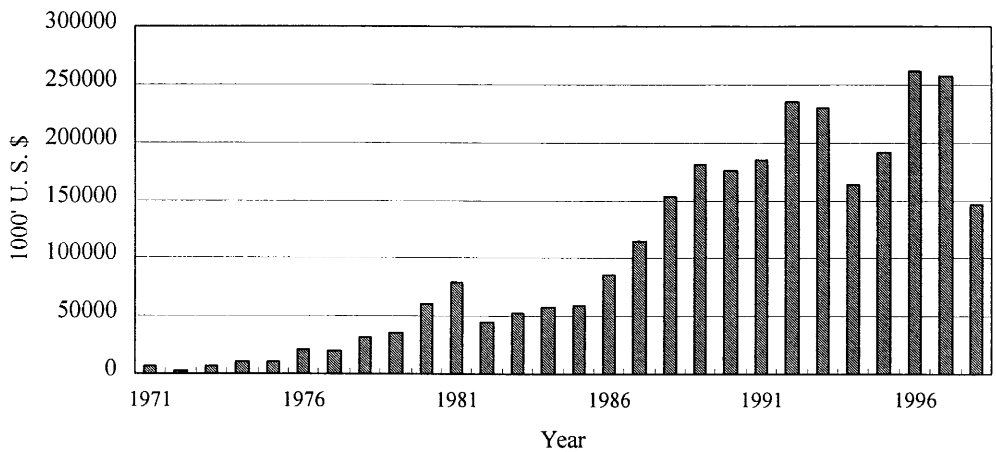

Figure 2. Expenditure on Watershed Management in Taiwan (1971)

Table 6. Selected debris flow events in central Taiwan (from Cheng et al., 1997).

Debris Flow Location	Date	Rainfall Event	Impacts on Life and Property
Tung-Men, Hualin	23 June 1990	475 mm / 3 hr	29 deaths, 6 missing, 7 injured, 24 houses destroyed, severe road damage
Er-Bu-Keng, Nantou	31 July - 1 Aug. 1996	>700 mm in less than 2 days	5 deaths, 10 houses & 3.8 ha fruit orchard destroyed
Tung-Fu, Nantou	31 July - 1 Aug. 1996	>1300 mm in less than 2 days	2 deaths, 18 houses destroyed or damaged
Shen-Mu Village, Nantou	31 July - 1 Aug. 1996	>1600 mm in less than 2 days	5 deaths, 6 injured, 8 houses destroyed, 3 ha fruit orchard damaged

Landslide prevention and treatment measures usually include excavation of unstable materials, proper drainage, restraining structures such as retaining walls, buttresses, piling, and rehabilitation of devastated slopes by appropriate engineering and revegetation techniques according to the specific site conditions. Stream channel stabilization measures often involve the construction of check dams, submerged sills, bank protection dikes, and stream regulation works.

Despite continuous watershed management efforts for many years by structural and nonstructural means, the people of Taiwan continue to experience landslides, debris flows, and floods. Consequently, natural resource managers and engineers are under strong pressure to do a better job to safeguard the safety and well being of the people on the island by designing and implementing an effective watershed management program.

Important Specific Issues in Managing Taiwan's Watersheds

As a result of unfavorable environmental conditions, and rapid social-economic and political changes in a maturing democratic country like Taiwan, watershed problems have become increasingly complicated. Several important specific issues should be properly addressed to ensure effective management of Taiwan's upland watersheds.

Land Users' Reluctance in Adopting Soil Conservation Measures for Slopelands

Many slopeland farmers and users are reluctant to adopt conservation measures, because of high production cost and low profitability in slopeland agriculture as a result of labor shortage in the rural area, rapid appreciation of Taiwan's currency, and strong competition of overseas agricultural products after the relaxation of import restriction.

Cultivation of Steep Mountainous Areas

Financial incentives in recent years have been favorable for the cultivation of high elevation tea, betel nuts (figure 3), fruit trees and mountain vegetables. Consequently, many forested slopes have been cleared and cultivated illegally, in many instances. During the initial stages of converting forests to other uses, the soils are exposed and disturbed, leading to soil erosion rates exceeding 220/t/ha/yr (Wu 1998). The replacement of forest cover with agricultural crops also reduces the stability of hillslopes. However, regular patrol, detection, monitoring, and administration of land use changes and problem sites on the ground have been a difficult task due to steep, inaccessible, and

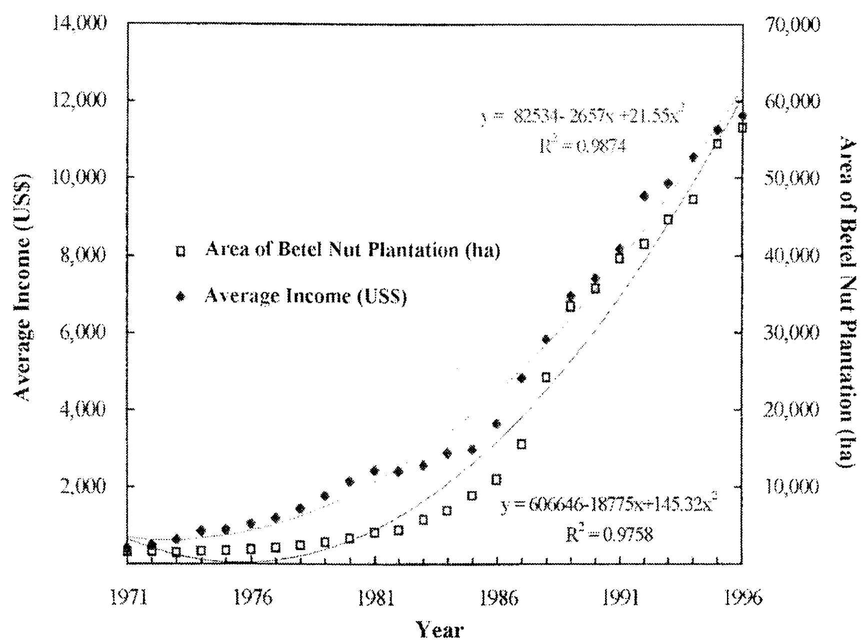

Figure 3. Comparison of Annual Area of Betel Nut Plantation with Average Per Capital Income in Taiwan (1971-1996).

dangerous terrains in many headwaters watersheds. Consequently, modern techniques such as remote sensing, geographic information system (GIS), and even the remotely piloted vehicle (RPV) are being applied with various degree of success.

Nonagricultural Uses of Hillslopes and Cumulative Effects

Because available plain lands are limited in Taiwan, it is unavoidable that even forested hillslopes are in demand for various nonagricultural uses such as residential and recreational developments. For example, among 81 golf course applications that were approved in the 10-year period after 1983, many were constructed on slopelands that originally were forested. Construction activities increased water-born sediment, and the resulting golf courses do not have the same hydrologic attributes of the original forests.

Removal of forests for permanent conversion to other uses on steep and rugged hillslopes pose serious slope stability problems, as well as opening up previously inaccessible areas to greater development activities such as urban encroachment and expansion of recreational areas. Of particular concern are the cumulative watershed effects of these land use changes and development activities. Improper nonagricultural uses of hillslopes in recent years had resulted in severe disasters with significant property damages and loss of lives.

Modifying Natural Systems and Human Behavior

Coping with landslide, debris flows, and flooding problems has involved extensive use of engineering measures throughout the island. Hillslope stabilization structures, debris flow control structures in mountain drainages, and concrete channels with energy dissipaters are common. The emphasis on structural solutions to protect people from landslides, debris flows, and floods has sometimes resulted in a false sense of security by downstream communities. In addition, channelization and associated stream alterations from headwaters to floodplain areas poses questions concerning impacts on downstream flooding in contrast to natural stream systems with their riparian vegetation intact. Solutions most likely will include modifying both the natural systems and human behavior on the watershed. Modifying natural systems to mitigate disasters requires a good understanding of their processes and governing factors, and an understanding of how mitigation actions impact the environment. Modifying human behavior requires an understanding of human systems and participation of social scientists as principal players. It is important to have a solid understanding of the roles of forest cover, other vegetative measures and engineering methods as components of an integrated watershed management approach.

Poor Inter-Departmental Coordination

Implementation of the protection forest policy since 1901 has certain watershed management benefits. However, protection forest system cannot be implemented in isolation from policies governing the use and management of all watershed lands in Taiwan. Protection forests must be managed in concert with production forests, national parks, private and other lands to achieve objectives of streamflow regulation, erosion control, and other environmental protection purposes (Koh et al. 1988).

In a maturing democratic country like Taiwan, policy decisionmaking requires careful consideration of overall political and social implications. Policy implementation depends on whether there is an effective coordination among government agencies and various sectors and interest groups. For example, at the Wu-ling Farm in headwaters area of Ta-chia river in central Taiwan, the Vocational Assistance Commission for Retired Servicemen (VACRS) promotes high-elevation fruit and vegetable farming due to its high profitability. This farm has been criticized by conservation groups and the public for its unrestrained exploitation of environmentally sensitive hillslopes, resulting in siltation problem of downstream Techi reservoir and detrimental impacts on water quality of Chichiawan Creek, a protected ecological area. However, VACRS operations are closely tied to the lives of military veterans, and, therefore, the problems caused by the farm have been difficult to resolve due to political considerations.

Comprehensive Program Evaluation for Improved Watershed Management

A comprehensive program evaluation is required to ensure all aspects related to watershed management are considered for improved program planning, priority determination, and effective implementation of projects and initiatives for identified problems and issues.

Legislation, Policy and Institutional Arrangements

The Soil and Water Conservation Act and the Statute on the Conservation and Use of Slopeland Resources provide the legislative basis for watershed management. The management of forested and non-forested watersheds is the responsibilities of several organizations, each with their own agendas. The Watershed Management Division of Taiwan Forest Research Institute and universities share the major responsibility for conducting watershed research.

The number of different agencies involved with watershed management, each with their own respective missions, roles and priorities is problematic. Either some type of effective coordinating mechanisms or organization is needed, or one agency should be charged with the overall responsibility for watershed management. It is suggested that such arrangements be made at the highest level of central government. With adequate resources and expertise, a clearly defined mission, and well-defined roles and responsibilities, the coordination and management of Taiwan's watersheds can be improved.

Some policy, legislative, and administrative aspects must also be considered and included for effective implementation of watershed conservation and management program. For example, proper policies must be formulated and necessary legislation amended to retire from production some cultivated slopelands with highly erodible soils. Mechanisms should be developed to provide adequate compensation for owners of lands targeted for retirement. Mandatory compliance legislation should also be put in place that requires land owners to carry out a conservation plan within a certain time limit and conduct necessary maintenance for their erodible slopelands, if they are to remain eligible for government benefits such as price and income supports, crop insurance, and free or low-interest loans.

Technical and Scientific Challenges

As in other parts of the world, a good deal of public confusion exists on just how forests and forest management practices affect water resources and water-related disasters. On one hand, some believe forests somehow act as storage reservoirs that can store water during the flood season (somewhat true for deeper soils, but with a limited effect on major flood events) and then release water during the dry season (which is false). Furthermore, some still attribute forest cover with the ability to attract rainfall, which has been shown not to be the case worldwide (Bosch and Hewlett 1982; Whitehead and Robinson 1993). Claims that betel nut trees can transpire more than 10 m of water annually have come forth with no scientific support. In addition, the popular press commonly attributes flooding disasters only to improper land use and contends that natural forest cover can prevent floods from occurring.

In light of local and overseas watershed study results (Bosh and Hewlett 1982; Hsia and Koh 1982; Whitehead and Robisun 1993), some conclusions regarding forest watershed management can be reached. However, more efforts should be in researching and developing knowledge and techniques for watershed conservation and management.

Forests provide the most desirable cover on upland watersheds to meet most soil and water conservation objectives, but no matter what type of vegetative or structural measures are implemented, they have limited effects on disasters caused by extreme hydro-meteorological events. The extent to which forest cover and other vegetative and structural technologies can mitigate the adverse effects of floods, landslides, debris flows, and droughts should be properly determined (Brooks 1998).

Forests represent the best vegetative cover type for producing high quality surface water and groundwater. Nutrient budgets for natural hardwood stands have been conducted (Liu and Sheu 1997), but further research is needed for the various forest types on the island. Forest clearing in headwater watersheds to augment water supplies during the dry season is not realistic, given the above concerns and the inability to predict the timing and magnitude of streamflow changes (Hsia and Koh 1982; Koh et al. 1988).

Articles in the popular press have claimed that betel nut plantations result in excessive water losses through evapotranspiration on one hand, and aggravate conditions for landslides and debris flows on the other hand. As a result, studies have been established to address the soil and water conservation effects of this particular land use change (Wu 1998). The proliferation of betel nut plantations on mountain slopes is probably an issue that has to be first resolved in political and social and economic arena.

The improved knowledge base must be developed for making rational decisions regarding nonagricultural development and the cultivation of highly profitable cash crops on environmentally sensitive and fragile slopelands. There is still much to be done in developing solutions for the problems of slopeland farms as non-point sources of pollution and for better integration of land and water management activities on a watershed scale.

Studies should be undertaken to assess the usefulness of buffer strips to: (1) improve and protect stream and riparian habitats, (2) remove nutrients from runoff and overbank floodwaters, and (3) improve the stability of reservoir shorelines and stream banks. There is also a need to create an interdisciplinary "Watershed Research Group" to address the watershed management issues of buffer strips, nutrient management, land use management, habitat protection and water quality (Agpoa et al. 1996). Interdisciplinary studies must emphasize social-economic and human aspects of watershed management problems and issues.

The effectiveness and socioeconomic benefits of the watershed management program must also be properly evaluated. One method that can be used is to determine whether the actual annual sedimentation rate exceeds the design value at the time of reservoir construction. The other approach is to estimate savings in rehabilitation costs due to reduced severity of disasters after completion of watershed protection projects.

Social-Economical and Political Perspectives

The significant and rapid changing socioeconomic and political conditions in the past five decades have altered the needs and aspirations, as well as public policy decisionmaking and program implementation processes. These significant changes include (1) the increasing wealth of the people and nation as a result of rapid industrial development and fast growth in international trade, (2) the decreasing importance of agriculture in the national economy, (3) a growing proportion of well-educated and environmentally conscious people, and (4) a maturing democratic political system.

The highly educated, affluent and environmentally conscious population is becoming more concerned and vocal about issues related to conservation of nature and resources as well as environmental protection. People also demand to be better informed of and involved in the whole spectrum of problems, issues, and decisionmaking related to environmental protection and natural resource management. Conservation and environmental issues are often raised in recent national and local elections.

To help resolve conflicts in a democratic society on policy and issues related to watershed management, public input is solicited to gain consensus through public participation and consultation. The involvement of a well-informed, knowledgeable public can directly or indirectly contribute to goal setting, policy formulation, priority determination, and program implementation for watershed management. Of particular importance is the support and participation of every citizen to ensure effective implementation of proper land-use planning and regulation based on land capability classification which is the key to sustainable watershed management. Therefore, a properly designed and implemented public education program is essential to ensure that the general public, politicians, conservation groups, educators, and the media are all knowledgeable about the interrelationships and complexities of issues, problems, and governing factors related to watershed management, on basis of results from studies on impact of land uses on soil and water resources. Equally important is the need to educate the decisionmakers and the population at large about the need to limit urban expansion in areas vulnerable to the hazards of typhoons, and the limitations that human have in controlling the magnitudes of disasters caused by extreme hydro-meteorological events. This sub-program should make effective use of regular school education system as well as mass media such as televisions and radios.

Volunteers made up mainly of school teachers, university students, housewives, and retired people can form a major part of the public involvement sub-program. However, consideration should be given in the future to new initiatives, such as setting up localized conservation youth crops and specific community groups under cooperate sponsorship and government technical assistance to carry out small worthwhile special watershed conservation management and projects during weekends or the winter and summer vacations.

Effective extension of watershed management measures and techniques is currently in program implementation in the field. Publication of information materials such as the periodically updated and revised Soil and Water Conservation Handbook (COA et al. 1992) is useful to extension work and standardization of conservation methods and techniques used by field practitioners.

Future Prospects of Taiwan's Watershed Management Program

Integral Partner in Government's Overall Program of Providing Goods and Services

The mission of watershed management program for the 21st century should be determined on a broader perspective to reflect the rapidly changing social-economic and political conditions of Taiwan. The program should be an integral partner in achieving the nation's overall goals of nature conservation, environmental protection, and disaster prevention and minimization. In other words, it should be integrated with the government's other efforts to provide goods and services responsive to a rapidly changing nation with diverse needs and aspirations, and to improve the income and welfare of farmers and rural communities. Several recent sub-programs of the watershed conservation and management program of Taiwan are already reflecting these new roles and new challenges (table 7).

Table 7. Sub-programs of Watershed Management and Soil Conservation in Recent Years.

Program Goals	Sub-Programs
Environmental Protection, Disaster Prevention and Minimization Sustainable Management of Soil and Water Resources	a. Integrated watershed protection and flood control, b. Urgent disaster prevention on slopelands, c. Reservoir watershed conservation, d. Conservation of soil and water resources for small and medium-sized watersheds.
Enhancing the Income and Welfares of Farmers and Rural Communities by Improving Agricultural Production and Living Conditions in the Rural Areas	e. Farm road construction and improvement, f. Assistance for slopeland agricultural management, g. Slopeland conservation and utilization load, h. Integrated development of farming communities. i. Conservation and landscape management of riparian zones along streams.

Environmentally Sound Slopeland Agriculture Renewal

A top priority in the watershed management program is to design and implement an environmentally sound initiatives for slopeland agriculture renewal. A prosperous and healthy agricultural sector remains essential to maintain the social, political, and economic stability of Taiwan. Despite of its current decreased economic importance, slopeland agriculture can be diversified with new initiatives that are both profitable and sustainable with minimal detrimental impacts on the environment.

Innovative ideas and initiatives are important to a renewal program for prosperous and sustainable slopeland agriculture. For example, some selected hillslope landscapes with proper conservation and infrastructure facilities might be developed into alternative sightseeing and recreational spots for the enjoyment of both residents and vacationing tourists from urban areas. Some traditional farms or orchards are already being converted to recreational farms especially in scenic areas with certain success. The responsible government agencies provide assistance in designing farm houses, landscapes, and suitable amenities such as fish ponds, camping grounds, flower beds, selection of grass and plant materials, and construction of farm roads. Visitors to these farms can enjoy camping, fishing, picking fruits, or drinking tea while staying at recreational farms (Chuang et al. 1992). The visitor can also engage in more educational activities such as observing how tea is grown, harvested, and processed.

Enhancing the Income and Welfares of Rural Communities

Implementation of watershed management projects located mostly in the rural areas can help generate much-needed short-term employment opportunities and, through purchasing required goods and services locally, provide supplementary incomes and revenues for the farm families and communities in areas adjacent to the project sites. This can help reduce social conflicts and promote political stability by a more equitable distribution of national wealth.

Improving Land Use Planning and Regulation

Another top priority for watershed management in the new century is to solve the problems of improper cultivation and non-agricultural developments of steep hillslopes by better planning and effective control and regulation of land uses based on land capability classification. Effective land-use regulation is closely related to strong law enforcement and proper compensation and incentives. However, for a country like Taiwan, whose people traditionally dislike the interferences from governments and regulations and have not yet understood sufficiently their citizen's rights and responsibilities in a maturing democratic society, any "strong" law enforcement attempts will encounter objections from individuals or organized groups. It is, therefore, important to start the basic work of implementing a well-designed law education program that gradually will have beneficial impacts on land use control and regulation which is essential key to sustainable watershed management.

Assisting Asia Pacific Countries in Watershed Management

The knowledge and practical experiences of Taiwan in dealing with watershed problems may be valuable to other countries, particularly those in the Asia Pacific region. It is, therefore, an important new challenge for Taiwan to play a greater role in assisting other Asia Pacific nations in problem identification and solution development for both agricultural and non-agricultural uses of slopelands. Successful establishment and operation of a center for international assistance in watershed management must be high in priority among many new initiatives. This can also help enhance international cooperation and friendship between Taiwan and countries in the Asia Pacific region.

Conclusion

Hydro-meteorologic extremes, steep topography, young and weak geologic formations, earthquakes, erodible soil, and improper land uses are factors contributing to the frequent occurrence of erosion, landslides, debris flows, and floods during heavy torrential rainfalls in the May-October typhoon season at many locations in the mountainous watersheds of Taiwan. Therefore, watershed management for disasters mitigation and sustainable development is an matter of great importance that has steady and strong public and government support.

Protecting people against the hazards of landslides, debris flows, and flooding in Taiwan generally involves developing appropriate institutions and policies, and suitable methods targeted for identified issues and problems. However, the rapidly changing political and social-economic conditions in the past 50 years have affected the needs and aspirations of the people as well as the public policy decisionmaking and implementation processes. Therefore, it is important that watershed management programs are periodically evaluated and revised according to scientific and technical advances to foster watershed land stewardship for optimum benefits in term of disaster mitigation, sustainable development, and integration with other government services to meet diverse needs of the people and the nation. Major challenges are to develop initiatives and projects in forest management, bioengineering, and combinations of structural and non-structural conservation measures to achieve watershed management goals.

Efforts must also be concentrated on controlling human behavior on watershed as much as attempting to modify the natural system with biophysical conservation measures. Moreover, the success of watershed conservation and management depends strongly on a properly designed and implemented public information, education and involvement sub-program to help generate and sustain public's awareness, appreciation, support, and participation of the watershed management program. After all, watershed conservation and management is everybody's business. Only with all-out efforts of the whole nation, can the goal of watershed management for disaster mitigation and sustainable management of our land and water resources be achieved.

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Integrated Studies of the Azraq Basin in Jordan

M. Shahbaz[1] and B. Sunna[2]

Abstract.—Many historical indications of the eastern Mediterranean Basin exhibit climatic changes or alterations effecting the status of water resources, hence, effecting human-kind and the quality of life. It is essential to deeply understand the nature of climates and geological structures employing state of the art techniques to assess rainfall, runoff, and floods that replenish groundwater in arid regions of the Middle East. The integrated watershed management approach being implemented in the Azraq Basin of eastern Jordan presents a unique opportunity to study the effectiveness of this approach to land and water management. Development and sustainable use of the available resources in this basin is essential for the future.

Introduction

Water scarcity has traditionally restricted development in the Middle East, and could be one of the limiting factors in the future if it is not fully and rationally evaluated. Watershed management, evaluation of water resources, defining target areas for exploring the groundwater, and development of appropriate supplies have been important goals of the current work in the Badia of eastern Jordan. It is worth mentioning that almost all previous work has concentrated on the surface water and groundwater resources in the upper aquifer of the Azraq Basin.

An integrated approach has to be applied to the development of surface and groundwater resources, in which management has to meet growing water demands. The integrated watershed management approach should take into consideration great variety of other development activities, which has an effect on the water resources. Mining, road construction, building of various types, agricultural activities, and exploitation of oil fields can influence water resources. Most water resources management activities are primarily aiming at the increased efficiency of water use and land resources. However, in a number of cases, these activities have had negative effects on the geologic-hydrologic environment including a decrease in the productivity of water resources, pollution of groundwater, and intensification of superficial geological processes.

Scope of Paper

This paper describes the activities of a project of integrated studies implemented under the umbrella of the Higher Council for Science and Technology entitled "Integrated Studies of Azraq Basin for Optimum Utilization of the Natural Resources." Specifically, the paper describes methodology applied to better assess and evaluate natural resources with particular emphasis on water resources management. Results of these studies will target new areas for groundwater, minerals, and energy exploration, defining areas for agricultural applications, and for development of exploration strategies regarding natural resources in the basin as a pilot area for other basins in Jordan. The aim is also to show the value of the integration of geology and geophysics for land survey and land resources appraisal. The studies consist of:

- Photogeologic mapping and interpretation using aerial photographs, and high quality satellite photography and imagery.
- Subsurface studies integrating the information obtained from geological and geophysical data. Principal means of investigating the subsurface geology and structure of the basin are gravity and magnetic data, and an extensive network of seismic reflection data gathered in the course of exploration for oil and gas. Seismic lines were interpreted, augmented by information from deep boreholes and surface geological maps.

Azraq Basin

The Azraq Basin, about 12,750 km^2 in size, is located in the northeastern Badia region; the Badia forms 85% of Jordan's land surface. The drainage pattern of the main basin has been delineated as shown in figure 1. Few

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climatic changes have occurred in the region since the Neolithic age (8,500-3,750 BC); the climate is hot and dry. Evidence exists that a large lake totaling 4,500 km^2 covered the Azraq depression in the Pleistocene age.

Geology

The basin incorporates exposures of sedimentary rocks and basalt, ranging in age from Cretaceous to Quaternary. In the southern part of the basin and on the surface, the Quaternary deposits and recent sediments cover the underlying Tertiary deposits. The latter are intermittently exposed at the surface in the south, southwest, and southeast. Eocene and top Tertiary sediments lie on the top of the sequence beyond the "Fuluk" fault to the south and southeast at Wadi Hazim and the Jebel El-Fuluk. The sedimentary sequence includes limestone, chert, marl, chalk, sandstone, clay, and evaporites. These rocks are frequently covered with a variably thick sequence of superficial deposits including alluvium, mud-silt flats, chert pavement, Pleistocene gravels, and sand and evaporite incrustations.

To the north and northeast, basalt eruptions of different age appear on the surface and extend northwards to cover a wide area known as the "Basalt Plateau." This basalt area is related to the North Arabian Volcanic Province, which extends from Syria across Jordan into Saudi Arabia, covering in Jordan an area of 1,1000 km^2.

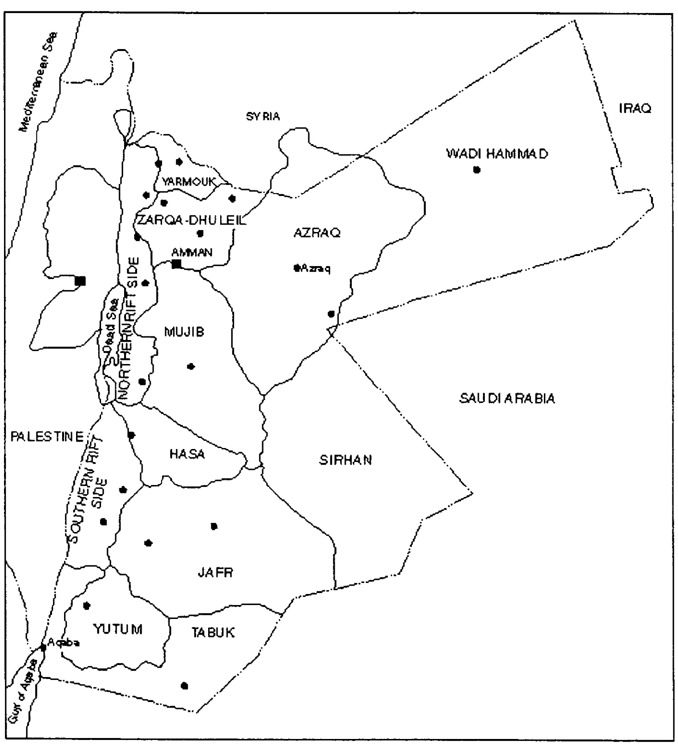

Figure 1. Map of the Azraq Basin.

The Azraq Basin represents a thick stratigraphic section. The area has been subject to extensive oil exploration activities, which added a lot of information regarding the stratigraphic sequence and sedimentary section. In the subsurface, a thick sedimentary section that is changing in thickness and varying in the lithostratigraphic and formation units represents the basin. These sediments range in age from early Paleozoic to Pleistocene, and are primarily composed of carbonates, sandstones and shales. The major thickness reduction in the sequence appears towards the south and southwest directions, while a remarkable increase in thickness is observed east of Azraq town towards the Fuluq fault.

The Cretaceous-Tertiary deposits in the basin comprise a thick sedimentary section measuring more than 3,500 m of mostly marine deposits. The lower Cretaceous boundary, identified by a recognizable sandstone unit of the Nubian type known as the "Kurnub Sandstone," is identified in several wells, as the sandstone formation underlying the carbonate facies of the Cenomanian age. This sandstone unit varies in thickness and depth, and marks the transition zone on the major unconformity between the Jurassic and the early Cretaceous.

The basin is characterized by the presence of distinctive structures including the Sirhan-Fuluq Siwaqa, Zarqa Main, and Baqa'- Wisad fault systems. Structurally, the area is tectonically active and dominated with NW-SE, E-W, NE-SW and N-S faults and lineaments; the NW-SE and the E-W fault systems are the main ones believed to have controlled the development of the Azraq depression and Azraq Lake. The regional dip is towards northeast. Folds are relatively small with gentle dip and mainly associated with some NE faults and lineaments.

Hydrology and Hydrogeology

The town of Azraq in the center of the basin was built around an oasis formed by the emergence of groundwater spring. The oasis is the base-level of groundwater and surface water of a large part of eastern Jordan. Over recent decades, expansion of irrigated agriculture; increases in populations and, consequently, the need for water in nearby major cities such as Irbid and Amman; and raised standards of living have forced greater groundwater abstraction from the basin. This has resulted in depression of the regional groundwater table and the consequent degradation of most of the oasis.

Although there are regular, short-duration floods during winter in the wadis flowing south from Jabal al-Arab, these flows have not been measured. However, total flows have been estimated from rainfall data to average 27 million m^3/year. Although some surface water flows through the Marabs and supports natural vegetation, most of the water runs onto the mudflats of the Qa'as and is lost through evaporation. Flood frequencies and magnitudes have declined in recent years, due largely to the construction of dams on the upper reaches of the wadis in Syria. A Jordanian dam was constructed on the lower reach of Wadi Rajil in the 1980s, but the reservoir has only filled once, in the winter of 1994-95.

Groundwater Resources

Three main aquifers in the basin are the shallow aquifer, which consists of Basalt and Rijam Formations separated in places by the marls and chalk of the Shallala formation; the middle aquifer system which consists of Amman and Wadi Sir formations; and the lower (deep aquifer) which consists of the Kurnub Sandstone formation. Groundwater that discharges at Azraq is one of the major sources of water in northern and eastern Jordan.

Extraction of Groundwater

The upper aquifer contains substantial volumes of high quality, easily exploited water. In the last 20 years, there has been a significant increase in the number of irrigation wells constructed by the private sector abstracting water. On a basin scale, current extraction exceeds recharge and, therefore, groundwater is being "mined" from storage. The total volume of groundwater removed from storage is between 40 and 45 MCM/year (about 15-25 MCM/year is being pumped to the Amman area), while the calculated recharge ranges between 10 and 35 MCM/year.

The upper aquifer is being exploited beyond its safe yield, and storage depletion and water quality deterioration will continue to occur (Noble 1998). Consequently, current extraction of groundwater are already unsustainable, with a detrimental impact on the unique environment of the Azraq oasis. The piezometric groundwater level in the well field has lowered by as much as 5 m. Wells are concentrated in the three demand centers of Azraq, Umm al-Quttain, and southern Syria. Unfortunately, it was not possible to obtain an estimate of water demand from the Syrian part of the Azraq Basin.

The Amman Water and Sewage Authority drilled a well field north of Azraq Druz to avoid unwanted ecological consequences for the basin's nature reserve area and neighboring farms. Restrictions have been placed on further drilling due to the Government's uncertainty of what effects withdrawals in this area will have on the long-term quantity and quality of the spring discharge.

The Umm al-Quttain well field is located in the northwestern part of the basin, where early settlements obtained water by storing flash-flood runoff in reservoirs. This method of obtaining water has been replaced by groundwater extractions from deep boreholes. The Umm al-Quttain region is different from Azraq in that it covers a larger area of 34 villages, has an older and less sophisticated distribution system, and the water is abstracted by a widely spaced network of 11 municipal wells. Umm al-Quttain and surrounding villages have seen a dramatic increase in groundwater abstraction over the last decade. Total abstraction was 6.7 MCM in 1993, 81% of which was exported from the region.

Groundwater Chemistry

Another problem is the salinity of groundwater in both the basin and in the mud pan of Qa' Azraq (Azraq lake). Because water leaves this closed basin only by evaporation, always leaving the dissolved matter behind, salt concentrations are highly elevated in the center of the basin. Consequently, an interface between fresh and saline groundwater has developed. It is necessary to know the location and gradient of this interface to assess this danger. The geological model being developed will help re-evaluate such relations. Several wells located north of Azraq were sampled in 1993 for chemical analysis. The results indicate that the water is either sodium chloride type or calcium carbonate type. Evolution of the ion chemistry can be explained by the relatively high volume of recharge of rainwater in the north, and saline conditions further south due to infiltration of smaller volumes of water that are charged with salts derived by dissolution of evaporitic crust (Drury 1998).

Phases of the Integrated Studies

Effective watershed management cannot be carried out successfully without integrating surface with the subsurface information. With respect to the long-term, there is a need to attain sufficient knowledge of the hydrological cycle to achieve effective watershed management and conservation of the critical fresh water resources. The approach adopted as the basis of the Badia Programme to bring together a set of technologies and methodologies to focus upon a wide range of problems. This approach in watershed management consists of carrying out studies in a Manual Integration Phase, a Monitoring Phase, Development of a Geographic Information System, and a Watershed Management Phase.

Manual Integration Phase

The integrated approach brings together a set of disciplines (geology, geophysics, mineral, energy, and water resources, agriculture, and environment) and a set of technologies and methodologies to focus upon a wide range of problems. Integration of the geological and geophysical data is considered in this paper. The methodology includes the following studies and activities.

Collection of Data and Reconnaissance Studies

Collection of data involves a review of relevant literature to develop a geological data-base consisting of geomorphological, geological, geophysical, and soil data; it also includes gathering of detailed information on the previous studies and data from wells drilled for various oil, water, and mineral exploration targets. This phase includes preparing and collection the base maps, satellite images, aerial photographs, and geological maps covering the basin; gravity and magnetic maps; geoelectric maps and sections; seismic lines which include index maps for the seismic lines and paper print of the following lines: geological maps scales of 1:250,000, 1:100,000, and 1:50,000; and data concerning all the drilled boreholes for various purposes.

Photogeologic-Geomorphic Analysis and Remote Sensing Studies

The objective here is to map the basin by remote sensing and identify distinctive geomorphic, morphotectonic and geologic units, while focusing on areas of high economic potential and those suitable for agricultural purposes. Remote sensing studies using high-quality satellite photography and imagery, and manual interpretation and digital image processing of Landsat TM and MSS satellite imagery, are carried out.

The photogeologic-geomorphic analysis using aerial photographs (at a scale 1:100,000) represents one of the most comprehensive and detailed analyses of the geology of Azraq Basin. The uniqueness and value of this study stem from the set of high-quality satellite imagery used and the methodology utilized for its interpretation. The photogeologic-geomorphic study is concerned with determining the degree of influence that structure and lithology had on the morphological development of the area.

The most extensive information on the basin is presented on geomorphological and geological maps whose analysis reveals features such as surface runoff patterns, the recharge, transit, and discharge areas of groundwater, and the relationship between surface and groundwater resources. Based on 1:100,000 scale imagery, remote sensing allows geomorphic subdivisions of the area to be identified, and the boundary of the soil and rock formations to be delineated. The imagery and methodology have facilitated mapping of local and regional structures in a comprehensive fashion unique to geologic mapping from space. This mapping provides useful information for distinguishing areas or structures with the greatest exploration potential.

A study of Landsat imagery provides valuable information on the geology and hydrology of the area. Such an analysis contributes to the general knowledge of the basin's geology, the location and distribution of aquifers, and presence of geologic anomalies that can denote the presence of groundwater, mineralization, or hydrocarbons. The satellite data contributes to the accuracy of the final products, and to the speed with which geologic mapping is accomplished. Geological remote sensing techniques are being employed to minimize costs and maximize results of ground-based geologic investigation.

Land Form Analysis

In desert areas such as the Azraq Basin, outcropping rocks are often directly observable, and their characters of bedding, hardness, tone, color, setting, fracturation, and mutual relationships among different geological information can be recognized. However, thickness of superficial deposits prevent direct observation; in this case, recognition of geological features on image is based on the interpretation of the surface effects of the geological substratum. The Azraq Basin comprises two dominant landform components, volcanic basalt and sedimentary rocks shown in figure 2.

The volcanic basalt component, located in the northern part of the basin, is occupied by a terrain composed of basalt flow, volcanic centers, isolated volcanic rocks, and

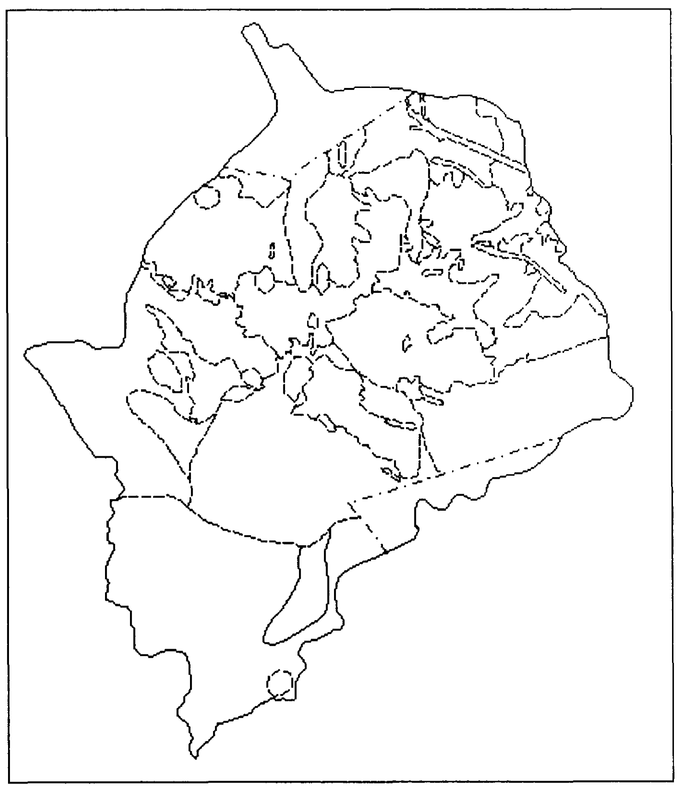

Figure 2. Physiographic Provinces of the Azraq Basin.

basaltic ridges (fissure effusion). Basalt boulders cover most of the ground surface. The size and spacing of clasts varies, with associations between lava flow type and stone cover. The component has a high density of wadis and numerous small Qa' deposits. Most wadis drain south, southwest, and southeast. In most places, continuity of cover forms a desert pavement protecting the underlying fine-grained, orange-brown sediment; in other places, boulders are much larger, approaching 50 cm in diameter, with spaces between individual clasts revealing the underlying sediment. Elevation of the basalt gradually decreases from about 1,500 m at Jebel Drouz in Syria to 1,100 m at Syrian-Jordan border to about 550 m near north of Azraq. This Basaltic Plateau has a gentle undulating surface of low relief.

The sedimentary rock component consists of an extensive flat or gently sloping flint- or chert-covered surfaces with a distinctive fern-like dendritic and drainage pattern. It is further characterized by horizontal or gently dipping limestone, marls, and chert beds which form table scarps of outliners, partially covered by unconsolidated Quaternary deposits.

These two landform components can be subdivided into zones delineated according to stratigraphy, structural evolution, types of deformation, drainage pattern, landform, fracture patterns, and image tonal characteristics. These zones represent the main landscape units as defined by data from Landsat images hard copy. The volcanic basalt has been subdivided into 14 zones and the sedimentary rocks into 6 zones as shown in figure 2.

Drainage Analysis

The drainage network map of the Azraq Basin shows several main wadis draining from all sides towards the central portion of the basin in a centripetal form. Analysis of the six basic drainage patterns (dendritic, trellis, parallel, radial, annular, and centripetal) revealed significant relationships between their pattern and the soils and bedrock of the basin and the structural setup. Fine, medium, and coarse drainage textures have been identified.

Structure and Fracture Patterns

The basin is a northwest topographic and structural depression positioned between the Jordan Arch-Central plateau region on the west and the northeastern plateau-Risha area on the east. Its shape and configuration is outlined by Tertiary and Quaternary deposits in its central axial part. Numerous faults and strong surface alignments indicate the presence of complex structural conditions beneath the young surface sediments. Several of these faults are known from seismic data to represent major structural zones of weakness in the deeper beds. Mapping of individual faults, fractures, and alignment, and their resultant areal pattern gives clues to geologic features of significance. Photogeologic-geomorphic evaluations have revealed the presence of numerous distinctive surface alignments and lineaments of varying length and trend.

Important Results of this Study Phase

One result of this phase of the study has been the preparation of updated geological maps, establishing a new classification for the basalt, and defining the exact locations of some of the most important major fault, which has a direct influence on the groundwater movement. Development of a three-dimensional geological model, shown in figure 3, is another noteworthy results. This model is an essential complement to the other hydrological data. To develop a proper structural model, it was necessary to integrate information derived from the previous mentioned studies with data derived from the subsurface (geophysical and well) data.

A key feature of the model is the Azraq depression, a prominent structural basin since the Paleozoic time. This feature, located within the Azraq Outer Basin, was formed as a result of four majors grabens and fault systems crossing the outer Azraq Basin; these are the Ghadaf-Makhruq Graben from the south, the Fuluq fault from the east, the Sirhan fault system from the west, and the Baqa'- Wisad fault system from the north. The depression is a fault-

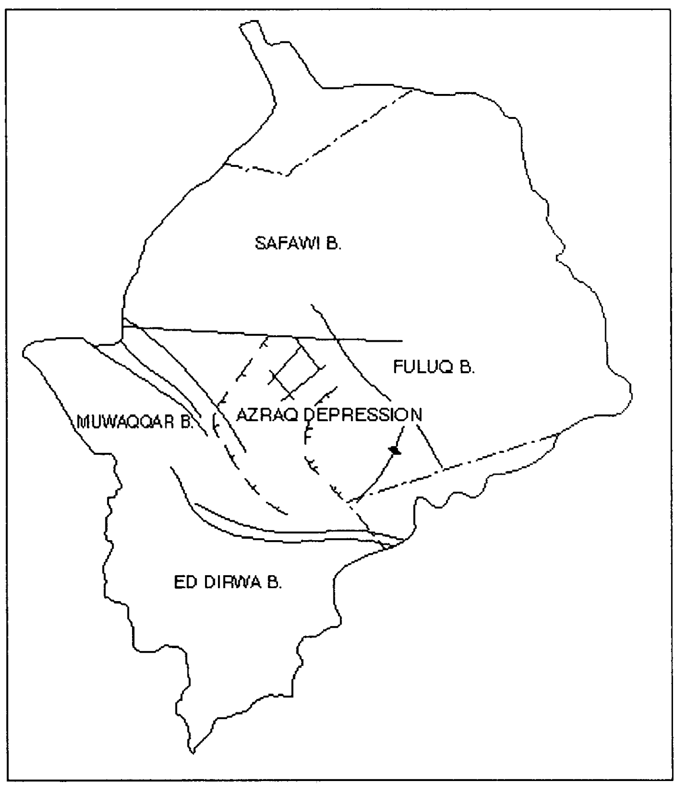

Figure 3. Geological Model of the Azraq Basin.

bounded major block with Mesozoic fill. Location of this depression within the outer basin, with the presence of the major fault systems, resulted in separating the Azraq outer basin into several blocks surrounding the central depression, including the eastern (Fuluq) block, the southern (Al Dhirwa) block, the northern (Safawi) block, and the western (Muwaqqar) block.

A comprehensive vision of water resources and structure in the Azraq Basin has also been obtained. A better definition of the geomorphic units of surface water resources has been obtained; there is an increased understanding of surface runoff processes; and the potential drainage system for surface flows has been delineated. A better geologic-hydrologic model of groundwater resources has also been obtained; a better understanding of recharge areas for the groundwater aquifers has been achieved; and, importantly, target areas for groundwater exploration have been identified.

Assumptions have been made in the development of a conceptual geologic-hydrologic model for targeting groundwater exploration in the Azraq Basin to compensate for the lack of factual information. These assumptions were that faults and joints in the bedrock influence the development of drainage patterns easily in the geomorphic evolution of the basin; that lineaments mark the location of faults and joints; that fine-grained silty clay materials transported by drainage systems are located within the central part of the basin; that a fine drainage texture indicates fine-grained sediments and areas where water infiltrate slowly; that areas close to crossing points of major faults are favorable sites for well drilling; that anomalies in vegetation, lithology, soils moisture, and that their pattern of distribution can be indicative of underlying groundwater conditions; that groundwater moves down the lower slopes, and down the alluvial valleys in the same direction as surface streams; and that the major structural features revealed by the photogeologic study are indicative of the probable control of movement and entrapment of groundwater.

Making use of existing and developing new water resources, important for the whole country, are the main aims of the integrated study. Results of the integrated studies showed that the geological succession in Azraq Basin could be hydrogeologically subdivided into lithostratigraphic units, which form systems of aquifers and aquicludes. These systems have been grouped by the Lower Deep Aquifer System, the Middle Aquifer System, and the Upper Shallow Aquifer System.

Isopach maps and structural contour maps for the top of these systems have been prepared to help identify the thickness of and depth to each system or group. Each of these systems comprises one or more aquifers. It is important to note that the subdivision into shallow, middle, and deep systems is based mainly on the geological succession, and has nothing to do with depth. Some of the deep aquifers of the middle system which are deep in the center of the basin are shallow in other parts of Jordan, or even in some of the blocks of the Azraq Basin itself. Some of the deep aquifers of the lower system are shallow as in the Disi area.

Monitoring Phase

This study phase consists of monitoring the dynamics of water replenishment by detection of direct indicators such as outcrops of the water table or the water table in water wells; or by the analysis of indirect indicators based on the surface and subsurface geological conditions and the vegetative aspect. Establishing a monitoring network utilizing the existing wells, the monitoring should continue during the management phase; in addition new monitoring boreholes need to be established.

Principal features of the monitoring strategy are to support the surface and groundwater protection strategy on the regional (also municipal, district, basin, or provincial) and the national levels. The aim of this strategy is preserving natural properties of water especially for drinking purposes; provide representative data on the current state; supply correct and accurate data to help identify the existing and potential point and diffuse pollution sources; and study the time and spatial changes in the quality of water.

Monitoring Objectives

Monitoring objectives are to identify the physical, chemical, and biological properties of the surface and groundwater; define the water resources' quality and quantity; define the effects of natural processes and human impacts on hydrogeological system; forecast long-term trends in the groundwater quality and quantity; define measures to be adopted to prevent groundwater depletion and pollution, or to restore the aquifers which have already been affected; and determine priorities and conflicts among the users of water resources and other natural resources.

Monitoring Program

The form of the monitoring program is governed mainly by the monitoring objectives, extent of the territory to be monitored, duration of the monitoring effort, and effects of the monitoring on the hydrogeological system. The monitoring program should be planned on national, regional (basins), and local (site-specific) networks.

The methods used for design and implementation of the networks depend on the objectives of the monitoring. A simplified scheme of a monitoring system in Azraq Basin is shown in figure 4. This scheme should satisfy the demand driven polices of the government.

Development of a Geographic Information System

Assembling, storing, manipulating, and displaying the collected geographically referenced information will be

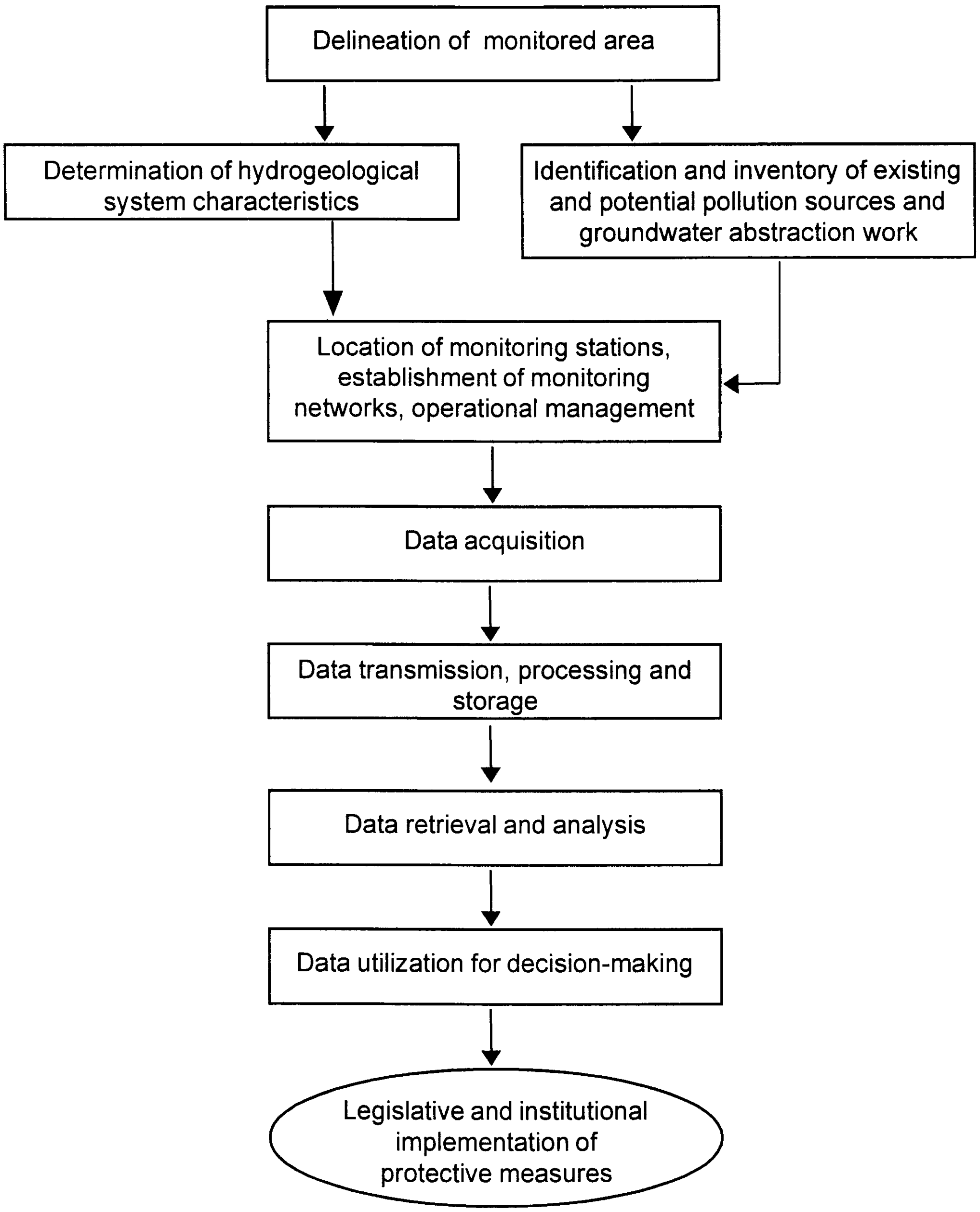

Figure 4. A simplified scheme of a monitoring system in the Azraq Basin.

the next step in the study, not only for the watershed management, but also for scientific investigations, resource management, and development planning. Development of the geographic information system (GIS) is still in progress; however, it is planned that the system will consist of relating information from different sources; capturing of data; integration of data; projection and registration; data structures and modeling; an information retrieval network; and data output. The use of GIS may encourage cooperation and communication among the agencies involved in resource management and environmental protection.

Watershed Management Phase

Watershed management efficiency can be measured by its performance. Sound management occurs when all water resources and their use in a basin is considered. Appropriate watershed management practices should be addressed within a comprehensive framework of the potential quantity and quality aspects of water and other natural resources. Since it is essential to consider the smallest development unit as a water basin for arid land development, the water resources available in the Azraq Basin should be able to support any developmental activity that takes place in the basin (table 1).

A long-term objective of this concept is to integrate such a model across the rest of the basins in Jordan. In this case, considering a National Water Carrier that is anticipated to be constructed, demands for water can be managed more efficiently. Needs can then be satisfied through a central operations unit. Another long-term objective can be achieved through sound future planning of water resources.

Table 1. A tentative water balance for the Azraq basin.

	Out (MCM/Yr)	In (MCM/Yr)	Balance (MCM/Yr)
Public Supply	28.84		
Agriculture	47.71	22.9	
Leakage	93.30	29.3	
Recharge		37	
Total (With leakage)	169.85	89.23	-80.6
Total (without leakage)	76.55	59.93	-16.62

Summary

Watershed management in the Azraq Basin incorporates all aspects of water and other natural resources (minerals, energy, and agriculture), developmental issues and various uses of both surface and groundwater resources, and other relevant environmental and economic issues. Satellite images have been useful in providing hydrological data for the analysis and evaluation of the surface water resources and major structural features revealed by the photogeologic study with respect to probable control of movement and entrapment of groundwater; maps of surface water bodies as small as several hectares to determine the extent of water reserves; a basis for surveying and monitoring of surface conditions in this large watershed as a guide to management; maps of the extent and duration of flooded areas as a basis for flood protection and land capability assessment; and a framework for the development of an operational geologic-hydrologic model. The geologic-hydrologic model should help describe the active constituents and respond to the following needs: short-term (days or weeks) to predict actual needs; medium-term (months); and long-term (years). Development of a circulation geologic-hydrologic model in connection with the other models for the rest of the basins in Jordan is also necessary.

Acknowledgments

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Water and Watershed Management in India: Policy Issues and Priority Areas for Future Research

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Abstract.—India's present food requirements of 220 million tonnes will likely increase to 340 million tonnes in 20 years. Expansion in the agriculture sector to meet these demands can be achieved only by devoting greater attention to restoring watershed lands previously degraded by excessive soil erosion to higher productivity and more efficiently utilizing the country's water resources. This challenge is intimately related to the proper management of land, water, and vegetation resources. Management of water and, more comprehensively, watershed resources is paramount to meeting this challenge. Water and watershed management in India are reviewed in this paper within the context of relevant policy issues and priority areas for future research endeavors.

Introduction

India is the seventh largest and second most populous country in the world. Bounded by the Himalayas in the north, the country stretches southwards and, at the Tropic of Cancer, tapers off into the Indian Ocean between the Bay of Bengal on the east and the Arabian Sea to the west. India has an estimated 1 billion people, which is expected to increase to 1.1 billion people in 10 years. With the growing human population and, concurrently, improvements in their consumptive levels, it is estimated that the country's present food requirements of 220 million tonnes will increase to 340 million tonnes in 20 years. Expansion in the agriculture sector to meet these demands can be achieved only by devoting greater attention to restoring watershed lands previously degraded by excessive soil erosion to higher productivity and more efficiently utilizing the country's water resources.

The challenge of restoring degraded lands, preventing soil erosion, and sustaining or, wherever possible, improving the availability of water resources is intimately related to the proper management of land, water, and vegetation resources. Management of water and, more comprehensively, watershed resources is paramount to meeting this challenge. Water and watershed management in India are reviewed in this paper within the context of relevant policy issues and priority areas for future research endeavors.

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Foreign-Assisted Projects

India has a long history of foreign-assisted watershed management projects. These projects have helped the country develop its water and watershed resources include agriculture, livestock, and forestry, and have helped foster the incorporation of watershed management contributions into better stewardship of the country's resources.

Examples

The World Bank assisted Integrated Watershed Development Project (Hills) was initiated in 1991 to lower ecological degradation by promoting sustainable rainwater conservation measures and diversified agricultural production system. This project was designed to address the integrated development of hilly areas, especially of ecologically degraded Shivalik, Karewas ranges in Haryana, Himachal Pradesh, Jammu-Kashmir, and Punjab for a period of seven years; it was subsequently extended to June 1998.

The European Economic Community-assisted Bhimtal Integrated Watershed Management Project was launched in 1991 to halt deforestation and help soil protection in the hilly districts of Utter Pradesh, which are subjected to local ecological degradation; and to meet needs of local people for fuel, fodder and timber in an ecologically sustainable manner. The Doon Valley Project assisted by European Economic Community was initiated in 1993 to arrest and, as far as possible, reverse on-going degradation of the Doon Valley environment.

The Indo-Swiss Participatory Watershed Development Project, Karnataka, was implemented in December 1995, and continued to March 1998 under support from the Swiss Development Corporation. Under the people's action for watershed management initiatives, Rajasthan, with Swiss Development Corporation support in the first phase (1996-1999), an area of 15,000 ha in the Districts of Chittorgarh and Alwar has been designated to community development. With two NGOs to facilitate planning and execution of the project an area of 1,524 ha has been developed to date.

A German Kreditanstant for Wiederaufbau (KFW) assisted Watershed Management Project is being implemented in Karnataka to restore 53,633 ha of degraded land. The program was implemented in August 1996 with the active participation of six NGOs, and will continue to the year 2002. KFW assisted watershed management in Maharashtra was implemented through NABRARD in April 1992, again, with active participation of NGOs. A project on institutional capacity-building is underway through NGOs working with KFW for replication of watershed management, with a total project cost of Rs. 251,000. The project will create institutional framework for watershed management in cooperation with NGOs.

A DANIDA aided comprehensive watershed management project, Tirunelveli, Tamail Nadu, was launched in 1990-91 to arrest further erosion of badly degraded watershed lands; and to develop sustainable and cost-effective utilization of several types of land to create long term employment opportunities for marginal farmers and landless agricultural laborers. Main components of the project are survey, extension and training, planting of shelterbelts, establishment of demonstration plots, and study tours.

A comprehensive watershed management project, Ramanathapuram, Tamil Nadu, another DANIDA aided project, was launched in 1994-95. The objectives of this project are to enable land-users in priority watersheds to practice dryland agriculture, range management, horticulture and forestry including conservation and use of natural resources on a sustainable basis. Another comprehensive watershed management project, Karnataka, again aided by DANIDA, was launched in 1990-91 to develop an appropriate land-use system through soil and moisture conservation activities; to establish tree plantation to increase the overall production in the area; and to improve the living conditions of landless, small holders and especially rural women, by increasing production of fodder, wood and minor forest products on waste lands.

A comprehensive watershed management project, Korapur, Orissa, aided by DANIDA, was launched in 1993-94. The objectives of the project are to establish sustainable and locally acceptable land-use system which are sustainable and ecologically sound. The land-use systems would enable the poorer rural communities to improve their living conditions and their supply of food, fuel and other essentials without exploiting the natural resources to harmful stress. Another comprehensive watershed management project, Madhya Pradesh, approved by DANIDA is being implemented from March 1997 for a period of five years and covers about 1,34,000 ha area in Jhabua, Dhar, Rathlam, Districts of Western Madhya Pradesh.

Lessons Learned

Lessons learned from foreign assisted watershed management projects indicate that sustainability of watershed management is possible only through peoples' participation. Therefore, to ensure people's participation and cost sharing, project priorities have to be demand-driven with sufficient flexibility. Capacity-building for technical competence of project staffs, all stakeholders from the Government of India (GOI), NGOs, and the beneficiaries for institutional development should start from the planning stage and should be a continuous process. Importantly, the role of women is crucial in watershed management, as demonstrated by the contributions of women to projects in Himachal Pradesh and Rajasthan, and also in tribal districts of Orissa.

Collaboration among donors, and donors with GOI-state governments and NGOs should be established to develop complementarity and uniformity among programs; monitoring and evaluation by independent agencies should be a part of the project activity; and if poverty alleviation and equity are the objectives of a project, the scope of the project should be widened to include infrastructure facilities and other support activities based on local potential, and the approach should be the development of a defined area on watershed basis.

Drought Mitigation Projects

Of special concern to watershed management in India is the occurrence of droughts. The first tract of drought comprising the desert and semi-arid regions in India, approximately 60 million ha in extent, forms a rectangular from Ahmedabad to Kanpur on one side and Kanpur to Jalundhar on the other. Rainfall in this region is less than 750 mm and at some places less than even 400 mm. Some of the areas in this region where irrigation is not provided, are among the worst drought affected tracts of country.

The second tract comprises of the regions east of the Western Ghats to a width of about 300 km known as the shadow areas of the Western Ghats. Rainfall in this region is less than 750 mm and highly erratic. This area is heavily populated and, therefore, the periodic drought conditions cause considerable suffering and damage. This region is bounded on the south by a line passing from Madhya (Karnataka) to Chittor (Andhra Pradesh) and on the coast by a line passing from Chittor to Tapi Basin. The Eastern Ghats are low and highly broken up in the Krishna Basin, and the semi-arid region extends along the Krishna River to within 30 km from the coast. This region is 37 million ha.

Besides the two principal areas indicated above, there are pockets of drought in several parts of India. Some of these are Tirunel Veli District, south of Vaigai River, Coimbatore area, Saurashtra and Kutch regions, Mirjapur plateau and Palamau regions, Purulia District of West Bengal, and Kalahandi region of Orissa. The scattered packets total about 10 million ha.

Drought Characteristics

The chief characteristics of drought are associated with a decrease of water availability in a particular period and over a particular area for specific use(s). To a hydrologist, drought can mean below average content in streams, reservoirs, lakes, tanks, groundwater aquifers, and soil moisture. Drought means a prolonged shortage of soil moisture in the crop root-zone to an agriculturist. The meteorologist is concerned with drought in the context of a period of below normal precipitation, and the economist is concerned with drought in the context of a period of low water supply which affects society's productive and consumptive activities.

Droughts have the four components of magnitude (average water deficiency), duration, severity (cumulative water deficiency), and frequency. Another aspect of drought is its beginning and ending. Since drought is a creeping phenomenon, making an accurate prediction of either its onset or end is a difficult task. To most observers, drought seems to start with the delay in the timing (or failure) of the rains. The commencement of hydrological drought can be delayed because of the damping effect of groundwater reserves which continue to support water flows, at least for a while after the cessation of the rainfall. It is easier to determine the end of drought, particularly when abundant rainfall saturates the soil mass, raises the flows, reservoir levels and groundwater tables.

India has witnessed consecutive droughts in the year 1985-86 and 1986-87, during which country has suffered heavily. In the drought of the year 1985-86, about 260 districts, 1,490 lakh population, and 435 lakh ha cropped area were affected; the situation was similar in 1986-87. The increasing rate of the annual expenditure on natural relief in the country is indicative of the increased incidence and recurrence of the natural disasters. The extent of damages caused by drought can be assessed from the shortage of water for domestic and livestock demands, scarcity of fodder, reduced agricultural production and the assistance sanctioned by the center or state governments for drought relief. During the years 1985-86 and 1986-87 alone, over Rs. 10,000 crores were provided as central assistance as against much smaller amount provided during early plan periods; this indicates the impact of droughts of 1985-86 and 1986-87 on the economy of the country.

Studies of Drought

A major problem involved in studies of drought and its management is that data required for drought studies are collected by different agencies. Generally, the coordination among these agencies is not to the desired extent, and as a result the information needed for planning effective strategies is not available at one place. It is necessary, therefore, to have integrated country-wide hydrological monitoring system. Such an integrated system will need to monitor all data concerning hydrological variables, water use statistics, catchment details, and socioeconomic data.

A difficulty arises in analyzing drought is due to the fact that drought occurrence depends on the interaction between the natural occurrence of hydro-meteorologic factors and the intended use of water. Different perceptions of drought from the view-points of meteorologist, agriculturist, and hydrologist is an example of this difficulty. There is a need to develop drought indices integrating the different perception of drought.

Remote sensing plays important roles in the study of drought, particularly for prediction of drought to estimate soil moisture status, evaporation rates, and biomass levels. Studies involving remote sensing techniques can be carried out and, accordingly, drought management strategies planned.

In view of frequent occurrences of drought in recent years, and considerable damages incurred as a result, attention has been directed to more careful planning for future droughts. It is in this direction that comprehensive drought response plans have been prepared in various countries throughout the world to reflect the water supply characteristics, problems of the states and potential impacts; there is a need to formulate such plans in India also. In developing such plans, it is important to identify the activities, which have relatively more importance from water availability point of view.

A number of measures based on increasing available water supplies and reducing demands, or to minimize impacts must be taken to mitigate drought consequences. All of these measures have varying degrees of effectiveness relative to the circumstances of each drought. Experiences gained from the occurrences of drought in the past might be utilized to form a judicious combination of measures, which can be helpful for mitigating the future drought and their consequences.

Water conservation needs more emphasis so as to augment existing water supply and avert critical water shortage. Water conservation campaigns through education and information dissemination are necessary to create awareness in the users, and make adoption of water conservation measures a success by inducing social acceptability; this is by far the most vital of all the means to alleviate drought problem.

Policies to Deal with Drought

During the early part of post-independence era, emphasis was placed on relief works for minimisation of impact of droughts. These programs include remission of land revenue, streamlining, communication, and providing employment through relief works and irrigation facilities. The Irrigation Commission (1972) accorded high priority to the development of irrigation facilities in drought-prone areas. The Drought-Prone Area Program was launched by the GOI in 1973 to reduce the impact of severity of drought, and to provide employment in drought-prone areas. A program for Minor Irrigation Works has been underway since 1983-84 under centrally sponsored small and Marginal Farmers Assistance Program.

For inter-basin water transfer, the idea of National Water Grid, was mooted by Rao and Kathuria (1992), who proposed to provide a Ganga-Cauvery link. This proposal involved net power requirements of 5 kw, which the country could not afford; the proposal, therefore, was not considered. Captain Dinshah Dastur presented a proposal for Garland Canal Scheme. Although in concept it was interesting, it was technically unsound and economically prohibitive. Hence, this proposal was also dropped. The Ministry of Irrigation, presently the Ministry of Water Resources, evolved a National Perspective Plan in 1980 for creation of optimum storages linking various river systems to provide multi-purpose benefits.

The National Perspective Plan envisages a broad approach to the existing uses, to allow normal water development under existing legal and constitutional frame work to meet reasonable needs of the basins and the states for the foreseeable future; this would help achieve the most efficient use of land and water to plan optimum development of available storage sites, and to transfer over long distance by linking various systems so that drought affected and backward areas are assured a minimum supply of water. As a first step towards taking up the National Perspective Plan, a center has set up a National Water Development Agency to undertake detailed surveys and investigations to determine the feasibility of the proposal of Peninsular River Development, and prepare reports of various components of the scheme.

Commenting on the National Perspective Plan, Rao (1981) observed that the cost of Rs. 500 billion for the project, though a great under estimate is too astronomical and astounding for the country; the expenditure involved is too high in relation to the benefits of irrigation, power generation, etc. He suggested various water management measures such as increasing irrigation efficiency, implementing water harvesting, installation of pump canals, changes in cropping patterns, and adoption of dryland technologies to bring more benefits that envisaged in the perspective plan without legal, constitutional or social problems.

It has been proposed that a Drought Mitigation Program should be launched to mitigate the impact of drought over a period of time, to optimize the utilization of all resources for crop production in the areas, and to improve the living standards of the rural poor suffering the catastrophe. Development strategies should be aimed at removing regional imbalances in the country by improving the overall productivity and restoring a proper ecological balance to the drought-prone areas through development and management of irrigation sources; initiating soil and water conservation and afforestation programs; modifying the cropping pattern and pasture development, livestock development; and development of small and marginal farmers. A critical assessment of prevailing water use policies and practices at various levels and for various purposes is needed for developing guidelines for better use as part of the overall development strategy. The roles of information and communication technology need to be acknowledged for disseminating information and knowledge regarding the existing status, problems, and opportunities for improving the management of India's scarce water resources. The GOI should examine various alternative plans for inter-basin water transfer in close co-ordination with state governments to finalize most feasible plan considering economical, social, environmental, technical and other factors.

Socioeconomic Development Programs

Activities presently undertaken in watershed management projects for the poor and women do not empower them to be equal partners with men. Unless we progress from the attitude that the poor and women are to be treated as disadvantaged to the point where they are treated as integral members of the community, and involve them in decisionmaking, watershed management projects will continue to remain welfare-oriented as far as the poor and women are concerned.

Women are disadvantaged because their contribution to the rural economy is not recognized. Consequently, they do not receive their rightful compensation in terms of wages, or in terms of ownership of productive assets and benefits accrued from them. The importance of increasing women's participation in watershed management projects has been recognized, and efforts are being made in this direction. However, there is still a need to sensitize policy-makers and the staffs of project implementing agencies (PIAs) to understand the core issues related to ensuring benefits to poor and women from watershed management projects.

Main Issues

Programs for agriculture development have always targeted men rather than women, since women are rarely looked upon as farmers. In watershed management, too, it is the farmers who first come forward to participate in the programs. Women perform more tasks and spend more hours than men in agricultural production; we need to recognize that they are farmers, too. Since women rarely own or control productive assets, they are not looked upon as decisionmakers in the management of natural resources. Common-property resources provide women with livelihood options that are not always visible. Restrictions on access to common-property resources increases drudgery in fuel and fodder collection, and reduces the livelihood options available to women. An assessment of the interface between livelihoods and the resource base would help to keep in focus issues related to the economic survival of women resource users, through both the planning and implementation stages of the project.

The number of women appointed to Watershed Committees has been largely token, since one or two women on male dominated committees are unable to effectively contribute to the decisionmaking process. Besides, one or two women from the community usually do not represent the interests of all the women in the community. Women-area heterogeneous group, and women from different sectors of the community have different needs. Women are often unable to participate in community activities without the support of their families. It is the responsibility of the PIAs to facilitate the participation of women in community activities by setting up support systems. It is also important, therefore, for the PIAs to have specially trained staff.

Since watershed management has a central technical component, it is important that women are also given technical training, so that they have the option to move up in the decisionmaking hierarchy set up for the implementation of projects. Another important area that needs to be looked into is that of equity issues in wage employment in watershed management programs. Disparities are found in wages paid to men and women for agricultural labor and physical works undertaken in the project. Gender disparities also arise from the unequal distribution of ownership and control of productive assets between men and women. If decisions related to access and sharing of resources remain in the hands of men, it is likely that women will never receive their share of benefits from these resources. It is difficult to address issues related to inter-household benefit sharing, but attempts can certainly be made to improve intra-household benefit sharing for women through community projects.

Recommendations

Watershed management projects should be implemented in two stages. During the first stage, the PIAs should understand the community, conduct a livelihood-resource survey, and build women's organizations. The budget provided for entry-point activities could be used for this. In addition, some extra budget could be provided for capacity-building for PIAs' staffs. The second stage should consist of the implementation of project activities. The implementation should be performance- and target-oriented, with monitoring and evaluation being an integral part.

Proposals submitted by the PIAs should indicate how under-privileged and women's issues will be addressed, and what should be the indicators of success for the integration of gender in the program. The budget available for activities for women is normally only a small percentage of the total budget. Therefore, funds should be available for strengthening women's groups. Livelihood options should be provided to women through appropriate income generating activities. To create an environment for, and facilitate the participation of the poor and women in village-level committees, the representation of women should be made 50%. Capacity-building for PIA staff, village leaders, motivators, and committee members should be emphasized.

Opportunities For Future Programs

Since the end of the 1970s, important changes of a positive nature have taken place in India regarding soil and water conservation policies. These changes came as a result of an increase in the awareness at the high decisionmaking level towards the seriousness of the country's erosion problems and the urgency to solve them. However, a greater effort is needed in terms of improving the institutional weaknesses and capacity-building; special emphasis has been placed on building the capacity for effective watershed management programs.

Capacity Building

Human resources development (HRD) is one of the important approaches in watershed management. It is essential for effective and sensitive implementation of the watershed management; more successful experiences in India illustrate that HRD and institutional capacity-building is a critical factor for peoples' participation and sustainable development. In the last 50 years experience of soil and water conservation in India, capacity-building means that the competence of individuals and organizations are augmented to enable those implementing watershed management projects to work together responsibility. Similarly, capacity-building means that individuals and institutions supporting the watershed project are enabled to facilitate project implementation sensitively and become more responsive and flexible in delivering services.

Capacity-building can be considered in three categories. *Individual capacity-building* deals with knowledge, attitude, technical, managerial, and participatory skills, and job-related, field-oriented operational skills which are crucial for all implementors and individuals at whatever level they work; these cut across all types of organizations. Organizational capacity-building is necessary whether it is a government department, NGO, or any other organization. For an organization to become more effective and have better capabilities, all individuals should go through individual capacity-building within the organization. Internal management procedures should be revamped and improved as necessary to make them more flexible and responsive in the light of the aim of capacity-building in watershed management; this includes the whole gamut of human-resource management policies starting with recruitment, placement, promotions, and incentives, and organizational restructuring of the organizations. Institutional capacity-building is also important, since institutional arrangements need to be improved to support both individuals and organizations to deliver whatever needed services. These improvements can be done through linkages and coordination mechanisms, setting up new institutions, technical and financial support and enabling policy environment.

Key Issues

The key issues (questions) in capacity-building are whether the present balance between "hardware" and "software" of watershed management projects is appropriate in terms of allocation of time, funds, manpower and attention; and whether everyone agrees on what needs to be done for improving the quality of watershed management. It should be kept in mind that scaling-up involves massive reorientations of the government and other development agencies, considering that the strategies should be adopted to make the best use of training infrastructures, facilities, and training materials and methodologies; and that the roles played by the GOI, state governments, NGOs, and donors in this strategy be known.

Future Directions

Future directions of capacity-building can be viewed at watershed, district, state, and national levels. At the *watershed level*, PIAs should focus on the capacity-building needs of the watershed communities and follow a bottom-up, demand-based, step-by-step approach. PIAs should also expand the scope of capacity-building for watershed communities to cover integrated water-use management, animal husbandry, horticulture and other production systems, and land-use systems to improve livelihood sustainability. PIAs should use progressive farmers-villagers as resource persons and pay for their opportunity cost to develop them as a sustainable alternative.

Need-based exposure visits to successful watershed management projects should also be organized. PIAs might draw upon other project staffs or district-level training centers for resource persons. Specialized need-based packages should be developed for local Water Associations and Watershed Committees. And, importantly, the village watershed communities should be involved in developing and monitoring their own monitoring and evaluation indicators.

Attempts should be made to use progressive PIAs as exposure centers and resource persons for the sustainability of capacity-building at the district level. Orientation programs should be run for the Panchyat Raj institution functionaries to enlist their cooperation. District authorities should act as a clearing house for information, support and coordination of training centers, resource persons, and materials and methods within the district, and coordinate all activities at the district level.

State governments should play a lead role in coordinating the efforts of state training institutions, support NGOs in identification of training needs at the *state level*, upgrade and equip training infrastructures, develop faculty skills, and ensure synergy and optimum capacity utilization. State governments need to make sure that all key functionaries at the state and district levels are fully sensitized and trained. State training institutions should run only orientation and sensitization programs for senior officials at their headquarters.

Guidelines at the *national level* need to be amended to incorporate more comprehensive watershed-based development, which is likely to lead to more sustainable rural livelihood. Attempts should be made to amend these guidelines to provide for a discrete second stage of capacity-building for the PIAs in the project approval cycle; this might slow down the program but would ensure quality and more sustainable development. Participatory mechanisms should be set up for thorough reviews of the guidelines to incorporate earlier experiences. Capacity-building coordination units need to be strengthen to enable them to play the critical role of clearing house in the capacity-building sector.

Education and Training

Watershed management is not presently included as a separate specialization in formal courses in India. It is, however, being increasingly covered in undergraduate and post-graduate courses. Opportunities are generally offered at agricultural universities, with courses offered on soil conservation and watershed management by faculties of agricultural engineering, agronomy, and soil science; at IIT, Kharagpur, through the Departments of Agricultural Engineering and WTC of IARI; at engineering universities, like Roorkee through the Department of Hydrology and Water Resources Development Center; and at IARI, Delhi, IIT Kharagpur, University Roorkee, IIM, Ahmedabad, Anna University, Guindy, and agricultural universities.

In the absence of facilities with formal educational institutes, SCB created facilities and offered foundation courses in watershed management in the early 1950s. These courses were designed to inculcate multidisciplinary perception and on-the-job competence to the officials of the Departments of Soil Conservation, Agriculture, Forests, Agricultural Engineering, and Land Development Corporations. The courses covered elements of watershed management from the broad-subject matter areas of soil and water conservation including agro-meteorology, watershed hydrology, and sedimentation; to soil science and land-use survey, including aerial photo interpretation, land evaluation, and amendments for reclamation conservation cropping; to conservation techniques involving agroforestry, agrostology, and horticulture; and to conservation forestry, farm forestry, fuel and fodder production, and pasture development.

These courses, for durations of 3 months to one year, include classroom discourses; field practicals; project-oriented work covering investigation, surveying, and planning; and study tours to acquaint the participants with diverse problems in different soil and water conservation regions and with indigenous variations in remedial measures.

Summary

The major objectives of watershed management programs in India are to retard environmental degradation to permissible limits, and to increase biomass production to optimum levels. Meeting these two objectives help in achieving sustainable overall production on watershed lands. However, there is large variability in the types of biomass, degradation and biological factors, and their interactions. For a successful management strategy, it is necessary to understand and quantify these interactions in space and time. Experiences over last five decades in watershed development, water management, and biomass production are exhaustive. But, most of these experiences are the outcome of sectoral and short-term goal-oriented programs, which are incompatible to the sustainability concept; or, are not pursued enough to result in their acceptance and adoption by people. There are a few field-level successes which hint at the need for a change towards people-oriented programs in watershed management for achieving sustainability of these programs; however, this calls for reorienting our research approach to fulfil this gap.

Major research issues to be addressed in developing appropriate implementation procedures and activity schedules for watershed-based development and management include tools for measuring the overall degradation of natural resources; methodologies for assessing biomass production through a single index; models for determining temporal-water availability on watersheds; tools and models for assessing water requirements of plants on watershed lands; detailed analyses of farming systems and their development in relation to environmental sustainability; analyses of irrigation systems in relation to water availability potentials and management; prescribing energy management practices through systems analysis approaches and mechanization; evaluating the impacts of use of inorganic fertilizer, insecticide, pesticide and imported water on natural resources and environment; and developing measures of the socioeconomic status of the inhabitants of watershed lands.

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SYNTHESIS PAPERS

A Retrospective Viewpoint

Changing Perceptions of Watershed Management from a Retrospective Viewpoint

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Abstract.—Watershed management, an ancient concept, was defined in Vedic texts from India that date from 1,000 B.C. This concept has been an integral part of forest and rangeland management in North America throughout the 20th century, but its scope has broadened significantly. Although the Forest Reserve Act of 1891 created the reserves that were to become the core of the National Forest System, it was the Pettigrew Amendment to the 1897 Sundry Civil Appropriations Bill that defined the purpose of the forest reserves. The amendment stated that the reserves could be established only to "...improve and protect the forest within the reservation, or for the purpose of securing favorable conditions of water flows...." Clearly, the interpretation of watershed management within the context of forestry in 1897 was for water supply and flood prevention. By mid-century, forest and watershed management had broadened to encompass recreation, range, wildlife, and fish purposes (Multiple Use Act of 1960). In the latter quarter of the 20th century, legislation, like the National Forest Management Act, National Environmental Protection Act, the Clean Water Act, and the Endangered Species Act, and concepts like ecosystem management have further broadened the goals and importance of watershed management beyond that of water supply production and flood prevention.

Introduction

"Water is the best of all things."
Greek Poet Pindar 522 to 433 B.C.

"We made water everything."
The Koran 632 A.D.

Meinzer (1942) described hydrology and its central concept of the hydrologic cycle as the science that relates to water. He also noted that hydrology is mostly concerned with the course of water from the time it is precipitated on land and flows into the sea or is evaporated. Wisler and Brater (1963) defined hydrology as, "...the science that deals with the processes governing the depletion and replenishment of the water resources of the land areas of the earth." Although the physical processes of the hydrologic cycle have been active since the formation of the earth, rapidly expanding human activities and management of the landscapes have profoundly interacted with hydrology to affect the planet and human habitat. An understanding of hydrology is the key to an endeavor of much greater importance, watershed management.

Watershed management, often thought of as a 20th century development, is rooted in the history of human civilization. Indian texts from Vedic times (1,000 B.C.) indicated an understanding of the hydrologic cycle, the concept upon which the modern science of hydrology is based (Chandra 1990). There is a verse in the Atharva Veda texts from 800 B.C. that can be considered the first definition of watershed management. Atharva Veda verse 19,2.1 states that:

> "...one should take proper managerial action to use and conserve water from mountains, wells, rivers and also rainwater for use in drinking, agriculture, industries..." (Chandra 1990).

Another text directed the king to build canals across mountains to provide water for his subjects for agriculture, industry, and to facilitate navigation; evidence of the first of many government water development projects in the course of human history. Later texts from around 400 B.C. describe the measurement of rainfall. These texts indicate that civilization in the Indian sub-continent had evolved from one at the mercy of climate to one of active water and watershed management.

The development of cities in the Middle East and the Mediterranean Sea basin depended upon the agricultural revolution, and also upon water management (Illich 1986). There is mention in Egyptian texts of well development and extension as early as 2,500 B.C. The Minoan (1700 B.C.) and Mycenaean (1400 B.C.) civilizations of Crete and Greece had a good understanding of water management as indicated by the extensive water facilities they created for their cities (Tainter 1988). Cities like Ninevah and Troy had aqueducts too bring water from 10 to 80 km away in the 7th and 6th centuries B.C. . Rome, founded in 441 B.C., initially used the Tiber River, springs, and wells for its water supply. The first aqueduct supplying Rome was built in 312 B.C. By 97 A.D., Rome was a city of over 1 million people with 9 aqueducts 400 km in length bringing in 450 L / person / day of fresh water. Continued population expansion in Rome necessitated the construction of an additional 5 aqueducts by 300 A.D.

Watershed management and engineering skills declined with the collapse of Rome and the entry of Western European civilization into the Dark Ages. Hundreds of

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years passed before watershed management skills were regenerated. In 1215, King Louis the VI of France promulgated an ordinance The Decree of Waters and Forests in recognition of the interrelationships between water and forests (Kittredge 1948).

During the Renaissance and subsequent periods, observation, measurement, and experimentation with water resources expanded. The Swiss were leaders in the resurrection of watershed management in Europe. The first watershed protection forests were set aside in 1342 (Kittredge 1948). Between 1535 and 1777, Switzerland set aside 322 forests as watershed reserves and avalanche protection zones. Men of science, such as Leonardo Da Vinci (Italy), Bernard Palissy (France), Edmund Halley (England), rediscovered the philosophical musings on the hydrologic cycle produced by Greek and Roman scholars such as Homer, Plato, Aristotle, Lucretius, Seneca, and Pliny (Chow 1964). French and Italian scientists published treatises between 1801 and 1840 that recognized the relationships between hydrology, vegetation, and climate, and the serious erosional impacts of deforestation. The German naturalist Von Humbolt (1849) made a remark in a publication of his that indicated that the concept of watershed management was well developed again in European scientific circles. He said, "How foolish do men appear destroying the forest cover of the world without regard to consequences, for they rob themselves of wood and water." But as late as 1826, Paris could only supply 3 L / person / day to its population (Illich 1986). London's water supply capacity was only 37 L / person / day by 1936.

In the western hemisphere, early Native American cultures made substantial achievements in watershed management. Between 200 B.C. and 700 A.D., the Huari and Tiahuanaco empires of Peru and Bolivia built extensive irrigation canals and agricultural terracing to create a large artificial agricultural landscape to support their burgeoning populations (Tainter 1988). The Inca civilization that followed these 2 empires had cities of 200,000 people supplied with water by lengthy aqueducts (Kerr 1960). These cities had conveniences, such as subterranean sewerage, drainage systems, indoor running water, and toilets, long before the major cities of Renaissance Europe.

The Mayan culture (1,000 B.C. to 1,000 A.D.) of the Southern Lowlands of Mexico modified their landscapes extensively to provide water for Ramon tree, maize, squash, avocado, cacao, and cotton agriculture (Tainter 1988). Up to 2,500 km^2 of the southern lowlands were modified by canal systems that brought water into agricultural areas during dry seasons. Nearly 180 km of transportation canals were dug to move raw materials and agricultural produce.

The Hohokam culture that occupied areas of the Sonoran Desert in Arizona from 600 to 1200 A.D. was noteworthy among North American native peoples for its development of extensive networks of irrigation canals (Reid and Whittlesey 1997). The River Hohokam living near Phoenix were the first to develop canal systems to irrigate their corn, bean, and squash crops in the arid Sonoran Desert that averaged less than 200 mm of annual precipitation (McGuire 1982). The Hohokam learned to modify their habitat with irrigation canals. These systems contained main canals up to 10 m wide and 2 m deep, smaller secondary canals, and numerous feeder ditches. One network that was 240 km in total length contained 50 main canals, some as long as 26 km. For their low level of technology, the Hohokam were amazing. They were the first to practice watershed management in Arizona. More watershed managers would arrive in the state in the 19th and 20th centuries.

Late 19th Century

> "No one knows the value of water until he is deprived of it"
>
> *David Livingstone 1813 to 1873*

Water deprivation strongly influenced the Mormon view of water and watershed management during their settlement of the Great Salt Lake Valley in Utah. Arriving in 1846, they found a desert landscape next to a salt sea. The Mormons launched into water development projects with a fervor that by the turn of the century would result in 2.4 million ha of irrigated agriculture in several states. The experience of the Mormons would significantly affect the viewpoints and approaches of U.S. Bureau of Reclamation water development programs through much of the 20th Century.

Watershed management in the United States gained a strong foothold with the creation of the national forests. The Forest Reserve Act of 1891 created the reserves that were to become the core of the National Forest System (Steen 1976). During deliberations on the bill before Congress, Secretary of the Interior John W. Noble, at the urging of Bernhard E, Fernow, personally intervened to add Section 24 authorizing the President to create forest reserves. By the end of 1892, President Harrison had added 15 reserves totaling 5.3 million ha, primarily to protect water supplies. In 1896, the forest reserves were up to 8.1 million ha. President Cleveland initiated a land reservation furor by adding another 8.5 million ha in early 1897.

It was the Pettigrew Amendment to the 1897 Sundry Civil Appropriations Bill that defined the purpose of the forest reserves (Steen 1976). The amendment stated that the reserves could be established only to, "...improve and protect the forest within the reservation, or for the purpose of securing favorable conditions of water flows....” By 1897, the interpretation of watershed management within the context of forestry was for water supply and flood prevention.

Early 20th Century (1900 to 1930)

> “Whiskey is for drinking, water is for fighting over.”
>
> *Unknown Arizona Cowboy 1901*

The early 20th century was unique in that it experienced the beginnings of watershed management research. The Sperbelgraben and Rappengraben experimental catchments were established in 1903 near Emmental, Switzerland (Penman 1963). This was followed by establishment of the Ota watershed study in Japan in 1908 and the Wagon Wheel Gap study in Colorado, in 1910. This period was also notable for a number of legislative actions that affected watershed management in the United States.

The Reclamation Act of 1902 was passed to increase settlement of large areas of public land in the western United States through public works watershed management projects (Reisner 1986). This approach involved Federal government construction of reservoirs and irrigation canals on a large scale throughout the arid western USA for agricultural and municipal use. The legislation created the Reclamation Service, which floundered repeatedly as a government enterprise until it was transformed into the Bureau of Reclamation in 1923 and received major infusions of public works funds during the 1930s Depression.

The Weeks Law of 1911 recognized the value of vegetation covered watersheds and ended most of the legislative debate caused by Presidential reservations of forest land in the last decade of the 19th Century. This act authorized the President to, “...reserve any part of the public lands wholly or in part covered with timber or undergrowth, whether of commercial value or not, as public reservations.” (Kittredge 1948, Steen 1976).

The purpose of the Weeks Law was to protect navigable waterways from the ravages of floods emanating from denuded landscapes (Steen 1976). This law recognized that poorly managed watersheds increased flood flows and produced considerable fluvial and riparian damage. The law encouraged watershed management by designation of forest reserves that were to be managed for their water resource values. However, the most important part of the Weeks Law was scarcely discussed in the heated congressional debates. Section 2 authorized federal matching funds for state forest lands, and their management agencies, within the watersheds of navigable streams. This section created the whole concept of cooperation of the federal government with state agencies for watershed management improvement.

The Clark McNary Act of 1924 added another twist to the watershed management efforts of the federal government (Steen 1976). At that time, the 323.8 million ha of forest standing at time of European settlement had been reduced to less than 56.7 million ha of unlogged stands and 32.8 million ha of barren, logged-over shrubland in poor hydrologic condition. The Clark McNary Act offered incentives to state and private landowners to restore their forests by reforesting their logged-over lands to improve timber production and watershed protection.

Mid 20th Century (1930 to 1970)

> “In the old days, ranchers shot each other for water. Today it is a lot tougher. Bureaucrats are in charge.”
>
> *Will Rogers 1879 to 1935*

The mid 20th century in the United States saw a tremendous amount of activity and investment by federal government agencies in watershed management. The principal agencies that were leaders in watershed management programs were the U.S. Bureau of Reclamation, the Soil Conservation Service, the U.S. Army Corps of Engineers, and the USDA Forest Service.

At this time period, the Forest Service was active in watershed management through its various watershed programs to manage existing forests and to acquire and rehabilitate abandoned and eroded lands. Major watershed management research investments were made at the Coweeta Hydrologic Laboratory (1933) and the San Dimas (1933), Sierra Ancha (1932), Hubbard Brook (1963), Fernow (1934), Fraser (1937), Beaver Creek (1957), and H.J. Andrews (1948) experimental forests.

A major proponent of watershed management by water development in the Western United States was the U.S. Bureau of Reclamation. As recounted by Reisner’s (1986) The Cadillac Desert, this period began with completion of the Hoover Dam on the Colorado River and ended with the filling of Lake Powell behind the Glen Canyon Dam. In between these actions, numerous dams and irrigation developments were completed on every major river system in the Western United States (Colorado, Columbia, Yellowstone-Missouri, Sacramento, etc.). Most of this development (85%) conducted by the Bureau of Reclamation was targeted for agricultural irrigation, with the remainder for municipal water supplies. The dams also provided attenuation of flood peaks and relatively inexpensive electrical power to support urbanization of much of the Western United States. California alone had 1,251 reservoirs constructed by the end of this mid century period (Reisner 1986). Unfortunately, this narrow view of watershed management as water development did not consider ecological impacts to aquatic and riparian biota. There would be a complete rethinking of the values of water development relative to ecological impacts by the end of the century .

The Dust Bowl of the Great Plains in the early 1930s was the impetus for the Soil Conservation Act of 1935 that created the Soil Conservation Service. The mission of the Soil Conservation Service (now the Natural Resources Conservation Service) was to provide for the control and prevention of soil erosion at a national scale (Steiner 1987). The objectives of its soil-based watershed management programs were, from the beginning, to preserve natural resources, control floods, prevent reservoir impairment, maintain river and harbor navigability, and protect public health and lands. The Flood Control Act of 1936 mandated the Soil Conservation Service to conduct watershed management programs on upstream areas to reduce flooding. The Watershed Protection and Flood Prevention Act of 1954 created the small watershed restoration and management program that worked with both private and public landowners to maintain or improve soil productivity conditions and reduce destructive flood flows (Held and Clawson 1965). A decade after implementation, the small watershed program (headwater catchments smaller than 101,000 ha) included 2,088 projects on 60.7 million ha.

The Flood Control Act of 1936, which asserted federal responsibility for flood control on navigable rivers and their tributaries, dramatically initiated involvement of the U.S. Army Corps of Engineers in the watershed management arena (Leopold and Maddock 1954). The act stated that watershed improvement is in the best interest of the country, and that flood control is a proper federal function. The approach of the Corps to watershed management was through large structure engineering to control floods and erosion on the downstream portions of large watersheds. The Corps of Engineers program often conflicted with that of the Soil Conservation Service due to a lack of definition of the boundary between the responsibilities of each agency within individual watersheds.

Stoddart and Smith's (1943) treatise on range management defined that profession as the science and art of planning and directing the use of rangeland vegetation to obtain the maximum sustained livestock production while conserving the multiple resources of the landscape. They recognized that the inherent nature of range management is watershed management when they stated that, "One of the most important but at the same time least realized functions of natural vegetation is the protection of the watersheds and the conservation of soil and water."

Stoddart and Smith (1943) commented that at mid century about 85% of the streamflow in the Western United States was from lands that were 79% actively managed rangelands. They pointed out very clearly at the beginning of their text that a prerequisite of good range management is maintenance of good range vegetation conditions to ensure optimum multiple use of watersheds. Indeed, they believed that the most important function of range management is the protection of watersheds that are used for water supply.

Kittredge (1948) substantive milestone work on forest influences used the 1944 Society of American Foresters definition of watershed management (SAF 1944). He stated that watershed management is, "...the administration and regulation of the aggregate resources of a drainage basin for the production of water and the control of erosion, streamflow, and floods." This definition has a heavy commodity (water supply) and protection of human values (erosion control, flood protection, etc.) emphasis. Kittredge (1948) elaborated on the definition by outlining 4 phases of watershed management. He identified these phases as resource recognition (surveying, location, etc.), restoration (correction of unstable conditions), protection (guarding from disturbance and maintenance of existing conditions), and improvement (practices to increase water yield). Although this definition incorporated concepts (restoration and protection) that would grow in importance in the latter part of the century, the emphasis was clearly on the commodity of water.

Francois (1950) commented on the objectives of forest watershed protection and management policies in a United Nations report on forest policies in Europe. He recognized the values of non-commodity products when he stated that forest management policy should, "...provide for the protective, productive, and accessory (recreation, aesthetics, and wildlife habitat) of the forest, as well as for changing demands for wood and the other products and benefits of forest land." Pavari (1962) expanded on the thoughts of Francois (1950) concerning the relationships between forestry and watershed management by saying that, "The objective today is not only to establish forests of proper size and character to protect the soil, the climate, and the water resources of a country and to meet the nation's requirements for wood, water, and other products; it is also to secure the fullest use of all lands in the general interest of the country."

Colman (1953) produced a major synthesis of the effects of vegetation management on hydrologic processes and water yield. His approach to watershed management focused on the importance of manipulating vegetation to alter hydrologic processes and to achieve watershed management goals. He stated that:

> "The need for control over water yield arises because of the development of population

centers, industry, and agriculture. All of these need protection against floods, and all need water of proper quality delivered in sufficient quantity at the right time."

The International Glossary of Hydrology (WMO/ UNESCO 1969) presented a very simple definition of watershed management. It states that watershed management is the, "...planned use of drainage basins in accordance with pre-determined objectives."

Although the mid 20th century in the United States is noted for the great water development projects of the Bureau of Reclamation, this period also saw the rise of a land ethic and a consideration for ecological consequences in watershed management (Leopold 1949). Aldo Leopold's concept of land ethics took watershed management beyond the economic, commodity driven approach to watershed resources. He noted that:

> "All ethics so far evolved rest upon a single premise: that the individual is a member of a community of interdependent parts. The land ethic simply enlarges the boundaries of the community to include soils, waters, plants, and animals, or collectively: the land."

He further stated that:

> "In short, a land ethic changes the role of *Homo sapiens* from conqueror of the land-community to plain member and citizen of it. It implies respect for his fellow-members, and also respect for the community as such."

The key point of his message was that, "Conservation is a state of harmony between men and land." Leopold bemoaned the fact that conservation was moving ahead at a snail's pace. What he was asking for was a monumental change in our approach to land (watershed) management. Leopold noted that, "No important change in ethics was ever accomplished without an internal change in our intellectual emphasis, loyalties, affections, and convictions." He challenged land managers to move from a purely economic, commodity paradigm to one of holistic ecosystem management.

On June 12, 1960, President Eisenhower signed into law the Multiple-Use Sustained Yield Act. For the first time, the 5 major uses of watersheds (wood, water, wildlife, range, and recreation) were specifically mentioned in one federal law (Steen 1976). The Multiple-Use Act contained the concept that national forest management did not have a resource priority, instead of all resource uses should be managed for their sustainability. Four decades later we still struggle to incorporate those concepts into action on the ground. However, the Multiple-Use Act did broaden the objectives of watershed management.

Ogrosky and Mockus (1964), in a paper on agricultural hydrology that appeared in V.T. Chow's 1964 Manual of Hydrology, defined watershed management as, "Management of a small watershed to conserve soil and water resources that the land be used within its capabilities and treated according to its needs." In another paper in Chow's 1964 volume, Dixon (1964) referred to watershed management as, "...the conservation and improvement of the soil, sediment abatement, runoff retardation, forest and grassland improvement, and protection of water supplies." Both of these definitions focused on the physical aspects of watershed management without biological or ecological considerations.

In the late 1960s, Dortignac (1967), head of the Water Resource Branch, USDA Forest Service, stated that the discipline of watershed management was on the threshold of great opportunity in land management, since the water supply inadequacies previously only a problem in arid and semi-arid regions of the United States had suddenly arrived on the doorstep of the humid eastern United States. He believed that watershed management on forests, shrublands, and untilled grasslands could make a substantial contribution to improving water supplies. Dortignac said that:

> "Watershed management can play an important role under the present increasing population pressures and the public demand for greater productivity and multiple use of forest and related lands. Scientific prescriptions that utilize the wood, forage, wildlife, and recreation resources as well as improve water yields and control, maintain, or improve soil stability provide the means." (Dortignac 1967).

Dortignac's views of watershed management were affected by the multiple use philosophy of the mid century and the importance of water as a commodity. However, his views reflected a holistic view of the discipline. He considered that practice watershed management was of greater importance than reactive management to repair or mitigate human mistakes.

Late 20th Century (1970 to 2000)

> "If we solve every other problem in the Middle East but do not satisfactorily resolve the water problem, our region will explode."
>
> *Yitzhak Rabin 1922 to 1995*

John Bullein (1562) noted that, "Water is a very good servant, but it is a cruel master." (Mencken 1966). At the end of the 20th century, water has become increasingly cruel to the human inhabitants of the planet. Although no water wars have broken out in the 20th century, human suffering at the hand of this cruel master is continuing to increase. United Nations estimates indicate that 9,500 children die each day due to lack of water or water pollution (Simon 1998). Others place the child death rate at 2 to 4 times that figure because of water-borne diseases like malaria, diarrhea, and schistosomiasis. As Clarke (1991) points out, 51% of the countries in the world have low to very low fresh water availability (<5,000 m^3/person/year). Because of simple watershed management errors, ecological disaster has occurred in the Aral Sea area of the Russian Federation (Aronson 1998). Stream diversions for cotton agriculture starting in the 1950s prevented the world's 4th largest lake from keeping up with 33 to 36 km^3 of annual evaporation. The result has been shrinkage of this body of water to half its former size, isolation of coastal villages and destruction of the pre-diversion local economy, extinction of 20 fish species, and a 30- to 60-fold increase in human kidney, liver, arthritic, and bronchial diseases.

The World Bank uses the watershed management approach in assessing the environmental benefits of development projects (Brooks et al. 1992). This organization believes that this approach is the key to identifying the linkages between landscape improvements, productivity increases, and attainment of true natural resource sustainability. Their definition of watershed management is that it:

> "...is the process of guiding and organizing the use of the land and other resources on a watershed to provide desired goods and services without harming soil and water resources. The interrelationships among land use, soil, and water, and the linkages between uplands and downstream areas are recognized in this concept."

The World Bank recognizes that, as part of the watershed management approach, people are affected by the interaction of water with other resources, and they influence the nature and magnitude of those interactions. They recognize that the impacts of water resource interactions follow watershed boundaries, not political ones, but that political externalities have to be factored into watershed management analyses, and that costs and benefits must be distributed among political units, communities, and individuals.

In 1990, most European countries began the process for developing management guidelines and criteria to ensure conservation and sustainable management of forests (Helsinki Process 1994). Criterion Five of Helsinki Process is to, "Maintain and develop the role of forests in water supply and protection against erosion." A parallel, but independent, effort was initiated by Canada and joined by other countries with temperate or boreal forests. The Canadian effort came up with similar criteria for measuring the sustainability of forest management (Montreal Process 1995). Criterion 4 of the Montreal Process is very similar. This criterion includes the conservation of soil and water resources and the protective and productive functions of forests. Since the chemical, physical, and biological characteristics of aquatic systems and their watersheds are excellent indicators of the condition and sustainability of the lands around them (Breckenridge et al. 1995), key conditions of soil and water resources were selected as indicators of sustainability.

Eight out of 67 indicators selected in the Montreal Process and endorsed by the 10 nations that drafted the Santiago Declaration in 1995 pertain to soil, watershed condition, and the quantity and quality of water resources. Briefly, they are: (1) area and percent of forest with significant soil erosion, (2) area and percent of forest managed primarily for protective functions, (3) percent of stream length in forested catchments in which stream flow and timing has significantly deviated from the historic range, (4) area and percent of forest with significantly diminished soil organic matter and/or changes in other soil chemical properties, (5) area and percent of forest with significant soil compaction or change in soil physical properties resulting from human activities, (6) percent of water bodies with significant variance of biological diversity from the historic range of variability, (7) percent of water bodies with significant variation in water quality from the historic range of variability, and (8) area and percent of forest land experiencing significant accumulation of persistent toxic substances. The USDA Forest Service has adopted these water and soil indicators of the Santiago Declaration on sustainability as guidance for its land management activities.

Brooks et al. 1997, in their text on hydrology and watershed management, expanded on the definition proposed by the World Bank (Brooks et al. 1992). They noted that their perspective is different from traditional ones because it recognizes the importance of land productivity as an integral component of watershed management. They defined watershed management as:

> "...the process of organizing and guiding land and other resource use on a watershed to provide desired goods and services without adversely affecting soil and water resources. Embedded in the concept of watershed management is the recognition of the interrelationships among land use, soil, and water, and the linkages between uplands and downstream areas."

Brooks et al. (1997) emphasized that by having a good perspective of a how a watershed functions and a clear understanding of the linkages between the uplands and downstream areas, watershed managers should be able to design long-term, sustainable solutions to human natural resource problems and avoid the disasters that can cause human suffering due to a lack of water or water pollution.

Reimold (1998) has a short but thorough definition of watershed management that also reflects thinking on the discipline at the end of the 20th Century. He states that, "Effective management of a watershed depends on a comprehensive human understanding of the components of watersheds and their interactions." Reimold's definition incorporates the holistic approach to the watershed as an ecosystem, not just physical processes. He commented on why, at the end of this century, "...comprehensive human understanding..." still does not exist. He paraphrased Aldo Leopold by saying, "Humans do not seem to be able to understand a system that they did not build; instead they seemingly must partially destroy and rebuild the system before its use and limitations are understood and appreciated."

In the waning years of the 20th century, major debates continue in the Western United States about how to undo some of the ecological consequences caused by extensive water development in the mid century period by breaching major dams on the Snake, Columbia, and Colorado Rivers. The main factor fueling these arguments is consideration for plant and animal species covered under the Threatened and Endangered Species Act. It will be interesting to note if this debate carries on into the 21st Century with any sort of credence and forcefulness.

21st Century

> "Water, like energy in the late 1970s, will probably become the most critical natural resource issue facing most parts of the world by the start of the next century."
>
> *Financial Times, London*

After this retrospective look at the changing perceptions of watershed management to date, I would like to briefly peer into the crystal ball of the 21st century. Making predictions is easy, but looking ahead with clarity is another matter. Lacking a Palladian glass ball, I will refer to the comments of others for the future definition and roles of watershed management.

Faculty of the University of Arizona Watershed Resources Program in the School of Renewable Natural Resources drafted a definition of watershed management and a future vision statement for their program that clearly states what the profession is about and where it needs to go in the 21st century (Cortner 1999). Their definition is a reflection of the one offered by Brooks et al. 1997. It stated:

> "Watershed management is a holistic approach to managing the biological, physical, and social elements in a landscape defined by watershed boundaries. It is the art and science of manipulating land and other resources on a watershed to provide goods and services to society without adversely affecting soil and water resources. Watershed Management relies heavily on the science of watershed (forest / range / wildland / land use) hydrology, a branch of hydrology, that addresses the effects of vegetation and land management on water quality, erosion, and sedimentation. Embedded in both watershed hydrology and management is the acknowledgment of the linkages between uplands and downstream areas and interrelationships among land use, soil and water. With increasing awareness that land management decisions can not be made in isolation, the principles of watershed management are being used as the basis for many environmental and natural resource management decisions."

The University of Arizona watershed management definition document goes highlighted the interdisciplinary nature of watershed management training, knowledge, and experience. The document notes that the profession's uniqueness is its integration of ecology and hydrology to solve land management problems and conflicts. Watershed management in the 21st Century must shift its traditional wildland focus to include urban fringe or urbanized areas to keep pace with society's needs. In the future, watershed management professionals must become more involved in land use planning and public education to maximize the effectiveness and social impact of their discipline.

Faculty of the University of Arizona Watershed Resources Program further stated that the goal of watershed management is to:

> "...evaluate the effect of current and future land use conditions on the soil and water resources, and assess the potential social and ecological impacts. Watershed management must also be capable of providing solutions to watershed problems, such as plans for water augmentation or watershed restoration."

They concluded that the profession encompasses a wide range of expertise. What links everyone together is the common goal of solving watershed management problems, not the specific areas of expertise.

Albert Rango (1995), Chief of the Hydrology Laboratory, USDA Agricultural Research Service, Beltsville, Maryland, presented a paper on the future of watershed management at an American Society of Civil Engineers symposium on Watershed Management Planning in the 21st century. His definition of watershed management is more narrow than that proposed by the University of Arizona Watershed Management program. Rango broadened the definition found in the International Glossary of Hydrology (WMO / UNESCO 1969) to be, "...the optimization of the quantity, quality, and timing of runoff through planned use of a drainage basin." Rango (1995) believed that watershed management would continue as an identifiable discipline into the 21st century because the demand, scarcity, and price of water will continue to increase. He identified the early 21st century as the beginning of the era of Global Hydrology for watershed management. In this era, worldwide emphasis will be on large-area assessments using modeling, remote sensing, and watershed management expertise. Large-area assessments are already happening in some countries (e.g., Interior Columbia Basin Ecosystem Management Project in the United States and the Eastern Anatolia Project in Turkey). As a parting comment, Rango (1995) recommended expanding the area of interest and training of watershed management from mainly forests, rangelands and other wildlands to include agricultural and urbanized areas. He also reiterated that watershed management technology transfer efforts must be expanded nationally and internationally to allow developing countries desperately in need of water information to easily access recent research results.

In a June 1999 address to Western United States water officials at the University of Colorado, Secretary of the Interior Bruce Babbitt stated, "In the coming century, water policy must be made in the context of the entire watershed." (Associated Press 1999). He went on to say that, "Water is a natural resource with no fixed address, and any water use inevitably affects many other uses, both upstream and downstream." Babbitt believes that water can no longer be managed, as it has been in the past, as a separate entity or commodity. Water must be managed within the holistic concept of watershed management. He further remarked that, "The big task of the coming century will be to restore rivers, wetlands, and fisheries." (McKinnon 1999).

Accomplishing this task will require approaching the problem from a watershed management viewpoint.

Leadership from the federal government of the United States in watershed management policy for the 21st century is eminent. The U.S. Departments of Agriculture and Interior are currently working on a draft Unified Federal Policy (UFP) with other Federal agencies, states, tribes, and other interested stakeholders. The intent of the UFP is, "...to enhance watershed management for protection of water quality and the aquatic ecosystem health on Federal lands." (Kennedy 1999). This policy , a breakthrough for watershed management as a science and profession in the 21st century, will certainly answer some of the key concerns raised by Rango (1995). Among other things, the UFP is committed to the concept of watershed management, to use watersheds as the management unit for soil and water resources, and to incorporate science in development of management programs. Regarding watershed management, the draft UFP states that:

> (1) "Stream characteristics are a result of the condition of the lands that drain them", (2) "Watershed assessments are necessary to determine existing and potential conditions", (3) "Assessments are used to define management programs for maintenance and improvement of watershed condition", (4) "Resources are focused on identified priority watersheds", (5) "Monitoring is used to measure success of land management prescription", (6) "Watershed management programs must include all owners", and (7) Good watershed conditions are essential for long-term productivity and sustainability of forest and rangeland health."

The original timetable for release of the UFP was December 1999, that may be delayed by the political debates being waged between the Administration and Congress.

The need for cooperation, not rivalry, in international watershed management in the 21st century will become more acute. The English word rival derives from the Latin word that means someone who shares the same stream. However, the English word rival implies that the sharing inherent in the Latin word is really competition. There are 200 basins worldwide that are each shared by at least 2 countries (Simon 1998). Dr. Wally N'Dow, Head of the United Nations Center For Human Settlements, stated in a 1996 interview with Robin Wright of the Los Angeles Times that was quoted by Simon (1998) that:

> "In the past 50 years nations have gone to war over oil. In the next 50 years, we are going to go to war over water. The crisis point is going to be 15 to 20 years from now."

By 2020, over 35 countries in water-short regions are expected to have severe water scarcity problems due to declines in available freshwater per capita. An Associated Press (1995) article quoted in Simon (1998) contained a very telling statement from Ismail Serageldin, World Bank Vice President for Environmentally Sustainable Development. He pointedly noted that:

> "We are warning the world that there is a huge problem (water) looming out there.... The experts all agree on the need to do something

fast. The main problem is the lack of political will to carry out these recommendation."

To avoid ending this paper on a dark note, I will throw out a challenge. Professionals in watershed management need to exhibit leadership and energize the public and the politicians of the 21st century to ensure that future use of water resources is done in the spirit of cooperation and not competition. The importance of watershed management must be clearly identified, widely articulated, and holistically conducted to meet the biological, physical, and social needs of all nations, not just a few powerful ones. Watershed management professionals must examine and answer the 3 questions posed Rango (1995) related to the future of the discipline, training of the next generation of specialists, and the important watershed science areas of emphasis.

Summary

"It always rains after a dry spell."
Marshall Trimble, Arizona Cowboy Folklorist

Over the span of the 20th century, the perception of what constitutes watershed management has grown considerably. At the beginning of the century, watershed management was mostly concerned about the development and maintenance of water supplies. At the end of the century, it is probably best defined in the words of R.J Reimold (1998), "Effective management of a watershed depends on a comprehensive human understanding of the components of watersheds and their interactions." Reimold's (1998) definition also reflects the thinking on the discipline at the end of the 20th century that watershed management incorporates the holistic approach to a watershed as an ecosystem, and not just manipulation of physical processes. The goal of watershed management is to assess the effects of current and future land uses on soil and water resources, determine the potential social and ecological impacts, and provide solutions to watershed problems.

As Rango (1995) pointed out, the increase in the world's human population (now at 6 billion) will cause the demand, scarcity, and price of water to expand on a global scale into the foreseeable future. His forecast is that, in this era of Global Hydrology for watershed management, worldwide emphasis will be placed on large-area assessments using modeling, remote sensing, and watershed management expertise. The technological tools are in place. The key to the future success of these endeavors lies in watershed management expertise and the actions of watershed management professionals.

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Lessons Learned in Watershed Management: A Retrospective View

Walter F. Megahan[1] and Jim Hornbeck[2]

Abstract.— Forest watershed management research is mandated by over 100 years of legislation, from the Organic Act and Weeks Law enacted around the beginning of the 20th century, to a variety of environmental protection acts passed over the past several decades. Research results have come primarily from studies of a multitude of gaged watersheds selected to represent a variety of geographic locations, forest types, topography and climate. These studies have show the effects of forests and forest disturbances on water yield, peak and flood flows, snow accumulation and melt, soil erosion, and water quality including sedimentation and turbidity, chemicals and temperature. The resulting knowledge of hydrologic, nutrient and energy cycles and soil erosion has been incorporated into land and water management primarily through best management practices and an ever-increasing array of procedures including computer simulation models to help assess cumulative watershed effects. This paper reviews some important lessons learned from watershed management research across the nation and discusses management implications.

Introduction

Over the past century, knowledge of linkages between forests and streams has been gathered through watershed management and watershed ecosystem research. These studies, most often conducted on small, experimental watersheds, have shown how contributions of water, sediment, chemicals and heat from forests to streams change as forests undergo succession or experience natural and human-related disturbances. Our job is to summarize the lessons learned from these studies. This is a daunting task at best and requires some sideboards: 1) we will focus on forestry issues (convenient because that's what we know about) and mention other important watershed management activities including range, agriculture and urbanization effects only in passing; 2) although considerable, excellent work has been done elsewhere, we will confine our discussion to the U.S. and 3) we provide only a cursory overview of the subject matter (if we miss your pet interest, we apologize).

We start with a summary of the key legislation influencing the growth and direction of watershed management and a historical overview of watershed management research resulting therefrom. This will lead to a brief discussion of important lessons learned about watershed function followed by an overview on what we know about management implications.

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Key Legislation

The Organic Act of 1897 defined water as one of the primary reasons for establishment of the national forests as follows: "No national forest shall be established, except to improve and protect the forest within the boundaries, or for the purpose of securing favorable conditions of water flows, and to furnish a continuous supply of timber for the use and necessities of citizens of the United States." This concern was reinforced by the 1911 Weeks Law that stated: "The Secretary of Agriculture is authorized and directed to examine, locate, and recommend for purchase such forest, cutover or denuded lands within the watersheds of navigable streams as in his judgment may be necessary to the regulation of the flow of navigable streams or for the production of timber." Although research has refined our understanding over the years, it is clear that early legislators recognized as a key issue the ties between forest cultural operations and streamflow.

A variety of subsequent legislation has been enacted to maintain and enhance the quality of soil and water resources on forest and other lands. Important acts for managing National Forest lands such as the Multiple Use-Sustained Yield Act, the Forest and Rangeland Renewable Resources Planning Act, and the National Forest Management Act all include protection of soil and water resources as a central theme. Additional legislation including the Watershed Protection and Flood Prevention Act, The Resource Conservation Act , the National Environmental Policy Act, the Federal Water Pollution Act, the Coastal Zone Management Act and the Clean Water Act all help to protect soil and water resources on all lands, not just forests. Last, but certainly not least, the Endangered Species Act promises to have profound effects on watershed management on all lands as well. In addition to the federal legislation, many states have adopted state forest practices acts and other laws directed at conserving soil and water resources.

History of Forest Watershed Research

The first watershed experiment began in 1909 at Wagon Wheel Gap in Colorado. This was a comprehensive study utilizing a control and treatment watershed design to quantify the effects of deforestation on the volume and timing of streamflow, soil erosion and sediment loading (Bates, 1911). Since that time similar study designs, mostly on experimental small catchments less than 200 ha, have been conducted throughout the U.S. At their peak in 1960, there were a total of about 150 experimental watersheds scattered throughout the U.S. devoted to forest hydrology studies. This total has dwindled since that time due primarily to budget constraints and a lack of commitment to long-term watershed scale studies.

Watershed experiments are excellent for defining what happens at the catchment scale but it is often difficult to document exactly how and why. This prompted the development of studies designed to evaluate how individual hydrologic processes operate and respond to forest management activities. Process studies often involve field and/or laboratory plots designed to study basic hydrologic functions such as runoff (evapotranspiration, infiltration, subsurface and groundwater flow), erosion (surface and mass erosion) and sediment transport, nutrient cycling, function of riparian areas, etc.

Early attempts to understand and extrapolate hydrologic information led to the development of empirically based, statistical models. More recently, information gained from process and watershed scale studies coupled with the development of computers, remote sensing and geographical information systems has made it possible to create computer simulation models for watershed function and response.

Lessons Learned

Streamflow

Annual Water Yield

Questions about the role of forests in regulating water yield have been prevalent for the past century. The Wagon Wheel Gap watershed study initiated in 1909 (Bates 1911) was the first North American study to address such questions. However, it was not until the late 1930s and the introduction of statistically designed, paired watershed studies at Coweeta and San Dimas that the scope of information regarding relationships between forests and water really began to broaden. Since then, a multitude of gaged watershed studies have been conducted, spanning a variety of geographic locations, forest types, topography, climate, and forest disturbances.

The watershed studies have provided careful, long-term measurements of precipitation and streamflow, and estimates of how much water forests return to the atmosphere as evapotranspiration (ET). Studies of throughfall have allowed separation of the canopy interception component within ET. Process studies have helped to identify source areas for streamflow, and to understand how water moves through forest ecosystems. Using this background knowledge for undisturbed forests as a basis, treatments on experimental watersheds have shown how hydrologic relationships and processes are changed by disturbances such as cutting, fire, and species conversion.

Hibbert (1967) summarized the results from 39 such experiments involving treated watersheds and developed three generalizations.

1. Reduction of forest cover increases water yield.
2. Establishment of forest cover on sparsely vegetated land decreases water yield.
3. Response to treatment is highly variable and, for the most part, unpredictable.

The magnitude of the increases alluded to in the first generalization was highly variable. First-year responses to complete forest reduction ranged from 34 mm to >450 mm of increased streamflow, thus giving rise to Hibbert's third generalization.

Bosch and Hewlett (1982) updated Hibbert's (1967) review with an additional 55 studies conducted on gaged watersheds. Their findings reinforced Hibbert's first and second generalizations. However, Bosch and Hewlett (1982) felt that knowledge and explanations for the increases had reached a point where responses to forest treatments were no longer unpredictable, as expressed in Hewlett's third generalization. Bosch and Hewlett (1982) based their arguments in part on the premise that the increases could be modeled with computer simulators, and were thus to some degree understood and predictable.

Most watershed studies indicate that responses of water yield to forest treatment are dependent on amount of precipitation. Yield changes are greater under higher precipitation regimes, reinforcing Hewlett's (1967) axiom about forest increases and water yield: "It takes water to fetch water." Under similar precipitation regimes, increases in water yield are roughly proportional to percentage reduction in stand basal area, with at least a 20-30%

reduction being necessary to generate detectable increases in annual water yield (Douglass and Swank 1972, Bosch and Hewlett 1982, Hornbeck et al 1997). Coniferous forests have greater influences on water yield than deciduous forests, and species conversions from softwoods to hardwoods or grass will usually increase water yields. A number of studies have shown that water yield increases following partial cuttings are related to the configuration and / or location of the cuttings in relation to source areas for streamflow (Hornbeck et al 1993; Troendle 1983).

The duration of water yield increases is again related strongly to amount of precipitation. Increases are prolonged in drier areas because disturbed sites are slow to revegetate. In more well-watered areas, rapid revegetation often limits meaningful water yield increases to the first 3 to 5 years after treatment (Hornbeck et al 1993). Deeper soils of the southeastern U.S. seem to help sustain water yield increases (Swank et al. 1988).

Water yield studies have found widespread application in northeastern US where forested watersheds serve as sources of water for more than 1,000 municipalities ranging from small, rural communities to large urban centers such as Boston and New York (Hornbeck et al. 1993, O'Connor et al. 1995). Elsewhere in the U.S., especially in the western states, water yield continues to be an issue (Harr, 1983; Troendle, 1983) but given the increasing emphasis on environmental issues, forest management for water yield alone is not a realistic forest management goal.

There are still lessons to be learned regarding water yield from forests. In particular, there are concerns about how global climate change and continually rising levels of atmospheric CO_2 may affect species composition, transpiration rates, and water yield. Paired watershed studies which have several decades of continuous hydrologic data are proving to be valuable for addressing these questions (Hornbeck et al. 1993, Amthor and Hornbeck 1999).

Flow Distribution

Given the widely documented increases in annual water yield from forest cutting, it is clear that streamflow increases following timber harvest; the question remains as to how the flow changes are distributed.

In this discussion, we differentiate between peak flows and flood flows. Peak flows are the maximum flows resulting from a runoff event. Flood flows are those peak flows that exceed channel capacity as defined by bankfull levels. Much of the early concern was based on the assumption that forests are necessary "...to prevent destructive floods and corresponding periods of low water" (Pinchot 1947). The issue of forest cutting and floods has diminished but continues to this day. Lull and Reinhart (1972) developed a comprehensive literature review of the effects of forests on floods in the eastern U.S. They conclude that (compared to cropland, pasture and urban – suburban land) "The forest is the best of all possible natural cover for minimizing overland flow, runoff and erosion. The flood-reduction potential of the forest can be realized through continued fire protection and careful logging ¼". In this context, careful logging is defined as any silvicultural method that generates minimal compaction with a carefully designed and located road system.

Harr (1979) reviewed the results of watershed studies to evaluate the effects of forest practices on peakflows at 11 different locations along the Pacific slope. The most common cause of increased flows was wetter, more hydrologically responsive soils in the fall caused by decreased evapotranspiration losses after timber cutting. Less rainfall is needed to recharge soils under such conditions resulting in relatively large peak flow increases. Generally, storms are small during this time of year so the large flow increases are limited to the smaller flow events. Later in the fall as soil moisture differences become less important, the magnitude of peak flow differences become smaller or non-existent. It is during this time of year that large, flood producing runoff events occur so that flood flows are not likely to increase. Other possible causes of peak flow increases from forest practices were identified including soil compaction, forest road construction and differences in snow accumulation and melt rates. In general, effects tend to decrease over time as forest stands regrow. Summarizing the results of the reported studies, Harr (1979) concludes: "Taken collectively, results of watershed studies indicate that size of peak flows may be increased, decreased, or remain unchanged after logging. Whether or not a change occurs depends on what part of the hydrologic system is altered, to what degree, and how permanent the alteration is." Subsequent studies on both small watersheds (Harr 1986; Wright et al. 1990; Thomas and Megahan 1998) and larger river basins (Duncan 1986; Storck et al. 1998) suggest that Harr's 1979 conclusions for Pacific Slope basins still apply.

Troendle et al. (1998) studied effects of timber harvest on the Coon Creek watershed in the snow zone of Wyoming. They found that the highest flows in this 1.7 km^2 basin were not significantly increased although the duration of the higher, near bankfull discharges was extended. The authors report that findings at Coon Creek support and are comparable with documented observations on smaller, experimental watershed studies elsewhere in the snow zone.

Natural disturbances, especially wildfire, may affect peak flows. Light forest burning has no effect on flood flows in the eastern U.S. (Lull and Reinhart 1972) but intense wildfire can increase flood flows by up to two orders of magnitude, especially on steep forest lands in the western U.S. (Bolton and Ward, 1987). Increased soil water repellency resulting from the intense burning is suggested as an important factor leading to the increased flood flows.

Even if flood flows were to increase on small watersheds, for example as a result of intense wildfire, the chances of detecting the effects in large river basins diminishes because of increased channel storage along larger streams. Chow (1964) states: "A distinct characteristic of small basins is that the effect of overland flow rather than the effect of channel flow is a dominating factor affecting the peak runoff. Also, small basins are very sensitive both to high-intensity rainfalls of short duration and to land use. On large basins, the effect of channel storage is so pronounced that such sensitivities are greatly suppressed."

If flood flows aren't likely to increase following timber harvest, then lower flows must if water yields are to increase. Most increases in water yield occur at low flow levels, or as augmented baseflow or delayed flow. Furthermore, the yield increases tend to occur primarily in the growing season when they are most beneficial for aquatic biota, recreational activities, and water supplies. This is because the difference in soil water storage at this time of year is the greatest due to reduced evapotranspiration demands. (Hornbeck et al. 1997). Although flood flows do not tend to increase, several researchers point out that increases in the duration of flows near bankfull may lead to bank and bed erosion problems in channels that are susceptible (Troendle et al. 1998; Van Haveren 1988).

As the above discussion suggests, we have learned many lessons over the years about the relationships between forests and water. New and interesting findings continue to crop up from gaged watershed studies, but the ample, existing knowledge is being widely used to incorporate streamflow considerations into management activities. This is being done by direct application of the appropriate literature, or by use of computer models of hydrologic cycles for forests such as BROOK90 (Federer 1995), OWLS (Chen and Beschta 1999) and DSHVM (Storck et al. 1998). Such models allow managers to simulate changes in streamflow resulting from different management and harvesting activities.

Erosion

Erosion is a normal geologic process that varies over time in response to changing climatic and site conditions. Erosion rates are usually minimal on undisturbed, forested watersheds. However, both surface and mass erosion can and does occur under such conditions. Forest disturbance, either natural (e.g., extreme storm events, wildfire) or human caused (e.g., timber harvest, road construction) can increase erosion rates, sometimes to extreme levels.

Surface Erosion

Surface erosion is the movement of individual soil particles by a force such as raindrop impact or overland flow and is described as interrill, rill or gully erosion depending on the degree of concentration of surface flow. Surface erosion is an issue on agricultural lands because of concerns about long term site productivity. In the past, site productivity has not been an issue on forest lands primarily because cutting rotations extend for many years. However, long term site productivity is becoming an issue on forest lands as forest practices intensify, particularly in the southeastern U.S.

Considerable effort has gone into the development of empirical studies to predict surface erosion over the years. Most notable was the development of the Universal Soil Loss Equation or USLE (Wischmeier and Smith 1978) and its iterations (Renard et al. 1991; Williams 1975) for application on agricultural and range lands. The USLE has been adapted for application on forest lands in the southeast U.S. (Dissmeyer and Foster 1985). Subsequent research has led to the development of additional empirical and process based models to predict surface erosion on forest land (Elliot et al 1996) and on forest roads (Tysdal et al. 1997; Cline et al. 1981, Ward 1985). Except for locations where intensive site preparation practices are used (presently confined to some sites in the southeastern U.S.) studies on forest land show that surface erosion following logging is confined to severely disturbed and compacted areas and thus is limited to skid trails, log landings and roads (Martin 1988; Megahan and Kidd 1972). A variety of Best Management Practices (BMP's) have been devised to cope with surface erosion from timber harvest activities (National Council of the paper industry for Air and Stream Improvement [NCASI] 1994; Martin and Hornbeck 1994).

Mass Erosion

Mass erosion is the movement of a group of soil particles en masse in response to gravitational force. Landslides are classified as either shallow (debris flows, avalanches and torrents) or deep seated (slumps and earthflows) depending on the nature of the slope failure process. Because of the strong influence of gravity, landslides occur most often on steep terrain, generally in excess of 30 degrees for the shallow types of slides. In such areas, mass erosion is usually the dominant erosion process for supplying sediment to streams.

Forest cutting has been shown to increase the risk of shallow landslides by reducing root strength and increasing soil water contents (Sidle et al. 1985). Most studies have relied on the use of aerial photos to identify slide activity on cut vs. uncut forest slopes. A recent study used a detailed field inventory to show that many of the earlier studies are biased because slides are often impossible to identify on aerial photos of uncut forest slopes (Robison et al. 1999). GIS based models to evaluate the topographic risk of shallow landslides provide a way to assess risks of timber cutting in landslide prone terrain (Montgomery and Dietrich 1994; Pack et al. In press).

Effect of Roads

Roads have been shown to be particularly problematic for erosion, especially in mountainous areas, because of exposure of erodible soil and subsoil by construction, reduced infiltration on the road surface, increased gradient on cut and fill slopes and concentration of overland flow from precipitation excess and interception of subsurface flow. Megahan and Kidd (1972) working on granitic soils in Idaho, showed that unit area rates of erosion were increased by an average of 1.6 times by cable logging. Road construction in the study watersheds increased unit area erosion rates by an average of 220 times as the result of surface erosion and an additional 550 times as the result of mass erosion over the 6 year study period. Numerous other studies have documented the potential severity of surface erosion (McCashion and Rice 1983; Swift 1984; Reid and Dunne 1984) and mass erosion (Megahan et al 1979; Robison et al. 1999; McClellend et al. 1996) on forest roads. A variety of BMP's have been developed to reduce surface erosion on road cut and fill slopes, on the road tread and in road ditches (Megahan 1977; Burroughs and King 1989). Mass erosion on forest roads can be reduced by avoiding high hazard areas and/or by careful road design, construction and maintenance.

Natural Events

Natural events, such as large storms, earthquakes, and especially wildfire, can have a profound effect on both surface and mass erosion. By increasing soil saturation at slope locations that are normally unsaturated, large storms can trigger shallow landslides and accelerate the movement of deep seated landslides even on undisturbed forest lands (Robison et al. 1999). Normally, surface erosion is not increased by large storm events except on disturbed areas where mineral soil is exposed. Wildfire can greatly increase risks for both surface and mass erosion depending on the intensity of the fire (Connaughton 1935; Benda and Dunne 1997a). Very intense wildfires greatly increase surface erosion potentials by consuming organic materials that protect the soil surface and retard runoff and by creating soil water repellency that leads to overland flow. Increases in annual sediment yields of 2 to 3 orders of magnitude can occur from a single storm following severe wildfire on steep forest lands in the western US (Schultz et al. 1992; Moody and Martin 1999). Severe wildfire also increases landslide activity. A recent study by Benda and Dunne (1997a) shows that severe wildfires were a major cause of landslides on prehistoric landscapes in the coast range of Oregon.

Sedimentation

Sedimentation is the complementary natural process to erosion. It includes the transfer of eroded materials downslope to streams and downstream through the drainage system. Because of storage en route, on-site surface erosion does not equate to downstream sediment yield. Differences between watershed erosion and sediment yields, often quantified using a delivery ratio, account for the effects of long term sediment storage at different points in the watershed.

Increased sedimentation can cause a variety of environmental problems. The Environmental Protection Agency (US EPA 1992) found that sedimentation impairs a greater length of streams than any other type of pollutant including nutrients, pathogens, pesticides and organic enrichment and dissolved oxygen. On forested watersheds, concern for sedimentation is often keyed to fishery values. At high concentrations, suspended sediments can damage the gills of aquatic insects and fish. Bedload sediments can be of particular concern because of the potential for interference with both fish spawning and rearing success. In addition, fine organic sediments and clay sized lithic sediments may act as vectors for downstream transport of adsorbed pollutants such as pesticides, organic chemicals, radio nuclides, or heavy metals.

Sediment Delivery from Surface Erosion

Much of the sediment resulting from surface erosion on harvest areas and roads does not reach the stream channel network because of deposition on the slope below. Sediment from diffuse sources, such as a timber cutting unit or a road fill, moves very short distances if there are no concentrated sources of runoff. Megahan and Ketcheson (1996) found that sediment travel distance averaged about 6 meters for road fills where runoff originated only from the road fill. Sediment from concentrated runoff sources such as road cross drain culverts traveled much further, averaging about 53 meters. Sediment travel distance below road cross drains has been shown to vary with a number of site characteristics such as obstructions on the slope below the road, amount of road runoff, volume of erosion, and gradient of the slope below the road (Packer 1967; Swift 1986; Megahan and Ketcheson 1996). The volume of sediment deposition decreases exponentially downslope so that most of the sediment is stored nearest the source. Ketcheson et al. (1999) found that only about 4 percent of the material removed by surface erosion on forest roads in Idaho was delivered to streams over a 4 year period following construction. Surface erosion is selective to the smaller soil particles so sediment produced therefrom consists of silts and clays and some sands.

Sediment Delivery from Mass Erosion

Sediment delivery to streams from mass erosion tends to be higher than that from surface erosion. Debris-avalanche types of slides are usually located in areas of water concentration at the heads of steep drainages and follow the drainage path down into the lower channel system. Megahan et al. (1979) reported an average of 23 percent of the sediment volume from 629 landslides was delivered to streams over a three year period on the Clearwater National Forest in Idaho. More recent studies in the same area reported an average of about 50 percent delivery from a total of 905 landslides as the result of large storms in 1995 and 1996 (McClelland et al. 1997). Work by Benda and Cundy (1990) and Ward (1994) show that slope gradient below the slide, tributary junction angle, distance from stream, and landslide length all influence landslide delivery to streams. Unlike the fine materials supplied to channels from surface erosion, the particle size distribution of sediment delivered to streams can range from clay to boulders. Landslide activity is not necessarily detrimental. Benda and Dunne (1997b) show that sediments supplied from landslides following wildfires in the coast range of Oregon are essential to the long term maintenance of aquatic habitat in the channels.

Sediment Transport in Streams

Small sediments less than about 0.06 mm (silt) size tend to move relatively rapidly through the channel system as wash load. These fine sediments are a major factor influencing turbidity. Larger sediments move as bed material load and can have short to long residence times in the channel system depending on particle size. Bunte' and MacDonald (1998) made a comprehensive review of the literature dealing with sediment transport distance as a function of particle size. Travel distance for suspended load (wash load plus some sands) ranges from 2 to 20 km / year whereas bedload consisting of pebbles and cobbles travel only 0.02 to 0.5 km / yr. For low gradient channels such as those found in portions of the Lake states and the southeastern US, residence times for sands can range from 50 to 100 years (Dissmeyer 1976; Trimble 1981; Phillips 1993) Studies in the western U.S. show sediment storage times within the active stream channel ranging from 5 to 100's of years depending on particle size and the type of sediment deposit (Megahan et al. 1980; Madej and Ozaki 1996; Ziemer et al. 1991).

Sedimentation Cumulative Watershed Effects

The issue of cumulative watershed effects was first defined in the National Environmental Policy Act in 1969. Considerable debate ensued regarding the definition of cumulative effects. A definition by Reid (1993) summarizes the common elements of several definitions: "¼ a cumulative effect is any environmental change influenced by a combination of land-use activities." Given this definition, sedimentation cumulative effects are a distinct possibility, for example because of the potential for long residence time of bedload sediments.

The South Fork of the Salmon River in Idaho provides an excellent example of sedimentation cumulative effects. Logging in the 1950s and early 1960s was done on steep, granitic soils with little knowledge of the potential for accelerated erosion that existed in the area. Sediments began to accumulate in tributary channels as timber harvest spread to more areas. Large storm events in 1964 and 1965 flushed new and accumulated sediments into the river channel causing severe sediment deposition on valuable salmon spawning and rearing habitats. In this case, sediment deposits were almost entirely surface sands most of which was flushed out of the system within 5 years after the cessation of continued soil disturbance and a road rehabilitation program (Megahan et al. 1980). Longer duration sedimentation cumulative effects were found on Redwood Creek in California. Madej and Ozaki (1996) measured channel changes following extensive sediment deposition as the result of widespread timber harvest and road construction combined with a series of large floods. Their studies documented the occurrence of a large sediment wave in the lower 26 km of the gravel bedded river that is moving downstream at a rate of 800-1600 m / yr.

The sedimentation cumulative watershed effects (CWE) cited above are extreme examples that would be easily recognized by even the casual observer. Unfortunately, most sedimentation CWE are much more difficult to detect. Bunte' and MacDonald (1999) provide a comprehensive review of the literature of factors affecting the detectability of sedimentary CWE. Considering the effects of spatial and temporal scale and the problems of measuring sediment transport, they conclude *"Taken together, these factors suggest that we should not expect to detect less than a twofold change in sediment transport rates or sediment yields. Changes in measurement techniques, calculation procedures, or the period of comparison can create the appearance of a sedimentary CWE when none actually exists. The inherent spatial and temporal variability suggests that at least 5-10 years of both pre- and post-monitoring are likely to be necessary to reliably detect a sedimentary CWE."*

In lieu of measuring sediment transport or sediment yields, MacDonald et al. (1991) describe a series of channel response indicators that can be used to help assess sedimentary CWE. Sediment budgeting also provides a means to avoid many of the problems described by Bunte' and MacDonald (1999). A sediment budget is an accounting of the sources and disposition of sediment as it travels from its point of origin to its eventual exit from a drainage basin. Techniques have been developed to conduct sediment budgets for purposes of evaluating sedimentary CWE (Reid and Dunne 1996).

Water Quality

Water quality has long been a part of gaged watershed studies. As suggested by the earlier discussion, sediment (or turbidity as an index of sediment) has usually been the water quality parameter of most interest, followed by temperature. In the 1960s it was recognized that gaged watersheds were also a good tool for studying nutrient cycling, impacts of introduced chemicals (e.g., atmospheric deposition, fertilizers, and pesticides) and water temperature.

Nutrient Cycling

Nutrient cycling studies on gaged watersheds began at Hubbard Brook Experimental Forest in 1963 and gradually became important additions to watershed studies at many other locations. This broad holistic approach to paired watershed studies led to the introduction of the term "watershed ecosystem analysis" (Hornbeck and Swank 1992).

The basic premise of watershed ecosystem analysis is that the many physical, chemical, and biological processes occurring within an ecosystem are interrelated. This approach attempts to understand these processes and to attach values to pools and fluxes of the chemical parameters in question. These pools and fluxes become the basis for assessing impacts of human-related or natural changes. Watershed ecosystem analysis can thus be used to evaluate how individual or combinations of uses might affect nutrient cycles and, in turn, the health and productivity of forest ecosystems, or the chemistry and biota of forest streams.

Nutrient leaching from forests to streams is affected by various factors including mineral weathering, soil and hydrologic characteristics, vegetation, climate, biological processes, and natural and human disturbances. Most studies have shown that forests free of recent disturbances have relatively "tight" nutrient cycles and that baseline concentrations of nutrients in forest streams are low. Thus nutrient concentrations are seldom an issue in terms of water quality, but they are an important consideration regarding stream biota and watershed nutrient capitals (Hornbeck et al. 1997).

One of the earliest applications of watershed ecosystem analysis was to help resolve the controversy caused by the increasing use of clearcutting during the late 1960s and early 1970s. There was widespread concern that clearcutting would increase nutrient concentrations in streams and deplete forest nutrient capitals (Horwitz 1974). A number of studies using watersheds showed that clearcutting would indeed increase both nutrient concentrations in streams and losses to leaching. Base cations and nitrate were the most susceptible. However, in all cases involving commercial harvests, the changes were short lived and of little significance to stream biota, water quality standards, or forest nutrient capitals (Hornbeck et al. 1987; Johnson et al. 1987; Saliman and Beschta 1991).

Watershed ecosystem analysis has played an important role in studies of atmospheric deposition. Studies in the eastern US have shown that acidic deposition can lower the pH of forest streams and mobilize inorganic aluminum to levels that are toxic to aquatic biota (Cronan and Schofield 1990). Strong mineral acids in precipitation can cause depletion of base cations in forest soils, and in certain situations may affect forest health and productivity (Cronan and Grigal 1995; Shortle and Smith 1988; Federer et al. 1989). Studies are in progress using acidifying chemicals applied to whole watersheds to mimic but hasten effects of acid precipitation on soils, streams, and plants (Adams et al. 1993; Rustad et al. 1996). These studies are intended to accelerate the development of strategies for controls and mitigation of atmospheric deposition, and thus protection of forest and aquatic ecosystems.

Due to temporal variations in weather and wet and dry deposition, watershed ecosystem analysis is inherently long term. Some parameters must be measured for decades to define variability. However, long-term data on nutrient concentrations of streams, some of which now spans 30 or more years, have proved of great value in studying trends related to forest succession and atmospheric deposition. For example, Driscoll et al. (1989) found that controls of sulfur emissions mandated in the 1970s have led to a gradual decline in sulfate concentrations of forest streams of the Northeast.

Introduced Chemicals

Norris et al. (1991) provided a thorough review of the extensive information regarding impacts of other introduced chemicals (including pesticides, fertilizers, and fire retardants) on water quality and aquatic ecosystems. The review points out that direct toxic effects of chemicals on aquatic organisms are major concerns, but that forest chemicals may also have indirect effects on aquatic ecosystems at concentrations much lower than those observed to cause mortality. The authors suggest that potential effects of forest chemicals must be evaluated on the basis of four factors: (1) changes in aquatic communities caused by forest chemicals, (2) subsequent changes in other communities of aquatic organisms, (3) alteration of terrestrial systems that influence aquatic ecosystems, and (4) effects on patterns of recovery in watersheds that have already been altered by logging or fire.

NCASI (1999) has summarized responses of stream water chemistry to forest fertilization. The results show that the most commonly occurring effect from fertilization is an increase in peak concentrations of nitrate in stream water. However, the increases remain within drinking water standards, and increases in average concentrations are much less than those in peak concentrations.

The processes by which chemicals reach streams include direct application, drift from nearby treatments, and mobilization of residues in ephemeral stream channels during the first storms after application (Norris et al. 1991). Margins of safety can be calculated for fish based on maximum acute and short-term chronic exposures likely to occur when applying forest chemicals (Norris et al. 1991). Streams are 5-10 times less likely to be affected when they are not in treated areas, when buffer strips are used along streams, and when full attention is given to preventing drift and direct application to streams.

Water Temperature

The temperature of aquatic systems greatly influences fish production, recreational use, and value for water and temperature changes can be detrimental or beneficial depending on local conditions. Early studies suggested that the principal source of heat for streams draining forests is solar energy striking directly on the surface of the stream (Brown 1980). Thus shade from overhanging vegetation is an important factor regulating the temperature of streams. In some situations other factors regulating stream temperature including groundwater inflow, evaporation and condensation and conduction from air and streambed are also important. Stream temperatures normally exhibit fairly predictable annual, seasonal and daily variations. Spatial variations also occur with a general tendency for temperature increase from headlands to lowlands even under mature forest conditions (Sullivan et al. 1990). Coniferous forests generally provide greater shade than deciduous forests and thus have lower stream temperatures. Elimination of stream shading by harvest or fire can increase maximum daily stream temperatures up to 10^0C (Lynch et al. 1975; Beschta et al. 1987). Streams from exposed areas cool when flowing through shaded areas primarily due to inflow from cool groundwater and cooling from ambient air temperature. Channel length required for the stream to return to its characteristic temperature signature can be as little as 150 meters depending on channel properties (Zwieniecki and Newton 1999).

In summary, considerable information exists about the relationships of forests and water quality. Much of this information has been synthesized and passed to managers in the form of BMPs and monitoring guidelines (MacDonald et al. 1991).

Management Implications

The bottom-line lesson is that nearly everything that happens on forested landscapes has some effect, ranging from very minor to very major, on the volume, quality, and timing of streamflow and the habitat characteristics of streams. As our discussion suggests, much is known about the various linkages between forests and streams. The challenge is to incorporate this knowledge into management practices. This will be easiest when pertinent site specific information is available about rates of the various contributions from forests to streams. But in the absence of or in combination with site-specific information, computer models are rapidly improving as a tool that can be used for indicating the effects of various management options.

It is important to consider the role of riparian areas. A properly designed and managed riparian area can provide a variety of amenities and still protect against stream temperature changes, assure a continuous supply of large woody debris and organic matter, absorb nutrients, sediment, and water from upslope, and maintain a diversity of species composition. However, the protective capabilities of riparian areas must be supported by careful management of forests both within and outside the riparian area.

In the case of harvesting disturbances, application of BMPs is essential. It has been shown time and again that BMPs can protect soil and water resources. Beyond BMPs it is helpful to think in terms of long-term cumulative effects. That is to answer the question — "Will the combined effects of multiple disturbances over space and time still result in acceptable watershed performance?". In this case, watershed performance includes not only the more traditional goals of regulating streamflow quantity, timing and quality, but also the broader concepts of maintaining ecosystem and aquatic habitat integrity as well. Assessment and management of cumulative effects requires linking cause and effect in order to be effective. Establishing such linkages may be difficult and time consuming given natural spatial and temporal variability and the effects of major episodic events that can totally "reset" established watershed processes. There is no easy answer to cumulative effects issues; simple indicators such as acres of harvest areas or road density do not suffice as either assessment or management tools.

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Documenting Historical Data and Accessing it on the World Wide Web

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Abstract.—New computer technologies facilitate the storage, retrieval, and summarization of watershed-based data sets on the World Wide Web. These data sets are used by researchers when testing and validating predictive models, managers when planning and implementing watershed management practices, educators when learning about hydrologic processes, and decisionmakers when selecting the best course of action from a set of alternatives. Data sets from the Beaver Creek watershed in north central Arizona have been incorporated into a Web site to illustrate this application (http://www.rms.nau.edu/wsmgt/beavercr/). These particular data sets represent natural resource responses to watershed management practices in ponderosa pine forest and pinyon-juniper woodland types in the Southwest. This paper describes procedures to store, retrieve, and summarize watershed-based data, such as those obtained on Beaver Creek, on the World Wide Web.

Introduction

In the summer of 1955, several ranchers met with a USDA Forest Service representative and an official with the Salt River Project on the Beaver Creek watershed in north central Arizona, near Flagstaff, Arizona. These people were concerned that increasing densities of trees and shrubs on upland watersheds on the Salt and Verde River Basins might be reducing the stream flow and the livestock forage. As a result of this meeting, the University of Arizona was commissioned by the Arizona Land Department to investigate the potential for increasing the water yield from the state's forests and ranges. The findings of this investigation, presented in a report titled Recovering Rainfall: More Water for Irrigation (Barr 1956), better known as the Barr Report, were that surface-water runoff from mountain watersheds increases when high water-using plants, such as trees and shrubs, are replaced with low-water users, such as grasses. This 1956 report spurred demand for an immediate action program. In response to this demand, the USDA Forest Service's Arizona Water Program was initiated in the late 1950s to evaluate the usefulness of selected vegetative management programs in increasing water yields and other multiple resource benefits in the Salt and Verde River Basins (Fox 1958). The Beaver Creek watershed project became a significant component of this program.

The 20-plus years of research conducted during the Beaver Creek watershed project resulted in a large collection of physiographic, climatic, streamflow, floral, and faunal data with inconsistent formats (both spacial and temporal). This information has been difficult to retrieve by even those familiar with the project. Computers have greatly simplified access to large, varied data bases, and the World Wide Web has further advanced our ability to assess and disseminate such data. The data collected during the Beaver Creek project is used to illustrate the use of the Web for storing, retrieving, and summarizing watershed data. These data include precipitation, air temperature and humidity, wind and snowfall, streamflow, sedimentation and erosion, water quality (sediment and nutrient), and herbage and timber production. These data sets were collected at varying time steps ranging from minutes, to daily, to yearly, or more on 40 watersheds ranging in size from 4 to 6,600 ha.

Beaver Creek Watershed

The Beaver Creek watershed is located between 34° 30' and 35° north latitudes and 111° 30' to 112° west longitude in north central Arizona (http://www.rms.nau.edu/beaver_cr/, http://ag.arizona.edu/OALS/watershed/, and http://www.verde.org/). The center of the watershed is about 50 km south of Flagstaff, Arizona (figure 1). The Beaver Creek watershed, encompassing 111,300 ha upstream from the junction of Beaver Creek and the Verde River, is part of the Salt and Verde River Basins, which are major river drainages in central Arizona (Baker 1999). The Salt and Verde Rivers provide much of the surface water for Phoenix and other communities in the heavily populated Salt River Valley. The Beaver Creek watershed was selected for study because it represents of extensive areas of ponderosa pine (*Pinus ponderosa*) forests and pinyon-juniper (*P. edulis-Juniperus* sp.) woodlands in the Southwest.

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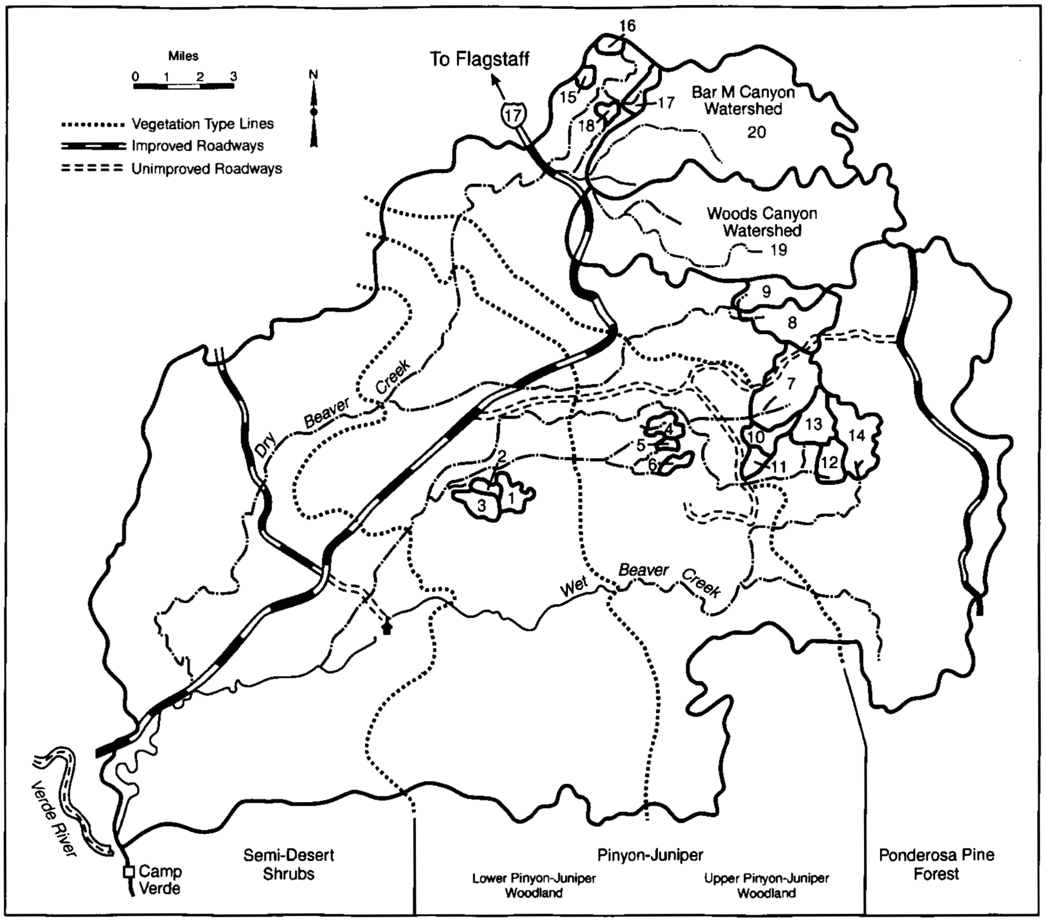

Figure 1. The Beaver Creek Watershed located upstream from the junction of Beaver Creek and the Verde River. Numbers indicate watersheds.

Annual precipitation on the Beaver Creek watershed varies greatly from year-to-year, which is characteristic of the climate in the Southwest (Baker 1999). On average, the ponderosa pine forests receive 500 to 635 mm of water and the pinyon-juniper woodlands receive 460 to 500 mm annually from rain and snow. Most of the annual runoff (95% in the ponderosa pine and 85% in the pinyon-juniper woodlands) is from the melting snowpack, which occurs largely in March and April.

In descending order with respect to elevation, the 3 vegetation types on the watershed are ponderosa pine, pinyon juniper (including alligator juniper [*Juniperus deppeana*] and Utah juniper [*J. osteosperma*] subtypes), and semidesert shrubs (figure 1). Ponderosa pine, characteristic of 4.5 million ha in the Southwest, dominate the hillsides and plateau above 2,000 m (Brown et al. 1974). Scattered throughout these forests are clumps of Gambel oak (*Quercus gambelii*), which is the predominant deciduous tree on Beaver Creek. This oak species is valued for the food and shelter it provides to wildlife. Woodlands of intermingled pinyon (*P. edulis*), Utah juniper, and alligator juniper grow between 1,370 and 2,000 m elevation, as they do on some 20.6 million ha in the Southwest (Clary et al. 1974). Representative plant and animal lists (scientific and common names) by vegetation type are available at http://ag.arizona.edu/OALS/watershed.

People have modified the Beaver Creek watershed since the late 19th century. The earliest modification was the introduction of domestic livestock. Most of the ponderosa pine area has also been logged, which has changed the size and age-class distribution of trees but has not caused major ecosystem changes. Suppression of naturally occurring fire since the early 1900s has had a slow, cumulative effect. Approximately 16,500 ha of pinyon-juniper woodlands were converted in the early 1960s to improve range conditions and water yields. Conversion was accomplished by uprooting trees with a cable or heavy chain (chaining) or by pushing trees out of the ground with a tractor (pushing). In addition, the watersheds have been altered by road and fence construction and watering site development. At the lower end of the watershed, near the Verde River, several small residential communities have developed, while summer home developments have evolved on isolated parcels at higher elevations (e.g., Double Cabin Park, K-T Ranch, and Stoneman Lake). Other important impacts on the Beaver Creek watershed include sand and gravel operations on the Verde River and its tributaries, agriculture use, increase groundwater demand for irrigation and domestic use, and invasion of riparian areas by introduced plant species such as tamarix (*Tamarix pentandra*) or salt cedar

Methods of Data Collection

A system of paired pilot watersheds, established within a given vegetation type, received a single treatment at a given time for evaluation. Initial comparisons of the water yield and other products from these small, natural watersheds were completed before any treatments were applied. After the pretreatment evaluation, one of the paired watersheds was altered by vegetative manipulations and the other was used as a control. Twenty pilot watersheds within the Beaver Creek area (Brown et al. 1974, Clary et al. 1974) were established between 1957 and 1962 to test treatment effects (figure 1). Of these, 18 watershed were from 27 to 824 ha in size. The other 2 basins, encompassing 4,900 and 6,680 ha, were created to demonstrate the effects of management practices on areas similar to those common to land managers. In the early 1970s, 24 smaller subwatersheds, each having more uniform soil, plant life, and topography, were delineated in areas of diverse ecological characteristics. Seventeen of these subwatersheds were on the Beaver Creek watershed. Information from these watersheds helped refine and verify findings from studies on the pilot watersheds and promoted application to a wider range of conditions.

Studies in ponderosa pine forests and pinyon-juniper woodlands evolved from evaluation of changes in water yield to evaluation of changes in livestock forage, timber production, wildlife habitats, recreational values, and soil movement. A wide range of management treatments were tested on Beaver Creek (Baker 1999, Brown et al. 1974, Clary et al. 1974). Treatments included conversion of vegetation type in the pinyon-juniper woodlands, and practices, such as clearcutting, severe thinning, and strip cutting, to increase water yields, patch cutting to favor wildlife, and shelterwood cutting to promote maximum sustained timber production in the ponderosa pine forest. Hydrologic response, timber and forage yields, soil erosion, sediment production, water quality, scenic beauty, and the dynamics of insect, bird, small animals, and big game populations were measured posttreatment. Early research was summarized in state-of-the-art publications (Brown et al. 1974, Clary et al. 1974).

Data Sets and Coverage

Data sets from Beaver Creek are organized to reflect the components of a water budget; that is, precipitation inputs (quantity and quality) minus streamflow outputs (quantity and quality) equals evapotransiration (as modified by geology, soil, elevation, and vegetation). Data are expressed in English units of measure as was used in data collection. Computers allow rapid conversion to other units of measure, if desired.

The Beaver Creek watershed Web site (http://www.rms.nau.edu/wsmgt/beavercr/) has links to the categories described below. Searchable lists of the various types of information available about the Beaver Creek watershed project are available to users. Drop down lists are also available for easy access to various data for specific years and particular watersheds.

- *Overview* provides a brief narrative on why, when, and where the project was initiated. There is a site description and history, a description of research, and highlights of research findings.
- *Publications Data Base* links to the project's searchable publication data base (www.rms.nau.edu/beaver_cr/) that contains nearly 700 annotated citations for publications and reports that were developed during the Beaver Creek project (Baker and Ffolliott 1998, Baker et al. 2000a).
- *Personnel* lists names, status (deceased, working, or retired), and address (where appropriate).
- *Data* categories include weather, precipitation, streamflow, vegetation, soil, and fauna. All data categories have drop down lists for specific years and particular watersheds allowing users to make their own selection. Most data collecting was terminated by October 1983.
- *Weather* contains air temperature and humidity, wind speed and direction, snow, and solar radiation.
- *Precipitation* includes precipitation depth by gage and watershed and precipitation chemistry.
- *Stream* consists of instantaneous and daily streamflow information by watershed and stream flow chemistry.
- *Vegetation* includes timber and range data by inventory dates for the various watersheds. Plant species lists (scientific and common names) are included for the major vegetation types; ponderosa pine, pinyon juniper, and desert shrub.

- *Soil* contains soil descriptions, type, texture, and depth by watershed.
- *Fauna* includes data for the various animal inventories by date and watershed. Animal species lists (scientific and common names) for the major vegetation types are included.
- Watershed Description includes watershed number, area, slope, aspect, elevation, universal transverse mercator coordinates of gages, vegetation type, stream gage type, year initiated and terminated, treatment information, and comments.
- *Image Data Base* provides a link to the project's searchable image data base (www.rms.nau.edu/imagedb/wm/) that contain over 2,000 images collected during the Beaver Creek project (Baker et al. 2000b).
- *Related Links* include those with a direct connection to the Beaver Creek watershed project.
- *Contacts* is a list of people to reach for information about the Beaver Creek project that was not found on the Web site.

Additional Information

To help understand the Web site data sets for better interrogation and interpretation of the information, the following is presented.

Precipitation Data

Precipitation (inches) falling on the Beaver Creek watershed was measured with a network of about 60 gages from 1957 through 1982. All hydrologic data were collected on a water-year basis from October 1, Julian Day (JD) 274 through September 30, JD 273.

We used 4 types of rain gages on Beaver Creek. Recording rain gages (0100 series), standard 20.3 cm (8 inch) rain gages located next to recording gages (0200 series), remote (not adjacent to a recording gage) standard rain gages (0300 series), and Sacramento storage gages (0400 series). Generally at least one recording rain gage (0100 series) and its companion standard gage (0200 series) was located on each watershed. A number of additional standard rain gages (0300 series) were located on each watershed (the number of additional gages depended on the size of the watershed). These gages were visited weekly. The Sacramento storage gages, large gages capable of storing up to 40 inches of precipitation, were used in very remote locations that were difficult to reach and were serviced twice a year. Gage locations were selected on the bases of access and adequate coverage of each watershed. Precipitation measured in the standard 20.3-cm (8 inch) rain gage was used to designate the true amount at each site. The nearest recording gages was used to prorate the amounts measured in all non-recording gages.

All watersheds on Beaver Creek contained 2 to 6 precipitation gages. Average watershed precipitation inputs were subsequently determined using the Theissen Method of averaging for the allotted number of precipitation gages. Point rainfall amounts for 8 frequencies (15 min to 24 hr) and durations of 2, 5, 10, 25, 50, and 100 years were derived from Arizona State maps of precipitation (U.S. Department of Commerce 1968).

Air Temperature and Relative Humidity

A weather station was located in the Utah juniper vegetation type on watershed 3 (WS3) (0001), in the alligator juniper type on WS4 (0009), and 3 stations in the ponderosa pine type, WS8 (0020), WS17 (0035), and WS20 (0038). Analog hygrothermographs were used with a weekly chart. Period of record is usually from water year 1957 through 1982.

Streamflow Data

Streamflow was measured using the Beaver Creek, supercritical, trapezoidal flume on the 18 pilot watersheds (Baker 1986). Larger flumes, developed to measure flow in excess of 28.3 m^3/sec but with sufficient precision for long-term hydrologic investigations, were located on Woods Canyon (WS19) and Bar M Canyon (WS 20), the two largest watersheds (Brown 1969). Streamflow from the 24 subwatersheds, established in the early 1970s, was measured in 0.6 m H flumes with a maximum capacity of 0.3 m^3/sec. Daily streamflow data includes total flow in m^3 and area mm, peak discharge in m^3 /sec and time of occurrence. Monthly flow is included for all water years of record.

Annual peak discharge for each watershed and water year are included. The discharges are expressed in m^3/sec per ha so flow from areas of different sizes are comparable.

Applications

Availability of data sets, such as illustrated in this paper, has unlimited use by researchers, land managers, educators, policy makers, and interested public. These and similar data sets provide a basis to help watershed managers resolve future land stewardship issues. Although these data bases are in the public domain, they are minimally useful if access is limited by knowledge of their existence and by physical accessibility. Accessing these data bases via the Web allows individuals to down load them into software packages and models that did not exist when the data were being collected. Research results from the Beaver Creek watershed project find application in many arid and semi-arid regions of the world and provide long-term resource data for new analysis techniques and model application. There have been over 70 technical publications produced since the project was terminated in 1982 (Baker and Ffolliott 1998).

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Emerging Tools and Technologies in Watershed Management

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Abstract.—The field of watershed management is highly dependent on spatially distributed data. Over the past decade, significant advances have been made toward the capture, storage, and use of spatial data. Emerging tools and technologies hold great promise for improving the scientific understanding of watershed processes and are already revolutionizing watershed research. Issues of scale, error, and uncertainty are highly relevant to understanding surface processes and are intimately tied to these emerging tools. This paper provides a summary of some of the ways in which global positioning systems, geographic information systems, remote sensing and distributed models are being integrated to provide information to the scientific and management communities

Introduction

One of the underlying principles of watershed management is the recognition of the interrelationships among land use, soil, and water, and the linkages between uplands and downstream areas (Brooks et al. 1997). Watershed management has always required synthesizing a vast array of spatial information to assess downstream impacts. Moreover, it is important to know not only the percent of a given land use, but also its distribution in a watershed. For example, runoff and sediment from a dirt road has a greater probability of reaching a stream channel if the road is located in a floodplain rather than on a ridge top.

In the past, obtaining spatial information has been time consuming and difficult. As a result, many of our watershed assessment methods and are predicated on only general information regarding the spatial characteristics of our watersheds. A good example of such an approach is the SCS Curve Number Runoff Model (Haan et al. 1994), a lumped parameter model, necessitating only the percentage of different land use types that occur on each soil type for parameterization (i.e. selecting the curve number). However, even the relatively simple task of manually overlaying land use and soil maps, delineating the watershed and soil/land use boundaries, and then finding their with a planimeter could take a watershed manager days, if not weeks, to accomplish for a complex watershed. Using conventional means, the time it takes to perform such analyses at regular intervals to assess the effects of dynamic land use is prohibitive.

The revolution currently occurring in the field of information technology is changing the profession of watershed management. New tools such as global positioning systems (GPS) and remote sensing are being developed to inventory and monitor watershed characteristics. Geographic information systems (GIS) have the power to collect, store, analyze and display georeferenced information. Maps have always been one of the principal tools of a watershed manager and these computerized maps are becoming one of the most important tools in watershed management (NRC 1999; Goodchild et al. 1993; Franklin 1994). In turn, GIS are being linked to simulation models and decision support systems. This change is fueled by rapid expansion in the computer industry that is providing technology capable of delivering, storing, and analyzing vast quantities of information.

In theory, given a suite of sophisticated research tools, solving the aforementioned Curve Number problem should now be simple and quick. Unfortunately, that is usually not the case. The spatial (GIS) data for soils and land use first must be gathered and entered into the computer, models redesigned and encoded to efficiently use the new information, and watershed managers trained to use the new technology. This investment in developing new processes is essentially an up-front cost that will diminish and pay large dividends as techniques are developed and improved.

The profession of watershed management has already embarked on this process. Databases are being developed (Lytle et al. 1996) and spatial data is becoming readily available through the Internet (NRC 1999, Appendix B). Models and decision support systems (DSS) that can utilize the spatial information are becoming available at a rapid rate (NRC 1999; Corwin et al. 1999; Poiani and Bedford 1995). Universities are starting to offer advanced courses and workshops on GIS

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applications for hydrology and watershed management (Miller and Guertin 1999). Increasingly, young professionals have knowledge and experience that will accelerate the process of utilizing these emerging tools and technologies.

The goal of this paper is to review the status of emerging information technologies in relation to their contributions to watershed management. Special emphasis will be paid to GIS, which is becoming a key component to many of the new tools being developed. An attempt will be made to identify research needs to advance not only technological development, but also the wise use of these powerful tools.

Information Technology and the Decision Making Process

The art and science of planning and decision making has always involved the gathering, analysis and synthesis of raw data to derive information to assist decision makers. While new technologies are improving this process, the basic objectives remain the same. The steps in the process incorporating the use of the new technologies in watershed management are illustrated in figure 1.

The first step remains data acquisition of spatial and non-spatial data and the creation of a database to support later activities. New tools such GPS, remote sensing, and real-time telemetry have augmented traditional surveying and inventory methods. GIS are increasingly being used to store both georeferenced data and associated attribution information and can be linked to relational databases, thereby improving the ability to store and access large data sets.

The importance of GIS in for inventorying and monitoring was identified by Franklin (1994). For example, GIS can provide a "snapshot" in time of a watershed or landscape features. By updating the GIS database through time changes can be observed, studied and quantified. GIS not only have the capability to capture and store georeferenced data but can also be used as analysis tools (Burrough and McDonnell 1998). Secondary data layers can be created through spatial analysis, and the raw and secondary layers then synthesized through the use of a model to create products useful to land managers. Modeling can either be done within GIS (Tomlin 1990) or the GIS can provide data to parameterize an external model. Likewise, information can be used directly in a GIS to support decision making (Guertin et al. 1998) or model results entered into a decision support tool or optimization package (Johnson 1992; Lane et al. 1991, Lawrence et al. 1997).

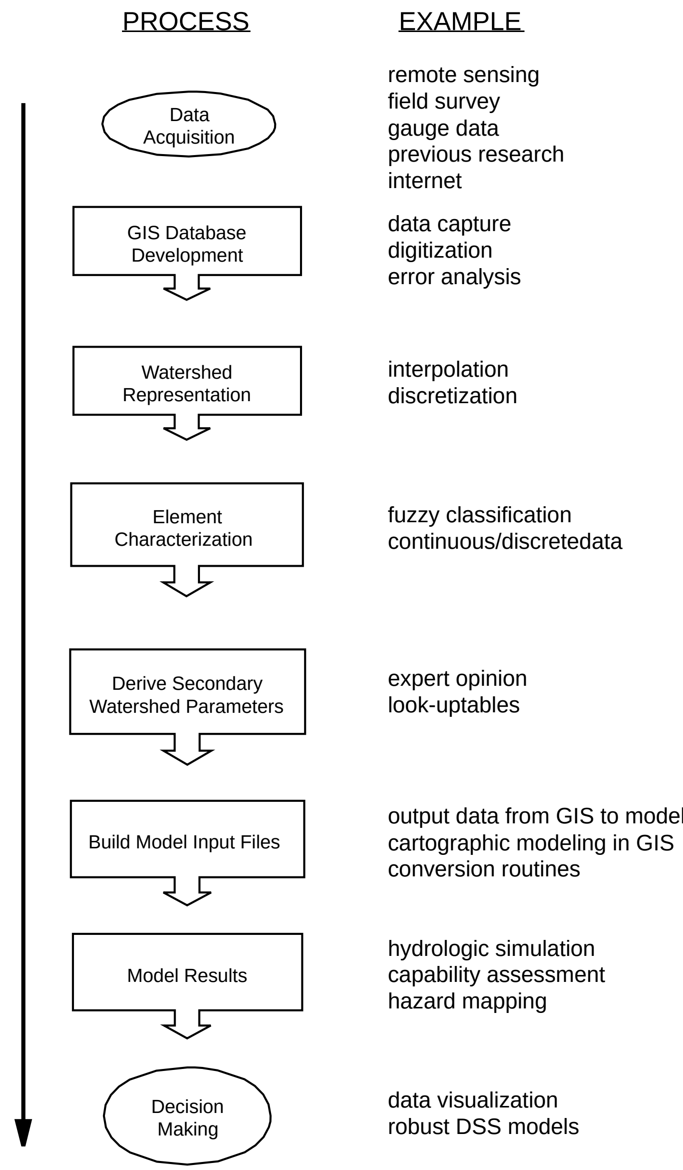

Figure 1. Schematic illustrating the use of emerging tools and technology in watershed management.

Data Acquisition

By definition, watershed and landscape processes are spatially distributed, and a host of surface characteristics dictate hydrological responses to landscape change. Assessment and modeling techniques must therefore account for the spatial variability of important variables, including soil, vegetation, management, topographic, geologic, and hydrologic characteristics. Determining the precise boundaries of these and other characteristics is critical, yet a daunting proposition. Mapping techniques relying on surface travel and surveying equipment are tedious, locally intensive but non-continuous, and relatively inaccurate. Advances in the spatial characterization of the earth, specifically the advent of remote sensing and global positioning systems (GPS), allow for the rapid and precise assessment and mapping of spatially distributed surface properties.

Global Positioning Systems

Since the late 1970's GPS satellites have been launched which are designed and operated by the US Department of Defense (DOD) and recently private corporations and foreign governments have been making GPS signal data available (US Coast Guard 1999). In 1995 a full constellation providing global coverage was achieved by the DOD. This configuration provides continuous coverage with a minimum of four visible satellites to any point on Earth (Twigg 1998). GPS satellite orbits are well known, and their positions highly predictable through time. These satellites broadcast two radio signals (L1 and L2) which carry navigation codes and messages. Ground sensors, which are freely available and may be purchased for less than $200, receive the signals. The codes and messages are used by the unit to calculate distances among the satellites, and geometric algorithms are employed to determine the precise position of the receiver.

While each satellite broadcasts signals accessible by any GPS unit, the DOD adjusts the signal for security purposes. This process of adjusting the signal, known as selective availability (SA) reduces the accuracy of any GPS position that does not contain an anti-SA encryption chip to less than 100m in the horizontal and less than 150m in the vertical directions. The L1 signal provides a precise position code to receivers containing encryption chips to provide accuracy to less than 15m. Receivers that are incapable of interpreting the L1 signal rely on the L2 signal, and must employ differential GPS techniques to improve the positional accuracy (US Navy 1999).

The advantages held by GPS over traditional field survey techniques for watershed management are many and its potential in hydrology and watershed management profound. Some examples of how GPS technology is advancing field surveying: navigation to research sites is made easier; accurate positioning of important positions is direct; the boundaries of spatially distributed characteristics can be traced. Field hydrologists can use a GPS to fix the location of observation points, such as channel cross section, precipitation gauges, weather stations, flumes, soil plots, observation wells, and vegetation plots. GPS are being employed in such diverse fields as precision agriculture, topographic mapping, and bathymetric surveying (Clark and Lee 1998; Wilson et al. 1998; Yang et al. 1997). For example, Guay et al. (1999) used GPS coupled with sonar to map the bathymetry of Topock Marsh in Arizona much faster that traditional surveying techniques. It should be recognized that the use of GPS is limited in its ability to fully spatially characterize an area. It is most useful for point and boundary surveys, and other tools must be employed on large areas or where fully distributed information is required.

Remote Sensing

For the purposes of this paper, we will use Schott's (1997) definition of remote sensing, as the field of study associated with extracting information about an object without coming into contact with it. While broad, this definition reinforces the notion that data can be attained without physical inspection and allows for large-scale synaptic research linking ground and remotely based observations. We will make a further distinction and only focus on remote sensing of the electromagnetic spectrum (EM) in this discussion, thus obviating magnetic, sound, and nuclear waves. Two types of EM sensing are employed in landscape studies: optical, which focuses on short wavelength from the ultraviolet to the long-wave infrared spectra; and radar, which uses the microwave (long wavelength) portion of the EM spectrum (figure 2). Many types of imaging, including vision, photography (both ground- and aerial-based), satellite observation, radar, sonar, and astronomy are classified as remote sensing, and these techniques are widely applied in earth science observation, landscape characterization, modeling, and management. An emerging field, remote sensing is expanding rapidly in consort with advanced computing and engineering technologies.

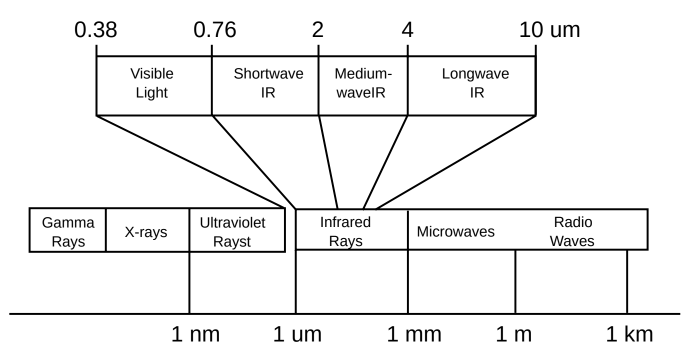

Figure 2. The electromagnetic spectrum.

Optical

Optical remote sensing, as stated earlier, utilizes the shorter wavelength rays of the EM spectrum. Energy across the EM spectrum is transmitted from the Sun to Earth, where it interacts with the atmosphere and is scattered, reflected, refracted and transmitted before encountering the Earth's surface. Some of the energy is absorbed on the surface, and the remainder is reflected or re-transmitted to the atmosphere. Optical remote sensing instruments are passive devices that record the EM waves as they are emitted from the Earth's surface. Since different land cover combinations interact with the EM field in different ways, it is possible to interpret the signal for landscape characterization purposes.

A host of remote sensing platforms is currently in operation, with many more having served their useable lives and others in production and design phases. Early satellite platforms were limited in the array of sensors deployed, and small windows in the EM spectrum were targeted for specific applications. With improvements in design, engineering materials, and computing power, multi-spectral platforms have been employed that can sense large portions of the EM spectrum, thereby improving classification capabilities. Besides being limited to daylight operation, a significant drawback to optical remote sensing is that it is a passive exercise, highly dependent on atmospheric condition. Clouds or smoke mask surface signals from the sensor, and large areas of the Earth are highly restrictive due to the presence of such atmospheric conditions.

As aptly stated by Schott (1997), traditional surface studies are limited by sample size and because they are point-based. Remote sensing provides a different perspective on the earth, and is suitable for large-scale investigations into surface patterns, trends, and the coordination with ground-based observations for purposes of extrapolation or interpolation. Since different objects, such as soils, geologic material, anthropogenic structures and vegetation affect the EM signal, algorithms can be developed to interpret landscape characteristics (Allen, 1994; Cleland et al. 1994; Lachowski et al., 1998). Many such algorithms have been developed for case-specific applications in vegetation classification, soil analysis, geomorphology, oceanography, and atmospheric sciences (Moran et al. 1994; Wilkinson 1996). A classic example of such an algorithm is the normalized difference vegetation index (NDVI), which uses the spectral ratio between the infrared and red spectra to predict biomass over large areas (Rouse et al., 1973). Advanced image processing tools utilize statistical techniques to classify landscapes into regions of similarity, upon which more specific categorization algorithms may be imposed.

Microwave

As is shown in figure 2, the wavelengths within the microwave spectrum are orders of magnitude longer than those that are sensed in the optical range. Radio Detection And Ranging (RADAR) uses these longer wavelengths to make inferences regarding surface properties for landscape classification. While some RADAR applications are passive, the majority are active systems, wherein a satellite or aircraft emits a microwave signal towards the object of interest and records the signal upon its return. As is the case with optical techniques, RADAR relies on the fact that the object under investigation alters the signal. Algorithms are used to decode the impact of various combinations of surface characteristics on signal behavior.

Synthetic aperture radar (SAR) is an emerging research tool that allows for highly detailed surface mapping through the processing of RADAR signals such that the azimuth resolution is improved in direct proportion to the system aperture size (Henderson and Lewis, 1998). Although the concept of SAR processing was introduced in 1951, advances in the field were held in check by the lack of computers capable of processing the complex signal. The benefits of SAR data are currently hot topics in remote sensing and natural resource research (Henderson and Lewis, 1998; Metternicht and Zinck, 1998; Moran et al 1998).

SAR has great potential for application in natural resource science since it can provide high resolution images, is not affected by atmospheric conditions, is an active system, the return signal is highly affected by the imaged target, the signal can be polarized and is coherent, providing both amplitude and phase as a function of the target. Polarization is useful for landscape, specifically vegetation classification since various land covers alter the polarization to a greater or lesser extent. Inteferometric SAR (IFSAR), wherein a target is sensed multiple times from different positions, can be used to provide highly detailed topographic maps (Lanari et al. 1996; Madsen et al. 1993). Various IFSAR instruments have been used to detect land surface change, flood extent, tree harvesting, ocean currents, sea ice characteristics, and provide digital elevation models (DEMs) superior to and more rapidly than those created by conventional means (Izenberg et al. 1996; Nykanen et al. 1998; Tobita et al. 1998).

Data Delivery

Although the development in GPS and remote sensing has greatly reduced the cost in creating data sets and making information more readily available, the availability of information through the Internet may have more far reaching effects. The University of Arizona has compiled a list of approximately 300 active land-surface hydrology data links (http://www.hwr.arizona.edu / hydro_link.html). Watershed managers can obtain streamflow records (http://h2o.usgs.gov), watershed boundaries (http://water.usgs.gov/public/gis) and digital terrain data (http://nsdi.usgs.gov/nsdi/pages/nsdi004.html) from the U.S. Geological Survey, water quality data, as both maps and numbers, from the EPA's "Surf Your Watershed" site (http://www.epa.gov/surf/), and weather data from the National Climate Data Center (http:/www.ncdc.noaa.gov).

Through the Internet, government agencies and private organizations are now able to make their data and related information available at little or no cost. Even individual watersheds now have their own Web sites, including the Verde River in Arizona (http://www.verde.org) and St. John River in Florida (http://www.riverpage.com). The Internet is allowing access to data, most of it produced by government agencies, to flow freely, and with information being posted on the Web continuously, problems regarding data availability are decreasing steadily.

Spatial Analysis and Modeling

The major obstacles to using GIS to address watershed problems have been the lack of spatial data and computer hardware and software requirements for large data sets. Only a few years ago, using GIS for management applications required creating a new database, a process that could take years. An investment in powerful workstations or main frame computers, which not only had a high initial cost, but additional costs of system support and training, was also necessitated. As such, GIS was the provenance of large government agencies capable of assembling such research facilities. However, with GIS data becoming more readily available and the increased power of desktop personal computers, GIS is becoming available to most hydrologists and watershed managers. Consequently, GIS is emerging as an important tool for watershed management, with tools for spatial analysis and modeling being adapted for its use.

Spatial Analysis

Spatial analysis for hydrology and watershed management has long been an important research field. Many common GIS algorithms were originally developed to address hydrologic applications, such as watershed delineation (Band 1986; Jenson and Dominque 1988) and the computation of flow paths (Quinn et al. 1992). The use of DEMs for watershed characterization has received considerable attention (Beven and Moore 1992). Moore et al. (1992), in their review of terrain modeling, discussed many topographic attributes of hydrologic significance and illustrated their computations. Others have created GIS-based tools for exacting watershed information from DEMs for watershed characterization and model parameterization (Eash 1994; Garbrecht et al. 1996; Miller et al. 1996; Miller et al., 1999). Hutchinson (1989) developed a procedure for gridding elevation that automatically removes spurious pits and incorporates a drainage enforcement algorithm to maintain fidelity with a catchment's drainage network Hutchinson's algorithm has since been incorporated in the GIS software ARC/INFO and many of the watershed characterization procedures are now standard functions in desktop GIS software (ESRI 1996).

Interpolation routines have been developed for GIS applications. Using these techniques, point observations can be interpolated to create spatially distributed coverages across a watershed. Geostatistical techniques are also becoming integrated into GIS, although current GIS-based geostatistics lag behind stand-alone software and GIS is best used to provide input data to these packages. Such approaches, including kriging, multiquadratic, and principle components analysis, are used to interpolate soil information, rainfall, and contaminants (Burrough and McDonnell 1998).

Modeling

In the near future most, if not all, hydrologic models and watershed analysis techniques will utilize GIS. GIS are used to represent the watershed under study for modeling purposes, often through the interpolation of point data (such as rainfall gauge records) and subcatchment definition (figure 1). Once the watershed has been divided into modeling units in this fashion, each element is characterized according to necessary model inputs, and the data input into the specified model. The modeling approaches can be split into two classes. In the first class the model is incorporated entirely within a GIS using cartographic modeling techniques (Tomlin 1990). The products of this approach are usually new GIS coverages containing model results. Land capability or suitability (Sheng et al. 1997), landslide hazard mapping (Carra et al.1991; Montgomery et al. 1997; Montgomery and Dietrich. 1994), and erosion hazard (Warren 1989) are examples of this type of analysis.

Warren (1989) estimated erosion within the GIS using the Universal Soil Loss Equation and used the results to identify areas that need rest or rehabilitation from military training because of severe erosion potential. GIS coverages show areas under stress were created and then used to move military training activities to less impacted areas. Sheng et al. (1997) developed a procedure for developing countries to classify watersheds and target problem areas so as to more wisely allocate watershed protection funds. In the proposed scheme a watershed is classified as a function of slope, soil erodibility, vegetation cover, rainfall intensity and critical areas. Guertin et al. (1998) developed a GIS-based tool for sustainable livestock management. This tool, RANGEMAP, was developed from grazing allotment management decision-making that address resource production and conservation. The tool was developed using the desktop GIS ARCVIEW GIS 3.1, with the Spatial Analyst extension (ESRI 1996) with a "user-friendly" interface so range conservationists and ranchers can more easily use it. The tool can estimate forage production, utilization rates, stocking rates by pasture, and erosion potential and can be used to determine the effect of different management schemes, such as location of water, grazing systems, and exclusion of riparian areas, on stocking rates and erosion potential. The second class consists of models that are external to the GIS, but use GIS output data for parameterization. Many older and widely used models have already been adapted to link to a GIS for parameterization. Examples include HEC-RAS, an update of HEC-2 (U.S. Army Corps of Engineers 1995), MMS (Leavesley et al. 1996), AGNPS (Young et al. 1989), HUMUS (Wang and Srinivasan 1997), WEPP (Savabi et al., 1995), and BASINS (Lahlou et al. 1996).

Research Needs

Hydrology and watershed management share similar issues with other fields using emerging computer technology: the implementation of distributed computing, improving interoperability of dispersed data sets, the future role of the Internet and legal rights to data. These issues are of secondary importance to scientific advancement, however, and there are several research areas particularly important to watershed management: those of scale, error analysis, geographic representation, and new model development.

Scale

Scale refers to the resolution at which information is represented and utilized. Information captured and entered into a GIS in raster format is defined by its resolution, while vector-based data is a function of its accuracy. The resolution of the data will have direct effects on analysis results at a range in scales. For example, as a DEM's cell size is increased, local slope estimates decrease (Jensen 1991; Zhang and Montgomery 1994). As a cell increases in size it represents a larger area, hence the averaging of elevations of large areas will result in a smoother, less steep, surface (Wolock and Price 1994). This in turn has an impact on processes such as soil erosion since erosion is directly related to slope.

Miller et al. (1999) found that a high resolution DEMs created using IFSAR provided significantly different results at small scales when compared to other lower resolution DEMs. In this study a range in DEMs was used to generate stream channels for a rangeland watershed using a GIS flow direction algorithm. Figure 3 illustrates the influence of DEM resolution and model type on stream network generation. Note that variability in complexity and number of smaller channels exists among the maps, yet the underlying structure remains constant. Syed (1999) used the same suite of DEMs to parameterize a distributed hydrologic model and found that the choice of DEM significantly altered the results at smaller scales.

Research is needed to address the proper level of complexity, and resolution of spatially distributed data to adequately model and manage watersheds. Different hydrologic processes predominate at different scales, and the level of resolution is largely a function of scale. Small-scale variability in soil properties is important at the plot and hillslope scale since hydrologic processes are highly determined by this factor, but such variability becomes less important at the watershed or basin scale. Furthermore, detailed characterization at larger scales is overly complex and can potentially lead to parameter estimation error in modeling, and hence management. Bloschl and Sivapalan (1995) provide a synopsis of scale issues in hydrology. Both spatial and temporal scaling are dominant factors in watershed management, and GIS together with hydrologic models provides an avenue of research into these subjects.

Error Assessment

As new procedure for integrating GIS-based processes into watershed management are developed and spatial data flows more freely via the Internet, it is important that issues surrounding spatially distributed error and model behavior are addressed. Error can be introduced to the decision-making process at every step illustrated in figure 1. The effects of error have been widely studied in hydrologic modeling through sensitivity analysis, and there is a need for research of this kind to address issues of uncertainty and error in GIS systems.

Thapa and Bessler (1992) provided an overview of sources of error and the authors rightly point to the lure of easy data acquisition as a potential source for unaccounted

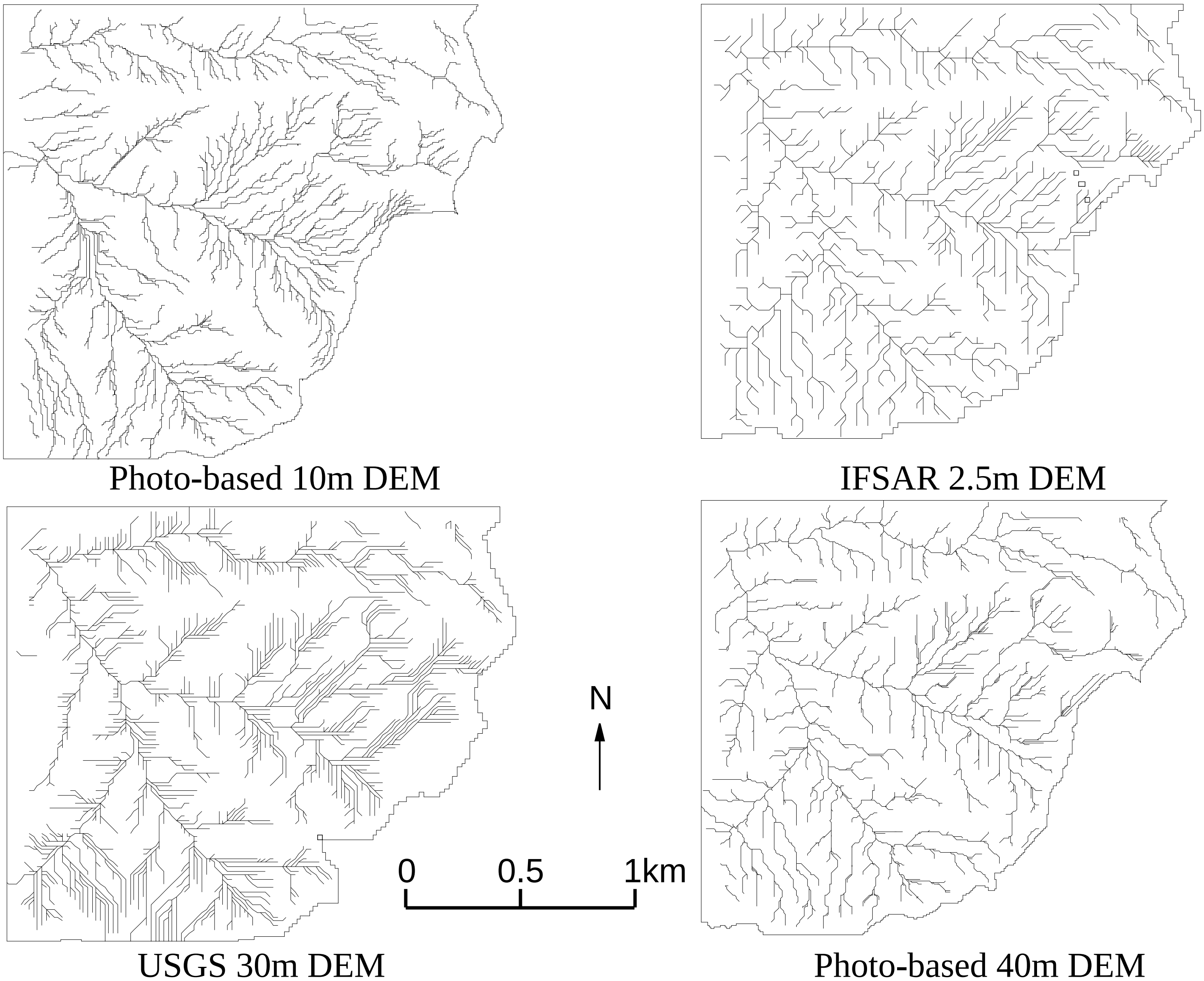

Figure 3. Influence of DEM resolution and type on drainage network representation (from Miller et al., 1999).

error. While data availability has improved the ability to quickly develop GIS applications, it is important to quantify problems associated with various techniques (Choudry and Morad 1998; Davis and Keller 1997; Lark and Bolam 1997).

New Model Development

The advent of GIS has altered the prospective for hydrologic modeling substantially. First, the rapid acquisition of spatially variable data allows for the rapid parameterization of models. Second, the potential for providing input to fully distributed models has been greatly enhanced. Physically based models that require extensive data are being developed both within and outside of GIS (Jeton and Smith 1993; Shu-Quiang and Unwin 1992; Srinivasen and Arnold 1994).

This ability to fully describe watershed characteristics at a range of scales provides opportunity for the development of new generations of watershed and basin-scale models. Large area modeling has previously been hindered by the lack of spatial data and by limited computer power. As has been discussed in this paper, both these issues are rapidly disappearing. Arnold et al. (1998) are developing modeling tools for basin assessment using GIS and the basin-scale SWAT model. A statewide system for assessing water quality using GIS tools was presented by Hamlett et al (1992) wherein agricultural practices were modeled for downstream impacts. Raper and Livingstone (1995) argue that the field of geomorphological modeling would be served best by the development of new models that take advantage of object-oriented programming and avoid the geometric limitations of GIS. Walsh (1992) called for the development of spatial decision support systems integrating GIS, expert opinion, and a host of models. The field of spatial modeling is currently undergoing rapid change driven by the emergence of new tools and technologies that facilitate the development and application of cutting-edge models.

Conclusions

In the future, watershed assessments and analysis will primarily be done using GPS, remote sensing, GIS, and related models and tools. This trend will allow watershed managers to quickly and cost effectively address watershed problems in a spatially explicit manner not previously available. However, this advancing technology is not unhindered by concerns (Congalton and Green 1992; Lovejoy 1997). Congalton and Green discussed the problem of being disconnected to the real work when working solely indoors on a computer. Lovejoy questioned the need for "high-tech", relatively expensive GIS-based solutions when "low-tech" solutions may be adequate. A primary function of GIS is the production of computer generated graphics, which are rarely questioned by the public. The graphic capabilities of GIS can lead to misrepresenting the results through the choose of symbols and colors (Monmonier 1996).

Emerging technologies like GPS and GIS hold the promise of making research and management tasks easier and provide capabilities previously unknown. New modeling systems will allow use to ask spatial explicit questions, such as what effect will a buffer have down stream water quality. However, using the new technology does not remove the need of having clear objectives and then determine at what level the new technology will be used.

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A Sociocultural Perspective on the Development of U.S. Natural Resource Partnerships in the 20th Century

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Abstract.—Equable natural resource management partnerships between the public and private sectors are a relatively recent development in the United States. Modern resource management partnership forms are interpreted to be a result of an interaction of social, political and economic forces not normally associated with natural resource management activities. These forces are identified, discussed, and placed in historical context. Possible future trends in public / private management partnerships are extrapolated from current approaches.

Introduction

This paper examines the social, historical, and political context of public / private partnerships in natural resource planning over the past century. The antecedents to current approaches in natural resource management are examined to provide a context for a discussion of current methods and future trends. The approach is necessarily "broad-brush", due to the length of time discussed, as well as the huge number of resource management projects that have taken place in the United States in the last 100 years.

This paper will focus primarily on the "human" aspects of watershed management. In a recent paper, Penny Firth, the administrator of the joint National Science Foundation (NSF) / Environmental Protection Agency (EPA) / US Department of Agriculture (USDA) "Water and Watersheds" grant program, provided a long series of water related environmental and natural resource problems and concerns (Firth 1999). None of the issues discussed by Firth would have been a problem, without either, 1. Direct human action, such as pesticide contamination of groundwater, or 2. Direct human concern, such as loss of potable groundwater supplies in urban areas. Humans arguably cause many, if not most, natural resource "problems". Only human perception and interpretation of natural conditions result in perceived "shortages" and "concerns". Given this entirely, and uniquely, human problem, why are the opinions, wishes, and desires of concerned people not fully addressed in much of modern natural resource planning? At the end of the 20th century, experience is showing us that without fully involving affected communities and individuals in the earliest stages of planning, "management" and "stewardship" activities are rarely successful (Toupal and Johnson 1998; Endicott 1993; Daly 1994).

Natural resource planning and management is a dynamic and evolving practice (Daly 1994; Kenney 1999; Griffin 1999; Nazarea et. al. 1998). Resource management began in earnest in the United States in the early part of this century. As U.S. economic and resource policy and concerns evolved, so did methods and approaches to natural resource management. In order to understand contemporary approaches, a brief discussion of the historical and political context of natural resource management in the United States during the 20th century is in order. For the most part, except where noted, changes in U.S. federal policy and practice are used synonymously with changes in "public" policies. Private sector changes generally refer to efforts of non-federal government groups and individuals.

Historical Development of Natural Resource Management

For purposes of this discussion, the 20th century has been broken into three broad time periods; the early period, from 1900-1960, the NEPA period, from 1961-1980, and the modern period, from 1981 to the present.

Early Period: 1900-1960

This period of time is marked by several characteristics that both form the basis for development of partnerships later and are *not* typical of later partnerships. One of the more striking characteristics is the role played by governments, particularly the federal government, during this period.

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A series of large-scale socioeconomic events took place during the first three decades of this century that centralized more power in the federal government and eroded the power of the private sector (Keller 1994). World War I, and the American involvement in the war, engendered an air of national success, national confidence, and a great expansion in the industrial and economic capacities of the private sector. This was followed by the collapse of American and other economic markets during the stock market crash of 1929, which in turn, precipitated the American Great Depression (Garraty 1986; Saint-Etienne 1984; Louis 1968). As the economic stability of the private sector in America collapsed, the public turned to the government to provide security, in economic and many other senses (Garraty 1986).

The American federal government, while initially unprepared for the disastrous consequences of the Depression, responded relatively quickly with programs like the Civilian Conservation Corps (CCC) and the Work Projects Administration (WPA) (Lorence 1996; Garraty 1986; Keller 1994). The advent of these programs saw some of the first widespread, federally sponsored, efforts at natural resource conservation (Sklar 1992; Smith 1984).

A consequence of the use of programs such as the CCC and WPA was the development of a number of perceptions of the federal government on the part of the general populace. CCC and WPA work was carried out by American citizens from all walks of life. Few of these workers had formal training in natural resource management and conservation work. The federal government hired the few "natural resource" experts available, as well as other professionals, such as engineers, and put these individuals in charge of large groups of workers (Garraty 1986). Due to this style of labor management, a perception was born that the government provided "experts", and was a repository of specialized knowledge that the average worker did not have. This, in turn, led to the federal government occupying a role in natural resource management projects that was both paternalistic and dictatorial (Keller 1994).

Another consequence of this period of social and political development in American federal natural resource management was a tendency to focus on easily recognized and assessed portions of the natural environment. It was easy to see soil erosion; it was relatively easy to point at deforestation as a problem. These were important elements in programs such as the CCC and WPA, which needed large scale problems that were easily addressed by relatively simple, brute-force approaches (Smith 1984). Dams could be built, thousands of seedlings could be planted, and channels could be dug by untrained people under the supervision of a small number of "experts". The federal government defined the problems, defined the solutions, and then "fixed" the problems by employing lots of people. Everyone was happy. Nobody ever thought to ask the people who lived in an area that had "problems" what they thought about a "solution". The government knew best, and the average citizen had an almost blind trust in the federal definition of problems and solutions. Those problems were almost always defined in biophysical terms, such as soil erosion (Smith 1984; Sampson 1981). Rarely were causes, such as overgrazing, or farming that caused increased runoff, addressed. Underlying factors, such as traditional agricultural practices unsuited for more modern farming technologies were simply not addressed at all. In other words, symptoms were being treated, but not the root of the problem. This reactive state of natural resource management and watershed efforts lasted until the advent of World War II, in the late 1930s (Held and Clawson 1967).

World War II, while serving to lift America out of economic depression, also further solidified the role of the federal government as a controlling, and somewhat omniscient, body of experts. The economic boom and general feeling of national solidarity and success that followed the second World War, extended into an expanded federal interest in land and natural resource management. The massive industrial growth in the United States in reaction to the need for war materiel also fueled an equally huge increase in the need for raw materials, as production switched over to products suitable for civilian consumption. The "baby boom" following the war increased the demand for agricultural produce and building materials to previously unseen levels (Findling and Thackeray 1996).

These, and many other factors, caused natural resource management efforts to be driven by primarily economic pressures, such as increasing timber production, hydroelectric power supplies, or agricultural production. This trend, coupled with the previously established focus on biophysical resources within a watershed, resulted in natural resource management and watershed efforts that were controlled, to a large degree, by corporate interests, such as power or timber companies (Evans 1998; MacGaffey 1985) as a willing partner in most of these efforts, cooperating because of perceived benefits of economic development.

The Early Period of watershed management in the U.S. is characterized by the development of a "top-down" relationship between the federal government and other concerned groups and individuals. A centralization of decision-making and funding authority marks the federal government's efforts in natural resource management prior to 1960.

NEPA Period: 1961-1980

The National Environmental Policy Act (NEPA, 42 U.S.C. 4332), passed in 1969, was the result of a reaction on the part of the American people to the ongoing unilateral and dictatorial actions of the federal government. By the late 1950s and early 1960s, the numbers of people with greater education and professional expertise in the general populace was increasing rapidly, primarily as a result of the increased subsidization opportunities and lowered costs of higher education following the Second World War (Moss 1993; Galambos 1983). This component of the population began to question both the economic and management decisions of the federal government.

The reasons for the questioning of federal decisions are many and varied, and appear to be symptomatic of the era in general (Evans 1998; Moss 1993). Throughout the 1960s, it was shown with increasing frequency that the federal government was often not making decisions with the best interests of local populations in mind (Galambos 1983). Mounting evidence indicated the federal government was basing many decisions on economic and political drives and motives that often resulted in adverse consequences for local communities (Moss 1993; Evans 1998). At roughly this juncture it becomes clear that the general populace had lost a substantial amount of trust in the federal government, for a wide variety of reasons (Moss 1993). Federal decisions were viewed with increased skepticism, and local communities were demanding to be recognized and allowed input in the federal planning processes. It was in this social and political atmosphere that NEPA was conceived and passed.

Section 102 of NEPA explicitly calls for environmental impact statements for federal projects that might cause a significant effect to the human environment. The federal government was told to be accountable for its actions relative to environmental concerns, and specifically with regard to those actions that might affect the "human environment" (Rodgers 1996). As with many pieces of legislation, the greater part of implementation strategy was left to individual departments and agencies of the federal government. NEPA, as originally written, is a broad policy statement, and only in later regulations were specific requirements for public participation spelled out. What resulted was the federal government generally implementing a review process consisting of federal problem identification. Usually, a problem was identified by the federal government, which was then "scoped" with limited input from local groups and experts. Several alternative solutions to the problem would be developed, once again by the concerned lead federal agency (the birth of the "do-nothing" alternative). At this point, the public was usually asked, through a series of public meetings, to provide input on which alternative would be the most acceptable (Rodgers 1996; Lazarus 1991).

This model of public involvement assumed that the federal government "knew best", and allowed only a restricted range of public inputs. The federal government also assumed that allowing public input into selection of federally defined and determined "alternatives" was sufficient to meet the strictures of NEPA. Very rarely were concerned local communities fully involved in the development of "alternatives" (Grieder, Krannich, and Berry 1991; Lazarus 1991; Salamon, Farnsworth, and Rendziak 1998).

Experience with NEPA and the "NEPA process", i.e., scoping, alternative identification, public participation of various kinds, and problem solution, trundled ahead through the 1970s. Federal agencies, in good faith, did their best to implement the broad, sweeping strictures of NEPA, and there was an apparent increase in several areas of environmental quality during this period (Rodgers 1996). Simultaneously, the public was beginning to recognize and decry the limitations of the NEPA process, as used by federal agencies. Individuals and groups soon learned that they wanted more input, earlier in the planning process, and wanted more impact on alternative development and selection. Federal agencies, just beginning to adjust to the existence of NEPA and other environmental laws, were faced with a new set of demands for public participation and involvement. About this time, another type of issue was also being raised by the increasingly knowledgeable public: multiple use (Daly 1994; Cleary 1988; Hoffman 1994; Romm 1995).

Modern Period: 1981-Present

NEPA stipulated one of the first environmental reporting standards and processes that federal agencies were required to comply with. The public participation model provided by NEPA and its implementing regulations served to mold the federal perception of what appropriate public participation should be (Adams 1993). During the 1970s and early 1980s, this perception was institutionalized in the form of agency level policies and procedures (NRCS 1996).

The concerned public, however, was demanding an ever-increasing level of accountability and information release by federal agencies (Lazarus 1991). In addition, NEPA and its various forms of implementation by various agencies had been scrutinized by many organizations, private and public. Several points of the law had been called into question, and clarified, mostly by regulation (Rodgers 1996). In the U.S., environmental organizations were progressing into a "post-NEPA" state of expertise. "Public participation", as stipulated under NEPA, was no longer considered adequate. The process of federal alternative formulation used by most agencies was also being increasingly called into question (Adams 1993).

The dictatorial, "top-down" nature of earlier federal efforts in natural resource management was recognized as being a part of the perceived problem (Adams 1993;

Adler 1995). By the late 1980s, different approaches to planning were being developed that emphasized a "bottom-up", or "grass-roots" approach to natural resource planning (Salamon, Farnsworth, and Rendziak 1998). These approaches were intentionally and explicitly aimed at involving local people and communities in the planning process. A goal of these planning efforts was in the identification of problems and solutions in conjunction with concerned individuals and communities, rather than by the federal government alone(Endicott 1993; Cleary 1988; Hicks 1992).

By the early 1990s, non-governmental organizations (NGOs) were rapidly increasing in both number and popularity. Watershed councils, and other locally formed and driven forms of participation, were being increasingly used by concerned communities to give voice to concerns in natural resource planning (Kenney 1999; Griffin 1999).

The close of the century sees locally led planning efforts developing at a rapid rate. The rate of change in private sector organization and expertise has accelerated markedly in the last thirty years of this century (Lant 1999). This accelerated rate of change may be viewed as the result of a complex trend in U.S. society in general, as well as a specific change the relationship between the public and private sectors.

Modern Partnership Development: Primary Factors

The foregoing discussion has been intended to show that natural resource partnerships in the U.S. have only recently evolved from less equable approaches. The idea of partnerships, in which all members of the relationship have equal say and decision making power, is a relatively new approach to natural resource planning.

Four primary factors are postulated to have been key in the development of modern natural resource partnerships in the United States. These factors are: 1. A loss of trust in the federal government, resulting in greater skepticism toward federal planning efforts on the part of the public, 2. Dramatically increased general public access to information in print, broadcast, and digital, forms. This relatively rapid advance in communication and data manage technologies has led to an markedly increased level of awareness of federal environmental actions, relative to pre-NEPA levels, 3. An increased focus on "non-commodity" aspects of the natural environment, such as aesthetics and recreational values, and 4. An increasing demand on the part of the public to actively incorporate multiple uses in natural resource planning. Natural resource management and land stewardship activities in the U.S. are benefitting from the atmosphere an increased interest and participation. An examination of these primary change factors will illustrate the impetus behind the current shift to a partnership approach.

The first factor, loss of trust in the federal implementation of environmental and natural resource legislation and programs, appears to the result of multiple causes. These causes include, but are not limited to, lack of a clear environmental agenda that extends over multiple presidential administrations; a fragmentation of compliance responsibilities among multiple agencies; and a lack of funding necessary to implement both legal restrictions and programs (Lazarus 1991). This lack of trust has caused non-governmental organizations (NGOs), private citizens, and private interest groups to assume an adversarial stance, relative to federal actions. Current efforts at partnership building, particularly between federal agencies and private individuals and groups, have resurfaced the issue of trust as being of primary importance to partnership success (Toupal and Johnson 1998; Salamon, Farnsworth, and Rendziak 1998).

The second factor, the importance of dramatically increased access to multiple sources of reasonably accurate information, cannot be overstated. During the NEPA period, one commonly identified drawback of the public meeting method of gaining input was a lack of knowledge on the part of interested people about the timing and location of meetings (Kenney 1999; Griffin 1999). Today, anyone with access to the World Wide Web can almost immediately receive a staggering variety of materials on almost any subject. The Internet and World Wide Web are rapidly becoming preferred methods of distributing information for federal agencies, as well as the private sector (Tapscott 1999; Wolinsky 1999). It is increasingly easy to rapidly distribute accurate, timely information to a very large audience using these digital communication methods. No longer do agencies have to rely on physical meetings to gain input. A Web page with a well structured questionnaire and good background material can provide the equivalent of months of meeting and interview information to federal decision makers in a relatively short time. Equally, private sector partners can provide immediate feedback during planning, or can raise issues and concerns before the planning process proceeds, based on erroneous assumptions (Tapscott 1999).

The increased availability of information, compared to the communication technologies of even 20 years ago, has sharply raised the public's level of awareness of federal activities. Many private organizations maintain a watch over federal and other agencies, monitoring planning and environmental compliance activities. These "watchdogs" use multiple media sources to immediately bring the public's attention to bear on perceived mistakes or failures to comply with environmental law. This "watchdog" activity, coupled with a rapidly expanding use of the Internet and World Wide Web as media platforms, allows a person to become very familiar with a wide range of actions and issues within a relatively short time.

The third factor that has brought about the current state of public / private partnerships is an increased focus on "non-commodity" aspects of the environment and natural resources (Griffin 1999). These aspects include non-traditional resources such as landscape aesthetics, recreation potential of landscapes, indigenous traditional beliefs about land and other natural resources, and non-tangible uses of land and resources, as well as the development of a "non-use" ethic (Nowak 1992; Brunson 1996; Griffin 1999). None of these things are particularly amenable to traditional, capitalist, economic valuation, but are perceived by many people to be vital parts of watersheds that must be appropriately addressed in management planning (Griffin 1999). Most of these "non-commodity" aspects of natural resource management are also difficult to adequately address without sound relationships between concerned local individuals and communities and planners. One way to achieve such relationships is through the development and use of shared-power partnerships, rather than a more traditional, "top-down" approach to planning (Austin 1998; Nazarea et. al. 1998).

The fourth, and final factor, is an increasing demand on the part of the public to actively and realistically incorporate multiple uses into natural resource management planning (Brunson and Kennedy 1995). No longer are management plans that are driven only by the interests of a single group or economic concern considered sufficient (Kaufmann et al 1994; Cleary 1988; Brunson 1996). This factor is very important in most modern public / private partnerships: shared power and shared decision making authority (Toupal and Johnson 1998). An array of concerns must be balanced in modern partnerships, and economics can no longer be assumed to be the most important factor in decision making (Nazarea et. al. 1998; Johnson 1998). Appropriate and meaningful incorporation of multiple concerns in the management of land and other natural resources is the goal of most modern partnerships.

Current Approaches to Natural Resource Management

Currently, there are a number of approaches being used in the U.S. to pursue natural resource planning. Most of these new approaches are much broader in scope and intent than earlier efforts. Modern approaches also tend to emphasize, to greater or lesser degrees, involvement of local people and communities in the planning process. Two of the most popular of these current approaches are discussed here to illustrate the trend and direction of recent efforts.

Ecosystem Management

One of the most widely publicized terms in recent natural resource management efforts has been ecosystem management (Kaufmann et al 1994; IEMTF 1995; FEMAT 1993; Cortner and Moote 1999). Debate is still ongoing as to the definition of the term, and there appears to be widespread discussion about appropriate units of measurement in ecosystem approaches (Ruhl 1999; IEMTF 1995; Cortner and Moote 1994; Grumbine 1994). Regardless of the technical criticisms of ecosystem management, it appears to be a political reality (Ruhl 1999; Cortner and Moote 1999), and is therefore used as a discussion tool in most environmental policy debates.

It is difficult to find a single, universally accepted definition of ecosystem management. As noted by Ruhl (1999:519):

"The term "ecosystem" is much like Darwinism and Marxism, in that everybody "knows" what it means, but after not very much discussion of the subject it turns out everybody's meaning differs to some degree."

In general, however, it appears that ecosystem management generally means incorporating multiple concerns, both human and biophysical, in planning, for areas that are defined by ecological, rather than geopolitical, factors (IEMTF 1995). It also appears to be an explicit effort, on the part of some federal natural resource planners, to move to a much broader, or holistic, approach, to natural resource planning (USFS 1999a).

Ecosystem management, from a socioeconomic perspective, has some shortcomings. First, the lack of an easily definable scale that is both scientifically and politically useful makes it difficult to determine the scope of community involvement for ecosystem management efforts (Kaufmann et al 1994). In a similar vein, the lack of consistently definable biophysical scales makes it difficult to develop management strategies that can be implemented in a practical and cost effective way. When pragmatic local decisions are made in an attempt to implement ecosystem management, it often becomes difficult to tie such decisions back to an overarching ecosystem level management plan in any meaningful way (Kaufmann et al 1994; Ruhl 1999). This may not be as much a critique of the concept of ecosystem management, as it is a comment on the lack of appropriate methodologies.

Ecosystem management also runs the risk of becoming yet another "top-down" approach, given its initial heavy reliance on "science" heavy environmental factors

(Kaufmann et al, 1994) to define problems and concerns. Public agencies who use the ecosystem approach must remain cognizant of the need to incorporate locally defined, intangible resource concerns in planning, as well as scientifically defined, biophysical resource issues.

As an example, humans are acknowledged by most public planning agencies as being vital and highly influential components of ecosystems (USFS 1999a, 1999b; BLM 1997; Kaufmann et al 1994; IEMTF 1995). While making this acknowledgment, most agencies purporting to utilize an ecosystem approach continue to produce natural resource management schemes that are focused, almost entirely, on biophysical resources, with an emphasis on economically important portions of the natural resource spectrum, such as timber or grazing land (USFS 1999a, 1999b; BLM 1997; IEMTF 1995). Multiple use and other "human" concerns are included in supporting documentation, but it is rare to find long term management goals that address such issues in a substantive way (USFS 1999a, 1999b; BLM 1997).

Community-Based Planning

Many federal agencies have stated that "community based", or "locally led" planning is either a component of a broader approach to holistic planning, such as the ecosystem approach, or is a primary method used to accurately capture and incorporate local social, economic, and other "human" concerns in the planning and management process (USFS 1999a, 1999b; BLM 1997; NRCS 1996; IEMTF 1995).

There have been several adaptations of community based planning used by various private sector NGOs and other groups (Western and Wright 1994; Endicott 1993). Community based, or locally led, planning is an explicitly "bottom-up" approach. The flexibility of the approach results in multiple definitions of the term, as nearly every groups of users adds their own specific "twist" to the locally led concept (Endicott 1993; Salamon, Farnsworth, and Rendziak 1998).

Community based / locally led planning efforts can be generally characterized as initiated by concerned local individuals or groups who desire meaningful, broadly representative, input into a planning process (Western and Wright 1994). These planning processes may or may not have been initiated by public sector entities. The locally led planning process may be centered around organizing private individuals and information to bring a local concern to the attention of public planning agencies.

Community based / locally led natural resource planning efforts are usually issue or concern driven (Western and Wright 1994). This allows such efforts to define spatial limits of concern based on interest and occurrence, rather than on geopolitical boundaries. This approach may also introduce difficulties into the planning process, as it encourages initially unrealistic definitions of areas of concern.

Compared to ecosystem management, community based / locally led planning efforts initially rely less heavily on biophysical, "science" based, problem definitions for scoping purposes. Community based planning efforts usually collect and define issues and concerns raised by local individuals and groups, and then pursue the "science" of those concerns. This approach usually results in a much higher level of community involvement in planning, as well as a higher level of stakeholder identification with, and acceptance of, the results of the planning effort (Brunson and Kennedy 1995; Salamon, Farnsworth, and Rendziak 1998; Cortese 1999).

As the foregoing discussions of ecosystem management and community based planning illustrate, change is indeed afoot in natural resource management circles. Public agencies, particularly federal agencies, are rapidly becoming more aware of the need to incorporate local concerns and knowledge into natural resource planning. Private sector NGOs and other groups are quickly recognizing the potential benefits of early and substantial involvement in natural resource planning efforts. What does this mean for the future?

Trends and Changes

The number of locally led, community based, ecosystem scaled, natural resource planning efforts is increasing (Lant 1999; Firth 1999). This trend shows few signs of weakening, and probably will not, given the citizenry's continued low level of trust in public sector decision making (Lazarus 1991). It appears that there will be a continued decentralization of decision-making, shifting power away from centralized, bureaucratic management of natural resources. This shift to what has been variously termed, community led decision making, watershed democracy, or civic republicanism (Griffin 1999; Adler 1995; John 1994) appears to be gaining in popularity across the U.S.

What does this shift mean to public sector agencies? Federal agencies, in particular, are going to have to develop new methods to address local concerns and issues. Some fundamental federal policies on natural resource issue definition and measurement must be changed. These policies are currently centered almost completely around the definition and quantifiable assessment of biophysical resources, such as water quality, soil loss, or biomass density. These policies must be altered to accept local assessments of intangible resources, or resources that are not easily quantified, such as aesthetics or viewscape perceptions (and other uniquely "human" perceptions of the environment).

Public sector planners must step back from their current positions in the planning process and examine the degree to which decision making is shared, or not shared. Shared decision making authority is vital to successful natural resource partnerships.

Better methods of assessing the variety and interests of local communities must be developed. Social scientists are really only starting to explore how to work with communities in the U.S. to further natural resource planning efforts. Methods that have been shown to work well in other cultures and countries are being adapted to work with communities of agriculturists, environmentalists, and other concerned groups here at home. Previously unrecognized biases and assumptions are being questioned with each new project. This trend, hopefully, will continue well into the future, providing both the private and public sectors with new and improved tools.

Finally, public agencies are going to have to revise how they address issues raised by natural resource partnerships. New approaches must be developed that recognize the expertise of local communities in problem identification. The federal government must change from an autocratic judge of what is valid and invalid in natural resource planning efforts, to a provider of technical and fiscal support and facilitation.

In closing, it must be noted that natural resource partnerships between the public and private sectors are in their nascent stage. It is not often that one realizes they are in the middle of one of those much-touted paradigm shifts. The ongoing movement to involve local concerns and local knowledge in planning efforts, is having, and will continue to have, growing pains. This is a fascinating and eventful period in the development of natural resource management partnerships, and the future holds nothing but promise.

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SYNTHESIS PAPERS

Watershed Management Contributions to Future Land Stewardship

Securing Clean Water: A Secret to Success

Michael Somerville[1] and Dino DeSimone[2]

Abstract.—Securing clean water is a primary goal for many agencies, organizations, and concerned citizens. To achieve that goal, agencies have traditionally taken a mostly regulatory approach. In recent years, however, a major trend in government has been to move decision-making and action-taking to the local level. Conservation Districts, watershed organizations, and other local groups have taken on increased roles and responsibilities for ensuring a healthy environment. This relatively new phenomenon, alternatively referred to as "locally led conservation" and the "watershed approach", is proving to be a secret to success for securing clean water in Arizona and the nation.

Introduction

Protection and enhancement of water quality is a universal goal. This much is known. What is not always so clear is just how best to secure clean water for all. During the past half-century, a series of federal and state laws have been enacted aimed at water quality protection. The Clean Water Act, as amended, and related laws have set up a primarily regulatory framework. In response, most government agency efforts have focused on a top-down, compliance-based approach.

During this same time, however, Conservation Districts and other grassroots organizations have been busy identifying and addressing water quality and other natural resources concerns within their local areas. Formed under state or tribal law, Conservation Districts are empowered to design and carry out voluntary programs of natural resources conservation with the people they serve.

More recently, watershed organizations have been established as forums for people to discuss, educate, and build consensus regarding water quality and other issues of concern. These groups provide support to local conservation efforts, and often sponsor restoration and enhancement projects.

State and federal agencies in Arizona and elsewhere have begun to recognize the value of these local groups in achieving effective, long-lasting solutions to water quality and other natural resource problems. The Arizona Department of Environmental Quality, for example, has identified local groups as key players in the development and implementation of watershed initiatives in the state. The Arizona Department of Water Resources is actively cooperating with several watershed organizations in putting together local action plans and developing scopes of work for needed research.

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Local Conservation and the Watershed Approach

The National Association of Conservation Districts (NACD) defines locally led conservation as "Local people, with leadership from Conservation Districts, assessing natural resource conditions and needs; setting goals; identifying programs and other resources needed to solve these goals; developing proposals and recommendations; implementing solutions; and measuring success" (National Association of Conservation Districts 1998). NACD goes on to state that this process is based on the premise that community members are best suited to identify and resolve natural resource problems, and that locally led conservation focuses on voluntary, incentive-based approaches before use of regulatory measures.

With the passage of the 1996 Farm Bill, Conservation Districts were given an even greater role in ensuring that local conservation priorities are addressed. Conservation Districts are now responsible for convening local work groups and soliciting broad public involvement for the development of the local conservation program. Traditionally, Conservation Districts have worked hand in hand with cooperating land owners and partner agencies such as the USDA Natural Resources Conservation Service and the State conservation agency. Now more than ever, however, the emphasis is on direct participation by citizens, organizations, and interested local, state and federal agencies. This process assures that the needs of all affected parties are considered and included.

The "watershed approach" is a term used by many agencies and organizations to describe a comprehensive process whereby local people and interested organizations and agencies (stakeholders) work together to address natural resources and related issues within a geographic area, usually a hydrologic drainage basin. The Environmental Protection Agency characterizes the watershed approach as consisting of three main principles

(Environmental Protection Agency 1991). First, target watersheds should be those where pollution poses the greatest risk to human health, ecologic resources, desirable uses of the water, or a combination of these. Second, all parties with a stake in the specific local situation should participate in the analysis of problems and the creation of solutions. Third, actions undertaken should draw on the full range of methods and tools available, integrating them into a coordinated, multi-organization attack on the problems.

The recent synthesis of these two complementary philosophies has resulted in a successful formula for addressing water quality and other natural resources issues in Arizona and in many other areas of the country.

An Arizona Success Story

The Verde River Watershed covers 6,600 square miles in the heart of central Arizona. One of the state's largest perennial streams, the Verde River is free-flowing for about 125 miles before reaching Horseshoe Reservoir near Phoenix. The watershed is a major source of water for the Phoenix metropolitan area. Numerous state parks, wilderness areas, national monuments and national forests lie within the watershed. Four American Indian communities are present. Six Natural Resource Conservation Districts (NRCD's) serve the people of the watershed.

The Verde River Watershed has experienced tremendous change in recent years. The population has surged as people flock to the area to partake of the scenic vistas, temperate climate, and abundant recreational opportunities. Timber harvesting and other natural resource uses are declining, while recreation use in its many forms is on the rise. Agricultural lands have been subdivided and built upon. Water use has increased to meet the needs of the new residents. Water quality has remained generally good, and people want to keep it that way. These rapid changes present significant challenges for the Conservation Districts and others working to sustain the health of the watershed.

To meet these challenges, the Conservation Districts of the watershed are leading local programs of natural resources conservation. The main staple of these programs is day-to-day assistance to individual land owners for planning and applying soil and water conservation practices on their property. These projects are designed to conserve water, maintain and improve water quality, reduce erosion, and protect and restore riparian areas and other sensitive habitat. In addition to the basic conservation program, the Big Sandy, Chino Winds, Coconino, and Verde NRCD's recently established Geographic Priority Area projects under the USDA's Environmental Quality Incentives Program. Through these special projects, local people are receiving accelerated educational, technical and financial assistance for installing needed conservation measures on private and state lands.

The Verde Watershed Association (VWA), organized nearly a decade ago, is a forum for bringing together people representing the many varied interests throughout the watershed. Membership in the VWA includes residents, organizations, NRCD's, and representatives of local, state and federal agencies. The VWA engages the public in local natural resources issues through regular meetings, a monthly newsletter, and by pursuing scientific research to increase the level of understanding of the watershed's land and water resources. Agencies routinely look to VWA as a valuable source of input and support in developing and implementing action plans and strategies.

Summary

Locally led conservation, using a watershed approach, is the secret to success for securing clean water and a healthy environment. Local leadership, from Conservation Districts, watershed organizations, and other local groups, is key to this success. Experience has shown that local people, when given the opportunity, and provided the necessary support, are most capable of resolving the natural resources problems affecting their area. The challenge before those of us involved in water quality protection and natural resources conservation is to continue to work towards making local empowerment for action the way of doing business.

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Sustaining Flows of Crucial Watershed Resources

J.E. de Steiguer[1]

Abstract.—Watersheds are the source of a number of resources which are of benefit to society. These resources include water, timber, grazing, recreation, wildlife and others, often described as multiple-use resources. In addition, however, watersheds also produce a number of less tangible resources and uses, which are also socially important. These include amenity, option values, bequest, existence and stewardship values. Watershed resources are usually subject to joint production, that is, the production of one resource is linked to the production of the others. The socially optimal amount of watershed goods and services should not be simply the sustained even flow of commodities, but rather as the flow which maximizes the present net benefits to society. The best way of achieving this maximum is through integrated resources planning on the watershed.

Watershed Resources

Natural Resources

Watersheds are the source of a variety of natural resources that benefit humans (National Research Council 1999). Indeed, the papers presented in these proceedings have discussed these resources in some detail. Chief among these, of course, is water supplies. Watersheds are the principal receiver, collector and conveyer of water for users. The majority of the world's water supplies originate on watersheds. Some watersheds, especially in the world's arid regions, are located at great distances from the towns and cities where end-users reside. Water is important to households where it is essential to human life. Cooking, cleaning, watering of gardens and yards, personal hygiene are all key domestic uses of water. Dependable water supplies are the figurative lifeblood of the world's economies. As such, they are essential to the development of agricultural and industrial economic sectors. The growing demand for irrigation water, and to a lesser extent industrial uses, have been the main forces behind the world's growing demand for water (World Resources Institute 1996). National pressures on freshwater supplies are measured by the so called "water stress index" (World Resources Institute 1996). On the basis of past experience, it is estimate that 1,000 m^3 per capita per year of freshwater is the minimum needed to sustain human health and economic development. By this measure, it is estimated that as much as one-quarter of the world's nations are threatened with inadequate water supplies.

Water quality is another important watershed resource. Not only do the world's watersheds supply simply quantities of water, but also most of our quality water as well. Water quality is dependent upon both natural and anthropogenic factors. However, anthropogenic factors are far more important in terms of the threat posed to human welfare (National Research Council 1999). A major source of anthropogenic pollution in the United States affecting watersheds is non-point source pollution. Important sources of non-point source pollution include croplands, livestock operations, urban development, forestry operations, mining, recreation sites and roads. Improving the quality of water from watersheds is largely a problem of controlling these non-point sources of pollution. Some substantive progress has been made over the last quarter century of the 20th century toward controlling point sources of pollution. However, non-point sources, largely through legal exemptions and political pressure, continue to pose a problem.

Erosion and sediment control are important watershed resource issues which extends beyond merely water quality concerns. Erosion of surface material can affect not only water quality, but other resources as well. Among these would be cropland productivity, aquatic habitats, navigation and recreational uses of water. Sediment-rich waters also usually contain high pollutant loadings.

Flood control is another watershed activity which creates important benefits for society. Engineering projects such as dams, levees and reservoirs, as well as vegetation management, have been the means by which flooding from watersheds has historically been controlled. Indeed, it was the practical need to control flooding which was the earliest motivator of watershed management (National Research Council 1999). For example, in the late 1800s, the French national forestry school at Nancy added to its name and curriculum the study of watershed management largely for the purpose of educating foresters regarding the proper management methods for controlling flooding (de Steiguer 1994).

Hydroelectric power is another resource from watersheds. It is generated largely from reservoirs and dams and is thus an additional benefit associated with flood

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control. Hydroelectric power supplies about 20% of the world's electricity (Miller 1996). It is generally recognized as one of the cheaper types of energy. However, there are several potential environmental problems associated mainly with the dams and reservoirs. Among these are interruption of migrating fish stocks, deprivation of flood plain siltation, and large evaporative losses of water, especially in arid regions.

Navigation is yet another resource coming from watersheds. Rivers emanating from watersheds sometimes are transportation corridors carrying coal, grain and other commodities to the marketplace. Major river arteries such as the Ohio, Missouri, Columbia and the Mississippi are examples of the importance of river travel to national commerce.

Watersheds are the source of many outdoor recreation opportunities which, in turn, provide great public benefits. Dams and reservoirs provide camping, boating, wildlife and fishing possibilities. Wildlife for both consumptive and non-consumptive uses can be found in many watersheds. Whitewater flows are important to rafters, kayakers and canoers. Anglers also take advantage of downstream water flows.

Many of the world's watersheds are covered with forests. Thus, watersheds can also be the source of timber supplies for manufacturing lumber and paper products. The relationship of timber harvesting to water flow, as previously stated, has long been an issue of interest to foresters and other land managers. Care must be taken to balance timber removals with the maintenance of manageable, clean water supplies.

Agriculture and grazing of domestic livestock are still another important possible watershed resources. Arable land exists on many watersheds which produces a variety of crops for human and animal consumption. Whether forested or rangeland, most of the land contained within watershed is also used for livestock grazing.

In addition to those mentioned, there are numerous, locally important resources which come from watersheds. Examples would include crab and oyster fisheries in Chesapeake Bay; cranberry harvests and dairy production on Willapa Bay Watershed, Oregon; and so forth (National Research Council 1999). Clearly, watersheds are the source of numerous resources which are beneficial to the public both in the United States and around the world.

Economic Resources

When discussing resources which come from watersheds, it is often useful to describe them, as we just have, in physical terms as natural resources. However, there is another view, that of the economist, which provides an informative perspective on the topic of watershed resources. And, as we later shall see, the economist's perspective is fundamental in developing a complete strategy for sustaining flows of watershed resources. A common classification system used by economists to describe resources is by their values, as follows: a) use values and b) non-use values. Furthermore, use values can be subdivided into: i) market and ii) non-market values.

A discussion of these resource economic classifications follows:

Use values describes the values derived by an individual from his / her direct consumption, or use, of a resource. Examples of these use values derived from the watershed include essentially any of the resources previously listed: water, timber, hydroelectric power, navigation and so forth. Each of these represents resources which individuals can consume or use directly rather than just contemplate or enjoy in a passive manner.

Market values are those resources, or values, which are traded in cash markets, where buyers and sellers meet and exchange the good or service for money. Production costs of the seller and willingness to pay by the consumer serve, in the market place, to set the price of the good or service in question. Several of the resources previously discussed can be placed into this market value category. Certainly timber, hydroelectric power as well as some forms of water and recreation (e.g., whitewater rafting) are market commodities. These resources are produced and then consumed by users who pay a price which at least approximates their value to consumers.

Non-market values are obtained from the direct use or consumption of resources too. However, there is no payment made to the producer for the resource. This does not mean that they are without value. Rather, only that their value is not reflected in cash transactions. Flood control is an example where no cash market exists for the good (i.e., dams and reservoirs for flood control) in question. (There is, however, a market for another loss prevention measure, flood control insurance.) Perhaps an even better example of non-market values, and one certainly every bit as real to consumers as flood control, is that of resource amenity values. These would be the unpriced values that individuals receive strictly from the passive, aesthetic enjoyment of a resource. It is not at all difficult to find such values coming from watersheds. The public receives amenity values from viewing cold, clear flowing water in streams, from scenic forest vistas, from wildlife observation, from oxygen-laden mountain air and various other non-consumptive uses. Although intangible, these resource values are just as real and meaningful to society as those derived from resource consumption.

The goods and services from which these non-market values are derived are classified as *public goods*. Public goods are those which, if provided by a producer, have the technical characteristics of being both indivisible and fully accessible to all (Tietenberg 1988). Indivisibility means that the resource cannot readily be broken-up into consumable units. For example, a producer cannot easily subdivide or package for consumption (as one might candy bars or gallons of gasoline) a flowing stream or a scenic view. Full accessibility means that use by one person does not exclude another from also using the resource. An example is a scenic view; your viewing does not exclude anyone else's viewing of the same scene at the same time.

Public goods stand in contrast to private goods. The latter, which comprises consumer goods, are those goods which can be divided for packaging and sale and also can be made exclusive, i.e., available only to paying consumers. There is an incentive for private markets to provide private goods because producers can capture completely the profits from such sales. However, public goods, such as flood control, some forms of outdoor recreation, navigational aides, and amenities where profits cannot be captured, most often are provided to the public by the government to whom the prospects of profit is not a primary motivating factor.

Non-use value is the second categorization of economic values. Included here are resources where the values are derived, not from current use, but from the possibility of use at some future time, and perhaps not even by person currently conveying value to the resource (Fields 1994). The sub-categorizations of non-use values are: *option value* which is the amount a person would be willing to pay to preserve the option of being able to personally use a particular amenity in the future; e*xistence value* is the willingness to pay simply to know that a resource will continue to exist even if the person never uses it; *bequest value* is the willingness to pay in order to maintain resources for use by future generations; *stewardship value* is the value arising not from possible human use, but rather to maintain the health of the environment for the continued use by all living organisms.

The preceding discussion has presented an array of resource values which are often not included in a listing of physical watershed natural resources. Nevertheless, these are real resources with real social values which must be considered when managing watershed resources. Not only economists, but many planners and lawmakers now recognize the relevance of non-market and non-use values to natural resources decisions. Development of methods for determining the money values of these non-market and non-use resources has progressed substantially over the past 25 years. Whereas it is not the intent of this paper to delve into the technical aspects of these non-market valuation methods, the interested reader is referred to works such as Bromley (1995). There one can learn about travel cost, contingent valuation and other methods which have become widely adopted for resource valuation even in court cases involving monetary damages.

Joint Production Processes

Another perspective provided by economics regarding "crucial watershed resources" is that of the watershed resource *production process*. It is possible to view the watershed itself as a complex production facility. The resources of the watershed, when combined with labor and capital, "produce" the array of socially beneficial goods and services we have just discussed. The issue here is the nature of that production facility. Namely, that it is a *joint* production facility which produces, or at least potentially produces, this array of goods and services more or less simultaneously. One fixed area of land, the watershed, produces, at once, clean water, timber, recreation, amenity values and so forth. Quite clearly, with a fixed land base, fixed management budgets and fixed technologies, the production of one item is governed by the production of all the others. This interdependency is referred to as a "joint production process" (Henderson and Quandt 1980)

Joint production is an important consideration for the multiple use management which occurs on most watersheds. Joint production exists because two or more outputs are technically interdependent using some of the same physical production inputs, such as land (Henderson and Quandt 1980) and thus have related production costs (Krutilla and Bowes 1989). An example: Managers of a watershed might want to produce both timber and wildlife from a given area of land. Because the goods are jointly produced, they compete for the same production inputs, in this case, land. When both goods are produced from a fixed land area simultaneously, neither can be produced at their individual maxima. Thus, the two commodities are *substitutes* for one another. Joint production almost always involves such trade-offs. That is, to get more of one resource output, the other resource outputs must be reduced. Joint production is a important economic characteristic to bear in mind when speaking of managing watersheds for sustained flows of resources. Without improvements in production technologies or increases in management budgets for labor and other inputs, more of one resource will almost always mean less of the others.

Sustaining Flows ... Of What?

The notion of sustained flows of resources from the watershed is, in the mind of many natural resource managers, a question of sustained *even* periodic physical resource yields. That is, year after year, decade after decade, the watershed will be managed to produce an equal periodic flow of goods and services. The philosophy of a sustained, even-flow of natural resources seems to have evolved in the United States early in the 20th century from a national concern over timber shortages, and the economically destabilizing effects which might arise from exaggerated supply fluctuations (Krutilla and Bowes 1989). This concern, in turn, stemmed from a general distrust of the private market as a manager of natural resources because of the then rapid harvesting of forestlands. Consequently, the nation turned to public forest management as the solution.

Concern for forest protection, stability and high yields led to the adoption by public managers of some policy rules-of-thumb (Krutilla and Bowes 1989). The first policy is that of maximum sustained yield. Under maximum sustained yield, forests are regenerated and cut at an age so as to produce the maximum biological yield over time. This age is generally regard as the point of culmination of mean annual increment. The second policy was that of even-flow management. Under this policy, current harvest levels were set at a constant level that could be maintained forever. Combining these two principles resulted in the so called "fully regulated forest," that is, a forest which has a sustained even-flow of harvests over time at the forest's maximum biological potential.

The fully regulated forest has intuitive appeal. However, it has been criticized on the grounds that it is devoid of economic rationale. It says nothing about wise investment in lands of varying productivity capability. It says nothing about how the manager should respond to changing temporal patterns of resource demands for timber, water, wildlife, range, recreational and amenity services. Furthermore, the philosophy of sustained, even-flow can result in the sacrifice of consumption in times of plentiful resource stocks and to the uneconomic management of relatively abundant resources (Krutilla and Bowes 1989).

Nowadays, the notion of managing for an even-flow of resources has been largely replaced by that of managing the economic flow of resources. The economic goal of the multiple use problem is the selection of a sequence of management actions to maximize the present value of net benefits from the flow of timber and other resource values over time (Krutilla and Bowes 1989). This notion of maximizing the economic benefits of resources has been embodied in legislation such as the Forest and Rangelands Renewable Resources Planning Act of 1974 as amended by the National Forest Management Act of 1976. These acts provide a mandate to the public land manager to maximize the net benefits from multiple-use, sustained yield management with consideration given to the relative values of all resources while preserving the integrity of the land.

Management prescriptions based on maximization of the present net worth of resource flows are complex. They require large amounts of data and computer analyses. However, public land management agencies have, in fact, developed operational models for maximizing the present value of resource flows. Most notable among these efforts has been the development of the FORPLAN (now SPECTRUM) model by the USDA Forest Service. FORPLAN is a linear programming model which allocates land to various management activities so as to maximize the present net value of the flow of goods and services from the land. FORPLAN has been hailed by some as an important attempt to plan forest and watershed management activities in such a way that will provide the greatest benefit to society. However, others have been critical of FORPLAN saying that, while it has enormous analytical capacity, it "requires massive amounts of data, includes non-use values, e.g., protecting watersheds or improving aesthetics, only as constraints on uses and outputs, and poorly addresses spatial concerns" (Office of Technology Assessment 1992).

Despite the criticism of FORPLAN, the goal of maximizing the present net benefits of resource flows must still be regarded as the correct stance for watershed management. Planners should attempt to quantify and maximize the sustained net economic flow of watershed resources rather than simply providing a sustained, even-flow of goods and services.

The Solution: Integrated Resource Planning

Five Questions

The solution to providing sustained economically efficient flows of crucial watershed resources is through *integrated resource planning*. In saying this, we provide no great surprise. Integrated resources planning has long been recognized as the best means for achieving an economically optimal flow of watershed resources. Rather, our position simply supports and confirms the conventional wisdom in this regard. Furthermore, at least in the United States, the National Environmental Policy Act process must be followed in the development of plans. This is true if a federal agency is involved or if the proposed plan involves the obtaining of federal permits.

Integrated natural resources planning is the process of organizing the different natural resource management activities in a way so as to produce the greatest value of goods and services for society over a given period of time (Loomis 1993). Ideally, a comprehensive plan will include both use and non-use values, as well as both direct and indirect resource effects all of which will be quantified and compared among alternative plans and uses. This, of course, presents a formidable, if not overwhelming, challenge to the watershed manager. However, it must be regarded as an ideal toward which to strive. Indeed, we only compare public land planning of 25 years ago to what is occurring today to see that resource managers have made definite progress toward this ideal.

There are five basic question in the planning process (adapted from Loomis 1993):

1. Who has the planning responsibility and authority?
2. Where are we?
3. Where do we want to be?
4. What alternative actions will best get us there?
5. Did we make it?

These questions provide a reasonable and comprehensive framework to discuss the integrated planning process for natural resources. Thus, in the following sections, we shall discuss the meaning and relevance of each.

Who Has the Planning Responsibility and Authority?

Planning on watersheds often involves a dizzying array of federal, state and local agencies with overlapping and conflicting responsibilities. Also, the planning process can involve a number of federal, state and local laws. In the past, this morass of agencies and laws sometimes led to the development of "super" authorities such as the Tennessee Valley Authority for the administration of the watershed planning process (National Research Council 1999).

Nowadays, however, the super authority approach has been largely replaced by the "partnership" approach to planning (National Research Council 1999). Using this method, the principal agencies seek to involve not only the federal, state and local agencies with interest in, and possibly jurisdiction over, some of the elements of watershed planning. They also involve private landowners, watershed associations, soil and water conservation districts and state natural resource and game and fish agencies. By involving broad public participation, the agencies are more likely to be in compliance with the public involvement portions of NEPA. Furthermore, they are much more likely to achieve acceptance of the final plans once they are completed.

Where Are We Now?

The second step in planning, determining "where are we now," calls for an inventory. This inventory requires an enumeration of the physical resources on the watershed, such as the amount of timber; volume and flow rate of streams; current water quality; wildlife censuses; etc. Maps must be developed, perhaps as part of a geographic information system. Acreages and quantities of resources must also be determined. Also, the inventory must also include the assets and resources of the agency such as personnel, budgets, equipment, and so on (Loomis 1993).

The data collected at this stage of the planning process, can help to determine the direction of the next stages in the planning process. For example, shall we continue in recreation management or shall we consider more intensive timber management? Also, the resources of the watershed and those of the agency will serve as constraints on any future plans. The agency can only produce within the possibilities afforded by the resources it has at its disposal.

Where Do We Want to Be?

The third step of the planning process is that of determining where the agency and the public wants to be, in terms of the productive possibilities of the watershed, at some time in the future. Some federal agencies, such as the USDA Forest Service, develop plans with a 5 to 15 year time horizon. Other decisions, such as construction of a dam and reservoir, can require a much longer planning horizon. This step usually requires that "scoping" sessions take place in order to identify alternative futures for the watershed. Increasingly, it has been recognized that the planning agencies must be required to draw upon input from the public for this stage of the process. As we have said, plans that do not involve the public will not be in compliance with the National Environmental Policy Act nor will they likely be accepted by the public.

What Actions Will Best Get Us There?

This the fourth step of the planning process is the most demanding. Here, a principle action must be proposed, but then alternative actions must be proposed and explored as well. Indeed, one of the actions considered must be "no action."

This planning step will certainly involve the collection of research data. It will perhaps even require the establishment of watershed experiments to determine the response of the various resources to specific land management treatments. We will recall, that these responses are in the form of trade-offs due to the joint nature of the production process. Once the joint response of resources to treatments has been determined, estimates of the costs of various actions must be made as well as the benefits of outputs. Perhaps even optimization methods such as linear programming will be employed to determine the most economically efficient watershed management alternatives. Once the planning alternatives have been evaluated, the most desirable course of action will be chosen and implemented.

Did We Make It?

The final stage of the planning process is to address the question "did we make it?" This is the time for monitoring the plan which was implemented. In a sense, the planning process has gone full circle with this step. Inventories are again required to determined precisely what the management actions have achieved in terms of resource outputs. Also, this is the time for corrective measures to redirect actions that may not be achieving their targeted outputs. The monitoring step is, in fact, an on-going process which continues throughout the planning process.

Conclusion

When sustaining the flows of crucial watershed resources, watershed managers must recognize that the "crucial resources" involve not only those tangible, commodity resources such as clean water, timber, recreation and the like. Crucial resources also include intangibles such as amenity, option, bequest, existence and stewardship values. These latter values have increasingly been recognized as having significant economic value to society.

Furthermore, managers should replace even-flow production criteria with the more relevant objective of maximizing the net social benefits from watershed production. The maximization of net benefits criteria insures that watershed management best serves the economic needs of society. Significant progress has been made in recent years toward the quantification of resources benefits. Furthermore, mathematical optimization methods for selecting the best production strategies have been in use for planning on public lands for about the past 25 years.

The planning process requires input from other agencies and the public, inventorying and mapping of current resources, choosing production targets, selecting alternative courses of management action, implementing the optimal management strategy and, finally, monitoring the results. Planning for the sustained yield of watershed resources is a complex process. It is also, quite likely, the most important function of the watershed manager.

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The Watershed-Riparian Connection: A Recent Concern?

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Abstract.—Management impacts on a watershed can cause a variety of complex responses by the encompassed riparian-stream system. Information about these responses will help land managers select practices that provide the riparian area with the best chance for future health and stability. Since we now recognize that people have been impacting riparian areas for a long time through their actions on the surrounding watersheds, it is appropriate that we apply our knowledge of history to guide our actions in the direction of stabilized watersheds and healthy riparian areas.

Introduction

There have been some over simplifications, and some connections have been overlooked, in discussions about riparian areas. Land managers and the public often fail to recognize the importance of the links between channel response and impacts caused by natural or human-caused events in the surrounding watershed (Baker and others 1998).

The Problem

Human-induced disturbances brought about by land-use activities on the surrounding watersheds probably have a greater potential for introducing enduring changes to the structure and function of riparian-stream systems than human-caused disturbances within the riparian systems (FISRWG 1998). Although much has been written about the many values of riparian areas and how various intensive uses have degraded these areas, only relatively recently have publications described how upland watershed practices have affected riparian areas (DeBano and Schmidt 1989a).

Maintenance of historic riparian physical and biological conditions requires maintenance of appropriate, preferably historic, instream flow and sediment conditions (Rieman and Clayton 1997, Rinne 1996). Stream flows can be greatly reduced by pumping aquifers or diverting flow for irrigation purposes, or the flows can be increased due to vegetation change, soil loss, or road conditions. Although increased flow, particularly peak flow, can be very damaging to riparian areas, in situations where upland management is focused on or contributes to water-yield increases, riparian systems have expanded (DeBano et al. 1984, DeBano and Schmidt 1990, Rinne 1995). The primary focus of this paper is the conditions of disturbed watersheds that create increased flood flows and sediment loads.

Erosional Processes

Riparian areas should be managed within the context of the entire watershed. A balance exists between health, diversity, and productivity of riparian communities and the watershed conditions where they are contained (DeBano and Schmidt 1989b, McGurrin and Forsgren 1997). All tributary effects accumulate to influence riparian health and stability. Upland watersheds in satisfactory condition absorb storm energies, provide stormflow regulation through the soil mantle, and contribute stability to the entire watershed. In contrast, watersheds that have experienced past abuse often have developed channel systems, including gully networks, throughout the watershed in response to the increased surface flows. These gully networks cause rapid, concentrated surface runoff with increased peak flows and sediment loads (DeBano and Schmidt 1989b). Channelized flow from intermittent and low-order streams is a primary sediment source in mountainous regions where large amounts of material can move long distances into streams. In general, small streams are more affected by hillslope activities than larger streams and, as adjacent slopes become steeper, the likelihood of disturbance from in-stream effects increases (Lee et al. 1997, Megahan and Ketcheson 1996).

Channels are formed, maintained, and altered by the water and sediment they carry. A stream constructs and maintains its channel size to enable most sediment to be carried during short periods when the flow is near bankfull (FISRWG 1998, Leopold 1994, Whiting et al. 1999). If riparian systems are in dynamic equilibrium, the volumes

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of incoming sediment equal the volumes of exiting sediment. Normally, under such conditions there are few rapid changes in stream meander cutting, growth of point bars, or erosion of channel beds. Characteristics of channel profile, stream morphology, and vegetation mutually adjust to accommodate prevalent conditions (DeBano et al. 1996, Heede 1980).

Erosion is a temporally discontinuous process that transports sediment from a source area through a channel system with intermittent periods of storage (Wolman 1977). Most of the sediment is transported in riparian systems during major streamflow events (DeBano et al. 1996). Sediment is often deposited in a channel until a sufficiently large peak-flow event occurs that moves it further downstream. Sediment can be stored in a channel for years making it difficult to interpret the sediment generating process on the surrounding hillslopes (DeBano et al. 1996, Heede et al. 1988). The bedload component of total sediment varies greatly from area to area, but it always plays an important role in channel structure and function. The unsteady movement of sediment involving aggradation and degradation is important in maintaining the stability of downstream riparian systems (DeBano and others 1996).

Decreased Plant Cover

Vegetation regulates sediment by slowing streamflow and dissipating energy so that water infiltrates into the soil. Increased infiltration prevents excessive erosion, maintains the physical stability of the landscape, and provides moisture to the streambanks to maintain riparian vegetation (DeBano et al. 1996). Conversely, disturbing vegetation cover accelerates erosion and increases sediment yield. Vegetation and topography interact to stabilize and store sediment within intermittent drainage systems and in small headwater basins.. Periodically, these sites are flushed by floods that remove some or most of the material. A period of relative stability results in colluvium accumulation (Lee et al. 1997).

Under conditions of dynamic watershed equilibrium and minimum on-site disturbance, the riparian vegetation remains vigorous but does not encroach into the active mean annual flood channel (DeBano et al. 1996). When sufficiently large changes in erosion and deposition occur, the riparian area may lose equilibrium as it is no longer able to quickly adjust to change. The area may remain in a state of disequilibrium for long periods of time. Without the stabilizing influence of a rhizomatous, heavily-rooted riparian plant community, greater bank erosion and vertical or lateral channel instability can occur (Medina 1996). Channel incision can intercept and drain existing floodplain water tables, desiccating the site with the accompanying loss of the riparian plant community. Alternatively, when excessive deposition takes place and the aggrading channel becomes braided and shallow with rapidly shifting bank and channel erosion, the wetland vegetation may be overwhelmed (Baker et al. 1998).

For most streams, streambank and channel stability is one the most important attributes of a properly functioning riparian system. Adapted wetland plants are important in sustaining desirable functional processes, particularly those of channel stability (Medina 1996). If flood flows and sediment loads from partially denuded uplands continually impact the wetland plant communities through changed hydrologic regimes, incised channels, debris flows, etc., a long-term unstable riparian system will result (Clary et al. 1996).

Increased Plant Cover

Traditional Western United States land uses (e.g., grazing, logging, mining) are normally mentioned when landscape degradation associated with decreases in vegetation density and cover is considered. However, the indirect affects of various forestland management practices that have increased plant cover are also of great concern. Selective and extensive timber harvest, fire suppression, and grazing practices have significantly altered forest structure and fuel loads. Forests that were once mosaics of species, ages, and patterns have been simplified. Many are now dominated by higher-density, middle-aged stands (often referred to as the “forest health problem”) which are more vulnerable to pest infestations and fire. The more homogeneous, interconnected vegetation patterns and the increased fuel loadings are thought to increase landscape vulnerability to high-intensity stand-replacing wildfire events (Rieman and Clayton 1997, Rieman et al. 1997). Fires originating in the surrounding landscapes can affect riparian areas directly and indirectly. Direct effects include stream heating and changes in water chemistry. Indirect effects include changes in hydrologic regime, erosion, debris flows, woody debris loading, and reductions in riparian vegetation and cover (Rieman et al. 1997).

Fire and the associated hydrologic effects have been characterized as pulsed disturbances, while effects caused by permanent road networks are considered as chronic or press disturbances. Many aquatic organisms, including native salmonids, may be adapted to pulsed disturbances (Rieman and Clayton 1997). Characteristics that allow populations to persist with disturbance may well depend upon large, well-connected, spatially complex habitats that can be lost through chronic effects of management. Attempts to reduce the cover of currently over-dense forest stands by conventional roading and timber harvest may cause chronic delivery of fine sediment into riparian-aquatic systems resulting in more long-term damage to those systems than that caused by extreme wildfires (Rieman and Clayton 1997).

Conclusions

Major watershed disturbances affect the quality and quantity of streamflow, bank storage, channel stability, and vegetation in the riparian zone (Baker et al. 1998).

Many widespread uses of watersheds, such as agriculture, extensive unmanaged livestock grazing, forest clearing, other forestry practices, and mining, coupled with roads and trail construction and maintenance, have some common effects that conflict with the hydrologic and geomorphic functions of riparian-stream systems. To various degrees, these activities reduce vegetation cover, compact soils, and decrease infiltration. Such disturbances result in productivity loss, reduced soil porosity, reduced soil infiltration, increased surface runoff, increased flood peaks, increased sheet, rill, gully, and bank erosion, unstable stream channels, and impaired habitat (DeBano and Schmidt 1989b, Eldridge 1995, Frasier et al. 1995, Johnson 1995, Krueper 1996). Increased channel sedimentation reduces channel capacity, increases width / depth ratios, and induces bank erosion and other instabilities. Alternatively, excessive water reaching a stream system **without** additional sediment loading, as often occurs with water diversions, can erode the channel bottoms, thus incising the channel (FISRWG 1998).

Is this Something New?

Riparian zone problems from management activities on the surrounding landscapes are a recent concern that is related to modern societies–right? Wrong. European settlers came to a continent in which ecosystems had been changing for thousands of years in response to American Indian populations. These indigenous populations had been increasing in numbers, and their society was becoming more complex and required significant amounts of resources (Jennings 1993, Periman 1999, Tainter and Tainter 1996). As agricultural-based communities developed in Southwestern river valleys, settlements of up to 2,000 to 3,000 rooms were built. Land was cleared for agriculture, and wood for construction, cooking, heating, and other uses that was available within transporting distance would have been consumed within a short time (Tainter and Tainter 1996). It has been estimated that a prehistory settlement of 1,000 people would have cleared a 3.5 mile radius of trees around a village within one generation (Spoerl and Ravesloot 1995). Landscape impacts from deliberate setting of fires would have been extensive and undoubtedly greatly affected the herbaceous and woody plant composition of the time (Spoerl and Ravesloot 1995).

The floodplains in some areas were greatly modified as American Indian canal systems and other water control structures were developed and used (Spoerl and Ravesloot 1995). Such systems were often highly vulnerable to extreme climatic events. Periods of erosion and channel entrenchment correlate with periods of prehistoric human modifications of the floodplain (Spoerl and Ravesloot 1995). Another prehistoric feature was the cobble-mulch gardens of the Anasazi. Cobble-mulch gardens and associated water harvesting features covered vast areas along specific drainages, in some cases covering 50% of the total terrace area. In these areas, less water would have reached riparian areas, thus affecting riparian vegetation and hydrological dynamics. Water harvesting features can persist and affect ecosystems for hundreds of years after abandonment (Periman 1996).

Such situations were not limited to a few localized circumstances in North America (Periman 1999). The region of ancient Mesopotamia and surrounding locality may have contributed more to the advancement of complex societies than any other equivalent area. The chief resources were fertile valley lands and the waters of the Tigris and the Euphrates rivers. This area, largely contained within the current country of Iraq, supported thriving populations for several thousand years through the use of irrigated agriculture. Over the centuries, over-irrigation resulted in soil salinization (Adams 1981), and sediment from rivers filled and blocked the irrigations systems (Carter and Dale 1974). Much of the sediment came from uplands that had been denuded by deforestation and overgrazing. Thus, human activities on the uplands and the lowlands contributed to the degradation of the lowlands. Today, much of the central floodplain of the ancient Euphrates River is beyond the bounds of cultivation and supports only a fraction of the earlier human population levels (Adams 1981, Carter and Dale 1974). Records suggest that similar experiences have occurred around the world. Much of the problem has been the eroding watersheds that are depleted of productive soils, and the degraded, sediment choked waterways (Carter and Dale 1974). It has been stated that “civilized man has marched across the face of the earth and left a desert in his footprints.” Perhaps this is a slight exaggeration (Carter and Dale 1974). The internal collapse of complex societies often initiated abandonment of landscapes (Tainter 1988).

Desertification and other forms of land degradation are occurring globally. Soil erosion is proceeding at rates in excess of natural soil development (Brooks and Ffolliott 1995). The resulting accelerated rates of sediment and debris flows reduce upland productivity, impact riparian areas, clog stream channels, and fill reservoirs. Planners should strive to link costs and benefits between watershed and riparian areas. Pouring money into degraded stream systems that are continuously disturbed by surrounding land-use activities is futile and raises false hopes of improved aquatic conditions (McGurrin and Forsgren 1997). Correcting or mitigating the fundamental causes of degradation, whether it be road construction, timber harvest, mining, or overgrazing, will facilitate the natural recovery of eroding hillsides and streambanks (Wood et al. 1997). Considering a watershed perspective would help planners justify expending funds to protect or improve conditions in one portion of a watershed to benefit activities in another portion of a watershed. For example, siltation of reservoirs costs the U.S. economy about $6 billion annually, yet the value of forests and rangelands in preventing erosion is rarely considered in the analysis of wildland worth (Dobrowolski and Thurow 1995). “It remains a great irony that U.S. residents are more attuned to the decline of distant tropical rain forests than they are to the loss of natural resources in our own backyard” (Tilt and Williams 1997).

Conclusions

1. Riparian areas exist within the context of the surrounding watershed.
2. Unstable uplands produce a continuously unstable riparian area.
3. Begin restorative efforts at the watershed divide and work towards the riparian area. “Band Aid” approaches are not recommended (Dobrowolski 1995).
4. Conduct all management knowing that uplands and riparian areas are linked physically, biologically, socially, and economically.
5. Planning tools can provide predictive capability that contributes to your understanding of the effect of watershed actions upon the riparian-stream system below (Bettinger et al. 1998).
6. Break some rules and learn from what we already know! Remember, “Every time history repeats itself, the price goes up” (quoted by Tainter 1988).

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Cibecue Watershed Projects: Then, Now, and in the Future

Jonathan W. Long[1]

Abstract.—The White Mountain Apache Tribe has undertaken a watershed analysis and various demonstration projects in the Cibecue watershed in east-central Arizona. The results support an adaptive management strategy to promote ecological health, enhance economic opportunities, and protect cultural values. Some of the problems faced by today's program are similar to those faced by a Cibecue watershed management project in the 1960s overseen by the Bureau of Indian Affairs (BIA). However, the Tribe's current project has a more holistic goal of restoring streams to health through community-based efforts.

Introduction

The White Mountain Apache Tribe Watershed Program has coordinated a watershed management project in Cibecue for the past three years. The Land Operations Division of the BIA coordinated a watershed management project in Cibecue in the early 1960s. Although both projects confronted deteriorated upland conditions, the goals and methods between the two periods are radically different. The current tribal program has a focus on ecological health, particularly for streams and wetlands. The BIA's "vegetation modification program" cited goals of increasing forage production and reducing soil erosion. However, the program was driven by a fundamental motive of increasing water yields for downstream water users. Analysis of current conditions supports the general community belief that most of the management efforts of the 1960s did not generate lasting improvements for Cibecue. When the anticipated water yields failed to materialize, the program ended. The Tribe's and the community's perception of ulterior motives eroded their trust in the BIA's watershed management efforts. Today's tribal program copes with the legacy of these past efforts as it works to restore the health of streams in the watershed.

Watershed Setting

The Cibecue watershed encompasses 750 km^2 (186,000 acres) located entirely within the Fort Apache Indian Reservation. The village of Cibecue lies in the center of the watershed along both sides of Cibecue Creek. Cibecue Creek flows year-round below two major springs several miles north of the community. Flows in the watershed commence in mixed-conifer forest at 2286 m (7,500 feet), pass through ponderosa pine forest, pinyon-juniper woodland, and blue grama grasslands, and finally reach the Salt River within Upper Sonoran desert scrub at 960 m (3,150 feet). This natural diversity makes Cibecue a beautiful and challenge place to work, and it also made Cibecue a prime candidate for experimental watershed treatments in the 1960s (BIA 1960).

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Program Goals

The fundamental concern of watershed management programs in both the 1960s and the 1990s is water. In the arid Southwest, water is a keystone resource, and it has determined the viability of civilizations in the Cibecue watershed since prehistoric times. Grasshopper Pueblo, located a few miles west of Cibecue, once supported more people than does Cibecue today, but it ultimately may have been abandoned when local water sources dried up and soil fertility declined due to erosion (Welch 1996).

Both the 1960s and the 1990s programs recognized the need to manage watershed conditions such as soil erosion and vegetative cover to sustain water flows. However, the 1960s program was supported by off-Reservation desires to increase downstream water runoff. Today's program seeks to restore waterbodies to a healthy condition for the lasting benefit of the local community and the larger ecosystem.

BIA Watershed Project: 1960s

The BIA's project was underwritten by the U.S. Government and the State of Arizona with the goal of increasing water runoff to the Salt River valley through "vegetation manipulation" (BIA 1960). The program was tied into the Arizona Watershed Program through funding it received from the Arizona Water Resources Committee. The Arizona Watershed Program was the offspring of the Barr Report, which was commissioned by the Arizona State Land Department and the Salt River Valley Water Users Association to evaluate methods of increasing water yield

(State of Arizona 1957). The mission of the Cibecue program reflected these origins, as its stated goals included not only improving timber and forage production and reducing soil erosion, but also increasing water yield (BIA 1960).

The BIA's program faced a watershed in poor condition due to several decades of overgrazing that began when the Federal Government issued non-Indian grazing permits well in excess of the land's carrying capacity (White Mountain Apache Tribe vs. US 1987). This overgrazing was a major factor in the widespread encroachment of juniper trees and other woody vegetation into grassland areas. These issues were a major concern to the Tribe and the BIA because of the associated declines in forage production and soil erosion. However, they were also a concern to downstream water users who feared a decline in water yields (State of Arizona 1957).

The BIA conducted a number of activities that are essential to any sound watershed management program, including an intensive soil survey and construction of many miles of new fence to manage livestock (BIA 1964). They also worked with the livestock associations to modify range management practices. However, the main focus of the program was on dramatic vegetation "modifications" to alter the water cycle of the rangelands. The program employed aggressive treatments that including clearing vegetation with heavy chains pulled by bulldozers, chemical eradication of junipers and beargrass, and reseeding with grasses, most of which were exotic species (Robinson 1966). Another major element of the project was "phreatophyte control," the poisoning and girdling of cottonwood trees along riparian areas. Touted as a pioneering endeavor (BIA 1964), this task proved to be the most controversial and the most destructive in the eyes of the community.

Although the BIA reports claim that hundreds of meetings were held concerning the project, community members assert that the purpose, consequences, and risks of tasks such as the cottonwood eradication were never explained to them. After the cottonwood eradication got underway, community response was decidedly hostile and several tribal members quit the project (Basso 1970). The newly-established tribal Recreation Enterprise voiced concerns about potential impacts to tourism, so some areas were apparently spared. Today residents point to the cottonwood eradication as a major factor in the unraveling of Cibecue and other creeks.

Tribal Watershed Project: 1990s

The period between the mid-1960s and the mid-1990s saw the Tribe dramatically increase its control and sophistication in all its affairs, and especially in natural resource management. Unfortunately, many of the Reservation's streams and watersheds, including Cibecue, continued to deteriorate. To address this challenge, the Tribe established a Watershed Program in 1994 with a mission of protecting and restoring water quality and stream health. In 1996, the Tribe's initiated a community-based effort to promote the health of the Cibecue watershed. Through a competitive process, the US Environmental Protection Agency selected the Tribe as one of four tribes nationwide to conduct pilot projects for developing an appropriate Watershed Analysis and Management (WAM) approach for Indian country (Pacific Watershed Institute 1999). Specific goals of the Tribe's project included:

- compiling existing information about watershed and riparian conditions in a format that can be used to plan future land management activities;
- addressing questions and places of greatest concern to the community;
- identifying priority areas for restoration and other forms of special management;
- training tribal members from Cibecue in watershed assessment and restoration techniques;
- providing a forum for discussion of watershed management issues among community members, local students, resource managers, and tribal leaders; and,
- collecting new field data at several sites in the watershed to evaluate current conditions and better understand important processes in the watershed; andimplementing demonstration restoration projects at sites important to the community.

Advantages of Watershed Analysis and Management Approach

The WAM framework provided a shell for the larger Cibecue restoration project. The WAM process is an ecological-based approach to assessing watershed conditions and processes (Pacific Watershed Institute 1999). This approach was well-suited to the Tribe's needs because it focused on streams, it provided systematic methods to collect and organize information, and it could be modified to meet local needs. The project is discussed in detail below to explain the choices and findings of this approach, and especially to highlight efforts to engage the local community.

Methods

We relied on several methods to collect information for the watershed analysis. We analyzed aerial photos and videography to identify areas of erosion. We collected field data on riparian vegetation, channel morphology, and water quality. Students from the local high school helped the project manager collect stream data and conduct interviews with residents to identify community concerns. We worked with various other programs to implement demonstration projects that are discussed in the results section below.

Critical Questions

The WAM methodology seeks to answer "critical questions" about the watershed (PWI 1999). We had four major questions to address:

- What are reference conditions for streams in the Cibecue Watershed?
- How have streams and uplands changed in recent decades?
- How have changes in functional processes (such as sediment transport and vegetation growth) affected beneficial uses in Cibecue?
- What concerns do the residents of Cibecue have for the watershed?

Technical Support Team

The full-time Project Manager, a tribal member originally from Cibecue, worked with the Watershed Planner to conduct the analysis. Tribal and BIA Geographic Information Systems specialists prepared maps for the analysis. The Tribal Hydrologist and Tribal Fisheries Biologist provided technical assistance for particular modules. Staff from the Rocky Mountain Research Station in Flagstaff provided reviews and other technical assistance.

Modules

The heart of the WAM approach is a series of modules to investigate particular resource concerns and then integrate them through a final module called synthesis. We focused on the following modules:

Community Concerns

For this module, the Project Manager conducted dozens of interviews with residents. He was assisted by high school students as part of a school project.

Vegetation

We conducted vegetation surveys at several sites in the watershed. We identified key wetland species in the watershed and in adjacent watersheds. We compared densities of these plants with reference areas and old photos.

Channel Morphology

We relied on the Rosgen channel classification system and assessment methodology (Rosgen 1996). We did pebble counts and cross-sections as well as channel typing to identify unstable areas.

Water Quality

We compiled existing water quality data and collected new samples for fecal coliform, turbidity, temperature and phosphorous.

Cultural Concerns

We conducted interviews and site visits with cultural advisors, including members of the Tribe's Cultural Advisory Board. We identified plants of particular concern and examined relationships of the plants to watershed conditions.

Erosion

We referred to the soil survey in identifying high hazard areas. We analyzed aerial photos and conducted field investigations to identify erosion source areas. We looked for features such as gullies, landslides, and alluvial fans and then correlated these features with soil types.

Synthesis

Through synthesis we connected processes in the uplands and the riparian areas. The challenge lay less in understanding these relationships than in trying to compare the relative importance of different factors. Although our level of analysis was not detailed enough to quantify conditions throughout the watershed, the results are sufficient to plan restoration activities.

Results of the Watershed Analysis Project

The project has resulted in an analysis of watershed conditions that highlights various indicators of degradation. The analysis has identified opportunities for restoration, some of which have become demonstration projects. We have engaged the community in watershed restoration activities by establishing an Adopt-a-Watershed Program with the local school, coordinating projects with various tribal programs at the local level, and training community members in watershed assessments and restoration. Finally, we have a database of information that will guide future projects.

Indicators of Degradation

The analysis confirmed the general community perception that the riparian ecosystems of Cibecue Creek were well below their potential condition. We examined vegetation, hydro-geomorphology, and soil conditions to identify the extent of degradation.

Vegetation

Native wetland graminoids (sedges, rushes, cattails, bulrushes, reeds, etc.) are no longer dominant along much of Cibecue Creek. These plants were formerly abundant throughout the perennial reaches, according to literature (Buskirk 1954), interviews, and old photos. For example, advisors reported that cattails and reeds were common along the reach passing through town. People reportedly used to gather cattails along the stream above the community. Photos from a 1965 *Arizona Highways* article depict a stream lined with lush graminoids. Today many reaches have an impoverished herbaceous understory.

Hydro-Geomorphology

Cibecue Creek has been disrupted by a variety of impacts to the channel. The main stem of the creek appears to be adjusting to elevated sediment loads from gullies, roads, and burned areas in the uplands. Channels in the community area tend to be wide, shallow, and relatively straight. In-stream bars and braiding are signs of aggradation in these reaches.

Soils

Aside from the floodplain terraces, riparian soils along the creek show little development owing to the continual shifting of channel substrates. The substrates adjacent to the stream are dominated by cobbles and gravels, but clays and sands accumulate in some areas. Soil organic matter in these deposits promotes the growth of lush vegetation. These findings show that we need to retain fine sediments in the riparian areas to restore herbaceous vegetation.

Identification of Restoration Opportunities

The guiding principle for restoration of the Cibecue watershed is to reduce sediment flow from the uplands while promoting the ability of the riparian ecosystems to process that sediment into stable streambanks and productive wetland soils. Numerous opportunities to benefit the Cibecue watershed were identified and explored through the analysis. Some of the highlights include:

- Road closures in the upper watershed, since several minor roads appear to be significant contributors of sediment.
- Irrigation diversions, since some diversions are a significant impact to the main channel by disrupting sediment transport and altering channel morphology.
- Grazing impacts, since continuous grazing, particularly by horses, was the most widespread problem affecting both streams and uplands.
- Unstable channel conditions, since channels exhibit aggradation and bank erosion.

Demonstration Projects

We conducted a number of projects to evaluate potential for restoring watershed health. Successful projects serve as showcases to the community and tribal leaders. By identifying complications in these pilot projects, we can design better, larger-scale efforts in the future.

Cibecue Bridge Projects

With direction from our program, the BIA Branch of Roads used heavy equipment to clear two bridge areas of accumulated sediments and redirect the channel through the bridge. Members of the local livestock association built a fence around the upper bridge site to protect the rich wetlands at the site. The Project Manager supervised a crew of high school students in transplanting, reseeding, and thinning the bridge area. The response of vegetation has been acclaimed by community members, some of whom are now gathering plants from the site for their use.

White Springs

This important spring had been devastated following the White Springs fire of 1996. Tribal Council members arranged to close roads leading to this spring. We hired members of the local livestock association to build a fence around the area. Restricting access by animals and vehicles has dramatically improved the appearance of the spring area. We constructed large rock riffle structures to prevent further downcutting and to raise the water level in the downcut reach. The structures have stopped the downcutting and promoted rapid recovery of vegetation at the site.

Little Springs

This wetland was fenced by members of the local livestock association to establish a botanical refuge area that now serves as a source of transplant materials.

Stockman's Diversion

This irrigation diversion had been moved many times in the past several decades in response to the shifting channel. For our project, the channel was relocated to its original position, and the diversion was reconstructed as a much wider and more natural riffle feature. Access to the diversion was restricted with fencing. The diversion has been replanted with cattails (*Typha latifolia*) and has thus far survived several heavy floods.

Adopt-a-Watershed Program

The Cibecue School has made Cibecue watershed an outdoor learning laboratory for its high school science curriculum. The first graduates of the high school had the opportunity to learn about their watershed and how to restore different areas within it. The Adopt-A-Watershed program led to an exchange with Nueva Vista High School in Concord, California.

Students from the partner school in California first visited Cibecue to help with the White Springs restoration project. Then the Cibecue students flew to California, where they learned to care for monarch butterflies. Following that trip, the Cibecue School established a garden area to attract butterflies.

Several students from the Cibecue School have made presentations based on their involvement with the Adopt-a-Watershed program. Students held a community meeting to present results of their assessment activities and proposals for restoration projects. Two students also made presentations at a salmonid restoration conference in California.

Cross-Program Interactions

Although most of the assessment work was done by Watershed Program staff, numerous entities took the lead on demonstration projects. Members of Cibecue Livestock Association built sturdy fences at the restoration sites. The BIA Roads Department and Cibecue Land Operations irrigation crew used their heavy equipment to modify the channels.

Tribal and BIA forestry programs implemented a woodland thinning demonstration project that was studied by project staff and high school students. An intern from the tribal fisheries program sampled fish populations with assistance from the project supervisor and high school students. We assisted the Tribal Wildlife and Outdoor Recreation Division training tribal guides, including two residents of Cibecue, to lead nature tours into lower Cibecue Canyon The Grasshopper and Cibecue Livestock Associations and Tribal Range Program rounded up maverick animals to improve range conditions. BIA Fire Management conducted one of the first low-elevation prescribed burns in many years. In reviewing the burn proposal, members of the Tribal Cultural Advisory Board reflected on the tradition of burning such areas to improve conditions for livestock. All these cooperative efforts involved local residents in promoting the health of the watershed.

Training Tribal Members

A top priority of the project was to train tribal members in assessing and restoring watershed health so that future generations would understand the history and methods of the program. This training provided useful and interesting work for many young Cibecue residents. The Project Manager received many days of intensive, hands-on training in assessment and restoration activities. As a result, he is able to make recommendations to other tribal land management entities and to design restoration projects. High school students were trained in assessment methods and had the opportunities to explore challenges facing the watershed. As a result, they were able to better understanding how activities need to be changed within the community. For example, many students discussed the importance of managing horses in the community to protect their streams.

Database

A major feature of the WAM approach is its capacity to organize information from a variety of sources. We found that old photos from the *Arizona Highways* magazine were particularly valuable in visualizing past conditions. Aerial photos served to identify sediment source areas. By examining maps, working with cultural advisors and other community members, and consulting with resource managers, we identified wetland habitats in the watershed.

Community Interactions

Despite the general interest of the community in watershed issues, we found that community meetings did not yield a strong turnout. Radio presentations by the Project

Manager and Council members were a more effective way to get information to the community. Several field trips with the Tribal Council, resource managers, and school teachers were helpful in drawing attention to the watershed issues and restoration efforts. For example, teacher aides visiting White Springs reacted very positively to the work that had been done there. The most reliable method of interaction with community members was personal communications by the Project Manager.

Future Plans

We have planned several demonstration projects in the watershed, including a large restoration project on the creek at the north end of the community. We plan to realign the channel along a stable morphology, remove excess woody vegetation, slope-eroded streambanks, and promote growth of herbaceous wetland species. Local landowners are being consulted on the design of the project. At Martinez Ranch, we are fencing an important spring area from ungulates and plugging gullies to reduce erosion. We will continue to monitor restoration and new management activities (burning, thinning plots, reseeding, gully control projects) to see how areas respond to treatments. We will then return to the watershed analysis to evaluate restoration capabilities and appropriate techniques for different sites.

Currently, the Cibecue Watershed Project is funded through a grant from the Tribe's own Land Restoration Fund. The Tribe established this permanent fund using a portion of its settlement against the Federal Government for mismanagement, including the overgrazing of tribal rangelands. The Tribe is enlisting additional funding sources in its efforts to reverse the process of degradation, but any funds must be fully compatible with the Tribe's goals for managing its watersheds.

Conclusions

The watershed management programs of the 1960s and the 1990s both had to confront degraded range conditions stemming from over grazing under the non-Indian permit system administered by the Federal Government. The program of the 1960s viewed the problem of watershed degradation as a need to increase economic returns from the land and to increase water yields. Thus, the health of the land tended to be valued as an instrument rather than as an end. This approach was not consistent with traditional cultural norms, as evidenced by the hostility of many community members towards various aspects of the program. Because the BIA's program depended on promoting the needs of downstream water users, it failed to provide lasting benefits and instead engendered distrust among the community. While the land managers initially may have sought a "win-win" solution for the local community and downstream users, they sacrificed local concerns, such as preservation of cottonwood trees, to satisfy the downstream interests.

Changes in societal values have moved watershed management away from large-scale vegetation manipulation to increase water yield (Ffolliot et al. 1998), and more towards restoration to sustain ecological functions and biodiversity. However, the experience of Cibecue teaches us that in addition to changing goals, we must follow processes that empower land-based communities in sustainably managing their watersheds.

Today, the Tribe's Watershed Program works to help tribal communities achieve their goal of healthy streams. Today's tribal program recognizes that economic progress, community development, ecological restoration, and environmental education are interconnected. Promoting the functions and stability of the watersheds will serve to sustain the economy and culture of the communities that live within them. Location, a long history, economic uses and cultural ties makes Cibecue an outstanding example of such a "watershed community" in which the people, the land, and the streams are linked inextricably. The Tribe's watershed analysis project in Cibecue was conducted with these connections firmly in mind, and future watershed management activities must continue to promote this unique association.

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SYNTHESIS PAPERS

Future Protocols

Anticipating Future Landscape Conditions: A Case Study

Bill McDonald[1]

Abstract.—Anticipating landscape conditions in the 21st century is a difficult, if not impossible task. Different people have different perceptions of what future landscapes should look like. One group of people, a group of ranchers in the Malpai Borderland Region of the southwestern United States, have come together to work with government agencies, universities, and environmental groups in attempting to reduce the threat of property and ecosystem fragmentation in the region. These collaborative efforts are also finding ways to increase the productivity and biological diversity of the area's rangelands.

Introduction

The Malpai Borderlands Region of southeastern Arizona and southwestern New Mexico covers approximately one million acres in the San Bernardino and Animas Valleys east of Douglas, Arizona. The region ranges from 4,500 to 8,500 ft in elevation and contains a variety of ecosystems extending from low elevation desert shrub and tabosa grasslands to high elevation ponderosa pine and Douglas-fir stands. The mountains and valleys are home to diverse plant and wildlife populations, including some species that are rarely found within the United States. Land ownership is divided between private individuals and state and federal agencies. The Malpai Borderlands Region is home to a viable ranching community. Property and ecosystem fragmentation, which is obvious in many adjacent valleys, has not reached the area. We are endeavoring to make sure that it never does.

Malpai Borderlands Group

A group of ranchers, known as the Malpai Borderlands Group, organized themselves in 1992 to find ways to reduce the threat of property and ecosystem fragmentation and to increase the productivity and biological diversity of the area's rangelands (McDonald 1995, 1996). The Malpai Borderlands Group felt that their efforts should be based on good science, contain a strong conservation ethic, be economically feasible, and be initiated and led by the private sector with government agencies, universities, and environmental groups as partners.

Land management based on good science has been a key part of efforts in the Malpai Borderlands Region. The Malpai Borderlands Group and affiliated organizations have sponsored many research studies and inventory activities. The Rocky Mountain Research Station, USDA Forest Service, became involved in these studies in 1994 when it was awarded a national ecosystem management grant to conduct a research program within the Borderlands. The objective of this project is to achieve sound ecosystem management in the Borderlands area through coordinated research-management partnerships. The Rocky Mountain Research Station has initiated studies, but more importantly, has developed research partnerships with scientists and managers from many state agencies, universities, and conservation organizations, and independent investigators (Gottfried et al. 1999). These collaborations have provided expertise to address the wide variety of questions that are basic to good ecosystem management to sustain and create healthy, productive ecosystems into the future.

One Rancher's Perspective of the Future

Ranchers do have economic interest in their land (McDonald 1999). But, newspapers give the view that ranchers have only economic interest in their land. I submit to you that anyone who gets into ranching for only economic reasons is an idiot. Yes, ranchers have to make a living, but that is not why we get into ranching. There are many easier ways to make a living. You can take the same amount of money, put it into almost anything else, and get a better return on your investment. Ranchers started ranching for the same reasons that scientists and managers got into research or management; it was not to become millionaires. If you are a scientist or work for a management agency, you likely did not get into it to submit to the kind of grief you get for what you are being paid. You have a feeling for the land; there is a pull there you cannot resist. I love everything about the land. I do not like being compelled to defend my way of life. But, I thoroughly enjoy learning, as I am at this conference, more about the

[1] *Rancher, Douglas, AZ*

land that I have lived on and hope to live on the rest of my life. I enjoy the insights and being able to share mine with folks who look at things differently. I think it gives us all something that we can hand down to the next generation so they can do an even better job of living with this landscape, if it is still here.

There is another side to ranching. It is a business, an unforgiving business. If you get caught up in the cattle price cycle and are on the wrong side of it, it can be devastating. The last boom to make money in ranching was during and after World War II. There was good money to be made until the middle 1950s, when there was a devastating drought in the region. There was a tremendous die-off of mesquites in the 1950s; that is how bad it was. My grandfather sold off all of his cattle. My grandmother went into the hospital with what would be called severe depression now.

The 1960s were not a profitable time to be in ranching either. The 1970s were a good time to get yourself in debt. Land prices went up, banks were willing to lend money, and in the farm sector a lot of people crashed. The 1980s were a relatively good period. We had the weather patterns that helped to improve forage production that was good for cattle weights, and the prices stayed high. Unfortunately, the 1990s have been very bad for ranching. We have had uneven weather patterns and depressed prices. In 1995, the price fell 35% from the year before, and last year it fell almost 40% from the year before.

Imagine trying to live and plan on this uneven flow of income. This is one of the factors working against small and medium-sized outfits. This is the way America is going. I believe that big government and big corporations tend to like each other, and a small entrepreneur has to figure it out on his own. The feedlots are becoming more and more consolidated. Ranchers are tenacious sons-of-guns, and they have not figured out how to get rid of us yet, but they are trying.

I think ranchers are going to have to get into niche marketing. The Malpai Borderlands Group offers a good possibility to find a way to niche market beef to people who have the same concerns we do and would like to support us. But, we have not figured out how to do that yet. Attempts at niche marketing have failed miserably, so we have to be very careful. On the cost side, the weather has always been the major factor in the Southwest. Drought is the main thing we have had to worry about. It is difficult because you do not know when it starts until you are well into it, and you never know when it is going to end. Consequences for a cattle herd are huge. You try to hang on without destroying the resources you depend on. We spent $30,000 on supplemental feed in 1996 in six months trying to hang on to our cattle herd. On the other hand, you will get a year where the rains come at the right time. There was low average rainfall in 1998, but fortunately the rain fell at the right time, so the cattle herd is in good shape.

There are so many things out of our control. If ranchers seem standoffish, rigid, and conservative, it is because we have had to take a lot of shots, and people have often tried to take advantage of us for one reason or another. So, we are reluctant to jump into the newest idea. On the other hand, we are very flexible. We are the epitome of adaptive management, because we will not survive if we do not adapt. We have to deal with these factors that we cannot control.

One thing we have some control over, but not a lot, is government regulations, which more and more are coming into play in ranching. I do not like to get hit with surprises. It bothers me more than anything else does. Government agencies have kept ranchers in a reactive mode. We do not know what is happening until it hits us in the form of a letter or a paper, and then it is already a done deal. When you have to react to a crisis situation, your decision making is not the best, your social skills do not rise to the top, and it makes for a bad scene. That is how business has been done on public lands for years, and it needs to change. I think the Malpai Borderland Group offers a forum for the types of communication that, hopefully, will allow us to avoid that sort of thing. We are not there yet, but we are getting there. When you have a large organization, you are used to running things a certain way and have laws to follow, and it is hard. But, we might be able to use the Malpai Borderlands Group as an example of how we can make things work.

Inheritance taxes and estate planning present big challenges. This is where many ranches bite the dust and become developments. It is tough changing from generation to generation. Grandpa does not want to let go of it. I know men in their sixties who have not made a major decision on the ranch yet because their parents are still making the calls. Many young people leave ranches in frustration over that sort of thing. Also, many people do not do estate planning. It is complicated. You do not really know for sure until the owner dies whether the next generation will be able to keep that ranch or not.

These things all have great significance for what everyone in the Malpai Borderlands Region cares about, which are the area's habitats and landscapes. And, if we are not talking to each other, if we are pointing fingers at each other, we will all lose. The first thing to suffer will be the habitats and the landscape. A viable ranching economy is still an important piece of this puzzle, and if it becomes a moot point, you will be dealing with a landscape that is very different from what it is today.

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Responding to Increased Needs and Demands for Water

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Abstract.—The nature of the increased needs and demands for water relate to water quantity and quality, bringing in the dimensions of timing and location of water flows. Some key past international activities related to water and watershed policy are reviewed. The common threads that are shaping likely future responses relate to technical vs. institutional means of addressing problems, participatory stakeholder management, developing integrated solutions, and decentralization and privatization of management. Two major response areas are reviewed, namely, that of increasing efficiency in use to reduce per capita consumption and that of developing improved supplies of water through improved management.

Introduction

Other papers at this conference have established the rapidly growing demands for water, land and related natural resources, globally, nationally and locally. Sustainability of the flows of goods and services from land and water resources is high on the agendas of many countries now and will go higher over the next decade and beyond. Scientists and the media throughout the world have documented increasing water scarcity, crises, land degradation, and shortages and problems in meeting the demands for renewable natural resources.

The questions that we were asked to address in this paper is: How do we respond to these growing demands and needs; and how do we develop and manage resources to avoid crisis in the future? We recognize that this conference is dealing broadly with watershed and natural resources management and the multiple outputs from such management. However, for several reasons, we focus here on watershed management in relation to increased demands and need for water. First, we believe like many others that water will become the key land management issue in the 21st century. Second, water is the unifying theme that draws together the elements in integrated watershed management. Third, water is perhaps the best and most dramatic example of why responding with watershed management innovations (i.e., addressing the supply side) is not enough. We also will need to address the demand, or requirements, side of the picture.

To What Are We Responding?

The basic issues — the water scarcities and related crises to which we will need to respond — include those related to water quantity and quality, and land available to meet the various needs of growing populations with ever increasing per capita demands on the limited and fixed land base.

There is no question that water will become a more expensive resource to use in most parts of the world. The increased cost will, to some extent, reduce use and waste of water. However, we still will see increasing scarcities of water of acceptable quality. Into the 21st century, it not only is the physical quantity available for consumption and use that will be important, but also the quality of such water in terms of safeguarding human health, and the flows of water needed to ensure sustainable aquatic ecosystems and their health and beauty.

The types of issues that will come to the forefront have been discussed in detail elsewhere in this Conference and need not be repeated here. The problems that need to be addressed also were highlighted at the major 1995 International Conference, 2020 Vision for Food, Agriculture, and the Environment, and in followup papers to the conference (cf. IFPRI 1995, Rosegrant 1997 and Scherr 1999).

Broadly speaking, there are some threads that already have come together to point the way to the priority future needs in the area of water and watershed management. First, there is accumulating evidence that we have been quite successful in developing the *technical* means to secure the most and best water that can be made available at any given time in any given place. And we have been spending billions of dollars putting the various pieces in place to have quality water for economic development, especially in most of the developed countries. Thus, Lant (1999) suggests that "the legacy of the 20th century water

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resources management is one dominated by federally funded civil and environmental engineering which, for the most part, has successfully achieved the fundamental objectives of putting water resources to the task of economic development and improving the quality of human life." While continuing technical research on water resources will be a necessity, the focus will need to turn more to the institutional and management means for effectively utilizing technologies on the shelf.

Second, there is increasing evidence that in time of crisis and resource shortages, e.g., droughts and floods, people and their institutions in the United States and other countries can and do respond effectively to shortages of resources by reducing consumption and increasing investments, e.g., in the case of water supply and use (see Appendix 1). However, it also is evident that most of the emphasis has been on crisis management and not on developing the mitigation strategies that will change conditions to avoid future unsustainable resource use and development and crises in availability. Thus, Wilhite (1997) notes that while more than 27 states in the U.S. had prepared drought response plans by 1997, the plans are still largely reactive in nature, treating drought in an emergency response mode. He notes that "the transition from crisis to risk management is a difficult task."

A third thread is the emerging trend towards decentralization of responsibilities for the environment and towards participatory management of water resources and associated watersheds. By 1999, there were over 1,500 locally-led watershed management initiatives in the United States, almost all established since 1990 (Lant 1999). Participatory or "co-management" of natural resources is a growing phenomenon worldwide. We use the term co-management to refer to schemes that involve both government agencies and other groups in civil society, such as communities, cooperatives, associations and so forth.

The evidence of success in participatory management as a tool for sustainable development and ecosystem management is mounting. The way to the future will likely involve further development of innovative institutional mechanisms involving local participation.

A fourth trend is the increased importance given to globalization of environmental issues and responses. Over the past few decades, we have had growing international trade and a proliferation of international conventions and programs dealing with the environment and natural resources. Those dealing with biodiversity, climate change, desertification, and fisheries are just a few of the many agreements that have been reached among nations. In the future we most likely will see increased activity in this area.

In sum, we have to focus in the future on developing more appropriate and effective combinations of local and global institutional responses to mounting scarcities of resources, responses that can (a) take full advantage of the growing accumulation of technical knowledge of how to manage natural resources, (b) utilize the sophistication of the local users of natural resources in terms of their understanding of the issues and options associated with sustainable ecosystem management, and (c) help resolve potential conflicts between the actions of users who are in different locations in the watershed (upstream-downstream conflicts).

Recent International Responses to Water Issues

The International Conference on Water and the Environment (ICWE) was held in Dublin, Ireland on January 26-31, 1992. It is generally regarded as the most comprehensive international water-policy conference yet held. In attendance were more than 500 participants, including government-designated experts from a hundred countries and representatives of eighty international, intergovernmental and non-governmental organizations.

At its closing session, the Conference adopted the so-called Dublin Statement and the Conference Report (World Meteorological Organization, Hydrology and Water Resources Programme 1999, World Bank 1993). In the Report, the participants presented four principles to guide the development of freshwater policies in the nations of the world. Furthermore, the participants recommended 10 new policies for the assessment, development and management of freshwater resources. The principles and policies provide an appropriate jumping off point for discussing specific response mechanisms and actions for the future.

The four principles were as follows:

Principle No. 1 - *Freshwater is a finite and vulnerable resource, essential to sustain life, development and the environment.*

Principle No. 2 - *Water development and management should be based on a participatory approach, involving users, planners and policy-makers at all levels.*

Principle No. 3 - *Women should play a central part in the provision, management and safeguarding of water.*

Principle No. 4 - *Water has an economic value in all its competing uses and should be recognized as an economic good.*

Based on these four guiding principles, the Conference participants developed recommendations for an international freshwater policy agenda to enable countries to tackle their water resources problems on a wide range of fronts. The 10 points of that freshwater policy agenda are as follows together with an interpretation of the urgency of each and the way forward in terms of response to global needs:

1. *Alleviate poverty and disease*

   At the start of the 1990s, more than a quarter of the world's population still lacks the basic human needs of enough food to eat, a clean water supply and hygienic means of sanitation. The Conference recommends that priority be given in water resources development and management to the accelerated provision of food, water and sanitation to these unserved millions. However by the end of the 1990s it was clear that the lack of enough food was not a production problem but a lack of income and distribution problem.

2. *Protect against natural disasters*

   Lack of preparedness, often aggravated by lack of data, means that droughts and floods take a huge toll in deaths, and cause misery and economic loss. Economic losses from natural disasters, including floods and droughts, increased three-fold between the 1960s and the 1980s. Development is being set back for years in some developing countries, because investments have not been made in basic data collection and disaster preparedness. Projected climate change and rising sea-levels will intensify the risk for some, while also threatening the apparent security of existing water resources. Damages and loss of life from floods and droughts can be drastically reduced by the disaster preparedness actions recommended in the Dublin Conference Report.

3. *Contribute to water conservation and reuse*

   Current patterns of water use involve excessive waste. There is great scope for water savings in agriculture, in industry and in domestic water supplies. Irrigated agriculture accounts for about 69% of water withdrawals in the world. In many irrigation schemes, up to 60% of this water is lost on its way from the source to the plant. More efficient irrigation practices will lead to substantial freshwater savings although in many cases the water lost in irrigation will be used downstream as return flows. Thus the potential for real water savings is considerably less than 60%.

   Recycling could reduce the consumption of many industrial consumers by 50% or more, with the additional benefit of reduced pollution. Application of the "polluter pays" principle and realistic water pricing will encourage conservation and reuse. On average, 36% of the water produced by urban water utilities in developing countries is "unaccounted for." Better management could reduce these costly losses.

   Combined savings in agriculture, industry and domestic water supplies could significantly defer investment in costly new water-resource development and have enormous impact on the sustainability of future supplies. More savings will come from multiple use of water. Compliance with effective discharge standards, based on new water protection objectives, will enable successive downstream consumers to reuse water, which presently is too contaminated after the first use.

4. *Provide for sustainable urban development*

   The sustainability of urban growth is threatened by curtailment of the copious supplies of cheap water, as a result of the depletion and degradation caused by past profligacy. After a generation or more of excessive water use and reckless discharge of municipal and industrial wastes, the situation in the majority of the world's major cities is appalling and getting worse. As water scarcity and pollution force development of ever more distant sources, the marginal costs of meeting fresh demands are growing rapidly. Future guaranteed supplies must be based on appropriate water charges and discharge controls. Residual contamination of land and water can no longer be seen as a reasonable trade-off for the jobs and prosperity brought by industrial growth.

5. *Contribute to agricultural production and rural water supply*

   Achieving food security is a high priority in many countries, and agriculture must not only provide food for rising populations, but also save water for other uses. The challenge is to develop and apply water-saving technology and management methods, and, through capacity building, enable communities to introduce institutions and incentives for the rural population to adopt new approaches, for both rainfed and irrigated agriculture. The rural population must also have better access to a potable water supply and to sanitation services. It is an immense task, but not an impossible one, provided appropriate policies and programs are adopted at all levels: local, national and international.

6. *Protect aquatic ecosystems*

   Water is a vital part of the environment and a home for many forms of life on which the well-being of humans ultimately depends. Disruption of flows has reduced the productivity of many such ecosystems, devastated fisheries, agriculture and grazing, and marginalized the rural communities which rely on these. Various kinds of pollution, including transboundary pollution, exacerbate these problems, degrade water supplies, require more expensive water treatment, destroy aquatic fauna, and deny recreation opportunities.

Integrated management of river basins provides the opportunity to safeguard aquatic ecosystems, and make their benefits available to society on a sustainable basis.

7. *Resolve water conflicts*

The most appropriate geographical entity for the planning and management of water resources is the river basin, including surface and groundwater. Ideally, the effective integrated planning and development of transboundary river or lake basins has similar institutional requirements to a basin entirely within one country. The essential function of existing international basin organizations is one of reconciling and harmonizing the interests of riparian countries, monitoring water quantity and quality, development of concerted action programs, exchange of information, and enforcing agreements.

In the coming decades, management of international watersheds will greatly increase in importance. A high priority should therefore be given to the preparation and implementation of integrated management plans, endorsed by all affected governments and backed by international agreements.

8. *Invest in people and institutions*

Implementation of action programs for water and sustainable development will require a substantial investment, not only in the capital projects concerned, but, crucially, in building the capacity of people and institutions to plan and implement those projects.

9. *Enhance the knowledge base*

Measurement of components of the water cycle, in quantity and quality, and of other characteristics of the environment affecting water are an essential basis for undertaking effective water management. Research and analysis techniques, applied on an interdisciplinary basis, permit the understanding of these data and their application to many uses.

With the threat of global warming due to increasing greenhouse gas concentrations in the atmosphere, the need for measurements and data exchange on the hydrological cycle on a global scale is evident. The data are required to understand both the world's climate system and the potential impacts on water resources of climate change and sea level rise. All countries must participate and, where necessary, be assisted to take part in the global monitoring, the study of the effects and the development of appropriate response strategies.

10. *Improve personnel, institutional and legal arrangements*

All actions identified in the Dublin Conference Report require well-trained and qualified personnel. Countries should identify, as part of national development plans, training needs for water-resources assessment and management, and take steps internally and, if necessary with technical co-operation agencies, to provide the required training, and working conditions which help to retain the trained personnel. Governments must also assess their capacity to equip their water and other specialists to implement the full range of activities for integrated water-resources management. This requires provision of an enabling environment in terms of institutional and legal arrangements, including those for effective water-demand management.

Awareness raising is a vital part of a participatory approach to water resources management. Information, education and communication support programs must be an integral part of the development process.

Following the Dublin Conference, the Dublin Statement was commended to the world leaders assembled at the United Nations Conference on Environment and Development (UNCED) in Rio de Janeiro in June 1992. The Dublin Statement, in turn, formed the basis for the UNCED Conference participants' recommendations regarding new policies for water and sustainable development. Since then, the Global Partnership on Water was developed. This partnership among nations of the world, has as its objectives to:

- Support integrated water resources management programs by collaboration, at their request, with governments and existing networks and by forging new collaborative arrangements.
- Encourage governments, aid agencies and other stakeholders to adopt consistent, mutually complementary policies and programs.
- Build mechanisms for sharing information and experiences.

- Develop innovative and effective solutions to problems common to integrated water resources management.
- Suggest practical policies and good practices based on those solutions.
- Help match needs to available resources.

Future Responses to Water Issues

The implications of the Dublin Conference, the 2020 Conference and similar policy oriented gatherings are all too clear: Major increases will be needed in our future efforts to meet water demands if mounting crises and shortages of water are to be avoided in some countries. Thus, the simple answer to the question asked of us in this paper is that we need to:

- Address the problems in a more intense and an integrated fashion and to draw on the most cost effective means available, both on the demand and supply sides.
- Create the institutions that will permit effective management of water supplies and use. We need to create incentives and other means to use available water more effectively and efficiently (demand side).
- Manage more effectively the existing supply of resources and search for new sources of water (supply side).

Below we dissect this broad answer and look at the multitude of specific, interrelated ways in which we can increase efficiency and effectiveness in use and expand the sources of water and quantities available in given places at given times.

Specific Actions and Policies

Figure 1 provides a summary of two major areas of response to increasing demand for, and scarcity of water. One involves reductions in per capita consumption of water, chiefly through improvements in the efficiency of water use. The other involves finding and developing new and improved supplies of water. Within each category, there are several distinct actions to consider, as indicated in the figure.

Increasing Efficiency in Use: Reducing Per Capita Consumption

Total water consumption is a function of per capita consumption and the size of the population directly or indirectly consuming water. Direct consumption of water by households is a small but critical part of the total fresh water use in the world. However, it does not put much pressure on water supplies other than in arid and / or areas where available water is extremely scarce. The main pressure on water supplies comes through indirect human consumption, where the direct impacts are associated with water use by agriculture and industry. Levels of indirect consumption are heavily influenced by the efficiency with which water is used by agriculture and industry. (Agriculture alone accounts for over two-thirds of the world's consumption of fresh water). Given the fact that about one third of the world's crops are produced with irrigation and this proportion is increasing, it follows that, if the efficiency of use in irrigation is increased, this could have a notable effect on per capita indirect consumption of water.

As indicated in figure 1, greater efficiency in use and reduced per capita consumption can be achieved by (a) changing technologies to ones that make more efficient and effective use of water, (b) giving people greater responsibility for their water supplies, so they reduce waste, and (c) increasing prices to reflect the true scarcity value of water and the cost of supplying it.

The Supply Side: Developing New and Improved Supplies of Water

Populations in key areas are growing, so we cannot rely on reductions in per capita consumption alone - although such reductions can go a long way towards easing the pressure on existing supplies and avoiding future scarcity and crisis. We also need to be concerned with increasing supplies at given times in given places. As discussed in earlier sessions, effective, *usable* supplies can be increased in a number of ways. First, timing of natural water flows can be manipulated to some extent through watershed management, ensuring supplies of water when it otherwise would not be available. Second, usable quantity of water at any given time can be increased to some extent through various techniques such as water harvesting, gaining access to deep aquifers, increasing storage and changing storage techniques to reduce evaporation. Third, by changing quality of water, e.g., through desalinization, the effectively usable amount of water can be increased dramatically, although often at a significantly higher cost than other water sources.

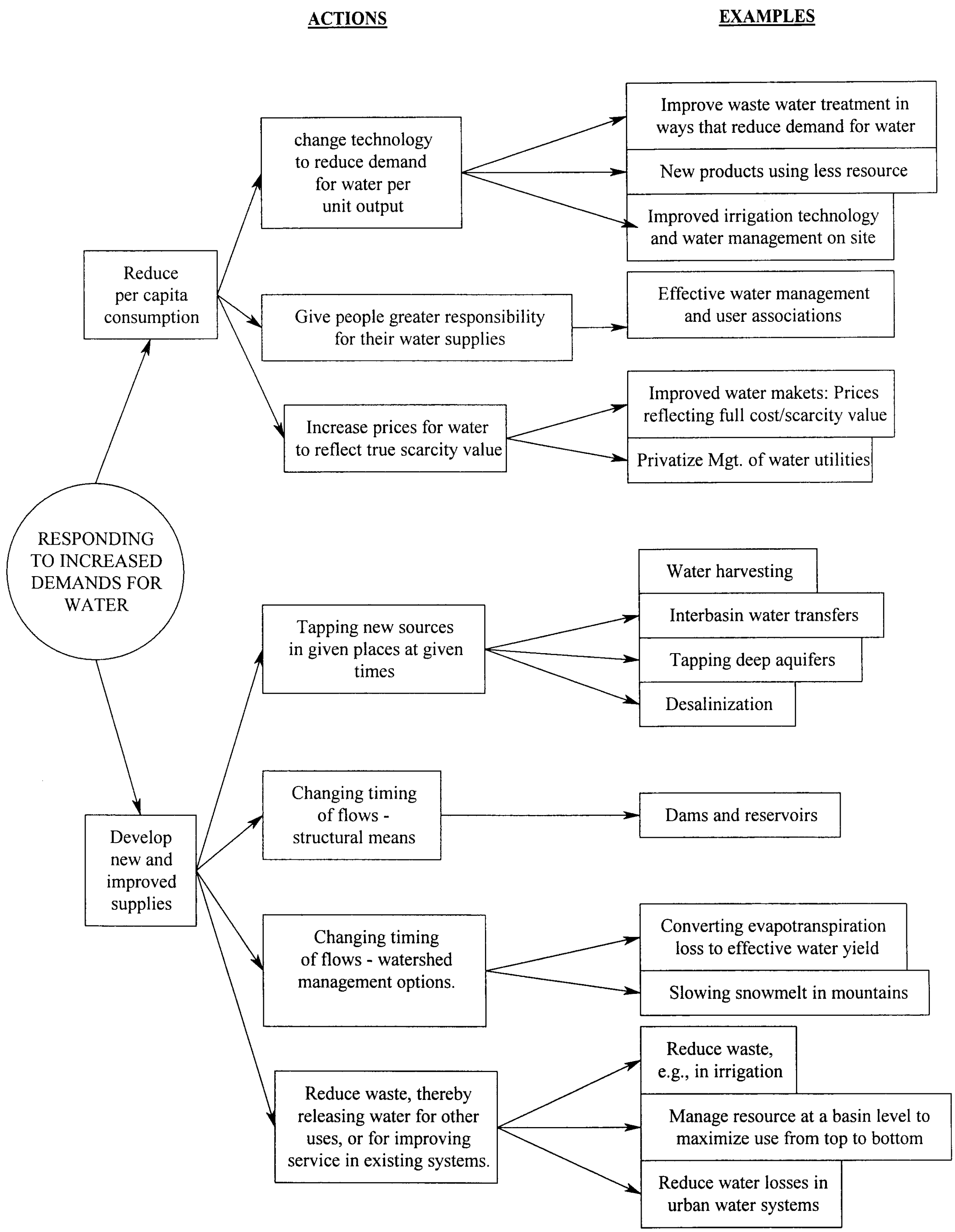

Figure 1. Responding to increased demands and needs for water.

The problem never has been and never will be the total quantity of water available on and under the earth's surface. Water covers three quarters of the surface of the globe (an avg. of 7,000 m3 per person flows into the rivers and underground channels of the earth each year). It is estimated that humans effectively use less than 1 percent of water that exists at any given time. Rather, the issue is the amount of *effectively* usable fresh water of a given quality, available at a given time in a given place *at reasonable cost* (The Economist [322(7752):11,12]). In looking at potential supply side responses to increased water needs, it is necessary to consider timing, location, quality, and cost issues.

Managing the Available Water

In the future we need to focus on improving the management of our existing supplies of water and other, related natural resources. After a long period during the past century of constructing large water projects, especially for irrigation, hydropower and flood control, the water agencies in many countries find that their mission has changed. Agencies like the U.S. Bureau of Reclamation find that their major concern regarding water supply now is being focused on better management of existing systems rather than building new systems. For a number of countries the transition from a construction mentality to a management mentality has been difficult. Many don't have the skills that are required for effective operation and management of large, complex water systems. They lack the basic motivation to provide service to the users. To make the transition, governments need to alter roles, functions, and responsibilities of water and land management agencies and change how agencies relate to one another. When more than one water agency exists, they should be encouraged or required to exchange information, communicate on a regular basis, and coordinate operations. Management procedures should be promoted that are transparent, decentralized, and responsive to users' requests.

One way of doing this has been to foster formal and informal water-user associations that have a strong sense of owning the water. The feeling of ownership can grow out of users' direct involvement in planning, construction and management. It also can occur through granting water rights to the water associations and/or the direct involvement of users in financing water structures. Other options include establishing financially independent water utilities or concessional management contracts with private firms.

A key is to effectively introduce and implement private market incentives in the management of scarce water resources. Policymakers need to make sure that clear lines of accountability and responsibility are developed. It needs to be quite clear as to who is responsible and accountable for delivering water to consumers or water-user associations. Management also must develop and use a system of data collection, monitoring, and information delivery. Water managers need information about water supplies and demand, while users, such as farmers, must know about likely supplies so they can plant the right crops. Timely information can improve decisions at all levels. Without good information and monitoring, it will be difficult to assign responsibility and hold water managers accountable for performance.

Policies and Policy Instruments for Effective Response

A great number of laws and policies exist in the United States and in most developed countries that guide the effectiveness with which the above responses to increasing demands and needs for water are implemented. Thus, implementation of these policies is accomplished through use of four main types of mechanisms: (1) promotion of local commitment and participation, (2) regulatory mechanisms, (3) fiscal and financial mechanisms to influence private behavior, and (4) public investment and improved management of resources.

Policy design and actions take place within a social and institutional setting that is unique for every country. The uniqueness relate to differences in organizations, customs, laws, rights, responsibilities, regulations and informal rules that guide and influence the success or failure of a particular policy or action. Effective policy actions may require changing institutions as well as developing new policy instruments.

Institutional arrangements specify who benefits from water use; and they establish incentives that guide water use. Well-designed and functioning institutional arrangements can set up regulations, pricing mechanisms, water rights, and government interventions to effectively guide water use. However, inadequate institutional arrangements can impede efficient water use and cause serious problems of waste and misuse.

Institutional arrangements also establish the interface between government and the private sectors in water and watershed management. Management usually involves a mix of government and private sector activity. Once the mix has been decided on, the next step is to select the policy instruments that will work best. Usually some combinations of policy actions and instruments are more effective than just a simple action or instrument. An example is a rapidly growing city that faces very expensive new water supplies. Instead of choosing the costly option of developing new water sources (dam or water transfer) the water agency decides on a strategy of replacing leaky pipes, charging higher water fees, and providing users with water conservation assistance.

Clearly, any effective water policy will have to change basic incentive structures. Policies and organization can be changed to provide water managers with a strong incentive to improve the efficiency and equity of water distribution. This might be done by giving users more responsibility for the costs of, and benefits from, water delivery and allocation. Another way would be to give water users tradable water rights, and then let them employ the water managers much like they are doing in some irrigation systems in Mexico. A third possibility is to have the manager's salaries depending on the efficiency of water delivery and / or the percentage of fees collected from water users. In several countries, such as the Philippines, water managers receive a bonus, for good service or when a high percentage of farmers pay their water fees (90%). The important point is to have a strong link between those using the water and those managing it.

Incentives also are needed to encourage water users to make efficient use decisions concerning their supplies. This can be difficult when many users are involved or when monitoring is difficult. The two most effective instruments are water markets and prices that are based on the opportunity cost of providing the water. Water markets are probably the easiest means of introducing the appropriate incentives for efficient water use if rights have been established and allocated. On the other hand, it may be very difficult to establish and allocate water rights separate from land rights. Both are essential for establishing effective water markets.

Where it is not possible to allocate water rights to users, then administrative water pricing although not as flexible as pricing by market, can provide needed incentives. This option works best for domestic and industrial uses where the water is piped directly to the users. It is much easier to meter than the delivery of water to widely dispersed farmers. To lessen the impact of higher water prices on low income families, the price increases can be combined with assistance for using water conservation measures. Bogor, Indonesia, cut water use by over 50% by using such measures as price increases and conservation measures.

Another option is not to provide all the water users demand and in this way create a scarcity value for the water they receive. In irrigated areas, this might mean they only receive enough water to irrigate 75% of their land. This would force users to conserve water and adopt new technology to make better use of the water. If farmers were also allowed to trade water then you could get the added efficiency of moving more of the water to the most productive farmers.

The key factor is that users and managers need incentives to improve water use and allocation. Where these incentives have been changed major improvements in water use have occurred. Changes are coming for both users and managers. Thirty years from now we will be all very surprised by what has been achieved. For example, who could have predicted thirty years ago that we would have an international market for bottled water and that bottled water would be available in small villages all over the world?

Conclusion

This conference, as well as others such as the 1992 International Conference on Water and the Environment held in Dublin, Ireland, has recognized the potential gravity of social problems associated with inadequate global supplies of quality water. Past efforts to alleviate the problem have focused largely on increasing water supplies through engineering projects. Future efforts must, however, also address ways of stemming excessive demand. Thus, the future will require a complete examination of both the supply and demand side of water issues. Specific actions will require a reduction in per capita use of water, development of new and improved water supplies, and better management of existing water projects. Keys to future improvement of the world water situation will be: 1) promotion of local commitment and participation, 2) regulatory mechanisms, 3) fiscal and financial mechanisms to influence private behavior, and 4) public investment and improved management of resources.

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Appendix 1. Community Response to Water Crisis: The 1986-1992 California Drought

The 1986-1992 drought in California was severe for many cities in the state. Santa Barbara, for example, was dependent on local sources for its water supply. Based on their study of Santa Barbara's response to the drought, Loaiciga and Renehan (1997) found that:

- Water use dropped 46% at the height of the drought relative to pre-drought water use; and water use remained (in 1997) at 61% of the pre-drought level.
- Average cost of water rose by $3.08 per unit (100 cu.ft.), largely because of investments aimed at supply augmentation and conservation mitigate future drought. The rise includes part of the cost of hedging against future drought risks.
- The gap between average cost of supply and average revenue per unit of water rose in real terms from $0.14 per unit in 1986 to $0.75 in 1996; this is a disturbing development, since it limits the ability to build up funds for future hazards to water supply.

Ensuring the Common for the Goose: Implementing Effective Watershed Policies

Hanna J. Cortner[1] and Margaret A. Moote[2]

Abstract.—Addressing public and scientific concerns about human impacts on long-term ecological sustainability will require new approaches to resource management. These new approaches, which place considerable emphasis on management on the landscape or watershed scale, stress holistic and integrated science, meaningful public involvement to reflect changing social goals and objectives, collaborative decisionmaking, and flexible and adaptable institutions. New policies that incorporate ecological understanding as well as promote democratic ideals will be required. Five guidelines can assist in designing an effective policy framework in which watershed management makes a significant contribution to the goal of long-term ecological sustainability. They include: integrate the political from the outset, build bridges to citizens, reexamine laws, rights, and responsibilities, strengthen administrative capacity, and look beyond the watershed.

Introduction

The law locks up both man and woman
Who steals the goose from the common
Buts lets the greater felon loose
Who steals the common from the goose

—Anonymous English poem

Public and scientific concerns about human impacts on long-term ecological sustainability have prompted serious scientific and political reconsideration of the requirements for effective natural resource management. It is increasingly recognized that not only must we focus on the potential harm that can be done unintendedly to discrete ecological units, but we must also focus on issues surrounding the integrity and stability of the larger common; the landscape, ecosystem, or watershed. Politically this means designing more effective policies that incorporate ecological understanding as well as promote democratic ideals of equality, liberty, popular sovereignty, and equity.

Many of our traditional approaches to natural resource management are no longer adequate to meet tomorrow's challenges, and these approaches have come under severe criticism. In the United States, for example, implementation of current regulatory regimes for clean air and water are said to have created a "pathological cycle of regulatory failure, crisis, and controversy" (Lazarus 1991, p. 146). Natural resource policies are said to be characterized by a "pathology of natural resource management" (Holling and Meffe 1996). Many water, timber, grazing, and mining policies have been termed the "lords of yesterday," i.e, policies that while outmoded continue to exert tremendous influence (Wilkinson 1992). These policies have often had quite devastating effects not only upon the landscape, but upon democracy as well (Cortner and Moote 1999; Ingram and Wallace 1997; Klyza 1996). Thus, new approaches to natural resource management are increasingly being formulated and applied.

A central goal of new ecological approaches is usually long-term ecological sustainability, i.e., maintaining ecological attributes and functions into perpetuity, therefore ensuring that future societies enjoy the same ecosystem values that we do today. Unlike traditional resource management, the first priority of ecosystem management is conserving ecological sustainability; long-term maintenance of ecosystem integrity, productivity, and resilience; levels of commodity outputs are adjusted to meet that goal (Christensen 1996; Grumbine 1994; Wood 1994). Commodity production is considered a secondary byproduct, much like interest on capital (Brooks and Grant 1992). Ecosystem management stresses holistic, integrated science, meaningful public involvement to reflect changing social goals and objectives, collaborative decisionmaking, and flexible and adaptable institutions (Cortner and Moote 1999).

Watersheds play an important role in ecosystem management, and the search for new management paradigms has brought a resurgence of interest in watersheds and watershed management, broadly defined. Watersheds, it is argued, are natural, logical organizing units for land use planning and ecosystem analysis. In many areas of the United States watershed-based organizations are experimenting with collaborative and inclusive decisionmaking processes as part of an ecosystem approach (Natural Resources Law Center 1996; Yaffee et al. 1996; Toupal and Johnson 1998; Weber 1999). Watershed-scale management recognizes the interconnections of upstream and downstream areas, not only in terms of hydrology and

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biology, but also in terms of land ownership and resource management institutions. Biophysically and institutionally, watersheds are natural laboratories of experiments for the collaborative and adaptive management emphases of new ecological approaches to resource management.

This paper addresses the central question of designing an effective policy framework premised on the goal of long-term ecological sustainability. While the focus of the discussion is specific to the United States, many challenges to designing policies that incorporate a broad ecosystem perspective are not nation-specific. The paper suggests five guidelines for designing an effective policy framework in which watershed management can make significant contributions to the goal of long-term ecological sustainability. While these guidelines do not represent an inclusive list, they are suggestive of some significant and important first steps. They include: integrate the political from the outset: build bridges to citizens; reexamine laws, rights, and responsibilities; strengthen administrative capacity; and look beyond the watershed.

Integrate the Political

While natural resource management professionals are want to lament that citizens increasingly appear separated from resources, the traditional myths and cultures of the resource management professions have reinforced that separation. Too often we have separated politics and resource management, treating fundamentally political problems, such as forest planning or endangered species protection, as technical problems that can be fixed with technical solutions and science-based optimal decisionmaking. Questions of politics are viewed as discrete issues, reflecting our historical tendency to separate humans from resources, the political from the technical, the social from the physical. All too often institutional and policy issues are left to the end (the end of a bioregional assessment, the end of a planning process) or are ignored altogether. We nod knowingly when reminded that resource management is embedded in a social-political context and that we need to be conversant with that context; then we continue to exhibit behavior in our management and research establishments that demonstrates that we really don't want to accept that in practice. This can no longer be the case.

It is relatively easy to ask how the watershed is functioning, but leave out the people and their preferences. But most problems are not simply technical in nature, they are political. Political and institutional considerations need to be integrated from the outset. Designing effective policies is not something to be relegated to the end-of-the-pipe process after the watershed science or the hydrology gets figured out. Socially defined goals and objectives frame the expectations for ecosystem management. This means beginning with an understanding of the social and political context, using that information to prioritize problems, and integrating that information into all aspects of assessment and alternative development and evaluation. Implementation considerations, which are heavily people-dependent, need to be factored into the process, not left for policy makers and managers to figure out after most of the scientists go home.

Build Bridges

Involving interested publics in decisions that affect the management of watersheds is necessary for stewardship, for ensuring that policies adequately reflect social and goals and objectives, for carrying out policy directives, and for monitoring landscape and policy responses. Including people in policy decisions is no simple task, however. Effective watershed policies are therefore dependent first upon building and sustaining social capital and active citizen engagement. Citizens' capacity and willingness to engage in governance depend upon a reserve of social capital, which are those features of social life , networks, norms, and trust , which facilitate citizen association and enable participants to act together more effectively to pursue shared objectives (Putnam 1995). Social capital influences citizens' collective ability "to respond to external and internal stresses; to create and take advantage of opportunities; and to meet the needs of residents, diversely defined" (Kusel 1996, p. 369). The collection of characteristics encompassed by the concept of social capital is enhanced by the presence of existing social networks, such as clubs, professional associations, religious organizations, and other groups; the "associations" that the 19th century French political observer Alexis de Tocqueville (1900) defined as critical to American democracy. Through participation in these associations, citizens realize their collective power to change local conditions and influence society (Machlis 1990; Etzioni 1995). Citizen participation in civic organizations is considered important to democracy in part because it is through participation in these voluntary institutions that people develop the trust and skills needed for participation in political groups.

Today, however, some observers are greatly concerned about declining levels of civic engagement. According to one prominent social scientist: "By almost every measure, Americans' direct engagement in politics and government has fallen steadily and sharply over the last generation.... despite the fact that average levels of education —

the best individual-level predictor of political participation — have risen sharply throughout this period. Every year over the last decade or two, millions more have withdrawn from the affairs of their communities" (Putnam 1995).

People are also increasingly separating themselves from the traditional institutions of government. If one hallmark of mass participation in a democracy is the election, we should take no comfort from voting statistics. American voting turnout, if measured by the percentage of voting age population, is one of the lowest of democratic countries. It is lower now than in the latter half of the nineteenth century. Moreover, polls track a significant and continuing decline in citizen trust in government (Nye et al. 1997). Where polls once showed 75 percent of Americans trusted their government, today only 25 percent do so. Like the term "politics" the term "government" is increasingly used in a pejorative sense. Parallel to the decline in public trust and confidence in the federal government has been a sharp decline in public confidence in leaders of many other institutions, including the military, universities and colleges, the press, and medicine. Moreover, similar declines in confidence are found in other developed countries. As economic development takes place people become more secure about basic existence needs and more likely to challenge traditional authoritative institutions (Inglehart 1997).

While Americans have always distrusted government to one degree or another, the question is, when does the separation of citizens from governance in this country cut so deep that it precludes timely political reform? Despite the long history of an adaptive and resilient political system, the danger is that we may reach the point where the system is incapable of recovery and regeneration. Therefore, if a strong reservoir of social capital is indeed a precondition for the effective performance of political institutions, effective policies will depend upon rebuilding social capital. It will also be imperative to either to reinvigorate traditional governance institutions, or alternatively to experiment with new, more participatory forms of governance outside traditional structures (Nye et al. 1997).

Building social capital and a renewed conception of public life will require countering the destructive aspects of individualism, showing the collective benefit, and breaking down barriers to public participation. While significant institutional barriers to more participatory democratic forms still exist, the increasing interest in collaborative processes when local community concerns are at stake is an encouraging sign of grass-roots civic engagement. Useful lessons are being provided by a number of community-based forest organizations and watershed groups. These groups are attempting to make local communities and local people more effective participants in the process of governance, and have embraced the idea of sustainable resources and sustainable communities. Many environmental groups, however, remain skeptical of the call for more community-level participation in natural resource management, believing it is a ploy to reverse environmental gains won at the national level and shore up the power of traditional consumptive users. In response, many groups in the community movement insist that the issue is not local control, but inclusivity and more explicit recognition of the contributions communities as well as nonlocal citizens can make in the decision making process and toward achieving the goal of effective resource stewardship. The experiences of other nations with community-scale conservation and watershed management are also being looked to as prototypes of more participatory and localized involvement in resource management (Western and Wright 1994).

Watershed scientists, not just managers, have obligations to build bridges to citizens. Watershed science has an obligation to civic action and the creation of "civic science" in which scientists act as part of the community. This is necessary to ensure that the integrated, holistic science, which is a hallmark of the new ecosystem approaches, does not become a rationale for the construction and conduct of "big science" projects dominated by experts. In big science only experts will be able to determine how complex ecosystems function, and devise standards and criteria for meeting the goal of sustainability (Cooperrider 1996; Klyza 1996; Cawley and Freemuth 1997). And while people may be recognized as part of ecosystems, they will still be viewed as objects to studied and managed rather than meaningfully consulted (Cawley and Freemuth 1997).

Civic science, on the other hand, is participatory; policy makers and citizens also have roles in designing, undertaking, and interpreting research. Participatory and discursive research designs promote democratic deliberation about the problems people, not just experts, see as important, give greater status to grassroots knowledge, and foster collaborative learning and deliberation about values (Cooperrider 1996; Schneider and Ingram 1997). Discursive designs democratize expert cultures. They emphasize learning among participants. They are highly collaborative. They seek to supplement, not replace, the standard analysis that focuses on efficient means to given ends with qualitative discussions of the means themselves (Fischer 1990, p. 366). They are a catalyst for adaptive management (Shannon and Antypas 1996; Lee 1993).

> "In should be clear that civic science cannot be simply a device through which citizens are enrolled as helpers in a scientific process....civic science is not simply citizens doing the procedures of science with the help of scientists. Rather, *civic science involves scientists as citizens and citizens as lay scientists* in a process in which knowledge production is integrated with and therefore cannot be separated from the enlightenment function of self-discovery and the

moral effects of political deliberation and choice" (Shannon and Antypas 1996, p. 68 emphasis in original).

There is much new ground to cultivate here and challenges for scientists, citizens, as well as for those who teach science and research methodology. In civic science there is no set formula for a collaborative learning approach, and no standard protocols for understanding the needs, interests, and values of participants. While "scientific methodology texts, perhaps unfortunately, can be organized like cookbooks ... an art form is different" (Fischer 1990, p. 372).

Reexamine Laws, Rights, and Responsibilities

Implementing new ecological approaches that are the foundation of ecological conditions challenges us to rethink how human-nature relationships are structured through social and governmental institutions. These approaches will not be successful without significant and substantial institutional change. In addition to building social capital, this will require reexamining laws, aligning market operations with the goal of sustainability; and rethinking property rights and responsibilities, both private and public.

First, the broad array of laws that govern the use, protection, and restoration of natural resources must be evaluated for compatibility with new ecological approaches. Consider the following criticisms about the laws in the United States that affect watershed management. The Multiple-Use/Sustained Yield Act of 1960, which as implemented has tended to favor commodity production over ecosystem protection and restoration, may have outlived its usefulness. The rational-comprehensive planning approaches outlined in laws such as the National Forest Management Act and the Federal Land Policy and Management Act and their implementing regulations may be too rigid, inflexible, expensive, and inimical to adaptive management. Similarly, the Endangered Species Act's species-by-species approach may be counterproductive to efforts to look at species distribution and mix over larger ecosystems. Laws such as the Clean Water Act and the Clean Air Act may be so complex that it is doubtful if the administrative capacity to implement them can ever be fully developed (Klyza 1996; Wilkinson 1992; Behan 1992; Behan 1990; Gordon 1994; Keiter et al. 1995; Rosenbaum 1998; Rohlf 1994; Franklin 1993). Finally, the framework established by these laws does not include any explicit mandates for watershed management, land stewardship, or ecosystem management. It may thus be an appropriate time to make a thorough examination of conflicting legal requirements, look for novel ways to address the political and institutional challenges of achieving long-term ecological sustainability, and make recommendations for new and corrective legislation. The Forest Service is in the process of adapting recommendations made by the Committee of Scientist's Report regarding regulatory implementation .

Second, there is a need to recognize that economics is also a vital part of the solution and to align government laws and policies that affect market operations with the goal of sustainability (President's Council on Sustainable Development 1996). Markets are a highly controlled political institution. The availability of goods and services and the prices at which those goods and services are bought and sold are heavily influenced by governmental law and policy both here and abroad. Many principles and theories of economic theory, which influence how we use conventions such as the discount rate and how government constructs and uses indicators of economic productivity and health (such as the gross national product), are government sanctioned. In the past, such conventions have often given short shrift to the values of ecological services and the costs of environmental damages.

Consequently, changes in government policy can create an institutional climate in which market forces are allowed to work in a positive manner, promote ecological behavior, and reward the private sector for producing ecosystem benefits and pursuing long-term ecological sustainability. Government can establish market-based incentives through tax and spending policy and other economic incentives, it can privatize certain governmental functions through the creation of marketable rights and permits, and it can revise budgetary and accounting policies to acknowledge the values of natural capital. Clearly traditional economic ideology and modern ecological awareness must find a common ground from which to cobble a transition toward, and shared responsibility for, fully realizable sustainable practices.

Finally, efforts to manage at a landscape or watershed scale will fail unless both public and private lands are part of the management picture. Management plans cannot be divorced from ownership realities and the different objectives of private and public land owners or they will become mired in political conflict (Flick and King 1995; Hargrove 1980; Cribbet 1986). The property rights movement of the last several years, for example, is indicative of the extremely deep feelings that Americans have about private property.

Property is a social construction that is always undergoing continual modification through court rulings, new philosophical and ethical currents, and changing societal values about labor and capital. In reality, property tenure systems in today's society are dynamic and diverse (Geisler and Kittel 1994). Societal understanding of property rights and the appropriate extent of government regulation should be expected to evolve, just as the definition of good stewardship changes as more is learned about ecosystems (Cribbet 1986; Sax 1993). For example, societal perception of wetlands has shifted considerably in recent years. Not long ago wetlands were considered unproductive wastelands best drained and reclaimed for productive use. Today wetlands are highly valued as wildlife habitat and water purifiers, among other things, and under current law landowners no longer have the right to drain swamps at will. As population has grown and the technological capacity to do significant ecological damage has increased, there are simply a lot more instances where doing what one wants with property hurts someone else (Weeks 1997). In the future, public-private cooperation and new types of property, such as shared land ownership, may well result in further changes in the way society views private and public property.

Property is also a classic example of the responsibilities that attend rights. One does not have the right to use one's land to the point that it becomes a nuisance to others. It is generally accepted, for instance, that pollution spewing uncontrolled from an effluent pipe or a smokestack may be regulated for the greater good. More recently, the legal responsibilities of landowners have been found to include a responsibility to resident endangered species and their habitat. Although arguments are frequently heard that the current legal framework contains "too much regulation," the writings of Aldo Leopold remind us that those who rail against government regulations are often those who are failing in their own obligations to practice stewardship: "Individual landowners and users, especially lumbermen and stockmen, are inclined to wail long and loudly about the extension of government ownership and regulation of land, but (with notable exceptions) they show little disposition to develop the only visible alternative: the voluntary practice of conservation on their own lands" (Leopold 1949, p. 213). The modern reality is that landowner responsibilities are simply greater than they once were, and regulation is often the price paid for failure to attend to the responsibilities attached to property rights. Recognizing the increasing responsibilities of landowners and changing citizens' philosophical orientation to nature to acknowledge responsibilities for stewarding public and private resources can do much to ensure that property rights serve both ecological sustainability and democracy and reduce the need for government regulation.

Strengthen Administrative Capacity

Agency cultures are a substantial barrier to building institutional capacity. Professional norms affect the identification of management goals and the formulation and adoption of the means for achieving those goals. A strong professional ethos can serve an agency well, giving it purpose and making it cohesive. But such insularity can also be damaging when professional beliefs and myths persist in the face of either new scientific evidence or markedly changing social values (Schiff 1962; Clarke and McCool 1996). Agencies become wedded to routine, and deeply resistant to any alteration that doesn't agree with their own professional view of what should be done. Issues become framed as "them versus us," and divisions between the professional expert and the public are sharpened.

Incentives and rewards systems in resource management agencies have traditionally been heavily weighted toward commodity production; efforts toward improving ecological conditions have not been rewarded. Management incentives also exist to control information (Boyle et al. 1994). When faced with conflict, conformity rather than dissent and innovation is rewarded. As a result, agency cultures have yet to foster a spirit of cooperation and a willingness to give up resources and hence power to other agencies and entities. Agencies have been reluctant to shift from linear step-by-step approaches to public participation to those that are flexible, open, and encourage a rich public discourse (Kennedy and Dombeck 1995). Innovation and new forms of leadership have been impeded by hierarchical decision making structures, the risk aversion found in upper levels of decision making, and standards for organizational promotion. There are some evident changes, however. Efforts to diversify the workforce by discipline, gender, ethnicity, and philosophy have brought new attitudes and perceptions that are providing some support for new approaches (Boyle et al. 1994). Moreover, employee loyalty is increasingly not to the organization but to issues such as protection of resources or to the employee's own sense of personal ethics. While such individuals are simultaneously praised as brilliant entrepreneurs and lambasted as deviant insubordinates, they are nonetheless indicative of attempts by lower and mid-level employees to shape organizational change (O'Leary 1994).

Overcoming organizational biases and rigidity, however, is not a trivial task. Proponents of participatory democracy note that opening resource management decisionmaking will require a shift from the current agency / government focus on efficiency. "The criteria for evaluating policy in a democratic process are the accessibility of the process and / or the responsiveness of the policy to those who are affected by it, rather than efficiency or rationality of the decision" (Kweit and Kweit 1987, p. 22). Rather than simple, linear, cause and effect models, organizational cultures will need to move toward more complex and integrated systems thinking (Kennedy and Dombeck 1995; Senge 1990). New, more participatory shared-leadership models will be required (Berry and Gordon 1993; Sirmon et al. 1993).

As long as multiple agencies and levels of government remain protective of their own turf and define their own visions and management objectives apart from each other, it will be difficult to effectively manage at the landscape or watershed scale. Interagency and intergovernmental coordination are needed to meet data and research requirements, reduce repetition, ensure data comparability, and share results. Since water, plants, animals, pollutants, and people are in large part oblivious to administrative boundaries and cross them at will, resource managers will need to acknowledge mutual responsibility for ecosystem components and coordinate processes those transcend those boundaries (Keiter 1994; Keiter 1989).

While there are numerous legal requirements for coordination and many available techniques, bureaucratic efforts to protect agency domains have been long recognized as one of the main impediments to coordination. Turf battles persist among agencies and different levels of government; specialists in one agency don't trust similar specialists in another. Cultural barriers divide managers and scientists (Forest Ecosystem Management Assessment Team 1993). Even within agencies there may be competition among specialists or different parts of the agency. Better external coordination can occur only when there is better internal coordination (Sample et al. 1994).

It is also important to remember that requirements for coordination are not the same thing as opportunities for coordination. Coordination is both a process and a structure of relationships that distributes power, access, and resources. Too often in the past coordination has been treated as a formal procedure to meet requirements that can be satisfied by notice and consultation. Coordination can be strengthened by making it frequent, personal, and ongoing (Cowart and Fairfax 1988; Fulk 1990).

Beyond the Watershed

The number of changes to be considered is indeed numerous and expansive. Yet, the net must be cast broadly. Of course, we must focus on those things that are normally within our professional radar scope, such as, for example, understanding climate effects upon watershed processes, improving water quality monitoring, creating new watershed organizations, or developing more effective technical assistance and economic incentives for watershed stewardship. But effective watershed management policies will also depend upon participation in addressing things not normally thought of as "green." Designing effective policies for watersheds is dependent upon a healthy and adaptive political system that has the capacity to address interrelationships among policy arenas. Consider three examples.

First, reviving citizen trust in government and moving away from the politics of interest that pervades all fields of government, not just natural resources, will require attention to campaign finance reform. Campaign contributions have a wealth and income bias that is greater than for any other mode of political participation (Lijphart 1997). Interests that want to protect short-term gains have disproportionate political power over those advocating change for the long-term interest (Rivlin 1993). The current system of campaign financing creates unequal access and power; at its worst public officials are bought and sold. It has bred corruption and public distrust. Figuring out the mess of campaign financing without stifling free debate is one of the most immediate and important challenges to ensuring the health and integrity of the American political system.

Second, how we treat each other as humans inevitably affects how we treat nature. Racism is not just this nation's enduring curse, it is the world's curse. It squanders both national and human resources with devastating effects on the physical and institutional landscapes. Resources become pawns in the game to gain ascendence over other races or ethnic lineages. Similarly, subjugation of women affects their health, education, and employment opportunities which are factors affecting population policies as well as fundamental human rights. If we cannot treat different races, ethnicities and genders with respect, our relationship to nonhuman objects is also likely to be one of mastery.

Third, the growing disparity between the rich and the poor is of concern. In the United States there is a growing gap between the haves and have nots (Reich 1997). While this gap has not yet become significant politically, it is a latent and explosive issue. It is beginning to affect power structures, define who can afford to politically participate, and separate people from one another. It could unravel the social fabric and affect the legitimacy granted governance structures. In addition to generally reshaping the general political environment in which public policy making takes place, it could also affect how resources, such as watersheds, come to be publicly perceived especially if watershed preserves or certain management practices are widely seen as benefitting the haves at the expense of the have nots.

More apparent are the differences between the rich and poor nations. Developing countries aspire to the same kind of productive, consumptive economy that characterizes the U.S. But without significant cuts in consumption by the developed world, the costs of narrowing the income disparities between the rich and poor countries will have horrendous impacts on the worlds's resources and its watersheds. True, consumption and population are often given lip service as important factors in discussions about effective natural resource policies, but they are just as frequently dropped as either too big to handle within the confined sphere of the problem at hand or potentially too controversial. Very rarely are policies for dealing with population, over-consumption, or wealth inequalities part of our proceedings.

Thinking holistically about natural resources and the environment doesn't just mean expanding the biophysical scope of interest from the stand to the entire watershed or addressing human dimensions by doing more social-economic assessments of watershed communities. It also means broadening our policy and scientific research agendas to include attention to a much broader set of problems and how they relate to the values, goals, and strategies of long-term ecological sustainability. Effective policies in the area of watershed management are dependent upon policies that create vital and well-functioning governance structures.

Conclusion

New approaches to resource management call for integrated, holistic approaches to the management of land and water resources. These new approaches place long-term ecological sustainability as the central goal of resource management. They place considerably more emphasis on management at the landscape or watershed scale. Without doubt, the way natural resource management has been approached in the past requires changing. No longer is ecological condition simply a constraint on efforts to produce efficiently and effectively the most goods and services that can be provided; ecological condition is the fundamental goal.

There are significant opportunities for watershed management programs to become prototypes of an interdisciplinary, holistic, participatory approach to long-term ecological sustainability. Such programs can take the lead in the design and implementation of changes that will be needed in our politics, our traditional scientific protocols, and our organizational cultures. Participation in this process will require watershed managers and scientists to integrate the political from the outset, build bridges to citizens, reexamine laws, rights, and responsibilities, strengthen administrative capacity, and look beyond the watershed. These prescriptions for action, however, do entail redistributions and shifts in the current configuration of power and will spawn the conflicts such shifts entail. Resolving those conflicts will necessitate crafting more effective political connections among humans, nature, science, and government, and heightening concern for the intergenerational impacts of actions. It will require attention not only to watershed science, but also to democratic science. Achieving long-term ecological sustainability and ensuring resilient and adaptive watersheds is intimately connected to the health, resilience, and integrity of the larger polity. Our attention must not only be focused within the boundaries of the watershed and discrete functions within that watershed, but to problems and processes within the larger policy. Significant work remains to be done by scientists, managers, and citizens to design an effective policy framework that ensures that, in addition to not stealing the goose from the common, in the long-term the common is also not stolen from the goose.

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POSTER PAPERS

Watershed-Related Research Projects

Arbuscule Mycorrhizae: A Linkage Between Erosion and Plant Processes in a Southwest Grassland

Mary O'Dea[1], D. Phillip Guertin[1], and C.P.P. Reid[1]

Abstract.--Plant and soil processes within a natural ecosystem interact with surface hydrology through their influence on surface roughness, soil structure, and evaporation, and through their relation with soil biota. In the Southwest, decreases in perennial grass cover and erosion on uplands and stream channels can initiate a decline in watershed condition. Agronomic literature has recognized the role of the vesicular-arbuscular mycorrhizae (VAM) in maintaining soil structure and aggregate stability, seeing beyond the plant nutritional relationship of the host and endophyte. Results confirm the role of VAM hyphae as a primary mechanism in the binding of microaggregates into macroaggregates. Little is understood as to how this relationship functions in natural ecosystems, particularly in terms of its role in the erosion process. This paper describes the perennial grass community and its associated VA-mycorrhizal fungi, quantifies changes in the mycorrhizae and physical soil factors following an erosion event and fire disturbance, and describes the role of VA-mycorrhizal fungi in maintaining soil structure through aggregate stability.

Introduction

Within an ecosystem, plant and soil processes interact to affect surface hydrology through their influence on surface roughness, soil structure, evaporation, and their relationship with below-ground processes. In the Southwest, decreases in perennial grass cover and erosion of uplands can initiate a decline in watershed condition. We recognize that through explicit research and a priori knowledge that the processes that characterize a watershed, such as the geomorphology, hydrology, soil and vegetation, are linked together. But what is not well known are the linkages between these processes, and the drivers that can advance the disruption of this integrated system.

Mycorrhizal fungi act as unique linkages between the biotic and abiotic processes of an ecosystem. Mycorrhizae are symbiotic relationships between host plants and certain fungi. In the case of arbuscule mycorrhizae (AM), the fungi are obligate biotrophs dependent upon the presence of a live host. While the host acts as a source of carbon for the fungi, the plant in turn can receive nutritional benefits and protection from pathogens. Current agronomic literature has described the role of AM in maintaining soil structure and aggregate stability, seeing beyond the plant nutritional relationship(Schrier et al.1997) and describing the role of AM hyphae as a primary mechanism in the binding of microaggregates (Tisdall and Oades, 1982). Yet, little is understood as to how this relationship functions in the wildland ecosystem, particularly in terms of its role in the erosion process.

The goal of this paper is to present the linkages and potential feedback mechanisms between above- and below-ground processes that can lead to the apparent disintegration of watershed condition in a disturbed perennial Southwest grassland (figure 1). This paper presents first year results following treatment application and the 1998 monsoon season (95.6 mm of rainfall).

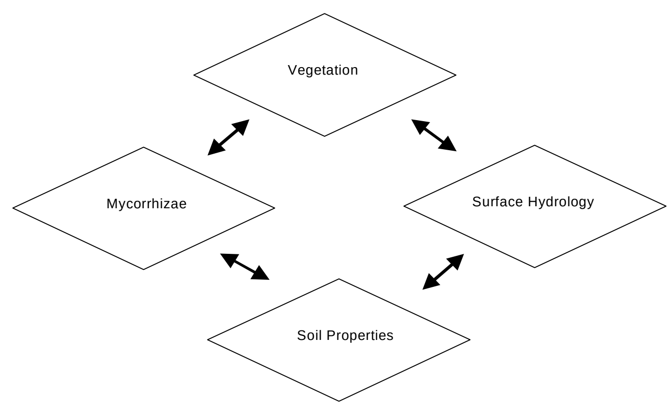

Figure 1. Schematic diagram of integrated processes which impact watershed condition.

The Study

The study area is a small watershed located in Elgin, Arizona. The perennial grassland community contains native grasses represented primarily by the *Eragrostis*, *Bouteloua* and *Muhlenbergia* genera. A variety of shrubs, cacti, and trees are also present. The soil is a relatively deep gravelly loam, with permeability characterized as moderate to slow (0.06 - 0.2 $inhr^{-1}$) and a high shrink-swell potential within the surface layer (SCS Soil Survey for Santa Cruz Co., and parts of Cochise and Pima Cos., Az.)

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The study is a randomized complete block (block = replicate) with a split-plot design. Six blocks each containing four permanent runoff subplots with sediment pans were established. Four treatments were randomly applied: simulated erosion, prescribed burn (late spring), simulation and burn(simulated erosion following the prescribed burn), and a control. Following the application of the burn treatment, the plots assigned simulated erosion were treated with a rotating-boom rainfall simulator at a rate of 2.5 $inhr^{-1}$ for 40 minutes. Twelve permanent sampling points were systematically established within each subplot and sampled annually following the monsoon season (early fall). All tests of hypotheses for treatment effect were evaluated at a level of statistical significance of $p \leq 0.05$.

Treatment Effect on Plant Properties

There were no significant differences in mean percent vegetative, cryptogam or rock cover prior to treatment application. Following the first post-treatment growing season both perennial grass and annual herbaceous cover significantly changed, reflecting treatment effects. Burned plots had significantly lower mean percent perennial grass cover. In addition, mean annual herbaceous cover was significantly higher within the simulation and burn treatment compared with the control (figure 2). There were also significant decreases in perennial grass basal area among the burned plots, 185.3 cm^2 (prescribed burn) and 24.7 cm^2 (simulation and burn), as well as between burned and unburned. There was no significant difference in basal area among the control (254.8 cm^2) and simulated erosion (319.8 cm^2) treatments. The significant decreases in perennial grass cover with concurrent increases in annual cover within the burned plots lead to questions regarding the stability of the highly disturbed community.

Treatment Effect on Soil Properties

There were no significant treatment effects on either particle size distribution or percent stable aggregates (aggregate stability) following the first season. Given the stable aggregates were 0.3 mm or smaller, the wet sieving method used to evaluate aggregate stability may not be appropriate to detect differences. The burned treatments showed significant differences in both bulk density and surface infiltration rates compared to the unburned. The burned treatments had significantly higher bulk density for the top 10 cm of the soil profile than the control, but the simulated erosion treatment did not differ significantly from any of the treatments (figure 3). Given the changes in the bulk density measurements, it was not surprising to see similar patterns in the results for surface infiltration rates. As expected, the burned treatments had significantly lower rates than the unburned treatments.

Treatment Effect on Mycorrhizal Fungi

Changes within the mycorrhizal fungal community were evaluated by the presence of spores and fungal biomass. Spores, because of their importance as inoculm for host plants, and fungal biomass because of its role as a soil binder. Within the bulk soil, mean AM spore number

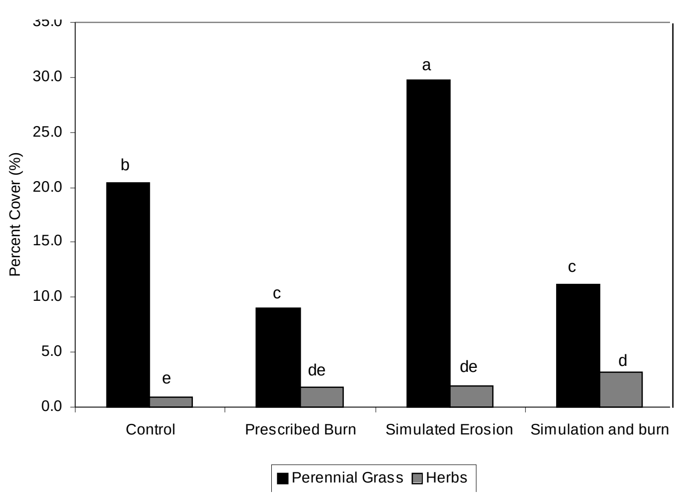

Figure 2. A comparison among treatments: percent cover of perennial grass and annual herbaceous plants.

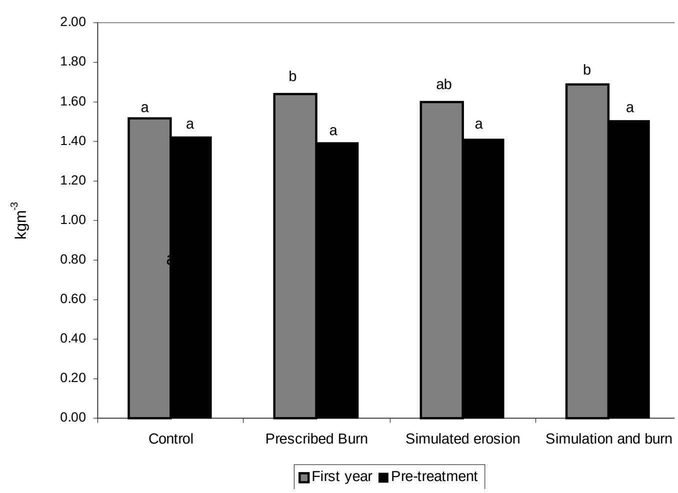

Figure 3. A comparison among treatments: changes in bulk density.

was significantly greater in unburned treatments compared to the burned. Within the sediment pans, mean spore counts appeared to be reflective sediment yields. There was a significantly lower mean spore count within the sediment from the control compared with the other treatments. Changes in fungal biomass with treatment were also present. Fungal biomass significantly decreased within the surface 5 cm of soil following the simulation and burn treatment, but there were no significant differences among the remaining treatments. However, within the burned treatments there is significantly greater biomass lower in the soil profile, at the 6 to 10 cm depth than for the unburned treatments (figure 4).

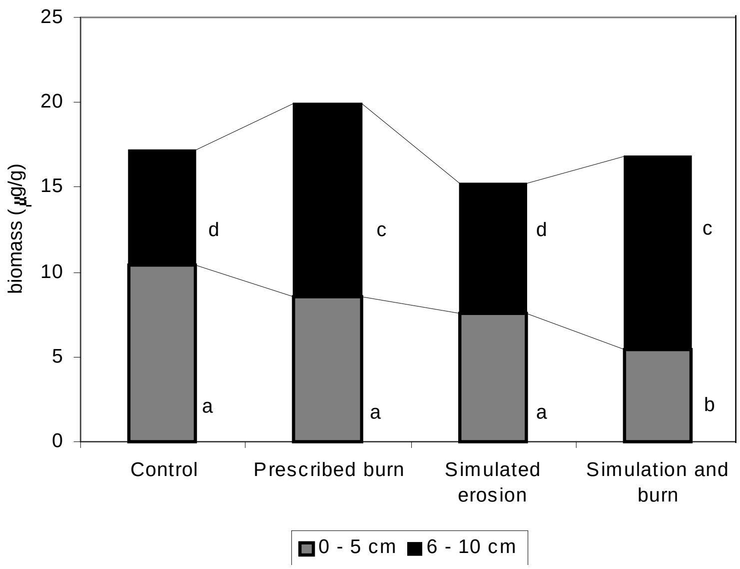

Figure 4. A comparison among treatments: changes in fungal biomass with depth.

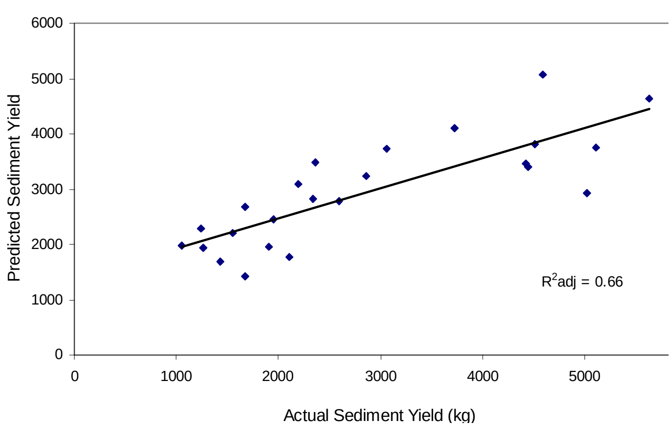

Figure 5. Sediment yield as a function of stable aggregate size, fungal biomass and treatment.

Following the first post-treatment growing season, stable aggregate size (150 mm), fungal biomass, and treatment parameters were significant predictors of sediment yield, and helped to describe the important relationship (R^2_{adj} = 0.66) between biotic parameters and sediment yield (figure 5).

Treatment Effect on Surface Hydrologic Properties

Given the changes within the plant and fungal communities and soil structure, changes in surface hydrology were expected. Using total runoff (volume within the sediment pans) and total sediment yield (within the sediment pan) captured during the monsoon season as measures of hydrologic change, there a clear indications of treatment effect.

Total runoff was significantly greater from the plots which had been treated with the rainfall simulator compared to those which had not, but runoff among the simulator plots was not significantly different. Monsoonal runoff was significantly greater for the simulation and burn treatment compared to the other treatments (figure 6). These results were not unexpected given that the simulator treatment delivered approximately 40% of the total monsoonal rainfall for 1998. Total sediment yield was highly variable among the treatments (figure 7). Sediment yield was significantly greater for the simulation and burn treatment compared to the control. However, the simula-

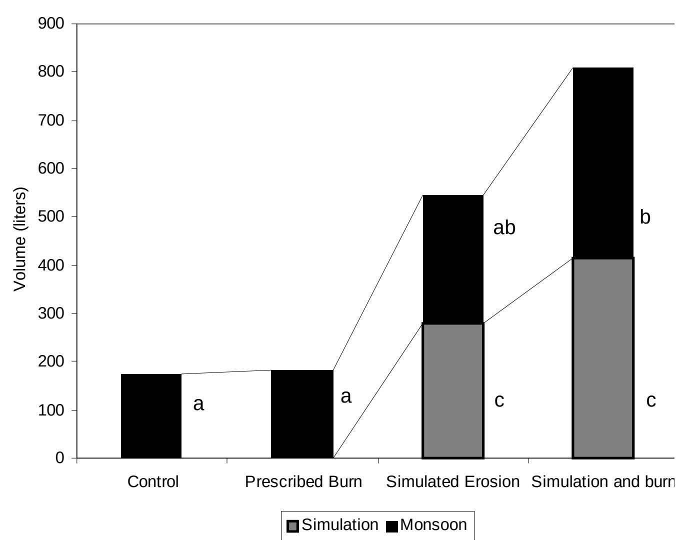

Figure 6. A comparison among treatments: total runoff volume from July 1, 1998 to October 1, 1998. The values do not take in to account losses due to evaporation or pan leakage.

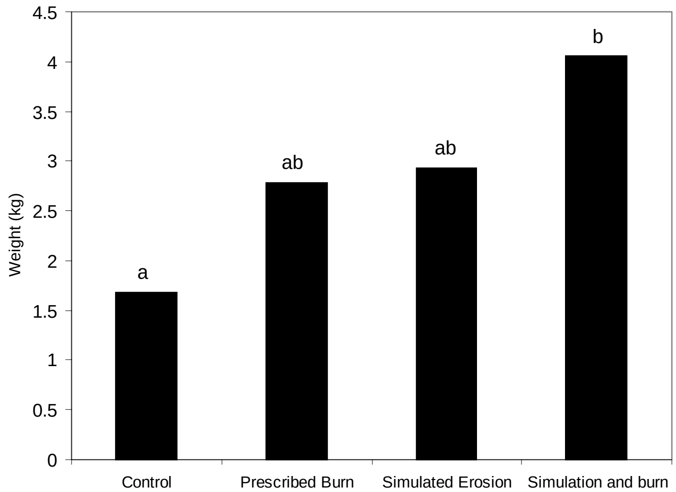

Figure 7. A comparison among treatments: sediment yield between July to October 1998.

tion and burn treatment was not significantly different from the remaining treatments.

Conclusion

The burned plots showed the most dramatic changes in the first year following treatment. These plots had lowered perennial plant cover and basal area, with a shift to increased annual cover. The presence of mycorrhizal fungi was also diminished within the burned plots, most significantly within the simulation and burn treatment. Moreover, the burned plots also displayed the highest values for bulk density, the slowest values for surface infiltration rates, and the greatest sediment yield. It is important to note that although the sediment yield was not significantly different between the prescribed burn and the simulated erosion treatments, the simulated erosion treatment had been subjected to a greater amount of rainfall (approximately 40 %).

Although fire is a natural disturbance within these ecosystems, the removal of host plants significantly diminishes the presence of obligate biotrophic fungi (AM), which are significant contributors to the stability of surface soil structure and plant community dynamics. Moreover, the disruption of soil structure or vegetative cover can directly affect hillslope hydrology and erosion dynamics. The functioning of the watershed is dependent upon the concomitant ecosystem processes operating within it, as well as the linkages between them. From these initial findings it appears that the interaction of prescribed fire and monsoonal rainfall have the potential to create an environment in which significant changes within the plant, mycorrhizae, soil, and surface hydrologic processes may occur, and thereby lead to questions about watershed condition.

Acknowledgments

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Tree Production in Desert Regions Using Effluent and Water Harvesting

Martin M. Karpiscak[1] and Gerald J. Gottfried[2]

Abstract.—Treated municipal effluent combined with water harvesting can be used for land restoration and enhancing the growth of important riparian tree species. Paired studies in Arizona are assessing the potential of growing trees using mixtures of effluent and potable water. Trees are grown in the field and in containers. Initial results from the field show high survival for four of the six species; cottonwood and willow had rapid growth.

Introduction

In the Southwestern United States, Israel, and many other arid areas of the world, the prudent use of limited water supplies is critical for improving the management of desert environments. Growing competition for water has heightened interest in a variety of approaches for increasing available water. As the major metropolitan regions in arid areas continue to grow, the availability and volume of treated effluent have increased. This treated wastewater combined with harvested rainfall can be used for the restoration of degraded lands, and the growth of vegetation having commercial and environmental value may be possible.

It is believed that arboreal species take up large amounts of water and minerals, serving as effective biological sieves that inhibit recharge of the wastewater to the underground aquifer and reduce accumulation of minerals in the soil and the underground aquifer (Nelson 1995). The use of sewage water for irrigation has been shown to increase tree growth (Attiwill and Cromer 1982; Bialkirwicz 1978; Cromer et al. 1983; Dighton and Jones 1991; Stewart and Flinn 1984) and to increase the amount of minerals in the foliage of the plants (Brister and Schultz 1981, Neilsen et al. 1989). Results from Australia, however, (Hopmans et al. 1990) indicate that tree species differ greatly in their ability to absorb minerals when irrigated with municipal effluent.

The reuse of treated water as a source of supplemental water for constructed wetlands and maintaining riparian areas in Arizona is an important management alternative (Karpiscak et al.1996). Water harvesting techniques and appropriate use of treated effluent may provide opportunities for the rehabilitation and preservation of important riparian communities where irrigation and water diversion have lowered local water tables.

Studies established in the 1990s in the U.S. and Israel are evaluating the potential of growing trees using combinations of potable and effluent water supplemented by harvested rainwater for irrigation. The studies are part of a collaborative research program among The University of Arizona, the Volcani Center at Bet-Dagan, Israel, and the USDA Forest Service.

The major hypothesis of this research effort is that the use of reclaimed municipal effluent for irrigation of arboreal species will increase the growth rate of these plants in arid areas compared to irrigation with fresh water. A second hypothesis is that environmentally, there is no critical uptake of harmful constituents from the effluent by the plants or any adverse impacts to the soil irrigated with effluent.

Specific objectives of the research study both at The University of Arizona and in Israel are: (1) to study the effects of effluent irrigation on tree growth and production, (2) to determine the benefits of water harvesting techniques used in conjunction with wastewater irrigation on trees, and (3) to evaluate the ability of the selected tree species to absorb minerals and pollutants found in effluent.

This paper describes initial observations from the Arizona study and focuses on the tree survival rates and growth under different irrigation regimes. Detailed findings on water harvesting and soil and plant tissue analyses will be presented in subsequent reports. Project results from the Israeli study will be published in separate papers. No statistical analyses will be presented in this preliminary report; however, the 5% level will be used in the future to determine significance in growth among treatments.

Methods

The 1.3 ha field plot is located at a University of Arizona research farm. The plot consists of 13 rows with 5 m wide

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water harvesting catchments graded perpendicular to the slope of the field. Separate drip lines along each row allow irrigation with a combination of reclaimed and potable water. Both lines are equipped with timers to ensure that proper amounts of irrigation water are provided to the individual plants if harvested rainfall is not available. Irrigation treatments reflecting five mixtures of water are applied. The five mixtures, expressed as % fresh water:% reclaimed municipal effluent are: 100:0, 75:25, 50:50, 25:75 and 0:100. Total water applied by the irrigation system is adjusted based on seasonal evapotranspirational losses. Plots are periodically treated by application of herbicides or by cultivation to control weeds.

Species planted include velvet ash (*Fraxinus velutina*), black willow (*Salix nigra*), Fremont cottonwood (*Populus fremontii*), Arizona sycamore (*Platanus wrightii*), eucalyptus (*Eucalyptus camaldulensis*) and Mondell pine (*Pinus eldarica*). Fifty individuals of each of the tree species were placed in a randomized complete block design along the rows. The first four species were selected because they are important riparian species in the Southwest. They were grown from pole cuttings. Mondell pine and eucalyptus are popular ornamental species in major urban areas of Arizona and were planted as transplants from plastic sleeves and 10 cm pots, respectively. The same species of eucalyptus is used in the experiments in Israel.

Planting of all species in the field was completed in December 1996. Ash and sycamore were replanted because of poor survival after the initial planting. The trees initially were fenced to protect them from rabbits and rodents until they had achieved adequate growth and size to survive browsing. Height measurements of pine and eucalyptus were begun in December 1996 and, of the other four species, in May 1997. Tree diameter at breast height measurements began in September 1997.

Soil samples were collected prior to planting in 1996 and again in December 1997. The first tissue samples will be collected from the field plants in late 1999 after they have achieved sufficient size to sustain the harvesting of 100 to 125 grams of leaf and stem tissue. The tissues will be analyzed for selected parameters such as sodium, chloride, phosphate, nitrate and copper.

A concurrent study was performed in containers to avoid the influence of differences in field soils. Experiments began in April 1997 at the Constructed Ecosystems Research Facility (CERF), about 0.8 km from the field plot when 120 plastic 120-liter containers were filled with clean mortar sand (<1 mm grain size). Ten replicates of each of the same six tree species as in the field plot were planted randomly in the containers. Pine and eucalyptus were planted as seedlings in May 1997; cottonwood, black willow, ash and sycamore were planted as poles, the first two species in June 1997, and the second in August 1997. Because of poor survival, cottonwood was replanted in November 1997.

Drip lines were installed to each of the containers, one to deliver fresh or potable water and one to deliver treated effluent. Emitters are placed randomly and each container is supplied with either 100% fresh water or 100% effluent water. The lines were equipped with timers so that each tree received an equal amount of effluent or fresh water as designated. No water mixtures were tested due to the logistics of installing more irrigation lines and maintaining large numbers of trees in containers.

Results and Discussion

Survival

Tree survival at the field site in December 1998 is shown in figure 1. Nearly 100% survival was achieved for pine, cottonwood and willow, regardless of the water mix. Ash had about an 80% survival rate overall while sycamore had about 60%. These rates for ash and sycamore are higher than the 30% and 50% survival rates observed in August 1997. It appears that pole plants of these two species are slower to take root and show less growth than willow and cottonwood. Eucalyptus had the lowest overall survival rate with mortality increasing between August 1997 and December 1998.

There appears to be little correlation between a species' survival rate and irrigation treatment in the field. All

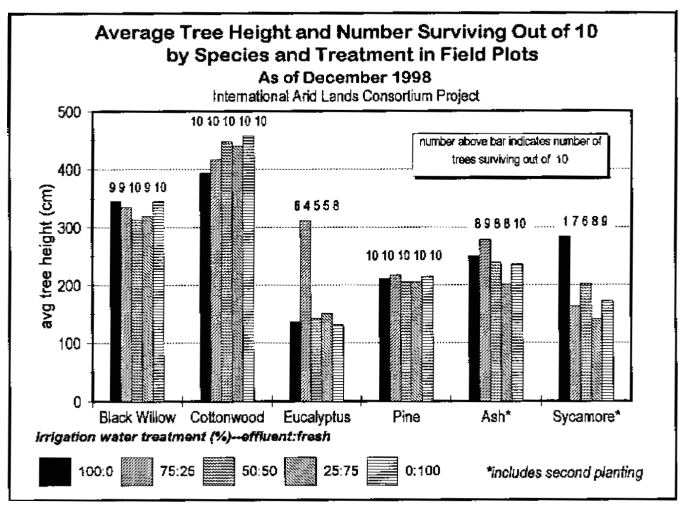

Figure 1. Average Tree Height and Number Surviving Out of 10 by Species and Treatment in Field Plots as of December 1998.

cottonwood and pine and most willows and ash survived regardless of irrigation scheme. For sycamore, however, the survival rate was only 10% when irrigated solely with effluent, but 90% when irrigated with 100% fresh water. Eucalyptus transplants had inconsistent survival responses to effluent irrigation, varying from 40% when treated with 75% effluent to 80% when supplied with only fresh water. However, in all instances in which there were differences in survival, plants supplied solely with fresh water appeared to have a slightly higher survival rate.

Survival data for the container trees are shown in figure 2. Willow, cottonwood and eucalyptus survival rates were similar but not identical, whether irrigated with fresh or effluent water. There was a slightly reduced survival for willow and cottonwood when irrigated with effluent. All eucalyptus seedlings survived, whether irrigated with fresh or effluent water. Pine appeared to have higher survival (100%) when irrigated with fresh water while ash did better (60%) with effluent water. No sycamore plants appeared to be alive in the containers in December 1998 (fig. 2).

One of the most interesting observations was the failure of the cottonwood pole plants (some 60 cuttings) to become established in the containers during the initial planting, in contrast to the nearly 100% survival obtained in the field. This finding also is in contrast to the survival of similar transplants in the gravel-filled subsurface constructed wetland cells at CERF. The survival rate for fresh water-irrigated container-grown vs. field-grown pine trees is 20% compared to 100%, a large difference. Sycamore also shows a large difference in survival: no container-grown trees survived in December 1998 vs. about 60% of field-grown trees (figs. 1 and 2).

Growth

Cottonwood and black willow grew rapidly in the field plots. Many of the cottonwood trees were over 400 cm in height by December 1998 (fig. 1). Except for eucalyptus and sycamore, tree heights were more or less the same for a single species independent of the irrigation regime (fig. 1). Eucalyptus irrigated with 75% effluent:25% fresh water were almost twice as high (300 cm vs. 130 cm) as eucalyptus irrigated with the other treatments and sycamore grew to almost 300 cm when irrigated with 100% effluent.

As of December 1998, all species except eucalyptus showed more growth in the field than in the containers. This is due in part to the 6-month difference in planting time, but also perhaps to the difference in growing media. All container-grown species irrigated with effluent grew taller than those irrigated with fresh water (fig. 3). Eucalyptus seems to grow better in the sand in the containers than in the field (fig. 3). However, some individual eucalyptus trees in the field plots showed rapid growth. This finding supports results found by the Israeli team members. Pine initially responded well both in the field and in containers, but many of the container-grown trees have shown stress. Because of the need to keep the sand moist to establish other plants, the pines may have been over watered.

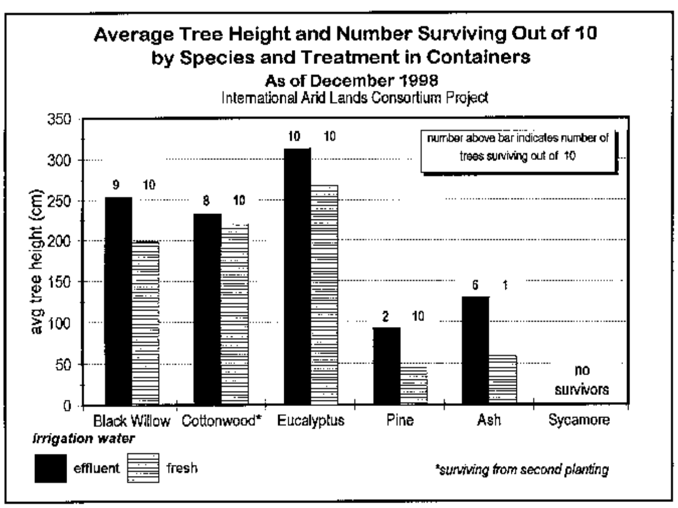

Figure 2. Average Tree Height and Number Surviving Out of 10 by Species and Treatment in Containers as of December 1998.

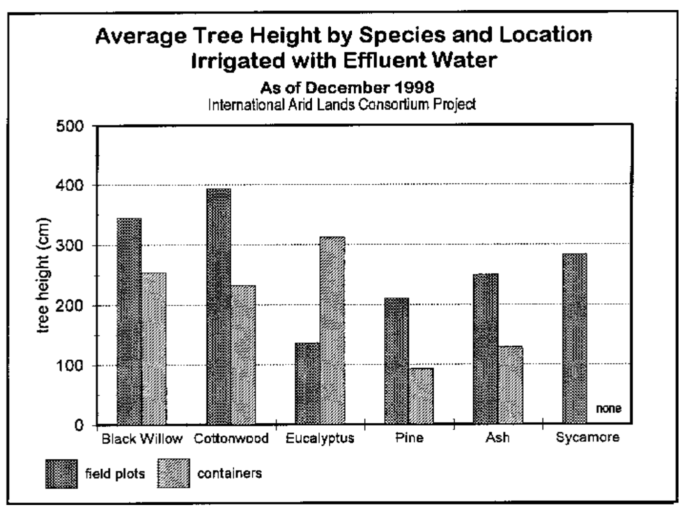

Figure 3. Average Tree Height by Species and Location Irrigated with Effluent Water as of December 1998.

Conclusions

Field tree survival rates in Arizona were 80% to 100% for most species. Initial survival rates for container-grown trees varied from those grown in the field. Sycamore pole-plants appear to have a higher rate of survival in field plots when supplied with fresh water, while ash in the containers appears to be the only species to have a higher survival rate when irrigated with effluent. Overall average growth appears best in cottonwood and willow grown in the field. The use of effluent may reduce survival rates slightly, but it also may stimulate the growth of some species once established because of nutrients found in the wastewater. However, this preliminary observation still needs to be statistically evaluated.

The use of supplemental irrigation water for trees in arid environments can achieve rapid establishment and growth of some trees such as cottonwood, willow and some eucalyptus. Initial results have shown that some species, especially cottonwood and willow in the field, grew to heights of 230 to 300 cm within 12 months of planting. In Arizona, all species except eucalyptus grew more in the field plots compared to growth in the containers when irrigated with effluent (fig. 3). These results indicate the potential for use of effluent for growing selected tree crops for wood production, aesthetics and environmental benefits.

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Effects of Mesquite Control and Mulching Treatments on Herbage Production on Semiarid Shrub-Grasslands

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Abstract.—Effects of complete removal of mesquite overstory, complete removal of mesquite overstory with control of post-treatment sprouts, and retention of the mesquite overstory as a control on herbage production are described. Mulching treatments included applications of a chip mulch, a commercial compost, lopped-and-scattered mesquite branchwood, and an untreated control. Preliminary results of this study provide an insight on the changes in herbage production as a result of mesquite overstory control and the addition of mulches.

Introduction

Encroachment of woody species on rangelands in the southwestern United States has been observed since the early 1900s. Increases in woody species such as mesquite (*Prosopis* spp.) have been a long-time concern to rangeland managers and livestock producers because the encroachment has often reduced herbage production and, therefore, livestock production. This phenomenon has been documented in studies that have observed, conversely, that total grass density increased and soil erosion decreased on sites where mesquite was controlled (Heitschmidt and Dowhower 1991, Martin and Morton 1993). The encroachment of mesquite and other woody species onto rangelands has been attributed to over-grazing, reduced fire frequency, and climate change.

The intent of this study is to determine the changes in herbage production, if any occur, in response to mesquite overstory control, the addition of mulches, and combinations thereof. Such information could be then incorporated into management practices to enhance the productivity and stewardship of semi-desert grass-shrub rangelands in the future. Preliminary results of the study are presented in this paper.

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Study Description

Study Area

The study area was the Santa Rita Experimental Range, approximately 50 km south of Tucson, Arizona. The experimental range, established in 1903, encompasses nearly 21,500 ha that are representative of the semi-desert grass-shrub rangelands in southern Arizona, New Mexico and Texas. The range is located on a broad sloping bajada cut by shallow washes draining northwest into the Santa Cruz River basin. Soils are composed of Pleistocene alluvium that are formed from sloping fans extending from the Santa Rita Mountains to the Santa Cruz River Valley (Martin and Reynolds 1973). The climate is typically arid: precipitation is sparse, relative humidity is low, and high winds occurring during the spring can be desiccating. Precipitation, about 250 mm at 900 m elevation, increasing to 500 mm at 1,370 m, is mostly rainfall, with 60% occurring between July and September. There are two growing seasons for herbaceous plants: one occurs in early spring when the temperatures become favorable, while the another is late summer or early fall when the rains begin and end the summer dry season.

Woody vegetation on the Santa Rita Experimental Range is dominated by stands of velvet mesquite (*Prosopis velutina)*. An increase in shrubs such as velvet mesquite, cholla and prickly pear cactus (*Opuntia* spp.), and burroweed (*Haplopappus tenuisectus)* has been observed on the range since the early 1900s. The dominant grass species is Lehmann lovegrass *(Eragrostis lehmanniana*), an introduced species that was first planted at the Santa Rita Experimental Range in 1937. Black grama (*Bouteloua eriopoda*) and Arizona cottontop (*Digitaria californica*) are also found intermixed.

Study Design and Treatments

The study design consisted of 60, 5 x 5 m, plots, with a 1 m buffer between them, excluded from large herbivores. The plots were blocked for subsequent statistical analysis based on information from a pretreatment overstory inventory; the treatments were then randomly assigned to the plots.

The treatments, applied in July 1995, consisted of three overstory treatments and four mulching treatments within each of the overstory treatments. Each combination of overstory and mulching treatments was replicated 5 times. The three overstory treatments were complete removal of mesquite overstory, complete removal of mesquite overstory with control of post-treatment sprouts in July 1997, and an untreated control. The mulching treatments included applications of a chip mulch, a commercial compost, lopped-and-scattered mesquite branchwood, and a control. The chip mulch, derived from chipping the cut mesquite branchwood, was distributed on the plots to a depth of 15 to 25 mm on the plots. The commercial compost was fir-based with 0.5% nitrogen, 0.1% iron, and 0.2% sulfur; approximately 0.25 m^3 of compost was applied to the plots. The lopped-and-scattered mesquite branchwood was spread in a manner to completely cover the plot.

Data Collection and Analysis

A pretreatment estimate of herbage production was made in June 1995 to provide a point-of-reference for post-treatment estimates. Post-treatment herbage production was estimated biannually (spring and fall) during May and October, respectively, from 1996 to 1998. Herbage production was estimated by the weight-estimate method (Pechanec and Pickford 1937) on 9.6 square-foot sample plots. Collected samples were then allowed to dry. Once completely dried, the herbage samples were separated by plant species, weighed, and extrapolated to pounds per acre.

Analyses of variance were made to determine if statistically significant differences occurred in post-treatment herbage production among the overstory treatments, mulching treatments, and years following treatment; production of early (spring) growers and late (fall) growers were analyzed separately. Tukey-Kramer HSD was used to determine which treatments had a significantly different effects on herbage production. All statistical analyses were evaluated at a 0.05 level of significance.

Results and Discussion

Pretreatment herbage production (including a mixture of early and late growers) was approximately 930 kg / ha. Average post-treatment production of early growers on the control plots was 525 kg / ha, and average post-treatment production of late growers was 2,600 kg / ha.

Overstory treatments had no effect on either early or late herbage production over the initial 4-year post-treatment study period. There were no differences in the production of early growers among the mulching treatments. However, there was a difference in the production of late growers; this difference was between the lopped-and-scattered mesquite branchwood and the control. Herbage production was lower on plots with the lopped-and-scatter mulching treatment than on the control plots, suggesting that the former treatment might have suppressed the growth of late growers.

A difference was found in early and late herbage production in the post-treatment years of the study. The greatest difference the production of early growers was found between 1995 and 1996, this being a reduction in herbage production from pre-treatment in 1995 to post-treatment in 1996. Production of early growers began to increase with each year after 1996, but not to the level of production in 1995. The largest difference in production of late growers occurred between 1995 and 1997. Late herbage production declined with each year until 1998, at which time there was an increase in production, but again not enough to bring the level of production up to the pre-treatment level.

Effects of the treatments on changes in soil properties will be evaluated in the future. It is possible that a linkage between herbage production and soil properties can be identified to help in explaining the initial results of the study reported here.

Conclusions

As encroachment of mesquite shrubs continues to be a concern on many southwestern rangelands, understanding the processes of semi-arid shrub-grassland ecosystems has become an important focus of research. This study seeks to determine the effects of mesquite overstory control and the modification of soil properties by adding mulches on herbage production. It is hoped that further insights of the effects of the treatments on herbage production can be obtained with the planned analyses of changes in soil properties following the treatments.

Future evaluations of precipitation regimes might also prove useful; the study period included a prolonged drought period (with departures in average annual precipitation of 30% or more), which might have masked the treatment effects. Cable (1975, 1976) found that 65-to-90% of the year-to-year variability in herbage production on semi-arid shrub-grasslands can be attributed to the amount of precipitation. The effects of the treatments, therefore, may become more apparent as the study continues. In similar studies where mesquite was controlled and herbage production was monitored, it took 3 years and longer before changes in perennial grass densities became evident (Martin 1975, Martin and Morton 1993).

One explanation for the observed reduction in herbage production after the treatments could be the alteration of microclimates as a result of the elimination of the mesquite overstory. A mesquite overstory can function to improve soil conditions under their canopies by a redistribution of nutrient ions from areas beyond their canopies to areas beneath their canopies (Tiedemann and Klemmedson 1973); removal of this overstory, therefore, could have the opposite effect.

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Mesquite: A Multi-Purpose Species in Two Locations of San Luis Potosi, Mexico

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Abstract.—The mesquite woodland distributed in approximately 200,000 ha in Llanos de Angostura, and Pozo del Carmen, San Luis Potosi, represents a main source of firewood, construction material, honey, and forage for the rural people that inhabit part of the lowlands of the hydrological region RH26 and RH37. Firewood collection in this region averages 142 m^3 / week. Most of this wood is used by brick makers to fuel the kilns, and for domestic purposes (i.e., cooking and heating). Mesquite pod yields fluctuate by year. A three-year study, sampling pod production in two native stands located in Llanos de Angostura having 75 trees ha^{-1} (29 trees less than 15 cm and 46 trees greater than 15 cm in basal diameter) and Pozos del Carmen, with 450 trees ha^{-1} greater than 15 cm in basal diameter, indicated an annual pod yield of 500 to 900 kg ha^{-1}. Livestock industry is the major consumer of mesquite pods as forage and occasionally local people consume it boiled or grilled as candies. The mesquite gum as a substitute of the Arabic gum represents a potential economical income for the rural people of this region. Even though mesquite gum is generally produced under abnormal conditions (i.e., very dry episodes) the region has the potential to produce at least 10 metric tons of gum per year. A long-term management strategy of the mesquite woodlands in San Luis Potosi is necessary to establish silvicultural management techniques based on structure of the vegetation, pod production, and rates of growth. Currently, a project is being carried out to develop techniques for reforestation of mesquite in semiarid areas, and carry out thinnings of suppressed trees, and branch pruning on native young stands to evaluate its behavior in growth. Mesquite woodlands in San Luis Potosi continue to be destroyed and more careful management needs to be done to ensure future production and watershed protection of this resource.

Introduction

The management of watershed resources to produce more than one product or amenity is a common practice in many of the Mexican basins. The state of San Luis Potosi, located in central Mexico is bisected by two large hydrological regions RH37 (35 167 km^2) and RH26 (27 140 km^2), each one encompassed by several watersheds embedded in dominant semi-arid to semi-humid conditions.

Rural populations living in some of the watersheds depend upon a variety of resources that are produced in upland and lowland areas. However, intensive livestock grazing, changes in land use, wood harvesting, and overexploitation of underground water for irrigation purposes are leading to their degradation.

The mesquite woodland is one of the dominant vegetation types in these watersheds and has been intensively used during the last hundred years (Rzedowski 1966). Changes in land use have traditionally impacted native mesquite woodland stands mainly through the complete removal of vegetation for rain-fed and irrigated agricultural lands. Some mesquite woodland relicts currently covering an area of 50,000 ha in the region are highly disturbed, and they are intensively used by rural people as a source of firewood, furniture wood, timber, forage, and nectar for honey bees.

The integration of watershed management with multiple use of mesquite woodlands in San Luis Potosi demands a careful evaluation of the capability of mesquite trees to provide the amenities at the rate currently demanded by local people

Methodology

The study area is located in the watershed "Rio Verde 26CH" (21° 25'-22° 42'N; 99° 15'-100° 46'W) covering a total area of 9189 km^2 (figure 1). Northern, eastern, and western sections of this watershed are bordered by watersheds belonging to hydrological region RH37. Environmental conditions of this watershed are highly variable. The upper section of the watershed is characterized by semiarid conditions, vegetation is dominated by desert shrublands, grasslands, and mesquite woodlands; total annual precipitation ranges between 300 to 400 mm and precipitation increases to 500 mm at the northern and central portion of the watershed where mesquite density increases.

Two sites located in watershed 26CH were selected for this study, "Llanos de Angostura", Rioverde (22° 03' 53" N, 100° 01' 19" W, 1051 m elevation), and "Pozo del Carmen", Armadillo de los Infante (22° 19' 30"N, 1000, 36' 18"W, 1590 m elevation). Structure of vegetation and gum production were obtained using plots of 4 x 30 m laid along a line transect and a point-centered quarter method. Each single mesquite tree was measured to get diameter at

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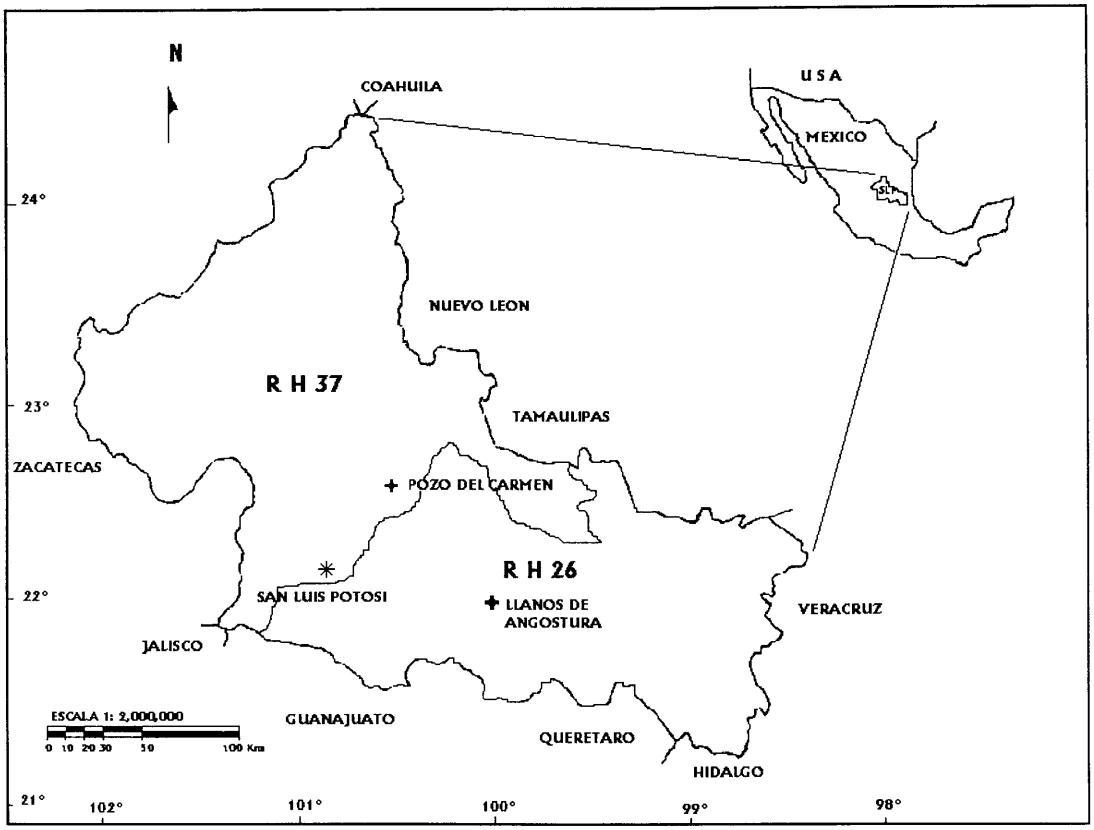

Figure 1. Location of studied mesquite woodland stands in San Luis Potosi, Mexico.

root collar, number of stems and main branches, height, canopy cover, mean distance between trees, and firewood volume.

Density, canopy cover, relative frequency, and average distance between trees were obtained according to Muller-Dombois and Ellenberg (1974).

A permanent plot of 162 m x 492 m (7.97 ha) with dominant mesquite woodland vegetation was established. Twenty-six trees of different size were randomly selected in the plot in order to determine gum and pod yield from a stand base.

Exuding gum was removed from existing wounds on the tree using a sharp knife and then cleaned and weighted with an electronic scale. Similarly, fallen dry pods were collected on the ground and evaluated for each of the selected trees.

Gum and pod yield were statistically described (i.e., mean, standard deviation, confidence intervals). Single regression analyses were carried out for both gum and pod production, and other tree variables (i.e., total height, canopy cover, size diameter).

Associations of gum collectors, honey bee producers, brick makers, firewood cutters, and woodworkers were interviewed in the region to determine the amount of resources that were required to fulfill each need.

Results

Structure of Vegetation

The structural analysis indicated that the mesquite stands in Llanos de Angostura have an average density of 248 trees ha^{-1}, arranged in a prominent contagious distribution. In this locality, 11 size classes were identified, but dominant size-class diameters were 0 – 4.9 and 5.0 – 9.9 cm with frequencies of 43% and 27%, respectively (figure 2). On average, the mesquite canopy covers 48% of the sampled area, tree height ranged between 3 to 7 m, and

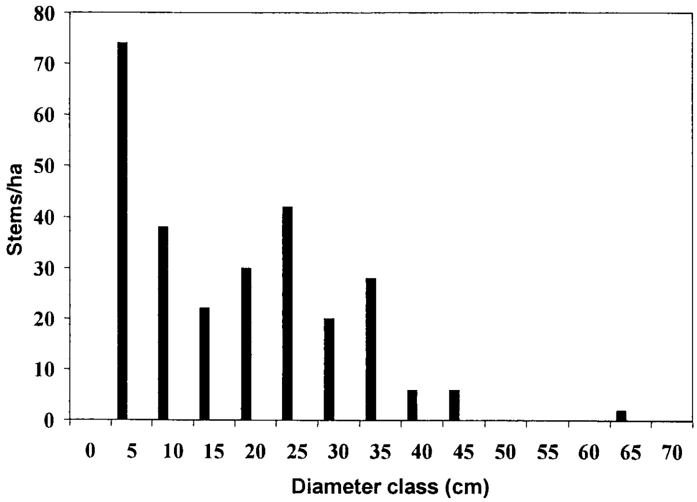

Figure 2. Diameter-size distribution of a mesquite woodland stand in "Llanos de Angostura", Rioverde, San Luis Potosi, Mexico.

mean distance between trees was 11.6 m. Tree density (610 trees ha^{-1}) was comparatively higher in the Pozo del Carmen stand, and tree height fluctuated between 5 to 8 m with a basal diameter of 30.5 to 140 cm.

Size-class diameter distribution, apparently was influenced by the capability of mesquite trees to coppice, as evidenced by the dominance of young trees mostly from resprouts.

Gum Production

Gum production per tree has been monitored for three consecutive years (1997, 1998, and 1999). In 1997, gum production was greater in August and lowest or none in November. No significant gum production was measured in 1998 at the study site, and it has been relatively low during the present year (January-April of 1999) (table 1).

Gum production does not occur simultaneously on all trees. Some trees may start exuding early during the drought season, some during the late drought season and some never produce. Only, about 50% of the sampled trees could be classified as gum producers.

Regression analyses did not show any significant relation (p≥0.05) between gum production per tree (dependent variable) and height, canopy cover, or basal diameter (independent variables). Gum production may be less in large vigorous trees as compared to smaller size weaker trees. Likewise, gum production is higher at sites with shallow soils having gypsic or petrocalcic diagnostic horizons, usually showing low water holding capacity as compared to deeper soils. Natural wounds due to insects or other biotic or abiotic factors enhanced by dry weather conditions, stresses the tree, which favors gum secretion. Once gum has been removed by natural or artificial means, gum secretion continues appearing through the dry period.

In the same region, gum production may change significantly from one place to another. In 1998, it was not detected a measurable amount of gum in the study site, however, in other places of the same region a total amount of 1.0 metric ton of gum was reported. Previous reports

Table 1. Gum production for the years 1997, 1998, and 1999 from selected trees of "Llanos de Angostura, Rioverde, S.L.P. Mex.

Basal Diameter Class (cm)	Frequency (Trees ha^{-1})	1977			1999	
		February Gum Yield (g ha^{-1})	August Gum Yield (g ha^{-1})	[a] November Gum Yield (g ha^{-1})	January Gum Yield (g ha^{-1})	April Gum Yield (g ha^{-1})
10.1-15	22	0.0	57.2	NC	29.7	0.0
15.1-20	30	54.2	0.0	NC	4.4	0.0
20.1-25	22	214.7	182.0	NC	91.3	20.5
25.1-30	20	22.74	169.0	NC	37.0	78.0
30.1-35	20	8.18	280.0	NC	14.5	4.82
35.1-40	8	22.4	10.8	NC	9.22	0.0
40.1-45	6	0.0	0.0	NC	9.0	0.0
45.1-50	0	0.0	0.0	NC	0.0	0.0
50.1-55	2	4.16	6.40	NC	0.0	0.0
Total	126	326.4	705.4	NC	195.1	103.3

[a] *NC: Non-Commercial, gum was present but in amounts too low to be quantified.*

indicate a production from 3.0 to over 10 metric tons of gum for the region collected in a four-month period. Given the density of mesquite trees and gum production per tree, the study region has the potential to produce at least 60 metric tons per year.

Gum collectors in this region are able to gather from 5 to 7 kg per day of gum in a 10-hour period. The price of gum fluctuates from $ 1.0 to 1.2 U.S per kg. The income earned from this activity represents more than a minimum local wage salary for a person.

Pod Yield

Mesquite pod yields vary considerable by year, species, site, and even among trees of the same species in a given site (Silbert 1988). Pod production has fluctuated in the study area from 10 to 22 kg per tree (Villanueva, 1985). Two years of observations (1997, 1998) have indicated pod yields from 560 to 902 kg ha^{-1} yr^{-1} (table 2). Pod production is mainly used to manufacture concentrated livestock feedstuff, and the remaining is used for other purposes (Galindo and Moya 1986, Silbert 1988).

Table 2. Dry pod yields in 1997 and 1998 in a selected mesquite woodland stand located in Llanos de Angostura, Rioverde, S.L.P., Mexico.

Basal diameter class (cm	Trees ha^{-1}	Sampled trees per class	Pod yield (kg ha^{-1}) 1997	Pod yield (kg ha^{-1}) 1998
10.1 – 15.0	22	1	27.5	111.0
15.1 – 20.0	30	3	270.0	158.0
20.1 – 25.0	22	7	132.0	102.0
25.1 – 30.0	20	5	115.0	119.0
30.1 – 35.0	20	4	235.0	54.0
35.1 – 40.0	8	4	88.4	11.0
40.1 – 45.0	2	1	14.4	4.2
45.1 – 50.0	-	-	-	-
50.1 – 55.0	2	1	19.2	-
Total	126	26	901.5	559.0

Honey Bee Production

The flowering of mesquite in springtime represents an appreciable source of nectar for honey bees. To take advantage of this resource, rural people install beehives in mesquite woodlands to produce honey bee. Average honey bee production during the flowering period is 20 to 24 kg per beehive. However, the nectar of associated vegetation contributes with 10 additional kilograms after the rainy season. Total production per beehive reaches 30 to 34 kg per year. Based on these values, the region has the potential to produce 945 metric tons of honey annually.

Firewood

The exploitation of mesquite woodlands for firewood purposes is one of the main uses provided to this vegetation type. Brick makers with a volume of 4,800 m^3 per year and wood-only households with 2,000 m^3 per year, are the greatest exploiters of mesquite firewood in the region. Mesquite wood represents an inexpensive source of energy for most of the rural people in the region. In other parts of the country, annual firewood demand averages 800 kg per capita (Evans 1984), being over 1.0 metric ton per capita on the region. Firewood collectors supply most of the firewood regional demand. However, due to firewood shortage, currently people are cutting not only dry wood but also green wood. This situation is generating a great negative impact on the preservation of mesquite woodlands in the region, currently being traduced in lower biomass production, poor tree conformation due to resprouting, and the presence of pests and diseases that affect mesquite tree growth.

Furniture

Mesquite wood is highly appreciated in the local furniture industry due to its beauty and durability. In colonial times, this activity was widely dispersed in central Mexico (Galindo and Moya 1986). However, encroachment of mesquite woodland populations due to deforestation for agricultural purposes and other land uses, is making more difficult to find suitable mesquite trees to carry this activity.

In the region, exists a woodworker association integrated by 100 members; 25% of them use mesquite wood for furniture. On average, 300 mesquite trees are cut annually in the region. Selected trees are the biggest ones, having good conformation and apparently sound wood. Considering an average timber volume of 2.0 m^3 per tree, only 30% of that wood will be classified as suitable for furniture purposes, the rest (70%) is considered waste and is used as firewood. Carpenters exploit 600 m^3 of wood per year in the whole area.

Watershed Management Implications

The mesquite woodland in San Luis Potosi, as part of the watershed, represents an important resource from an economical and ecological perspective. Intensive use of this vegetation type, however, is leading to an accelerated degradation of this woodland ecosystem, as evidenced by reduced tree growth, soil loss, and the disappearance of fodder species.

Evaluations of annual pod yield, gum, honey bee, firewood, and wood production in native stands indicates that the mesquite woodland based on a sound management strategy represents a sustainable productive system for the region. Regulatory forest laws, however, based on both short- and long-term biomass production of these woodlands, should be enforced by SEMARNAP (Secretary of Environment, Natural Resources, and Fisheries) and implemented by the "ejidos" (communal lands owned and governed by the village residents) that are the owners and main users of the resource.

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Ecological Transitions in Arizona's Subalpine and Montane Grasslands

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Abstract.—Important components of Southwest forest ecosystem are subalpine and montane grassland communities, Grassland communities provide habitat diversity for wildlife, forage for domestic livestock and wildlife, and contribute to the visual quality of an area. The objectives of this research were to determine if: 1) vegetation attributes and soil-surface cover variables of interest have changed, or if they have maintained equilibrium relative to conditions in 1913 through 1915; and 2) a correlation exists between the ecological diversity-stability hypothesis (Huston 1979, Pimm 1984, McNaughton 1994, Tilman 1994). The hypotheses tested were: 1) subalpine and montane grasslands have changed since 1913 through 1915, specifically, relative native species richness has declined and relative species composition has shifted, while annual and exotic species richness has increased with concurrent increases in exposed soil surface area; and 2) shifts in species composition and increases in species richness and exposed soil surface are not evidence of ecological community stability.

The vegetation attributes of interest are individual species and total plant cover, plant frequency, relative species composition, perennial and annual species richness, alpha and beta diversity, life form, keystone species, and relative abundance of indigenous and exotic species. The soil surface cover variables of interest are total ground cover provided by plants, litter, and rock, and amount of exposed soil surface area.

The years 1913 through 1915 were used as baseline years for comparison with current conditions. These years were chosen because of the availability of a historic data set. This data set was collected during the first range reconnaissance survey conducted on the Apache National Forest and contains quantitative information on vegetation cover and soils surface conditions. Although this information is not pre-EuroAmerican, the question can still be asked, "How does 1913 compare to 1998?" Because this information was collected before livestock management under systematically planned, intensive grazing systems and before organized fire suppression. Using 1913 through 1915 as controls, spatial and temporal changes can be evaluated for the last 85 years. A modification of Daubenmirre's (1959) sampling methodology (Medina 1987) was used to collect vegetative cover data. The covariates were herbivory, fire suppression, and annual precipitation. Statistical analysis included measures of central tendency, Mann Whiney U test, Wilconon paired sample test, Spearmans rank correlation, fitting of resistant lines, canonical correlation, analysis of variance, covariance, and multivariate analysis.

This research related to primary (human) use of Southwestern subalpine and montane grasslands on public lands; domestic livestock grazing. It also provides some needed scientific information concerning structural, functional, and compositional changes in these grasslands over time. This research project provided valuable information about the role of domestic livestock grazing, fire suppression, climatic variations on succession retrogression, validity of intensive grazing management systems, and diversity-stability hypothesis. All of these items provide useful information to help develop judicious and ecologically-oriented management plans.

Snowpack Hydrology in the Southwestern United States: Contributions to Watershed Management

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Abstract.—Less than 10% of the annual precipitation in the Southwestern United States is recovered for use by people; most of the precipitation is lost by evapotranspiration. A large portion of the precipitation that is recovered originates on watersheds in montane forests. Even here, 80% to 90% of the precipitation is currently unavailable to downstream users. The possibility of increasing the amount of recoverable precipitation in this region is greater for snow than rain. A 50-year review of snow hydrology in the Southwestern United States is presented to indicate the possibilities for increasing snowmelt-water yields within integrated watershed management.

Introduction

Less than 10% of the annual precipitation in the Southwestern United States is recovered for use by people; most of the precipitation is lost by evapotranspiration. A large portion of the precipitation that is recovered originates on forested watersheds in mountainous areas, where currently 80% to 90% is unavailable for downstream users. The possibility of increasing the amount of recoverable precipitation from forested watersheds is greater for snow than for rain (Ffolliott et al. 1989, Ffolliott 1993). Snow accumulates throughout the winter, providing a reservoir of water potentially available for downstream use in the spring. If snowmelt-water yields were increased significantly, additional water would be available to refill reservoirs or recharge groundwater aquifers.

Snowpack Conditions

Snowpack conditions in the Southwestern United States are often either excessively high or low in comparison to other regions of the country. Fluctuations in winter precipitation patterns result in a few wet years interspersed with several average and below average years (Diaz 1983). These fluctuations greatly affect the intermittent snowpack buildups on high-elevation forested watersheds. Intermittent snowpacks, which often disappear between successive storms, vary greatly in their contributions to annual water yields and to the flow of water to downstream users.

Forest Management Practices

Forest management practices to increase recoverable water yields from snow include forest thinning and forest overstory clearing (Ffolliott et al. 1989). Various intensities of forest thinning and arrangements, sizes, and patterns of clearing are possible.

Forest Thinning

Inventory-prediction relationships describing snowpack conditions within the region's montane forests of the region indicate that snowpack-water equivalents generally increase as forest densities decrease. With inventory-prediction relationships, watershed managers can prescribe thinning practices to increase snowpack-water equivalents on-site, which will then convert into recoverable water.

Storage-duration values, obtained by adding snowpack-water equivalent measurements from successive sampling dates (Wilm 1948), provide information on the temporal variabilities of snowpack conditions. Maximum-index values indicate high initial storage and slow melt, while minimum-index values indicated low initial storage and rapid melt. Studies have shown that maximum storage-duration values are associated with low forest densities, cool sites, and high elevations, while low storage-duration values are associated with high forest densities, warm sites, and low elevations.

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Clearing

Greater accumulations of snow for possible conversion into recoverable water are available in cleared openings than under forest canopies. The greatest accumulations of snow are in cleared strips and patches with less than 1-1/2H (H = height of adjacent trees) in size. While clearing forest overstories affects snowfall accumulation patterns, the amount of snowfall onto the watershed remains unchanged.

A series of three-dimensional, time-space models that describe snowpack conditions in and adjacent to openings can be used to formulate forest management practices that maximize or minimize the effects of patch cutting on snowpack conditions (Ffolliott 1983). Information from these models is helpful to watershed managers when increased water yields from snowpacks are possible.

Process and Theoretical Studies

Results from process and theoretical studies allow watershed managers to better understand the causal nature of relationships between snowpack conditions and forest overstories. Deposition of intercepted snow in tree canopies has been evaluated with time-lapse imagery to determine the relative significance of snowfall interception in the water budget (Tennyson et al. 1974). Most of the intercepted snow eventually reaches the ground by snowslide, wind erosion, or canopy melt; thus, it does not necessarily represent a significant loss of the water budget.

Loss of snow from a landscape is due to melting of the snowpack or to a combination of melting, evaporation, and sublimation. Factors influencing evaporation and sublimation include site (aspect, slope, etc.), latitude, distance from the ocean, and elevation (Avery et al. 1992). Sublimation rates are higher for more northerly sites, increasingly inland sites, and higher elevations. Studies in the Southwestern United States indicate that snow cover losses, as little as 25% and as much as 70%, are due to melting alone or to a combination of melting, evaporation, and sublimation.

Theoretical studies have centered on synthesis of models to describe short- and long-wave solar radiation exchanges between snowpacks and forest canopies (Bohren and Thorud 1973, Bohren and Barkstrom 1974). These short-wave and long-wave radiation exchanges vary with tree canopy structures. Furthermore, the effects of manipulating forest overstories on short-wave and long-wave solar radiation transfer and the accumulation and subsequent ablation of snowpacks are predictable.

Runoff Efficiencies

One measure of the effects of physiographical and climatological factors on the quantity of snowmelt runoff from a watershed is runoff efficiency, which is the portion of a snowpack's water equivalent that is converted into surface runoff (Solomon at al. 1975). Both fixed and variable factors influence runoff-efficiency values. Fixed factors include slope percent, aspect, soil type and depth, and watershed configuration. Variable factors are year-to-year differences in the rates of snowmelt on the watershed and preceding moisture conditions.

Equations that predict runoff efficiency from variables measured before peak seasonal snowpack accumulation and during the snowmelt-runoff regime are available (Solomon et al. 1975). Watersheds with the greatest peak seasonal snowpack accumulations and at the highest elevations have the most efficient snowmelt-water yields. Consequently, forest management activities implemented to increase snowpack-water equivalents at peak seasonal accumulation have the greatest potential for snowmelt-water yield improvement.

Simulation Models

Snowpack conditions at a point-in-time reflect the combined effects of accumulation, redistribution, and melt processes that occurred before that point-in-time. Simulation models are available to separate the complexities of these processes and to allow for prescription of forest management activities to manipulate snowpack conditions. These simulators are useful in quantifying on-site snowpack accumulation, redistribution, and melt processes within a dynamic framework (Ffolliott and Rasmussen 1979). It is also necessary to know the contributions of the melting snowpacks to streamflow regimes from these high elevation watersheds.

Modification of a snowmelt simulation model for Colorado subalpine forests provides predictions of the contributions of the relatively shallow and intermittent snowpacks in the Southwestern United States to streamflow. This generalized model requires limited knowledge of watershed and snowpack parameters to initialize (Solomon et al. 1976). The driving variables are daily values of maximum and minimum air temperatures, precipitation amounts, and impinging solar radiation loads. Verification of the simulation model on watersheds representing a range of conditions common to high elevation, forested watersheds in the region has been satisfactory. Interrogations of the model provide information on watershed conditions most favorable to increased snowmelt-water yields.

Management Implications

Implementation of forest management practices has increased annual water yields from watersheds in the mountains of the Southwestern United States from 5% to 100% (Ffolliott et al. 1989, Ffolliott 1993). Larger increases occur in wet years, when the soil mantle was recharged before snowmelt began. Little or no increase in snowmelt-water yields occur in very dry years, when most of the snowmelt recharges the soil mantle.

There is debate on what proportion of streamflow increases attributed to forest management practices actually contributes to downstream water supplies. Brown and Fogel (1987) suggested that the proportion is relatively small because of transmission losses, evaporation, seepage, and reservoir spills. Simulation of water routing with and without implementation of forest management practices by these authors indicated that less than half of the streamflow increase is likely to reach consumptive users downstream.

Summary

Empirical field observations, process and theoretical studies, and simulation investigations provide a basis for the formulation of management guidelines to enhance snowmelt-water yields on high-elevation forested watersheds in the Southwestern United States. Forest management practices can be designed to increase the amount of recoverable water from melting snowpacks on watersheds with high-runoff efficiencies. These management practices can also furnish livestock and wildlife forage, wildlife habitats, wood, and amenity values in combinations needed by people in the region into the coming century.

Acknowledgments

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The Role of Dendrochronology in Natural Resource Management

Ramzi Touchan[1] and Malcolm Hughes[2]

Abstract.—The discipline of dendrochronology, that is, development and use of time series of annual growth rings of trees, is a set of techniques by which the annual growth layers of trees may be assigned to definite calendar years. The history of changes in the trees' environment may be reconstructed using various properties of tree rings. In this paper we will discuss how tree- ring measurement series can be used to reconstruct past river flow, precipitation, and forest fires over time spans of several centuries and occasionally over millennia. With an understanding of these variables, land and water resource managers will be able to reduce the risk of failure in planning.

Introduction

Dendrochronology is a name derived from the Greek words for "tree" and "knowing the time." Dendrochronology is a highly specialized field by which the annual growth layers of trees may be assigned to the specific years of their formation. Dendrochronology can be used in a broad array of applications, such as dendroclimatology (Fritts, 1976; D'Arrigo et al, 1996; Touchan et al, 1999; Hughes et al, 1994, Hughes et al, 1999), dendrohydrology (Stockton and Jacoby, 1976; Smith and Stockton, 1982; Meko and Graybill, 1995), forest ecology (Fritts and Swetnam, 1989; Touchan et al, 1996; Swetnam and Baisan, 1996), and many other applications. In this paper we will discuss three applications of dendrochronology, focusing on reconstructions of Colorado River flow in the Southwestern United States (dendrohydrology), precipitation of southern Jordan in the Near East (dendroclimatology), and forest fires in northern New Mexico (dendroecology). The results of these studies should be employed as guidance and direction to mitigate the risks in managing water and other natural resources on a sustainable basis.

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Applications of Dendrochronology

Dendrohydrology: Streamflow Levels in the Upper Colorado River Basin

In the past, it has been unusual for studies and management plans of water and other natural resources to use tree rings as a tool for reconstructing long-term means and variability in precipitation and streamflow. One of the most outstanding examples of a problem where the lack of historical information caused severe water resource overallocation is the case of the Colorado River Water Compact in the Southwestern United States. Around 1922, when tree-ring studies were limited, planners for the Colorado River Basin met to agree on the distribution of rights to the water coming down the Colorado River. The 2,667-kilometer river flows through some of the most arid lands in North America, including parts of seven states in the U.S. and a small portion of two states in Mexico. From existing instrumental records, planners estimated that the Colorado River had an average annual flow of 19,985 billion cubic meters. This estimate was based on the 17 years of precipitation and streamflow data that were available (1906 to 1922). In 1976 at the Laboratory of Tree-Ring Research of the University of Arizona, Stockton and Jacoby (1976) reconstructed the flow of the Colorado River back to A.D. 1564 (450 years) using time series derived from tree-ring studies. Their reconstruction indicated that the period from 1906 to 1930 was the longest period of sustained high streamflow during the past 450 years. The short period of the instrumental record was simply not representative of the long-term flow of the river. Therefore, the allocation of water among states of the United States and Mexico was based on an anomalously high value, which resulted in shortages when all of the entities involved demanded their share of the available water.

Dendroclimatology: Reconstruction of Precipitation in Southern Jordan

Water is the most limiting factor for agricultural production in the Near East. Careful planning and management of water resources in dry land regions requires sufficient information on what frequency and severity of extreme events to anticipate, such as prolonged drought. One needs to know the variability of the climate of the area on time scales of decades to centuries to understand drought conditions and the resultant probability of increased desertification. Dendrochronology is a valuable tool for the study of past climate variability and increases our knowledge of climate variability beyond the short period covered by the instrumental data. Touchan et al. (1999) developed the first dendroclimatic reconstruction in the Near East for southern Jordan, a 396-year-long reconstruction of October-May precipitation based on two chronologies of *Juniperus phoenicia* (figures 1 and 2). They showed that the longest reconstructed drought, as defined by consecutive years below a threshold of 80% of the 1946-1995 mean observed October-May precipitation, lasted four years. The longest drought recorded in the 1946-95 instrumental data lasted three years. Based on the results of the reconstruction, seven droughts of three or more years have occurred during the past 400 years. A Monte Carlo analysis designed to account for uncertainty in the reconstruction indicates a lower than 50% chance that southern Jordan has experienced drought longer than five years in the past 400 years (figure 3). The chronology from southern Jordan covers 527 years (1469-1995).

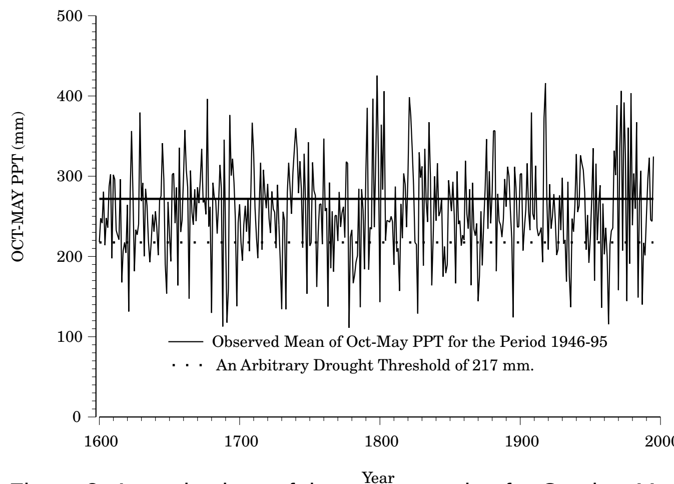

Figure 2. Annual values of the reconstruction for October-May precipitation for the period from 1600-1995.

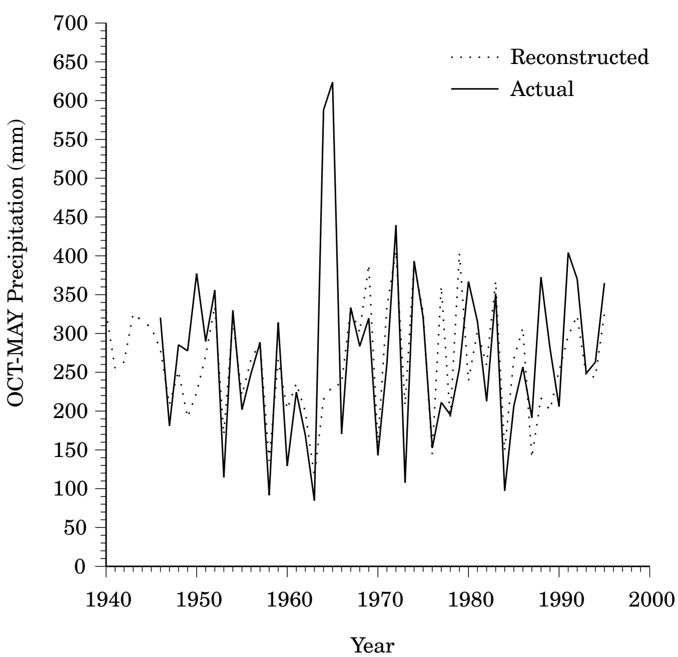

Figure 1. Comparison between actual and estimated October-May precipitation for southern Jordan, A.D. 1946-1995. Calibration R^2 is 0.44. Corresponding values for cross-validation is 0.41 (Touchan et al. 1999).

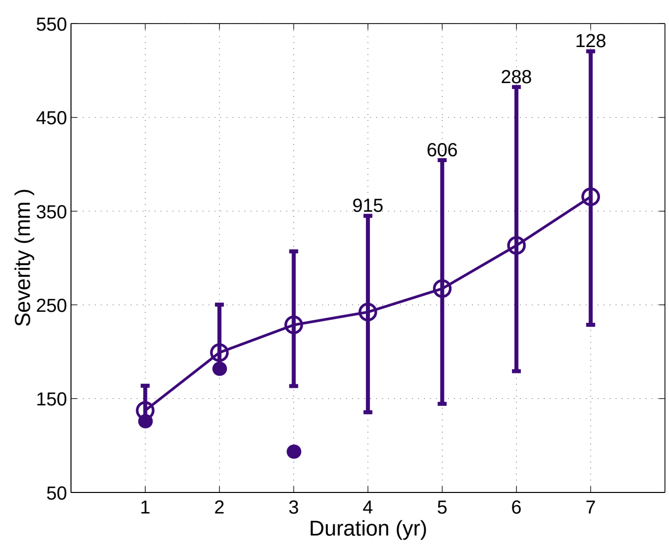

Figure 3. Median, 5th, and 95th percentiles of severity of most severe *n*-year droughts in noise-added reconstructions, 1600-1995. Black dots mark most severe *n*-year droughts in the observed precipitation series, 1946-95. Severity defined as run-sum below an arbitrary drought threshold of 80% of the mean observed October-May precipitation (217 mm). Results based on 1000 simulations. Number of simulations having at least one n-year drought annotated unless all simulations have a n-year drought (Touchan et al. 1999).

Dendroecology: Fire History and Climatic Patterns in Forests of Northern New Mexico

Fire has played a major role in shaping ecosystems of North America. In many areas, the presence or absence of fire controls vegetation succession, wildlife habitat, and nutrient cycles, as well as regulating biotic productivity, diversity, and stability. Fire is widely recognized as an integral and nearly ubiquitous element of forested landscapes in the western United States. Recognition of the importance of fire as a natural agent of change in the west has brought a corresponding interest in learning about the frequency, character, and impact of prehistoric and historic fires in this region. Touchan et al. (1996) reconstructed fire history in ponderosa pine and mixed-conifer forests in the Jemez Mountains in northern New Mexico. They found that prior to 1900, ponderosa pine forests were characterized by a high frequency, low intensity surface fire regime (figure 4). The mixed-conifer forests sustained somewhat less frequent surface fires, along with patchy crown fires (figure 5). They also examined the interaction between fires and winter-spring precipitation, finding

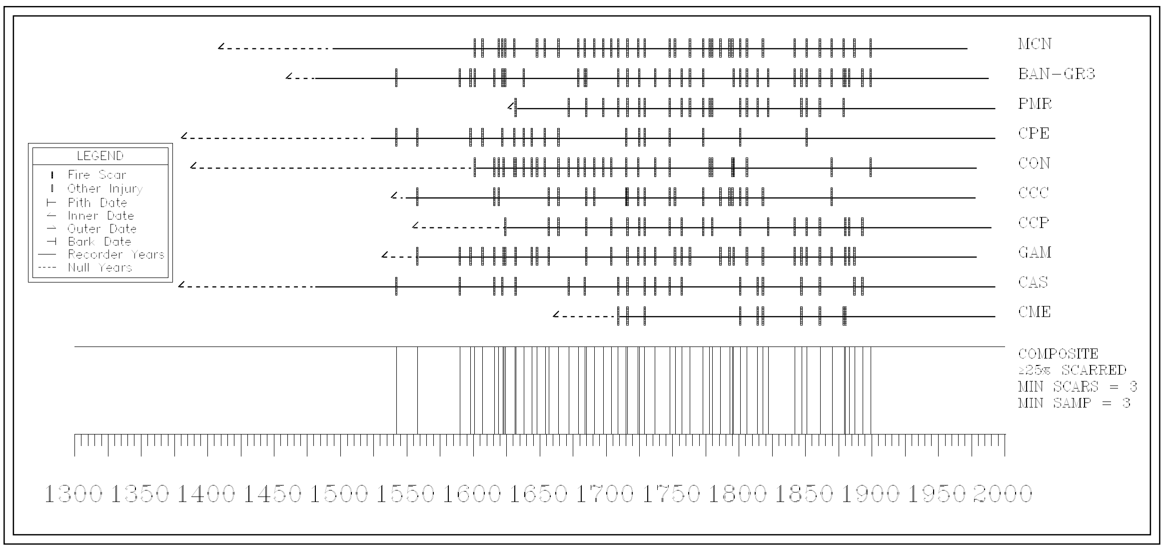

Figure 4. Composite fire history chart for the ponderosa pine forests. Horizontal lines are maximum life span of trees within each site. Vertical lines are composite fire dates recorded by 25% or more of the trees within each site (Touchan et al. 1996).

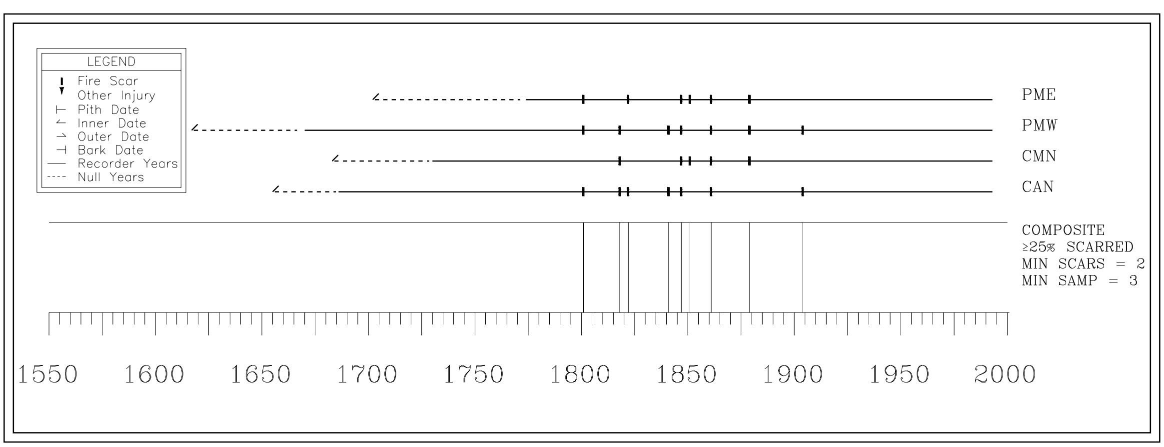

Figure 5. Composite fire history chart for the mixed-conifer forests. Horizontal lines are maximum life span of trees within each site. Vertical lines are composite fire dates recorded by 25% or more of the trees within each site (Touchan et al. 1996).

that in both forest types, precipitation was significantly reduced in the winter-spring period immediately prior to fire occurrence (figure 6). In the ponderosa pine forests, the winter-spring precipitation during the second year preceding major fire years was significantly greater. This study provided baseline knowledge concerning the ecological role of fire in both forest types. Results of the study are considered vital to support ongoing ecosystem management efforts in the Jemez Mountains.

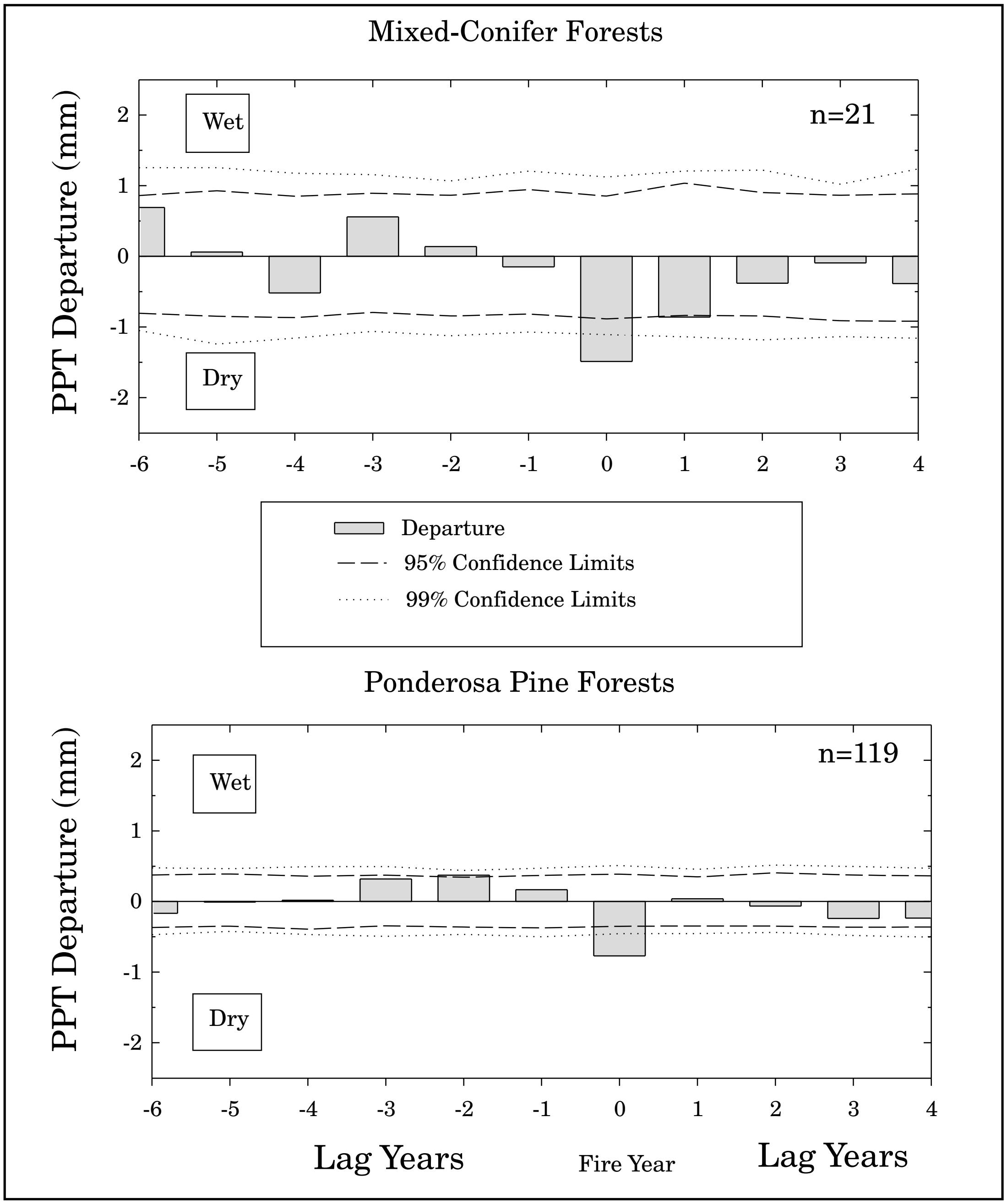

Figure 6. The superposed-epoch analysis for both the mixed-conifer (all fire dates) and the ponderosa pine forests (fire dates based on at least 10% trees scarred) for the period 1653-1986. The precipitation time series used was based on a tree-ring reconstruction of December-June precipitation. Departures were computed as the difference between the long-term mean precipitation level (1653-1986) and the observed mean precipitation during the fire years and lagged years (Touchan et al. 1996).

Conclusion

Tree-ring reconstruction of river flow, precipitation, and forest fires will help natural resource managers and decision makers understand these variables and execute low-risk, long-term action plans to accomplish desired conservation and sustainable use of natural resources. Such understanding can lead to a more realistic evaluation than is possible from direct observations of the nature and implications of environmental variability on timescales of decades to centuries. Understanding these variables will thus place managers in a better position to mitigate the risks affecting conservation and sustainable development of natural resources.

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Soil Erosion Studies in Buffelgrass Pastures

Diego Valdez-Zamudio[1] and D. Philip Guertin[1]

Abstract.—The introduction of exotic grasses in native rangelands to increase the production of forage has been a good alternative for the cattle industry in North America. Different studies have demonstrated that buffelgrass (*Cenchrus ciliaris* L.), a plant introduced from Africa, increases the annual green forage production approximately three times in comparison to production in areas with native species in rangelands of Sonora, Mexico. However, soil erosion processes caused by natural circumstances and/or natural resources mismanagement can decrease productivity of buffelgrass pastures. Soil erosion rates for buffelgrass pastures in central Sonora, Mexico, were estimated using the Revised Universal Soil Loss Equation (RUSLE). Pastures differed in geographical location, environmental conditions and type of management. It was demonstrated that in buffelgrass pastures, soil loss caused by hydrologic factors is positively correlated with plant density, soil surface micro-relief, and erosion features. It correlates negatively with soil crust development and pasture management index. Stepwise regression analyses make evident the effect that soil surface erosion features, pasture management practices, and density of buffelgrass plants have on the soil loss rates of these grazing lands.

Introduction

In an attempt to increase the forage production in the rangelands of Sonora, Mexico, in the mid 1950s the African T-4464 buffelgrass (*Cenchrus ciliaris L.*) was introduced. According to Martin-R. and others (1995), the annual green forage production in pastures with this species increased approximately three times in comparison to production in areas with native species. However, many natural or anthropogenic processes that affect the functionality of these agroecosystems have not been completely studied. One of these processes is soil erosion caused by water.

Soil erosion is the process of detachment and subsequent removal of soil particles and small aggregates from land surfaces by wind and/or water in a specified time period (Brooks and others 1997; Nearing and others 1994). Soil loss due to erosion processes is a serious problem in many regions of the world.

Financial and material constraints make it impossible to estimate and monitor the soil loss effects of weather and land management practices in all ecosystems, and it is difficult to extrapolate beyond local study areas. One alternative approach is to develop simulation models to achieve these goals. Thus, in 1965, the USDA Soil Conservation Service created the Universal Soil Loss Equation (USLE) to predict soil erosion. The USLE is an empirical mathematical model designed to compute long time average soil losses due to sheet and rill erosion across the land surface. The equation has been modified through time; the most recent version is called Revised Universal Soil Loss Equation (RUSLE). It groups the interrelated physical and management parameters that influence erosion into six factors such that erosion is the product of those factors as follows:

$$A = R\ K\ (LS)\ C\ P$$

where: A = computed annual soil loss in tons per unit area (in this case, km).

R = a rainfall - runoff erosivity factor;

K = a soil erodibility factor, based on soil characteristics such as texture, structure, and permeability;

LS = a dimensionless topographic factor combining slope length, L, and slope steepness, S;

C = a dimensionless land cover-management factor; and

P = an erosion control factor, based on soil conservation support practices (Brooks and others 1997).

The principal objective of this study was to estimate the erosion rates in buffelgrass pastures exposed to different environmental conditions and management styles. These pastures are located in the central part of Sonora, Mexico.

Methods

Study Area

The study area covers the central part of Sonora, Mexico, from 28° 30′ N latitude to 29° 30′ N latitude and from the Gulf of California to the state border of Sonora (figure 1). Within this zone, there exists a east-west trending gradient of precipitation, temperature, and elevation. Mean annual precipitation values increase towards the east,

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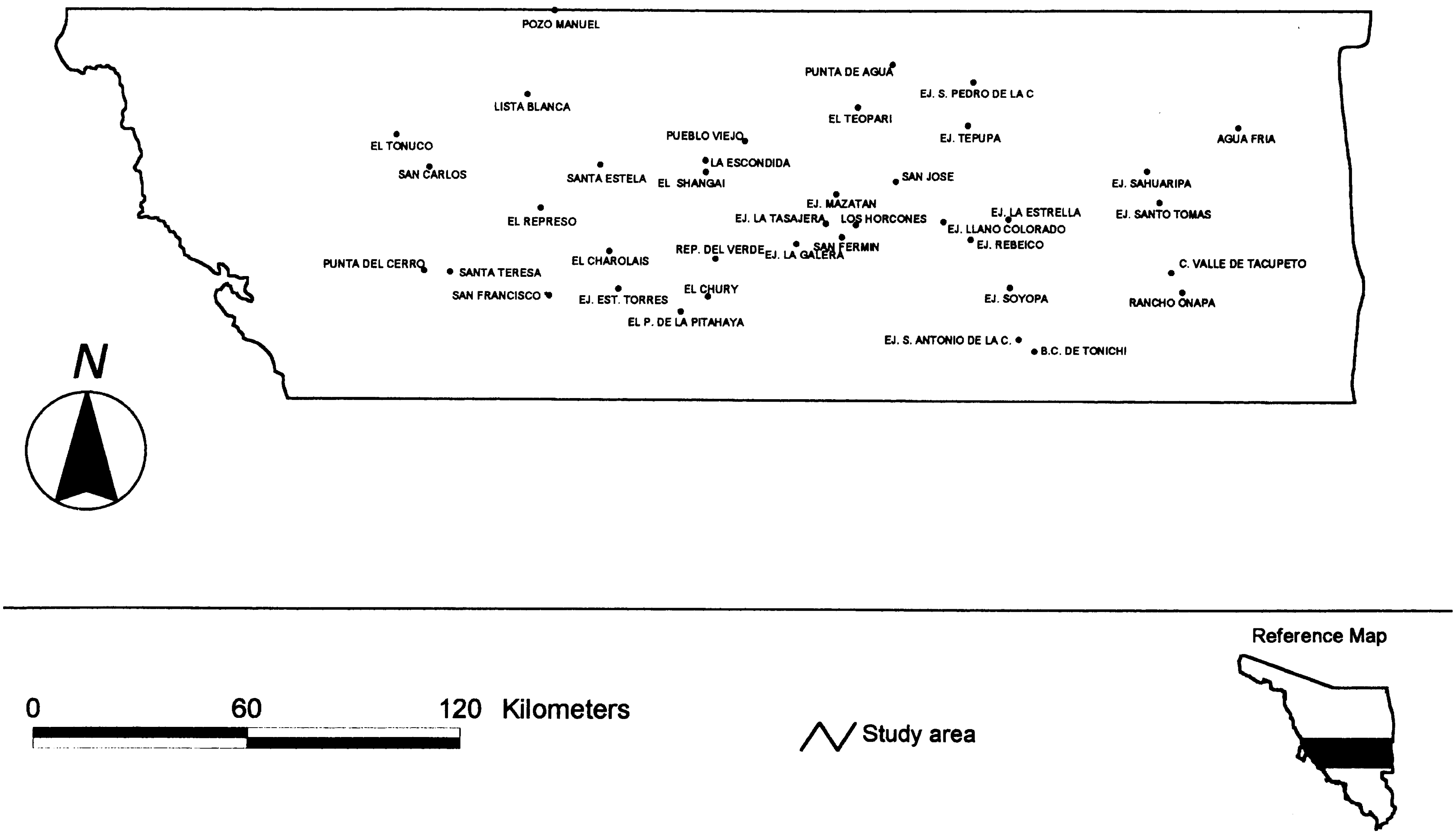

Figure 1. Distribution of sampling sites in the study area.

ranging from less than 150 mm at the western extent to over 800 mm in the east. Mean annual temperature values decrease over the same area, ranging from more than 25°C to less than 21°C. Thirty-seven ranches were arbitrarily selected within the study area in order to represent the greatest number of possible environmental and management scenarios.

Equation Parameters

The original soil erosion equation was created using data gathered from experiments done in the U.S.A.; in consequence, its extrapolation and applicability in other countries is limited. However, different authors have created equations that permit the users to obtain values for the RUSLE parameters using the unique data available in their regions or countries. In this particular project, there is only rainfall monthly data and, given the fact that there are no isoerodent maps for the study area, the R value was estimated using the climate index C created by Fournier and subsequently modified by FAO:

$$C_1 = \sum_{i=1} p_i^2/P$$

where C_1 = climate index
p_I = rainfall in month i
P = annual rainfall

This index summed for the whole year was found to be linearly correlated with R factor of RUSLE as follows:

$$R = b + a\,(C_1)$$

where the constants a and b vary widely among different climatic zones of the world (Lal and Elliot 1994). For this study, we assumed to be in an area with same values for constants a and b, such as the western region of the USA., where the value for intercept b is –3 and for coefficient a 0.66.

Given the chemical and physical characteristics of the soils like texture, organic matter content, soil structure, and permeability, the corresponding K factor values were determined using a special nomograph (Morgan 1995).

The LS factor values for buffel pastures were determined by using published tables where a slope-length relationship is calculated for different soil conditions and land uses (Renard and others 1994). The C and P factor values were also determined from tables created by the government (Morgan 1995). Because all pastures were found in an overgrazed condition, were given a C value of 0.1. The corresponding P value for the entire number of pastures was 0.5.

Additional Information

To relate the erosion rates to other factors, a number of measurements and estimations were performed in the study sites. Thus, density, basal area and relative yield were determined as plant attributes. As soil characteristics, we measured percentage of litter cover, percentage of crust development, soil microrelief, and surface erosion features. Microrelief refers to the vertical variation of soil surface. Smooth surfaces are given low values, while rough surfaces are given high values. Certain soil features (rills, scarps, flow lines, pedestals) indicate erosion, deposition or surface water flow (Tongway and Smith 1989). They were rated on a scale of zero to one according to the prominence of the features. For the entire pasture, parameters like PMI (pasture management index) and PCI (pasture condition index were also determined to perform the association with erosion rates.

Results and Discussion

Table 1 shows the resulting values in soil erosion for all studied pastures. There is a notable variability in erosion rates among all of them provoked by the contrast in soil characteristics, climate, and topography. These values are smaller than those obtained by Valdez-Zamudio (1994) for natural rangelands in northern Sonora. Performing an experiment on Australian soils, McIvor and others (1995) found that runoff and soil movement were greatest in native plant communities and least in developed pastures. In 1998, Perramond confirmed these results and concluded that "contrary to conventional wisdom, results indicate that buffelgrass is a very effective soil cover, and that soil rates are twice as high in native vegetation".

Statistical analyses demonstrated that buffelgrass erosion rates are positively correlated with plant densities, soil microrelief and erosion features values, while relationships with soil crust development and pasture management index are negatives. All these correlation results are understandable except the one related to plant density, because lower erosion rates would be expected as plant density increased. Probably the reason is that ranchers usually enlarge their herds of grazing animals beyond the carrying capacity of the ecosystem, increasing the erosion rates in the pastures.

Table 1. Parameter and erosion rate values for study sites.

No.	SITE	R	K	LS	C	P	A
1	SANTA TERESA	50	0.03	0.62	0.1	0.5	0.040
2	SAN FRANCISCO	58	0.01	0.50	0.1	0.5	0.019
3	SANTA ESTELA	57	0.12	0.26	0.1	0.5	0.087
4	EL TONUCO	53	0.10	0.50	0.1	0.5	0.138
5	SAN CARLOS	54	0.09	0.50	0.1	0.5	0.123
6	PUNTA DEL CERRO	66	0.10	0.50	0.1	0.5	0.172
7	POZO MANUEL	63	0.13	0.50	0.1	0.5	0.205
8	EL REPRESO	57	0.14	0.26	0.1	0.5	0.106
9	E. ESTACION TORRES	59	0.13	0.26	0.1	0.5	0.100
10	LISTA BLANCA	62	0.09	0.38	0.1	0.5	0.107
11	EL CHAROLAIS	59	0.12	0.26	0.1	0.5	0.090
12	EL POZO DE LA P.	60	0.08	0.62	0.1	0.5	0.145
13	EL CHURY	60	0.09	0.26	0.1	0.5	0.071
14	LA ESCONDIDA	58	0.09	0.62	0.1	0.5	0.164
15	PUEBLO VIEJO	66	0.13	0.26	0.1	0.5	0.112
16	E. TEPUPA	92	0.10	0.26	0.1	0.5	0.124
17	SAN PEDRO CUEVA	87	0.07	0.26	0.1	0.5	0.074
18	E. MAZATAN	84	0.12	0.62	0.1	0.5	0.305
19	E. LA GALERA	75	0.09	0.50	0.1	0.5	0.171
20	E. LA TASAJERA	77	0.20	0.38	0.1	0.5	0.285
21	REPRESO DEL VERDE	61	0.04	0.50	0.1	0.5	0.059
22	AGUA FRIA	95	0.09	0.62	0.1	0.5	0.268
23	E. SAHUARIPA	97	0.10	0.50	0.1	0.5	0.252
24	ONAPA	99	0.09	0.50	0.1	0.5	0.225
25	PUNTA DE AGUA	79	0.09	0.38	0.1	0.5	0.137
26	EL SHANGAI	62	0.09	0.26	0.1	0.5	0.073
27	EL TEOPARI	76	0.07	0.26	0.1	0.5	0.064
28	E. REBEICO	106	0.08	0.50	0.1	0.5	0.207
29	LLANO COLORADO	102	0.26	0.38	0.1	0.5	0.504
30	SAN FERMIN	80	0.07	0.26	0.1	0.5	0.068
31	SAN JOSE	85	0.08	0.26	0.1	0.5	0.086
32	S. ANTONIO HUERTA	93	0.12	0.74	0.1	0.6	0.483
33	C. TONICHI	89	0.09	0.26	0.1	0.5	0.105
34	SANTO TOMAS	101	0.07	0.26	0.1	0.5	0.085
35	E. LA ESTRELLA	102	0.14	0.74	0.1	0.6	0.648
36	E. SOYOPA	86	0.05	0.50	0.1	0.5	0.112
37	LOS HORCONES	83	0.16	0.26	0.1	0.5	0.168

Stepwise regression analyses (p = .25) demonstrated a significant positive association between soil erosion and plant densities and soil erosion features. A negative relation exists between soil erosion and pasture management index, indicating that the best-managed buffel pastures have the smallest erosion rates.

Summary and Conclusions

This study illustrates the potential use of soil erosion models for making environmental assessments, especially in rangelands areas. It is evident that erosion is affecting the buffelgrass pastures of central Sonora, Mexico. Increments in plant density and surface erosion features, in combination with inefficient pasture management, are the main causes of erosion in buffelgrass pastures of central Sonora. Soil erosion potential rates in buffelgrass pastures define an evident tendency of soil deterioration in central Sonora. Soil conservation programs need to be implemented in buffel pastures of Sonora to control the erosion processes and improve the actual conditions of those agroecosystems.

Acknowledgements

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Studies of Rock Characteristics and Timing of Creep at Selected Landslide Sites in Taiwan

Cheng-Yi Lee[1]

Abstract.—A study was conducted to investigate the causes of and rock characteristics at three landslide sites in the Tesngwen Reservoir watershed of southern Taiwan. Research methods used included the petrographic microscope, X-ray diffraction (XRD), scanning electron microscope (SEM), inductively coupled plasma spectroscope (ICP), constant head permeameter in triaxial apparatus, surface extensometer, and seismic exploration by wave-refraction processes. Chemical analyses of the rock indicated a higher Na than K content at all three landslide sites; iron normally occurs as Fe^{3+}. The relationships between percolation velocity (V) and gradient (I) were developed for the different sites. A prediction equation for the timing of landslide failure was also developed from surface extensometer measurements.

Introduction

Managers of many watersheds in Taiwan are concerned about landslides due to heavy torrential rains during the May through October typhoon season, steep topography, young and weak geological formations, erodible soils, and improper land uses. Many methods exist to mitigate these situations. However, land instability and land use capability are core concerns, which are successfully addressed through sound soil and water conservation practices.

With a design capacity of 650,000,000 m^3, the Tesngwen Reservoir located in southern Taiwan is the largest reservoir on the island. Serious landslides occur frequently at many locations around this reservoir. Generally, factors affecting these landslides are naturally occurring. Taiwan is located in an active tectonic area; the collision site between the Philippine Sea Plate and the margin of the Eurasian Plate (Lin, 1991). The topography and lithology reflect the interaction of the tectonic system with exogenetic processes. The purpose of this study was to investigate the causes of and rock characteristics at three landslide sites on this watershed.

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Methodology

Landslides often reflect the interaction of natural and human factors. A hillslope-material rupture mechanism model addresses the importance of this interaction (Lee, 1982). The methodology of this study followed this model using rock-petrographic microscope methods and the recognition, identification, and rupture timing of landslides of Taiwan.

The proposed concept is based on the nature and mechanism of landslides using direct boring core and surface geologic data. Landslides are caused by natural and environmental processes including the original landmass, hillslope material, and landforms. Techniques used in this study include petrographic microscope, X-ray diffraction (XRD), scanning electron microscope (SEM), inductively coupled plasma spectroscope (ICP), constant head permeameter in triaxial apparatus, surface extensometer (Hoek, 1981), and seismic exploration by wave-refraction processes. These methods emphasized reliability rather than statistical precision by careful sample selection and pretreatment measurements. A prediction model and seismic prospecting for the rupture timing and macrostructure of landslide were also developed.

Results

Field observation and lab techniques were used to analyze landslide properties, to obtain petrographic characteristics, to predict creep rupture timing, and to explore the depth of the slide layer. Landslide mechanisms were established in the Tsengwen reservoir watershed using landslide investigation data. Three landslide sites at Da-Pang, Ta-Tou and Mao-Pu-Tse, were arc-creep failure types. The occurrence of these landslides was caused by a combination of natural and environmental factors.

Petrographic analysis is useful to investigate the origin of rock material. Certain sets of rock-forming minerals are associated with rock core. Overlays and unconformities are suspected from certain discontinuities in the mineralogical composition of samples taken at different depths in a given landslide profile. The presence of sericite in rock specimens at these landslide sites may indicate altering rock deposit. Evidence of sericite and feldspan may be critical to explain some rock characteristics (table 1 and figures 1 through 3). The shape, size, and spacing of primary mineral grains may also be related to changes caused by weathering and rock-material development. Clay minerals (matrix) may force primary or skeletal rock-forming mineral grains to separate. Clay minerals control the rupture surface of the rock core at landslide sites. The condition of resistant minerals also answers some questions related to these landslides. Petrographic microscope techniques allow observation of rock-forming mineral in the process of alteration in the landslide profiles. Stages of weathering can be followed, and the source of secondary mineral (sericite) can be observed (Carroll, 1970; Cady, 1986; Wang, 1964).

Time-dependent behavior in hillslope material is referred to as creep landslide (Terzaghi, 1950; Saito, 1966; Roberts, 1977; Bates, 1987). In addition to the time factor, creep rupture is dependent on pore-water pressure, geostress, and temperature. Creep of rock detritus frequently occurs on hilly terrain. The motivating force is gravity, although lateral stress is sometimes important. The deformation mechanism is essentially one of plastic flow in which a slow downslope failure of the whole mass is combined with a vertical movement of fragments through the moving layer. Surface extensometers were used to measure displacements at different depths of a given profile at six landslide sites (figure 4).

Table 1. Mineral composition of rocks as determined by XRD method

Rock Samples	Quartz	Feldspar	Muscovite	Calcite	Illite	Chlorite	Kaolinite
Da-Pang LS							
TPL2-2	+++*	++	-	-	+	+	+
TPL2-6	+++	++	-	-	+	+	-
TPL3-5	+++	++	-	-	+	+	-
TPL3-6	+++	++	-	-	+	+	-
Ta-Tou LS							
TL5-4	+++	++	++	++	+	+	-
TL5-5	+++	++	-	++	+	+	-
TL6-2	+++	++	-	-	+	+	-
TL6-3(1)	+++	++	-	-	++	++	+
TL6-3(2)	+++	++	-	-	+	+	+
TB-7	+++	++	-	++	+	+	-
TB-8	+++	++	-	-	+	+	-
TD2-3a	+++	++	-	-	+	+	-
TD2-3b	+++	++	-	-	+	+	-
Mao-Pu-Tse LS							
MPL3-5	+++	++	-	-	-	-	-
MPL11-4a	+++	++	-	-	-	-	-
MPL11-4b	+++	++	-	-	-	-	-

*.+++: *dominant (38~58%) ; ++: major (18~38%) ; +: minor (<18%) ; -: not detected (ND)*

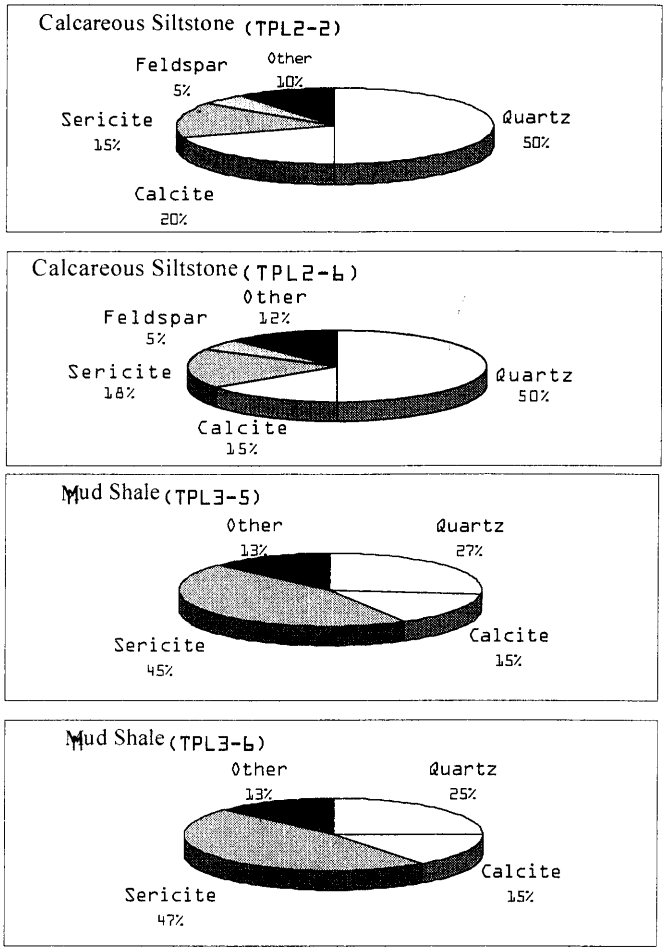

Figure 1. Relative abundance of mineral composition of rocks at Da-Pang landslide (volume %).

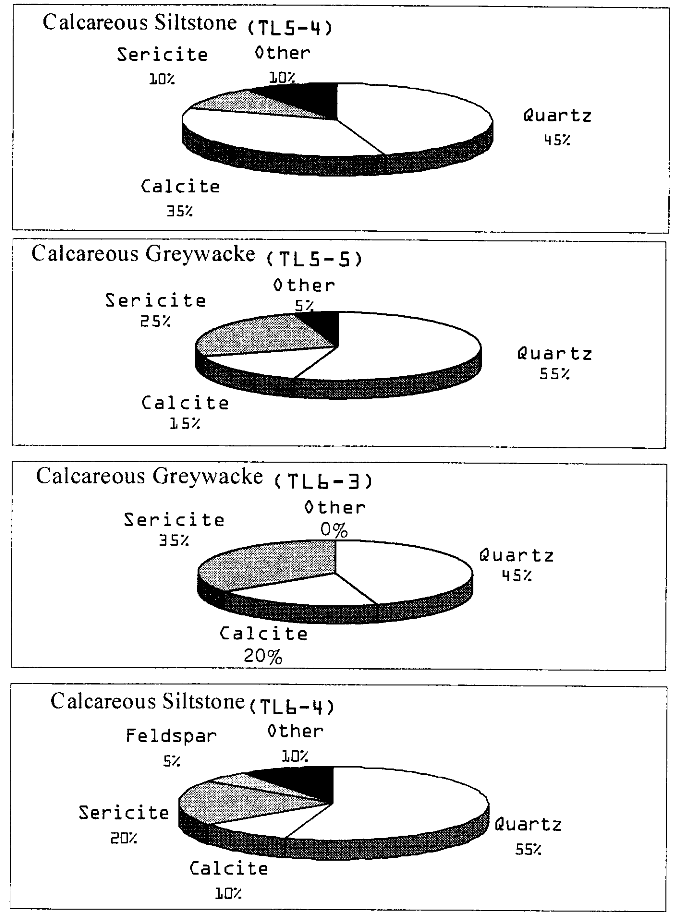

Figure 2. Relative abundance of mineral composition of rocks at Ta-Tou landslide (volume %).

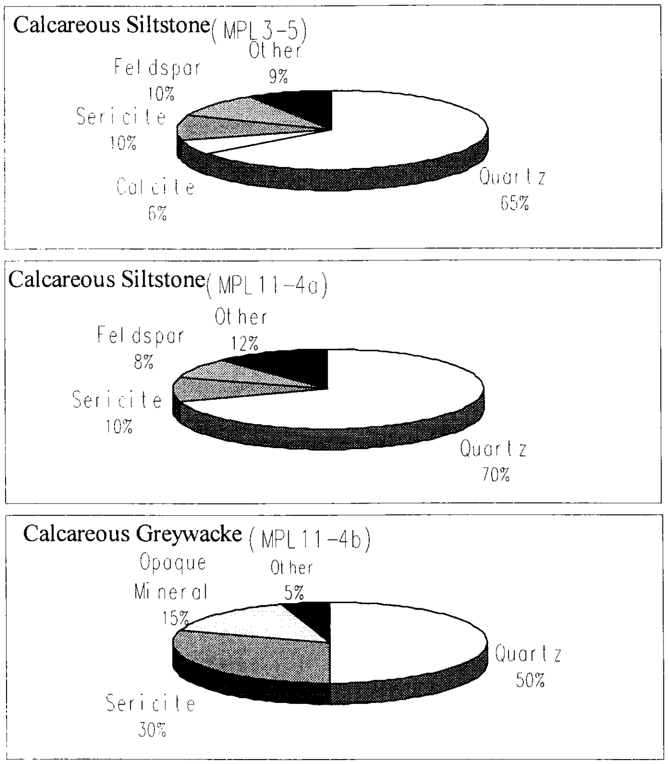

Figure 3. Relative abundance of mineral composition of rocks at Mao-Pu-Tes landslide (volume %).

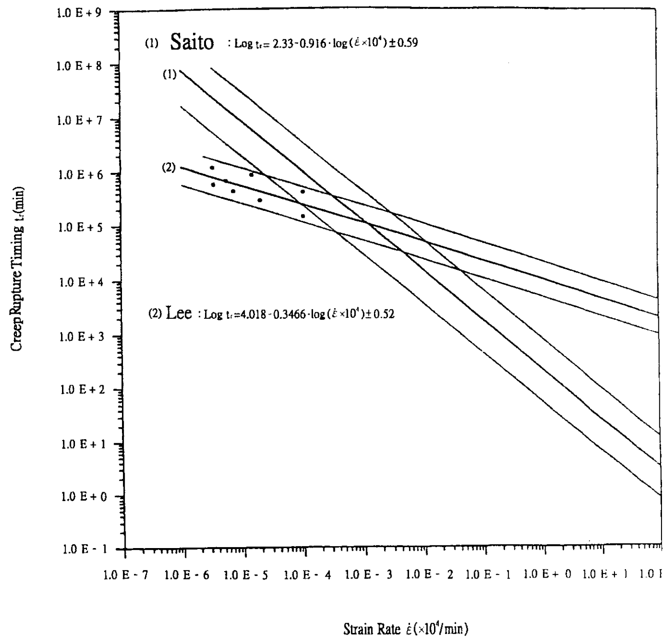

Figure 4. Comparison of rupture timing between Saito and Lee models.

Conclusion

The mechanisms, causes, and rock properties at three landslide sites in the Tsengwen Reservoir watershed in southern Taiwan were studied. A prediction model for the rupture timing of creep landslides was also developed. Critical results are summarized as follows:

- The Da-pang landslide is an arc-shape creep failure type. Landslide failure was due to the steep topography, a road cut, and saturated hillslope material from heavy summer rainstorms. The rock stratigraphic unit of the site is in the Neogene Middle Miocene Da-Pang Formation composed mainly of argillaceous shale and calcareous siltstone. The mineral components of argillaceous shale include sericite, quartz and calcite; calcareous siltstone includes quartz, calcite, sericite and feldspar.
- The Ta-Tou landslide, another arc-shape type creep landslide, was caused by road excavation, concentrated runoff, poor drainage, increased porewater pressure due to rain-storms, and gully head erosion on a steep slope. The site is located in the Neogene Late Miocene Nanchuang Formation with calcareous sandstone and calcareous shale containing quartz, calcite, sericite and feldspar, and quartz, sericite and calcite, respectively.
- The Mao-Pu-Tse landslide is also an arc-shape type failure. This landslide was caused by the fluctuating water levels of the reservoir and the flow of the hillside after extended submersion in water undercutting of the hillslope. The Neogene Late Miocene to Early Pleistocene Kueichulin Formation at the site contains siltstone and fine greywacke with quartz, sericite and feldspar.
- Chemical analyses of the rock indicate a higher Na content than K at all three landslide sites. Iron normally occurs as Fe^{3+}.
- For different pressure heads at the same depth, the relationship between permeability velocity (V) and hydraulic gradient (I) are:

  Da-Pang landslide site V=0.0100 ~0.0138I

  Ta-Tou landslide site V=0.0146 ~0.0211I

  Mao-Pu-Tse landslide site V=0.0099 ~0.0207I
- For different rock depths at the same pressure heads, the relationship between permeability velocity (V) and hydraulic gradient (I) are:

Da-Pang landslide site V=0.0121I

Ta-Tou landslide site V=0.0211I

Mao-Pu-Tse landslide site V=0.0144I

- The prediction model for the creep failure timing developed from surface extensometer measurements at six landslide sites is:

$$\text{Log tr} = 4.018 \sim 0.3466 \log (\in{*}10^4) \pm 0.52$$

where:

tr is the creep failure timing (T)

$\in$ is the strain rate (t^{-1})

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Streambank Response to Simulated Grazing

Warren P. Clary[1] and John W. Kinney[2]

Abstract.—Simulated grazing techniques were used to investigate livestock impacts on structural characteristics of streambanks. The treatments consisted of no grazing, moderate early summer grazing, moderate mid summer grazing, and heavy season-long grazing. The heavy season-long treatment resulted in a 11.5 cm depression of the streambank surface, while the moderate treatments depressed the streambank surface about 3 cm. There were no differences between no grazing and moderate grazing treatments on bank angle, bank retreat, or stream width. The heavy season-long treatment produced significant changes in these variables during the 2-year study.

Introduction

Concern about the impacts of livestock grazing, particularly cattle, in riparian zones is widespread across the public lands of the Western United States. Although there are multitudinous anecdotal accounts and observations of cattle breaking down streambanks (Adams and Lorne 1995, Martin and Schumaker 1998), there is little quantification of the actual impacts necessary to damage streambanks (Trimble and Mendel 1995). In the present study, simulated grazing techniques were used to investigate the stress level necessary to damage streambanks in a mountain meadow setting in central Idaho. The data presented here are part of a larger investigation.

Study Area and Methods

This study was conducted on 3 streams in central Idaho's Sawtooth Valley north of Stanley. Stanley Creek and Park Creek are in the Sawtooth National Forest and Thatcher Creek is in the Challis National Forest. Stanley Creek and Thatcher Creek soils are classified as Fluventic Ustochrepts, loamy, cryic and Park Creek soil is classified as Fluventic Haplaquoll, loamy, cryic. The A horizon of Stanley Creek is dark yellowish brown, of Park Creek is black, and of Thatcher Creek is brown. Thatcher Creek had the highest amount of rock fragments, while Park Creek had the highest amount of clay. All 3 study sites have buried soil horizons at 18 to 33 cm below the surface (D. Gilman, personal communication). Streamside vegetation at the study sites was dominated by water sedge *(Carex aquatilis)*, beaked sedge *(C. rostrata)*, Jones sedge *(C. jonesii)*, small-winged sedge *(C. microptera)*, Baltic rush *(Juncus balticus)*, field woodrush *(Luzula campestris)*, and Kentucky bluegrass *(Poa pratensis*).

The treatments applied were intended to simulate no grazing (treatment 1), moderate early summer grazing (treatment 2), moderate mid summer grazing (treatment 3), and heavy season-long grazing (treatment 4). Eight main plots were established per stream; 2 per treatment. Each main plot had two 1 m^2 subplots, each overlapping the streambank. A half meter buffer zone was established around the subplots for protection and access.

Grazing simulation treatments were patterned after those in Clary (1995) with initial suggestions contributed by Al Medina (RMRS, Flagstaff, AZ, personal communication 1988) and refinements from Pat Momont (Caldwell Research and Extension Center, Caldwell, ID, personal communication 1995). The moderate treatments were applied once in either late June or late July. Vegetation was defoliated to a height of 10 cm, trampling was simulated by 50 random impacts by a hoof imitator (14 kg steel weight with impact surface area of 100 cm^2 dropped from 75 cm), urine was represented by 0.8 g of urea in 1/4 liter of water, and fresh manure was applied at a rate of 66 g m^{-2}. The heavy season-long treatment was applied in late June, late July, and late August. Vegetation was defoliated to 1 cm in height, 120 random hoof imitator impacts were applied, urine was represented by 2.0 g urea in 1/4 liter of water, and fresh manure was applied at a rate of 165 g m^{-2}. Treatments were initiated in the spring of 1996 and ended in the fall of 1997. Final measurements were taken in the spring of 1998.

Changes in soil surface and bank profile were determined by a bankometer patterned after a rillmeter. A 1.3 cm conduit pipe, 3 m long with 0.6 cm holes drilled on 2.5 cm centers, was anchored to rebar stakes. Stainless steel rods, 0.6 cm in diameter, were positioned through the drilled holes in the conduit pipe and lowered to the soil surface (figure 1). The length remaining above the conduit was recorded for each rod position. Determination of treatment effect on streambank elevation was a function of the change in readings over time. Bankometer readings, bank angle from water's edge to top of bank, wetted

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Figure 1. Bankometer positioned on study plot.

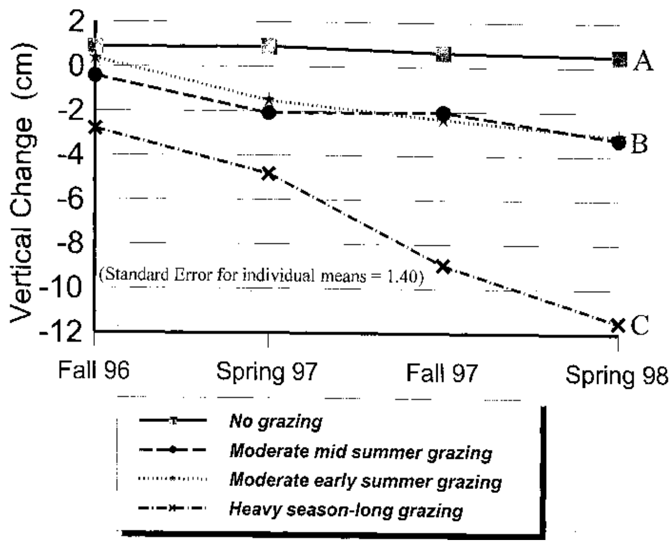

Figure 2. Mean depression of bank top related to time and treatment. Letters indicate significant differences.

stream width, and average stream depth were measured each spring and fall during the study. Bank retreat at water's edge during the treatment period was recorded at the end of the study. Moisture in the top 15 cm of soil was sampled gravimetrically with two 2.5 cm cores per subplot during each treatment period.

A mixed-model analysis of variance was used to analyze bank retreat data and a mixed-model analysis of variance with AR(1) error structure was used for the repeated measures analysis of bankometer, bank angle, and stream-width data. Effects of soil-moisture content and root-strength index were examined through correlation with response variables. Probability values of 0.05 or less were considered significant.

Results

Streambank elevations experienced a highly significant effect from the treatments ($P<0.01$). During the study, the plots receiving simulated grazing treatments had a cumulative reduction in average surface elevation as the streambank became progressively more deformed and broken (figure 2). The 2 moderate intensity treatments had about 3 cm of average surface depression, while the heavy season-long treatment had about 11.5 cm of average surface depression as the edge of the bank become severely deformed (figure 3).

Bank retreat, or the retreat of the streambank face at water's edge, demonstrated a treatment response ($P=0.01$). Treatments 1, 2, and 3 were comparable averaging about 3.5 cm bank retreat at the water's edge, but treatment 4 resulted in substantially greater bank retreat of about 12 cm over the study period.

Stream width, measured at the plot locations, changed differentially with treatment ($P=0.04$). Treatments 1, 2, and 3 had about 1/5 m narrower stream wetted-widths, reflecting lower stream depths at the end of the study (stream depth through control sections averaged 17 cm in 1998 versus 24 cm in 1996). However treatment 4, which caused the most severe impact, differed significantly and resulted in no reduction in stream width. No width reduction with lower stream depths suggested a relative increase in channel width.

Bank angle also experienced a significant change related to treatment ($P=0.05$). Treatments 1 and 3 had an average reduction in bank angle of less than 1 degree, while treatment 2 had an increase in bank angle of 7 degrees. Treatment 4 had an increase in bank angle of 27 degrees producing a substantial flattening of the bank face and creating a "laid back" appearance.

Discussion

One factor affecting the vulnerability of streambanks to trampling damage is the soil-moisture content. Montana researchers found a substantial correlation between changes in stream-channel area and streambank soil moisture, and little correlation between channel area and ob-

Figure 3. View of subplots following heavy, season-long treatment in 1997.

served cattle presence in the riparian area (Marlow and Pogacnik 1985, Marlow et al. 1987). They suggested that a primary guideline for grazing riparian areas would be to limit use to the seasonal periods of dry (<10% moisture) streambanks. Conversely, we found relatively limited correlation between variations in streambank soil moisture and streambank damage in this study. Perhaps one reason for the lack of a relationship was that the banks of the current study streams remained well above the 10% moisture threshold for bank toughness suggested by Marlow and Pogacnik (1985). The late summer streambank moisture in our study rarely dropped below 20%; Stanley Creek averaged 35%, Thatcher Creek averaged 39%, while Park Creek averaged over 100% in its rather boggy, high organic matter soils. No correlations were found with changes in bank angle, stream width, or elevation of the soil surface. A significant correlation occurred between streambank moisture and bank retreat on treated plots, but not those untreated.

Another factor that influences susceptibility of streambanks to deformation is vegetation. Herbaceous roots and rhizomes provide much of the compressive strength and soil stability for streambanks in meadow situations such as our study area (Dunaway and others 1994, Kleinfelder and others 1992). Streambanks on our sites were well vegetated with a variety of plant species. The graminoids most prevalent on 54% (Stanley Creek), 58% (Park Creek), and 90% (Thatcher Creek) of the plots were species with mid to low root strengths such as small-winged sedge and Kentucky bluegrass (USDA Forest Service 1992). The remaining plots were dominated by strongly rooted species as water sedge and Baltic rush. Thus, our study sites were not particularly resistant nor susceptible to streambank damage. Surprisingly, we found no correlation between an index of root strength for the dominant species (USDA Forest Service 1992) and bank response. Several possible reasons include: root-strength index confounded with soil moisture content and soil characteristics; and individual plots typically contained a mixture of species.

Although the benefits to plant composition using rotational or other specialized grazing systems are cited for many conditions (Heitschmidt and Taylor 1991, Holechek et al. 1989), the actual grazing system used has little effect on the total trampling impact (Guthery and Bingham 1996). Since the streambanks in our study did not dry to the level that could potentially allow seasonal protection from trampling damage, the specific grazing system used probably would not have great importance in the study area. Thus, since several of our streambank measures differed little between no grazing and moderate seasonal grazing, while heavy season-long grazing resulted in severe bank deformation within only 2 years, the primary way to control of streambank deformation on our sites is to concentrate on controlling the total animal use of streambank areas rather than to concentrate on manipulation of the grazing system. Control of livestock activity on streambanks is usually easier to accomplish in the spring when livestock are often attracted away from the wetter streamside areas to the floodplain and upland sites (Clary and Booth 1993, Siekert et al. 1985).

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Riparian-Fisheries Habitat Responses to Late Spring Cattle Grazing

Warren P. Clary[1] and John W. Kinney[2]

Abstract.—A grazing study was conducted on a cold, mountain meadow riparian system in central Idaho in response to cattle grazing-salmonid fisheries conflicts. Six pastures were established along a 3rd order, 2 to 3 m wide stream to study the effects on fisheries habitat of no grazing, light grazing (20 to 25% use), and medium grazing (35 to 50%) during late June. Most measurements of streamside variables moved closer to those beneficial for salmonid fisheries when pastures were grazed to a 10 cm stubble height; virtually all measurements improved when pastures were grazed to 14 cm stubble height, or when pastures were ungrazed. Many improvements were similar under all 3 treatments indicating that these riparian habitats are compatible with light to medium spring use by cattle (Clary 1999).

Introduction

Riparian areas, among the most important features of natural landscapes, have a unique biotic productivity and diversity compared with the surrounding mosaic of terrestrial habitats (Kondolf et al. 1996). These areas typically function to moderate hydrologic conditions (Hawkins 1994), and they are highly valued for their multiple-use values, including grazing. Concerns about the impacts of grazing on riparian areas have been raised in the last several decades (US GAO 1988). Therefore, there is a critical need for grazing practices that permit livestock production while preserving the riparian characteristics needed for wildlife habitat, native fisheries, and water quality.

The present study was initiated in response to grazing-fisheries conflicts in the Sawtooth National Recreation Area. This study spanned a 10-year period and examined the response of a cold, mountain meadow riparian system to three intensities of late June cattle grazing.

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Study Area

The grazing study was initiated in 1987 on Stanley Creek, Sawtooth National Recreation Area, Sawtooth National Forest, central Idaho. The study area is at latitude 44° 15' 46" N; longitude 114° 59' 02" W, where Stanley Creek flows through a broad, flat valley with a westerly aspect at an elevation of 1,950 m. The creek averages 2 to 3 m in width. Annual precipitation during the treatment years (1987 through 1995) was approximately 20% to 25% below the 389 mm average. Precipitation was 46% higher than average during the post-grazing year (1996) when final measurements were taken. Long-term average temperature during the June grazing period is 11 °C; average annual temperature is 2 °C.

The area is representative of a mountain meadows ecosystem in a forest zone of the Western United States containing wet to intermittently wet sites. Typical plant species included: Kentucky bluegrass *(Poa pratensis)*, tufted hairgrass *(Deschampsia cespitosa)*, water sedge *(Carex aquatilis)*, beaked sedge *(C. rostrata)*, Baltic rush (*Juncus balticus)*, foxtail *(Alopecurus* spp.*)*, timber danthonia *(Danthonia intermedia)*, thick-stemmed aster *(Aster integrifolius)*, cinquefoil *(Potentilla* spp.*)*, gentian *(Gentiana* spp.*)*, Lemmon's willow *(Salix lemmonii)*, and Drummond willow *(S. drummondiana)*.

Stanley Creek and the surrounding meadows have had a long history of use and disturbance by European settlers. Mining, water diversion, travel routes, and heavy grazing by sheep and cattle all occurred within the last 140 years. Few records of grazing history are available before the 1970s. In the decade immediately preceding this study the dry meadow areas were experiencing use rates of 60 to 65%. No records of use along the stream edge were available.

Materials and Methods

Six experimental pastures, 3.7 to 9.0 ha, were established along Stanley Creek in fall 1986. Grazing was conducted annually with cow-calf pairs in the last half of June from 1987 through 1995, except for 1993 when concerns about federal listing of chinook salmon *(Oncorhynchus tshawytscha)* as a threatened species precluded grazing. Two pastures were assigned to each of the three treatments: medium grazing (average of 2.20 animal units months [AUM] ha^{-1}), light grazing (average of 1.27 AUM ha^{-1}), and no grazing. Target use rates on the dry meadow portions of the pastures were 50% for the medium, 25% for the light, and 0% for the no grazing treatments. Stocking was adjusted so that all pastures were grazed for a similar period (usually 14 days).

Stream channel characteristics were determined on 31 cross-stream transects per pasture during mid summer in 1986, 1990, 1994, and 1996. Variables measured included wetted width, average wetted depth, bank stability, bank alteration, channel bottom embeddedness, and channel bottom textural composition. Streamside plant attributes were determined on 45 to 59 0.25-m^2 plots per pasture. Sampling was conducted in 1987, 1990, 1994, and 1996. Willow heights were measured at the beginning and the end of the study (1987 and 1996).

Analyses were based on comparisons between the initial reading for a variable and later readings. Stream profile variables were analyzed as proportional changes because stream channel width and width / depth ratio were physically limited in their potential response. Other variables were analyzed based on numeric differences between initial and later readings. Variables were transformed as necessary to normalize data distributions. Analyses of treatment effects were conducted by Analysis of Variance (ANOVA) using a General Linear Model. Repeated measures analysis was used when data included more than one response year. Plant community-type frequency of occurrence was examined by Chi-square analysis. Significant differences among means in ANOVA tests were identified using a protected Fisher's Least Significant Difference. Additional T-tests were conducted to determine if responses within individual treatments differed from the initial readings. Probabilities of 0.05 or less were considered significant in all analyses.

Results

Streamside graminoid use averaged 35.2% for the medium grazing treatment and 21.6% for the light grazing treatment (equivalent rates for the dry meadow were 51.8% and 25.0%). The residual streamside stubble heights for graminoids immediately following grazing were 10.5 cm for medium grazing and 14.1 cm for light grazing. Season-end stubble heights were 12.9 cm for medium grazing, 16.4 cm for light grazing, and 26.2 cm for no grazing. These use levels were apparently less severe, and the season of grazing more restricted, than had been the situation on the study site for most of this century.

Stream Channel

A decrease in stream width occurred under all treatment regimes from 1986 to 1996 (Clary 1999). The average amount of narrowing was inversely associated with grazing intensity. The ungrazed pastures, which displayed the greatest stream narrowing, showed the greatest increase in stream depth compared to 1986. The width / depth ratio decreased under all treatments at study end as compared to pre-study conditions; the ungrazed treatment produced greater decreases than either grazed treatment. Ratings of streambank stability improved at a similar rate for the three grazing treatments. Ratings of physical streambank alteration decreased under all treatments by the end of the study; the ungrazed treatment showed the most change. Large particle embeddedness in the stream channel bottom had decreased in all treatments at study end; the least change occurred under medium grazing. By the end of the study, fine sediments had decreased under light grazing, but they had remained the same under heavy grazing and no grazing.

Riparian Vegetation

Willow height and cover increased under all treatments during the study period (Clary 1999). The changes in height did not differ among treatments; whereas, the greatest increase in willow cover occurred in the absence of grazing. Graminoid heights and cover did not differ among treatments, nor did differences occur in frequencies of individual plant community-types in the streamside locations. An increase occurred, however, in frequency of a combined group of strongly-rooted, late seral species (water sedge, beaked sedge, baltic rush, and bluejoint reedgrass [*Calamagrostis canadensis*]) in the ungrazed and lightly grazed pastures. This increase was nearly matched by a nonsignificant downward trend in the Kentucky bluegrass community-type. The grazed treatments experienced a greater increase in total plant species during grazing than the ungrazed treatment.

Discussion

Grazing along streambanks does as much or more damage to stream-riparian habitats through bank alteration as through changes in vegetation biomass. Overuse by cattle can easily destabilize and break down streambanks as vegetation is weakened and hoofs shear bank segments. As grazing and trampling damage decrease, residual vegetation helps to trap sediments that serve as base material to rebuild streambanks (Clary et al. 1996). When streambanks rebuild and channels narrow, the decreased width / depth ratio improves the stream's hydraulic and sediment transport efficiency, and provides potential increases in fish hiding cover (Bjornn and Reiser 1991, Kozel et al. 1989, Morisawa 1968).

All treatments decreased in substrate embeddedness by the end of the study, but the decrease in proportion of the surface composed of fine sediments was variable. This response may have been affected by downstream movement of old dredge mining sediments. Channel bottom conditions are greatly affected by sediments from upstream sources and may not respond rapidly to on-site management (Rinne 1988).

Streamside vegetation canopies, particularly of various species of willow, provide fish with cover, modulate stream temperatures, and contribute leaf detritus and terrestrial insects that expand food sources for fish (Murphy and Meehan 1991). Willow characteristics of height and cover increased under all treatments of this study. Maintenance of an adequate herbaceous forage supply (Winward 1994, Pelster 1998) and control of grazing season (Kovalchik and Elmore 1992, Winward 1994) reduced impacts on the willow community compared to historic grazing procedures . Some impact on willows is typical even under managed grazing (Myers and Swanson 1995), thus, the positive growth response of willows in this study exceeded expectations.

The extent and strength of late seral, graminoid community-type roots and rhizomes provide essential stability to streambanks in meadow sites (Kleinfelder et al. 1992, Dunaway et al. 1994) allowing undercuts to form as habitat segments for salmonids (Platts 1991). The increase in frequency of these plants in moist streamside locations under light or no grazing was expected (Green and Kauffman 1995).

Although changes were slow in this cold mountain valley, these early season grazing regimes allowed improvements in stream channel conditions and streamside characteristics. Most measurements improved to some degree under all 3 treatments. This suggests that practices that leave 10 to 14 cm of residual forage stubble height provide an avenue for riparian habitat improvement while maintaining substantial livestock use of cold mountain meadow areas.

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Watersheds and Fisheries Relationships: State of Knowledge, Southwestern United States

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Abstract.—The relationships and interactions of stream courses, their watersheds, and their aquatic biota have become a contemporary paradigm. Principles and practices of these relationships are generally understood, however, understanding their implications at a landscape scale is embryonic. Because of the threatened and declining status of the native fish fauna of the Southwestern United States, understanding relationships between fish and watershed condition, and the influence of watershed management on stream habitats is critical. The native fish fauna of the American Southwest are low in diversity, unique, threatened and continually declining. The primary objectives of this paper are to briefly state what we know about fish and watershed relationships, define the status of our knowledge, discuss the effects of landscape-level management activities and natural episodic events, and provide recommendations for future habitat, fish research, and management activities.

Introduction

The relationships and interactions of streams, their watersheds, and their aquatic biota are a contemporary land management paradigm (Rosgen 1996). The principles and practices of these hydrologic, geomorphic, and ecologic relationships are generally known, however, a clear understanding of their implications at a landscape scale is incomplete. Although not completely implemented in our land management activities or research studies, the trend is to increase our understanding through integrated management and research. The recent Clean Water Action Plan, an administrative initiative, will increase our knowledge of the linkage of water quality and quantity, watershed condition, and land use. The Clean Water Action Plan, Organic Act of 1897 which established the Forest Service, and other environmental legislation enacted over the past 3 decades provides the legal basis to manage watersheds, their riparian-stream courses, and fish communities.

Because of the threatened and declining status of the native fish fauna of the Southwestern United States, understanding the relationships between fish and watershed condition, and the influence of watershed management on stream habitats is critical (Rinne and Stefferud 1999). The native fish fauna of the American Southwest is low in diversity, unique, threatened, and continually declining (Rinne and Stefferud 1998, Rinne and Minckley 1991).

This paper addresses a complex and currently contentious resource management issue. The primary objectives of this paper are to: state what we know about fish and watershed relationships, define the status of our knowledge in the Southwest, discuss the effects of landscape-level management activities and episodic events, and provide recommendations for future direction in research and land management.

Fish and Watershed Relationships

General Relationships

Early attempts to understand watersheds and their impacts on fishes and fisheries began in the 1970s from studies of the effects of timber management on salmonids in the Pacific Northwest (Chamberlain et al. 1991). The primary focus linking watershed effects on salmonid fishes and fisheries was water quality. Sediment production, including transport and deposition into stream gravels, and its effects on habitats for spawning salmonids, was a major element of study (Hicks et al. 1991). Numerous papers in the 1980s addressed the effects of this watershed management activity on salmonids. Eventually it became apparent that other watershed management activities, such as mining, road building, recreation, urbanization, grazing, and water impoundment and diversion, also impacted on aquatic ecosystems and their fish communities. For the most current discussions of all these factors and their effects on salmonid fishes and their habitats see Meehan (1991).

The Southwest

The relationships between watersheds and fish have only recently become an emphasis for management and

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research in the Southwest. Research and monitoring activity in both fields have basically evolved separately, with little effort placed on understanding the effects of watershed activities on stream ecosystems and, in turn, fish habitat and populations.

The earliest efforts in watershed research in the Southwest were in the 1950s. The Arizona Watershed Program was a joint venture of the State Land Department, the Department of Health Services, the Arizona Water Commission, the USDA Forest Service, and others (Ffolliott et al. 1998). The primary objective of this research program was to increase water yield in the arid southwestern landscape. The Forest Service initiated numerous studies at various locations throughout the state including the Beaver Creek Watershed in 1957 (Carder 1977). Research at Beaver Creek continued for over two decades and produced extensive information on the influence of land management activities (timber harvest, chaparral replacement, pinyon-juniper removal, snow pack management, etc.) on water yield. Although water quality data was a component of study, fish were not included.

During this time, the dam building era commenced with the first U.S. Bureau of Reclamation Dam (Roosevelt on the Salt River). Fisheries research was focused on the effects of mainstream structures on fish and their habitats (table 1). Accompanying the large, artificial water impoundments was an extensive introduction of nonnative fish species, largely from the Mississippi River drainage (Rinne 1991, 1994, 1995). Since the 1970s, research has been on the effects of these introduced fishes on riverine and stream habitat and on their native fish fauna. Until recently, no effort has been made to examine the relationships between watersheds and fish.

Consideration of the linkages between watersheds and fisheries began in the Southwest with passage of the National Environmental Policy Act of 1969, the Clean Water Act of 1972, and the Endangered Species Act of 1973. These acts required greater consideration of the relationships among ecosystem components and increased the focus on the effects of land use activities on fish and wildlife resources, especially threatened species (Rinne and Medina 1996). Federal agencies to give greater emphasis to examining watershed began to place greater emphasis on the effect of watershed use activities on native, listed fishes and their habitats. The earliest listings of fish were 2 native Southwestern montane species, the Apache and Gila trouts. Watershed influences on riparian-stream areas and fish continues to be a research focus. This effort is intensifying and is ddressing other listed fish in streams originating on National Forest System lands.

Unlike the Pacific Northwest, ungulate grazing rather than logging is the major land use activity that has affected the native fish fauna (table 1). However, the current research approach has been focused on studies within riparian-stream, not on watersheds. The effect of grazing on fish is not well understood (Rinne 1998), therefore the effects of grazing in watersheds on fish in turn on fishes, have not even started to be adequately addressed.

Physical Factors

The immense diversity of both the Southwest terrain and climate has and will continue to make study of watershed effects on fishes and their habitats extremely difficult. Cycles of flooding and drought together with introduced species are being demonstrated to be prime controlling factors for native fish populations in the Southwest (Rinne and Stefferud 1996, 1998; Rinne et al. 1998). These and other natural physical factors are proving to be overriding in comparison to many watershed management

Table 1. Watershed management activities, fish issues, and research needs in the Southwestern United States.

Watershed management activity	Fish concern	Research needs
Exotic fish introduction	Predation, displacement	High
Cattle grazing	Habitat alteration, erosion	High
Elk grazing	Habitat alteration, erosion	High
Groundwater development	Habitat loss	High
Wildfire	Habitat loss, erosion, water quality	High
Roads and logging	Sedimentation, water quality	High
Mining	Habitat loss, water quality	High
Diversions and dams	Habitat loss, population isolation	Medium
Recreation	Habitat alteration, water quality	Medium
Urbanization	Habitat alteration, water quality	High

activities conducted by humans. Wildfire also has had dramatic effects on fish habitats and populations in upper elevation streams (Table 1, Rinne 1996, Rinne and Neary 1996). As we move into a new century and millennium, there is increasing emphasis on the effects of watershed management on fishes. However, despite decades of watershed-scale research, efforts to link watershed management and fish population dynamics are embryonic, at best, and currently a predilection rife with faulty suppositions and hypotheses.

Future Recommendations

Ecosystem management (USFS 1992) and the watershed approach (Williams et al. 1997) are the current "buzzwords" in the Forest Service and other Federal agencies at the national level. Linking these two terms with fisheries management in the Southwest is the current challenge. The State of Arizona is in process of addressing their fisheries management in context of watersheds or river basins. The Forest Service is increasingly establishing ecosystem management areas. The key will be multi-agency approaches to watershed management such as the East Clear Creek Ecosystem Management area on the Coconino and Apache-Sitgreaves National Forests. In such management areas, all resources (timber, grazing, recreation, hydrology, fisheries, etc.) are being considered jointly. In absence of such cooperative endeavor, watersheds and fisheries will not be linked and interrelated in the near future. The recent Clean Water Action Plan has precipitated the formation of watershed demonstration areas. A half dozen river-stream demonstration areas spanning lower to upper elevation watersheds are being proposed for funding for Arizona and New Mexico. A watershed approach embraces, and is compatible with, a multi-species approach to fisheries management as opposed to single species (Rinne and Stefferud 1998).

Research and Management Cooperation

Collaborative efforts using the latest technologies such as GIS will be vital in moving forward our understanding of watershed-fishery relationships in the Southwest. Watersheds in the Southwest Region of the Forest Service are currently being converted into GIS databases. Similarly, in the very near future through collaborative efforts of Arizona State University and the Forest Service, all fish data such as location, species, life history, etc. for Arizona and New Mexico will be stored in a GIS data base. GIS layering of USFS land uses such as grazing, logging, recreation, presecribed and wild fires combined with State classified impaired watersheds, fish location data, diversions, dams and roads on watersheds, will greatly enhance the effort to intermesh watershed and fishery management and identify research additional needs. Conceptually, it will also increase the probability that native fish species will be sustained.

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Evaluating the Ecological Economic Success of Riparian Restoration Projects in Arizona

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Abstract.—In the past 4 years the Arizona Water Protection Fund provided more than $25 million to individuals and organizations for stream and riparian restoration projects in Arizona. Information which increases the awareness of the value of Arizona's riparian systems is crucial to the incorporation of ecosystem services into decision-making frameworks, which are largely structured in economic terms. Many individuals reject an anthropocentric perspective of the measure and valuation of ecological goods and services believing they should be protected for purely moral or aesthetic reasons. Others argue that recognizing the economic value of ecological goods and services is not only useful, but may in fact be necessary if we hope to succeed in sustaining the Earth's basic life-support systems. If conservation and restoration of ecosystem services can be shown to be of *economic value*, then the dialog becomes not one of discourse but of compliment. Just as firms must account for their capital depreciation and reinvest in their capital to remain viable, humans must account for *natural capital* depreciation and reinvest in conditionally renewable resources to be sustainable. This research seeks to develop a *natural capital* budget for the Upper Verde watershed. The analysis of total natural capital includes relevant ecological goods and services such as flood control, water purification, water supple, recreation and habitat.

Stream Channel Designs for Riparian and Wet Meadow Rangelands in the Southwestern United States

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Abstract.—Inappropriate land uses have degraded wetland and riparian ecosystems throughout the Southwestern United States. In 1996, the Cibola National Forest in New Mexico implemented a channel relocation project, as part of a road improvement project, to determine the feasibility of restoring wet meadow and riparian ecosystems degraded by inappropriately located roads and drainage structures. Results show that channel relocation can provide the hydrologic inputs needed to restore these degraded ecosystems.

Introduction

Wet meadows and riparian ecosystems in the Southwestern United States comprise less than 10% of the landscape. Despite their small size, they can support higher diversities of plant and animal species. Inappropriate land uses, such as roads, grazing, borrow pits and recreation, can contribute to the degradation of these areas and adjacent lands. Degraded wetland and riparian channel conditions can include incised channels, wide-braided, undefined channels, low channel sinuosity, dry or abandoned channels, flashy uncontrolled flows, and minimal water infiltration into surrounding soils.

The watershed management practices of public and some private land management agencies aim to protect and restore degraded wetland and riparian ecosystems. A permanent soil-water supply is a requirement in the restoration process. If degraded by incompatible uses, wetland and riparian ecosystems can often be restored and improved by modification or elimination of the incompatible uses. When elimination is not an option, stream channel restoration can provide opportunities to reinstate degraded hydrologic conditions.

Attempts to restore and relocate stream channels have yielded mixed results from increased runoff flows with longer durations and more habitat created for terrestrial and aquatic species to further site degradation (Kondolf and Micheli 1995). Documented successful and failed attempts at stream channel manipulations help managers and researchers understand why information about watershed hydrologic principles and practices are necessary (Rosgen 1996). Knowledge and information needs include precipitation and runoff relationships; soil characteristics include texture, depth and surface exposure; channel characteristics include width-depth ratios, sinuosity and slope; and vegetation characteristics include type, percent cover and root structure (Branson et al. 1981).

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New Mexico Experience

Cibola National Forest

The Cibola National Forest in New Mexico implemented the Agua Fria riparian meadow reestablishment project as part of a forest road improvement program in 1995 (Jemison et al. 1997). An assessment of the impacts of the old road on meadow ecosystem suggested that construction of the roadbeds altered the hydrologic conditions of the meadow surface where they were crossed. Before the project, an entrenched channel ran lengthwise down one side of the meadow passing below the road through a cement bridge, then diverting to the other side of the meadow (figure 1). Steps taken to implement the project included removal and earth fill of the bridge crossing; earth fill of the old channel in areas where it could be flooded by overland flow from the new channel; construction of a shallow, sinuous channel down the center of the meadow with a broad floodplain on each side; and installation of rock weirs at the beginning and end of each bend in the channel to create a step pool sequence.

Results

Results from 1996 to the present indicate runoff flowed in the constructed channel during the spring of 1996 and 1998 from snow melt at higher elevations. Over-bank flooding occurred for extended periods during those events. The water table below the meadow never in-

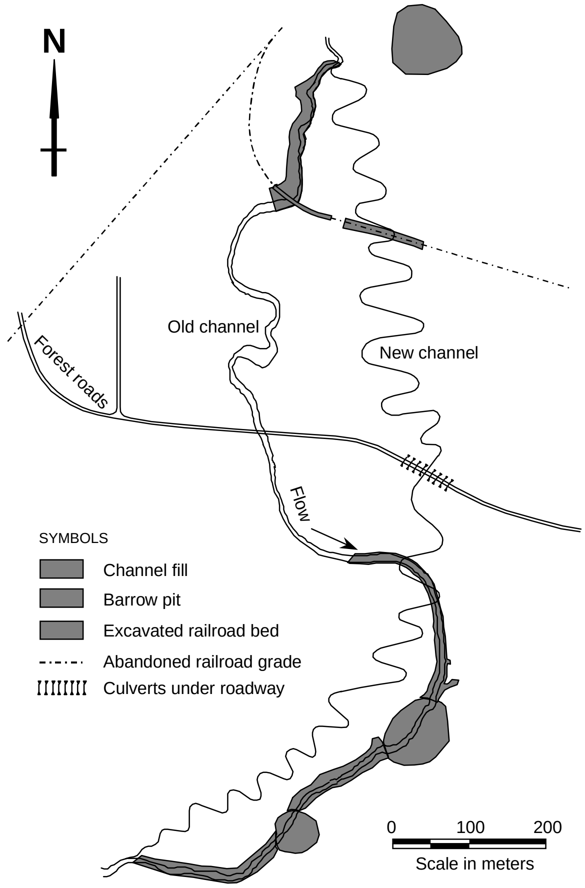

Figure 1. Layout of the Agua Fria channel reconstruction site.

creased to within 10 m (deepest well recorder) of the surface. Above the road crossing, the channel directed the water through the meadow as expected. However, below the road, water that flowed over the channel banks was diverted away from the channel by earth fill where it crossed a section of the old channel. The diverted water flowed along the fill and caused extensive head-cutting and surface erosion of the lower meadow. Results will be expanded upon as data are analyzed for runoff, channel profiles, soils and vegetation. These results will assist land managers and road engineers to design and build roads that are compatible with wetland and riparian ecosystems.

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Fire–Induced Water Repellency: An Erosional Factor in Wildland Environments

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Abstract.—Watershed managers and scientists throughout the world have been aware of fire-induced water-repellent soils for over three decades. Water repellency affects many hydrologic processes, including infiltration, overland flow, and surface erosion (rill and sheet erosion). This paper describes; the formation of fire-induced water-repellent soils, the effect of soil water repellency on infiltration and runoff, erosional processes unique to water-repellent soils, and the results of watershed and plot studies used to evaluate watershed-level responses to water repellency.

Introduction

Hard-to-wet soils are commonly found on freshly burned watersheds, particularly on those covered with chaparral brush. Hydrophobic organic compounds found in plant litter are vaporized during wildfires and condense at or near the mineral soils surface where they produce a water-repellent layer. This layer reduces infiltration of rain water into soil surface, causing overland flow and extensive surface erosion. This paper provides a theory for the formation of a water-repellent layer during a fire and describes the effects of fire-induced water repellency on postfire infiltration and erosion.

Fire-Induced Water Repellency

A hypothesis describing how a water-repellent layer is formed beneath the soil surface during a fire has been developed (DeBano et al., 1998). According to this hypothesis, organic matter accumulates on the soil surface under vegetation canopies during the intervals between fires. During fire-free intervals, some water repellency can be found in the organic-rich surface layers, particularly when they contain prolific fungal mycelia.

The combination of fuel combustion and heat transfer during wildfires produces steep temperature gradients in the surface layers of the mineral soil. Heat produced during combustion of litter and above-ground fuels vaporizes organic substances which are moved downward into the underlying mineral soil where they condense in the cooler underlying soil layers, forming a distinct water-repellent layer below and parallel to the soil surface.

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Water Movement and Erosion

Fire affects water entering the soil in two ways. First, the burned soil surface is unprotected from raindrop impact, which loosens and disperses fine soil and ash particles that can seal the soil surface. Secondly, soil heating during a fire produces a water-repellent layer at or near the soil surface that impedes infiltration into the soil. This severity of the water repellency in the surface soil layer, however, decreases over time as it is exposed to moisture; so that, in many cases, it does substantially affect infiltration beyond the first year following fire.

Raindrop Splash

When the water-repellent layer is formed at the soil surface, the hydrophobic particles are more sensitive to raindrop splash than a wettable soil surface when both soils are were exposed to different rainfall intensities, durations and soil surface inclinations (Terry and Shakesby, 1993). Synchronized measurements by video cameras have shown that raindrop impact on hydrophobic soils produced fewer, slower-moving ejection droplets, which carry more sediment a shorter distance than a wettable soil. The soil surfaces having an affinity for water (wettable soil) become sealed and compacted during a rainfall event which makes them increasingly resistant to splash detachment. Conversely, the hydrophobic soil remains dry, noncohesive and are easily displaced by splash when the raindrop breaks the surrounding water film.

Rill Formation

A reduction in infiltration caused by a water-repellent layer quickly causes a highly visible rainfall-runoff-erosion pattern to develop on burned watersheds. The increased surface runoff quickly entrains loose particles of soil and organic debris found on the soil surface following fire. Surface runoff may quickly concentrate into well-defined rills and increase surface erosion, particularly on steep slopes. As a result, extensive rill networks develop when rainfall exceeds infiltration rates during the first postfire rainstorms (Wells 1987).

The sequence of rill formation has been found to follow several well-defined stages. First, the wettable soil surface layer, if present, is saturated during initial infiltration. Water infiltrates into the wettable surface until it encounters a water-repellent layer (Wells 1987). This process occurs uniformly over the landscape so that when the wetting front reaches the water-repellent layer, it can neither drain downward or laterally. As rainfall continues, water fills all available pore space until the wettable soil layer becomes saturated. Because pores cannot drain, positive pore pressures build up immediately above a water-repellent layer. This increased pore pressure reduces intergranular stress among soil particles, and as a result, decreases shear strength in the soil mass and produces a failure zone at the boundary between the wettable and water-repellent layers where pore pressures are greatest. Pore pressure continues to increase and shear strength decreases until it is exceeded by the shear stress of gravity acting on the soil mass. When this happens, a failure occurs and a portion of the wettable soil begins to slide downslope. If the soil is coarse textured, initial failure causes a reorientation of the soil particles in the failure zone and causes them to momentarily lose contact with each other. The loss of intergranular contact further reduces shear strength and extends the failure zone downslope. When most of the soil grains lose contact, a condition develops in which the shearing soil is almost fluid. This fluid condition produces a miniature debris flow in the upper wettable soil layer, which propagates to the bottom of the slope or until it empties into a channel.

Water in the wettable soil layer adjacent to the debris flow is no longer confined and can flow out into the rill formed by the debris flow and the free-flowing water runs over, and erodes into, the water-repellent layer. Flowing water confined to the rill still cannot infiltrate into the water-repellent soil and, therefore, it flows down the debris flow track as free water in an open channel. As the water flows down the track, turbulent flow develops, which erodes and entrains particles from the water-repellent layer. The downward erosion of the water-repellent rill occurs until flow eventually cuts completely through the water-repellent layer and begins infiltrating into the underlying wettable soil. Flow then diminishes, turbulence is reduced, and downcutting ceases. Finally the rill is stabilized immediately below the lower edge of the water-repellent layer. The individual rills formed by the above process develop into a network that can extend the length of a small watershed.

Hillslope and Watershed Responses

Studies on the effects of fire-induced hillslope runoff and erosion from natural watersheds are much more difficult to establish than those dealing with the occurrence of specific erosional processes (e.g. raindrop splash, rill erosion). This is because wide spatial and temporal variation occurs in natural ecosystems. Two general techniques have been used to study the hydrologic responses to water repellency in outdoor environments. One uses small plots and the other focuses on entire watersheds.

Hillslope Responses

Small plots are a popular technique for studying water repellency under field conditions and have been used extensively for studying hillslope runoff and erosion. Rainfall can occur naturally or be applied with a rainfall simulator. For example, it was found on small hillside plots under an eucalyptus forest in Australia, that fire-induced water repellency produced localized runoff and sediment movement only on hillslopes, but did not appreciably affect watershed performance (Prosser and Williams, 1998). Plot studies have also been used to study the spatial variability of water repellency (Doerr et al., 1998) and the relationship between the spatial distribution of water repellency and the erosion potential produced during prescribed burning (Robichaud, 1996).

The results of several plot studies suggest that the hydrologic responses to fire-induced water repellency depend upon soil dryness. During evaluation of the hillslope module for the Water Erosion Prediction Project (WEPP), higher runoff coefficients were consistently measured during dry periods compared to the remainder of the year (Soto and Diaz-Fierros, 1998). The increased runoff was attributed to an increase in the severity of water repellency at lower soil water contents during the dry season. A study of overland flow from small burned and unburned plots in Portugal identified two mechanisms that were responsible for runoff. After long dry periods, overland flow was Hortonian and was linked closely to the presence of hydrophobic soils (Walsh et al., 1994). During wet periods, however, soils lost their hydrophobicity and overland flow resulted from a perched water table developing in shallow soils. A study on small plots in Portugal also concluded that during extended dry periods latent soil hydrophobicity appeared to become re-established, leading to increased runoff generation and soil loss (Terry, 1994). Water repellency in soil increases upon drying because additional, and more stable, organic coatings responsible for water repellency are formed (Dekker et al., 1998).

Watershed Responses

Predicting watershed responses by using information gained from conceptual models, laboratory studies, field observations, and runoff and erosion data from small plots is extremely difficult because extrapolating these relationships to a watershed scale often fails to recognize the increased variability found in these heterogeneous and highly complex natural systems. One useful technique for evaluating watershed responses to different treatments is to use paired watersheds with the control and treated watersheds having been calibrated against each for several years before and following a treatment (in this case, prescribed fire or wildfire).

The best documented studies reporting simultaneous measurements on fire-induced water repellency, runoff and erosion from small plots, and total watershed response have been done in South Africa. Although several studies were conducted, the most comprehensive study measured streamflow, stormflow, and sediment yields on four catchments following a fire (Scott 1993). Two catchments (Swartboskloof and Langrivier) were covered with over-mature scrub vegetation (fynbos) prior to burning, a third catchment (Ntabamhlope) was covered with eucalypt forest (*Eucalyptus fastigata*), and a fourth catchment (Bosboukloof) with pine (*Pinus radiata*). One of the fynbos catchments (Swartboskloof) was burned by a prescribed burn and all other watersheds were burned during wildfires. The catchments were instrumented to determine changes in total streamflow volume, some stormflow characteristics, and the sediment yields of each catchment in terms of suspended sediment and bedload. Soils were sampled for water repellency at 12 to 15 locations in each major vegetation type on two catchments (Bosboukloof and Swartboskloof) to assess the effect of fire on soil wettability. On the remaining catchments, only brief qualitative field surveys were carried out after the fires to determine the extent of water repellency in soils. In addition, overland flow plots (3 X 22 meters) were established after the fires on two of the catchments (Bosboukloof and Swartboskloof). On the other two watersheds plots were established but only total sediment yield was measured. The differences in burning conditions (prescribed fire versus wildfires) and the vegetation cover (scrub and forest trees) produced several measurable differences. Under severe fires, produced when heavy, dry fuel loads were consumed, postfire erodibility was increased. Prescribed burns, particularly after rains, did not completely consume fuel materials. Vegetation types which lead to the development of hydrophobic soils (i.e., eucalyptus and pine) produced sharp hydrological responses which played a part in generating surface runoff following fire. Neither of the two fynbos watersheds produced substantial increases in stormflow or total flow increases. In contrast, on the two timbered catchments, substantial increases in stormflow and soil losses occurred. The effects of fire were considered to cause the changes in stormflow generation consistent with an increased delivery of overland flow (surface runoff) to the stream channel. This was caused, in part, by the reduced infiltration resulting from water repellency in the soils of the burned catchments. Overall, the hydrological responses to fire were related to numerous interactive factors, including the degree of soil heating, the vegetation type, and the soil properties.

Summary

It has been well-established by numerous well-designed laboratory experiments and studies involving small hillslope plots that water repellency can be intensified by soil heating during a fire and that the resulting water repellency developing in soils impedes infiltration into the soil, leading to extensive surface erosion. However, extrapolating information gained from these laboratory and small plot studies to entire catchments is complex because of the spatial and temporal variability of fire-induced water-repellency patterns. The identification of specific effects of water repellency on catchment performance requires knowing how fire reduces vegetative cover, destroys surface litter, degrades soil structure, and changes a host of other parameters which also can affect the overall hydrologic performance of a catchment. Very few studies have evaluated on-site water repellency, hillslope hydrology, and watershed response simultaneously. Research to date, however, indicates that fire-induced water repellency can have a substantial effect on watershed responses, particularly during the first year following fire.

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Assessment of Effects of Canopy Disturbance on Plants in a Pinyon-Juniper Stand

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Abstract.—An important objective of studying understory/overstory relationships is to determine the patterns of succession or development within the understory plant community following a severe disturbance to the overstory. In 1988, a commercial fuelwood harvest was applied to a pinyon-juniper stand. The remaining noncommercial overstory was cut and lopped. Two years later, approximately two-thirds of the area was crushed by a roller-chopper, which breaks up the slash material and incorporates it into the soil. A year later, the remaining one-third of the non-crushed slash was burned. Three pairs of sites were examined: an intensely burned canopy site with, its adjacent blue grama interspace, a roller-crushed canopy site with its adjacent blue grama interspace, and an uncut canopy area with it adjacent blue grama interspace. Comparisons made between and among all treatment-site situations showed significant biomass productivity and species diversity differences. Biomass and species diversity appeared greatest in the roller-crushed area.

The Fire and Fire Surrogates Study: Providing Guidelines for Fire in Future Forest Watershed Management Decisions

Carleton B. Edminster[1], C. Phillip Weatherspoon[2], and Daniel G. Neary[3]

Abstract.—As part of the 1998 Joint USDA / USDI Fire Science Program, the Fire and Fire Surrogates Study was proposed to establish and evaluate cross-comparisons of fuels treatment practices and techniques to reduce wildfire risk. This study evaluates prescribed fire, thinning, and various mechanical treatment methods for treating, removing, or using woody biomass. Site-specific and study-wide evaluations will assess watershed impacts, soil disturbance, vegetation responses, wildlife changes, ecological consequences, social impacts, economics, and potential effects on wildfire size, severity, and cost. The study design is flexible to address local treatment variations and effects and will be installed at 10 locations representative of Interior Washington-Oregon, Northern California, Sierra Nevada, Rocky Mountain, Southwest Ponderosa Pine, Southern Pine, and mixed hardwood-oak forest ecosystems. This paper outlines the study components and discusses the potential for providing guidance on the treatment of fuels and use of fire for future watershed management decisions.

Introduction

Many forests in the Western United States, especially those with historically short-interval, low- to moderate-severity fire regimes, are too dense due to long-term fire exclusion and short-term reductions in timber harvesting (Parsons and DeBenedetti 1979). These forests have excessive quantities of fuels that increase their risk of catastrophic, severe, stand-replacing wildfires. Fire of this magnitude causes severe impacts on watershed resources and greatly complicates future watershed management (Agee 1993, Neary 1995, DeBano et al. 1996, DeBano et al. 1998).

Widespread silvicultural treatments are needed to restore ecological integrity and reduce the high risk of destructive, uncharacteristically severe fires in these forests (Weatherspoon and Skinner 1996). However, the appropriate balance among thinning, mechanical fuel treatments, and prescribed fire is often unclear. For improved decision making, resource managers need better information about the consequences of alternative management practices involving fire and mechanical / manual treatments.

Long-term, interdisciplinary research should be initiated to learn the consequences and tradeoffs of alternative fire and fire surrogate treatments. Ecological, economic, and social aspects must be included as integral research components. Such research will determine which fire ecosystem functions can be emulated satisfactorily by other means, which may be irreplaceable, and the management implications of either decision. The human dimensions of the problem are equally important. Treatment costs, utilization economics, and social and political acceptability influence decisions about treatment alternatives. Such research must be a cooperative effort, involving land managers, researchers, and other interested parties.

A team of scientists and land managers, with support from the USDA / USDI Joint Fire Science Program (http://www.nifc.gov/joint_fire_sci/index.html), is designing an integrated national network of long-term research sites to address this need. The steering group and other participants in this national Fire and Fire Surrogates (FFS) study represent federal and state agencies, universities, and private entities, from a wide range of disciplines and geographic regions. The study will use a common experimental design to promote broad applicability of results.

Objectives

The goal of the proposed FFS research is to quantify the ecological, economic, and social consequences of alternative fire and fire surrogate treatments in a variety of forest types and conditions in the United States. Priority is given to forests with low- to moderate-severity natural fire regimes. The specific objectives of the FFS study are:

1. Quantify the effects of fire and fire surrogate treatments on specific core response variables.
2. Provide an overall research design that: a) establishes and maintains the study as an integrated national network of long-term interdisciplinary research sites using a common core design to

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promote broad applicability of results; b) allows individual site distinction for statistical analysis and modeling, while being a component of the national network; and c) provides flexibility for investigators and other participants to augment, without compromising, the core design to address locally-important issues and to exploit local expertise and other resources.

3. Develop and validate models of ecosystem structure and function, and successively refine recommendations for ecosystem management.

4. Establish cooperative relationships, identify and establish network research sites, collect baseline data, implement initial treatments, document short-term responses to treatments, report results, and use research sites as demonstration areas for technology transfer to professionals and for the education of students and the public.

5. Develop and maintain an integrated and spatially-referenced database to archive data for all network sites, promote the development of multi disciplinary and multi-scale models, and integrate results across the network.

6. Identify, develop, and field test response variables or measures that are sensitive to treatment and are technically and logistically feasible for widespread use in management contexts.

Research Approach

Experimental Design

The benefits of an integrated study with multiple experimental sites located around the country, such as the FFS study proposed here, can be enhanced if a core experimental design is used. The core experimental design (i.e., elements common to all research sites in the network) consists of the following components.

Treatments

The following FFS treatments will be implemented at each research site: 1) untreated control, 2) prescribed fire only with periodic reburns, 3) initial and periodic thinning followed by residue removal and / or mechanical fuel treatment without prescribed fire, and 4) initial and periodic thinning followed by prescribed fire. Between thinning intervals, fire could be used without any other treatment one or more times. These treatments span a useful range both in terms of realistic management options and anticipated ecological effects. The non-control FFS treatments (treatments 2, 3, and 4) must be guided by a desired future condition (DFC). The DFC will be defined by the vegetation component of the ecosystem by specifying such targets as diameter distribution, species composition, canopy closure, spatial arrangements, and live and dead fuel characteristics. The following fire-related minimum standard will be a starting point for DFCs throughout the FFS network: Each non-control treatment will be designed to achieve stand and fuel conditions such that, if impacted by a head fire under 80th percentile weather conditions, at least 80% of the basal area of overstory trees (predominant, dominant, and codominant trees) will survive.

If this starting point is met for a research site, the DFC should incorporate additional management goals into the site and stand conditions and stakeholder expectations. Beyond the fire-related minimum standard for DFCs and the general treatment definitions given above, it is infeasible and undesirable to prescribe detailed definitions of a core DFC or to prescribe detailed treatment specifications that would apply to all research sites. Each research site must provide this detail to ensure consistent application of treatments at that site.

Replication and Plot Size

Each treatment will be replicated 3 times at each research site, using either a completely randomized or randomized block design. The core set of 4 treatments will be represented in 12 treatment plots at a research site. Each of these 12 core treatment plots will consist of a 10-ha measurement plot surrounded by a buffer. Core variables will be measured in each 10-ha plot. The buffer will receive the same treatment as the measurement plot it surrounds and will be at least as wide as the height of a best site potential tree. Where feasible, the replicated plots will be supplemented by much larger (200 to 400 ha or more) areas treated to the same specifications to promote the study of large-scale ecological and economic / operational questions.

Response Variables

A major aspect of the common design proposed for this study is a set of core response variables to be measured at all the research sites. Core variables encompass several broad disciplinary areas including fuel and fire behavior, vegetation, soils and forest floor / hydrology, wildlife, entomology, pathology, treatment costs and utilization /

economics, and social sciences. Corresponding disciplinary groups have been responsible for developing the core variables and associated measurement protocols including coordinating across groups to ensure consistency, compatibility, and non-duplication of data collection efforts. Intraplot sampling of all variables will be keyed to a 50-m square grid of permanent sample points to be established and maintained in each measurement plot. Spatial referencing of all data to the grid will promote both spatial and cross-disciplinary analyses.

The study is designed to balance the values of an integrated national network of research sites having a common design against the needs at each site to retain flexibility to address important local issues and to use expertise and other available (objective 2). Accordingly, at the discretion of investigators and other participants at a site, the core design can be augmented (provided it is not compromised) by adding FFS treatments, one or more DFCs, response variables, or replications, or by increasing treatment plot size (by increasing buffer width, the 10-ha measurement plot and core data collected within it would remain unchanged). However, such additions generally would require additional funding sources because, except where additions to the core design are specifically justified, the Fire and Fire Surrogates Study only supports implementing the core design at each site.

Research Site Locations

In selecting research locations, we have developed and used the following set of criteria. Each site must:

1. Represent forests with historically short-interval, low- to moderate-severity fire regime and a currently high risk of uncharacteristically severe fire.
2. Represent widespread forest conditions (site characteristics, forest type and structure, treatment history) that need and will benefit from fire or fire surrogate treatments, and in which such treatments are feasible.
3. Contribute to balancing the overall network through regional representation or land ownership type.
4. Have an adequate land base available.
5. Involve cooperators who are committed to and capable of participating in the program.
6. Include land managers with the ability and willingness to implement experimental treatments successfully within the required time frame, repeat treatments over time, and commit selected sites for long-term research uses.
7. Have partnerships that exist across agencies and with universities, and between researchers and managers. The proposed initial network comprises 10 main sites and 1 satellite site (with less than the full suite of core treatments).

All initial sites represent forests with a historically short-interval, low- to moderate-severity fire regime (table 1). Seven sites are in western coniferous forests, ranging from the Pacific Northwest to the Southwest. On all these sites, ponderosa pine is an overstory component,

Table 1. Proposed study sites.

Site or Geomorphic Province	Land Ownership	State
Mission Creek	Wenatchee N.F.	WA
Hungry Bob/Blue Mountains	Wallowa-Whitman N.F.	OR
Lubrecht Experimental Forest/ Northern Rocky Mountains	University of Montana	MT
Klamath Province	Klamath and/or Shasta-Trinity N.F.	CA
Kings District Study Area	Sierra N.F. and Sequoia-Kings Canyon N.P.	CA
Southwestern Plateau	Coconino N.F. and Kaibab N.F.	AZ
Jemez Mountains	Santa Fe N.F.	NM
Ohio Hill Country	Wayne N.F., Ohio Div. of For., Mead Paper Corp., The Nature Conservancy	OH
Southeastern Piedmont	Clemson Experimental Forest	SC
Southeastern Coastal Plain	Myakka River State Park	FL

but the composition of other conifers varies, and topographic and soil parameters differ substantially. Two sites are in the Southeastern United States (one in the Piedmont and one on the coastal plain) and are dominated by mixtures of slash pine and hardwoods. Rounding out the network is a site in the oak-hickory type of Ohio. Collectively, these sites comprise a network that is national in scope. Depending on the level of interest and support available, future sites in the same or other fire regimes may be added to the network.

Watershed Management Implications

Increasing wildfires in the United States in the past decade have raised widespread concerns about forest health, wildfire hazard, and potential damages to watershed condition. Fuel treatment prescriptions based on information from this study are needed to guide decisions in the 21st century to maintain and restore the quantity and quality of watershed resources.

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Simulating Soil Moisture Change in a Semiarid Rangeland Watershed with a Process-Based Water-Balance Model

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Abstract.—A process-based, simulation model for evaporation, soil water and streamflow (BROOK90[3]) was used to estimate soil moisture change on a semiarid rangeland watershed in southeastern Arizona. A sensitivity analysis was performed to select parameters affecting ET and soil moisture for calibration. Automatic parameter calibration was performed using a procedure based on a Gauss-type downhill search algorithm and a least squares objective function. Results indicated that BROOK90 can be used to simulate changes in soil moisture content in the upper 15 cm on semiarid rangeland environments, an important realization for watershed management in the southwest.

Introduction

Annual rainfall variability tends to increase with increasing aridity so that the coefficient of variation for annual rainfall tends to be higher in semiarid environments. In southeastern Arizona, rates of evapotranspiration (ET) are high, and soils tend to be dry. Winter rainfall tends to be less intense than the summer monsoons. Therefore, vegetation is under greater stress during the summer when rates of potential evapotranspiration are much higher than the actual transpiration.

The vegetation production and subsequent capacity of the land to support grazing therefore depends on rainfall that may vary significantly from year to year. By better understanding changes in soil moisture, it may be possible to improve the management of rangelands by reducing the number of grazing animals when soil moisture is low and plant stress is high.

In this study, soil moisture change was monitored across two very different years; one in which annual rainfall was high, and a second in which annual rainfall was low. These data were collected at different depths beneath vegetation and under bare soil conditions to improve understanding of the effect of vegetation on soil moisture.

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Objectives

The objectives of this study were to: 1) compare soil moisture variability temporally and with soil depth under bare and vegetated conditions across a dry and a wet year, and 2) determine if soil moisture can be modeled using a soil moisture accounting model, which might then be used as a management tool for estimating soil moisture and subsequent plant stress.

Methods

Soil Moisture Measurements

Volumetric soil moisture content was measured using time domain reflectometry (TDR) probes installed horizontally in pits located on the northern edge of the Lucky Hills 104 watershed. This watershed is operated by the USDA Agricultural Research Service, Walnut Gulch Experimental Watershed near Tombstone, AZ. Six pits were dug, three under desert shrub (shrub), and three in unshaded locations (bare). Probes were installed at depths of 5cm, 10cm, 15cm, 20 cm, 30 cm and 50 cm. The probes measured the volumetric moisture content averaging the 2.5 cm above and below the actual measurement point. Soil moisture data collected on the watershed in 1990 and 1991 were studied. For much of the monsoon in 1990 and 1991, soil moisture was sampled daily, decreasing to every 3 to 7 days by the end of the monsoon.

BROOK90 Model

The BROOK90 model (Federer, 1995) was used to model soil moisture. The model has a strong physically-based description of ET for sparse canopies (Shuttleworth and Wallace, 1985) and redistribution of infiltrated water (Clapp and Hornberger, 1978).

Initial parameter values for the Shuttleworth-Wallace (1985) relationship were estimated using values compiled by Federer et. al. (1996) for xeric shrub. Some minor modifications were made to reflect field observations. Clapp and Hornberger (1978) describe soil moisture movement as a non-linear function of soil wetness. Federer (1995) provides estimates for soil parameters at field capacity for the USDA soil textural classes.

In this study, net precipitation (i.e. measured precipitation – measured runoff), rather than total precipitation was used, so that BROOK90 operated only as a soil-moisture accounting model, rather than a rainfall-runoff model. Daily temperature data for Tombstone were used. Daily total horizontal solar radiation measured at Fort Huachuca was used. Vapor pressure was calculated using average daily dew point temperature recorded at Tucson, and daily wind speed was approximated using the monthly averages recorded at Tucson.

Sensitivity Analysis

A sensitivity analysis was performed to select parameters affecting ET and soil moisture. An initial set of ET parameters based on default values included in BROOK90 (Federer, 1995; Federer et al. 1996) were used. Canopy parameters were estimated based on initial default values. The upper and lower bounds for Clapp and Hornberger (1978) soil parameters were set at one standard deviation above or below the mean value for sandy loam or loamy sand based on the work of Li et. al (1976). Values of porosity were allowed to vary over the range of values determined by Whitaker (1993). The parameter values included the upper and lower value from the literature for any canopy type.

Parameter Estimation

Since data exists for six layers and ten parameters were modified, numerous possibilities of different parameter combination are possible. For this reason, a parameter estimation program called PEST (Watermark Software) was used to estimate optimal parameter values. This program uses a Gauss-type downhill search routine (Marquardt 1963). The objective function is based on a least-squares criterion and the convergence criterion is based largely on user choices.

Results and Discussion

Soil Moisture Measurements

The active depth of infiltration was estimated based on the observed volumetric moisture data collected in 1990 and 1991 for the shrub and bare conditions. Figure 1a shows a plot of volumetric soil moisture vs. day of the year for days 200 to 230 of 1990 for bare soil condition based on average values for the three sample pits. Figure 1b shows the shows soil moisture for the same period from the three pits under shrubs. For shrub condition, soil moisture seems to influence the upper 15 cm. In contrast, soil moisture changes in the 20cm, 30cm, and 50cm depths under shrubs are more gradual and changed very little on a rainfall day. Based on this observation, the top 15 cm were assumed to be the zone of active infiltration on a rainfall day. Under "bare" conditions, the infiltrated depth could be as deep as 20 cm. In 1991, soil moisture changes were similar to 1990, but in the deeper profile there was very little change throughout the summer.

In fact, soil moisture in these two years was found to be very different, especially deeper in the profile. The soil moisture observations for 1990 and 1991 show that the soil is more moist in 1990. Furthermore, average volumetric soil moisture is significantly higher in 1990 for 30cm + 50 cm measurements (16% vs. 9.1% for 1991 at the 0.025 level of significance).

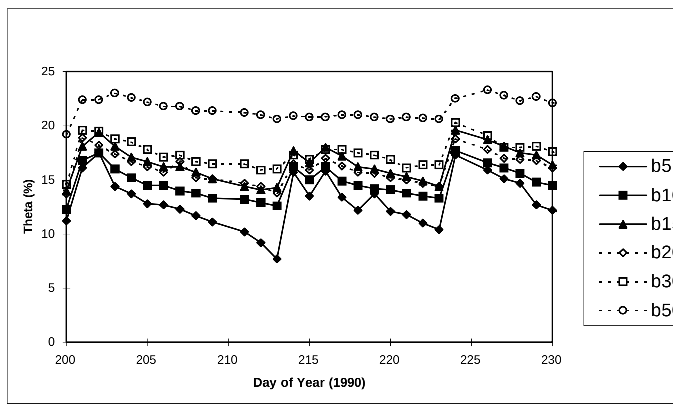

Figure 1a. Observed volumetric soil moisture under bare cover.

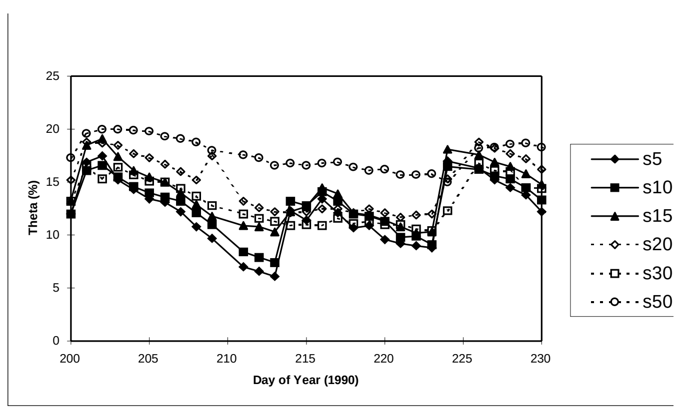

Figure 1b. Observed volumetric soil moisture under shrub.

Sensitivity Analysis

Results of the sensitivity analysis summarized in table 1 show that BROOK90 is sensitive to both soil and ET parameters (shaded rows indicate canopy parameters). The model is most sensitive to canopy density, volumetric moisture content at field capacity, maximum plant conductivity, maximum leaf area index, exponent on soil tension, soil evaporation resistance at field capacity, exponent of soil evaporation to water potential, matric potential at field capacity maximum leaf conductance, and hydraulic conductivity at field capacity. It is relatively insensitive to albedo, relative distribution of rainfall in the top three layers, allowing or disallowing deep drainage, and porosity.

Parameter Estimation

Among the difficulties encountered during parameter estimation were an inability to find the same set of parameter values, unrealistic parameter combinations, large errors in simulated vs. measured soil moisture for some layers, large errors toward the end of the simulation period where measurement were less frequent, and unrealistic changes in parameters from gauged to ungaged soil layers.

While a unique set of parameter values could not be obtained, measures of model efficiency indicated that the simulations were good with little bias. Model efficiencies exceeded 0.75 for both years, and there appears to be no systematic bias in the estimate of soil moisture in the upper 15 cm. Figure 2a shows a plot of the simulation and observed values for the top 15 cm of the profile (layers 1-3 of the simulation) for days 200 to 300 of 1990. Figure 2b

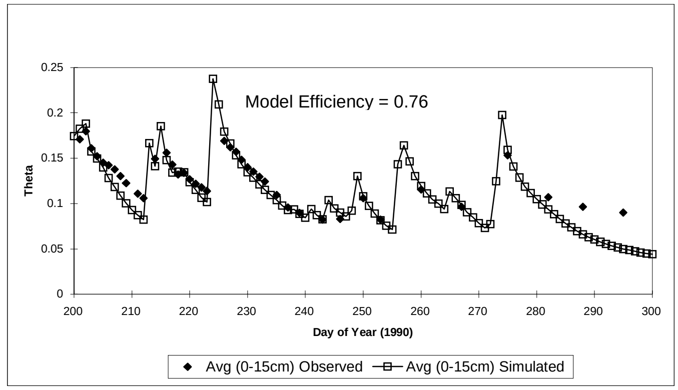

Figure 2a. Simulated and observed volumetric moisture content 1990 (0-15cm).

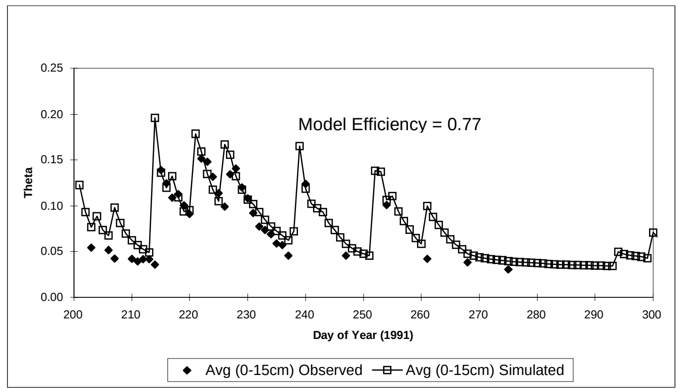

Figure 2b. Simulated and observed volumetric soil moisture 1991 (0-15cm).

Table 1. Results of Sensitivity Analysis. Shaded lines are for vegetation parameters affecting evapotranspiration. Unshaded lines are for soil parameters.

	UNITS	Initial	Perturbed	Mean	Maximum	Perturbed	Mean	Maximum
Canopy Density		0.4	1	-22%	-43%	0.2	27%	103%
Theta at Field Capacity		0.197a	0.175	-11%	-25%	0.230	17%	40%
Maximum Plant Conductivity	(mm/d)	8	12	-2%	-7%	4	16%	62%
Maximum Leaf Area Index (LAI)		3	6	-8%	-24%	2	15%	59%
Exponent on Soil Tension (b)		5.72a	3.20	-15%	-49%	6.70	5%	14%
Soil Evaporation Resistance at Field Cap.	(s/m)	500	250	-6%	-12%	1000	7%	17%
Exponent of Soil Evaporation		1	0.5	-6%	-16%	2	5%	13%
Matric Potential at Field Capacity	(kPa)	-9.17a	-4.70	0%	-21%	-24.00	6%	17%
Maximum Leaf Conductance	(cm/s)	0.53	0.80	-6%	-18%	0.50	1%	5%
Hydraulic Conductivity at Field Capacity	(mm/d)	2	4	0%	11%	1	3%	11%
Albedo		0.1617	0.1400	0%	-2%	0.2600	2%	7%
Distribution of Infiltration in Top 3 Layers		0.72	0.5	-1%	-2%	1	1%	3%
Deep Drainage		0	1	-1%	-5%	0.2	0%	-1%
Porosity		0.414a	0.350	0%	-1%	0.450	0%	1%

a. Average of all soil layers

shows those same plots for the simulation averaging the values for 1991. For comparison purposes, the simulated values are also plotted against the observed values, and the Nash and Suttcliffe (1970) model efficiency is used to describe the goodness of fit.

The model did not perform as well in estimating soil moisture in the lower portion of the soil profile as measured by the 30 cm + 50 cm volumetric soil moisture. The simulation for the wetter year (1990) was reasonably good as indicated by a model efficiency statistic of 0.53. However, the simulation was poor at the 30cm + 50cm depth as indicated by a -5.68 model efficiency in the drier year (1991) in part because the observed values of soil moisture did not change markedly at those depths in 1991.

Conclusions

The observed soil moisture in two subsequent years varied considerably in a semiarid rangeland watershed in southeastern Arizona. While soil moisture in the upper 15 cm showed no statistical difference in the two years, the soil moisture in the 30cm to 50cm depths varied considerably. This indicates that great soil moisture variability is expected to occur deeper in the profile from a wetter to a drier year. This suggests that the occurrence of summer rainfall may have a stronger effect on shallow-rooted vegetation and less effect on deep-rooted vegetation systems.

The significant overall variability of soil moisture between the two years presented a modeling difficulty. Calibration and simulation results showed that BROOK90 can be used to estimate soil moisture in the first 15 cm, but performed poorly in simulating soil water at deeper layers in the soil profile. Little systematic error was noted and fitted parameter values were within what can be considered reasonable for a sandy loam soil, which suggests that BROOK90 can be used to simulate changes in soil moisture content in the upper 15 cm on semiarid rangeland watersheds. Results from this study, therefore, suggest that the model might be used to simulate soil moisture in the upper portion of the soil profiles, an important realization for watershed management in the southwest.

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Integrated Landscape/Hydrologic Modeling Tool for Semiarid Watersheds

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Abstract.—An integrated hydrologic modeling / watershed assessment tool is being developed to aid in determining the susceptibility of semiarid landscapes to natural and human-induced changes across a range of scales. Watershed processes are by definition spatially distributed and are highly variable through time, and this approach is designed to account for their spatial and temporal variability. This tool will integrate geographical information systems and distributed hydrologic models in a user-friendly graphical environment. The hydrologic models work under a watershed analysis framework to simulate the influences of vegetation and land use characteristics on watershed response and will accommodate scientific advances in the quantification of watershed assessment via hydrologic process modeling.

Introduction

As populations grow and economic activity increases in the Western semiarid regions of the United States, there is increasing demand for scarce water resources. This focuses attention on maximizing the development and protection of renewable water resources. It is therefore essential to develop modeling techniques that can represent the dominant hydrological processes and their temporal variability so that the vulnerability of semiarid landscapes to a variety of natural and anthropogenic stressors at multiple scales can be investigated.

Watershed or ecosystem management requires a solid understanding of landscape-level ecosystem processes, and in particular the interaction of geomorphological, hydrological and biological processes (Stanley, 1995). At present, poor understanding and a lack of information regarding landscape-scale processes generally hinders assessment of the ecological consequences of human actions and helps institutionalize land use conflicts (Montgomery et al., 1998). Landform analysis can provide an understanding of geomorphological processes that influence hydrological and ecological processes and systems. Environmental impact analysis protocols developed in response to environmental legislation generally focus on site-, ownership-, or species-specific issues at scales inadequate for assessing ecosystem processes and condition (Montgomery et al., 1995). Hence, the integrated effects of local management decisions can be incompatible with broader-scale management objectives. Implementing ecosystem management requires a framework for gathering and interpreting environmental information at a scale and resolution necessary for addressing the tradeoffs between economic and ecological considerations inherent to making land management decisions (Slocombe, 1993).

Although a number of initiatives and strategies focus on large scales (WFPB, 1992; FEMAT, 1993), there is not yet a consensus on how to implement ecosystem management (Montgomery et al., 1998). A key element is the development of a practical operational framework for integrating ecosystem management into land use decision making. Watersheds define basic, hydrologically, ecologically and geomorphologically relevant management units (Chorley, 1969; Likens and Bormann, 1974; Lotspeich, 1980) and watershed analysis provides a practical analytical framework for spatially-explicit, process-oriented scientific assessment that provides information relevant to guiding management decisions.

The purpose of this paper is to present an approach for providing operational hydrologic modeling tools under a watershed analysis framework for determining the vulnerability of semiarid landscapes to natural and human-induced landscape pattern changes across multiple scale domains.

Semiarid Watershed Modeling

Site Descriptions

Walnut Gulch Experimental Watershed

The Walnut Gulch Experimental Watershed (WGEW) encompasses approximately 150 km^2 in southeastern Arizona, USA (figure 1) surrounding the historical western town of Tombstone. Walnut Gulch is a tributary of the San Pedro River, which originates in Sonora, Mexico and flows north into the United States. The watershed is representative of the brush and grass covered rangeland found throughout the semiarid Southwest and is a transition

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zone between the Chihuahuan and Sonoran Deserts. Elevation of the watershed ranges from 1,220 m to 1,890 m. For further details on the description of the Walnut Gulch Experimental Watershed see Renard et al. (1993).

San Pedro River Basin

The Upper San Pedro River Basin (SPRB) covers about 6,600 km^2 and spans the Mexico-US Border from northern Sonora into southeastern Arizona (figure 1). It has high topographic variability (1,200 m – 2,900 m) providing ecological and climatic diversity over distances as short as 20 km and significantly different cross-border land uses visible from satellite multi-spectral images. Diverse vegetation types include both Sonoran and Chihuahuan desertscrub, grasslands, chaparral, Madrean evergreen woodlands, and high-elevation conifer forests (McClaran and Brady, 1994). For further details on the description of the San Pedro River Basin see Goodrich (1994). While current research focuses on the Walnut Gulch and San Pedro watersheds, this research will be extended to a range of basins across the semiarid western United States. A range of basins with rainfall and runoff data will be selected to validate the assessment tool. These basins will be selected based on watershed characteristics such as size, geomorphology, ecology, land use, topography, and data availability.

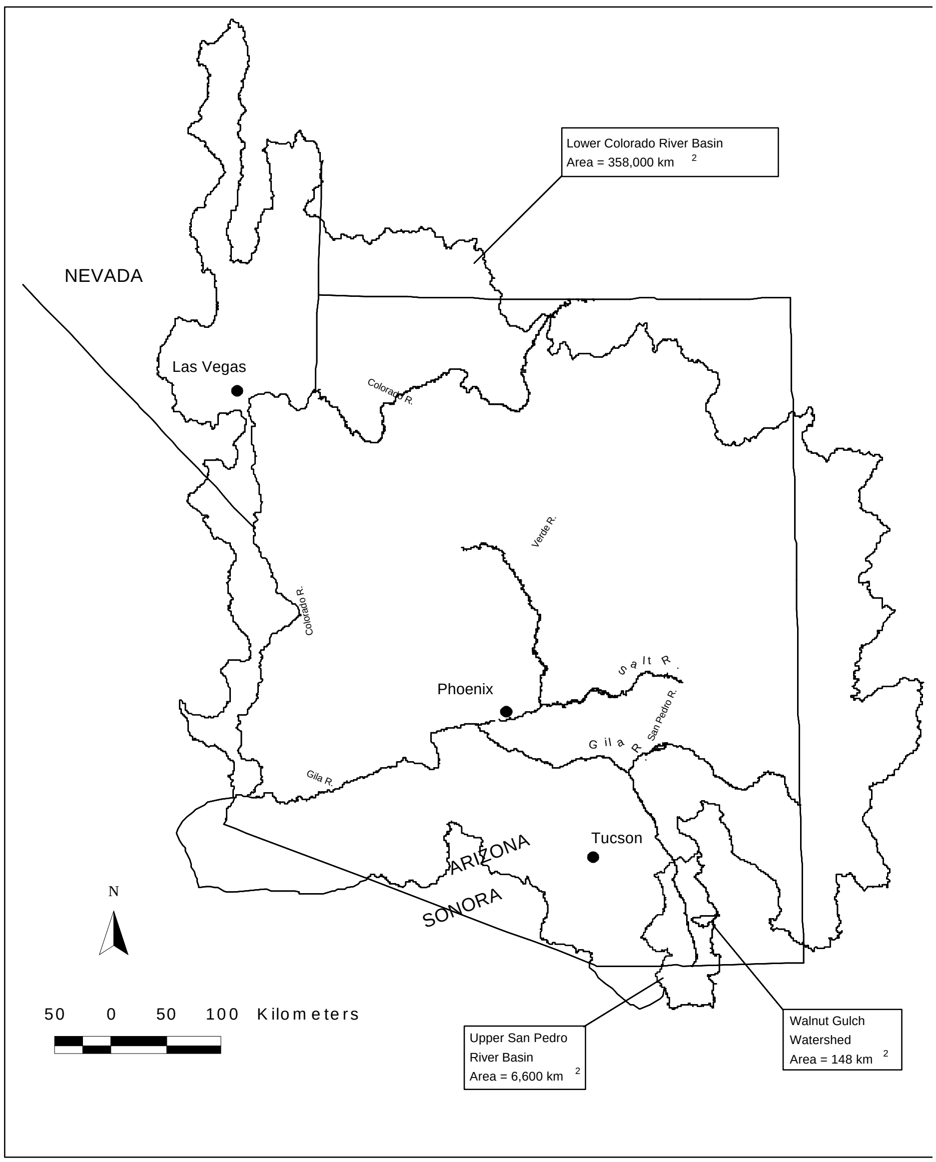

Figure 1. The Upper San Pedro River Basin.

Semiarid Watershed Hydrology

A large proportion of the Western United States is classified as arid or semiarid. These regions are characterized by larger relative extremes in components of the hydrologic cycle than in the humid climates, including: 1) low annual precipitation but high-intensity storms with significant spatial variability, 2) high potential evaporation, 3) low annual runoff but short-term high volume runoff, and 4) runoff losses in ephemeral channels (Branson et al., 1981). Furthermore, these regions are especially prone to erosion. Hydrologic models must therefore adequately account for these factors if they are to be used to assess the impacts of landscape change on hydrologic response in the Western United States.

Vegetation cover represents one of the most powerful factors influencing the runoff regime, since it modifies and moderates many others. It should be noted that methods for transforming various land cover and land use characteristics into distributed hydrologic model parameters are not well developed for a wide range of conditions. For management purposes, many approaches rely largely on empirical studies of small plots and watersheds to relate land cover and land use to hydrologic model parameters. The curve number method (USDA-SCS, 1972) is an example of this type of approach to relate land cover and land use to hydrologic model parameters.

Landscape/Hydrologic Modeling Tool

The landscape / hydrologic modeling tool is designed within a database management system framework, which comprises the following elements: database, simulation, and a graphical-user-interface. The integrated landscape / hydrologic modeling tool is described in figure 2. Each element is described in the following sections.

Database

This module covers all aspects of capturing spatial data from existing maps, field observations, and sensors (including aerial photography, satellites, and recording instruments) and converting them to a standard digital form. Once entered, the data will be checked for inaccuracies, omissions, and other errors.

The fundamental spatially distributed geographic information system (GIS) data that will serve as input to the hydrologic models are soils, land cover, and topography. It is proposed that topography be derived from available USGS 7.5' digital elevation models (DEMs), that soils

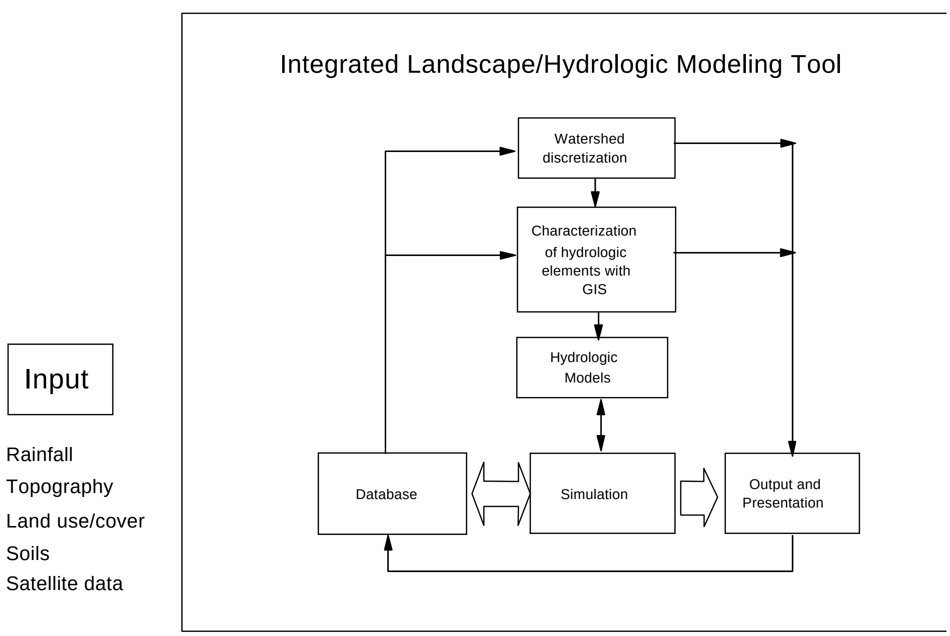

Figure 2. An integrated landscape/hydrologic modeling tool.

information be derived from USDA-NRCS STATSGO soil polygons, and that land cover come from Multi-Resolution Land Characteristics (MRLC) products. On Walnut Gulch, rainfall information will be compiled from historical 85-raingauge network data. Runoff data will come form various historical and current gaging structures. For the San Pedro Basin, rainfall data will be retrieved from the National Climatic Data Center database (US Department of Commerce, 1995), and stream flow data at Charleston will be obtained from the USGS database (USGS, 1999).

Simulation

The simulation component consists of a computer program to characterize watershed complexity and hydrologic models.

Watershed Complexity

The watershed discretization and characterization tool TOPAZ (TOpographic PArameteriZation)(Garbrecht and Martz, 1995) is used to delineate the hydrologic elements of a watershed. TOPAZ is a software package for automated analysis of digital landscape topography. A raster digital elevation model (DEM) is used by TOPAZ to identify and measure topographic features, define surface drainage, subdivide watersheds along drainage divides, quantify the drainage network, and calculate representative subcatchment parameters. TOPAZ is designed primarily to assist with topographic evaluation and watershed parameterization in support of hydrologic modeling and analysis.

Hydrologic models

In the selection process of the hydrologic models, strong emphasis was placed on models that were able to characterize complex watershed representations to explicitly account for the spatial variability of soils, distribution of rainfall, and heterogeneity of vegetation. The effects of land use and land cover on surface runoff and sediment yield were also stressed in the model selection criteria. Furthermore, models were chosen that adequately characterize the mechanism that produce surface runoff and sediment yield producing mechanisms. That is, the models are govern by equations based on fundamental principles of physics or robust empirical methods widely used in computing surface runoff and sediment yield. The following discussion provides an overview of the hydrologic models.

The "Soil and Water Assessment Tool" (SWAT) (Arnold et al. 1994) is public domain software developed and actively supported by the USDA-Agricultural Research Service at the Grassland, Soil and Water Research Laboratory in Temple, Texas. SWAT is a continuous-time model that operates on a daily time step to predict the impact of management on water, sediment and agricultural chemical yields in large ungaged basins. To satisfy the objective, the model (a) uses readily available inputs; (b) is computationally efficient to operate on large basins in a reasonable time; and (c) is continuous time and capable of simulating long periods for computing the effects of management changes. The SWAT components can be placed into eight major divisions: hydrology, weather, sedimentation, soil temperature, crop growth, nutrients, pesticides, and agricultural management.

KINEROS, an acronym for the KINematic runoff and EROSion model, has evolved over a number of years primarily as a research tool (Smith et al., 1995). KINEROS is public domain software developed by the USDA-Agricultural Research Service, and supported by the Southwest Watershed Research Center in Tucson, Arizona. KINEROS is an event oriented, physically based model that describes the processes of interception, infiltration, surface runoff, and erosion from small agricultural and urban watersheds. The watershed is represented by a cascade of planes and channels; and partial differential equations describing overland flow, channel flow and erosion, and sediment transport are solved by finite difference techniques. Spatial variability of rainfall and infiltration, runoff, and erosion parameters can be accommodated.

Graphical User Interface

As the models are integrated with the GIS data, a suite of programs will be developed to automate the parameterization of the hydrologic models. The development of graphical-user-interface (GUI) tools is a critical step towards implementing the techniques across a range of scales by a variety of clients. The largest drawbacks to hydrologic modeling at larger scales are the complexity of the input data and expert knowledge and proficiency required to initiate the model runs. The GUI will allow for the rapid and accurate application of SWAT and KINEROS at a range of basin scales given a minimum of expertise and input data. These tools will be critical for transferring this technology to resource managers and regional planners who are interested in projecting the impact of land use change on hydrologic response. Data output will be presented in a variety of ways ranging from the image on the computer screen, through hardcopy output drawn on printer or plotter to information recorded on magnetic media in digital form.

Conclusions

Simulation models can be used to quantify the interactions among variables across multiple scales domains.

Used together, the SWAT and KINEROS models comprise a viable tool for characterizing hydrologic processes in semiarid regions. The watershed function of complex watershed systems at a range of scale can be interpreted based on relationships among influential variables described by the models. Understanding these relationships and developing the mathematical expressions describing them is a goal of natural resources scientist. Additionally, the technology exists to extend research results and applications to decision makers and land managers. A landscape / hydrologic tool will provide an accessible scientific basis for land planning and decision making.

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Applying EXCEL[1] Solver to a Watershed Management Goal-Programming Problem

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Abstract.—This article demonstrates the application of EXCEL® spreadsheet linear programming (LP) solver to a watershed management multiple use goal programming (GP) problem. The data used to demonstrate the application are from a published study for a watershed in northern Colorado. GP has been used by natural resource managers for many years. However, the GP solution by means of EXCEL® spreadsheet presented here is thought to be novel.

Introduction

The natural resources professions have for many years employed goal programming (GP) to solve a wide variety of management problems. Past uses include the management of small woodlands, timber production, land use planning, Christmas tree production, multiple use management, range management and outdoor recreation planning (Dykstra 1984).

GP differs from linear programming (LP) principally in that, rather than attempting to optimize a single objective function subject to several constraints, a GP will have multiple objectives as well as possibly some ordinary constraint equations (Buongiorno and Gilless 1987). Each of the multiple objectives is stated in a goal target equation. The right hand side (RHS) of each goal target equation is a goal target (i.e., a numerical production goal which the manager wants to achieve). The lefthand side (LHS) of each goal target equation contains goal deviation variables which measure the positive or negative deviations from the RHS goal target. The objective of the GP is to minimize the sum of these positive and negative deviations. In this manner, the GP works toward the achievement of multiple goals rather than, as with the traditional LP, toward the optimization of a single objective bound by inflexible constraints.

A type of LP-related software which is currently growing rapidly in popularity is the so-called "spreadsheet LP solver." These spreadsheet solvers are capable of deriving LP and GP solutions using data entered on personal computer spreadsheets. However, the GP solution requires some creativity as the procedure is not generally set forth in the software documentation.

The purpose of this article is to illustrate the application of a standard spreadsheet LP solver to a watershed management GP problem. We use as a teaching example data for a multiple use watershed in northern Colorado along with Microsoft's EXCEL® Solver.

Watershed Management Application

Problem

The problem involves a 570 acre multiple use area located in a watershed in northern Colorado. The data for this exercise were adapted, with some changes, from Bottoms and Bartlett (1975). The manager of this public land wishes to manage the area for the following multiple uses: domestic forage production, wildlife forage production, recreational fish production, and recreation visitor days. Furthermore, the manager is concerned about controlling sediment production from these activities and also about not exceeding his/her annual budget allocation for management activities. In order to achieve the management goals, a variety of management activities can be applied to portions of the 570 acres. These activities include: no action, drain wetlands, aerial spraying of herbicides and fertilizers, aerial spraying and grass seeding, mechanical removal of vegetation, mechanical removal of vegetation and grass seeding, fertilization, fish stocking and, finally, campground development. Each management activity will yield resource outputs per acre and will also carry a per acre cost in 1998 dollars (table 1).

The manager has decided that certain management objectives are to be goals: 6,000 tons per acre of sediment; 1,000,000 lbs. of domestic animal forage; 500,000 lbs. per acre of wildlife forage; and 200,000 lbs. per year of stocked fish. However, certain activities are regarded as inflexible

[1] Registered trade name. Trade names are used for the information and convenience of the reader and do not imply endorsement or preferential treatment by the sponsoring organizations or the USDA Forest Service

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Table 1. Treatment yields and costs per acre or per year for land management practices on a Colorado watershed. Source: Bottoms and Bartlett (1975).

Yields	No action	Drain wetlands	Aerial spraying	Aerial spray 7 grass seeding	Mechanical removal	Mechanical removal & grass seeding	Fertili-zation	Camp-ground develop-ment
Sediment, tons per acre	2.5	6.5	5.0	4.4	9.5	8.5	2	27
Domestic forage, lbs. per acre	1270	1459	1647	1730	1786	2249	2006	0
Wildlife forage, lbs per acre	1500	975	150	75	750	375	1875	2250
Fish stocked, lbs. per acre	0	0	0	0	0	0	0	2000
RVDs, per year	0	0	0	0	0	0	575	0
Cost, 1998 dollars per acre	$0	$332.50	$9.13	$22.61	$66.50	$67.83	$15.96	$7,182.00

constraints, which must be met or exceeded. The manager must produce at least 60,000 recreation visitor days (RVDs) per year and the budget of $1,000,000 must be spent exactly.

The management question is: how many acres of land should be allocated to each management treatment so that the goal target deviations are minimized and all constraints are met? This particular goal programming problem will be one in which the manager wants to minimize the simultaneously the weighted sum of all goal target deviations. This stands in contrast to GP methods involving unweighted goal target deviations or ordinal ranking of goals (Schrage 1997). In this problem, the minimization of sedimentation in excess of the goal target is regarded as extremely important. Consequently, the goal of minimizing sedimentation over the target will be assigned a very large weight (i.e., 1000). All other goal weights will be equal to 1.

Entering the Problem into the Spreadsheet

This GP problem can be solved with EXCEL. Figure 1 depicts the left half of the land management data matrix on an EXCEL® spreadsheet. Figure 2 depicts the right half of the same continuous matrix. The data have been separated into figures 1 and 2 because of the extreme width of the matrix. In figure 1, the upper-most row of the matrix (cells B8 through I8) contain the decision variables (i.e., number of acres of land treated under each management option). In EXCEL® terminology these are called the "changing cells." These cells are best set, as in this case, initially to zero before solving the problem. The GP solution will eventually replace some of these zeros with positive numbers indicating the optimal acreage. The headings of each column (e.g., column B, C, etc.) indicates the management treatment applicable to that column (i.e., "no treatment," "drain wetlands," etc.). The lower six rows of the matrix (cells B9 through I14) contain the per acre treatment yield and cost coefficients. These are the data from table 1. When multiplied by the corresponding decision variable (i.e., acres in that treatment type), they will yield total cost, total lbs. of forage, etc.

Figure 2 depicts a continuation of the matrix from figure 1. The top row (cells J8 through Q8) contain the goal deviation variables which are now all set at zero. These variables indicate either under- or over- achievement of the goal targets. The lower matrix rows (cells J9 through Q12) contain the goal deviation variable coefficients. These are equal to 1 for an underachievement goal deviation variable, -1 for an over achievement goal deviation variable, and 0 if the goal deviation variable does not pertain to the goal equation on that particular row. Cells S8 through S14 contain numbers which will be used to form the RHS of the goal target and constraint equations.

Furthermore, certain cells on the spreadsheet contain hidden EXCEL® formulae as follows:

cell R8: =SUM(B8:I8)(1)

cell R9: =SUMPRODUCT($B$8:$Q$8, B9:Q9)(2)

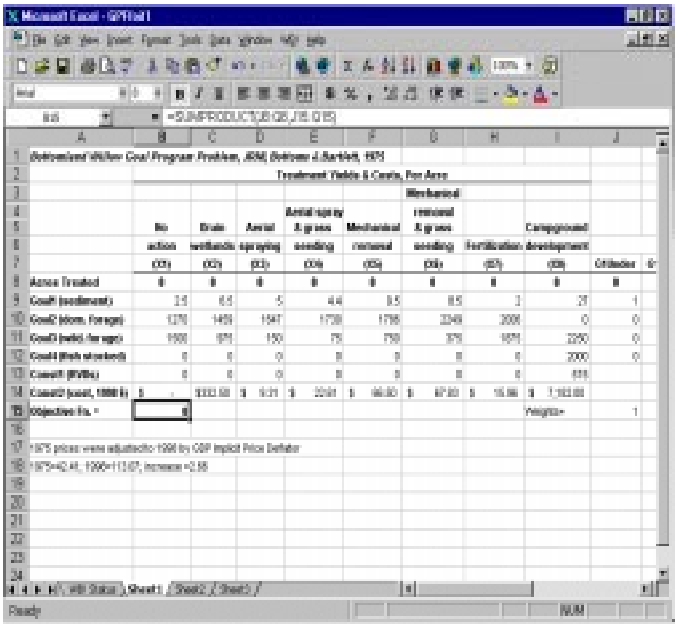

Figure 1. EXCEL® spreadsheet containing the left-half of the goal programming matrix. Cells B8 through I8 contain the acres of land in each management treatment (i.e., the decision variables). Cells B9 through I14 contain the problem coefficients. Cell B15 contains a hidden equation, which is the objective function of this weighted goal programming problem.

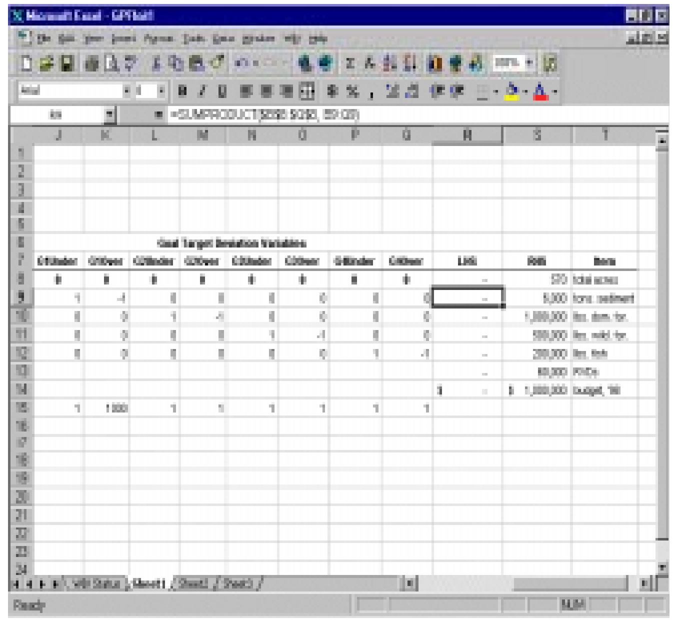

Figure 2. EXCEL® spreadsheet containing the right-half side of the goal programming matrix. Cells J8 through Q8 contain the goal deviation variables. Cells J9 through Q12 contain the coefficients for the goal target variables. Cells J15 through Q15 contain the weights. Cells R8 through R14 contain hidden equations expressing the left hand side of the goal and constraint equations. Cells S8 through S14 contain the right hand side of the goal and constraint equations.

cell R10: =SUMPRODUCT($B$8:$Q$8, B10:Q10)(3)

cell R11: =SUMPRODUCT($B$8:$Q$8, B11:Q11)(4)

cell R12: =SUMPRODUCT($B$8:$Q$8, B12:Q12)(5)

cell R13: =SUMPRODUCT(I8,I13)(6)

cell R14: =SUMPRODUCT(B14:I14,B8:I8)(7)

cell B15: =SUMPRODUCT(J8:Q8,J15:Q15)(8)

Items 1 through 7 above will be used later in the goal target and constraint equations. Item 8, the sum product of the goal deviation variable and weight vectors forms the objective function. In EXCEL® terminology, the cell containing the objective function is known as the "target cell."

Solving the Problem with EXCEL®

Once the matrices have been entered into EXCEL®, the analyst will click "Tools" on the EXCEL® toolbar. A drop-down menu will appear with one of the choices being "Solver." The analyst will click this also. (Note: if "Solver" does not appear on the drop-down menu, click "Add-ins" on the drop-down menu and proceed to add-in Solver.) When Solver is clicked, the "Solver Parameters" dialogue box (figure 3) will appear. Designate the target cell (i.e., objective function) by clicking cell B15 on the spreadsheet. Designate the changing cells (i.e., the decision variables and the goal deviation variables) by clicking and dragging the cursor across cells B8 through Q8.

Constraints are entered one-by-one in a multi-step procedure as follows: 1) click "Add," and a constraint dialogue box will appear; 2) click the cell on the spreadsheet that represents the lefthand side of the goal target or constraint equation; 3) indicate whether £, ³, or =; 4) click the cell on the spreadsheet that represents the right hand side of the equation; 5) repeat these steps until all constraints have been entered. The EXCEL® goal target and constraint equations for this problem are expressed using cell locations on the spreadsheet as follows:

R8 = S8(9)

R9 = S9(10)

R10 = S10(11)

R11 = S11(12)

R12 = S12(13)

R13 ³ S13(14)

R14 = S14(15)

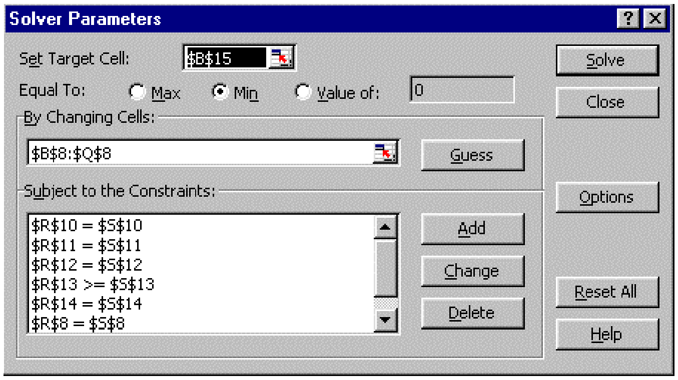

Figure 3. EXCEL® spreadsheet "Solver Parameters" dialogue box. The "target cell" contains the objective function. The "changing cells" contain the decision variables.

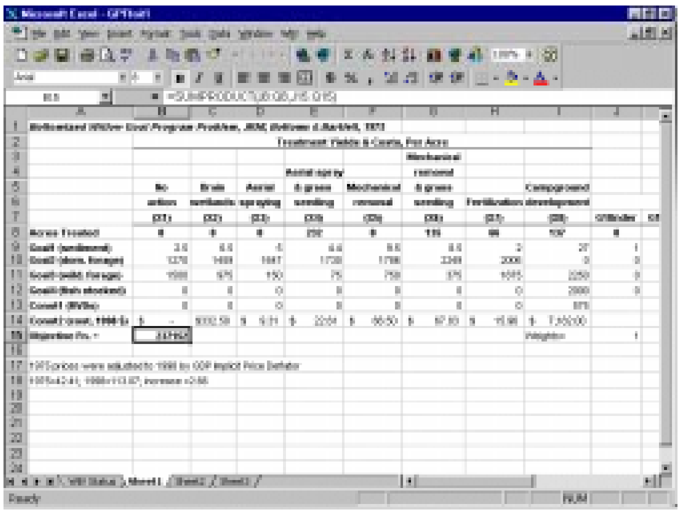

Figure 4. EXCEL® spreadsheet with the optimal GP solution. Cell B15 contains the value of the objective function (i.e., the minimized sum of the deviation variables). Cells B8 through I8 contain the optimal acreage allocations.

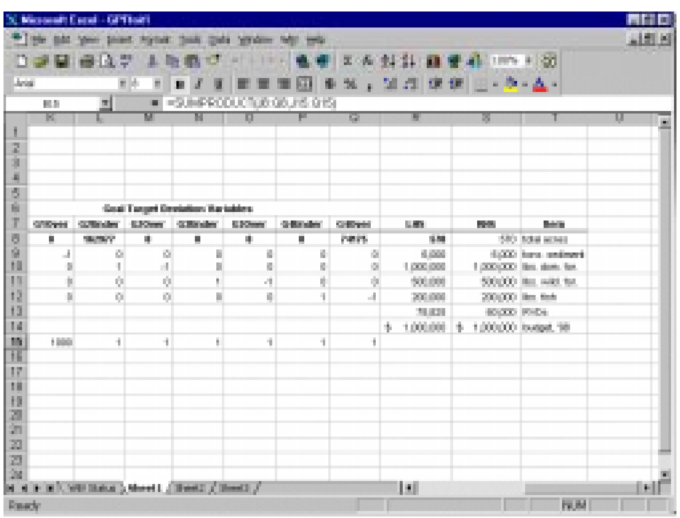

Figure 5. EXCEL® spreadsheet with deviation variables (cells K8 through Q8). Cells R9 through R14 contain the lefthand side values of the goal target and constraint equations.

Once all goal and constraint equations have been entered, return to the main Solver Parameters dialogue box (figure 3) and click "Options." The "Solver Options" dialogue box will appear. Using the cursor, click "Assume Linear Model" (this will insure a simplex algorithm solution), and also click "Assume Non-Negative" (insures that all Xs ³0). Click "OK" and the Solver Parameters dialogue box (Figure 3) will reappear. Click the "Solve" button and the GP should find a solution. In this case it does, and the optimal solution (237,152 deviation units) now appears in cell B15 while the optimal acreage treatment of management treatments, the answers of principal interest, appears in cells B8 through I8 (figure 4). The optimal solution indicates that the land manager should treat 232 acres with aerial spraying and grass seeding, 135 acres with mechanical removal and grass seeding, 66 acres with fertilization and 137 acres should be developed as a campground. All other treatment types indicated zero acres.

Inspection of cells K8 through Q8 in figure 5 indicate how well the manager did with respect to the specific values of the goal targets and constraints. Cell L8 indicates that the target domestic animal forage goal was underachieved by 162,977 lbs. Cell Q8 indicates that the target fish stocking goal was underachieved by 74,175 lbs. All other goals were met in accordance with the specified constraints.

Conclusion

Savage (1997) has stated that spreadsheet LP / GP solvers appear to be the new direction in LP / GP software. This is based on the widespread use of spreadsheet software and the fact that students are increasingly being exposed to spreadsheets in the college classroom. One of the desirable features of LP / GP problems formulated on spreadsheets is the highly visible display of the problem which seems to invite inquiry and experimentation. Also, the spreadsheet method facilitates a very flexible approach to LP / GP solving; the problems can be structured and solved in many different ways.

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Research Support for Land Management in the Southwestern Borderlands

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Abstract.—The Malpai Borderlands Group, Animas Foundation, other private organizations, and federal and state agencies are concerned about landscape fragmentation, declining productivity, and loss of biological diversity related to encroachment of woody species. In response, they are attempting to implement ecosystem management on almost 1 million acres of grasslands and woodlands in southeastern Arizona and southwestern New Mexico. Reintroduction of natural fire is an important component for achieving ecosystem sustainability. A number of government and private organizations are supporting or conducting research on ecosystem and landscape ecology and management techniques. The research covers several general areas including information syntheses, resource inventories, historical environmental changes, fire and Borderlands ecosystems, range restoration, and the relationship between species ecology and land management.

Introduction

The Southwestern Borderlands region of southeastern Arizona and southwestern New Mexico covers a unique, relatively unfragmented landscape of approximately 1 million acres including the San Bernardino, Upper San Simon and Animas valleys, and the southern Peloncillo and Animas mountains. Elevations range from about 3,800 to 8,500 feet. The area contains exceptional biological diversity with natural communities extending from desert shrub and tabosa (*Hilaria mutica*) grasslands to high elevation mixed conifer stands dominated by Arizona pine (*Pinus ponderosa* var. *arizonica*) and Douglas fir (*Pseudotsuga menziesii* var. *glauca*). The mountains and valleys are home to diverse plant and wildlife populations including species that are rarely found within the United States. The region is also home to a viable ranching community that recognizes that maintaining the health and productivity of these natural communities are critical in maintaining their local ranch economies. Property and ecosystem fragmentation, which exists in adjacent valleys, has not reached the Borderlands region. Land ownership and administration is diverse; 53% is in private ownership, 23% is owned by Arizona or New Mexico, 17% is administered by the Coronado National Forest, and 7% is administered by the Bureau of Land Management.

In 1990, a group of ranchers met at the Malpai Ranch, east of Douglas, Arizona, to discuss the ranching situation in the West and the future of the natural resources that they depend on for their livelihood (McDonald 1995). Some concerns expressed at this gathering were the encroachment of trees and shrubs on grasslands, the subsequent decline of the herbaceous cover, and the unnecessary suppression of potentially beneficial wildfires. Two years later the Malpai Borderlands Group was formally organized with the goals of reducing the threat of landscape fragmentation and increasing the productivity and biological diversity of the area's rangelands (McDonald 1995). The group's goal is to restore and maintain the natural processes, including fire, that create and protect healthy unfragmented landscapes and their component species within the Borderlands region. The members believe that their efforts should be based on good science, contain a strong conservation ethic, be economically feasible, and be initiated and led by the private sector with the federal and state agencies as partners.

Land management based on good science has been a key part of the efforts in the Borderlands region. The Malpai Borderlands Group and affiliated organizations, such as The Nature Conservancy and the Animas Foundation, have sponsored many research and inventory activities. The USDA Forest Service, Rocky Mountain Research Station became involved in 1994 when the Station was awarded one of the19 national ecosystem management research grants. The formation of the Southwestern Borderlands Ecosystem Management Research Project is the result of a successful proposal by Dr. Leonard DeBano (Supervisory Soil Scientist, Rocky Mountain Research Station, retired) and Larry Allen (Malpai Borderlands Project Coordinator, Coronado National Forest). One major factor for the proposal's success was the unified support of

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the Rocky Mountain Research Station, Coronado National Forest, the Malpai Borderlands Group, the Animas Foundation, The Nature Conservancy, the Natural Resources Conservation Service, the Bureau of Land Management, the School of Renewable Natural Resources, University of Arizona, and the University of New Mexico.

Information from research efforts in the Borderlands region should be applicable to natural resource management in the larger Madrean Archipelago Biogeographical region, which includes southern Arizona, southwestern New Mexico, west Texas, and northeastern Sonora and northwestern Chihuahua in Mexico.

Southwestern Borderlands Ecosystem Management Research Program

The Southwestern Borderlands Ecosystem Management Research Program objective is to contribute to the scientific basis for developing and implementing a comprehensive ecosystem management plan for the Borderlands area (Edminster and Gottfried 1999). The plan includes strategies for restoring natural processes, improving the productivity of grasslands and woodlands, providing wildlife habitats, maintaining an open landscape, and sustaining a viable rural economy and social structure.

The broad goals of the research program are to:

1. Provide the scientific basis to establish the desired future conditions based on the highest quality biological science integrated with desired future social and economic conditions within the context of private and agency partnerships.
2. Plan and implement a long-term systematic program of basic and applied research, coordinated monitoring to integrate past and future research findings, and contribute to developing guidelines for sustaining a viable economy and open spaces.

Research Strategy

The program focuses on: summarizing and synthesizing existing information, developing a comprehensive landscape inventory and monitoring system to serve research and management needs, and identifying specific research studies to fill priority knowledge gaps. The following discussion identifies topics within each focus area. The research program was described in detail, including current results, in January 1999 at a conference in Douglas, Arizona (Gottfried et al. 1999). The conference proceedings contain 34 contributions by scientists and land managers and notes from a panel discussion on future directions for research and management in the Malpai region. Many of the studies are continuing, however, some of the completed research has been or soon will be published by either the Rocky Mountain Research Station, by scientific journals, or will be presented in master degree theses and doctoral dissertations.

First Focus Area

Basic and applied research within the Madrean Archipelago region, including the Southwestern Borderlands, began before the 20th century. The Santa Rita Experimental Range, the first experimental area established by the Forest Service, was established south of Tucson in 1903. The initial focus of the Borderlands program was to summarize and synthesize existing information on topics having significant implications for management and research planning. It was important to learn what had already been done to prevent duplication and to establish a foundation for future research and management activities.

These efforts included a review of the knowledge about the role and importance of human and natural disturbances on plant communities in the Borderlands of the United States and Mexico. A second review of wildlife information in the Borderlands project area, which included a proposed experimental design to address future wildlife research and management needs in the region (Morrison et al. 1997) was also a focus of the research efforts. Other scientists conducted an archeological synthesis of the prehistory and early history of the Borderlands ecosystem and made recommendations for future research. Hydrological information is unavailable for most of the Borderlands region, but the neighboring Walnut Gulch Experimental Watersheds near Tombstone have a long history of hydrological research. The data from Walnut Gulch and neighboring watersheds in Arizona and New Mexico were compared to determine if they could be used as proxies to describe hydrological conditions on Animas Creek. One large task was to develop an annotated bibliography for the northern Madrean biogeographic province. General information about the bibliography has been published (Ffolliott et al. 1999), and the full bibliography is available at www.rms.nau.edu/publications/madrean/.

Second Focus Area

The second focus area is development of a comprehensive landscape inventory and monitoring system to serve research and management needs. The ongoing or concluded studies include mapping current vegetation of the

Borderlands ecosystem management area using thematic satellite imagery with intensive ground validation and delineation and interpretation of geomorphic surfaces and surficial and bedrock geology of the Borderlands area. These studies, along with soil survey data collected by the Natural Resources Conservation Service, will provide a basis for developing vegetation management strategies. Information on land-use history and historical landscape changes is being collected, often using photographic monitoring techniques. A digital archive for studies at the Santa Rita Experimental Range has been developed that will create a geo-referenced archive of research records and will provide a basis for data management in the Borderlands.

Third Focus Area

The third focus area includes specific research studies needed to fill priority knowledge gaps. The role of natural fire and its reintroduction into the Borderlands is a major emphasis. A number of program studies are related to natural fire and prescribed burning. Historical fire regimes in several of the ecosystems within the region and northern Mexico have been reconstructed. Scientists also are working to understand the spatial pattern of fire regimes and fire behavior at landscape scales including comprehensive fire regime reconstructions. These studies are regional in scope and are being conducted in cooperation with national forests throughout the Southwest. The concerns about the impacts of different fire frequencies on grassland ecosystem components, such as nutrient budgets and vegetation composition, are being evaluated. A number of studies are concentrating on the impacts of natural or prescribed fire on vegetation dynamics and animal populations, including selected threatened and endangered species. Techniques are being developed for fuels visualization, mapping, and fire-spread modeling in selected areas of the Chiricahua and Huachuca Sky Island mountain ranges.

Two studies have been established to determine techniques for reestablishing and maintaining native grasses on mesquite (*Prosopis glandulosa* var. *glandulosa*) dominated grasslands. Experimental vegetation and livestock management strategies, including mechanical treatments or intensive grazing and prescribed fire, have been designed to improve composition and productivity of perennial native grasses, reduce the dominance of woody shrubs, and improve soil properties and wildlife habitats. These studies are conducted in cooperation with the Natural Resources Conservation Service, the Arizona State Land Department, and several landowners. One of the experimental areas contains an important archeological site, and the implications of the range restoration treatments on cultural resources is an important part of the study.

Part of the third focus area includes the collection of information about the cultural and environmental history of the Borderlands with the objective of evaluating the implications of past land-use history for future management. Another important task is development of riparian ecosystem recovery priorities for the USDA Forest Service, Southwestern Region.

Landscape Scale Prescribed Fires

Several of the studies from the third focus group have been linked to the Peloncillo Programmatic Fire Plan. This plan advocates landscape-scale prescribed fires within the mountain range with the objective of establishing a balance of woody and herbaceous species and increasing fine fuels, as a precursor to the reintroduction of natural fire into the area's ecosystems. Landscape-scale prescribed fires were conducted in Baker Canyon in 1995 and in the Maverick Area in 1997. These fires, with highly variable burn intensities, created mosaics of burned and unburned areas. However, there were numerous questions about the effects of fire on important ecosystem components that needed to be answered before a final plan could be developed. Sponsored research included determining the effects of prescribed burning on bird populations, vegetation dynamics, Palmer agave (*Agave palmeri*) and foraging interactions with the endangered lesser long-nosed bats (*Leptonycteris curasoe yerbabuenae*) and Mexican long-nosed bats (*L. nivalis*), and survival and behavior of montane rattlesnakes including the threatened New Mexico ridgenosed rattlesnake (*Crotalus willardi obscurus*). Another study is evaluating remote sensing and GIS techniques for mapping and analyzing fuels and fire behavior on the Maverick Burn.

Future Research

Plans for the future include expanding monitoring efforts and investigating the effects of prescribed burning at the landscape scale on vegetation, wildlife, soil properties, and hydrological parameters. Efforts also will relate vegetation responses and changes in soil and site conditions, and adapt predictive models of fire behavior to prescribed burning in the Borderland grasslands and savannas. Several of the new studies will use a watershed approach to evaluate the effects of prescribed fire prescriptions on a number of ecosystem components within small watersheds. The experimental range restoration treatments will continue to be evaluated and additional options may be tested.

International Conferences

A key element of science is communication. The United States and Mexico have common ecosystem research and management questions. The Borderlands Management Research Program, in collaboration with the University of Arizona, conducted an international conference on the biodiversity and management of the Madrean Archipelago in September 1994 (DeBano et al. 1995). The purpose of the conference was to bring together scientists and managers from government agencies, universities, and private organizations to examine the biological, cultural, and physical diversity and management challenges of the region and to provide a basis for developing the research program. The University of Arizona and the Rocky Mountain Research Station also conducted two international conferences in 1996. One conference, with the University of Sonora, Mexico, concerned fire effects and management strategies (Ffolliott et al. 1996). The other conference focused on the future of arid grasslands (Tellman et al. 1998). The Rocky Mountain Research Station also was one of the sponsors of the Ninth U.S. / Mexico Border States Conference on Recreation, Parks and Wildlife (Gottfried et al. 1998).

Partners Providing Research Support

A number of other partners in the Borderlands ecosystem management efforts are supporting scientific and monitoring in this region. The Malpai Borderlands Group has supported research into the habitat requirements of the New Mexico ridgenosed rattlesnake and monitoring activities for the Mexican spotted owl (*Strix occidentalis lucida*). The group's range consultant also is assisting the Rocky Mountain Research Station scientists, and some of its cooperators, with vegetation monitoring. The Nature Conservancy provided support for the vegetation map of the Borderlands Region that was developed from LANDSAT satellite imagery. The Animas Foundation is donating logistical support for several studies on the Gray Ranch. The Foundation is a partner, along with the Bureau of Land Management, University of New Mexico, and the Rocky Mountain Research Station, on a study about how a combination of cattle grazing and fire can be used to moderate or reverse woody plant increases, and how disturbance processes affect grassland structure. A companion study will measure the influence of reintroduced black-tailed prairie dogs (*Cynomys ludovicianus* ssp. *arizonica*) on grasslands. The Animas Foundation also is assisting with a study of the effects of burning, with and without grazing, on the mix of grasses and mesquite plants and animals in the shrub invaded grasslands. Other scientists are working independently with financial support from their universities or other agencies and foundations.

Partners

A healthy, productive, and unfragmented landscape in the Southwestern Borderlands Region is only achieved with the cooperative efforts of numerous organizations and agencies and, more importantly, by the dedicated efforts of people. The Rocky Mountain Research Station, Malpai Borderlands Group, Natural Resources Conservation Service, Coronado National Forest, The Nature Conservancy, University of Arizona, and the Animas Foundation have been mentioned, but there are many more partners. At least 14 additional federal, Arizona State, and New Mexico State agencies and five additional private conservation and ecology organizations are involved with the Borderlands effort. In addition to scientists and students from different schools and departments of the University of Arizona and the University of New Mexico, faculty and staff from at least five other universities are working in the region. Contacts also are maintained with Mexican managers and scientists from the Secretaria de Media Ambiente, Recursos Naturales y Pesca (SEMARNAP) and the University of Sonora. This project is a national example of how private citizens, organizations, and public agencies can collaborate to ensure the health and future of large, open landscape areas.

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International Arid Lands Consortium: Better Land Stewardship in Water and Watershed Management

Peter F. Ffolliott[1], James T. Fisher[2], Menachem Sachs[3], Darrell W. DeBoer[4], Jeffrey O. Dawson[5], Timothy E. Fulbright[6], and John Tracy[7]

Abstract.—The International Arid Lands Consortium (IALC) was established in 1990 to promote research, education, and training for the development, management, and restoration of arid and semi-arid lands throughout the world. One activity of IALC members and cooperators is to support research and development and demonstration projects that enhance management of these fragile ecosystems for sustainable human use. Topics of interest include more effective water and watershed management practices, projects, and programs leading to better land stewardship in the coming century.

Introduction

The International Arid Lands Consortium (IALC) is a partnership of organizations dedicated to research, education, and training relative to development, management, restoration, and reclamation of arid and semi-arid lands throughout the world. Member institutions are the University of Arizona, New Mexico State University, the Jewish National Fund, South Dakota State University, the University of Illinois, Texas A&M University-Kingsville, and the Desert Research Institute, UCCSN, Nevada. Affiliate members are Egypt's Ministry of Agriculture and Land Reclamation, Under secretarial for Afforestation, and Jordan's Higher Council for Science and Technology. Collaboration with cooperators from other institutions, including the USDA Forest Service and Cooperative State Research, Education, and Extension Service, and those from other countries that strengthen the mission of the Consortium, is encouraged.

Resources and expertise brought together by the IALC, which are generally greater than those from a single institution, provide an opportunity for a comprehensive exchange of valuable research technologies. The IALC encourages collaboration between people and programs in land reclamation, land use, water resources conservation, water quality, inventory technology, ecosystem processes supporting sustainable management, and ecosystem enhancements of sustainable management. IALC funding of research and development and demonstration projects helps ensure that experts are researching and disseminating their results efficiently and effectively.

Research and Development Projects

Research and development projects lead to new knowledge and technologies for management of sustainable ecological systems. Three examples of IALC-sponsored research and development projects providing a foundation for more effective future water and watershed management are reviewed (Hegwood 1998).

Soil Salinization Induced by Runoff Collected in Small Forested Earthen Dams in the Negev Desert

Small earthen dams (limans) have been constructed in the Negev Desert for the past 45 years across ephemeral waterways to collect runoff during storms. Trees are planted in the limans to use the extra available water. However, the limans are closed systems that accumulate sediment fines and dissolved salts over time. As a consequence, these deposits might affect the survival and growth of the planted trees.

In one study, trenches were dug in 20 representative limans to determine whether salt accumulation was occurring in the systems. The soil profile was described at each trench, and soil samples were obtained to analyze properties impacted by salinization; runoff waters were also sampled to estimate the rate of salt inputs. Despite a relatively high salt input to the system, the hypothesis that limans were accumulating salts at levels that might affect

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tree survival and growth was not supported by this study. Soil to a depth of 3 m was non-saline, and salinity inside the limans was lower than in the control trenches. Apparently, afforestation efforts at this low level of technology will prove successful beyond the establishment phase.

Water Use by Tree and Shrub forms of Dryland Oaks

Conservation and sustainable use of oak woodlands in the southwestern United States and Israel require more complete knowledge of their ecological processes. Water use is critical, and affects all components of the ecosystems in these dryland environments. Understanding oak physiology is critical to understanding ecosystem dynamics.

Transpiration by oak trees was estimated by sap velocities measured by the heat-pulse method by researchers in both the U.S. and Israel. Individual tree measurements showed that seasonal trends of water use were related to diameter, height, and crown volume, and to precipitation patterns. Measurements from clusters of trees on undisturbed sites were compared to measurements on sites where trees had been previously harvested. Extrapolated to stand-use values, results indicated that annual water use by oak was about 45% of the annual precipitation on the undisturbed sites, while water use by oak on the harvested sites was nearly 70% of the precipitation. Vigorous sprouting from residual stumps was the attributing factor for this difference. Apparently, harvesting trees has the potential to significantly affect water budgets in oak woodlands.

Decision Support System for Wetland and Riparian Ecosystems

Wetland and riparian ecosystems must be protected from damage and, when necessary, restored to a desired previous condition. A methodology for examining the impacts of alternative management and design recommendations to protect or restore these fragile environments is being incorporated into a decision support system. This system will optimize a range of environmental, water resource, and economic benefits at a specific site.

This ongoing IALC-supported research and development project is modifying spatially-distributed hydrologic-hydraulics model, and combining the modified model with a geographic information system to account for site spatial variability. A surface-water quality module is also being linked to the hydrologic-hydraulics model to simulate changing water quality constituents associated with alternative management schemes and physical site configurations. Intensively monitored wetland and riparian ecosystems in the southwestern United States and Israel are being studied to test the newly developed decision support system for operational applications.

Demonstration Projects

IALC-supported demonstration projects for management of sustainable ecological systems represent practical applications of the available knowledge and technologies from research and development efforts. Conditions that demonstration projects must meet to be supported by the IALC have been outlined elsewhere by Ffolliott et al. (1998). Three examples of IALC-sponsored demonstration projects contributing to more effective water and watershed management are reviewed (Hegwood 1998).

International Workshop on Arid Lands Management

This workshop, held in Israel in 1994, established a state-of-knowledge on the functioning of arid and semi-arid land ecosystems and their management. This information has been used to ask the IALC, and other granting institutions that support research related to the ecological sustainability in these systems, to describe the state-of-knowledge and determine where to best allocate resources to increase the available information about arid and semi-arid ecology and management. Another use of this state-of-knowledge has been to distribute it to planners and managers, and other granting institutions with related programs, to incorporate this into their management programs.

The established state-of-knowledge published in the book Arid Lands Management: Towards Ecological Sustainability," is a reference for policy-makers, representatives of legislative bodies, planners, researchers, managers, and lay people interested in arid and semi-arid regions where effective water and watershed management is a priority concern. This publication is comprised of chapters on the ecological framework for conservation and sustainability; ecosystems of the desert and their management; land use and management in selected desert ecosystems of the world; and planning, simulation, and operations research approaches to arid and semi-arid lands management (Hoekstra and Shachak 1999).

Savannization in the Negev Desert

The objective of savannization, initiated by the Land Development Authority in 1986, has been to increase biological productivity and diversity of land-use in the degraded Negev Desert of Israel; and develop land management practices for sustained, ecologically-sound use of desert ecosystems. Savannization techniques focus on creating patches of relatively high productivity by planting trees in desert landscapes of lower productivity. These patches benefit from soil-water enhancement through collection of surface runoff from undisturbed adjacent areas by applying water harvesting techniques. Only small portions of effected landscapes are altered to create enriched patches within the poorer surrounding matrix.

Savannization increases fiber and fuel production, improves rangeland quality, enhances recreational assets, and increases dust control. Greater biological diversity and biomass productivity than on over-exploited desert landscapes result. This IALC-sponsored demonstration project synthesizes models to foster efficient methods of managing desert landscapes, enhancing their limited productivity, increasing and sustaining their use, and combating desertification.

Transfer of Management Information on Semi-Arid Watersheds

Watershed management involves manipulation of natural, agricultural, and human resources to achieve specified objectives, while considering the social, economic, and institutional factors operating within a river basin or other relevant region. Usefulness of watershed management practices to increase multiple-resource benefits has been, and continues to be, an interest of the IALC, USDA Forest Service, and other land management agencies and their cooperators.

Literature on watershed management practices in semi-arid regions has been scattered and, therefore, not readily accessible. Therefore, a three-pronged approach has been initiated to deliver this information to an audience broader than management professionals. This IALC-sponsored demonstration project is bringing this information to the public through the World Wide Web and other technology-delivery systems. Additionally, a telephone system provides people with recorded messages on the benefits of watershed management. Field days, held to introduce the concepts of integrated, multiple-use oriented watershed management to the public, allow participants to experience "hands on" demonstrations, conduct limited experiments, and perform watershed management monitoring techniques.

Multi-media Demonstrations of IALC-Supported Research Results

This technology-transfer project illustrates the effectiveness of IALC-supported research through print, video, and World Wide Web media. Target audiences include policy-makers, supporters of arid lands research and development, and stakeholders in the sustainable development of arid land resources. These audiences typically have limited time for extensive evaluations of research findings and might not fully understand the complexities or values of arid land resources. An important tool to help change misconceptions and alter social action and political policy is to present key concepts about management of arid and semi-arid land ecosystems to provide sustainable benefits with minimal environmental degradation; this is largely the objective of this project.

Summary

The IALC works to achieve research and development and demonstration projects, educational and training initiatives, workshops, and technology-transfer activities about the development, management, restoration, and reclamation of arid and semi-arid lands worldwide. All of these activities are supported by the IALC's member institutions through efforts aimed at sustaining arid and semi-arid land ecological systems and human populations inhabiting these systems. Included among these activities are efforts directed toward effective water and watershed management practices, projects, and programs to address land stewardship issues and constraints in the coming century.

Acknowledgments

The authors, members of the Research and Demonstration Advisory Committee of the IALC, wish to thank Donald A. Hegwood and Jim P. M. Chamie, Executive Vice President and Managing Director of the IALC, respectively, for their technical reviews of this paper.

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POSTER PAPERS

Applied Watershed Management Activities

Watershed Management Implications of Agroforestry Expansion on Minnesota's Farmlands

C. Hobart Perry[1], Ryan C. Miller[2], Anthony R. Kaster[3], and Kenneth N. Brooks[4]

Abstract.—Minnesota's agricultural landscape is changing. The increasing use of woody perennials in agricultural fields, living snow fences, windbreaks, and riparian areas has important watershed management implications for agricultural watersheds in northwestern Minnesota. These changes in land use could lead to reductions in annual water yield, annual flood peaks, and dry season flows, with reduced non-point source pollution of streams, lakes and ground water. Where woody crops become an important part of a watershed, we expect a reversal of hydrologic changes on agricultural lands that have resulted from wetland drainage and extensive annual cropping that has taken place over the past century.

Introduction

Minnesota's Landscape was Historically Adapted to Meet Agriculture's Needs

Since Europeans first settled Minnesota, the landscape has been significantly altered to promote agricultural development. Most of the prairie and vast areas of forest cover were replaced with agricultural cropping. Wetlands have been extensively drained, and rivers and their riparian systems have been modified. As a result, annual water yield and peak flow discharges associated with 1.5- to 50-year return periods have increased over pre-settlement conditions (Miller, 1999).

Now Agroforestry is Increasing in Minnesota

There is currently heightened interest in Minnesota in growing short-rotation woody crops (SRWCs) on farmlands, fields, and riparian zones. Although not expected to occur at the same scale, the conversion of annual crop lands to agroforestry and the establishment of tree plantations can potentially reverse some of these effects, at least at the local watershed level.

There is particular interest in short-rotation hybrid poplar, and Minnesota DNR (1995) projections of 30 000 to 40 000 ha of hybrid poplar being planted between 1995 and 2005 are coming to fruition. Josiah et al. (1998) discussed several factors motivating the trend of using SRWCs in agroforestry applications. They include: (1) a projected shortage of mature aspen (*Populus* spp.) available for harvest from natural stands in the next 10 to 20 years, which is already reflected in a four-fold increase in the price of stumpage since 1987; (2) long-term research progress in developing viable clones and the consideration of their use for biomass energy and carbon sequestration; (3) changes in the socioeconomic structure of the agricultural sector; (4) regional environmental issues; and (5) policy and institutional support for SRWCs.

Research Results

Including Trees in the Landscape Reduces Water Yield

The effects of forest cover changes on water yield are well documented, indicating for most non-cloud forest conditions that water yield increases as forest cover is reduced (Bosch and Hewlett, 1982; Hornbeck et al., 1993; Whitehead and Robinson, 1993). Many of the studies cited by these authors also indicate that as one converts vegetative cover from forest to shrubs to herbaceous cover, there is a corresponding increase in annual water yield.

In northern Minnesota, clearcutting mature aspen forests increases annual water yield by about 9 cm the first year (Verry, 1986). In general, annual water yield increases as the forested percentage of a watershed decreases. The reversal would also be expected; afforestation of cleared lands (such as farmlands that support annual crops) should reduce annual water yields accordingly. Such changes have not been measured on a watershed

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basis in Minnesota, however, there is sufficient research to suggest that these same changes would occur.

Recent studies of hybrid poplar plantations in northwestern Minnesota indicate that they have consumptive use characteristics similar to those of natural aspen stands. These results imply that any significant increase in tree cover on a watershed that was previously under an open, cultivated condition should reduce water yield. The volume and timing of water yield of mature natural aspen stands and short-rotation hybrid poplar plantations are functionally identical (Perry et al., 1999).

Land use conversion and total annual rainfall have interacting effects on annual water yield. A modeling study of the Pomme de Terre watershed of west-central Minnesota demonstrated that the conversion of cropland to hybrid poplar results in a 43% (3.0 cm) reduction in water yield during periods of average precipitation (Kaster, 1999). During periods of greater than average precipitation, the influence of agroforestry on annual water yield is much less. Using climatic extremes recorded during 1993, a conversion of agriculture to agroforestry with SRWCs reduced water yield by only 3% (0.6 cm) (Kaster, 1999).

Including Trees in the Landscape Reduces Peakflow Discharge

The hydrologic effects of increasing the acreage of hybrid poplar on the agricultural landscape have not been extensively studied in northwestern Minnesota. However, research in north central Minnesota indicated that clearcutting natural aspen stands can lead to a doubling of both average annual snowmelt peak discharges and rainfall storm flow peak discharges (Verry et al., 1983). These responses are within the same order of magnitude as changes in peak flow resulting from wetland drainage and conversion from prairie vegetation to annual cropping (Miller, 1999). In the case of rainfall, peakflows tend to increase as the percentage of forest that is clearcut increases. Therefore, increasing forest cover on the watershed should have the opposite effect. Furthermore, increasing tree cover along riparian zones and in floodplains has the added effects of streambank and channel stabilization (Rosgen, 1994).

The potential effects of converting annual crops to hybrid poplar on snowmelt runoff are numerous. In contrast to open fields, forest cover influence can alter snowmelt runoff response through changes in antecedent soil moisture conditions, soil frost, snow depositional patterns, and melt rates. Given the above discussion on water yield and evapotranspiration, one would expect soil moisture conditions on average to be drier entering the fall, than soils that have supported annual crops. Weitzman and Bay (1963) indicated that forest cover reduces the depth and type of soil frost in contrast to open fields (discussed by Baker (1972)). Soil frost is deeper, and concrete frost is more prevalent in cultivated fields than in hardwood forests. Snowpacks tend to be deeper in forest stands as they are not subjected to wind, but the snowpack melts at a slower rate and spreads out the period over which snowmelt runoff occurs. Snowmelt runoff under forest cover is, therefore, less efficient than snowmelt runoff from open, cultivated fields.

On a watershed basis, the magnitude of annual peak flow discharges from snowmelt runoff was found to be related to the percentage of the watershed that is forested vs. cleared or open (fig. 1) (Verry et al., 1983). As illustrated, increasing forest cover from 0 to about 40 to 50% on a watershed can significantly reduce snowmelt peakflow discharge as a result of desynchronization of snowmelt runoff.

With the recent observation that hybrid poplar plantations have hydrologic characteristics similar to those of natural aspen stands in northern Minnesota (Perry et al.,

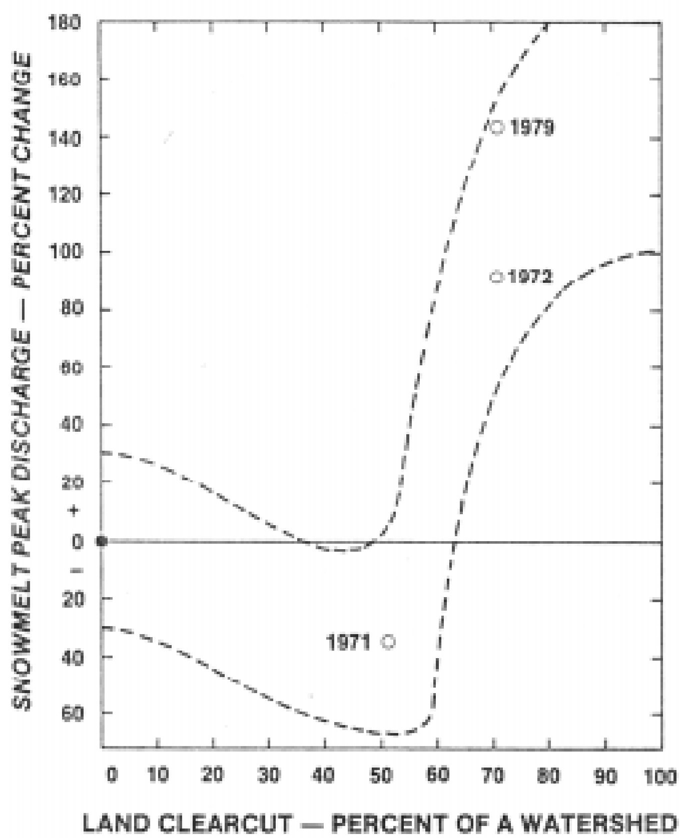

Figure 1. Relation between the portion of a watershed clearcut (with regrowth for at least nine years) and the change in snowmelt peak discharge compared to mature aspen forest conditions. Circles are measured; lines hypothesize an envelope of response for northern Lake State conditions. (From Verry et al., 1983)

1999), any significant increase in tree cover on a watershed that was previously under an open, cultivated condition should reduce peak flows from either rainfall or snowmelt.

Including Trees in the Landscape Improves Water Quality

Short-rotation woody crops have the potential to improve regional water quality when they replace annual agricultural crops. When measured over the course of a complete rotation, pesticide inputs to SRWCs are substantially less than the agricultural crops they replace. SRWCs will require approximately 11% of the herbicides applied to corn and 20% of those applied to soybeans (Ranney and Mann, 1994). Mature short rotation hybrid poplar also contributes much less total nitrogen to ground water than the agricultural crops they replace: 2.3 kg N ha^{-1} yr^{-1} versus 36.5 kg N ha^{-1} yr^{-1} (Lowrance, 1992; Perry, 1998). Water migrating through the unsaturated soil under riparian buffers that include SRWCs loses most of the associated NO_3-N at the field border beneath the strip, reducing nutrient loading to adjacent water bodies (Schultz et al., 1995). However, while water quality benefits of energy crop production are expected to be largely positive, some results suggest that recommended US Environmental Protection Agency (EPA) nitrate limits could be exceeded 1 or 2 years out of 20 in some locations (Ranney and Mann, 1994). Given the expected growth in forested acreage in northwestern Minnesota, nutrient loading to adjacent stream bodies and shallow ground water should be reduced.

Conclusions

Given the economic and environmental conditions in northwestern Minnesota, large acreages of farmland will likely be converted from annual cropping to short-rotation tree plantations. In terms of the effects of such land use changes on the Red River of the North, it is unlikely that a large percentage of the river basin would be converted to SRWCs. The eastern tributary watersheds along the prairie-forest border however could experience large increases in the percentage of watershed that is tree-covered. It is possible that such changes in plant cover could decrease antecedent soil moisture conditions in local watersheds; tree crops consume more water than annual crops (Lee, 1980). In addition to the expected reductions in annual average peak flows in streams (Verry et al., 1983), the reduction in soil moisture could also reduce the area of saturated soils contributing to stormflow during average events (Hewlett and Troendle, 1975). Flood flows in the level topography of the Red River of the North are dramatically affected by the areal extent of saturated soil.

The results of our studies, when combined with earlier forest hydrology - watershed studies in north central Minnesota, suggest that the conversion from non-forested, annual croplands to agroforestry with short-rotation hybrid poplar crops could reduce both the annual water yield and the magnitude of annual peakflow discharges from rainfall and snowmelt events. The economic conditions in the region are currently favorable for large acreages of marginal farmland to be planted with short-rotation hybrid poplar. If such is the case, and large percentages of tributary watersheds of the Red River of the North are so converted, there is the possibility that the magnitude of annual floods in these tributary streams could be reduced.

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Agroforestry Systems in the Sonora River Watershed, Mexico: An Example of Effective Land Stewardship

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Abstract.—The Sonora River watershed is located in the central part of the state of Sonora, Mexico, and is one of the most important watersheds in the region. Much of the state's economy depends on the natural resources, products, and productive activities developed in this watershed. Many natural areas along the river and its tributaries have been converted to a large variety of agroforestry systems, providing the inhabitants of the region with food, timber, medicines, economic inputs from agricultural crops, forage for livestock, and services like recreation. Land tenure forms are private and communal properties. Private owners use more advanced technology being dedicated to more extensive and intensive exploitation activities. Communal producers usually rent their lands or get little income from their land use activities.

Introduction

Watersheds are geographic areas that are often rich in natural resources that provide inhabitants with food, medicines, construction materials, and recreation. However, the spatial distribution of these resource types does not necessarily follow a uniform pattern within a watershed. This is caused by climatic, edaphic, and physiographic conditions varying irregularly from upland origins of a watershed to the discharge zone, generating a mosaic of ecosystems, each providing resources destined to different types of utilization.

According to Young (1994), the term *agroforestry* refers to sustainable land-use systems in which woody perennials are grown in association with herbaceous plants, and/or livestock, generating ecological and economic interactions between the trees and the other components of the system. Although the agroforestry system concept is well known and has been applied in many geographic areas throughout the world, its potential has not been fully explored in the drylands of Sonora, Mexico. Although producers practice agroforestry in distinct ways in this region, they have not fully perceived the role of such production systems in terms of productivity, socioeconomic importance for rural communities, and significance for wildlife species and recreational activities. They also are not familiar with methods to classify their agroforestry systems based on how the elements of the system are distributed.

The objective of this study was to characterize the agroforestry systems along the Sonora River watershed, contributing to the understanding of the potential these systems have in improving the living conditions of the inhabitants, and to encourage the utilization of the natural resources in a more efficient and sustainable manner.

Watershed Description

The Sonora River watershed is located in central Sonora, covering an approximate area of 26,010 km^2 of state land. Mean annual precipitation for the area is 375 mm, which occurs in late summer-early fall and winter-early spring. Slopes along the river range from steep in the upper part, to gradual in the valleys (INEGI 1993). The watershed supports a variety of vegetation types defined largely by latitudinal, elevation, temperature and precipitation gradients. Considering Brown and Lowe (1994) criteria, five biotic communities are found in the area. In order of importance by area covered, these are the Sinaloan thornscrub, plains of Sonora subdivision, semidesert grassland, Madrean evergreen woodland, and central gulf coast subdivision. The watershed is subdivided into six smaller watersheds. This study was carried out in the largest subdivision, which occupies 45% of the entire watershed; it is approximately 300 km in length and about 11,690 km^2 in area (figure 1).

Natural Resources

A variety of natural resources are found in the study area. This allows the application of different land-use options to local inhabitants for exploitation. Native and introduced species of flora and fauna, minerals, freshwater reservoirs, and thermal water springs represent the usable resources in the area. Vegetative communities are mainly used for livestock grazing, as a source of firewood

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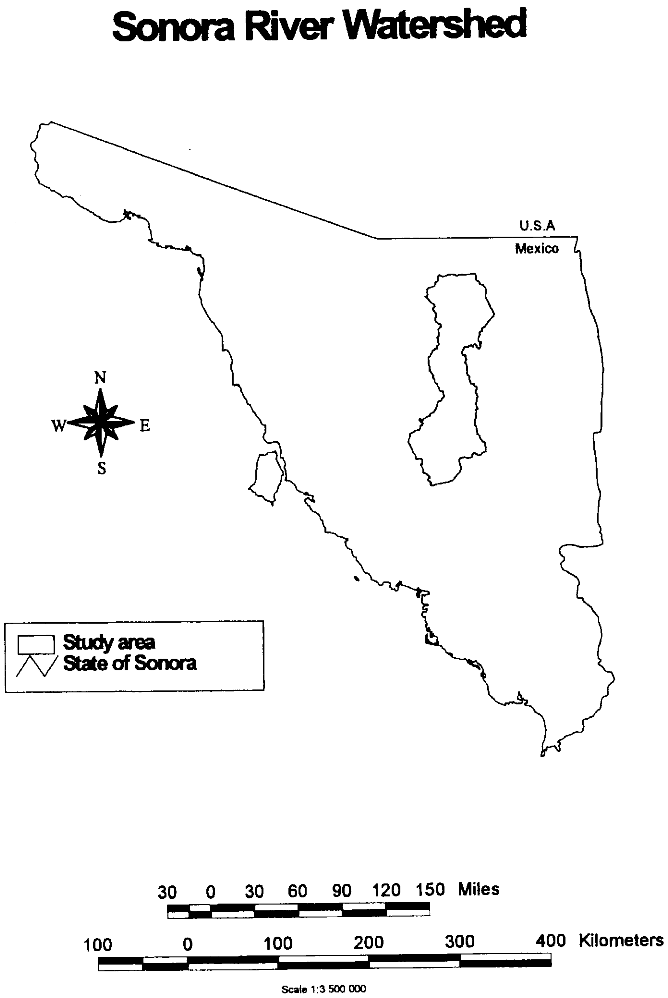

Figure 1. Location of study area.

and local construction materials, and recreational activities. The ranchers commercialize with cattle, milk, and cheese, and some also exploit native and exotic wildlife species by selling hunting permits to Mexican and international hunters. Mining activities are important in the area, especially copper extraction from the mine at Cananea City. This mine generates hundreds of jobs for local and regional inhabitants. Freshwater reservoirs and the river itself are places where people fish or spend their leisure time. A thermal water spring located in Aconchi, in the central part of the watershed, was remodeled by the state government and currently serves as an additional public recreational place within the watershed.

Agroforestry Systems

Most of the agroforestry systems found in the study area are along the riparian areas, with the exception of some grazing lands that occur in the uplands or small valleys away from the river floodplains. Native tree species, such as willow, mesquite, and cottonwood, are used to define the boundaries of land properties and as windbreaks. Other non-native tree species like pecans are also serve this function. Most of the plant species utilized as medicine, food and forage, are exotics. Only a few native species are exploited in these ways.

Classification

There are different criteria on how agroforestry systems can be classified. One set of criteria are based on functional, structural, ecological and socioeconomic bases (MacDicken and Vergara 1990, Nair 1993, Ffolliott et al. 1995). Agroforestry system classes can change in time according to the method of utilization. Therefore, agroforestry crop rotation systems (shifting cultivation) differ in time from permanent systems (Ffolliott et al. 1995). Agroforestry systems established along the Sonora River watershed are largely productive systems with a commercial criterion. However, some of them are subsistence systems. There are agrisilvicultural, agrosilvipastoral, and silvopastoral systems in the study area. Agrisilvicultural systems are characterized by native trees surrounding croplands, while agrosilvipastorial systems are represented by irrigated pastures fenced by native tree species, and non-irrigated pastures where introduced grasses like *Cenchrus ciliaris* (buffelgrass) grow in association with native vegetation. Silvopastoral systems are characterized by native trees, shrubs and grasses all supporting ranching activities.

The spatial arrangement of the elements within the agroforestry systems vary from a complete mixture of plant species to a well defined monoculture surrounded by trees. There are systems represented by a random mixture pattern of components (often characteristic of silvopastoral systems); irrigated pastures planted with a mixture of grass species, fenced off by trees; or areas where people grow flowers, fruit trees, vegetables, and medicinal plants simultaneously or shifted in time. Other producers establish plantations following a regular pattern represented by alternate rows or alternate strips, combining fruit trees (different varieties of citrus, peaches) with maize, beans or vegetables. Agroforestry systems such as monocultures of vegetables or grasses bordered by trees are also established in the study area. Some systems display a mosaic of different agroforestry components. For example, part of a individual's property can show a regular pattern of alternating rows or strips or both, while other pieces of land included cultivated plants following a random mixture pattern; this is common in areas known by the local people as *Huertos Familiares* (orchards for the family).

Technological Inputs

Capital-intensive commercial plantations are farmed using modern technology. The application of pesticides and fertilizers is common, and many farmlands are cultivated, irrigated, and harvested with advanced machinery. Subsistence agroforestry systems, in contrast, are farmed with hand tools and irrigated by small channels with water diverted from the Sonora River and local wells. Fertilizers, herbicides, or other agrochemicals not used in these systems, which are labor-intensive in operation. Weeding and harvesting of products from these subsistence systems is accomplished mostly by hand.

Socioeconomic Considerations

Farmers, ranchers, and homeowners were interviewed to gain a better understanding of the local socioeconomic conditions. Most of the inhabitants can be grouped in a communal-type of land tenure called *ejido*. Some ejido members work together over the entire area of the ejido; after the commercialization of the products, they divide the profits. In other ejidos, the members own individual pieces of land, which can be exploited or rented to other farmers to obtain income. There are also private-property owners of farmlands and rangelands. These owners tend to be the producers with higher technical education (agronomists, veterinarians, and livestock breeders) and the users of more advanced agricultural equipment and technologies. They also rent tracts of land from other farmers to extend their areas of exploitation. For these reasons, private property owners have the highest economic incomes within the watershed.

The majority of the products derived from the agroforestry systems of the watershed are sold *in situ*. The producers do not need to transport their animal or plant products to markets away of the closest towns because buyers coming from big cities (Hermosillo, Cananea, and Agua Prieta) acquire the products directly from them. Sometimes, the ranchers transport calves to the border and export them to the United States.

There are regional and state associations that group producers from rural areas into more economically efficient bodies , and provide them with advise on how to get bank credits, low-cost inputs like fertilizers and pesticides, and implement better land management practices and crop production; this enables participants to commercialize their products locally or outside the state or the country. Unfortunately, the smaller farmers are not participants in these kind of associations. Only people largely dedicated to cattle industry are organized and grouped in regional and state organizations, for example, the Asociacion Ganadera Local and Union Ganadera Regional de Sonora, receiving advisory services in range management and cattle production and animal and products commercialization, among other benefits.

Conclusions

A variety of agroforestry systems furnish the people of Sonora with opportunities to generate needed incomes while sustaining a high level of environmental quality. These agroforestry systems have been matched to the capabilities of the land to produce commercial and subsistence outputs. Relatively low levels of capital investments in some of these agroforestry systems allow almost all the people living in the Sonora River watershed to actively participate in these multiple-cropping interventions. This integrated form of sustainable land stewardship will continue, and likely will expand in the region into the 21st century with increasing technological inputs.

Acknowledgments

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Water Repellency of Casuarina (*Casuarina equisetifolia* Forst.) Windbreaks in Central Taiwan

Chao-Yuan Lin[1]

Abstract.—Water repellent layer (WRL) in the Casuarina plantation near Taichung harbor in Central Taiwan is mainly due to the development of filamentous fungi. Not only are hyphae of the isolated fungi, the metabolites of fungi strongly hydrophobic, TCHC-5 and TCHC-20 are also significantly hydrophobic. Humic substances decrease the phosphorus fixation and contribute to the formation of WRL. The hydrophobic properties of humic substances are unfavorable for the nutrient cycling at this area. Wetting angles of fulvic acids and humic acids are pH-dependent. Increasing solution pH reduces hydrophobic strength for fulvic acids and/or humic acids. Isolated fungi TCHC-15 and TCHC-16 exude strongly acidic metabolites (pH2.7-3.0), which will increase the hydrophobic strength of soil layers. Humic substances with aliphatic chain are the main components that form WRL in soils. Soil pH could be an indicator of hydrophobic potential for organic matter.

Introduction

Casuarina plants are the main plantation on the seashore and are usually used as windbreaks in Taiwan. Due to monsoon in the drought season, Casuarina stands usually accumulate more litter and result in highly hydrophobic and flammable litter layers because of mat formation and stimulated growth of some fungi. The purpose of this study was to search for a feasible method for the reclamation of WRL by investigating the mechanisms of fungi on the formation of water repellency and the nutrients cycling in the Casuarina stands.

Materials and Methods

Litters and soils were sampled randomly from three quadrates each with a width of about 2m x 2m at the Casuarina plantation suffering from water repellency with serious retardation growth. The samples cultivated under the controlled temperature of 26°C for 2 to 5 days with the Potato-Dextrose Agar (PDA), Penicillin G, and Rose Bengal added (see table 1). Their hyphae and/or spores were planted onto the chosen nutrient medium, until the individual colonies are subculture in pure culture for identification. Small pieces of the isolated colonies were planted onto a Yeast extract-Malt extract Agar (YMA). A slide was embedded on each plate for hyphae development, and incubated at the temperature of 26°C for 1 to 2 weeks, until each cultured colony's need had been fulfilled. The slides were picked out respectively for the observation of hydrophobic strength of each isolated fungus. Isolated fungi were punched 10 discs (ID=8mm) in the previous YMA cultured, and planted onto a Yeast extract-Malt extract Broth (YMB) subculture in an incubator (26°C, 100 rpm) for 2 weeks. Hyphae and culture solution of each fungus were collected for slide smear (wetting-angle measurement) and chemical analysis.

Soil property analysis are based on the recommendation of American Society of Agronomy (Klute, 1986; Page, 1982). The hydrophobic strengths of the samples were directly estimated from the wetting-angle measured by contact-angle meter (Mallik and Rahman, 1985). Macro elements of the litter were determined by the procedures of digestion with sulfuric acid and hydrogen peroxide. Trace elements of the litter were determined by the procedures of digestion with nitric acid and perchloric acid. The procedures of extraction of humic substances, in a sequence of extraction by the 0.1M HCl and 0.1M NaOH solution, are based on the recommended method of the International Humic Substance Society (Aiken, 1985). 10 ppm P of KH_2PO_4 was used as a tracer in columns containing

Table 1. Components of nutrient medium (g/l).

Components	PDA	YMA	YMB
Diced potato	200	—	—
Dextrose	20	10	10
Yeast extract	—	3	3
Malt extract	—	3	3
Peptone	—	5	5
Agar	15	20	—
Penicillin G	0.3		
Rose Bengal	0.5		

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topsoil (0-5 cm; hydrophobic) and subsoil (10-15cm; nonhydrophobic) respectively, which were sampled from Casuarina windbreak site and packed in the glass column. The soil columns were saturated by deionized water before displacement experiments.

Results and Discussions

Several fungi were isolated from the Casuarina stands in Taichung harbor. These included *Mucor, Rhizopus, Collybia, Aspergillus, Fusarium, Penicillium, Trichoderma,* and *Verticillium*. The wetting angle of cultured colony of each isolated fungus was difficult to measure accurately due to the fluffy texture; however, all of the isolated fungi were showing hydrophobic when using the water droplets on them. Wetting-angle measured from slide smear (hyphae + CS) revealed that the isolated fungi TCHC-2, TCHC-5, TCHC-12, TCHC-20 and TCHC-21 were significantly different in water repellency. Having filtered the culture solution to remove hyphae, fungi TCHC-5 and TCHC-20 were still hydrophobic (measured from slide smeared CS only). This showed that the metabolites of some fungi were hydrophobic. Fungi TCHC-15 and TCHC-16 exuded strongly acidic metabolites (pH2.7 - 3.0), which could affect the behavior of water repellency of hydrophobic substances in soil layers.

Humic acids and fulvic acids extracted from repellent soils of Casuarina windbreak were hydrophobic. Figure 1 and figure 2 show that wetting angles of fulvic acids and humic acids varied with solution pH. There was a trend of declining hydrophobic strength in accordance with increasing solution pH. Generally speaking, soil pH ranges from 4 to 8 at the natural soil environment. Under such soil pH condition, the difference of hydrophobic strength between fulvic acids and humic acids was not significant. Usually measured in a solum base, soil pH was an average value of the sampling solum. In fact, the real soil pH in local soil layers, due to the metabolites of microorganism, may be less than 4. Fungi TCHC-15 and TCHC-16 can exude strongly acidic metabolites. Such phenomenon will cause polymerization and/or precipitation of the fulvic acids and humic acids. It also suggests that it is easy to increase the hydrophobic strength of soil layers.

The breakthrough curve (P-sorption curve) and P-desorption curve is shown in figure 3. Hydrophobic soils had higher phosphorus concentration of effluent under the process of KH_2PO_4 solution displacement, and lower phosphorus concentration in the next process of H_2O displace-

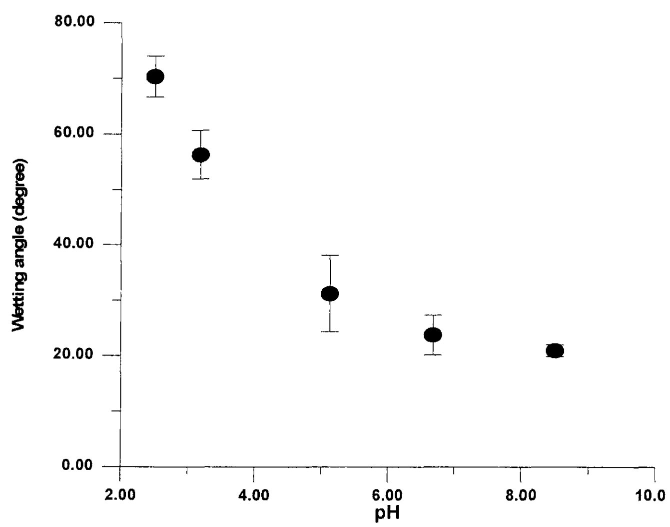

Figure 1. Changes of wetting angle of fulvic acids in different solution pH.

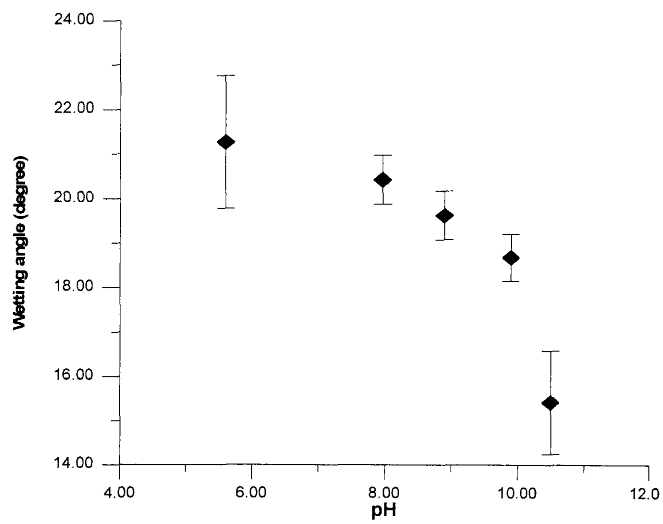

Figure 2. Changes of wetting angle of humic acids in different solution pH.

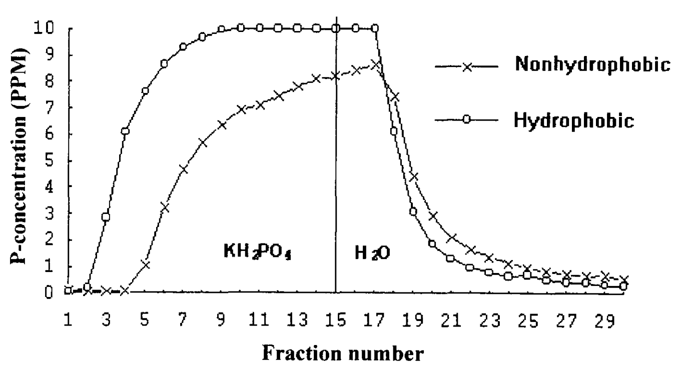

Figure 3. P-sorption and desorption curves of tested samples in the processes of miscible displacement.

ment. This shows that hydrophobic soils have lower P-sorption than non-hydrophobic soils. Besides, from the breakthrough curve of non-hydrophobic soils (C/Co =0.5, V/Vo =3.7), one can see there exists a significant P-sorption reaction in figure 4. Hydrophobic soils shows a slight P-sorption reaction in figure 5 (C/Co =1/2, V/Vo =1.0). Humic substances have the ability to reduce oxidized forms of certain metal ions, a typical case being the reduction of Fe III.

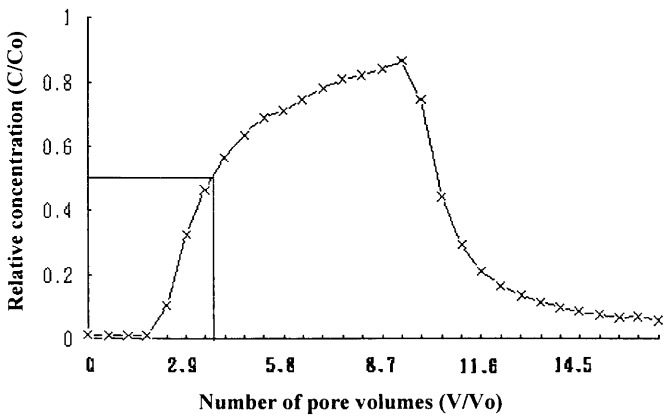

Figure 4. P-sorption and desorption curve of non-hydrophobic soils.

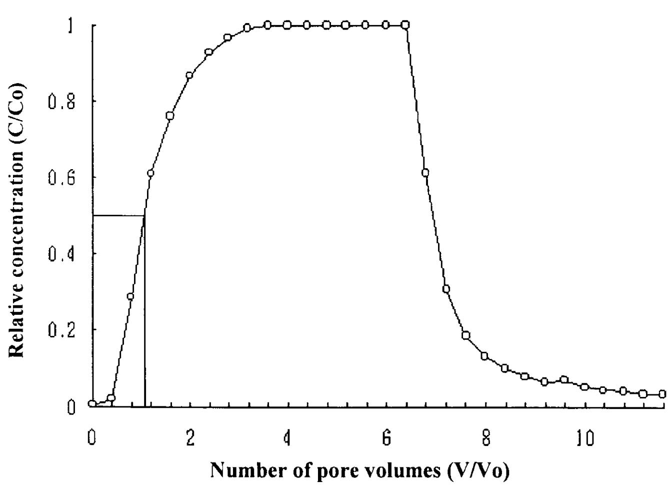

Figure 5. P-sorption and desorption curve of hydrophobic soils.

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Land Cover Changes in Central Sonora, Mexico

Diego Valdez-Zamudio[1], Alejandro Castellanos-Villegas[2], and Stuart E. Mash[3]

Abstract.— Remote sensing techniques have been demonstrated to be very effective tools to help detect, analyze, and evaluate land cover changes in natural areas of the world. Changes in land cover can generally be attributed to either natural or anthropogenic forces. Multitemporal satellite imagery and airborne videography were used to detect, analyze, and evaluate land cover changes in the central region of the Mexican State of Sonora. Observed land cover changes were analyzed in terms of the productive activity most likely responsible. The ecological consequences for the different impact intensity, area and percent of change are also discussed. Landsat MSS images were classified into five different land cover/land use categories for two time periods (1973 and 1992) and validated using airborne video imagery and fieldwork. About 85% of the entire land cover in the study area changed during that period of time. The Sinaloan thornscrub biotic community class had the highest rate of change; more than 28% of the original class evolved into other biotic categories.

The relationship between the land cover change with climatic patterns over the period of time considered is described. Future scenarios for watershed management in the region are analyzed.

Introduction

The term *Land Cover* relates to the type of feature present on the surface of the earth, including vegetation and nonvegetation features. The term *Land Use* relates to the human activity associated with a specific part of land and usually emphasizes the functional role of that land for economic activities (Lillesand, 1987; Campbell, 1987). Changes occurring in land cover and land use can generally be attributed to either natural or anthropogenic forces. Natural changes relate to both seasonal and annual variations in climatic conditions and are often reflected by variations in natural land cover; natural changes can also be related to fire. Changes resulting from anthropogenic forces are the result of human modification of the environment (Pilon et al., 1988). Geographic information systems (GIS) and remote sensing techniques are powerful tools in the analysis of temporal changes in land cover or land use, because spatial information from two or more time intervals can be compared more readily than by non computer-based methods. Since the earliest Landsat imagery appeared in 1972, paired images from subsequent dates have been used to detect land cover and land use changes in the landscape (Iverson and Risser, 1987).

In the study area, both the nature and intensity of land use patterns are changing. Agricultural activities and human population have increased in recent years. This growth suggests that the demand for urban and agricultural water will continue to expand. The exploitation of the underground water table and the expansion of agricultural activities in this region present a serious threat to the wildlife and vegetation dependent on the soil and water resources.

A better understanding of the historical land use change should provide additional knowledge of the conditions of the region. Therefore, the principal objective of this study was to estimate the land cover and land use changes that occurred in an area located in central Sonora between 1973 and 1992 using remote sensing and GIS techniques.

Methods

The study area is located in the central part of Sonora, Mexico, between North latitudes 28° 00' 00" and 29° 30' 00", and West longitudes 109° 30' 00" and 112° 00' 00" (figure 1).

Change detection in land use class areas was determined using Landsat MSS data processed with the remote sensing program ERDAS version 8.3.1 produced by Erdas, Inc., and the ArcView program version 3.1 developed by ESRI. The scenes used in this study were acquired from the North America Landscape Characterization (NALC) project through the EROS Data Center of the U.S. Geological Survey in Sioux Falls, SD. The scenes are from April 1973 and May 1992. The subsets defining the 1973 and 1992 study areas were extracted from the original scenes using ERDAS and the satellite imagery processing equipment available at the Remote Sensing Center, Office of Arid Lands Studies, University of Arizona.

The satellite imagery were atmospherically corrected and geographically registered before the classification process. By performing an unsupervised classification, five different land cover classes were determined according to the Brown and Lowe (1994) standard. The criteria

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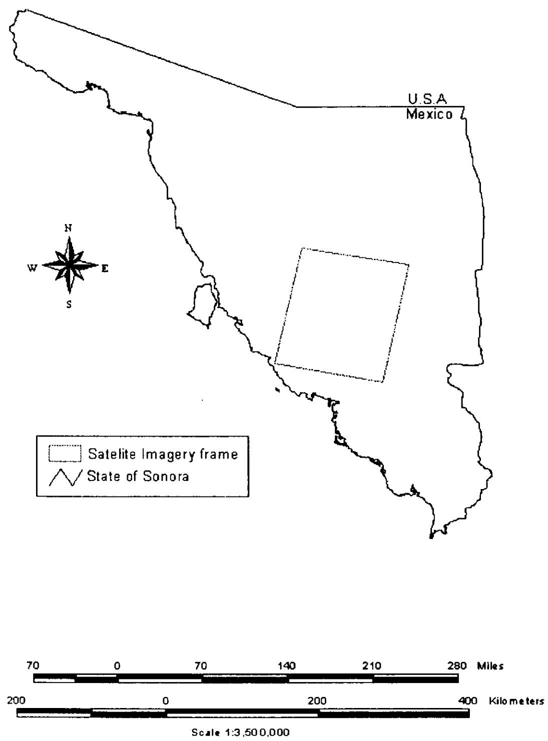

Figure 1. Location of the study area.

used to distinguish these land cover classes were based principally on feature reflectance values, topography, the association to other features on the image (i.e., a straight border on irrigated croplands), and video frames taken from flights over the study area.

Change analysis by image differencing (Jensen, 1986; Campbell, 1987; Singh, 1989) was used to detect land cover and land use differences between 1973 and 1992 (table 1). The subtraction process results in positive and negative values for pixels with reflectance value change and zero values for pixels with no change. In this study, subtracting the 1973 classification image from the 1992 classification image produced change detection values.

Results and Discussion

The classification categories identified in the 1973 and 1992 images were Madrean evergreen woodland, Sinaloan thornscrub, Plains of Sonora subdivision (Sonoran desertscrub), water bodies (dams and reservoirs), and farmland. The application of the image differencing technique to the two images shows that more than 85 % of the area changed classifications during that time. Madrean evergreen woodland, agricultural areas and Sonoran desertscrub decreased 28%, 24.3% and 31.4%, respectively. Water bodies and Sinaloan thornscrub classes increased by 13% and 25.0% respectively. Among the five classes analyzed in this study, Sonoran desertscrub was the least stable class, while agricultural areas comprised the most stable class.

Because desert vegetation is soon modified by climatic changes and considering that precipitation in the study area is the only factor of the environment which can cause a rapid change on vegetation (Cloudsley, 1977), it is presumed that most of the changes were due to natural causes. About 24% of the area changed as a result of direct human activities such as agriculture. These anthropogenic changes occurred as a result of Mexican government policies to generate jobs and improve the regional economy by financing clearing of natural areas for grazing pastures and farmlands (SARH, 1989).

However, this does not mean that all natural vegetation classes can be converted into croplands, since some areas are unsuitable for agricultural exploitation given their steepness, salinity, soil texture, or scarcity of water sources for crops irrigation. Although the anthropogenic changes obtained in this study do not represent a significant percent in terms of area, they are important in terms of environmental impact because they have generated a considerable number of ecological problems. The problems include: depletion of the groundwater table; disappearance of former perennial water bodies and streams that

Table 1. Comparison of area and percentage occupied by different classes on 1973 and 1992 images and percentage of change between those years.

TYPE OF FEATURE	1973 year		1992 year		Percentage Change between 1972 - 1992
	Hectares	Percentage	Hectares	Percentage	
Water	6633	0.3	7647.8	0.3	13.3
Woodland	773979.48	34.3	556880.4	24.7	-28.0
Thornscrub	1048572.4	46.5	1397354.8	62.0	25.0
Croplands	19378.8	0.9	14661.4	0.6	-24.0
Desertscrub	408085.2	18.0	280104.5	12.4	-31.4
TOTAL:	**2256648.8**	**100.0**	**2256648.8**	**100.0**	

were sources of water and habitat for wildlife and plant species; reduction of the wildlife population species; modification and suppression of natural habitats and ecosystems; ecosystems pollution by extensive and intensive use of agrochemicals; and dispersion and introduction of weeds and non-native species into natural adjacent ecosystems.

In comparison to other life zones, the desert more readily displays ephemeral, highly variable land cover changes that may not be significant over longer time periods. An isolated rainfall event, for instance, may induce a short-lived, dramatic vegetation response that does not reflect a permanent land cover change. In environments like the study area, it is thus important to examine the changes that have occurred over longer time spans. The two dates of this study were chosen to make the substantial and lasting land cover changes of the intervening years evident.

In addition, extreme changes in precipitation patterns in some years could affect the vegetation land cover classes, resulting in spectral differences between two images that could be interpreted as a permanent land cover change.

Change detection error can thus result if the source imagery captures the response to either a short-lived, isolated climatic event or a more sustained, anomalously pronounced one. Therefore, it is recommended that change detection studies be made at many frequent time intervals (i.e., every five years). This will permit the creation of simulation models of the change processes, which will lead to a better understanding of how different factors interact to cause land cover class modifications.

Acknowledgments

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Effects of Watershed Management Practices on Sediment Concentrations in the Southwestern United States: Management Implications

Vicente L. Lopes[1], Peter F. Ffolliott[2], and Malchus B. Baker, Jr.[3]

Abstract.—Effects of watershed management practices on suspended sediment concentrations from ponderosa pine forests and pinyon-juniper woodlands in the Southwestern United States are examined. Completely cleared and strip-cut ponderosa pine watersheds produced higher sediment concentrations than the control. Likewise, cabled and herbicide-treated pinyon-juniper watersheds yielded higher sediment-laden streamflows than the control. Soil disturbances associated with vegetative manipulations on these watersheds are the assumed causal factor. Management implications of the reported effects are described.

Introduction

One method of analyzing effects of vegetative treatments on sediment concentrations is through interpretations of sediment rating curves relating suspended sediment concentration to streamflow discharge (Lopes and Ffolliott 1993, Lopes et al. 1996). A sediment rating curve reflects the pattern of soil erosion and sediment delivery operating on a watershed, and provides a readily accessible starting point for investigating the impacts of vegetative treatments on in-stream sediment discharge. This paper reports on the derivation of sediment rating curves to estimate impacts of vegetative treatments on suspended sediment concentrations from the Beaver Creek watersheds in north-central Arizona.

Study Area

The Beaver Creek watersheds, located about 80 km south of Flagstaff, are situated in the Salt-Verde River Basin of north central Arizona. These watersheds are representative of extensive areas of ponderosa pine forests and pinyon-juniper woodlands found in the southwestern United States. Descriptions of vegetative characteristics, physiological features, and precipitation-streamflow regimes of these watersheds have been presented by Brown et al. (1974), Clary et al. (1974), and Baker (1982) and, therefore, will not be detailed here.

The most important precipitation from a streamflow-generation standpoint is that originating from frontal storms during October through April, when about 60% of the annual precipitation falls. A second precipitation season is July through early September, when high-intensity, short-duration, localized convectional storms are common. Most annual runoff is produced from melting snowpacks in March or April. Winter runoff accounts for 85% of the annual water yield (Baker 1982). Suspended sediment discharges are 75 to 80% of the total sediment discharge from the watersheds studied.

Vegetative Treatments Evaluated

Ponderosa Pine Watersheds

Vegetative treatments evaluated on ponderosa pine watersheds consisted of creating cleared openings in the forest overstories and reducing forest overstory densities. WS 12 (184 ha) was completely cleared. All merchantable timber was removed and the remaining non-merchantable wood, and all intermingling Gambel oak and alligator juniper, were felled in 1966-67. Residual slash and debris was machine windrowed to trap and retain snow, reduce evapotranspiration losses, and increase surface drainage efficiency. The windrows were burned in 1977 to determine whether their removal would influence water yield (Baker 1983). Ponderosa pine, Gambel oak, and alligator juniper were allowed to seed themselves or sprout and grow following the clearing treatment. Because hydrologic changes caused by the treatment cannot be separated from those caused by the windrows, the treatment evaluated consists of complete forest clearing; soil disturbances

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due to timber harvesting operations; and soil disturbances due to the presence of windrows. The treatment resulted in an average increase in annual water yield of about 30% (44.5 cm) for 7 years after treatment, at which time the post-treatment response became insignificant.

On WS 14 (546 ha), one-third of the ponderosa pine forest was cleared in irregular strips averaging 18 m wide in 1970. Slash was piled and burned in the cut strips. The forest overstory in the intervening leave strips, which averaged 37 m wide, was reduced by thinning to about 25% or 18 m^2 ha^{-1} of basal area, a density level thought optimal for subsequent growth. Slash and debris were piled and burned in the cleared strips. This treatment resulted in a 57% reduction in basal area on the watershed. Gambel oak was retained throughout the watershed for mast and browse production, important to indigenous wildlife. Annual water yield increased about 20% (24 cm) in the first four post-treatment years, after which the response was insignificantly low or negative.

WS 13 (369 ha) served as a control against which the completely cleared and strip-cut treatments were evaluated. While some commercial timber had been harvested in the early 1950s, conditions on this watershed at the time of this study represented those obtained through minimal managerial inputs.

Pinyon-Juniper Watersheds

Treatments on the pinyon-juniper watersheds consisted of converting the woodland overstories to covers of less water-consuming herbaceous plants. On WS 1 (131 ha), a cabling treatment was applied in 1963. Larger trees were uprooted by a heavy cable pulled between two bulldozers. Smaller trees missed by cabling were hand-chopped, slash was burned, and the watershed seeded with a mixture of forage species. This treatment did not result in significant increases in annual water yields.

On WS 3 (147 ha), a mixture of picloram (2.8 kg ha^{-1}) and 2,4-D (5.6 kg ha^{-1}) was applied by helicopter to 114 ha in 1968; the remaining 33 ha were either not treated or the trees were sprayed with a backpack mist-blower. This treatment resulted in a significant increase in annual water yields of about 160% (4.4 mm) for 8 post-treatment years, after which the residual dead trees were removed in a firewood sale.

WS 2 (51 ha) was a control against which the cabling and herbicide treatments were evaluated. Conditions on this watershed represented those obtained through minimal managerial inputs.

Methods

Suspended sediment concentration and streamflow data obtained from 1974 through 1982 were the source data for this study. Data sets reflecting immediate impacts of the vegetative treatments were excluded from the analysis to better describe long-term impacts of the treatments on sediment concentrations. Either grab samples, integrated samples obtained with a DH-48 hand sampler, or pumping samples were analyzed by filtration to determine sediment concentrations. Streamflow was measured in concrete trapezoidal flumes. When a sample of suspended sediment was collected, the time was indicated on a digital tape on the continuous water-level recorders at the gauging stations. Sediment data used in the development of the sediment rating curves were collected for streamflow discharges in excess of 0.05 m^3 s^{-1} and at time intervals greater than 1 hr to reduce possible effects of serial correlation.

Sediment rating curves are frequently expressed in terms of a power function form, such as $C = aQ^b$, where C = suspended sediment concentration (mg/L), Q = streamflow discharge (m^3/s), and a, b = regression coefficients for a particular stream. Sediment rating curves to be derived in a power function form are often approximated by least-square linear regressions of logarithmic-transformed data (Walling 1977); this transformation was used in this study. The procedure to overcome the possibility of bias when the regression estimates were detransformed and to minimize spurious conditions was outlined earlier by Duan (1983). Parameters "a" and "b" of the sediment rating curves for the sediment rating curves, with the 95% confidence limits, fitted standard errors, coefficients of determination, and F statistic, are presented in table 1.

Results

Ponderosa Pine Watersheds

There were significant differences in sediment rating curves among the treated ponderosa pine watersheds and control watershed. These differences indicated that for a similar streamflow discharge, sediment concentrations from the completely cleared watershed (WS 12) were significantly higher than those from the strip-cut watershed (WS 14), and that sediment concentrations from the

Table 1. Sediment rating curve parameters, with 95% confidence limits, standard errors, coefficients of determination and statistics for ponderosa pine and pinyon-juniper watersheds.

Watershed	N	a	95% Confidence Intervals		b	95% Confidence intervals		Standard error SE	r_a^2	F Statistics	Sig-nifi-cance
Ponderosa Pine											
12	353	154.579	121.667	196.413	1.042	0.947	1.137	125.97	0.57	468.54	**
13	204	28.679	21.804	37.717	0.677	0.579	0.776	61.40	0.47	183.40	**
14	473	56.590	43.335	68.681	0.974	0.919	1.097	74.94	0.50	475.87	**
Pinyon-juniper											
1	525	7.362	5.297	10.257	0.233	0.143	0.324	7.03	0.05	39.33	**
2	519	5.129	3.664	7.161	0.193	0.112	0.274	2.98	0.04	22.01	**
3	611	8.091	5.916	11.066	0.245	0.168	0.321	4.67	0.06	25.76	**

N=Sample size

F Statistic:Equation significant at a=0.05

Significance:Regression significance(**) at a=0.05

strip-cut watershed were higher than those from the control watershed (table 2).

WS 12 experienced watershed-wide soil disturbance from the complete clearing treatment, simultaneous breaking-up of the of herbaceous ground cover by the clearing operation, and follow-up pushing of the residual slash and debris into windrows. Soil disturbance on WS 14 was less extensive and more localized than what took place on WS 12. The most destructive portion of the disturbance on WS 14 occurred on the one-third of the watershed that was cut into irregular strips, where much of the protective herbaceous plant cover was disturbed, and where the residual slash and debris were piled and burned. Larger snowpack accumulations occurred in the strip-cuts in comparison to those in intervening leave strips. These strip-cuts had up-down-slope orientations, causing the increased overland water flows originating from melting of the larger snowpack buildups to be concentrated in the strips, where most of the sediment production on WS 14 took place.

Table 2. Minimum, mean, and maximum values of streamflow and suspendedsediment concentration for ponderosa-pine and pinyon-juniper watersheds.

Water-shed	Flow(m^3/s) Min	Mean	Max	Sediment (mg/l) Min	Mean	Max
Ponderosa pine						
WS12	0.048	0.456	3.198	6.53	68.20	519.08
WS14	0.048	0.528	6.679	2.94	30.38	359.76
WS13	0.034	0.693	5.009	2.91	22.37	85.37
Pinyon-juniper						
WS1	0.004	0.041	0.261	2.03	3.50	5.38
WS3	0.003	0.026	0.151	1.95	3.31	5.09
WS2	0.001	0.025	0.216	1.35	2.52	3.82

Pinyon-Juniper Watersheds

There were differences in sediment rating curves among the treated pinyon-juniper watersheds and the control watershed (Lopes et al. 1996). The main difference was higher sediment concentrations from the cabled watershed (WS 1) than the control watershed for similar streamflow discharges. Higher concentrations of suspended sediment on WS 1 were likely a reflection of the soil disturbances caused by uprooting trees in the cabling treatment.

There was also a difference between sediment rating curves derived for the watershed treated with herbicides (WS 3), which experienced little soil disturbances as a result of treatment, and the control watershed. However, soil disturbance caused by the follow-up removal of merchantable firewood, and piling and burning the residual slash 8 years after the herbicide treatment, was significant in terms of affecting suspended sediment discharge.

Management Implications

Soil disturbances from vegetative treatments on Beaver Creek watersheds in both vegetative types generally increases sediment concentrations above those of control watersheds. This response is reflected by their respective sediment rating curves. Completely cleared and strip-cut ponderosa pine watersheds produced higher suspended sediment concentrations than did the control watershed. Likewise, cabled and herbicide-treated pinyon-juniper watersheds yielded higher sediment-laden streamflows than did the control.

While significantly different, suspended sediment concentrations on the Beaver Creek watersheds are relatively low. This finding is not surprising, because erodibility of the volcanic soils on Beaver Creek is inherently low and, therefore, the sediment supply is limited (Lopes and Ffolliott 1993, Baker 1999). More than 50% of the ponderosa pine forests and pinyon-juniper woodlands in the Southwestern United States are found on soils of similar parent materials cover.

It is concluded that the watersheds studied can be severely disturbed by vegetative treatments and still yield relatively little sediment. Furthermore, effects of the disturbances decrease rapidly with time. These watersheds, therefore, appear to be resilient in terms of their soil / site stability and function.

Acknowledgments

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Restoration of Gooseberry Creek

Jonathan W. Long[1]

Abstract.—Grazing exclusion and channel modifications were used to restore wet meadows along a stream on the Fort Apache Indian Reservation. The efforts are reestablishing functional processes to promote long-term restoration of wetland health and species conservation.

Introduction

Restoration of riparian wetlands may require a combination of passive and active methods, particularly where channel geomorphology has been altered (Long and Lupe 1998). Gooseberry Creek has presented an opportunity to study the effects of integrating passive restoration through livestock exclusion with active channel modifications. The results have yielded insights into processes for restoring wetland functions in montane riparian wetlands.

Site Description

Gooseberry watershed drains over 40 square miles in the northeastern part of the Fort Apache Indian Reservation. Gooseberry Creek flows intermittently along much of its course, with some perennial reaches. It originates from springs and snowmelt in the White Mountains volcanic field that lies to the north of Mt. Baldy.

Riparian meadows occur along most reaches of the creek, starting east of McNary and continuing to the source waters at Gooseberry Spring, Moonshine Park, and San Juan Lake. Soils in the riparian meadows are a very dark silt loam that resists erosion and produces abundant forage (Soil Survey 1981).

Tribal elders recalled lush wetlands and perennial flow throughout the system in decades past. One remembered swimming and fishing in pools along the creek, and also recalled commonly hearing frogs along the creek. Several individuals reported that the creek formerly supported trout, possibly including Apache trout (*Oncorhynchus apache*). The creek also sustains several large populations of mature Bebb willow (*Salix bebbiana*). Despite degraded conditions, the creek supports an apparently robust population of macro-invertebrates and native speckled dace (*Rhinichthys osculus*).

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History of Degradation

Gooseberry watershed has changed due to a variety of influences. The Penrod wildfire struck a large forested area in the middle of the watershed. The lower portion of the creek was once dammed to create a reservoir near the McNary sawmill. The McNary ditch was built to divert water into Gooseberry Creek to supply the sawmill. Haystack Cienega, in the lower part of the watershed, was farmed in the early part of the twentieth century. To this day, much of the drier portion of this cienega is dominated by noxious weeds. Cattle and elk grazing had reduced the quality of riparian vegetation and contributed to bank erosion along the creek. Many road crossings had undersized culverts that constricted flows and eventually failed during floods.

Conditions Prior to Restoration

Channel Morphology

Several reaches along Gooseberry Creek had downcut to expose bedrock and large basalt boulders. The creek has multiple wide, trapezoidal channels as it courses through Haystack Cienega. Many of the streambanks were steep and bare due to the downcutting and freeze-thaw action.

Vegetation

Vegetative cover along several reaches of the downcut channel was in poor condition. Key native wetland species in the system are graminoids including Nebraska sedge (*Carex nebrascensis*), sawbeak sedge (*Carex stipata*), beaked sedge (*Carex utriculata*), woolly sedge (*Carex lanuginosa*), spikerush (*Eleocharis* sp.), burreed (*Sparganium* sp.) and rushes (*Juncus* sp.). Tall, mature bebb willows are scattered throughout the riparian meadows. The only other woody riparian plants in the system are a few other willow species (*Salix* sp.) that grow in association with beaver dams and the gooseberries (*Ribes* sp.) for which the creek is named.

Restoration treatments

Restoration treatments were selected to address many of the various impacts that had degraded the creek. A key strategy was to promote recovery by protecting wetland vegetation from grazing. However, the degraded channels required active intervention to speed the natural recovery process. Funding support for the project came from a variety of sources, including tribal programs, the Arizona Water Protection Fund, and a U.S. Fish and Wildlife Service Challenge Cost-Share award.

Grazing Management

The first stage in restoration was to redesign the livestock management for the area. The range management plan for both livestock associations in the area were revised. The range conservationist worked to reduce the number of animals brought to this summer range.

The next stage was to construct fences around key riparian areas to promote recovery of vegetation. Members of the livestock associations constructed many of the new fences. The range management plans provided for keeping livestock out of these riparian areas to promote growth of wetland vegetation. To offset these impacts, several drinkers were constructed outside of the riparian areas. A challenge to the plan was the large number of elk that also grazed the riparian areas.

Road Crossing Redesign

A major element of the restoration treatments were reconstruction of road crossings. One crossing in the upper watershed had a single undersized culvert replaced with three large culverts. Despite the increased capacity, this culvert has continued to suffer temporary blockages during spring runoff as debris has lodged in one or more of the culverts. A second culvert crossing was replaced with a low-water crossing using large (1 square meter) rectangular rocks to create a french drain.

Revegetation

The riparian meadows were reseeded with various native species including Baltic rush (*Juncus balticus*), tufted hairgrass (*Deschampsia caespitosa*), Nebraska sedge and beaked sedge. The seeds were sown during the late fall and early winter of 1997-1998.

Riffle Bars

Two reaches between Haystack Cienega and the Bebb Willow stand were treated by augmenting existing riffle features. In this method, a mixture of gravels, cobbles, and fine particles were added to riffles using heavy equipment. This approach recreates natural structural controls in the system. We observed many tall riffles composed of gravels, cobbles, and basalt boulders throughout Gooseberry Creek. These features are particularly pronounced in the intermittent reaches, as revealed in longitudinal profiles at the site (Watershed Program unpublished data).

Results

Many of the reaches along Gooseberry Creek have responded dramatically to the restoration treatments. The rest afforded the creek has promoted natural processes of morphological development. However, some reaches remain dysfunctional due to altered channel morphology.

The reach east of McNary has lush growth of wetland vegetation that thoroughly covers the stream bed and banks. The stream itself ceases to flow after spring runoff, but the area remains a hospitable wetland.

The reach between Haystack Cienega and the Bebb Willow stand has improved with vigorous growth of spikerush and Nebraska sedge in the channel bottom. Because we used seeds from plants that already existed at the site, we have been unable to determine how much of this growth is attributable to reseeding. However, we did observe sedge seedlings in the channel, suggesting that this effort may have been at least partially successful.

Spring runoff in 1998 and 1999 caused the augmented riffles to sink and moved some of the fine materials, but those particles appeared to be redeposited within the channel and then trapped by the vegetation. The french drain road crossing permits spring runoff to spread across the full width of the meadow and deposit sediments.

Although the riffles have been redistributed somewhat, we have not observed significant bank erosion in the treated reaches despite high flows during spring runoff.

Reaches within Haystack Cienega and at the Bebb Willow Stand have responded to grazing exclusion with growth of in-channel vegetation. However, the downcut channels and steep banks in these reaches have limited recovery. Active intervention is needed to restore these channels.

The meadow at Neagle Ranch, which was treated with fencing and reseeding, has grown vigorously with native wetland vegetation. Natural stream deposition is significant in this reach due to a high bedload during spring flows. The deposition has caused rewetting of the riparian meadow. The channel is continuing to reestablish a stable morphology, and some of the stream banks are still raw and steep. The creek from this reach to the headwaters has mostly perennial flow and represents the best potential trout habitat. However, the water level in the creek still drops precipitously during the early summer.

The deficiency of summer flows and overhanging streambanks have thus far discouraged us from reintroducing native trout to the watershed. We are hopeful that the recovery process will continue to reestablish conditions that will permit reintroduction. The creek is unlikely to ever become a viable fishery, but it can serve as a refugia for the native biota of the White Mountains.

Conclusion

Combinations of passive and active restoration treatments have promoted recovery of riparian meadows in the Gooseberry watershed. In some reaches, passive restoration through grazing exclusion and removal of culverts have reestablished functional processes such as riffle formation and bank development. These processes are serving to rewet the riparian meadows. In other reaches, degraded channel morphology prevents the same processes from occurring. This project demonstrates the value of integrating restoration treatments to promote long-term ecological restoration.

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Restoration of White Springs

Jonathan W. Long[1] and Delbin Endfield[2]

Abstract.—Rock structures, road closures, fencing and revegetation methods were employed to restore a culturally and ecologically important spring that had been damaged in the aftermath of a wildfire. The project has reestablished the stability of the spring and has moved it closer to its former condition. School groups were an essential part of the restoration project, and their involvement has helped to communicate the results to members of the community.

Introduction

For countless generations, White Springs has sustained perennial flow in Cibecue Creek and has provided the people of Cibecue with spring water for use in their homes. The stream below the spring supported trout until 1996, when a wildfire led to severe downcutting of the channel. Tribal elders have reported that the spring used to bubble up into a clear blue pool surrounded by various herbs and riparian trees. A photo of the spring in a 1965 issue of *Arizona Highways* provided a physical image to use as a reference. Comparisons of current conditions to both stories and photos revealed that the spring had degraded in recent decades. Due to the tremendous importance of the spring, we began integrated efforts to arrest further degradation and initiate recovery of the spring's past conditions.

Site Description

White Springs originates from the base of an old cottonwood tree. The area is underlain by sedimentary rocks permeated by springs and sinkholes. Although the spring flow varies throughout the year, it maintains perennial flow into Cibecue Creek. The spring water is highly mineralized, but meets tribal water quality standards for drinking water.

The spring is an inviting spot ringed by cottonwoods (*Populus angustifolia*), walnuts (*Juglans major*), and various herbaceous plants, particularly horsetail (*Equisetum* sp). Watercress (*Rorippa nasturtium-aquaticum*) grows profusely in the channel, especially since restoration.

History of Degradation

Photos of White Springs taken in 1994 revealed that the pool below the spring had lowered and had less vegetation compared to photos taken in 1965. Some of the trees had fallen over, exposing the banks. The area around the spring was heavily compacted by ungulate trampling and vehicular traffic.

In April 1996, the White Springs fire burned over 4,000 acres of ponderosa pine woodland in the White Springs subwatershed. Shortly after the fire, localized rain storms drenched the area triggering soil movement and erosion. The channels in the area underwent major geomorphic adjustments, with some reaches downcutting over 1 meter, and others filling in by similar depths (Watershed Program unpublished data). The channel below the confluence of the springs and the burned area downcut by over 1 meter. The downcutting in this reach triggered a headcut up to White Springs. Furthermore, surface runoff from roads leading to the spring washed out the side of the pool at the spring.

Animal trails from the burned area led directly to the spring, since it was the chief source of perennial water in the vicinity. Animal impacts contributed to bank erosion. The combination of impacts increased sediment in the pool below the spring, causing the water to become very murky and unpleasant. Garbage left behind by visitors added to water quality and aesthetic concerns. The sight of the spring was disconcerting to people who wanted to use the spring water and who felt that the water was not being shown proper respect.

Restoration Activities

The conditions at the spring made it a top priority for the Tribe's watershed restoration program in Cibecue.

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Preliminary efforts began in 1997 and led to an integrated restoration effort in 1998.

In 1997, upon the direction of a Tribal Council Representative from Cibecue, the road leading directly to the spring was closed with tall tank traps. Community members applauded this change.

The area surrounding the spring was fenced to keep livestock from grazing and trampling the area. Members of the Cibecue Livestock Association constructed the fence. Funds for this task came from a Challenge Cost-Share grant awarded to the Tribe by the US Fish and Wildlife Service.

Channel Structures

On March 13, 1998, students from the local high school in Cibecue conducted restoration activities at the spring. They were assisted by students from Nueva Vista High School in Concord, California, who were participating in an Adopt-a-Watershed exchange program. The group built three large rock check-dams below the spring to raise the water level and stop the headcutting. The structures served to dissipate the energy of the current during the spring snowmelt. The students also placed debris on the old road leading to the spring to disperse runoff. They seeded the area with native wetland graminoids and upland grasses.

Revegetation

In the next phase of the project, the Cibecue Project Manager supervised students from Cibecue High School during the summers of 1998 and 1999. They continued work at White Springs by transplanting rushes (*Juncus saximontanus*), spikerush (*Eleocharis* sp.), sedges (*Carex* sp.), three-square bulrush (*Scirpus pungens*) and common reed (*Phragmites australis*) from nearby wetlands.

In 1998, the crew built a large rock and log structure on the channel below the confluence of the spring and the drainage burned in the fire. This channel was still very unstable due to the aftereffects of the fire. The large structure was needed to keep the headcut from undermining the rock structures built on the spring channel.

Results

The rock structures stabilized the spring channel and reversed the downcutting that was occurring. The large structure quickly filled in with rocks and litter. Pools and riffles reformed upstream of the structure. The spring area became lush with plants including watercress, yellow monkey flower (*Mimulus guttatus*) and various grasses.

Visitors to the site have been pleased with the changes that have occurred. They particularly note the peacefulness and beauty of the area. The students have written articles in their school magazine about the work they have done at the spring. One student commented, “I was surprised to see how it looks now. There is a lot more vegetation, fresh air, and nice, clean spring water to drink.”

During the unusually heavy monsoon rains of late July 1999, a severe flood swept down off the burned area. The raging waters surged out of the channel and into the spring area. The flood completely washed out the large rock and log structure on the main channel; however, the structures upstream held their positions in the channel and along the banks. Many of the transplants survived. The vegetation laid over to protect the soils, although some erosion occurred where vegetation was still sparse. Due to the restoration work, the spring was able to withstand this severe disturbance.

Conclusion

Without these restoration efforts, White Springs would have been devastated by the recent floods. White Springs will continue to require restoration efforts until the upstream watershed conditions have stabilized. However, in important ways the spring already has been restored. People in the community are returning to White Springs for the refreshing taste of the water. Today it is shown the respect that it truly deserves.

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Restoration of Soldier Spring

Jonathan W. Long[1] and Benrita M. Burnette[2]

Abstract.—Various restoration techniques were employed to restore an ecologically and culturally important stream on the Fort Apache Indian Reservation. The methods were specially developed to address the unique character of this water body. The results show promise for restoring steep gradient riparian ecosystems.

Introduction

Soldier Spring emerges from a basalt hillside to form a perennial stream in the White Mountains of Arizona. The spring holds special importance to the White Mountain Apache people. The spring harbors plants and wildlife endemic to the White Mountains, including a genetically pure population of Apache trout (*Oncorhynchus apache*).

Assessments by staff from the Tribal Watershed Program and the US Fish and Wildlife Service Arizona Fishery Resources Office (AZFRO) determined that the stream and its fauna were threatened by downcutting and bank erosion. This finding led to a restoration effort to stabilize the channel and reestablish native wetland vegetation. We employed a combination of grazing exclusion, rock sill construction, transplanting, and reseeding.

Assessment of Conditions

Historical Evidence

Soldier Spring has changed dramatically over the past hundred years. An account from a tribal biologist describes Soldier Spring as being lush and marshy in the 1980s (Joe Jojola, pers. communication). Today the main channel is severely downcut along the reach just a short distance below the spring. An Apache legend recalls that willow trees once grew at the spring. We found a single Bebb willow (*Salix bebbiana*) on a steep bank along the creek.

Our effort to restore Soldier Spring apparently was not the first. A notched log weir remains intact below the spring, and two logs from another have been dislodged and now rest along the stream bank downstream. We do not know exactly when these structures were built, but most likely it was in the 1980s after the native trout were identified in the stream.

Feral horses, maverick cattle, and elk all have contributed to the degradation of Soldier Spring. The spring is one of the few water sources in a relatively dry area that has large populations of all three ungulate species. Its remote location posed a challenge to managing animals at this site.

Conditions Prior to Restoration

Staff from the Tribal Watershed and Fisheries Programs and the AZFRO jointly examined conditions at the site in 1996. We conducted a streambank vegetation survey that revealed a very diverse plant community due to the presence of both native and exotic species and the variability of soils from wet to relatively dry. The channel was downcut along most reaches. The channel averages a steep 2.7% slope (unpublished data, 1999) that poses a challenge to restoration efforts. Using the Rosgen classification system (Rosgen 1996), we concluded that the channel had downcut from a B-type step-pool channel into an entrenched G-type gully. Many of the streambanks were bare, and the soft soils easily eroded into the channel.

Returning to the site in 1998, we found that the downcutting had worsened. Vegetative cover along the downcut channel was low. Much of the reach was bare along the steepened banks and on benches adjacent to the channel. Several native wetland plants still grew in the channel, including buttercups (*Ranunculus aquatilis and R. hydrocharoides*), rushes (*Juncus* sp.) spikerush (*Eleocharis* sp.) and sedges (*Carex* sp.). More mesic, invasive species such as Kentucky bluegrass (*Poa pratensis*) and clovers (*Trifolium repens* and *T. pratense*) were abundant along the channel. Since we knew from historical evidence that the spring once was a lush wetland, it was sad to see it in such poor condition.

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Restoration Activities

After field visits in 1998 demonstrated that downcutting was worsening, the Tribal staff worked with AZFRO to initiate restoration using funds for fisheries habitat improvements. To arrest the degradation, we began constructing rock check dams in the steeper reaches. Participants in the Tribe's Summer Ecological Youth Camp constructed thirty rock check dams along the stream using rocks rolled from the slopes adjacent to the channel. In July and August of 1998, we constructed an 8-foot tall solar-powered electric fence to exclude all ungulates.

In 1999, we received additional funding support from the US Forest Service Rocky Mountain Research Station (RMRS). We planned to expand on the rock check-dams by creating large rock riffle structures designed by Alvin Medina of the RMRS. Once again, participants at the Ecological Youth Camp, including tribal members from Whiteriver and guests from Heritage Middle School in Chino Valley, conducted the work alongside staff from the Tribe and RMRS. In addition to using boulders and cobbles from the slopes, the riffles incorporated some gravel, soil, and plant materials in a specially arranged mixture. The riffles enhanced the pool habitats along the reach, slowed the water flow, and raised the water higher along the banks. The campers also transplanted sedge sod (mostly *Carex utriculata* and *Carex nebrascensis*) harvested from nearby restoration sites. The stream banks are being reseeded with native wetland species.

Results

The construction of the electric fence dramatically changed conditions at the site. The elimination of ungulate grazing and trampling has promoted plant growth.

Now, the plants are able to flower and seed more readily, helping us to identify the unusual diversity of this site.

The small rock check dams initially constructed at the site appeared to stop further degradation and promoted growth of extensive beds of water buttercup (*Ranunculus aquatilis*). We did not expect these check dams to withstand a strong flood; however, the most recently constructed rock riffles should last a very long time. Working in concert with the reestablishment of native wetland plants, the riffles should reestablish functional processes such as trapping sediments and forming banks. The deepening of pools along the reach and protection of rock substrates in the channel will enhance habitat for the native trout in this system. We are continuing to monitor and modify the riffles to respond to changes in the system.

Conclusion

Soldier Spring was an excellent site for restoration activities due to its biological diversity and significance to the community. A combination of ungulate impacts had propelled channel degradation that jeopardized its long-term health. Because its location made it difficult to actively manage animals, tall electric fence was the best choice for protecting this area. Fencing alone would not have been sufficient to restore this wetland due to the severely entrenched condition of the channel and the loss of habitat for native aquatic graminoids. The riffle structures appear well-suited to reestablishing a stable channel geomorphology. They should last longer and better promote stream functions than the log structures that were tried previously.

This project has promoted many values. Beyond conserving endemic fish and plant species, this restoration work has engaged young people in protecting an important water source. In this way, the site has continued to serve a role as a place of teaching. Through this restoration work, we have helped to return some of the favors that the spring has given the people.

Acknowledgments

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Wetland Storage to Reduce Flood Damages in the Red River

Steven Shultz[1]

Abstract.—The restoration of previously drained wetlands to store water was not found to be an economically feasible strategy to reduce flood related damages in two sub-watersheds of the Red River Valley (the Maple River Watershed in North Dakota, and the Wild Rice Watershed of Minnesota). Restoring wetlands, while providing full ecological services, was less feasible, even considering additional (non-flood related) benefits of wetlands. In contrast, the construction of impoundments with outlet control devices to regulate and store water in the upper reaches of watersheds was an economically feasible way to reduce downstream flood damages.

Introduction

Flooding in the Red RiverValley (RRV) has historically caused large-scale physical and economic damage to public and private property. There is wide consensus that new strategies are needed to improve the prediction, control, and mitigation of future flood events. However, there is a great deal of uncertainty and disagreement regarding the most efficient ways to reduce flooding damages.

There has been considerable speculation and debate regarding the relationships between wetlands and flooding in the RRV. On one side of the issue are those who believe that wetlands by storing water, can effectively reduce flooding impacts and that the extensive wetland drainage in the last century have exacerbated recent low frequency flood events. Others believe that wetlands have no significant impacts on channel or overland flows, especially during major (low frequency) flood events. Their rationale for this is that most wetlands are already full during the critical early spring season when major (low frequency) floods occur and because the amount of potential water storage in existing and drained wetlands is trivial when compared to total water volumes in the RRV.

The primary objective of this study is to evaluate the economic feasibility of restoring previously drained wetlands to reduce downstream flooding damages both within and on the main-stem of the RRV. The costs and benefits of wetland restoration primarily for flood storage and wetland restoration intended to restore the full ecological services of wetlands using established restoration criteria will be evaluated. Restoration for flood storage is relatively simple and low cost in that it basically only involves plugging up a wetland drain. Complete wetland restoration is much more complicated and expensive as it involves making sure that soil, slope water and vegetative characteristics of a restored wetland are very similar to natural wetlands in a particular area. It is important to evaluate the costs and benefits of alternative storage options because recent demands by conservation groups and others have not explicitly stated what form of wetland restorations they are proposing in order to reduce RRV flood damages.

The second objective of this study is to evaluate the economic feasibility of establishing impoundments (earthen berms or dikes, constructed in low-lying agricultural fields with outlet control devices) to reduce downstream flooding damages both within sub-watersheds and on the main-stem of the RRV. Impoundments on a per acre level are cheaper to implement than wetland restoration in large part because they can store more water than restored wetlands (about 4 acre-feet of water per acre of impoundment).

The study is focused on two sub-watersheds of the RRV: the Maple River Watershed in North Dakota and the Wild Rice Watershed in Minnesota. These two watersheds which are located west and northeast of the Fargo/Moorhead community, are 'typical' sub-watersheds of the RRV. Both are dominated by agricultural land uses, contain large acreage of both existing and drained wetlands, and are regularly subject to spring flood events and associated damages to crops, residences, and infrastructure.

The task of evaluating the feasibility of wetland restoration and impoundments to reduce flooding damages in these two watersheds will involve three distinct components.

First, historical flood damages during a 10-year period from 1989 to 1997 are collected from a variety of local, state, federal and non-governmental agencies and classified by type of damage (agricultural, residential, infrastructure, etc), date, and geographic location. This data is later used to estimate potential economic benefits associated with reduced peak flood volumes.

Second, the costs of restoring drained wetlands and establishing storage impoundments will be estimated under various scenarios in both the entire and upper sections of the watersheds. Data for these estimates are based on the National Wetland Inventory (NWI), local

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agricultural land prices, and previously conducted wetland restoration studies (Sip, 1998 and Eppich et al., 1998).

The final component of the feasibility evaluation involves evaluating the costs of alternative storage options with potential benefits over a 10-year period. Potential benefits are based on the results of a hydrological modeling exercise conducted by Bengston and Padmanabhan (1999), and the assumption that wetland storage volumes are directly or linearly related to reduced peak flood volumes and reduce flood damages.

Alternative Storage Programs

The location and quantity of previously drained wetlands in the watersheds were identified though a GIS based search of the National Wetlands Inventory (NWI). However, it is likely additional drained wetlands, especially those drained many years ago, are not captured in this database. For this reason, the feasibility of using wetland restoration to reduce flooding damages are also evaluated under the assumption that there are 50% more drained wetlands than captured in the NWI. Wetland restoration options are considered for implementation in the entire and upper sections of the watersheds. Finally, an evaluation is made of wetland restoration only on relatively low cost lands in the upper parts of the watersheds.

In the Maple, there are approximately 2,900 acres of drained wetlands in the entire watershed and 2,700 acres in the upper watershed. In the Wild Rice Watershed there are approximately 17,200 acres of drained wetlands in the entire watershed and 12,200 acres in the upper watershed.

Because the estimation of specific areas and locations available for impoundments requires detailed topological (elevation) data, our feasibility analysis of impoundments in the Maple and Wild Rice watershed will focus on a somewhat arbitrary but likely quantity of impoundments (3% of the total croplands in the watersheds). This would mean that 24,000 acres of cropland could be impounded in the Maple River Watershed and 12,500 acres in the Wild Rice Watershed. Because impoundments have outlet control devices, they and can store more water than restored wetlands (about 4 acre-feet of water per acre of impoundment versus the 1 acre-foot assumed for restored wetlands).

Costs of Storage Programs

Based on two reviews of wetland restoration costs in Northwest Minnesota (Sip, 1998 and Eppich et al., 1998), the initial construction costs required to restore wetlands for the purposes of water storage (without outlet flows) are estimated to be $300 / acre. The cost of restoring wetlands with full ecological functions (i.e., following Minnesota wetland restoration standards) is estimated at $3,000 / acre while impoundments are estimated to cost $475 / acre to construct.

Payments to farmers for the storage of water on their lands ($ / Acre) are considered to be the same regardless of the storage option being evaluated. Annual rental payments are used because they require less up-front costs, it is not known how long the storage programs will be required, and because reasonably accurate annual rental data exists for the study area.

Land rental values in the Maple River Watershed were obtained from average county level cropland rental values from 1993-1997 as reported by the North Dakota Agricultural Statistics Service. In the Wild Rice Watershed annual land value rates were estimated by making adjustments to assessed land values reported by the Minnesota Department of Revenue.

Total costs of wetland storage over 10 years are a summation of the present value of construction costs in year 1 and land rental payments in years 1 through 10. A discount rate of 5% was used to calculate present values.

Five different wetland restoration options are evaluated for each watershed. The first two scenarios are focused on the entire watershed using NWI estimates of drained wetlands and then the assumption that there exists 50% more drained wetlands available for restoration.

The remaining three wetland-storage scenarios are focused only in the upper sections of the watersheds. Again the first two are associated with drained wetlands using the NWI estimates of drained wetlands and then with an additional 50%. The last scenario involves restoring wetlands only in areas of the upper watersheds with the cheapest land rentals. This scenario requires the assumption that the total amount of drained wetlands exceed NWI estimates by 50% but because only the cheapest lands are utilized, total wetland acres restored are approximately equal to original NWI estimates.

Wetland restoration costs over a ten-year period range from $1.4 million to $2.8 million in the Maple River Watershed and between $7.1 million and $14 million in the Wild Rice. Restoring wetlands with full ecological services costs between $8.4 million and $12.8 million in the Maple Watershed and between $53.5 million and $80.3 million in the Wild Rice Watershed.

Wetland restoration costs are obviously dependent on the amount of wetland acres restored. Therefore, a useful indicator of the relative cost of alternative restoration scenarios is the annual cost per acre-foot of water stored (under the assumption that restored wetland store 1 acre-foot of water per surface acre of wetland). Wetland restoration in the Maple River Watershed costs between $54 and $64 per acre-foot of stored water and between $310 to $321 per acre foot of stored water when full ecological services of wetlands are provided. In the Wild Rice watershed restoration for storage purposes costs between $39 and $54 per acre foot of storage and between $305 and $311 per acre-foot of storage when all ecological services are restored.

Approximately 24,000 acres of the upper Maple River watershed could potentially be impounded at a cost of about $18.2 Million over a 10-year period. The corresponding values for the upper Wild Rice watershed are 12,500 acres impounded at a cost of $ 8.7 Million over a 10-year period using average cropland rental rates in the two watersheds. Assuming that such impoundments can store 4 acre-feet of water by draining water in the preceding fall and early in the spring before major flood events. Therefore, approximately 96,000 acre-feet of water would be stored in the Maple Watershed and 50,000 acre-feet would be stored in the Wild Rice Watershed . The annual cost of impounding an acre-foot of water is $19 in the Maple Watershed and $18 in the Wild Rice Watershed, which is considerably cheaper than any wetland restoration based storage options.

Potential Benefits of Storage Alternatives

Flood damages within the watersheds as estimated by Kjelland (1999), are $21.6 million for the Maple and $90.3 million for the Wild Rice, both over a 10-year period.

Flood related damages outside the sub-watersheds are assumed to be directly related to flooding in the downstream city of Grand Forks for which 10-year damages (based on the 1997 flood event) are estimated to be $9.8 million.

A hydrological modeling exercise of the Maple River watershed found that storage associated with restoring 2700 acres of wetlands reduced peak flows by 2.4% and flow volumes by 3.4% (Bengtson and Padmanahbahn, 1999). Therefore for all the storage scenarios evaluated, it will be assumed that stored water reduces peak flood volumes (averaged over time) and flood damages proportionately. Average peak flood flows in the Maple Watershed over the last 20 years are 108,000 acre-feet while the corresponding number for the Wild Rice Watershed is 198,000 acre-feet.

Conclusions: Feasibility of Storage Options

Four out of the five wetland restoration-storage options have a negative benefit-cost ratio of approximately 1:2 meaning that their costs are twice their expected benefits; therefore, they are not profitable or feasible.

The only wetland restoration based storage option that is profitable is in the upper Wild Rice Watershed based on the assumption that there are 50% more drained wetland acres than appear in the NWI. It is also assumed that wetland restoration would occur on only low cost lands (with rental values below the median level of the entire watershed). Even with these optimistic assumptions this option is just barely feasible with benefits exceeding costs by only $300,000 (5% of the total costs). Other assumptions in this evaluation were that wetlands can store an acre-foot of water per surface acre, that such storage directly reduces flood peak volumes and flood damages proportionately, and that the 10-year ‘wet cycle’ for which flood damages were collected is expected to continue.

Wetland restoration that provides full ecological services is even more expensive and is not considered feasible under any scenarios evaluated. It was also estimated that in order for this type of restoration to be feasible that non-flood related benefits of restored wetlands wound need to be between $2500 and $3000 per acre over 10-years, which greatly exceeds previous wetland benefit estimates in the region (Leitch and Hovde, 1996)

In contrast, the benefit-cost ratios of using impoundments to store water in the upper reaches of the watersheds and prevent downstream flooding were estimated to be 1.5 to 1 in the Maple and 2.8 to 1 in the Wild Rice. Therefore, the use of impoundment based storage in each of the watersheds appears to be an economically feasible way to reduce downstream flooding damages both within the watersheds and in a downstream (main-stem) community. Further research is warranted on the site-specific hydrological implications of alternative impoundment strategies and the short and long-term effects of impoundments on the ecological systems within sub-watersheds.

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The Role of Fire in Management of Watershed Responses

Malcolm J. Zwolinski[1]

Abstract.—Hydrologic responses of watersheds are strongly related to vegetation and soil disturbances. Many of the storage and transfer components of the global hydrologic cycle are altered by the occurrence of fire. The major effect of fire on the hydrologic functioning of watersheds is the removal of vegetation and litter materials that protect the soil surface. Reductions in interception and evapotranspiration losses, infiltration rates and soil moisture deficits following severe fires result in more water available for surface runoff and subsequent changes in peak discharges, erosion, sedimentation and water quality. Watershed management implications regarding fire severity, wildfire and prescribed burns are discussed.

Introduction

The hydrologic functioning of a watershed depends on its ability to receive, store, and transmit water and is strongly correlated with vegetation and soil disturbances. Fire, which has the potential to significantly alter vegetation and soil properties, can cause a wide variability in watershed hydrologic responses.

During the past several decades resource managers have acquired a better understanding of the role of fire in natural ecosystems, particularly by observing the spectrum of impacts ranging from catastrophic wildfires to carefully executed prescribed burns. The absence of periodic fires in fire-adapted ecosystems has caused substantial changes in fuel accumulations, nutrient cycling, soil moisture distribution and overall watershed productivity. As a result, fires often produce higher intensities and longer durations that result in increased fire severity. With the importance of watershed management continuing into the 21st century and the role of fire becoming better defined, land stewards will need to be more fully aware of these hydrologic responses of watersheds to different fire severities. This paper briefly examines the on-site and downstream impacts of fire on the hydrologic processes on watersheds.

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On-Site Fire Impacts

Interception

Interception of rain or snow by vegetation and litter results in a loss of water for streamflow. The magnitude of interception varies considerably depending on size of vegetation, density, foliage and branching characteristics (Ffolliott and Brooks 1996). A low severity fire that does not change the vegetation interception characteristics will have minimal impact on water yield. However, a severe fire that removes canopy foliage and litter material can result in significant increases in water flow and soil erosion. In situations where overstory vegetation is removed by fire, but some organic material remains to protect the soil surface (analogous to mechanical removal of trees and shrubs) water yields are initially increased and erosion rates remain low. However, the decreased interception allows a greater influx of solar radiation, resulting in removal of water from the site by evaporation and snow sublimation.

Evapotranspiration

Evapotranspiration is a term that combines water evaporation from soils, or standing water surfaces, with water released to the atmosphere by vegetation through transpiration. Watershed managers are interested in evapotranspiration because it represents a loss in the amount of water available for on-site and downstream use. The impacts of fire on this hydrologic process are largely dependent on the degree to which fire alters the vegetation canopy. As already mentioned, removal of interception surfaces, namely foliage, allows more precipitation to reach the soil surface. Also, foliage removal increases water yields because transpiration is reduced. For example, Ffolliott and Thorud (1977) reported that a 5% reduction in evapotranspiration following a burn on a forested watershed in the Southwestern United States resulted in a 30% increase in annual runoff. Increased watershed yields also can result when severe fire removes an existing deep-rooted vegetation type (tree, shrubs) and the site is subsequently occupied by shallow-rooted plant species (grasses). However, on the severely burned sites high rates of erosion occur, particularly the first few years following fire. Also, tree or shrub conversion to grass can often result in increased mass soil movement on steep slopes having shallow soils (Bailey and Rice 1969).

Infiltration

Infiltration is the physical process of water passing through the soil surface into the soil profile. Rates of infiltration are a function of soil texture and porosity, surface organic material and vegetative cover. Direct and indirect effects of fire can alter these parameters depending on fire severity. Minimal impacts are evidenced following fire when intensity and heat output are too low to result in complete litter and duff layer removal. Should a fire be severe enough to expose mineral soil, several conditions can occur to significantly decrease infiltration rates. First, the impact of falling raindrops on bare soil surfaces can lead to physical compaction and reduction in soil porosity. Second, exposure of mineral soil after fire normally implies that organic matter that structurally binds soil particles also has been consumed and that soil structure has collapsed. This results in increased soil bulk densities and decreased pore space (Zwolinski 1971). A third condition following severe fire is the displacement and saltation of soil particles by raindrop impacts and subsequent sealing or plugging of soil pores. These three conditions, often occurring simultaneously, can effectively reduce soil water infiltration. When soil water entry rates are markedly reduced and more water is available to surface runoff, then increased erosion and sedimentation problems are likely to occur.

On watersheds where vegetation produces high amounts of organic substances, i.e., chaparral, a non-wettable or hydrophobic layer formed at the soil surface restricts water infiltration. Heating from severe fires can volatilize the organics in the litter / duff and soil surface layers and, due to temperature gradients, transport these chemicals deeper into the soil profile where condensation and a new hydrophobic layer occur (DeBano 1981). This subsurface condition will impede further downward movement of infiltrated water and cause the saturated, wettable soil perched above the water repellent layer to slide downslope and create large uncontrollable mudslides and debris flows (Wells 1987).

Soil Moisture Storage

When the soil mantle becomes saturated, any further additions of water will result in surface runoff. Soil moisture can be depleted by evaporation and plant root absorption. The wilting point is reached when forces holding water in the soil matrix are balanced by the osmotic gradient drawing water into plant roots. Removal of a high water using vegetation type by a severe fire will reduce transpirational draft and result in a greater quantity of water remaining in soil storage (Tiedemann and Klock 1976). Therefore, a lesser amount of subsequent precipitation and infiltration is needed to bring the soil to its maximum water holding capacity and, ultimately, lead to surface runoff. Fires of lower severity, where vegetation is not drastically altered, will have little of no impact on soil moisture storage.

Snow Accumulation and Melt

Fires influence snow deposition and melt characteristics when openings are established in formerly dense forested overstories. The blackened remains of on-site fuels penetrating through the snowpack can change surface albedo and cause an earlier and more rapid snowmelt and runoff (DeBano, et al. 1998). Openings in vegetation types from fire will have reduced interception loss and allow greater snow accumulation. Solar radiation penetration to the surface under these open conditions also enhances earlier snowmelt and runoff.

Downstream Fire Impacts

Runoff Quantity

In examining the on-site impacts of fire on watershed hydrologic responses, it is apparent that severe fires can alter vegetation and soil characteristics resulting in increased flow volumes. Reductions in interception and evapotranspiration losses, infiltration rates and soil moisture deficits result in more water becoming available for overland flow and subsequent stream runoff. Low, or even moderate, severity fires will elicit runoff increases commensurate with the degree of vegetation and soil alteration.

Peak Flows and Timing

Increased peak flows and earlier runoff patterns have been reported following severe fire (Tiedemann and Klock 1976). This increased runoff results from rapid snowmelt caused by the removal of overstory vegetation and greater solar radiation influx.

Erosion and Sediment

Runoff and erosion are directly related to decreased infiltration, raindrop splash, surface erosion and sediment movement. Accelerated erosion often occurs following high severity fires (DeBano, et al. 1998). Sediment carried from a watershed as a result of erosion is subsequently deposited downstream. The quantity of suspended material is dependent upon soil properties, flow velocities, watershed geomorphology and scour potential of stream channels. Sediment-laden water flows also can result in substantial losses of aquatic organisms and fish habitat.

Water Quality

Water quality refers to the abiotic and biotic substances contained in water and their impacts on a particular use. Watershed managers are particularly concerned with suspended sediments, dissolved chemicals and bacteriological components. Combustion of organic fuels on watersheds by fire results in mineralization and release of chemical nutrients, principally Ca, Mg and K. These elements can increase soil pH by occupying cation exchange sites. Green up of a burned site shortly after fire is primarily due to increased nitrogen availability. Fire also can convert bound organic nitrogen and phosphorus to soluble forms. An indirect effect of increased N and P in streamflow following fire is the potential for eutrophication. This enrichment process promotes increased algal growth and adversely affects the dissolved oxygen content of water.

Management Implications

The major effect of fire on the hydrologic functioning of watersheds is the removal of vegetation and litter materials that protect the soil surface. The quantity of vegetation and litter cover removed determines the magnitude of watershed responses (DeBano, et al 1996). Consequently, fire severity becomes an important parameter for watershed managers to evaluate when assessing post-fire impacts. Although much of the information available on hydrologic responses has been obtained following wildfires, where large changes are readily measured, lower severity fires, i.e., prescribed, show little or no hydrologic impacts (Figure 1). Most prescribed burn plans, other than those for severe fires used to remove undesired vegetation types, ensure that litter / duff material remains on site to protect the soil surface. However, due to the wide variability in fuel loadings and on-site conditions, even prescribed

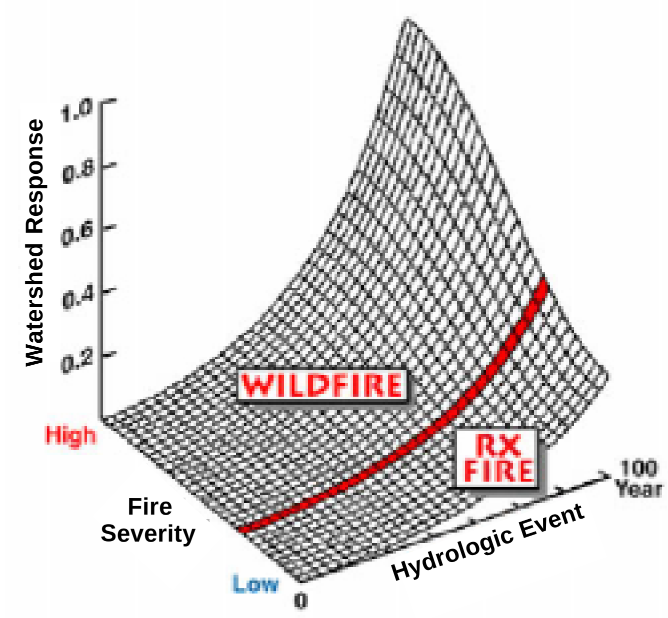

Figure 1. Fire severity continuum (Source: Neary, D. G., M.B. Baker, Jr., L.F. DeBano and P.F. Ffolliott [unpublished]).

fires can be severe enough to create small areas where mineral soil has been exposed.

Watersheds can be managed effectively for water production and other resource values using prescribed fire. Careful application of fire, with attention to maintaining the integrity of on-site vegetation and litter cover, also can reduce fuel loadings and promote positive forest, range and wildlife objectives. However, wildfires that consume large amounts of vegetation and litter can produce substantial increases in surface runoff, peak flows and sediment, even under average precipitation regimes.

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Soil and Vegetation Changes in a Pinyon-Juniper Area in Central Arizona after Prescribed Fire

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Abstract.—Prescribed fire has been used as an inexpensive and rapid method for disposing of slash following fuelwood sales in pinyon-juniper sites. Soil heating during a fire has a direct effect on soil nutrients and microbial activity. The potential for understory cover quantity and quality, along with soil nutrient changes should be the determining factors in management decisions to use prescribed fire for slash disposal. Our investigation measured soil nitrogen and phosphorus changes, and the understory community following a prescribed fire in a pinyon-juniper site in central Arizona.

Introduction

Woodland communities occupy 7 million ha in the Southwestern United States (Miller and Wigand 1994). Conflicting uses of pinyon-juniper woodlands has resulted due to the diversity of products produced such as fuelwood and forage (Clary and Jameson 1981). Demand for commercial and personal-use fuelwood harvesting provides managers with an inexpensive tool for tree removal. Several studies have shown an increase in herbaceous cover following tree thinning (Clary and Jameson 1981, Everett and Sharrow 1985, Bledsoe and Fowler 1992). Establishment of this herbaceous community is critical in preventing soil loss and maintaining watershed condition.

After tree harvesting, leaves, twigs, and smaller branches are left on site. This slash material can interfere with livestock and wildlife movement and is not aesthetically acceptable. Prescribed fire has been used as an inexpensive and rapid method for disposing of this slash.

Soil heating during fire has a direct effect on soil nutrients by oxidizing organic materials (Smith 1970, Stark 1977, DeBano and Conrad 1978, Stednick et al. 1982, Wright and Bailey 1982, Giovanni et al. 1988) and an indirect effect by modifying microbial populations (Ahlgren and Ahlgren 1965, Wright and Bailey 1982). With a volatilization temperature of 200 °C, a significant amount of nitrogen is lost during burning of pinyon-juniper slash (DeBano and Klopatek 1987). A variable amount of the phosphorus contained in soil and litter can also be lost depending on fire intensity.

The economic benefit of pinyon-juniper woodland treatments historically is an increase in forage production (Dalen and Snyder 1986). Current management emphasizes a variety of uses including fuelwood production, wildlife habitat enhancement, and livestock grazing. Our objective was to determine what vegetative community type returned, and the soil nutrient status following a fuelwood sale with slash removal by prescribed burning.

Material And Methods

Study Site

Hogg Pasture is located in central Arizona on the Coconino National Forest. The soils are classified Typic Haplustalf, fine, smectic, mesic. This site had approximately 60% overstory before harvesting, consisting of *Juniperus osteosperma* (Utah juniper) and *Pinus edulis* (pinyon). We sampled this site in mid-May of 1997, almost 2 years after a prescribed fire was used to remove slash following a fuelwood sale.

Soil

Transects were randomly located at 4 areas within the treated stand. These transects extended into adjacent untreated areas so comparisons between presumably similar treated and untreated sites could be made. Both treated and untreated area soils are classified as fine, smectic, mesic Haplustalfs. Vegetative cover was also assumed to be the same for both treated and untreated sites. Twenty soil cores were randomly taken to a depth of 10 cm along each transect, then composited based on whether they were under canopy or from interspace areas. Additional sampling included an individual tree and associated interspace area randomly picked along the transect from both

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treated and untreated sites and sampled for litter and soil. Litter was gathered from within a 0.1 m^2 plot frame and 3 soil cores were composited from within the litter frame.

Total organic carbon was determined using a modified Meibus procedure (Nelson and Sommers 1982). Total labile fraction analyses of soil nitrogen and phosphorus were performed using sulfuric acid-hydrogen peroxide digestant. Total nitrogen was determined by ion chromatography. Total phosphorus was determined by the phosphomolybdate method (Murphy and Riley 1962). Available ammonia, nitrate, and mineralizable nitrogen were analyzed using ion chromatography. Total nitrogen and phosphorus in the litter followed the same methods as described for soil.

Vegetation and Ground Surface

Five vegetation transects were randomly located in the treated area, with 3 in adjacent untreated area in close proximity to the soil transects. Again, we assumed the treated and untreated sites are the same before treatment. Each transect was measured using 25 quadrat samples (each 2x5 dm) spaced at 1 m intervals along the transect (Daubenmire 1959). Values at each transect were averaged from the 25 quadrat samples.

Analysis

When burning was done, no provision was made to compare effects of treatment, therefore, there is a lack of a true control. However, soil and watershed potential classification was the same for both treated and untreated sites. Since treated and untreated sites were located in close proximity to each other, we assumed the sites could be compared to provide the best available estimate of treatment effect. Analysis of soil determinations were performed using ANOVA procedures and Tukey's multiple range test utilizing SAS software. Analysis of the vegetation data was performed using a t-test.

Results

Soil analysis showed little difference in total organic carbon and total nitrogen due to burning, yet there was a distinct difference between canopy and interspace areas (table 1). Available ammonia and nitrate were significantly higher in the burned canopy sites compared to the other sites (table 1.). Interestingly, there was little mineralizable nitrogen under the burned canopy (table 1.) Total phosphorus was comparable across all sites, but available phosphorus appeared greater under the burned canopies (table 1.).

Burning resulted in over a 99% decrease in total litter biomass under canopy (table 2.). This dramatic biomass loss also reduced total phosphorus and nitrogen available for decomposition.

Total vegetative cover appeared greater in the burned area compared to the unburned area, along with a proportional increase in the number of species sampled (table 3.). However, no statistical differences in vegetation were found due to the high variability in the measured parameters. Most of the apparent difference was due to annuals, primarily *Heliomerius multiflora* (showy goldeneye), which was 11% higher in the burned areas. Other increases were in *Gutierrezia sarothrae* (snakeweed), *Hymenoxys* spp. (actinea), and *Menodora scabra*. Other notable forbs found in the burned areas were *Melilotus officinalis* (sweetclover)

Table 1. Soils analysis (0-10 cm) from Hogg Pasture in central Arizona following prescribed fire[a].

Nutrient	Mean burned canopy	Mean unburned canopy	Mean burned interspace	Mean unburned interspace
% total organic carbon	2.72a	2.61a	1.63b	1.09c
% total nitrogen	0.39a	0.27ab	0.12bc	0.07c
Mineralizable nitrogen (ug/g)	2.35b	28.76a	14.77ab	6.27b
KCl-extractable ammonia (ug/g)	28.25a	<0.01b	1.67b	0.99b
KCl-extractable nitrate (ug/g)	25.67a	1.29b	1.85b	1.03b
% total phosphorus	0.0068a	0.0057a	0.0045a	0.0045a
Extractable phosphorus (ug/g)	15.02a	3.06a	3.88a	0.96a

[a]*Means with same letter were not significantly different using ANOVA with Tukey's Studentized Range test (alpha=0.05, df=16).*

Table 2. Analysis of litter from Hogg Pasture in central Arizona following prescribed fire[a].

Nutrient	Mean burned canopy	Mean unburned canopy	Mean burned interspace	Mean unburned interspace
Total litter biomass (g/m^2)	37.50b	4805.00a	102.5b	165b
Total phosphorus (g/m^2)	0.002b	0.27a	0.0044b	0.0017b
Total nitrogen (g/m^2)	0.90b	48.80a	0.75b	0.60b

[a]*Means with same letter were not significantly different using ANOVA with Tukey's Studentized Range test (alpha=0.05, df=8).*

and *Linaria dalmatica* (toadflax). There was also a small decrease in the mean of bare soil, along with a slight increase in litter and rock-gravel cover, but the variability was very high for these parameters (table 3.).

Discussion

Soils organic-matter decomposition from the burned canopy areas was significantly reduced as evidenced by the dramatic decrease in mineralizable nitrogen. This could be either depression of the microbial community or lack of a readily available carbon source. Higher available nitrogen and phosphorus indicates that burned sites are more fertile than unburned sites, but the loss of mineralizable nitrogen indicates otherwise. The litter layer in these burned sites is greatly diminished, which decreases the organic-matter pool and increases soil temperatures, raises potential evaporation losses, and exposes the topsoil to greater raindrop impact and erosion potential.

Table 3. Vegetation and ground cover in 1997 at Hogg Pasture[a], (n = number of transects).

Vegetation (% cover)	Burn (n=5)	Control (n=3)
Perennial grasses	6 (2.5)	2 (1.9)
Perennial forbs	2 (1.4)	0.03 (0.03)
Annuals	12 (10.4)	0.03 (0.03)
Shrubs	7 (2.7)	9 (3.2)
Unidentified herbs	2 (1.1)	0.05 (0.05)
Species (number/transect)	24 (1.9)	16 (5.5)
Ground Surface (% cover)		
Litter	10 (3.2)	6 (4.1)
Rock-gravel	38 (7.5)	33 (14.8)
Soil	49 (10.9)	59 (14.6)
Basal area	2.3 (0.8)	0.7 (0.5)
Cryptograms	na	0.4 (na)
Coarse woody debris (CWD)	1.4 (0.9)	1.9 (na)
Total (litter to CWD)	101	101

[a] *Values in parenthesis are standard error of the mean.*

Perennial grasses were apparently 4% higher in the burned openings, with the greatest difference attributed to a single, unpalatable weedy composite. The remaining apparent increase is also from species that benefit neither cattle \ or wintering elk. An increase in forage is needed to justify the expense of treatment, but unpalatable, noxious, or ephemeral plants were the main respondents. Toadflax, recognized as a noxious alien, is rapidly increasing on the Coconino National Forest. From our observation, toadflax increases faster on bare soil such as occurs after a prescribed fire following fuelwood cutting. In terms of biomass, perennial grasses totaling 6% cover, would convert to less than 56 kg / ha.

Conclusions

The goal of this prescribed burn was to increase forage for livestock and wintering elk, and to improve the watershed condition by increasing vegetative cover. Slightly higher amounts of palatable species produced little overall increase in forage and little decrease in bare soil. Before fuelwood cutting, the overstory provided protection from raindrop impact, but following harvesting and prescribed fire, almost 50% of the soil was exposed. This degree of exposed soil poses a high potential for surface erosion, compounded with the loss in total and mineralizable nitrogen further degrading the soil resource.

From this study and observation of other similarly treated sites, our recommendation when the understory community is sparse with little perennial grass cover, is that slash should remain on site following fuelwood cutting. Other slash treatments are available such as lop and scatter, crushing, or leaving in place. The expense of crushing may not be recoverable by an increase in forage, but both of the other treatments would cost nothing and would provide soil erosion protection and seedling protection from grazing.

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Burned Area Emergency Watershed Rehabilitation: Program Goals, Techniques, Effectiveness, and Future Directions in the 21st Century

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Abstract.—Following wildfires, burned areas are assessed by special teams to determine if emergency watershed rehabilitation measures are required to restore watershed function and minimize damage to soil resources. The objective of burned area emergency rehabilitation (BAER) treatments is to restore watershed condition and reduce erosional losses on hillslopes, in channels, and on road surfaces and peripheral areas such as ditches. In the Western United States, a project is currently in progress to determine the costs and effectiveness of BAER projects in restoring watershed function. Results of this project will help establish the future directions of the BAER program into the 21st century.

Introduction

All disturbances produce impacts on forest ecosystems. The level and type of impact, whether negative or positive, depends on ecosystem resistance and resilience as well as the severity of the disturbance. Fire severity is important since it covers a spectrum that may or may not entirely occur on the same site (DeBano et al. 1998). The term "intensity" has often been confused with severity in documentation of wildfire damage to natural resources. Severity is qualitative measure of the effects of fire on soil and site resources although some aspects can be quantified (Hartford and Fransen 1992). The variability in soil and watershed damage, and resource response is highly dependent on fire severity (DeBano et al. 1998).

Soils are critical to the functioning of hydrological processes (DeBano et al. 1998). On a watershed basis, sediment increases and water-yield responses to fire are a function of fire severity and the occurrence of hydrologic events. The impacts of wildfires on hydrology and sediment loss can be minimal in the absence of an immediate precipitation event. However, when major precipitation events occur after large, moderate- to high-severity fires, impacts can be significant. For example, increased runoff, peakflows, and sediment delivery to streams can impact fish populations and habitat environment (Rinne 1997).

The hydrologic cycle quantifies the interactions between the atmosphere, geosphere, and hydrosphere (Brooks et al. 1997). Water, the primary driving force in ecosystem processes and fluxes, integrates the processes occurring on watersheds. The quantity and quality of water emanating from watersheds are indices of ecosystem condition. Watershed condition describes the ability of a watershed system and soils to receive and process precipitation without ecosystem degradation. Wildfires can have significant impacts on watershed condition (DeBano et al. 1998).

Fire destroys all or part of the organic forest floor and vegetation thereby altering infiltration and percolation capacity of the soil by exposing it to raindrop impacts. Under the right conditions, fire creates water repellent layers in the surface horizons of soil that prevent deep percolation of rainfall (DeBano et al. 1998). This action alters watershed condition, with erosion increasing as watershed condition deteriorates from good to poor. Loss of soil from hillslopes produces several significant ecosystem impacts. Soil movement into streams, lakes, and riparian zones deteriorates water quality, and changes the geomorphic and hydrologic characteristics of these systems. More importantly, soil loss from hillslopes results in reduced future ecosystem productivity.

The effects of disturbances on water yield from forest and shrub watershed studies throughout the world have been well documented and reviewed (Anderson et al. 1976, Bosch and Hewlett 1982, and Neary and Hornbeck 1994). Water yields increases when mature forests are harvested, burned, blown down, or attacked by insects. The magnitude of measured water-yield increases the first year after fire disturbance varies greatly depending on fire severity, climate, precipitation, geology, soils, watershed aspect, latitude, tree species, and proportion of the forest vegetation burned. Streamflow increases produced by forest disturbance decline as woody and herbaceous vegetation regrow. This recovery period can range from a

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few years to decades. Peakflow increases of 500% to 9600 % are common in the Southwestern United States while those measured in the Cascade region are much lower (<45 %) (Anderson et al. 1976). Another concern is the timing of stormflows or response time. Burned watersheds generally respond to rainfall faster, producing more flash floods (Anderson et al. 1976, DeBano et al. 1998).

Erosion is a natural process occurring on landscapes at different rates and scales depending on geology, topography, vegetation, and climate. Fires and fire suppression activities affect erosion processes. Erosion is the most visible and dramatic impact of fire apart from burned vegetation (DeBano et al. 1998).

Fire-related sediment yields vary from ecoregion to ecoregion depending on factors such as fire frequency, climate, vegetation, and geomorphic factors (e.g., topography, geology, and soils). In some ecoregions, over 60% of the total landscape sediment production over the long-term is fire-related. Much of that sediment loss can occur the first year after a wildfire (DeBano et al. 1998).

Post-wildfire sediment yields can range from very low on flat terrain without major rainfall events to extreme in steep terrain affected by high intensity thunderstorms. Erosion on burned areas usually declines in subsequent years as the site stabilizes, but the rate varies depending on fire severity (DeBano et al. 1998). Nearly all fires increase sediment yield, but wildfires in steep terrain produce the greatest increases.

Burned area emergency rehabilitation (BAER) treatments are designed to mitigate the impacts of severe wildfires on watershed condition. Consequently, BAER treatments can be very important in minimizing site damage. Few wildfire effects studies reported in the literature have examined the effects of post-fire BAER treatments on sediment yield.

BAER Program

History

Emergency watershed rehabilitation after wildfires first occurred in the late 1960s and early 1970s. At this time, no formal rehabilitation program existed, so funds were obtained from fire suppression accounts. In the early 1970s, a congressional inquiry, conducted to determine the need for and use of emergency watershed rehabilitation funds, led to formation of the BAER program in 1974. Initially, the BAER program was established to restore or repair burned-over areas to achieve soil stability, runoff control, and unimpaired stream channel carrying capacities. Later, restoring wildlife habitat, range forage, and recreation facilities also became program goals.

In the late 1980s, a coordinated interagency effort was initiated to train BAER team leaders and to coordinate evaluation of fire severity, funding request procedures, and treatment options. Annual BAER training programs at regional and national levels were also initiated. During this time, National Forest System specialists were encouraged to accomplish implementation monitoring as well as some form of effectiveness monitoring.

In the mid 1990s, there was a major effort to revise and update the BAER handbook. A steering group consisting of regional BAER coordinators and other specialists organized and developed the handbooks that used today. Since individual agencies had interpreted the congressional appropriations for BAER differently, a national effort was started in the late 1990s to establish consistent blend BAER policies across federal agency boundaries.

Treatments

BAER treatments have been traditionally grouped into hillslope, channel, and road treatments. Functionally, hillslope treatments are divided into revegetation, erosion barrier, physical soil manipulation, and other ground cover treatments. Channel BAER treatments consist of check dams, grade stabilizers, and other miscellaneous treatments. The functional groups for road treatments are culvert-bridge-ditch improvements, shaping, protection, and surface manipulations. Another group of BAER treatments can be classified as treatment protection (fencing, road / trail closures, signing, etc.).

Hillslope treatments are designed to either reduce erosion or hold soil and sediments on-site (Miles et al. 1989). Revegetation treatments to aid plant reestabishment on burned slopes consist of aerial and ground seeding, fertilization, and mulching. Erosion barriers, such as logs , straw wattles, straw bales, soil and sand bags, and silt fences, are placed to trap eroded soil material on the slope. Physical soil manipulations, such as contour trenching and ripping / tilling, are used to either trap and store eroding soil or to reduce erosion potential by improving surface roughness, depression storage, and infiltration capacity. Other ground cover techniques used to reduce erosion include slash spreading, felling snags along the contour, and laying erosion control fabric.

Channel treatments are designed to store sediment in channels or reduce the erosive power of water flow. Check dams are often used to detain sediment in channels. These can be straw wattles, straw bales, logs, rocks, or rock gabions. Grade stabilizers that lower the velocity of streamflow by reducing channel gradient via a series of steps can be constructed of logs or rocks. Other types of channel BAER treatments include debris basin construction, woody debris removal, small dams, and channel-bank armoring.

Road treatments are mainly used to help roads and road structures survive the additional streamflows and surface runoff that often occur after wildfires. Culvert, bridge, and ditch improvements, such as culvert upgrades, culvert removals, culvert riser installation, ditchline debris removal, and ditch check dam construction, help control additional water flow or prevent ditch downcutting and culvert blowouts. Shaping road surfaces by outsloping, water bar installation, and rolling dip construction limits erosion by reducing water velocity. Road protection can be accomplished by installing trash racks to trap woody debris that might block culverts, patrolling roads and culverts during storm events, and constructing overflows that provide relief to culverts during excessively high stormflows. Surface manipulations, such as outsloped resurfacing, ripping/tilling, and the armoring of crossings and drains, provide additional reductions of road surface and side-slope erosion during storm runoff events.

Treatment protections include temporary fencing, road and trail closures, and signing that are used to aid post-wildfire watershed restoration. They can be used on hillslopes, in channels, or on roads. The purpose of these treatments is keep vehicle, foot, and domestic animal traffic off of sensitive, fire-disturbed soils, road, and trail surfaces. Site vegetation and soil recovery occurs faster if additional post-fire disturbances are reduced or eliminated.

Program Assessment

The effectiveness of many emergency rehabilitation methods has not been systematically tested or validated. Although BAER expenditures accounted for <1% of total Forest Service fire expenditures in 1994 (Schuster et al. 1997), concerns about its effectiveness have been raised at a national level due to rapidly rising costs of this program in the 1990s. Over the past 3 decades, $83 million has been spent to treat 5.4 million acres of National Forest System lands. BAER team leaders and decision-makers often do not have information needed to thoroughly evaluate the short- and long-term benefits and costs of various treatment options. In 1998, a joint study was initialized between the Rocky Mountain Research Station and the Pacific Southwest Station to evaluate past BAER emergency rehabilitation methods. This assessment was undertaken to collect information on past usage of BAER treatments, attributes that made the treatments succeed or fail, and effectiveness of the treatment to achieve desired goals. Since much of the information was not published and was qualitative in nature, a survey was designed to ask resource specialists specific questions regarding their BAER programs. Additional information was obtained from BAER report files, monitoring reports, and related documents. Publication of the results is expected in the fall of 1999 (Robichaud et al. in press).

Future Directions

Three BAER program areas, increased training, policy consistency, and funding review, were targeted for improvement in the late 1990s. Three areas of training were enhanced including BAER Team Leader training, implementation training, and on-the-ground treatment installation training. Additional training is needed in the areas of effectiveness monitoring methods and resource impact assessment procedures (Robichaud et al. in press).

In 1999, the Forest Service, the Bureau of Land Management, the National Park Service, the Fish and Wildlife Service, and the Bureau of Indian Affairs approved a policy for a consistent approach to BAER. The new policy broadens the scope and application of BAER analysis and treatment by: 1) monitoring to determine if additional treatment is needed, 2) evaluating treatments to improve effectiveness, 3) repairing facilities for safety reasons, 4) stabilizing biotic communities, and 5) preventing unacceptable degradation of critical cultural sites and natural resources. Funding requests need careful scrutiny at the regional and national levels to ensure that they are reasonable, practicable and cost-effective and provide significant improvement over natural recovery.

Results of the current BAER program review suggest that in the future there should be increased use of native or sterile seed sources, consideration of longer-term benefits in the initial post-fire assessment, increased effectiveness monitoring, and improved prescriptions for local conditions. Current Forest Service policy requires an immediate assessment of site conditions following wildfire and, where necessary, implementation of BAER treatments to: 1) minimize the threat to life and property onsite and offsite, 2) reduce the loss of soil and onsite productivity, 3) reduce adverse changes in streamflow regimes, and 4) reduce deterioration of water quality. Increased Forest Service emphasis on ecosystem management and sustainability, as elucidated recently in the Chief's natural resources agenda, will also improve support for the BAER program.

Summary

The BAER program has been operational since the 1970s to immediately assess site conditions following wildfire. When necessary, emergency rehabilitation measures have been implemented to reduce the loss of soil and onsite productivity, and reduce deterioration of watershed condition, streamflow characteristics, and water quality. Future directions in the 21st century will include: 1) additional funded monitoring and research studies to better understand the effectiveness of BAER treatments on watershed restoration, 2) increased use of native or sterile seed sources, 3) consideration of long-term benefits, and 4) improved prescriptions for local conditions.

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Arizona Watershed Framework in the Verde River Watershed

Ren Northup[1]

Abstract.— The Arizona Department of Environmental Quality, Water Quality Division drafted a six-step approach to guide its staff and local participants in developing and implementing watershed management plans. From January 1999 through June 2000, the draft *Arizona Statewide Watershed Framework* will be tested in Arizona's Verde River watershed. This concept proofing compares the observed watershed planning process to the *Framework*; assesses the outcomes of the process; and concludes with recommendations for improving the *Framework*. The watershed process will be more effective if more time and flexibility are provided so that the process can involve and be driven by local stakeholders.

Introduction

Watershed approaches help stakeholders coordinate environmental management activities to improve water quality. Operating natural resource programs within hydrologically-defined areas helps stakeholders to: a) identify environmental goals; b) leverage and link financial, institutional and human resources; c) enhance communication; and d) reduce redundancy and conflict. With active and broad involvement, people grow more committed to supporting sustainable resource management by changing everyday practices, budgets, plans, and programs.

The Arizona Department of Environmental Quality (ADEQ), Water Quality Division is charged with restoring waters with impaired quality and protecting water quality where it is not impaired. This is achieved by issuing National Pollutant Discharge Elimination System (NPDES) permits and developing Total Maximum Daily Loads (TMDLs). Watershed stakeholders are involved in the TMDL process so that practices to reduce loads can be appropriate to local needs.

ADEQ has drafted a six-step approach to guide public and private stakeholders as they develop and carry out a watershed management plan. The draft *Arizona Statewide Watershed Framework* (Arizona Department of Environmental Quality, 1997) describes how the watershed approach could integrate ADEQ's activities with those of other public and private partners. It calls for ADEQ to rotate activities and resources among Arizona's ten watersheds on a five-year cycle. The *Framework* has not been carried out in Arizona because, by its own admission, ADEQ did not align its organization, finances, work plans, and management focus to ensure success (Arizona Department of Environmental Quality, 1999). This study identifies changes that could help implement the *Framework*.

The Arizona Watershed Framework

Between January 1999 and August 2000, the draft *Arizona Statewide Watershed Framework* will be tested in Arizona's Verde River Watershed. The *Framework's* six steps are described below. These steps are not intended to be followed in rigid sequence.

Step one, "Stakeholder Outreach and Involvement," is to enlist potential stakeholders, solicit a local sponsor and generate a community profile.

Step two, "Collect and Evaluate Watershed Data," is to identify areas of focus, evaluate monitoring data, and fill information gaps.

Step three, "List and Target Environmental Concerns," is to rank areas, evaluate issues to decide when they can and should be addressed, and list available resources.

Step four, "Develop Management Strategies and Measures of Success," is to develop a strategy, schedule and action plan and identify indicators of success to incorporate into a monitoring plan.

Step five, "Compile the Watershed Plan," is to document the results of steps one through four, ratify the plan, and formalize budgets and partnerships.

Step six, "Implement and Evaluate Watershed Plan," is to carry out activities and projects according to the plan, track progress, and evaluate success.

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The Verde Initiative

The Verde River watershed is struggling with rapid population growth as tourism joins mining and agriculture as local economic drivers. Population and land use changes have introduced and exacerbated water quantity and quality issues. Additionally, much of the Verde River's flow provides water for the metropolitan Phoenix area, 100 miles to the south.

The Verde River drains approximately 6,188 square miles and traverses about 140 miles in north central Arizona. It runs from the Sullivan Lake Dam east and southeast to join Fossil Creek, where it veers south to join the Salt River. Parts of the drainage are in the Prescott Aquifer Management Area (AMA); and 25 miles of the Verde River are in the Phoenix AMA.

Study Objectives

This study has three objectives. First is to compare the observed watershed planning process to the model presented in the draft *Arizona Statewide Watershed Framework*. The second objective is to draw conclusions about the outcomes of the watershed planning process. The last objective is to recommend improvements to the watershed planning process.

Methods

Objective One

Objective one is met by recording and describing the planning process as it is carried out. By observing the watershed groups' activities, and categorizing each activity by the step it helps achieve, each step's effectiveness can be evaluated to identify obstacles.

To help integrate ADEQ activities conducted under diverse water quality programs, the Verde Watershed Project Manager developed a detailed Verde Watershed Team Workplan. The Workplan compiles activities to be carried out in the Verde Watershed described in the FY 2000 Water Quality Division Workplan (Arizona Department of Environmental Quality, 1999). The Workplan will be continuously updated as milestones are reached, and to add new activities. Further, milestones are tracked using the Open Issues and Deliverables, a document maintained by the Verde Watershed Project Manager for the Assistant Division Director.

Watershed group activities are compared with the activities described in the *Framework*. The Open Issues and Deliverables list identifies activities, and the dates they were started and finished. Each activity on the list has been categorized by the *Framework* step it helps achieve.

Objective Two

Objective two will be met by defining and tracking measures of success. Success means meeting the objectives of ADEQ (total maximum daily loads, or TMDLs) and of the watershed (developing a watershed plan). This research is ongoing.

TMDL activities scheduled in the Verde Watershed during the study period include monitoring and assessing five lakes and reaches of Oak Creek and Beaver Creek. Monitoring data will be used to support delisting or to provide basic information to prepare TMDLs. Because a simple "yes or no" toggle may not be possible, interim milestones, such as data collection, public hearings held and models developed will be tracked.

Likewise, progress on the Integrated Watershed Plan cannot be measured as a simple toggle. By the end of the initiative, the plan might be completed as a draft document or a final document. A final document might be fully ratified, ratified by less than all the partners, or different partners might adopt different parts.

Objective Three

The focus of this manuscript is Objective 3, which is met by developing recommendations for improving future watershed planning efforts. Various sources of information on watershed planning techniques were referenced. These sources helped identify the challenges and opportunities that contributed to the successes and shortfalls in the Verde Initiative, and provided insights for improving the Watershed Framework. This manuscript reports preliminary recommendations, based on the chronology analysis, in the discussion.

Improving the Arizona Watershed Framework

Obtaining Buy-In

An obstacle to the Verde Initiative was the lack of perceived need at the local level and the lack of opportunity for local voice. The Verde Initiative was developed as an ADEQ management team-building exercise by Water Quality Division managers without involving the Verde

Watershed Coordinator, the Statewide Watershed Coordinator or local stakeholders. As a result, valuable time was lost educating and obtaining support from these parties.

Not only must initial buy-in be gained, but support must be cultivated throughout the process. Garnering support in a watershed requires clear two-way communication of needs and goals. In the Verde this open exchange is a big time investment, due to the many fora at which information is shared. Consensus building in the Verde watershed may require attending Verde Watershed Association (VWA) general membership and committee meetings, and also meetings of the Oak Creek Task Force, the Yavapai Water Advisory Group, and various Natural Resources Conservation Districts operating in the Verde Watershed. Attending each of these meetings cannot be achieved by one researcher in a given month, since some of these meetings conflict. A two-month communication process is needed to get information to all stakeholder groups. In addition, time must also be scheduled to provide additional information if requested, or to go through the required voting process of each group.

Communicating

Forums used in the Verde Initiative are the media, newsletters, mailings, E-mail user groups, workshops, field trips and fairs. The VWA asked several public libraries to donate shelf space so that minutes, reports and technical data can be made available to all. The effectiveness of outreach would be improved by streamlining the ADEQ's internal process for reviewing and approving press releases. Coordinating press releases and Internet postings with the VWA Outreach and Education Committee is an additional review process, which can delay late-breaking information and announcements so that they become moot or stale.

Organizing

Written operating procedures and bylaws help groups in Arizona qualify for funding. Memoranda of Understanding are common instruments for participants to ratify the scope and bylaws of the partnership. A separate signature sheet for each party allows partners to be added.

Before defining decision-making rules, the authority and scope of each participant must be defined, as well as the extent of the partnership's decision-making authority. The Yavapai County Water Advisory Group chose to limit the voice of some state and federal agencies in local decision-making. Because the group was formed by the Yavapai County Board of Supervisors, Gila County stakeholders' involvement is limited.

Partnerships can benefit from a trained facilitator. Watershed partnership training was offered to Verde stakeholders and focused largely on the planning process and team-building skills. An idea that could prove valuable, which has not yet been tried in the Verde, is to train a local leader in professional conflict mediation and facilitation skills.

Planning

The VWA's planning efforts have focused on developing an Upper/Middle Verde study, which will provide a comprehensive and detailed look at water resources in the watershed. Many members prefer to defer planning until results are available, over a two to ten-year period. This would effectively retard the planning process at step two, "Collect and Evaluate Watershed Data."

Technical assistance may provide a way around this obstacle. The ADEQ Verde Watershed Project Manager has offered to compile existing plans from public sector stakeholders and land managers. Place holders would be inserted for future data and plan components. This would offer a guiding document while still respecting the local need for more up-to-date information, without diverting local energy and resources from other activities. It would use ADEQ expertise, without bringing too strong an outside voice to local decision-making.

Conclusion

To date, the Verde Initiative has underscored the importance of respecting the needs of all participants, and the time required throughout the watershed process. As groups are formed, the authority of the participants and of the partnership must be considered. Ratification instruments should allow flexibility to add participants over time. Cultivating buy-in and consensus is thwarted by attempts to hurry the process. Reviewing proposed activities and press releases can be streamlined. Even the decision of whether and how to develop a plan document should remain at the local level.

More findings and results will be available March 14, 2000, at the poster session of the Conference on Land Stewardship in the 21st Century: Contributions of Watershed Management.

Acknowledgments

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Attributes of Successful Stock Water Ponds in Southern Arizona

Barry, L. Imler[1], Richard H. Hawkins[2], D. Phillip Guertin[3], and Don W. Young[4]

Abstract.—The attributes of 20 ponds (or stock tanks) on the Nogales Ranger District of the Coronado National Forest were studied in detail by groups. Two contrasting groups, judged to be either functional (n = 11) or nonfunctional (n = 9) were used in the study. Differences between the groups were evaluated on the basis of attributes of the ponds themselves, the contributing watersheds, and the local climate and modeled hydrology. There are no differences associated with the pond shape, materials used for dam construction, watershed Curve Number, hydrologic soil group, geology, range or hydrologic condition, mean number of days at capacity per year, or the fraction of runoff trapped. Differences are more apparent when considering pond depth, maximum pond capacity, watershed drainage area, and percent of days with no stored water.

Introduction

Stock tanks (stock ponds) are important in rangeland management in their obvious role of stock watering. The water supply they provide allows for widespread use of forage resources over otherwise waterless areas, a surface water source during extended dry periods, as well as providing benefits for wildlife and associated aquatic resources. Also, at least at the local level, they have unavoidable hydrologic impacts.

Stock tanks are costly, and potential environmental impacts - both positive and negative - are likely. Therefore, informed planning can minimize costs and unproductive installations, and avoid environmentally harmful effects. From a water development standpoint, the total surface water supply in arid areas is limited, so that efficient use calls for thoughtful placement of stock tanks. Thus, it is important to know at the conception and planning stage the likelihood of a successful effort. Or in other words: "What makes a good site for a stock tank?"

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Approach

A "good" site depends on the intent of development. Given the wide spectrum of benefits and costs possible, and the various lenses that different user groups use to view them, land managers develop pragmatic reality-based impressions of goodness. Some ponds obviously "work" well and some others obviously do not. This view may be composed of the cost of construction, the hydrologic /water supply dimensions, durability/maintenance concerns, and incidental benefits.

The construction dimension includes geomorphic suitability of the site, availability of suitable building materials, and heavy machinery access. The hydrologic concern includes the maximum amount and duration of water storage possible and the proximity to forage resources in the management scheme. The durability includes the need for periodic maintenance, sedimentation, spillway repairs, etc. Also, incidental uses such as recreation and wildlife and Endangered Species habitat may influence the worthiness. This work was aimed at isolating and contrasting these management-defined characteristics of stock tank success and failure.

Methods

Location

The location of this study was the Nogales Ranger District of the Coronado National Forest in southern Arizona. Pond elevations vary from about 1200 to 1800 meters, and average annual rainfall (there is little snow) ranges from ca 43 to 71 cm/yr. About 70% of this falls during the summer monsoons season as thunderstorms. Vegetative types include desert grasslands and broadleaf woodlands dominant in southern Arizona. Characteristic of this climate and setting, watershed runoff is almost entirely rainstorm response. There is little or no base flow or snowmelt, and few springs in the area.

Stock Tank Selection

Based on professional experience, management personnel from the Nogales Ranger District of the Coronado National Forest designated a series of candidate ponds based on the questions: "Did the pond fill at any time?", and "Did the pond provide adequate water supply?" as the guiding elements in the selection. Based on practical matters of information availability, access and other logistical and data factors, a total of 20 ponds were selected for study; 9 functioning and 11 nonfunctioning. These are shown in table 1.

Site and Watershed Factors

Site factors

Using existing agency files or specific site surveys the pond factors of the soils, the pond depth and storage capacity at spillway elevation, and the shape were determined. Limited coverage of this is also given in table 1.

Watershed factors

Available data on soils, geology, vegetative type and conditions were assembled for the 20 sites. Based on these, an AMC-II Runoff Curve Number was assigned to each watershed from handbook tables. This was mainly used to drive the hydrologic evaluations described next.

Climatic/Hydrologic Characteristics

A major concern in stock tank utility is the frequency and duration of filling. Such hydrologic data are not available for the sites, but was evaluated through the use of an elementary daily time step model based on a representative two years of rainfall and evaporation data from the Nogales, Arizona weather data. For each site, adjustments on daily values were based on regional regressions developed for this purpose. Daily runoff was generated for each watershed by the CN method based on moisture status, with the expected CN range derived from the land information and handbook values. The model included evaporation, storage, and spills from the ponds themselves. Model runs allowed the number of "dry" days (dry pond) and "wet"days (full pond) to be tabulated.

Table 1. Selected information on stock tanks and watersheds.

Tank Name	Pond			Watershed					
	Elev (m)	Volume (m3)	Depth (m)	DA (ha)	Elev (m)	Veg. type	HSG	CN	Precip (cm/yr)
Nonfuctioning (9)									
Beach	1286	4613	2.44	26	1362	Grassland	D	70	50.3
Box Canyon	1426	962	2.44	23	1603	Grassland	D	79	60.5
Fish	1707	1702	3.05	34	1811	Woodland	C	71	71.2
Lower Turner	1192	4416	3.05	238	1312	Grassland	C	39	46.3
Old Forester	1219	6315	3.66	43	1282	Grassland	C	79	46.7
South Boundary	1305	4552	2.74	115	1506	Grassland	D	74	55.5
Upper Turner	1219	5625	2.74	26	1262	Woodland	C	33	46.5
Warsaw #2	1305	1838	4.57	45	1414	Grassland	D	79	52.7
Warsaw #3	1256	925	3.05	47	1308	Woodland	D	79	50.0
Functioning (11)									
Agua Cercada	1253	13679	4.27	173	1372	Grassland	D	62	50.3
Barrel	1561	2997	2.74	34	1603	Woodland	B	37	59.8
Boundary	1207	2361	1.83	115	1367	Grassland	D	71	48.4
Castle Rock	1250	7660	4.57	27	1297	Grassland	D	78	46.9
Coches	1158	9658	3.96	111	1292	Grassland	D	75	46.7
Greaterville	1634	7994	3.66	68	1707	Woodland	D	68	66.9
Japanese	1317	2171	2.74	38	1366	Woodland	D	69	45.5
Lobo	1329	43492	7.32	496	1530	Woodland	D	86	58.5
Melendrez	1756	2331	3.96	3	1774	Woodland	C	74	71.1
Sierra	1164	5316	3.35	29	1204	Grassland	B	40	43.7
Warsaw	1280	7857	3.05	22	1329	Woodland	D	76	50.1

Note: "Woodland" = Broadleaf Woodland. "Grassland" = Desert Grasslands. HSG = Hydrologic Soil Group. CN is the table AMCII Curve Number based on soils, cover, and condition.

Results

Tables 2 and 3 give group summaries and statistical inference information for most of the variables considered. Group comparisons are made via "t" tests as shown. There are no significant differences at the traditional higher (i.e., 90-95%) confidence levels, but consistent evidence at more moderate levels.

Pond Materials and Characteristics

The functioning and nonfunctioning ponds showed no differences based on dam construction materials. A preferred clay content range around 20% was common, though it varied from 14% to 24% for nonfunctioning ponds to 8% to 32% for functioning ponds. Pond shape, which is not given in the tables here, was found to be completely unimportant.

Table 2 shows the summary findings on the differences between groups in accordance with pond characteristics. Given the relentless draw of evaporation from pond surfaces in hot arid climates, simple pond depth can be expected to be important. The criteria developed by Deal et al. (1997) were used as a measure of comparison. Most (64%) of the functioning ponds were deeper than recommended; most of the nonfunctioning ponds were shallower. However, as shown in table 2, the difference - while present - is not overpowering (72%),

The related attribute of pond capacity (or volume) was also evaluated. Aside from its geomorphic dependence on depth, a large capacity allows greater capture of the rarer extreme inflows. Table 2 shows a similar (75% probability) separation of the groups.

Watershed and Hydrologic Factors

Hydrologic Behavior

The Runoff Curve Number (CN) assigned from soils, vegetation, and land condition data use handbook estimates as beginning points in the hydrologic simulations. These represent the presumed fundamental influences on event runoff generation for the contributing watersheds. As shown in table 2, there is no difference between the two groups on the basis of Curve Number.

For the components that define CN, there were no differences found in vegetative type, range condition hydrologic condition, geologic type, or hydrologic soil groups.

From the model studies described briefly above, and as shown in table 3, there were - surprisingly - no apparent differences between the two groups in the mean number of filled days per year, or in the fraction of the runoff

Table 2. Pond and watershed results.

	Volume (m^3)	Depth (m)	DA (ha)	CN (-)
Nonfunctioning				
Minimum	925	2.44	23.0	33.0
Mean	3439	3.08	66.3	66.3
St Dev	2081	0.67	70.2	18.0
Maximum	6316	4.57	238.0	79.0
Functioning				
Minimum	2171	1.83	3.0	37.0
Mean	9592	3.77	101.5	66.9
Std Dev	11820	1.42	134.0	15.3
Maximum	43492	7.32	496.0	86.0
Differences				
Mean	6154	0.87	35.1	-0.1
Pooled S	8918	1.15	114.7	16.1
"t"	0.69	0.59	0.31	-0.01
Pr(t)	75	72	62	0

Notes: Pr(t) = probability of a lesser t statistic, in percent. CN is dimensionless.

Table 3. Hydrologic simulation results.

	Capacity Fraction (%)	Dry Days (#/yr)	Capacity Days (#/yr)
Nonfunctioning			
Minimum	1.3	0	0
Mean	19.1	47.4	16.2
St Dev	70.7	82.1	10.1
Maximum	100.0	236.0	29.0
Functioning			
Minimum	1.5	0	0
Mean	19.6	14.0	16.6
Std Dev	29.8	33.6	9.3
Maximum	100.0	9.3	33.6
Differences			
Mean	0.6	-33.4	0.4
Pooled S	30.7	60.2	9.6
"t"	0.02	-0.56	0.04
Pr(t)	0	71	0

Note: Pr(t) = probability of a lesser t statistic, in percent.

trapped by the ponds (i.e., the capacity fraction). However, the number of dry days was less for the functioning group, again at a modest level (71%) of confidence. It should be noted that many of these are not primary measured variables, but auxiliary measures produced from handbook tables or by modeling with estimated and extrapolated input.

Summary

There were no strong discriminating factors between functioning ponds and nonfunctioning ponds. However, several factors survive if the high rejection levels customarily used are reduced to the vicinity 70%. Such lower levels of assurance are not uncommon in natural resources management.

The watershed factors with little or no relevance were Curve Number, geologic type, hydrologic soil groups, vegetative type, vegetative and hydrologic condition. The site factors of construction soil and pond shape were not important. Similarly, the hydrologic factor of number of filled days was not important. Factors of modest identifiable importance and associated probability levels were pond capacity (75%), pond maximum depth (72%), drainage area (62%), and number of dry days (71%).

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A Regional Plan to Protect Open Spaces, Water Quality, and Fish and Wildlife Habitat

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Abstract.—In 1978, voters in the Multnomah, Washington, and Clackamas counties approved the creation of the first elected regional government, Metro to oversee land use planning and manage the urban growth boundary, and be consistent with state land use goals. Metro has authority under the charter and state law to require cities and counties to amend their comprehensive plans and implementing ordinances by requiring compliance with Metro's adopted functional plans that deal with among other issues such as water quality and fish and wildlife habitat.

Metro the directly elected government, has used various regulatory and non regulatory strategies to protect green spaces. They have included acquisition, easements and overlay zones. In 1992, Metro council approved the **Green Spaces Master Plan** that details the vision, goals and organizational framework of a regional system of natural areas, open space, trails and greenways for people and wildlife. In 1995, Metro voters approved a bond measure that resulted in $135.6 million dollars to buy green spaces. Currently, Metro owns over 4,800 acres of green spaces that will be protected in eternity to protect habitat for fish and wildlife. In 1997, Metro Council approved the Title 3, **Streams and Floodplain Protection Plan**. All streams and wetlands inside Metro's jurisdictional boundary will be protected with a buffer ranging from 50 to 200 feet. The width of the buffer is dependent upon the size of area drained. In addition, Metro requires that development in the floodplain use balanced cut and fill for all development activities in the floodplain. The 24 cities and 3 counties have until Dec 1999 to comply with Metro's Stream and Floodplain Protection Plan.

Currently, Metro is in the process of inventorying parks, green spaces, fish and wildlife habitat, riparian corridors and wildlife corridors, in public or private ownership, through satellite and aerial photographs. Metro is also developing additional regulations and incentives to protect fish and wildlife habitat identified through the inventory in order to satisfy the state land use and the Green spaces Master Plan goals. Through this process, Metro hopes to fulfill the vision of the **Green Spaces Master Plan** and successfully accomplish state land use goals to build a regional system of natural areas, open spaces, parks, trails and wildlife corridors for wildlife, fish, and people.

Sustaining Flows of Critical Resources: One Example

Jim Renthal, Bureau of Land Management, and Rick Koehler, Cochise County, AZ

Abstract.—As growth of communities throughout the west accelerates into the 21st century, resources that were once unseen and unused, except, perhaps, by ranchers, are in increasing demand. This trend is particularly apparent on the Public Land. The Bureau of Land Management (BLM) is responsible for sustaining the availability, the flow, of many natural resources from substantive forest products, leasable minerals, and livestock forage to the less tangible resources of aesthetics, solitude, and recreational experiences. Resolving conflicts among the diverse and numerous users of Public Land has become one of BLM's primary responsibilities. The Upper San Pedro River Basin in southeast, Arizona, is an area where the conflicts have been persistent. In many ways sustaining the flow of resources in the Upper San Pedro Basin, including the flow of the river itself, is a metaphor for resource management in a settings of increasing consumptive use by growing communities.

In the reach managed by BLM the Upper San Pedro River is one of the few remaining free-flowing, perennial streams in the Southwest. It provides critical bird habitat; it is the home or potential home of several threatened or endangered species; it is a magnet for research; it is a treasure for the citizens of the nation and the local community. However, its flow depends on the groundwater, which is being pumped by nearby homeowners, irrigators, municipalities, and an Army fort faster than it is being recharged. The dilemma is clear to the City of Sierra Vista, the army, Cochise County, and BLM: if the river is to retain its present character, future pumping and water use must be limited, groundwater recharge must be increased, or new sources of water must be developed.

Currently, work is underway to preserve the river by identifying and quantifying the factors that affect the surface flow and the groundwater aquifer. This work is being organized and funded by a diverse and committed partnership. The Upper San Pedro Partnership is a group of federal, state, local governments working together with private entities to establish a water resources plan. A broad range of possible solutions to the dilemma of sustainability of resources for both consumption and preservation is being tested and analyzed. This poster displays the issues in the Upper San Pedro debate, provides an overview of the area and the proposed array of projects being considered. The first projects are focusing on quantification of current uses, and effluent and storm water recharge. Although the work of the partnership has just begun, the poster will support the central proposition that sustainable flow of critical resources requires sustainable relationships among resource managers, users and their communities.

Coastal Management at Ojo De Liebre, Baja California Sur

Federico Salinas-Zavala[1], Alfredo Ortega-Rubio[1], Diego Valdéz-Zamudio[1], and Aradit Castellanos-Vera[1]

Abstract.— We analyzed the biotic, abiotic, and human components interacting at the coastal zone of the Ojo de Liebre Lagoon, Baja California Sur, Mexico. Using geographic information systems, satellite images, and the main biological, physical, and socioeconomic components, we developed an environmental characterization of the zone. According with the natural features of the zone, including the watershed characteristics, the ecological resources potential, and the soil aptitude, we propose the optimal activities to be developed in each unity. A map of land use containing all the identified unites and the activities proposed to be developed is presented. According to our results, biodiversity conservation and productive activities in this coastal zone are totally compatible.

Introduction

The environmental characterization of a zone is a required steep in order to attain it's sustainable development (López 1996; Zarate Lomelí et al. 1995). In Mexico, the environmental legislation recognize the importance for the proper development and conservation of the environmental characterization (INE 1996). The main goal of such characterization is to obtain an accurate separation and classification of the different ecological units and to establish their proper uses (Cendrero 1989)

In this work, we develop the environmental characterization of the coastal zone of Ojo de Liebre Lagoon.

Material and Methods

This work was developed at the coastal zone of Ojo de Liebre Lagoon, located at the Baja California Peninsula (27º 40', 28º 00' NL and 113º 40', 114º 20' WL; fig. 1). Using aerial photographs scale 1:70,000 and a satellite image Landsat MSS, we proceed to determine the main terrestrial characteristics of the zone, such as soil map, hydrology map, geomorphology map, land use map and vegetation map. All these maps were digitized in DXF format (Auto CAD) and converted to PC-Arc/INFO. All the maps were consecutively overlapped, following the order provided in the figure 2, in order to determine the similar landscape units.

After we determined the landscape units, we developed five stays of field work, each one of fifteen in order to confirm our findings. Posteriori, we determined the use capacity of each similar landscape units, following the traditional methods (Cendrero 1989), and based mainly in our knowledge of the zone and our experience of 20 years living in the region.

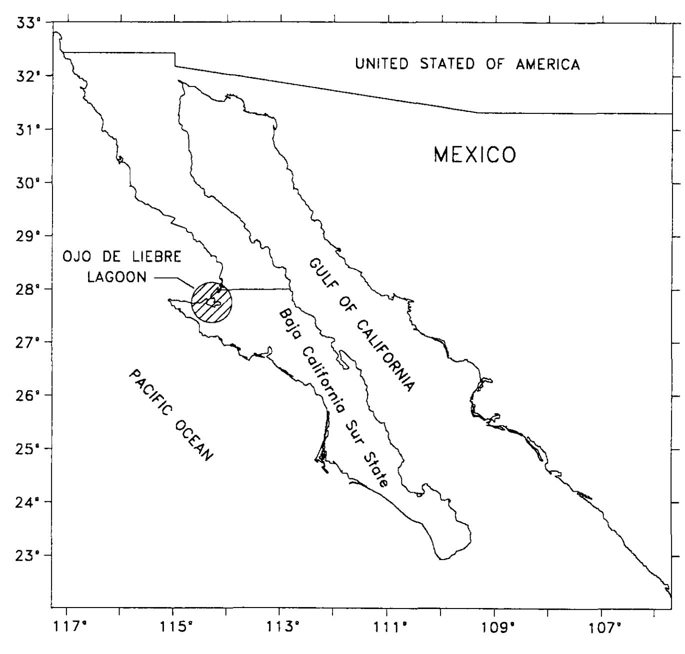

Figure 1. The coastal zone of Ojo de Liebre Lagoon, located at the Baja California Peninsula.

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Results and Discussion

In figure 3, it is possible to observe the main distinguished environmental units. Despite the first characterization distinguished 125 environmental units, we decided to reduce this number to a more manageable, grouping very similar units. In this way we can establish the main suggested uses for the studied region (fig. 3)

1. Salt production
2. Commercial fishery
3. Ecotourism

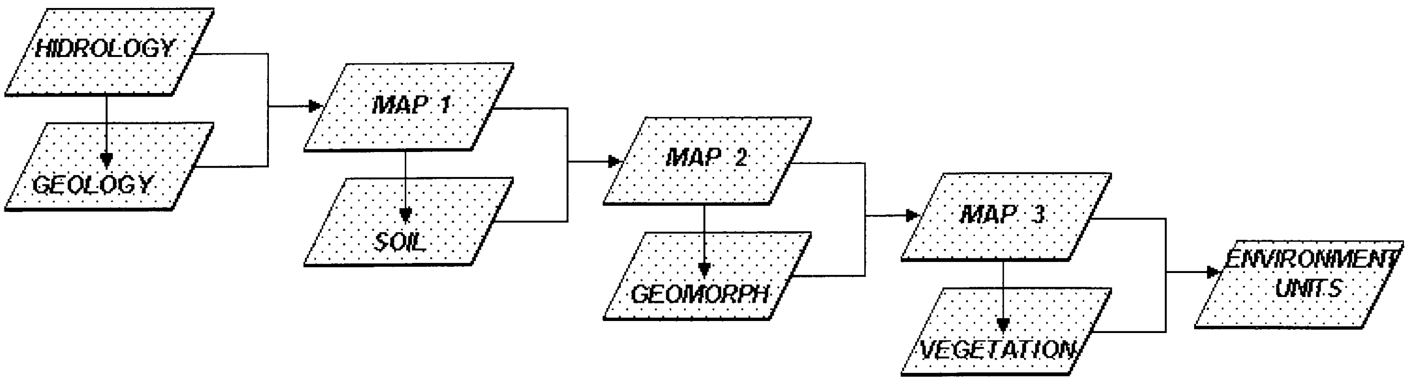

Figure 2. All maps were consecutively overlapped, following the order in this figure, to determine similar landscape units.

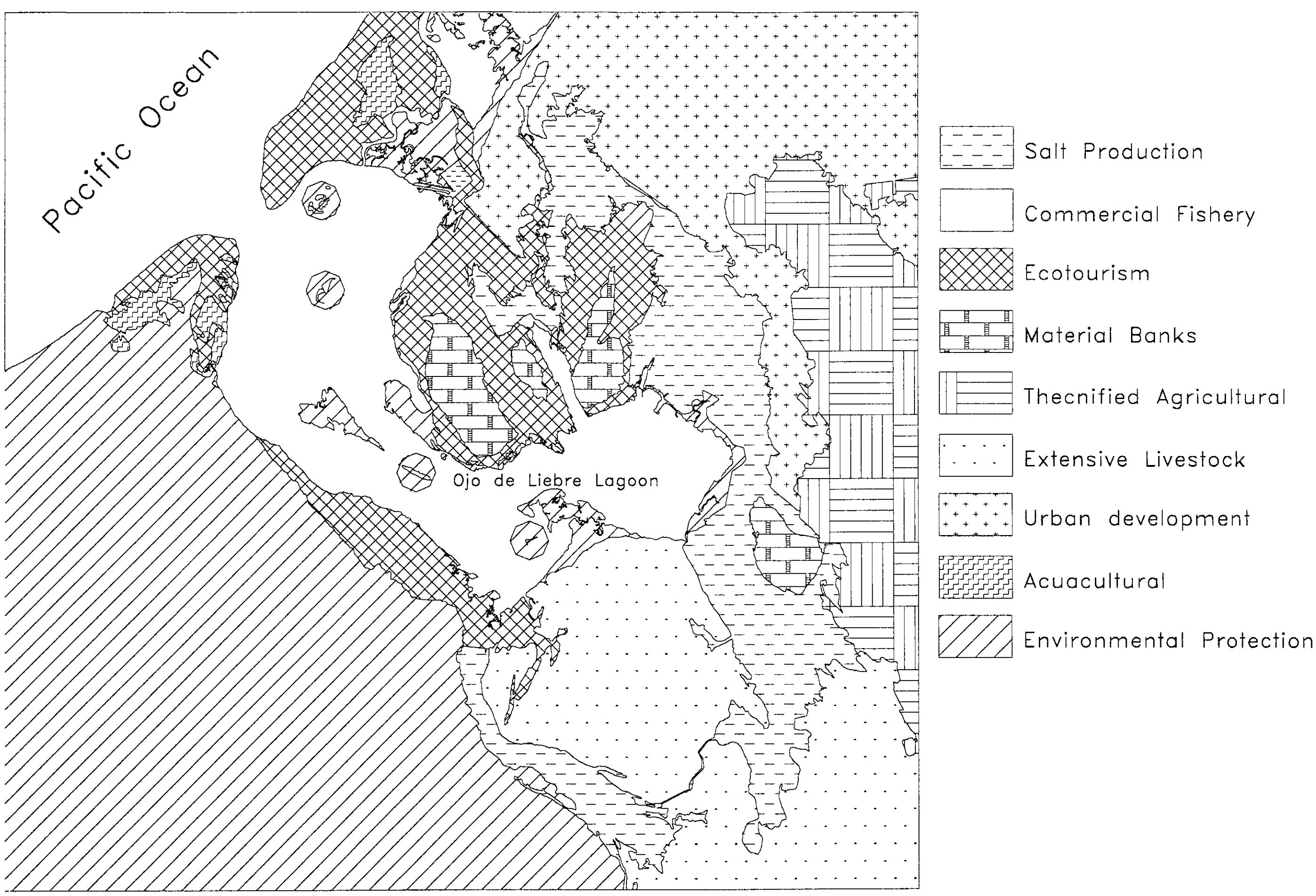

Figure 3. The primary distinguished environmental units.

4. Material banks
5. Thecnified agricultural
6. Extensive livestock
7. Urban development
8. Aquacultural
9. Environmental protection areas

The recommended uses for each zone are the result the objective analysis of the main physical, biological and socioeconomic components of this coastal zone. We are sure that, following the recommended activities suggested in this work, it will be feasible to attain the sustainable development of this key region

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Mining Activities and Arsenic in a Baja California Sur Watershed

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Abstract.— Mining is one of the most important sources of income for the Baja California Sur state. This state is the second most important area for mineral (gold, silver, copper) and non-mineral (salt) mining activities in the Mexican Republic. In the San Antonio-El Triunfo region, mineral-mining activities flourished during the 19th century. Tons of debris containing a high quantity of arsenic were deposited on the soil as a by-product of these activities. In 1998, local inhabitants reported their suspicion of the contamination of the region's wells. For this reason, we developed this study, which establishes the sampling of underground water in the region. Our results indicate that all the underground water sampled in the region's wells exceeded official safe limits (0.05 mg/l).

Introduction

Under normal conditions, most potentially toxic metals are fixed in geological formations. However, human activities such as mining can change this condition. Mining activities can result in the accumulation of toxic metals in large quantities and in soluble forms. This kind of pollution usually reaches higher trophic levels through bioaccumulation. If this pollution reaches human populations, it can cause health disorders and diseases (Jímenez 1994). We studied the arsenic concentration in the wells of two Baja California Sur towns located in a mining district.

Materials and Methods

A field study was developed in the mining district of San Antonio-El Triunfo, located in the southern part of the Baja California Sur State (23°48' to 23°49', NL; 110°06' to 110°03', WL) (figure 1). We sampled all the wells that provide water to the towns of San Antonio and El Triunfo from June to August 1997. For each well we sampled, we recorded its position using a GPS (Mark X), and it's altitude above sea level. All sampling equipment was submerged for 24 hours in nitric acid to avoid any possible contamination. Wells were sampled using a Vandor bottle and a plastic cord. Each sample was then transferred to plastic containers. Well-water parameters recorded were pH and temperature. Water samples were filtered by a pump (Vac Model) and 47 mm filters in the laboratory. Samples were then fixed with pH 2, nitric acid, and arsenic, and were quantified using the standard proceedure (Chapman and Parket 1991). Arsenic quantities were compared by ANOVA followed by the Tukey-Kramer test (Sokal and Rohlf, 1969) to find statical differences among the samples.

Results and Discussion

Table 1 shows the results of the arsenic concentrations found in the samples analyzed. All the samples contained arsenic levels above the safety limits established by the World Health Organization. However, arsenic in the wells of San Antonio were statistically higher than those of El Triunfo ($F_{(2,24)} = 17.51$; $p < 0.001$). Our results indicated that there are significantly high amounts of arsenic in the groundwater tested, which is used by the inhabitants of both towns. For this reason, we propose to prohibit the use of these wells and study the effects they have had on the health of the inhabitants of the region.

Acknowledgments

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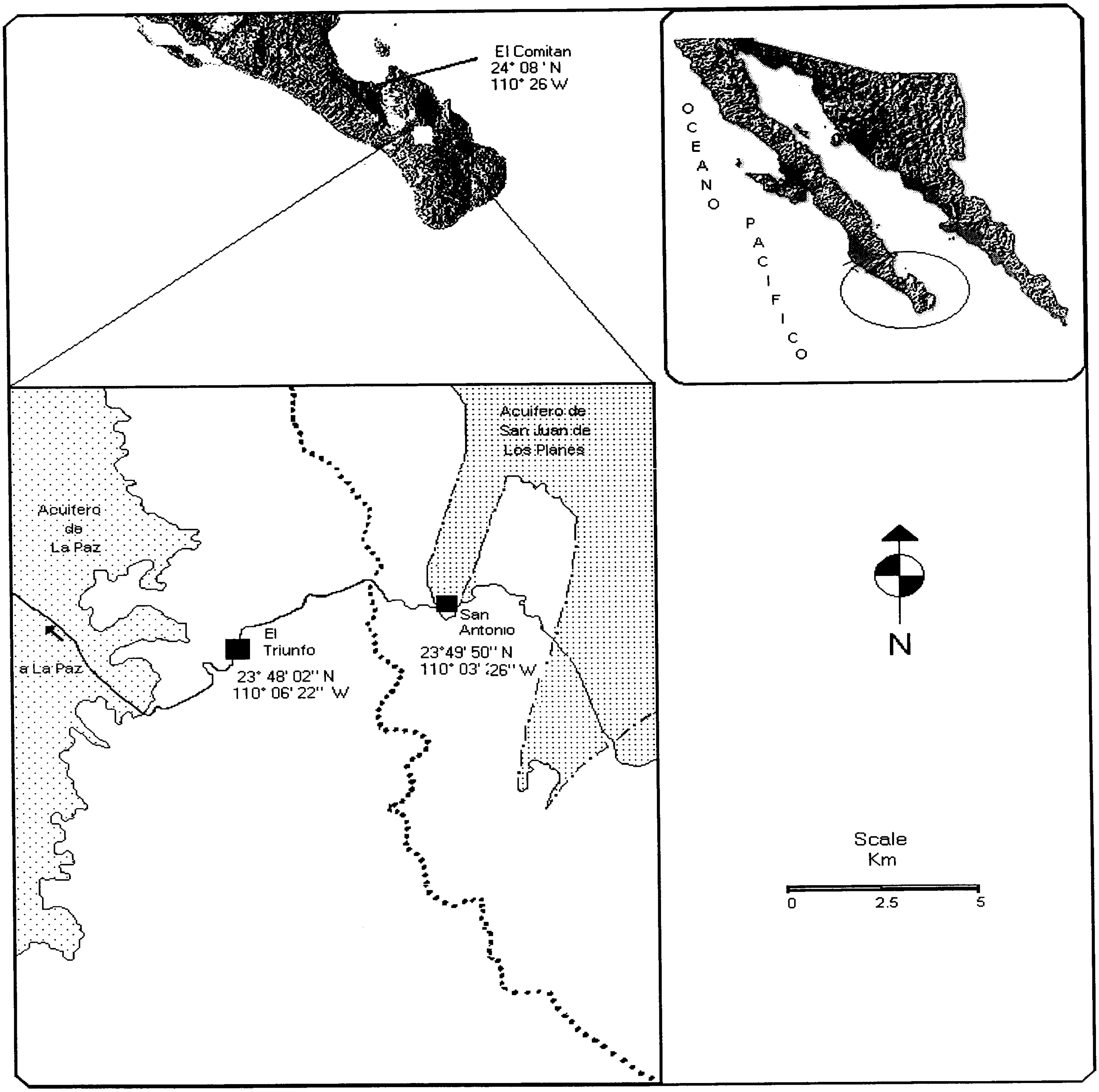

Figure 1. Mining district of San Antonio-El Triunfo, located in the southern part of the Baja California Sur state.

Table 1. Arsenic concentrations found in the underground water sampled.

Samples	Location	Well	Ubication	Conc. As (Mg/l)
		San Antonio		
1 a la 3	Los San Juanes	1	23°47'47 N 110°03'20 W	0.0871
4 a la 6	1 Km North Planta Los San Juanes	2	23°47'14 N 110°03'20 W	0.0903
7 a la 9	1.9 Km North Los San Juanes	3	23°47'11 N 110°03"27W	0.1904
10 a la 12	1.95 Km North of Los SanJuanes	4	23°47'11N 110°03'20W	0.1754
13 a la 15	2.85 Km North of Los San Juanes	5	23°48'50 N 110°03'10W	0.1676
16 a la 18	2.95 Km North of Los San Juanes	6	23°48'51 N 110°03'10W	0.2440
		El Triunfo		
19 a la 21	900m SE under stream Los Encinos	7	23°48'02 N 110°06'22 W	0.0942
22 a la 24	850 m SE under stream Los Encinos	8	23°48'03 N 110°06"22W	0.0430
		El Comitan		
25 a la 27	COM	9	24°08'10 N 110°26'30 W	**

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Application of Time Series Analysis for Assessing Reservoir Trophic Status

Paris Honglay Chen[1] and Ka-Chu Leung[2]

Abstract.—This study is to develop and apply a practical procedure for the time series analysis of reservoir eutrophication conditions. A multiplicative decomposition method is used to determine the trophic variations including seasonal, circular, long-term and irregular changes. The results indicate that (1) there is a long high peak for seven months from April to October yearly; (2) the long-term trend (T) increases with time (t) as following relationship: $T = 51.4231 + 0.0605t$; and (3) circular change period decreases from two or three years to about one year. The methodology is feasible to present the eutrophication changes numerically.

Introduction

Te-Chi is one of the main reservoirs in Taiwan. However, since 1981 its water quality has distinctly deteriorated due to excessive land use, improper felling of trees, soil washed out, as well as impact of pesticides and fertilizers, etc. Meanwhile, the concentrations of total phosphorus obviously exceeded the reservoir and lake's eutrophic limits of the U.S. Environmental Protection Agency (EPA) 0.020 mg/L. Therefore, a lot of investigators surveyed the water quality of Te-Chi reservoir from 1983 up to now. However, how does the data exhibit that the trophic status is improved, increased, or the same? Consequently, the objective of this study is to develop and apply a practical procedure for the time series analysis of reservoir eutrophication conditions using the data collected over a period more than ten years (R.O.C. Committee of Water Resources 1993; R.O.C. Tai Power et al. 1988-1992; R.O.C. Te-Chi Reservoir Watershed Management Committee et al. 1993-1996).

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Methods

For the numerical model of the eutrophication, Carlson (1977) developed a Trophic Status Index (TSI) including three expressions of total phosphorus (TP), chlorophyl a, and transparency to evaluate the trophic status of water. Because the data of TP was more complete than the others in the past investigations (R.O.C. Committee of Water Resources 1993; R.O.C. Tai Power et al. 1988-1992; R.O.C. Te-Chi Reservoir Watershed Management Committee et al. 1993-1996), we used a multiplicative decomposition (MD) method as well as TSI (Trophic Status Index) for TP, TSI (TP), to analyze time series on the trophic status in Te-Chi reservoir. In general, TSI (TP) can be written as (ROCEPA 1991):

$$[S](TP) = 10\left[\frac{3.70 - 0.98\mathrm{In}[TP]}{\mathrm{In}2}\right] \tag{1}$$

where

(TP) = concentration of total phosphorus, mg/m^3.

A time series is an ordered sequence of observations. The ordering is usually through time, particularly in terms of some equally spaced time intervals. A typical MD time series is constructed by the following four components (Chen et al. 1997):

1. Long-term trend: To describe a long-term growth or failing. This is the fundamental trend of long-term fluctuations including direction and strength.
2. Seasonal change: To describe a regular variation for specific time period that is usually equal to one year.
3. Circular change: To describe the periodic fluctuations over one year. The magnitude of the time period is irregular.
4. Irregular change: To describe a random or unexpected variation that is also a accidental fluctuation.

Theoretically, time series model is assumed to contain only the above four components. Additionally, we also assume that their net effect for observations is their product. If T = long-term trend, S = seasonal change, C = circular change, and I = irregular change, we can write the time series of Y as:

$$Y = T' \ S' \ C' \ I \tag{2}$$

Equation (2) is usually called the multiplicative model, which is particularly useful to decomposing the time series. The units of T and Y are all the same to observations, and S, C, and I are often unit less decimals (Chen et al. 1997).

Results and Discussion

Moving Average Calculation of 12 Months

The time series constructed by TSI (TP) of Te-Chi reservoir give a seasonal period of 12 months. In order to eliminate this seasonal variation, it is essential to seek the moving average (MA) of 12 months. Next, we use the centrical technology to obtain the MA of 2 months from each pair of neighboring MA, which is to identify the same time between MA and TSI (TP). After operation, the time series have not contained both factors of seasonal and irregular variation, i.e., the centralized MA represents a combination of long-term trend and circular change (T×C). Additionally, because of Y = T × C × S × I, the combination of seasonal and irregular change (S × I) is also estimated by Y/(T × C) (Chen et al. 1997). In this study, Y equals TSI (TP) of Te-Chi reservoir, and a plot of the TSI (TP) vs. time is shown in figure 1.

Seasonal Index Estimation

The values of S×I can be used to obtain seasonal variation (S) of the time series. S×I values are arranged in rows from month to month shown in table 1. The table indicates that the fluctuant trend is more regular. The means of S×I in each row (or the same month) can eliminate most of irregular change. Thus, the 12 means are useful to represent the seasonal variation indexes (S_m) of 12 months. Then, S_m is corrected to the seasonal adjustment index (S_c), and the relationship between S_m and S_c (Chen et al. 1997) is:

$$S_c S_m \left[12 / \sum_{f=1}^{12} S_m \right], t = 1,2,\ldots,12 \tag{3}$$

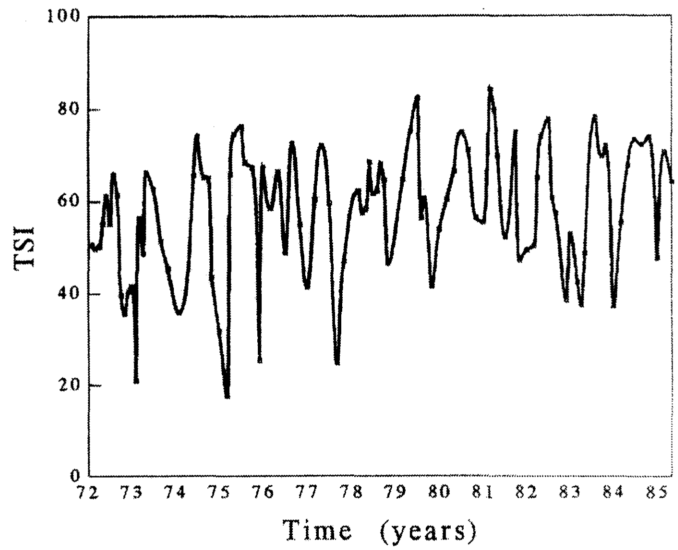

Figure 1. Variation of TSI (TP) with time.

Variation of S_c with time presented in figure 2 indicated that the peak months of the eutrophic status in Te-Chi reservoir continued for approximately 7 months from April to October.

Estimation of Seasonal Adjustment Index and Long-term Trend

From the seasonal adjustment index (S_c), we can deduce the long-term trend (T). Now, TSI (TP) (= Y) divided by the relative month's S_c is set to d, that is:

$$d = Y/S_c \tag{4}$$

In addition, because the relationship between T and time is linear, we can assume:

$$T = b_0 + b_1 t \tag{5}$$

Again, we use the least squares method to obtain:

$$b_0 = \left[\sum_{f=1}^{161} d/161 \right] - b_1 \left[\sum_{f=1}^{161} t/161 \right] \tag{6}$$

and

$$b_1 = \left[161 \sum_{f=1}^{161} td - \left(\sum_{f=1}^{161} t \right) \left(\sum_{f=1}^{161} d \right) \right] / \left[161 \sum_{f=1}^{161} t^2 - \left(\sum_{f=1}^{161} t \right)^2 \right] \tag{7}$$

Table 1. The data of seasonal variation (S).

Year / Month	72	73	74	75	76	77	78	79	80	81	82	83	84	S_m	S_c
1		0.85	-	0.57	1.13	0.69	-	-	0.90	0.80	0.81	1.05	0.58	0.82	0.85
2		5	0.65	7	4	9	-	-	2	7	3	2	3	5	4
3		0.43	7	-	-	-	1.07	0.99	-	-	-	-	-	0.54	0.56
4		3	-	0.31	1.02	1.07	3	8	0.99	1.26	0.81	0.84	0.87	5	4
5		1.20	-	6	9	5	0.94	-	8	2	0	5	5	0.95	0.98
6		3	-	1.18	-	-	6	1.17	-	1.19	1.06	0.73	-	3	6
7	1.08	1.04	1.12	6	1.17	1.39	0.95	7	1.06	4	6	4	1.07	1.02	1.06
8	3	5	8	1.31	6	7	4	-	1	1.04	1.20	0.84	2	9	5
9	1.33	1.38	1.31	9	-	-	1.12	1.31	-	4	8	5	-	1.14	1.18
10	3	9	6	-	0.82	1.15	1	1	1.17	-	-	-	1.14	9	9
11	1.27	-	-	1.37	5	0	1.00	0.91	1	0.79	1.31	-	2	1.12	1.16
12	1	1.26	1.19	2	-	-	9	0	-	4	0	1.41	-	5	4
	0.81	0	0	1.18	1.26	0.46	1.01	0.98	1.07	-	1.01	9	1.09	1.14	1.18
	6	-	1.23	3	7	9	9	0	6	-	9	-	0	5	5
	0.72	0.98	5	-	-	-	1.11	-	-	1.25	0.97	1.19	-	1.14	1.18
	5	9	0.79	1.07	0.94	0.89	3	0.68	0.80	8	1	0	1.09	7	7
	0.82	-	5	3	9	1	1.04	3	6	0.80	-	1.16	9	1.04	1.07
	6	0.89	-	-	-	-	8	-	-	4	-	5		2	9
		8		0.41			0.74			-	0.74	-		1.10	1.14
		-		4			0				2			3	2
							-							0.86	0.90
														9	0
														0.66	0.68
														1	4

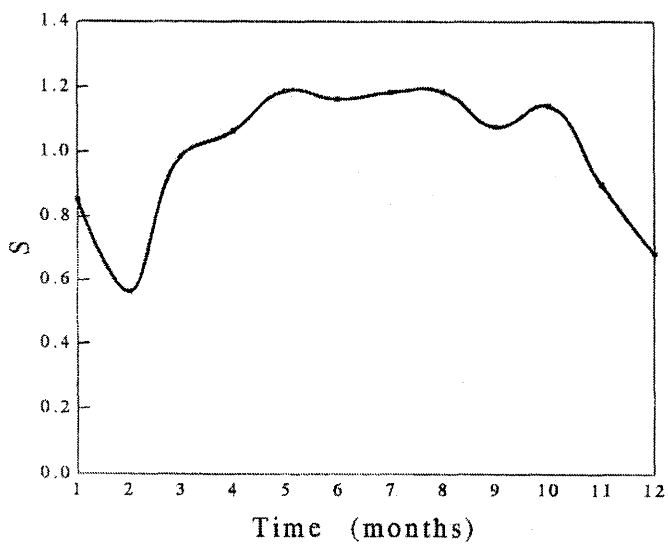

Figure 2. Seasonal variation (S) of eutrophication.

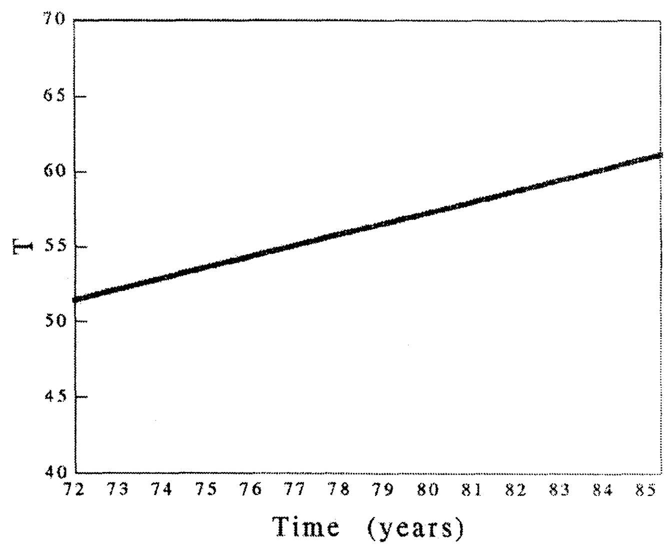

Figure 3. Long-term trend (T) of eutrophication.

In this study, the linear regression model of T is:

$$T = 51.4231 + 0.0605\,t, \quad t = 1, 2, 3, .., 161 \qquad (8)$$

More clearly, figure 3 exhibited that the long-term trend (T) of the eutrophic status in Te- Chi reservoir increased slowly with increasing time.

Circular and Irregular Change Analysis

By substituting the values of TSI (TP) (= Y), S (= S_c), and T on both sides of $Y = T \times C \times S \times I$, we can get a combination of circular and irregular change, i.e., $C \times I$ (Chen et al. 1997).

Next, because the irregular component (I) doesn't generally extend more than 3 months, we adopted the moving average (MA) of 9 months to eliminate the effect of I, and to estimate the effective C values of circular fluctuation. Again, the I values are also given by calculating $(C \times I)/C$ (Chen et al. 1997). Figures 4 and 5 presented the variation of C and I with increasing time, respectively.

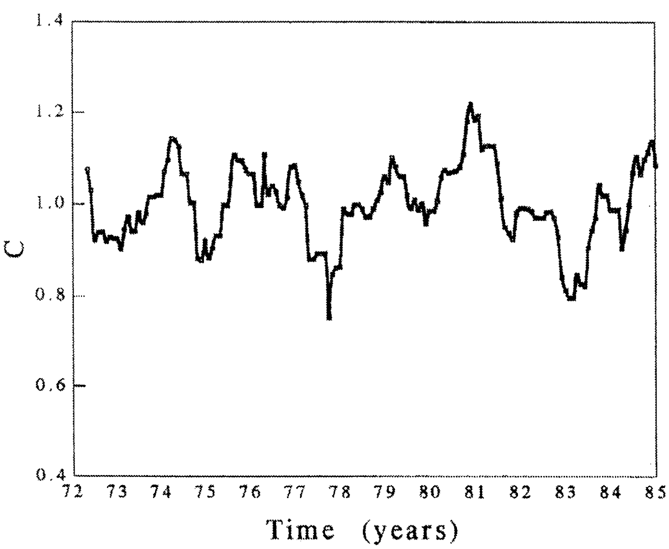

Figure 4. Circular variation (C) of eutrophication.

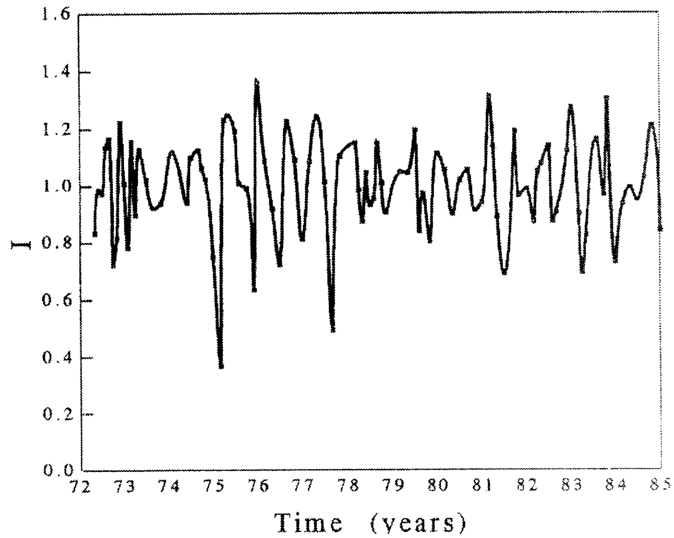

Figure 5. Irregular variation (I) of eutrophication.

Conclusions

The results of the time series analysis indicated that the eutrophic status deteriorates continuously for the water quality of Te-Chi reservoir. Therefore, collection and treatment of agricultural wastewater, setting of effluent standards, no discharge of effluent into reservoirs, and severe execution are all necessary. Simultaneously, setting of the protective zone at the upstream from reservoirs, and reduction of land use in the watershed of reservoirs also shall be done well. Additionally, excellent soil and water conservation practices can extend the service time of reservoirs, improve water quality, and reduce health and safety risks for downstream people.

Acknowledgments

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Application of Remotely Piloted Vehicle (RPV) in Monitoring and Detecting Watershed Land-Use Change and Problem Areas

Long-Ming Huang[1]

Abstract.— Improper cultivation of steep mountainous areas in Taiwan contributes to serious erosion and landslides. Regular patrol, detection, and administration of these problem areas has been an extremely difficult due to the steep and dangerous terrain of many of the forested watersheds in Taiwan. A remotely piloted vehicle (RPV) has been developed for various civil and military applications. This paper reports the results of a preliminary application of RPV in monitoring and detecting land-use changes and problem areas in inaccessible watershed areas. Preliminary results indicated that RPV, with its small size, low price, easy operation, and high mobility, should be a safe, economic, quick, and efficient way of obtainging information in problem areas for identification and watershed management planning and administration.

Introduction

Taiwan is a mountainous island with a limited amount of plains. Slope lands are in demand for various agricultural and non-agricultural uses. Activities on these lands often increase erosion, landslides, debris flows, and other disasters to stream and reservoir sedimentation, which poses significant threat to life and property.

For disaster mitigation, illegal and improper over-farming on hill slopes must be effectively regulated and controlled. Therefore, monitoring the condition of the watersheds affected is a priority. However, regular patrol, detection, and administration of these problem areas has been difficult due to the steep and dangerous terrain of many forested watersheds in Taiwan. Aerial photographs or satellites images are often used to gather the necessary information.

Precise interpretation using satellite images in areas with small variations is impossible due to insufficient image resolution. Therefore, it is important to develop new surveying and monitoring technologies to efficiently monitor field conditions and to improve watershed management. This would promote the effectiveness and dependability of disaster information and mitigate losses from disasters.

The Unmanned Aerial Vehicle (UAV) has numerous application possibilities. Besides military purposes, UAV can be used for field reconnaissance for urban development and construction projects, monitoring for environmental protection, highway detecting and searching, forest and hillside disaster prevention, coastal survey and control, pre-disaster monitoring and post disaster surveying. Because of its light weight, small size, high mobility, safety, easy maintenance, and low cost, UAV has been extensively used. Moreover, since there are no concerns about possible personnel casualty, UAV is capable of performing various weather missions in potentially dangerous locations. UAV's payload compartment can be designed for installing instruments of different weights and sizes and for surveying and monitoring applications in different fields. In comparison with traditional flying vehicles, UAV is economical, safe, mobile, and has extensive applications.

The purpose of this study was to use a color camera with charge coupled device (CCD) fitted on a vertical take-off/landing rotary-wing aircraft and horizontal take-off/landing fixed-wing aircraft for taking dynamic images. These images were instantly transmitted by coupling with radio transmission equipment (receiver/transmitter). Image processing and analysis was performed on the feed back data to acquire the relevant information. Sky remote surveying and instantaneous monitoring provides the necessary information to establish a policy for effective disaster warning, with adequate timing to reduce associated losses.

Principles

Charge Coupled Device (CCD) and Image Pick-up Principles

Images can be classified into 2 categories, analog image data and digital image data. All image data stored on a computer are digital, while the original formats for all the

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available image data are analog. Therefore, it is necessary to transform the analog image data to digital image data through interface processing (figure 1).

The CCD is a state-of-the-art technology that uses a solid-state image element on the camera to produce images with different resolutions. Since only digital image data can be processed by a computer, these data are in discrete format (i.e., the images are composed of single frame images of specific time difference); therefore, image frames can be selected individually during post processing. The video signal specifications currently used in Taiwan have standard NTSC (National Television System Committee) specifications, so NTSC video signal was adopted as the input format. The relationship among various NTSC signal frequencies are:

Frame frequency $f_R = 29.97$ Hz

Scanning line frequency $f_L = 15.734$ KHz $= 525\ f_R$

Color sub-carrier frequency $f_{SC} = 3579.545$ KHz $= 227.5\ f_L$

CCD images are input to the computer in standard NTSC video signals through a dynamic image capture card. The RGB color signals are not synthesized into a combined video signal, so a specific color system frequency zone can be intensified by using the image processing technique. While the images played can be recorded in standard AVI image play format using a dynamic image card, apart from CCD image resolution, the image capture card will also affect the pick-up speed and resolution. The image capture can be classified into static capture and dynamic capture. Each type of capture separates the video signals input from CCD into frames of images through the image capture card, which are then picked up and stored. Since memory capacity consumed by dynamic capture is large, image resolution is lower than that of static capture.

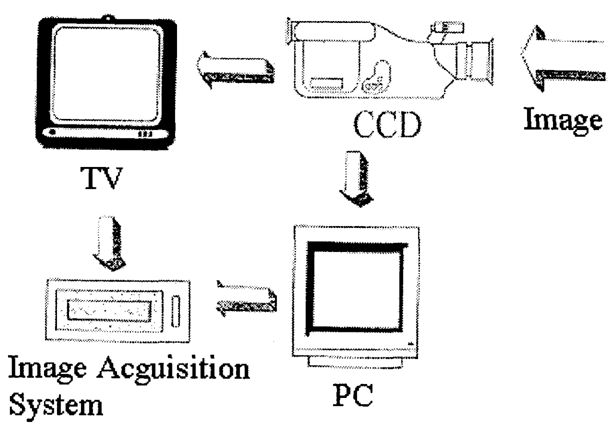

Figure 1. Flow chart for acquisition and storage images by the charge coupled device (CCD).

Equipment

Color CCD Camera

CD-5 color CCD camera with a 1/3" picture tube, resolution up to 410,000 pixels, power 5 VDC, weight 135g, transmission channels VHF 4ch to12ch, luminous intensity 5 lux min.

FT-900 Type Microwave Image Transmitter

FT-900 type transmitter, using a transmitting frequency of 1.2 GHz, transmits signals using a frequency modulation with transmission power between 0.5 W and 2.0 W, power applied 12 VDC to 13.8 VDC, weight 580 g, bandwidth for transmitting images 27 MHZ, TV output terminals of NTSC. FT-900 type receiver uses reception frequencies from 1.2 GHz to 1.3 GHz, at a voltage identical to that for the transmitter.

UPG-302 Dynamic Images Capture Card

Under NTSC specifications, 30 pictures of resolution 320 x 240 can be picked up per second; 24-bit full-color static images of resolution 640 x 480 pixels can also be picked up; 3 AVI image compression formats of Indeo 3.2, YUV 4:1:1, YUV 16:1:1 can be supported.

Working Platform for Aerial Photography

After repeated designs, tests, and improvements, a working platform for aerial photography with satisfactory balance was produced. This platform was made of aluminum alloy, carbon fiber compound material and was built with small hydraulic shock absorbers. FT-900 type microwave image transmitter and server, etc. were all fitted on the working platform. High-quality aerial images were obtained because of the shock absorbing systems installed on all XYZ axes.

Remotely Piloted Vehicle RPV

A remotely piloted fixed-wing aircraft and a helicopter were designed and built for this study to take aerial photographs in watersheds. The data were compared and evaluated for their applicability.

The specifications and functions were:

1. Horizontal Propeller Type RPV (fixed-wing aircraft) (figure 2 and photo 1)

   Body length 2.35 m, breadth 3.12 m, height 0.7 m, total weight 8 kgs, maximum payload 6 kgs, fuel tank capacity 1,000 cc, engine capacity 20 cc, maximum cruising time 50 minutes, operation radius 2,000 m, runway length for taking off 20m to 25 m, for landing 25 m to 40 m, maximum flying altitude 1,500 m above ground.

2. Vertical Rotary-Wing RPV (non-fixed-wing aircraft, i.e., helicopter)

   Body length 1.32 m, breadth 0.185 m, height 0.47 m, total weight 5 kgs, main rotary wing length 1.54 m, maximum payload 4 kgs, fuel tank 500 cc, engine capacity 9.8 cc, maximum cruising time 15 minutes, operation radius 800 m, take off/landing space 3 square m, maximum flying altitude 500 m above ground.

Methods

Before using RPV as the study vehicle, it was important to ensure that the total payload weight was smaller than the maximum payload of RPV. Electronic interference should be avoided and inside payload space of RPV should be considered.

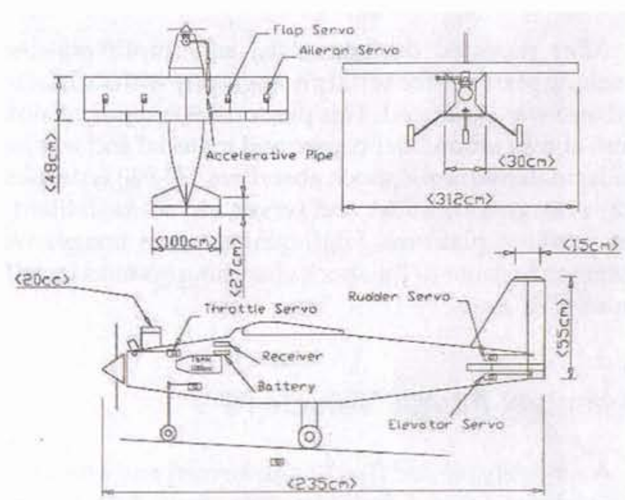

Figure 2. Three views of the remotely piloted fixed-wing aircraft.

Photo 1. Appearance and physical condition of the remotely piloted fixed-wing aircraft.

Set-up of Instantaneous Monitoring System

The instantaneous monitoring system was divided into RPV payload and ground reception station. RPV-carried CCD image signals were transmitted back to the ground through the transmitter. They were then received and decoded via reversed procedure and further monitored and recorded through a computer monitoring system.

Ground Simulation

An automobile was used as the substitute vehicle for RPV because of its high safety record. The integrity of the system and the loss rate of the data transmitted were tested in advance.

Procedures

1. Establish a mobile station: Install the CCD outside of a car with the lens facing the car's right side, feed the CCD images into the FT-900 type microwave image transmitter via a video signal cable, fit the antenna on top of the car, regularly check the transmitting condition.
2. Erect a ground station: Enter the image signals received from the FT-900 type microwave image receiver into a computer for monitoring through the instantaneous monitoring system.
3. When RPV moves, the main station receives and saves the data synchronously.

Photo 2. Payload flying test for the remotely piloted fixed-wing aircraft.

Photo 3. Silting condition of the check dam upstream of Feng Chiu bridge No.1 after repair.

RPV-Bound Experiment

As required by RPV experiment, a large, open area was used as the flying site. Photo 2 is a remotely piloted fixed-wing aircraft used to perform real-time image transmission and take-off, landing, and flying tests. The experiment procedure follows.

1. Establish a mobile station: Install the CCD under RPV with lens facing downward, feed the CCD images into the FT-900 type microwave image transmitter through a video signal cable, fit the antenna beneath RPV, regularly check the transmitting condition.
2. Erect a ground station: Enter the image signals received from the FT-900 type microwave image receiver into a computer for monitoring through the instantaneous monitoring system.
3. When RPV moves, the main station receives and saves the data synchronously.

Photo 4. Stream regulation and drainage ditch condition after repair downstream of Feng Chiu bridge No. 1.

Test Site Condition

The on-site aerial photographing location for this project was in the Feng Chiu area of Nan Tou County in central Taiwan. The watershed is 174 ha with an average grade of 6%, which occupies about 75% of the watershed. The slopes run mainly west and southwest. A majority of the collapses and erosion ditches in this area are approximately 1.6 km long and are concentrated in the forestland around the ridgeline. Because of the steep gradient, heavy rains generate surface run-offs. Any landslide has a high possibility of causing large debris flows. The devastating earth and sand disasters and loss of dwellings and lives caused by Typhoon Hope was the result of a large debris flow.

Mud and gravel flow disasters triggered during Typhoon Wayne in 1986, initiated construction of a gravity-type sand dam at the erosion ditch outlet near the upstream side to block or retard the flow. During Typhoon Herb in 1996, the main body of the dam remained intact, however, the dam wing on the left was damaged and the flow rectification work and drainage ditches downstream were either damaged or buried due to inadequate cross-sections or insufficient gradients. All damage has been fully repaired as shown in photos 3 and 4.

Results and Discussion

Ground Monitoring System

The ground software monitoring program can perform real-time display of the down-transmitted image pictures taken by RPV-bound CCD camera. The image pictures are then monitored and recorded using the computer monitoring system.

The CCD camera and the transmitter are fitted on the working platform for aerial photography. The cloud platform is installed in a capsule under the fuselage to prevent blurred CCD images from engine shocking. Since the real-time images taken are down-transmitted to the ground monitoring station by a FT-900 microwave image transmitter, the transmitted video and audio signals are subject to noise interference that would produce lines on the images. Interference can be minimized using a boosted-signal and a segregated-signal reception port.

Photos 5 through 9 are real-time CCD aerial pictures taken at different locations over Feng Chiu village in Nan Tou, Taiwan, when this system was being used for monitoring.

On-Site Aerial Image Evaluation

Evaluation of the on-site serial images (photos 5 and 6) reveals that the mud and gravel flows at this site were caused by extensive amounts of earth and rock collapses adjacent to the ridge line. Because this site experienced early stage collapses, the land was stratified and broken sandstone covered it in the form of a thick layer of earth and gravel. The topography is U shaped, with 3 sides surrounded by mountains and one side remaining open. The ground surface water and seepage water from the mountain top and the boundary merge at this site. During heavy rains, the broken sandstone pours down as a mud and gravel flow then bursts free. Because the river valley is quite steep and the earth mass was huge, a large area downstream was affected.

Earth and gravel deposited at this site came from collapsed earth and gravel in the forestland. Large particles rolled down to the erosion ditch triggering mud and gravel flows. The steep hillside upstream and the left bank of the erosion ditch are cover with forest. The areas on the right bank of the erosion ditch are developed. Approximately 40% of the watershed is developed, with 42 ha of farmed area at a gradient greater than 55%. The major crop on the downstream slope of the watershed is betel nuts (photo 7). The lower part of the steep slope land on right bank of the erosion ditch is Feng Chiu village (photo 8). Photo 9 shows new farm land on the left bank slope.

Evaluation of the Applicability of RPV

On-site aerial photographs illustrate that due to the geographical location and the weather of Taiwan, there is a relatively large variation of wind direction and air flow at 100 m to 800 m above ground compared to wind direction and air flow at 800 m to 1,500 m above ground. Because the elevation of the Feng Chiu area is between 600 m and 1,500 m, with unstable air flows at low altitude, a fixed-wing aircraft is more suitable. A non-fixed-wing aircraft (helicopter) is more suitable for special terrain, areas without a runway, or where the objects to be observed

Photo 5. Present condition of debris flow tracks site in Feng Chiu by aerial image (1).

Photo 6. Present condition of debris flow tracks site in Feng Chiu by aerial image (2).

Photo 7. Present condition of debris flow tracks site in Feng Chiu by aerial image (3).

move in irregular curves, etc. If still pictures or data, or low altitude and high-angle surveying is required, then a non-fixed-wing aircraft provides better flexibility.

Conclusions and Suggestions

Conclusions

1. The blurring of CCD images due to engine shocking can be improved through repeated designs and tests for higher quality aerial images.
2. A video-signal system has been successfully integrated and installed on RPV. Several aerial photography tests have been performed, which indicate the feasibility of employing RPV for surveying and monitoring in water collecting zones.
3. Remotely controlled aerial surveying for debris flow tracks in Feng Chiu has been completed with comprehensive video tapes recorded by aerial photographing.
4. Instantaneous transmitting of dynamic image data has been achieved and will serve as valuable reference material for watershed management.
5. Both fixed-wing and non-fixed-wing aircraft can produce aerial image data. However, each of these types of aircraft perform differently depending on flying altitude, airstrip availability, and mission requirements.

Suggestions

1. For conducting the relevant studies, other instruments such as GPS, approach angle indicator, drift angle indicator, fuel gauge, etc., on board RPV should be integrated to learn more about RPV condition. If inertia navigating instruments of gyroscope and accelerometer, etc. are added, then RPV attitude can be obtained. These data can be used as the advance operation for RPV automatic piloting.
2. Air flows in mountainous areas of Taiwan are extremely unstable. On-site flights have proved that fixed-wing aircraft have high applicability for unstable air-flow space at low altitudes if a runway can be provided on site.
3. Application of RPV has become a topic of great interest for studies in various fields. However, control skill and maintenance expertise can not be obtained quickly. Therefore, when these tests and studies are performed in the future, besides careful planning, organizing a cross-field study group is proposed.

Photo 8. Present condition of debris flow tracks site in Feng Chiu by aerial image (4).

Photo 9. Present condition of debris flow tracks site in Feng Chiu by aerial image (5).

Acknowledgments

The authors with to thank Peter F. Ffolliott, University of Arizona, Tucson, Arizona, and Malchus B. Baker, Jr. for their technical reviews of this paper.

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Water and Land Management: Some Examples of USDA International Programs

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Abstract.—Environmental degradation and inefficient use of natural resources pose a growing threat to the interests of the United States, and to the physical, economic, and social well-being of people throughout the world. In his book, *Global Paradox,* John Naisbit states, "We have never learned, or we have forgotten, that the environment is the basis of all life and for all production. Rather than being an interest competing with other interests for attention, it is in reality the playing field on which all interests compete . . . . We have consistently failed to recognized that the economic system is an open system in a closed and finite ecosystem." The International Cooperation and Development area of the Foreign Agricultural Service manages USDA's technical assistance, research, and training programs in collaboration with U.S. land grant universities and the private sector. Examples of technical assistance, research, and training programs in water and land management in Southeast Asia, the Middle East, and Latin America are provided to illustrate the focus and trends in international assistance and the progress being made in these areas as we enter the next millennium.

POSTER PAPERS

Technology Transfer Mechanisms

Application of Remote Sensing and Geographic Information Systems to Ecosystem-Based Urban Natural Resource Management

Xiaohui Zhang[1], George Ball[2], and Eve Halper[3]

Abstract.— This paper presents an integrated system to support urban natural resource mcnagement. With the application of remote sensing (RS) and geographic information systems (GIS), the paper emphasizes the methodology of integrating information technology and a scientific basis to support ecosystem-based management. First, a systematic integration framework is developed and the major functionality of each component is discussed. Next, an integrated urban storm water management system is discussed at an operational scale. Then, an application of RS and GIS with hydrologic modeling to improve storm water management is introduced. The preliminary results have shown that the integrated system has great potential to support urban sustainable development.

Introduction

Many urban areas are growing at a record pace. Urbanization affects all components of the environment, from air quality, water quality (surface water and groundwater) and soil quality to wildlife habitat. Sustainability has become the primary goal of both economic development and natural resource management. Many valuable urban resources have been adversely impacted. Ecosystem management is an attempt to optimally balance economic development and protection of environment.

A growing problem confronting natural resource managers is the management of several interdependent resources, each of which has multiple uses and multiple users with multiple value systems (McCormick 1999). The application of advanced information technology can not only speed up information retrieval and organization, it can also improve our understanding of complex ecosystem dynamics, better assess urban resources and protect / restore natural systems. Thus, remote sensing technology and GIS can directly benefit the assessment of natural resources. The powerful tool of GIS spatial analysis can monitor multiple attributes at different scales from multiple sources, and thus assess ecosystem change. Integration of RS and GIS with a modeling and simulation (MS) system can provide a new environment for risk analysis and decision-making support.

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Integration of RS, GIS and MS with Decision Support System

Peine et al. (1999) summarized the principles and practices of ecosystem management for sustainability. WEF and ASCE (1998) detailed urban storm water runoff quality management. However, very little discussion can be found on integration of RS and GIS with a decision support system in ecosystem management. We think it is important to develop an integration framework first, to systematically describe the system's components, their functionality, inputs/outputs, and sub-system coupling. Figure 1 shows a functional integration of urban resource management with application of RS, GIS, and simulation tools.

As illustrated in Figure 1, the proposed integrated system consists of five sub-systems: RS, GIS, tabular databases, modeling/simulation, and multiple criterion analysis. The coupling of the sub-system's inputs and outputs can be described as follows:

1. Remote sensing technology can provide spatial and temporal pixel information on land use, resources and site activities; this information can couple directly with a GIS geo- referenced database.
2. The tabular databases, compiled from multiple sources, link to a GIS database with multiple attributes to assess an ecosystem in light of spatial information.
3. GIS processes and displays spatial data for environmental analysis, identifies the ecosystem indices, and records the site activities. Then, GIS is used to organize the resource assessment and the input files for modeling and simulation.

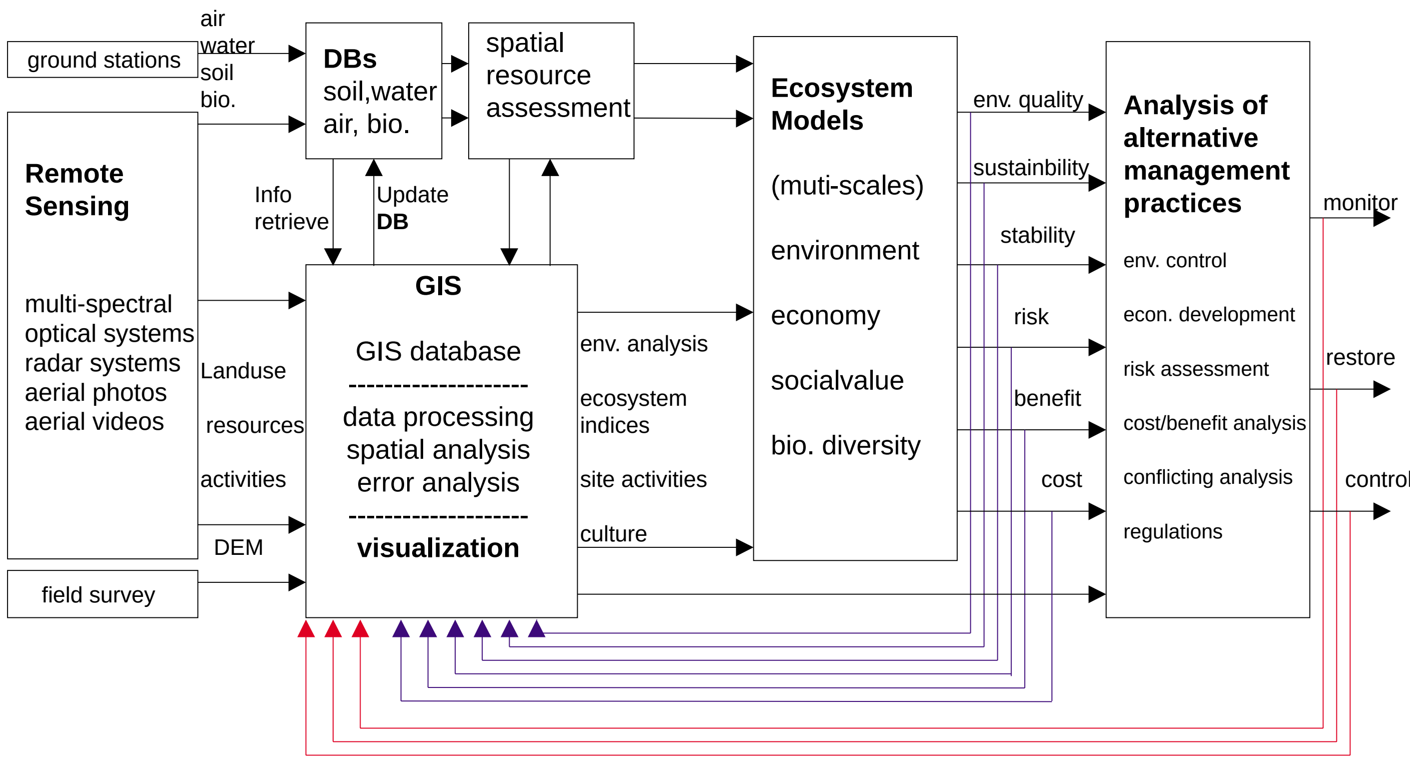

Figure 1. A functional diagram for ecosystem-based urban resource management.

4. Modeling and simulation cover the relationship of the regional environment, economy, social values and biological diversity. Under the given conditions, the regional models simulate scenarios and their environmental impacts, risk, cost, benefits, and then investigate ecosystem stability and sustainability.

5. Following regulations, a multiple criterion analysis system evaluates each scenario's consequences, risk, cost and benefits, resolves any conflicting objectives. Finally, it generates decision support reports.

As described above, GIS plays a central role in information management, as well as serving as a powerful tool in processing and visualizing spatial data.

Three major advantages of this integrated system can be identified. The spatial data collection from RS is fundamentally different from the traditional point measurements, in addition to the automatic manner in which it is acquired. Monitoring and modeling have been integrated with management to improve the scientific basis of ecosystem management. GIS can visualize a complex ecosystem at different scales, as well as spatially distributed environmental impacts.

Based on this framework, a preliminary research plan is introduced. It has implemented the above major components to support urban storm water management.

An Integrated System at an Operational Scale

The integration framework developed in previous section fits the general form of ecosystem management. To demonstrate its characteristics in watershed management practice at an operational level, an urban storm water management is taken as an illustration.

In a watershed, the hydrologic cycle integrates the physical, chemical and biological processes of a basin's ecosystem. Urban watershed-based management traditionally concerned approaches for water quantity related issues (conveyance oriented flood control and erosion control). Recently, water quality issues have been emphasized. Ecosystem-based management tries to protect and restore the ecological integrity of urban resources. Figure 2 shows a detailed functional diagram of an integrated urban storm water management system, which exactly follows Figure 1's structure, but at an operational scale. Figure 2 provides detailed information on the state variables, input/output couplings, parameters, model components, categories of analysis and actions.

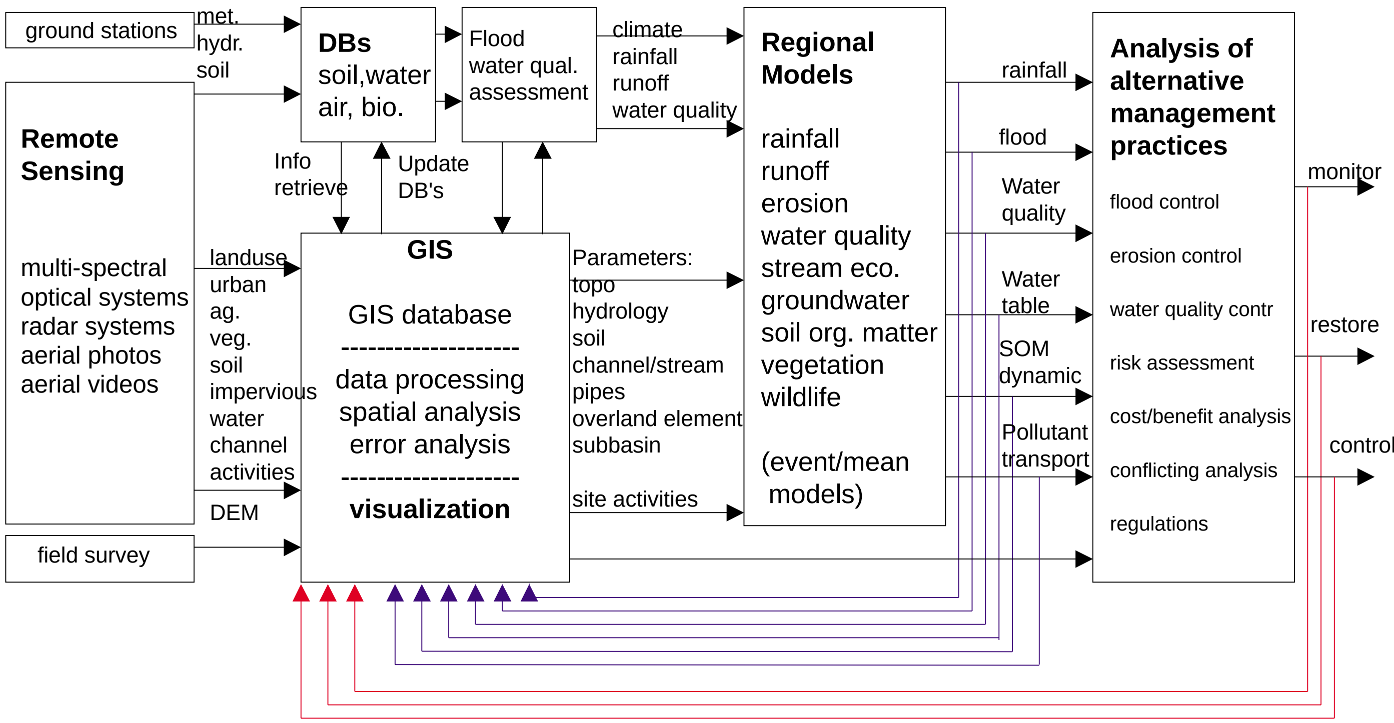

Figure 2. A functional diagram for integrated urban stormwater management.

An Application of Integrated Urban Storm Water Management

To demonstrate the characteristics of integration, a real application is introduced in this section. One research project in the Advanced Resource Technology (ART) Group, of The University of Arizona, is to implement an integration of RS and GIS with hydrologic simulation for urban storm water runoff management. The research was initialized from a project sponsored by NASA and the City of Scottsdale, Arizona in 1997. The major components of four subsystems in Figure 2 were implemented here. The study site is a highly developed urban area located in the city of Scottsdale. Multiple RS data were used, including aerial photos and different satellite images: Landsat TM, SPOT and NS001. A high-resolution GIS database was developed and digital terrain modeling was performed in ARC/INFO and ArcView. RS and GIS were integrated with a distributed hydrological simulation tool (Zhang et al 1998). The urban storm water runoff was simulated under a variety of conditions to improve flood prediction (Zhang et al 1999a). The distributed hydrologic simulations were modeled by the kinematic wave approach and implemented in HEC-1. GIS/Avenue, an ArcView programming language, was used to customize the information management system handling the data exchange and user interface (Zhang et al 1999b).

Figure 3 shows the application of RS and GIS to assess urban resources and monitor sensitive areas in an ecosystem. The processed satellite image provided eight categories of surface information: trees, grass, bare soil, gravel, water, asphalt, concrete and buildings. These RS data provided preliminary watershed characteristics regarding land use and urban development. Complemented with GIS data, RS data also identified and recorded some site activities. Aerial photos and geo-referenced site photos (integrated into the GIS database) detailed disturbed areas and conditions at the sensitive sites. For example, here is a construction site and the conjunction of a storm sewage pipe and a natural channel, which was partially blocked by deposited trash, used tires and other debris.

Figure 4 shows the simulated storm water runoff at different places within the watershed under the different conditions.

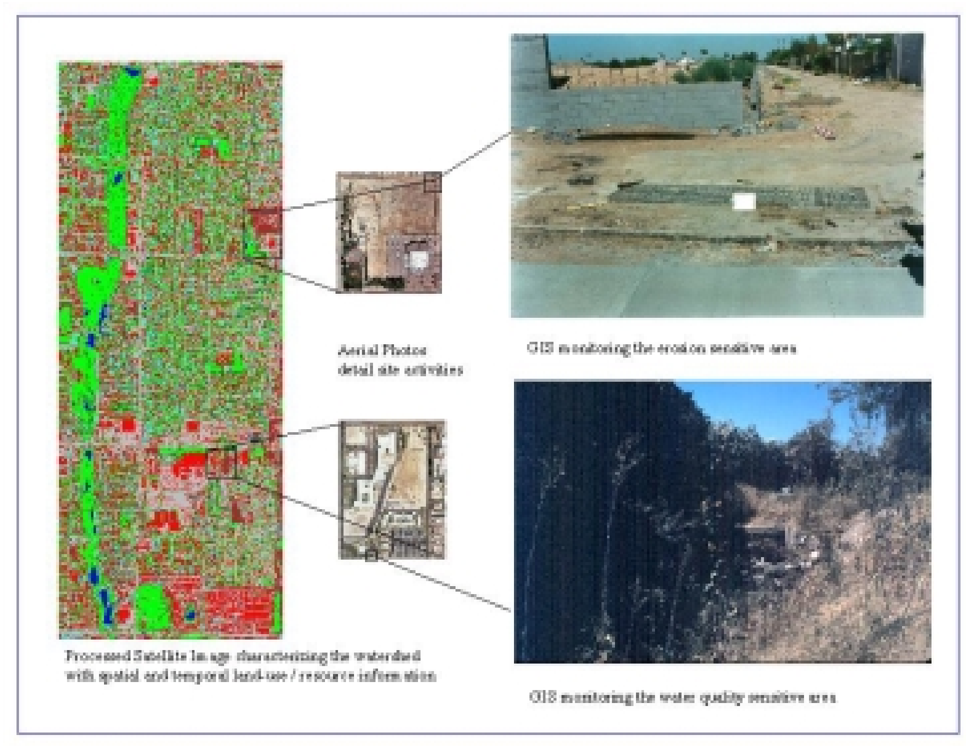

Figure 3. RS and GIS assess urban resources and monitor sensitive areas.

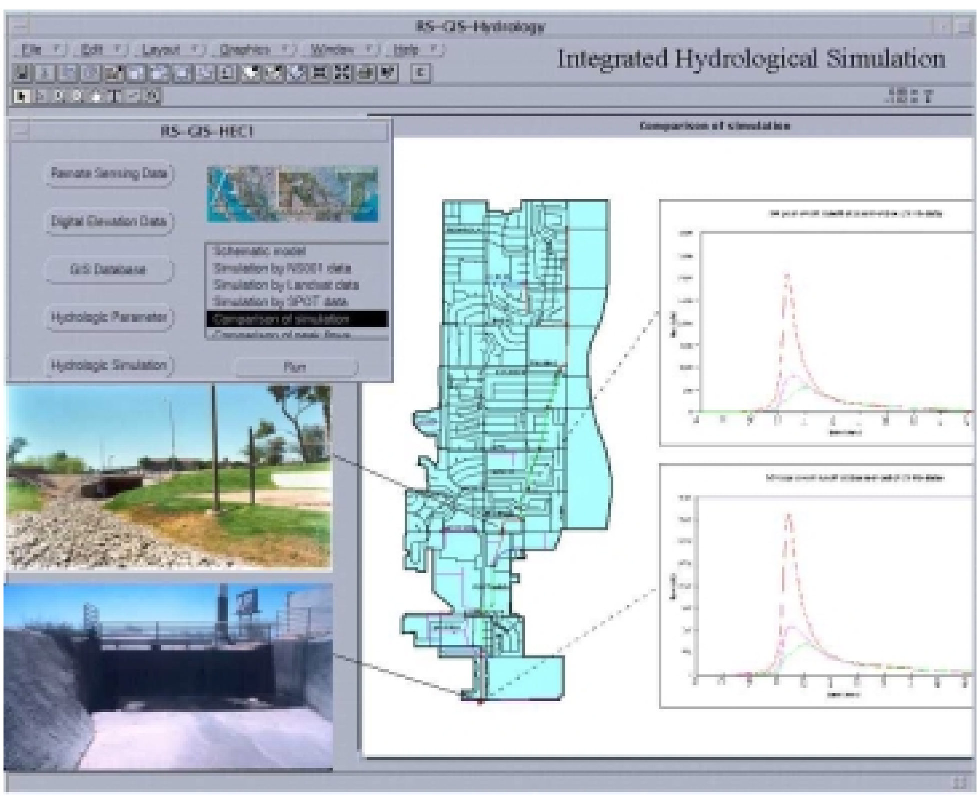

Figure 4. An integrated urban stormwater runoff simulation.

Summary and Discussion

An integration framework was systematically developed to support ecosystem- based management, with an application of RS, GIS, modeling/simulation and multiple criterion analysis. At an operational scale, an integrated urban storm water management was illustrated. An application of RS and GIS to improve storm water management was introduced. RS directly benefits resource assessment and monitoring. GIS plays a central role to process and visualize the spatial data. Modeling and simulation are tools that can evaluate alternatives, when the results of a given action might not be apparent for several years. The multiple criterion analysis tool evaluates predicted conditions under alternative actions. The integration of information technology and modeling tools provides a new environment for research of complex ecosystems, as well as a better scientific basis for management.

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GIS Soil Conservation Planning: A Case Study of a Pristine Central American Watershed

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Abstract.—In the Pacuare River Watershed in Costa Rica, farm size, ownership, and production data were collected and spatially referenced through global positioning surveys and farmer assessments of property boundaries in relation to cadastral maps and air photographs. Using GIS based spatial overlays, this data were integrated with previously collected land use and land degradation data. The resulting integrated database allowed for land use and degradation data to be classified by alternative farm sizes in order to assess the individual needs and relative priority of a soil conservation program for different farms. In spite of limited funding and many technical and data constraints in Central America, such GIS based methodologies linking farms and people to bio-physical based land use and degradation is seen as a feasible and cost effective approach to plan and implement soil conservation and other types of natural resource management projects.

Channel Morphology Investigations Using Geographic Information Systems and Field Research

Scott N. Miller[1], Ann Youberg[2], D. Phillip Guertin[3], and David C. Goodrich[4]

Abstract.—Stream channels are integral to watershed function and are affected by watershed management decisions. Given an understanding of the relationships among channel and watershed variables, they may serve as indicators of upland condition or used in distributed rainfall-runoff models. This paper presents a quantitative analysis of fluvial morphology as related to watershed characteristics for two disparate sites in Arizona. Detailed geographic information system (GIS) analyses were combined with 297 cross-section surveys. Statistical relationships among GIS-based watershed and field-based channel variables are presented and explanations for discrepancies between sites are given.

Introduction

Watershed management has long focused on the effects of land use practices on runoff, erosion, and off-site impacts. The drainage network plays a critical role in watershed processes since it serves to route water across and out of a watershed. Furthermore, stream channels serve as critical habitat and migration corridors for many species of birds, animals, and fish. In the semi-arid Southwest, riparian communities are recognized for their importance to a wide diversity of species. Physically-based hydrologic models rely on channel morphologic estimates to improve their predictive capabilities (Feldman, 1995; Smith et al., 1995). Given that stream channels play important roles in the hydrologic response of a watershed and in the complexity and diversity of ecological systems, understanding their responses to watershed management and subsequent effects on water quality and peak and volume runoff is important.

One avenue for investigating a stream channel and its connectivity to the surrounding watershed is the assessment of its morphology (i.e., size and shape) with respect to upland characteristics. Historically, the size and scope of such analyses limited research into this area. Prior to recent advances in geographic information systems (GIS) and computer tools, large-scale geomorphic investigations were overly time consuming, imprecise, and impractical (Guertin et al., 2000). This is not to imply that significant advances in the understanding of channel dynamics were lacking, rather that data requirements and high overhead limited the practical range of such research (see Abrahams, 1984 for a technical review). The advent of GIS allows for the pursuit of detailed large-scale geomorphic analysis relating channels to their uplands.

In this study, detailed channel morphology surveys were carried out in two regions of eastern Arizona representing a wide range in watershed characteristics. GIS tools were created to characterize the areas contributing runoff to the survey sites. Field and GIS data were correlated to assess the relationships among watershed characteristics and channel morphology. Strong predictive relationships were derived from these data that illustrate the watershed factors responsible for dictating fluvial response. These relationships hold implications for watershed practices and may be useful for hydrologic modeling studies on ungauged or remote watersheds.

Description of the Study Areas

Stream channels included in this study were surveyed on the Apache-Sitgreaves National Forest of east-central Arizona and USDA-ARS Walnut Gulch Experimental Watershed, located in southeastern Arizona. Within the Apache-Sitgreaves, five small perennial streams were studied: the West, East, and South Forks of the Little Colorado River, the West Fork of the Black River, and it's tributary Thompson Creek. Basalt and andesite flows form rolling topography to the east of Mount Baldy, an extinct volcano within the Apache-Sitgreaves. The climate of the Mount Baldy area has been classified as moist to subhumid (Merrill, 1970). Mean annual precipitation is 76 cm at Sheep Crossing on the West Fork of the Little Colorado River, with half of the yearly precipitation falling during summer thunderstorms (Merrill, 1970). Although there are seasonal fluctuations in these streams, flow occurs

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year round. Elevation ranges from 2256 to 3474.5 meters (7402 to 11403 feet). Vegetation types in the study area range from open ponderosa pine forests at the lower elevations near Greer, Arizona, to spruce and fir forests on the upper flanks of Mount Baldy (Elmore, 1976). Vegetation cover consists of forests with small meadows on Mount Baldy and within the canyons, and large open meadows with patches of forest on the volcanic flows.

The Walnut Gulch Experimental Watershed is a relatively small (150 km^2) experimental watershed encompassing the town of Tombstone, Arizona. The watershed is heavily instrumented with rain gauges and various runoff measuring devices amidst rolling hills ranging from 1190 to 2150 m elevation. Climate within the region has been classified as semi-arid or steppe (Renard et al., 1993). Approximately 60%-70% of annual rainfall occurs during summer monsoon rainstorms, with the remainder primarily falling during winter frontal storms. Vegetation within the watershed is representative of the transition zone between the Sonoran and Chihuahuan deserts, and is composed primarily of grasslands and desertscrub communities.

Smaller in size than the Apache-Sitgreaves study area, Walnut Gulch is consequently more homogeneous with less complex hydrology and geology. Stream channels are ephemeral, and the majority of runoff occurs during summer monsoonal activity. While talus slopes in gorges and well-developed soils in meadows and forests are found with meandering well-formed streams on the Apache-Sitgreaves region, Walnut Gulch is typified by poorly developed soils with swales in its uplands and sandy-bottom washes with high transmission losses in larger channels.

Methods

Channel cross-section surveys were carried out on 233 stream reaches within Walnut Gulch and 64 within the Apache-Sitgreaves study areas. Separate sampling methodologies were imposed on the two study areas: a random sample design was used on Walnut Gulch, while uniform sampling was carried out on Apache-Sitgreaves. Channels with slopes greater than 6% were excluded from the Apache-Sitgreaves because they were deemed unsuitable for geometric assessment. Likewise, unstable channels undergoing rapid adjustments or actively degrading channels were not sampled.

In all cases, multiple cross-sections were surveyed within each stream reach to ensure that the reach geometry was adequately characterized. Three cross-sections at each sample point were surveyed, and the results averaged to determine a standard reach geometry composed of average channel width, depth, and cross-section area. High-resolution orthophotographs were used to geo-locate cross-section sites on Walnut Gulch, while a global positioning system (GPS) served to provide coordinate locations for survey sites in Apache-Sitgreaves. These sites were input into a GIS to allow for spatial analysis with other GIS data layers.

Comprehensive GIS databases were constructed for Apache-Sitgreaves and Walnut Gulch. Of primary interest to this study were the topography, soils, vegetation, and geology data. A high-resolution (10 m) digital elevation model (DEM) was constructed from low-level aerial photography for Walnut Gulch, while a USGS DEM (30 m) was built for Apache-Sitgreaves. It is recognized that GIS analysis is dependent on the scale and quality of the input data (Miller et al., 1999) and that mixing data sources confounds quantitative comparative analysis. However, for the purposes of this paper, wherein empirical relationships among watershed characteristics and channel morphology were determined, differences due to DEM sources are less significant than in process-based analyses and so are assumed to be negligible.

Using each of the channel survey points as outlets, subwatersheds were derived using flow direction and flow accumulation algorithms based on the DEM surfaces (ESRI, 1997). Watershed characteristics were derived for each of the 297 subwatersheds, including area, slope, maximum flow length, cumulative channel length, drainage density, perimeter length, basin shape, elevation change, dominant soil type, geology, and vegetation.

Stream channel morphology variables collected in the field were correlated to GIS analysis using standard statistical techniques. Simple and multiple regression analyses were used to determine the principle deterministic relationships in the Apache-Sitgreaves and Walnut Gulch study areas. In this way, similarities and differences in fluvial geomorphic response to watershed characteristics between the two regions were detected. This paper is concerned primarily with channel width and cross-section area. Channel width is of prime importance to rainfall-runoff modeling, and cross-section area represents the total response of a channel to upland and local conditions.

Results

Channel characteristics measured in the Apache-Sitgreaves study area were distinct from those measured in Walnut Gulch for watersheds with similar properties. Differences in hydrologic regime, soils, and vegetation are presumed to be responsible for the observed morphologic variability. Some variability may be attributed to cross-section survey error in both study areas; however, systematic error in sampling methods between the two regions was absent. Student t-testing at the 95% confidence level showed that the sample populations of channel width, depth, and cross-section area were significantly different from one another. These results are more substantial given that the watersheds surveyed in the two regions overlapped in size, shape, and other factors that govern hydrologic response.

Linear regression models were fit between the channel morphology measurements and the GIS-derived watershed characteristics for each survey point. These results were used to investigate watershed factors that contribute to channel forming processes. Channel morphology is a function of local (bed and bank material, vegetation) and watershed (hydrologic response, size, geometry) control. The purpose of this research was to investigate the watershed factors that influence channel formation; consequently local variables were not measured. While this decision is recognized as a limitation on analysis, some inferences regarding local control were made based on field observation.

A host of watershed variables, listed earlier, were used in the preliminary analysis. A subset of these variables was found to be related to channel morphology at both study sites: watershed area (Aw), elevation change (E), and maximum flow length (Lm). These variables are closely tied to runoff processes, which are in turn responsible for channel formation. Figure 1 shows some of relationships among channel properties and watershed area and the maximum flow length within a watershed.

Note that there is an offset between Walnut Gulch and Apache-Sitgreaves data points, while the slopes of the relationships for width and cross-section area are very similar. In general, channels on Walnut Gulch are wider

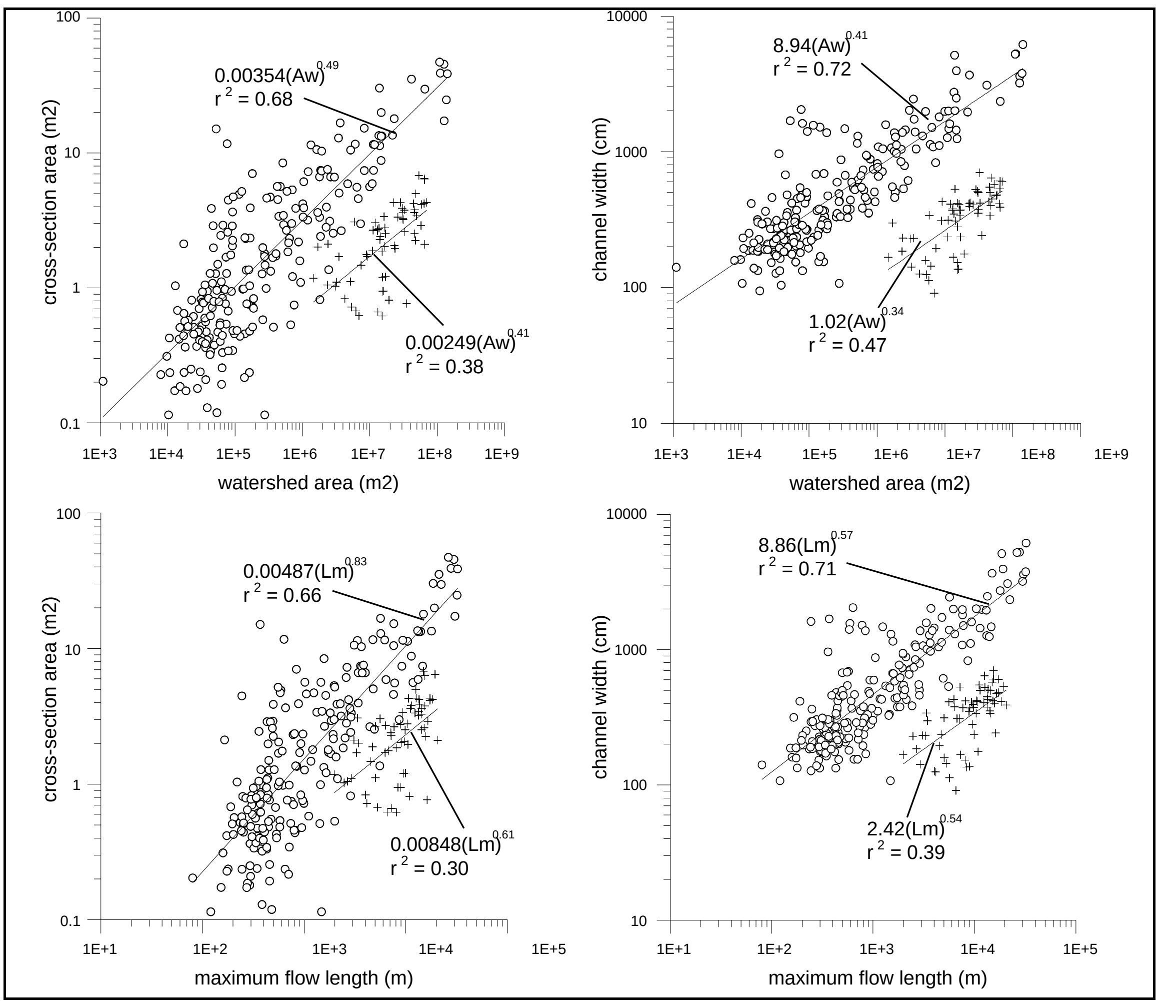

Figure 1. Relationships of channel width and cross-section area relative to watershed area and maximum flow length for Walnut Gulch and Apache-Sitgreaves study areas. Regression lines are shown to illustrate the offset and similarities in slopes between the two study areas.

and larger than on the Apache-Sitgreaves for similar watersheds, but channels on both areas increase in size at relatively the same rate. Recall that Apache-Sitgreaves data were collected on forested watersheds with perennial streams, while Walnut Gulch is a rangeland with ephemeral washes. Runoff on Walnut Gulch tends to be from flash floods and consequently more catastrophic. Furthermore, soils on Walnut Gulch contain less clay and are therefore less cohesive. These factors, in contrast to the stabilizing forces provided by vegetation and less violent runoff on Apache-Sitgreaves, combine to produce larger, wider channels on Walnut Gulch, thus creating the offset between the study sites. It is somewhat surprising, given these confounding factors, that the slopes of the relationships in figure 1are similar, implying that channels are increasing in size at approximately the same rate at both sites. Stream power, which is directly related to runoff volume and velocity and therefore channel excavation, appears to be increasing at similar rates on both study areas. Further research into runoff rates and hydraulic geometry is necessary to address this topic; unfortunately, while long-term gauging records are available for Walnut Gulch, a paucity of runoff data exists for Apache-Sitgreaves.

One of the goals of this research was to provide deterministic models for predicting channel morphology on ungauged basins for use in hydrologic modeling and hydraulic geometry research. Towards this end, simple and multiple regression models were developed to predict channel width and cross-section area. Results on both study areas were very promising when multiple regression techniques were used (table 1), but the Apache-Sitgreaves data contained greater variability than the Walnut Gulch data when related to a single watershed characteristic (figure 1).

Using multiple regression in the determination of channel morphology improved the predictive capability as illustrated by the high coefficients of determination (r^2) in those models shown in table 1. While the simple models work well on Walnut Gulch, models with high r^2 could not be found for Apache-Sitgreaves. Thus, it is suggested that the simpler models be applied on Southwest rangelands similar to Walnut Gulch, while the more complicated multiple regression models be employed on areas similar to Apache-Sitgreaves.

Conclusions

Stream channels within two areas of differing watershed and hydrologic characteristics (a rangeland and a forested area) were intensively surveyed and their contributing areas investigated with a GIS to determine the relationships among channel morphology and various watershed variables. Strong deterministic relationships for channel width and cross-sectional area were found for both areas. Variability in hydrologic response, soil cohesion, and vegetation, account for differences in the statistical models between the study sites. These statistical relationships should prove useful for future research into hydraulic geometry and rainfall-runoff modeling in the Southwest.

Table 1. A selection of linear regression models used in the prediction of channel width and cross-section area as a function of watershed properties.

Study area	Channel variable	Regression	r^2	RMSE
Walnut Gulch	area	1.82(Aw)+0.0028(E)+0.001(Lm)	0.91	3.54
Apache-Sitgreaves	area	5.69E-8(Aw)+0.0025(E)-3.54E-5(Lm)	0.88	1.04
Walnut Gulch	width	-9.73E-6(Aw)+2.11(E)+0.14(Lm)	0.84	506
Apache-Sitgreaves	width	2.94E-6(Aw)+0.344(E)+0.0071(Lm)	0.92	106

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Increasing Efficiency of Information Dissemination and Collection through the World Wide Web

Daniel P. Huebner[1], Malchus B. Baker, Jr.[2], and Peter F. Ffolliott[3]

Abstract.—Researchers, managers, and educators have access to revolutionary technology for information transfer through the World Wide Web (Web). Using the Web to effectively gather and distribute information is addressed in this paper. Tools, tips, and strategies are discussed. Companion Web sites are provided to guide users in selecting the most appropriate tool for searching and promoting Web sites, and to help users maximize the potential of the Web.

Introduction

Immediate access to scientific literature has been a dream of researchers, managers, and educators (Lawrence and Giles 1998). The greatest benefit the World Wide Web provides over traditional print media is its immediacy (Hilf 1998). Excitement surrounding Web use is pervasive as professionals discuss their successful use of the World Wide Web. However, excitement quickly turns into frustration for those unfamiliar with the technology. This paper is about helping people effectively use of the World Wide Web.

About the World Wide Web

The World Wide Web (WWW, Web, or W3) is the universe of network- accessible information, the embodiment of human knowledge (World Wide Web Consortium 1997). As of December of 1997, an estimated minimum of 320 million Web pages existed (Lawrence and Giles 1998). If, as some estimates suggest, the Web doubles in size every 4 months (Tyner 1998), there are over 20 billion Web pages as of March 2000. To view all these pages at a rate of 1 per second would take 450 years! With this volume of Web pages, it is expected that information exists on nearly any topic. Indeed, the Web mirrors the diversity of information subject matter and quality present worldwide. One can find publications, software, data, images, bibliographies, insight, and treasure in copious quantities on the Web.

Unfortunately, this tremendous quantity of information is not well organized. However, there are excellent tools available to help connect users and the information they seek.

Locating Information

It is difficult to learn the Web in a high-pressure, time stressed, environment where every moment must result in immediate productivity. Successful Web application requires an investment in "play time." to become familiar and comfortable with it. Often, this "play" environment, which pays large dividends in the long-run, is unavailable at work. Alternatives include exploration through a home account, or use of public access systems at libraries. However you manage to "play" on the Web, feel free to explore and experiment. Go everywhere. Mouse click on everything. Make mistakes. Make serendipitous discoveries. The time invested in this discovery "play" period will be extremely beneficial in your future ability to effectively access needed information.

Once you are comfortable with the Web and the use of a browser (software that allows access to the Internet), consider how to find specific information. Some excellent resources and powerful tools have been developed for this purpose. Two types of tools that help in the information quest follow.

Subject Guides

Subject guides are hierarchically organized indexes of subject categories that allow users to browse through lists of Web sites by subject in search of relevant information (Tyner 1998). Subject guides are "moderated", that is, there are people who decide if a site is relevant before a

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link is added. Because of the human involvement in this selection process, relevancy is high, but subject guides index only a very small fraction of the information available on the Web.

Using a subject guide is similar to looking through the yellow pages. To look for hydrology organizations one might start with the broad category **science**. Within that broad category find a sub category **hydrology** and then a sub category **Institutes** below this. Under **Institutes** might be listings for the National Weather Service, Hydrologic Research Laboratory, Utah Water Research Laboratory, and the Instituto Mexicano de Tecnologia del Agua.

Some subject guides are general, like Yahoo (http://www.yahoo.com) and Magellen (http://www.magellen.com). The top-level categories of these general subject guides are broad like arts and humanities, business and economy, computers and internet, or education. These general guides are useful to locate popular or common information. Other subject guides, like Hydrology Web, which links to sites that are relevant to hydrology, (http://etd.pnl.gov:2080/hydroweb.htm), are specialized. Because there are thousands of specialized subject guides, clearinghouse sites exist to help users access them. Examples include Argus Clearinghouse (http://www.clearinghouse.net/) and The WWW Virtual Library (http://www.vlib.org).

Subject guides work well for exploring resources about a broad topic area. If the desired information is specific, like water-yield data on the Beaver Creek watersheds in north central Arizona (Baker 1999), search engines are the Web tool of choice.

Search Engines

Search engines build an index or data base from existing Web pages and provides users with the ability to query the index. To build the index, search engines deploy software "robots" that automatically index the contents of a Web page. Then, the "robot" indexes the Web pages that are linked to the first page and on through cascading myriads of linked pages. Because of the automation that search engines employ, they index more of the Web than do subject guide. A larger index means that more pages relating to a narrow or focused topic are found and delivered. However, because search engines index innumerable pages, a large percent of them may lack relevancy. This is especially true if the query is overly broad.

From the user's perspective, all search engines work in a similar way. Users submit terms (**percolation soil**) or a phase (**beaver creek evaluation study**) to the search engine, which compares them to the index of Web sites it has built and returns links to pages considered relevant. No search engine indexes the entire Web. In fact, different search engines vary in what they index, how much they index, and how frequently they update the index. Not all Web pages can be indexed by a search engine. Some pages are blocked to public access (e.g., intranet pages) and some pages are temporary in nature (e.g., results from data base queries). The largest search engines index only 1/3 of the "indexable Web pages" (Lawrence and Giles 1998). Because of the varying sizes and the methods used by different search engines, users will obtain different results when issuing the same query to a variety of engines. If your search is unsuccessful, try a different engine or a Web tool that submits your query to many search engines simultaneously like DogPile (http://www.dogpile.com) or Metacrawler (http://www.go2net.com/).

For details on the use of specific search engines, check the online documentation, under "Help", of your Web software. Just as the Web is very dynamic so are its search engines. An excellent resource for tracking the latest changes and advances is Search Engine Watch (http://www.searchenginewatch.com). An online guide helps assist users in selecting appropriate search tools for various types of searches (http://www.rms.nau.edu/guides/search/).

Table 1 demonstrates how a search for information on water-yield data from the Beaver Creek evaluation study might unfold. The requested information is specific, so using a search engine will yield more appropriate results than a subject guide. AltaVista (http://www.altavista.com) is used for this example.

Distributing Information

When deciding whether the Web is the appropriate medium for information distribution, consider that less than 3% of the world's population has access to it. This limitation does not diminish the Web's significance as a revolutionary technology tool. Remember the printing press had a great impact on world communication even though most Europeans were illiterate at the time of its invention (Hilf 1998).

If the Web is a suitable medium to disseminate your information, consider how to put information on the Web so others can easily access it. This topic is not addressed here, as the how-to varies depending on organizational affiliation and so on. Its best to contact the computer system administrator or a colleague who has worked through the details, and have them assist you while getting started. The challenge is in developing the content rather than the nuts and bolts of the technical issues and language.

Tips for Efficient Web Searches

- **Stay focused**. The nature of Web searching ensures access to links of interesting Web pages that are irrelevant to the search. Exploring these pages derails the search and diminishes productivity. Users can mark interesting pages for later perusal using the browser's bookmark feature, which is explained under "Help."
- **Be persistent**. If the first, second, and third strategies do not work, try a fourth, fifth, and sixth. Try the same search a month later. Remember, the Web is a dynamic environment where persistence will increases the likelihood of success.
- **Be inventive**. If there is no success with the suggested, usual tool, try one that is designed for something else. For example, you might find a person using a general search tool after failing with a tool designed specifically for this purpose.
- **Use right-side truncation of the Web address to find parent pages**. Often a search leads to a page well below the site's home page. Deleting some of the address will move you up toward the site's main page. For example, at www.rms.nau.edu/publications/rm_gtr_295/chaper9.html, if you delete chapter9.html, you go to the publications main page. Truncate further to www.rms.nau.edu, and you go to the organization's main page.
- **Learn the features of specific search tools for greater efficacy**. Search tools describe specific features through their "Help" link.
- **Do not consider any listings to be comprehensive**. Comprehensive does not exist in the the Web world.
- **Understand and accept that the Web is huge and unorganized**.
- **Enjoy the process**.

Table 1. A search for information on water-yield data from the Beaver Creek evaluation study.

Typed into Query Box	Plain English	Results
beaver creek	the word **beaver** and the word **creek** occur on the page.	16,973 pages match the query, full of links to Beaver Creek resorts (for example, in Vail, CO and Michigan), Beaver Creek software company, etc. Query is much too broad. Try searching for the exact phrase "beaver creek evaluation study"
"beaver creek evaluation study"	the phrase **beaver creek evaluation study** occurs on the page	No document matches the query. Query is too narrow. Remove the quotes to search for pages that have these words in them without the requirement that they are next to each other (a phrase).
beaver creek evaluation study	the word **beaver** and the word **creek** and the word **evaluation** and the word **study** occur on the page	Relevant pages start showing up in results, most refer to the "beaver creek watershed." Try the phrase "beaver creek watershed"
"beaver creek watershed"	the phrase **beaver creek watershed** occurs on the page	Good relevance, links to Beaver Creek watershed history, data, publications, etc. Add the phrase "water yield" to focus the search.
+"beaver creek watershed" +"water yield"	the phrase **beaver creek watershed** must occur and the phrase **water yield** must occur	Success. Sites that discuss water yield on the Beaver Creek study area

After investing in putting information on the Web, users must to be able to find it. Several approaches follow that will help increase the use and thus, the value of your Web pages. In addition, an online guide is available to assist users in promoting their Web sites (http://www.rms.nau.edu/guides/promotion/).

Take advantage of search engines. To control the way search engines list your site and to help boost your ranking on results pages, use meta tags. Meta tags contain information about a Web page but are hidden from the viewer. See the Alta Vista help page (http://www.altavista.com/av/content/addurl_meta.htm) for a good explanation of meta tag use in Web pages. Once meta tags have been added submit pages to the major search engines. The best way to ensure that your pages are indexed by a search engine is to explicitly add them rather than to wait for the "robots" to stumble upon them.

Attach the address of Web pages to communications with colleagues. This includes e- mail messages, business cards, and other printed matter. It is sometimes useful to make a business card that highlights a web site. The familiar and convenient business card is often the easiest way for an interested person to go back to the office with your web site address.

Submit information about your web page, including the address, to topic news letters and mailing lists. Contact Web masters that maintain listings of links to similar sites, and ask them to add a link to your Web site; offer to do the same for their sites.

Summary

Subject guides are useful when you are "looking around" and do not have specific information needs. Search engines are best to find specific information. Use of many different search engines gives the most comprehensive results. An online guide helps users select the appropriate tool to use for a particular search (http://www.rms.nau.edu/guides/search/). When using Web pages to distribute your information, actively promote them. An online guide provides links to references on promoting your Web pages (http://www.rms.nau.edu/guides/promotion/).

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An On-line Image Data Base System: Managing Image Collections

Malchus B. Baker, Jr.[1], Daniel P. Huebner[2], and Peter F. Ffolliott[3]

Abstract.—Many researchers and land management personnel want photographic records of the phases of their studies or projects. Depending on the personnel and the type of project, a study can result in a few or hundreds of photographic images. A data base system allows users to query using various parameters, such as key words, dates, and project locations, and to view images matching the query. This application helps select and locate images for presentations, reports, and publications. The image data base is also available on the World Wide Web.

Introduction

It is often desirable or necessary to obtain photographic records of the phases of a study. A picture can be worth a thousand words, and these records provide documentation of both minor and major changes that are not accurately recalled from memory. Depending on the personnel and the type of project, a study can result in a few or hundreds of images. At best, the slides, negatives, or prints accumulate and are stored in a folder with brief notation and are later deposited in a filing cabinet.

This paper presents an archive system that combines image information and a medium resolution electronic version of an image in a searchable data base. Users can search the image data base using parameters, such as key words or subjects, dates, and locations, and then view a medium resolution version of images that meet the search criteria. This procedure provides a relatively easy method of locating a photo or slide for a presentation, report, or manuscript. The system provides a quick means to retrieve records and provides others with the ability to search and access images through the World Wide Web (Web).

Preliminary Considerations

The initial objective in creating this data base was to develop a relatively easy method of documenting, storing, and locating images for presentation, reports, and manuscripts. We wanted a process that could quickly locate a set of images from a collection at any future date. Therefore, we needed a system that could easily be searched using keywords to identify characteristics desired in an image and that could locate the image once identified.

In making images available for retrieval, copyright issues are an important consideration. However, the images we planned to include were in the public domain, thus eliminating the copyright issue. In collections not in the public domain, copyright would need to be determined early.

It was anticipated that the image archive system would be used by personnel at our lab who may have collections of different emphasis. An important consideration was to develop a system that a user could search all available collections with one query. This virtual pooling of collections increases the likelihood that users can find a suitable image, and it increases collaboration with colleagues. The desire to perform these cross-collection searches imposed some limitations on system design. To facilitate these searches it was decided to use the same data base structure for all collections. Using the same data base structure for diverse collections required that the structure be generalized. Figure 1 shows the basic structure for this data base.

The initial process of documenting the image was the most time consuming, and the ease of entering these data likely determines whether users will adopt the system. A major consideration was how to assign contents to the primary search field "subject." If one assigns subjects in a haphazard manor, searches are less effective and more difficult to formulate. A controlled vocabulary is often used to address this issue. An example of a controlled vocabulary is the Library of Congress Thesaurus for Graphic Materials I: Subject Terms (TGM I). While the uniformity of application with a controlled subject vocabulary would be advantageous to searchers, it is also time consuming to assign these terms and the scheme may not be precise enough for specialized collections. Requiring catalogers to apply TGM I for subject listings would likely discourage use by local custodians of important collections. To help local custodians create and apply a subject list that was concise and applicable to their collection a drop down subject list was developed on the data entry form. When catalogers begin an image collection, the subject list is empty. As the cataloger inputs subjects, they are added to the drop down list. The cataloger can

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then review the current list of subjects and either apply the appropriate one or add a new one. This system helps to minimize use of synonymous subject terms.

Another consideration was the format for storing the electronic images. Because we were going to share these images on the Web, our choices were effectively limited to GIF and JPG file formats. The JPG file format was selected because of the high level of file compression available. Since thousands of images were included in the collections, using small, compressed files was essential. We decided to store images at about 600 x 400 pixels, with a file size of about 150K bytes per image, which provides a balance between usability and storage space. This size image can be effectively used on a Web page or in an on-screen presentation. If a higher quality image is required, users would go back to the original image. With data base structure and image file format decided, we developed the data input system.

A data input station was established to build the data base and scan the images. This consisted of a computer running Windows 95, a Hewlett Packard (HP) PhotoSmart scanner and a Microsoft (MS) Access application developed for this purpose. MS Access was selected as a data base because of prior familiarity. The HP PhotoSmart scanner was selected because of its low cost and ability to easily scan 35mm slides and prints up to 4" x 5".

A custom form for data input was developed to make the process as easy and efficient as possible. The form (figure 2) provides a comfortable format for the user to input data into the fields. Drop down pick lists are used where appropriate for the user's convenience and to minimize typographic errors. The subject field drop down list helps to enforce a quasi-controlled vocabulary, as previously described.

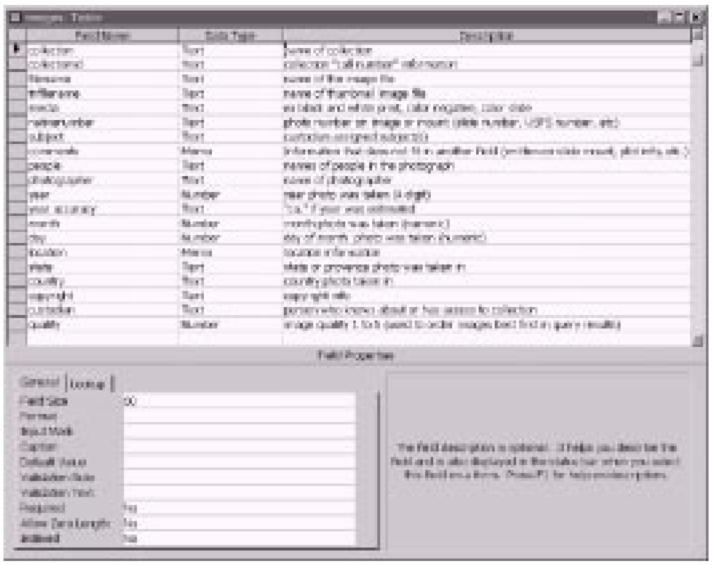

Figure 1. Basic data base structure.

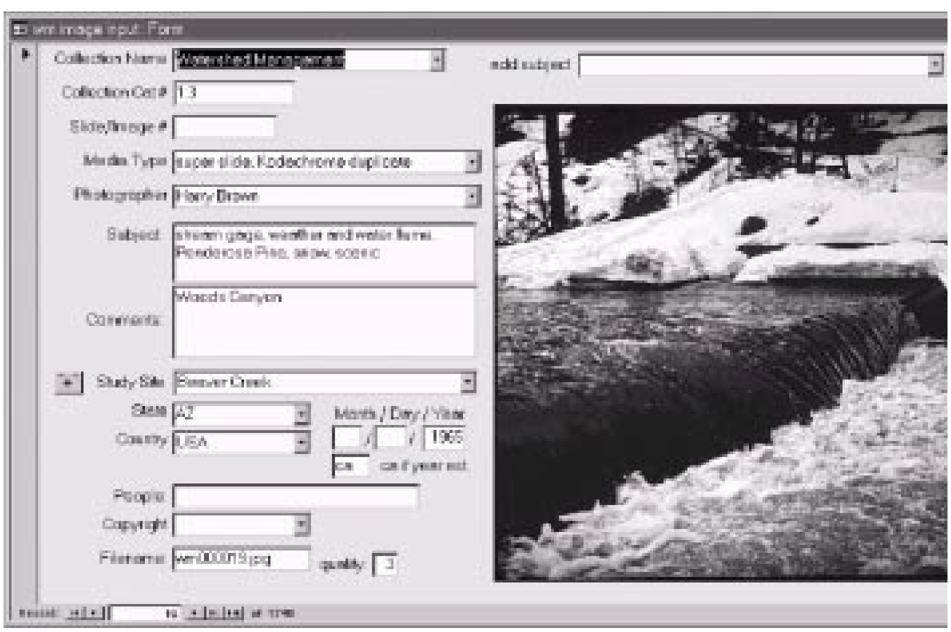

Figure 2. Data input form.

Using the System

With system components in place, a strategy for entering data was designed. The first step is to scan the images and to capture any information that was available on the slide frame or on image notes and enter this information into the data base. This cataloger function could be done by someone with technical competence. The second step is to review the records and apply appropriate subject terms or other information that were not captured in the first phase. This function must be done by a subject matter expert, with knowledge of the collection. Usually, this is the custodian. A two phase system like this minimizes the time commitment by the subject matter expert.

As an example, we will use a collection of slides that a hydrologist has accumulated over a 30-year period named watershed management (wm). The first slide in the watershed management collection is identified as wm000001, allowing for a total of 999,999 images in the collection. The cataloger enters this identifier and the .jpg extension in the “filename” box in lower left corner of the data entry form (figure 2.) This number wm1 is written on the slide. The image is then scanned and saved with the same filename (wm000001.jpg). The cataloger then captures any other available information about the image, and stores it in the appropriate fields on the form. A box for Comments is provided for entering information that does not comfortably reside in any other field. The cataloger then repeats the process for additional images.

Once the cataloger has scanned each image and added the available information about the image to the data base, the second step begins. The subject matter expert reviews each record (now consisting of an electronic image and associated information) and adds appropriate subject categories and any other information he or she recollects about the image.

The image data base is now ready to use. We share our data base over our local area network (LAN), so that our in-house colleagues can search and access it. Because many cooperators are unable to access our LAN, we added a web server with software to establish a common gateway interface to provide the link between Web pages and data bases.

Searching the Data Base

Our image data base is accessible at http://www.rms.nau.edu/imagedb/. To locate an image, users can apply a simple tool that locates their search term in any field in the data base. A search for **beaver** would match records where the subject contained beaver, or where the location contained beaver (as in Beaver Creek), etc. A more focused search tool, which is also available, allows users to search using a combination of fields. Figure 3 shows how users would use this tool to find images of riparian areas taken before 1976. Figure 4 shows the results of that search. To speed transfer of these images across the Internet, we use these smaller, thumbnail pictures on this preliminary results page. These thumbnails are about 160 x 100 pixels, with a file size of about 10K bytes. When searchers see an image of interest, they can click on the thumbnail to view the larger, scanned image (figure 5).

Managing the Physical Collection

Once the image is documented and digitized, it must be stored to facilitate future location. Hanging folders can store 20 35 mm slides, and a standard filing cabinet drawer can easily hold 6,000 slides. Our watershed management collection is stored in 2 filing cabinet drawers. It is essential that the collection custodian can physically locate an image when given the unique identification number (e. g., wm000001).

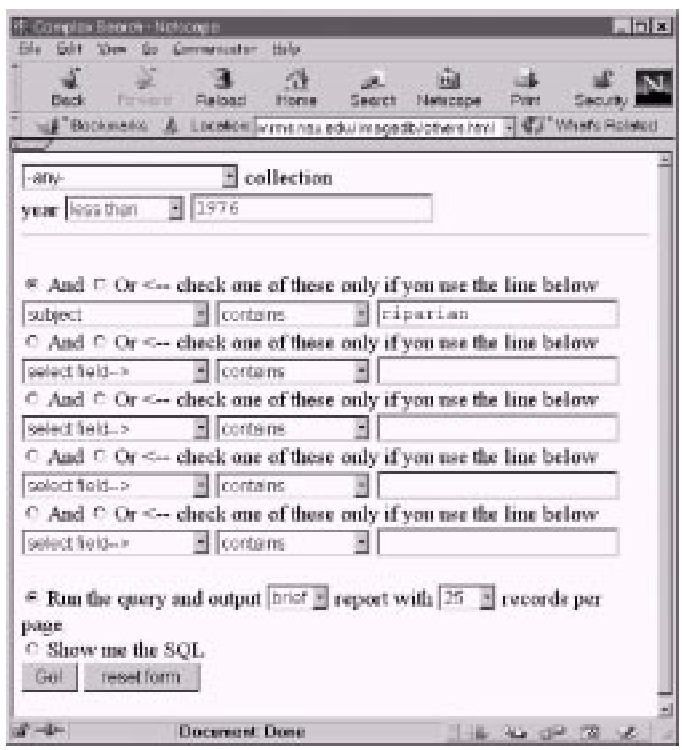

Figure 3. The more focused search tool.

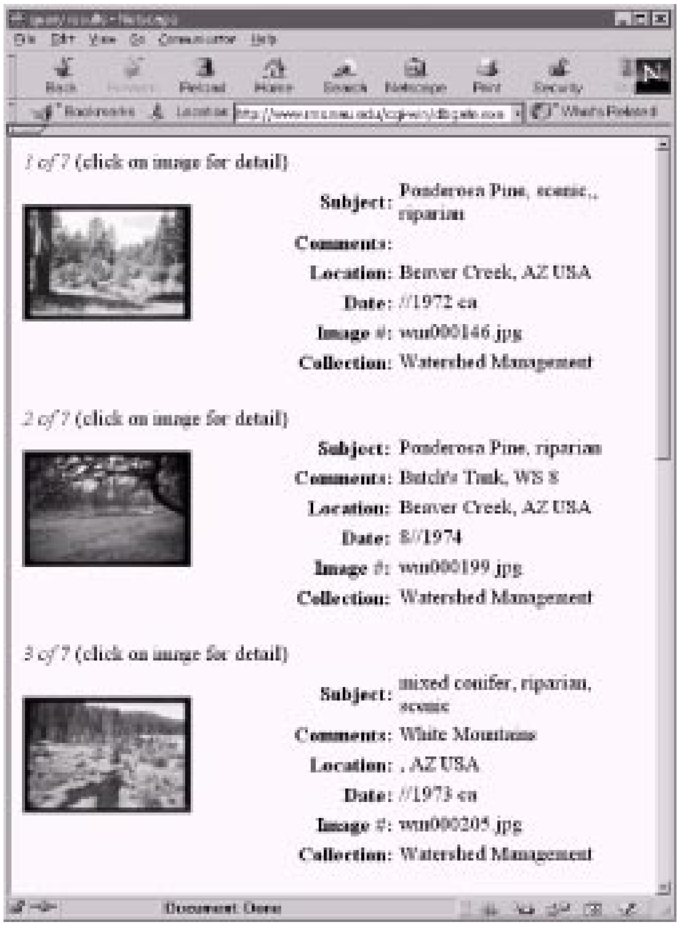

Figure 4. Results from the query in figure 3.

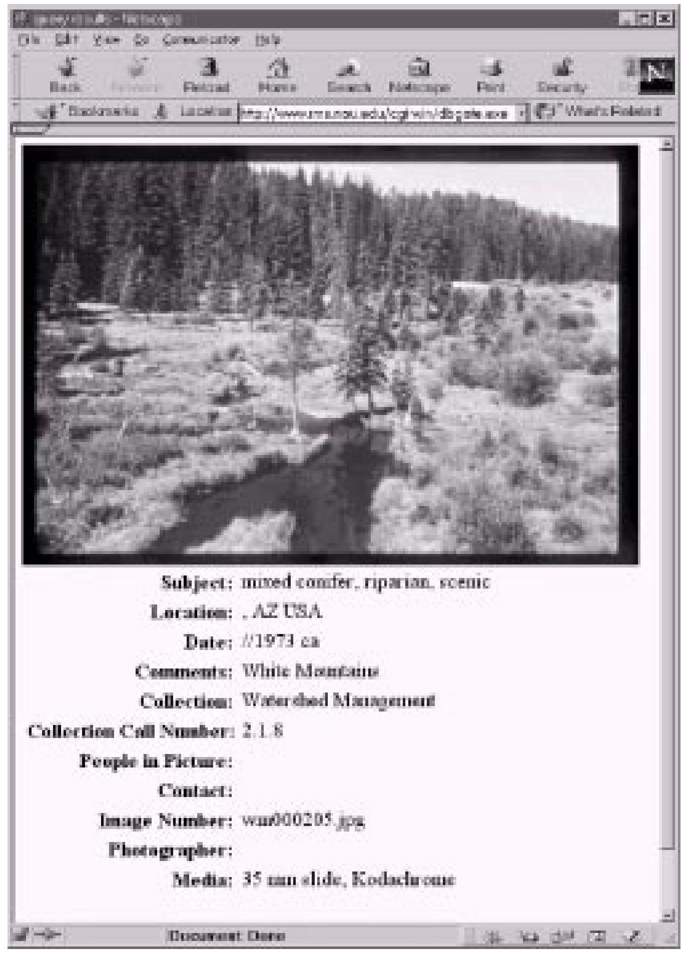

Figure 5. The larger scanned image that results from clicking on a thumbnail in figure 4.

Management Implications

Availability of a searchable image data base is a valuable asset to researcher, educators, and interested publics, particularly when it is available on a Web site. Researchers and educators are frequently asked to give technical and informational presentations to various interest groups. These presentations are more interesting when accompanied by slides. However, as the number of available images increases, the more time consuming it becomes to retrieve, use, and refile these images for future application. Although we are not advocating solicitation of images from individuals outside your work unit, our process allows for the exchange of images between colleagues.

With the advances in computer technology, it is expeditious and responsible to spend a little time documenting and archiving graphical data so the original expense of collecting is not lost and to ensure that these data are more readily available.

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Accessing a Personalized Bibliography with a Searchable System on the World Wide Web

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Abstract.—Researchers, educator's and land management personnel routinely construct bibliographies to assist them in managing publications that relate to their work. These personalized bibliographies are unique and valuable to others in the same discipline. This paper presents a computer data base system that provides users with the ability to search a bibliography through the World Wide Web (Web). To illustrate this system, a bibliography of publications produced by the USDA Forest Service and its cooperators is used. Users can search the references on the Web using parameters such as date, author, key words, title, or a combination of these fields. This procedure can increase the accessibility and value of personalized bibliographies.

Introduction

Computerized bibliographies are commonly used to manage publications relevant to one's discipline. Substantial time investment is needed to construct and maintain such personalized bibliographies. The time investment is justified because of the value of a searchable bibliography that is topically focused and relevant to one's discipline. This paper describes a computer data base system that capitalizes on the time investment by sharing the bibliography over the World Wide Web (Web) in a searchable form.

Methodology

Web access is the only requirement for access to the bibliography used in this example. However, if users want to make their bibliographies available to others, they must have access to a Web server with specialized software (a common gateway interface) that links to data bases. Users should consult with their local system administrator or computer technician to investigate options. If users want others to be able to download full-text copies of publications, they will also need access to a flatbed scanner and optical character recognition software.

Reference Documentation

Today, most researchers and educators use software to store and retrieve reference material. Because of the number of publications and rate that information is being produced, using a computer data base to track and maintain information in their fields of interest is necessary. To illustrate how this computer system works, we used a collection of annotated references for publications produced from the Beaver Creek watershed project in north central Arizona; a USDA Forest Service, Rocky Mountain Research Station project located at Flagstaff, Arizona. The Beaver Creek project was established in 1956 in response to public concern that the flow of streams and the amount of forage for livestock and wildlife on watersheds in the Salt-Verde River Basins were being reduced by increasing densities of ponderosa pine saplings and pinyon-juniper trees (Baker 1999). Nearly 700 publications were produced as a result of this project from 1956 to 1996 (Baker and Ffolliott, 1998). This bibliography of references is currently available at http://www.rms.nau.edu/beaver_cr/.

Reference Retrieval

The Beaver Creek bibliography is partitioned into 24 subject areas. Simple searches of the data base can be done using the format in figure 1. Five search options are available including keywords (subject areas), titles, authors, abstract, and publication information. The keyword option provides a drop down list for easy access and application. By reviewing this drop down list, one merely has to identify an area of interest, highlight it, click, and then click Go. To illustrate, selecting the Economic subject area, provides a listing of 63 references in this category. In the title search option, one can enter any keyword or phrase, for example, ponderosa pine, and get a listing of

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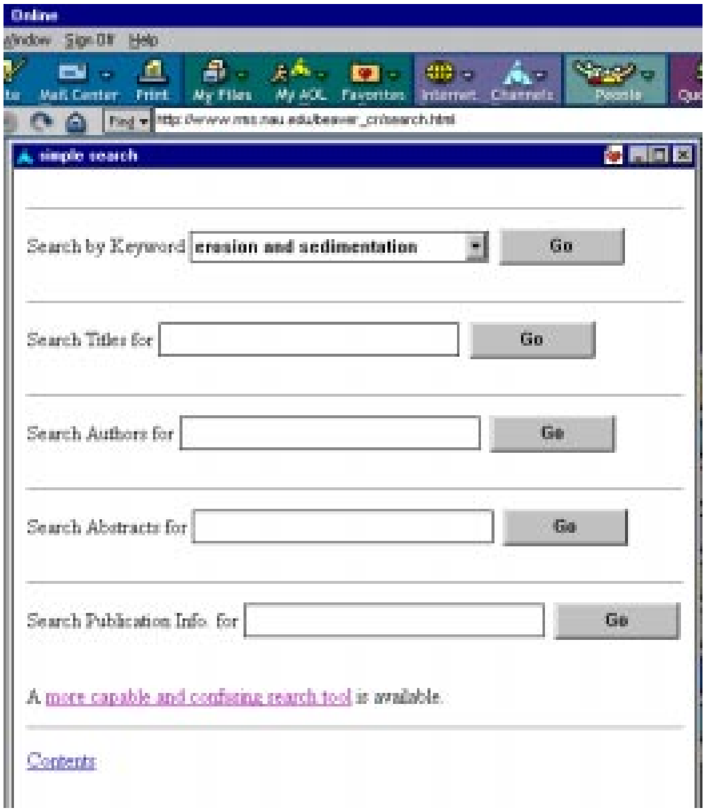

Figure 1. Format for simple searches of the Beaver Creek bibliography.

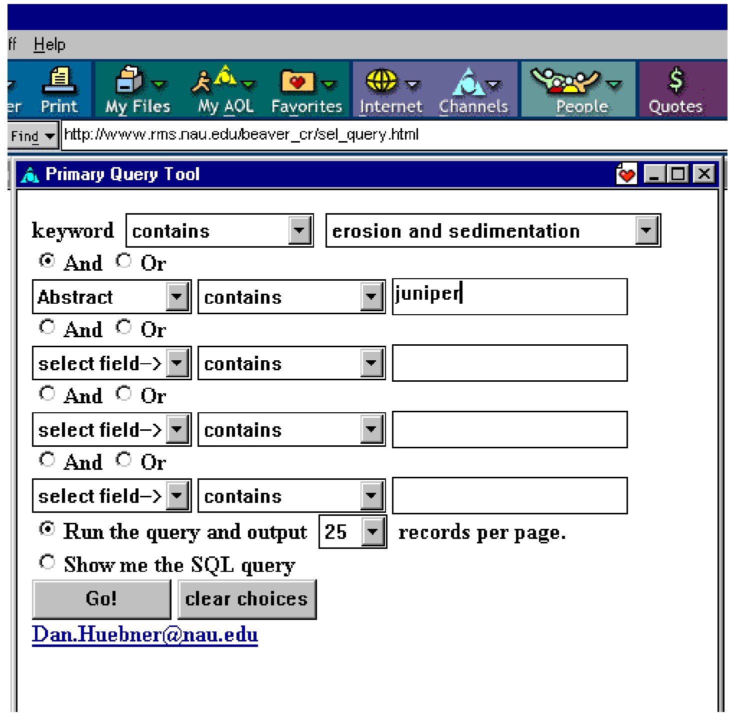

Figure 2. Layout of options available for making complex searches of the Beaver Creek bibliography.

137 references that have ponderosa pine in the title. Search of the author, abstract, and publication options are similar.

Often during a search process, a narrowly structured search is needed. Such a search is accomplished by selecting the option at the bottom of the simple search screen (figure 1) *A more capable search tool is available*. A search the of Beaver Creek bibliography for the author Ffolliott, produces a list of 215 publications. However, using the more complex search option, one can ask for author Ffolliott and publications since 1990, to obtain a narrow list of 45 (figure 2). As figure 2 indicates, there are many search options available. Users can input data into some or all subject areas, and use various combination of other fields either with or without delimiters.

Document Retrieval

Finding the reference accomplishes only half the task. In the past, after locating the desired reference, users would have to find and obtain the hardcopy from personal reprints, journals, or libraries. Today, many libraries have much of their reference material computerized, and access to these sources is becoming easier through the Web. Many people have hundreds of reprints that are a valuable source if users can access them. In the 21st century, accessibility to information will become even easier and faster. A commonly used form for delivering formatted documents online is an Adobe Acrobat file. This software allows users to view a document and print it in a format that is nearly identical to the paper original. The immediacy of this type of document retrieval is of great value.

Our computer system can archive and retrieve documents electronically. Although not all of the Beaver Creek documents are available online, we have a number of publications online to illustrate what is possible. These publications have been scanned and electronically stored so that they can be viewed and downloaded from our Web site. However, copyright laws also pertain to online publications. For copyrighted publications, appropriate approval is necessary. The History of Watershed Research in the Central Arizona Highlands, a USDA Forest Service publication, in the public domain, is currently available and not copyrighted.

Management Implications

Researchers and educators must continually peruse numerous publications and other sources of information to remain current in their fields of interest, and to document their publications and presentations. However, with the proliferation in publications and other sources of information, this process is becoming time consuming and difficult to catalogue, store, and retrieve. The availability of searchable, personalized bibliographic data bases is a valuable asset to researchers, educators, managers, and interested publics in obtaining information. Their availability on a Web site makes it easier and faster to obtain the reference, and ultimately the publication.

Computerized data bases on a Web site with searching capabilities can make reference searches easier, less time consuming, and increase our ability to share information. In this example, we used a bibliographic data base that includes publications from a specific project. However, individuals with common interests may wish to develop common reference collections, for example, a data base of riparian information. This can be accomplished with a minimum of expertise and expenditure of effort. Great strides have been made in the last century in all areas of watershed management. However, the challenge today is to efficiently use this information in solving problems with and management of our natural ecosystems. One way to accomplish this is to ensure that information is readily available.

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The authors wish to thank Linda M. Ffolliott, Information System Specialist, College of Agriculture, University of Arizona, Tucson, AZ and David W. Huffman, Research Specialist, School of Forestry, Northern Arizona University, Flagstaff, Arizona, for their comprehensive reviews of this paper.

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Dissemination of Watershed Management Information through the World Wide Web

Malchus B. Baker, Jr.[1] and Deborah J. Young[2]

Abstract.—Information and related literature on watershed management practices is sometimes not widely known nor readily accessible. New electronic technologies provide unique tools for disseminating research findings to scientists, educators, land management professionals, and the public. This paper illustrates how the usefulness and accessibility of research information from the Beaver Creek Experimental watershed in north central Arizona increases using the World Wide Web.

Introduction

Watershed management is formulating and implementing actions that manipulate natural and human resources for specific objectives. Watershed management in arid and semiarid regions is difficult because water supplies and resource productivity are limited. Watershed research, spearheaded by the USDA Forest Service and its cooperators, leads to increased understanding of the hydrology and ecology of our environment. This research effort also helps define management guidelines to meet the needs of a growing population in the Southwestern United States.

In the 20th century, our knowledge of all aspects of watershed management and our ability to manage our natural ecosystems has greatly improved. Simultaneously, dramatic changes in land management, partially as a result of the public's changing attitude about our environment, occurred. These changes will greatly effect management policies and actions in the 21st century. To help land managers make better management decisions, we must use computer technology to disseminate research information. Information obtained by the Forest Service and its cooperators from research on the Beaver Creek watershed study in north central Arizona illustrates technology transfer techniques.

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Web Site

The Internet's World Wide Web (Web) is a major technology transfer vehicle. The Web is a cost-effective way to transfer information between world regions that are challenged by similar environmental problems. In addition, using the Web, information is regularly and easily updated and revised. A Web site on the sustainable management of semiarid watersheds (http://ag.arizona.edu/OALS/watershed/index.html) features information from the Beaver Creek project. This site contains an annotated bibliography complied by M. B. Baker, Jr. and P. F. Ffolliott (Baker and Ffolliott 1998). The bibliography contains references to approximately 700 articles produced during 40 years of investigations on Beaver Creek and is an important source of natural resource information about ponderosa pine and pinyon-juniper vegetation types in the Southwestern United States. These references, dating from 1956 through 1996, cover 24 subject areas including climate, erosion control, hydrology, water-yield improvement, and silviculture.

Introductory Topics

The home page of this Web site (Watershed Management in the Southwest with Information from the Beaver Creek Biosphere Reserve) includes links to introductory topics (water and watersheds, public land responsibilities, and environmental aspects) and in-depth information on the central Arizona Highlands in general and on the Beaver Creek Biosphere Reserve in particular. A biosphere reserve is a component of a worldwide network of ecosystems in Unesco's Man and the Biosphere (MAB) Program. These areas are set aside for study and investigation of various ecosystem components. Each Web page has a search engine and a list of related Web sites on watershed management.

The Introductory Topics link includes sublinks to frequently asked questions and answers about water, watershed management, and environmental issues. Questions such as:

- What is a watershed?
- What is a riparian area?
- What is erosion?

Topics such as:

- water harvesting
- watershed safety
- stock tanks,
- climate and vegetation types of the central Arizona Highlands are addressed in 1 or 2 page fact sheet. The fact sheets were reviewed by subject matter experts from the Southwestern United States and can be printed and reproduced for use in various educational settings.

In-Depth Information

Topics on the In-depth Information page include:

- Training course in watershed management by Peter F. Ffolliott, University of Arizona, about the hydrologic cycle, water resource management, effects of management programs on water resources, and study questions.
- The Central Highlands Plateau of Arizona includes climate descriptions, vegetation types, and geographic regions where watershed research occurs.
  1. General Information
     - Climate and Vegetation Types of the Central Arizona Highlands contains a general description of the area's climate and specific information about mixed conifer, ponderosa pine, pinyon-juniper, chaparral, and riparian area vegetation.
     - Prescott Active Management Area discusses the 1980 Arizona Groundwater Code related to this area.
  2. Vegetation types contains specific information on vegetation distribution, soil type, climate preferred, and associated plant and animal species lists. Vegetation types in the Central Arizona Highlands include:
     - mixed conifer forests
     - ponderosa pine
     - mountain grasslands
     - pinyon-juniper woodlands
     - chaparral shrublands
     - riparian areas
  3. Geographic Regions contains detailed information on the various research sites studied by the USDA Forest Service in the central Arizona Highlands including:
     - Beaver Creek watersheds
     - Whitespar watersheds
     - Sierra Ancha watersheds
     - Three-Bar watersheds
     - Mingus Mountain watersheds
     - Battle Flat watersheds
     - Castle Creek watersheds
     - Willow Creek watersheds
     - Thomas Creek watersheds

Currently, of the above 9 geographic regions, the Beaver Creek watershed is linked to the greatest amount of additional information including:

- About the Beaver Creek Program
- Why Beaver Creek?
- Getting the Project Rolling
- Measuring Results
- Pinyon-Juniper Treatments and Results
- Tour of the Beaver Creek Watershed
- The Treatment Watersheds

  Access by clickable map

  Access by text index
- Plants and animals of the watershed
- Application for Designation of the Beaver Creek Watershed as a Biosphere Reserve
- Bibliography

The other 8 geographic regions are linked to currently available information.

4. History of the Arizona Watershed Program (Baker 1999) describes the history of all watershed research spearheaded by the USDA Forest Service and its cooperators across the central Arizona Highlands.

This Web site is currently linked to the USDA Forest Service, Rocky Mountain Research Station site (http://www.rms.nau.edu/lab), the International Arid Lands Consortium site (http://www.ialc/), the University of Arizona College of Agriculture site (http://ag.arizona.edu/), and AgNIC (http://ag.arizona.edu/OALS/agric/home/html), as well as others. This Web site provides a unique opportunity to combine the strengths of the USDA Forest Service as a major repository of watershed management information, the commitment of the University of Arizona Cooperative Extension to educational training and information dissemination to off-campus audiences, and the expertise of the University of Arizona Arid Land Information Center for the necessary Web site management.

Management Implications

The increased availability of the Beaver Creek data benefits professional practitioners, consultants, industrial personnel, students and faculty, citizens, federal, state, and local agencies, and policy makers. Disseminating practical and field-tested data on watershed management via the World Wide Web, provides a valuable service to the worldwide community of practitioners, educators, and policy makers. In addition, this project increases the usefulness of scientific information by helping the public make informed decisions about their natural resource use. Better access to land management information and technology contributes to the increased sustainability of semiarid watersheds.

A tremendous amount of data on all aspects of watershed management have been collected by various public agencies during the 20th century. Often, much of these data are lost or forgotten after a study ends. Computer technology, allows us to document and archive these data to ensure continuous, readily available access through the 21st century.

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The authors wish to thank Peter F. Ffolliott, Professor, School of Renewable Natural Resources, University of Arizona, Tucson, Arizona, and David W. Huffman, Research Specialist, School of Forestry, Northern Arizona University, Flagstaff, Arizona for their comprehensive reviews of this paper. Development of this web site was supportetd in part by funds provided by the International Arid Lands Consortium.

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Increasing the Visibility of Watershed Management as a Land Management Profession

Daniel G. Neary[1], Peter F. Ffolliott[2], and Kenneth N. Brooks[3]

Abstract.—Population increases will continue to severely pressure water resources in the 21st century. Consequently, the importance of watershed management will increase. The potential demand in the next century for information on, and individuals skilled in, watershed management raises several important issues: the need for watershed management to have a central voice to gain the attention of political, government agency, university, and business leaders; the adequacy of watershed management professional training; the need to identify watershed management as a discipline; and the need for a new organization with a central focus on watershed management to support for watershed management professionals. This paper addresses and solicits inputs on these issues to advance the watershed management into the 21st century.

Introduction

The importance of watershed management will continue to grow in the 21st century (Rango 1995). Population increases will continue to put severe pressure on finite and, in some instances, diminished water resources (Simon 1998). Other natural resources derived from managed watersheds, including wood, range, wildlife habitat, and recreational opportunities, will also be in high demand. In addition, many countries recognize the need to sustain ecosystems in order to perpetuate the flow of goods and services that natural resources provide. These countries have found the political will to go on record in the Santiago Declaration on forest sustainability to support sustainability as a goal of resource management. As Brooks et al. (1992) pointed out, proper watershed management is really the key to sustainability.

In an era when specialization is the model in most professional disciplines, watershed management is an exception. Watershed management synthesizes information by stressing integration of information from different disciplines to cope with complex spatial and temporal issues and problems that are due to the linkages between land and water (i.e., cumulative watershed effects). What is watershed management?

Satterlund and Adams (1992) state that: "Watershed management is the management of all the natural resources of a drainage basin to protect, maintain, or improve its water yields." Similar definitions, which are either more narrowly or widely defined, have been used throughout the 20th century (Neary this publication). Lee (1980) described watershed management as the "vocational counterpart" of forest hydrology. We suggest that watershed management is a widely defined discipline that represents an approach to natural resource management encompassing many disciplines. Watershed management provides a workable framework and a system for many disciplines to work together to manage land and water resources in a sustainable manner. Is it a vocation as Lee (1980) suggests? In the case of municipal watershed management, it is a defined vocation as exhibited in job advertisements. In a broader context, although we see watershed management programs and projects emerging because of needs (Neary 2000), there does not yet seem to be a widespread call for professionals in watershed management. But, such a demand may be forthcoming (Lant 1999).

The potential demand in the next century for information on, and individuals skilled in, watershed management raises several important questions. Should watershed management have a central voice to gain the attention of civic, state, national, and international political representatives, government agency decision makers, and university and business leaders? If the answer to this question is "yes", is watershed management a distinct profession? Should watershed management be supported by a professional society that focuses on watershed management? Or, should watershed management gain a greater emphasis within other, recognized professional societies? Is there an adequate number of natural resource professionals trained in, or training for the discipline of watershed management? Are existing natural resources societies adequately developing watershed management professionals for the 21st century?

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Professional Status of Watershed Management

Education

Educational programs have focused on watershed management for several decades. In the early 1960s, many universities in the Western United States offered degrees in Watershed Management. During this era, emphasis was placed on multiple use of public lands, and watershed management provided an important multi disciplinary background for natural resource managers. Interest in such programs leveled off in the 1970s and 1980s. With the rising international and national concerns over sustainable development, interest in the watershed management discipline has re-emerged.

The challenge for academia is to recognize the importance of watershed management and to produce graduates with the depth and breadth of knowledge and skills to provide a watershed management perspective to engineering, natural resource, urban development, social, and political programs. However, several questions need to be asked. To what extent can or should people be educated in watershed management? How best can this education be accomplished? What should constitute an academic program in watershed management? Should an academic program in watershed management be a graduate degree following an undergraduate degree in a natural resource discipline, a basic science, or an engineering field? Does an adequate professional society exist to ensure the continued development and certification of watershed management professionals?

Professional Society Support

Professional support for watershed management is currently fragmented among many natural resources and land management professional societies (table 1). To analyze the level of support of and interest in watershed

Table 1. Organizations with activities and a level of focus in watershed management.

Organization Name	Type	Focus
American Fisheries Society	Science	Low
American Geophysical Union	Science	Low
American Institute of Hydrology	Science/education	Medium
American River Management Society	Management	Medium
American Society of Agricultural Engineers	Management/science	Medium
American Society of Civil Engineers	Management/science	Medium
American Water Resources Association	Science/education	High
Ecological Society of America	Science	Low
Geological Society of America	Science	Low
International Association of Hydrological Sci.	Science	Medium
International Association on Water Quality	Trade/management	Low
International Water Resources Association	Science/management	High
IUFRO Unit 8.03.02 Forest Hydrology	Science	Medium
IUFRO Unit 8.04.04 Watershed Management	Science	High
National Water Resources Association	Management	High
Society for Range Management	Science/management	Medium
Society of American Foresters	Management/science	Medium
Society of Wetland Scientists	Science/management	Medium
Soil and Water Conservation Society	Management	Medium
Soil Science Society of America	Science	Low
Water Environment Federation	Education/technical	Low
Water Quality Association	Trade	Low
Watershed Management Council	Educational	High

management by these organizations, we will examine their mission statements. Only those with medium or high levels of focus are considered in this discussion.

The Society of American Foresters (SAF) mission "...is to advance the science, education, education technology, and practice of forestry; to enhance the competency of its members; to establish professional excellence; and to use the knowledge, skills and conservation ethic of the profession to ensure the continued health and use of forest ecosystems and the present and future availability of forest resources (i.e., water, wood, wildlife, recreation, range, nontraditional products, etc.) to benefit society...." (SAF 1999). The SAF Water Resources Working Group "...Focuses on forest hydrology and watershed management....". This organization's focus is forestry and forest land management, although watershed management is part of one of its smaller working groups. The SAF publishes several journals (e.g., *Forest Science, Journal of Forestry*, and the regional *Southern, Northern and Western Journal(s) of Applied Forestry*.

The Society for Range Management's (SRM) mission is "...to promote and enhance the stewardship of rangelands to meet human needs based on science and sound policy." (SRM 1999). As part of its concern about "...studying, conserving, managing, and sustaining the varied resources of the rangelands which comprise nearly half the land in the world....", this society addresses watershed management. Unlike the Society of American Foresters, the SRM organizational sections are geographical rather than disciplinary. Thus, they do not focus on watershed management. Two journals are published by the SRM, the *Journal of Range Management* and *Rangelands*.

The American Institute of Hydrology (AIH) was established primarily to "...strengthen the standing of hydrology as a science and a profession by: establishing standards and procedures to certify individuals qualified in hydrology, establishing and maintaining ethical standards, providing education and training in hydrology, and providing the public and government advice and guidance..." AIH (1999). Although the AIH provides certification for hydrologists, it does not implicitly list watershed management as a focus. The AIH publishes one professional Journal, *Hydrological Science and Technology*.

Two divisions of the International Union of Forest Research Organizations (IUFRO), 8.03.02 (Forest Hydrology) and 8.04.04 (Watershed Management, previously named Erosion Control by Watershed Management) emphasize watershed management (IUFRO 1999). These organizations are research-oriented and do not serve management professionals. They also do not have regular publications. Division 8.03.02's mission is, "To promote and advance the science of forest hydrology and to encourage the exchange of information and ideas....". Division 8.04.04 focuses on erosion, but it considers the broader concepts of the physical, chemical, and biological systems that interact within a watershed to produce an array of landforms, channels, streamflows, and sediment yields. This approach evaluates erosion control projects as part of larger watershed management efforts.

The International Association of Hydrological Sciences (IAHS) is the oldest nongovernmental organization concerned with hydrology and water resources (IAHS 1999). Established in 1922 "...for the study of all aspects of hydrology, ... publication of research results, and the initiation and coordination of research....", IAHS has a primary focus on research related to hydrology and watershed management. IAHS publishes the *Hydrological Sciences Journal* and other special publications, but does not certify its professional members.

The Soil and Water Conservation Society (SWCS) "...fosters the science and the art of soil, water, and related natural resource management to achieve sustainability...." (SWCS 1999). SWCS is an international organization of professionals and students that promotes soil and water conservation. This organization publishes the *Journal of Soil and Water Conservation* and certifies members in erosion and sediment control.

The Society of Wetland Scientists (SWS) was founded "...to encourage and evaluate the educational, scientific, and technological development and advancement of all branches of wetland science and practice, and to encourage the knowledgeable management of wetland resources...." (SWS 1999). SWS publishes the journal *Wetlands* and provides a certification program. As indicated in its objectives statement and name, SWS is more narrowly focused on wetlands.

The American River Management Society (ARMS) is a recent organization founded "...to promote the protection and management of river resources...." (ARMS 1999). ARMS was originally formed to promote river recreation, but it has since broadened its mission. This organization is dedicated to understanding river basin management using an ecosystem management approach, and developing member professional skills.

The International Water Resources Association (IWRA), an international organization promoting interdisciplinary dialog and cooperation related to water resources, was founded for the "...advancement of water resources planning, management, development, technology, research and education at international regional and national levels..." (IWRA 1999). IWRA promotes international dialog, information dissemination, and water resource programs through the triennial World Water Congress. The IWRA publishes the journal *Water International*, and does not have any certification program.

The National Water Resources Association (NWRA) is a federation of local and state agencies, commercial companies, and individuals that provide political advocacy for sound development, use, and protection of water and land resources at a national scale. This group publishes specialty papers, but no journals.

The Watershed Management Council's (WMC) original focus was on California issues, but it has since expanded to include concerns in 28 state and 3 countries. WMC has a wide range of activities central to its mission of "...promoting proper watershed management...." (WMC 1999). The council publishes a newsletter and is an advocate for watershed management, but it does not function as a professional society.

The American Water Resources Association (AWRA), a primary professional support organization for watershed management professionals, has a mission "...to promote understanding of water resources and related issues by providing a multi disciplinary forum for education, professional development and information exchange." (AWRA 1999). AWRA promotes water resources research and management through special conferences and proceedings, the *Journal of the American Water Resources Association*, and the *Water Resources Impact* newsletter. The AWRA is organized into geographic chapters. Of the membership areas of expertise, hydrology (19%), water resources (14%), hydrogeology/groundwater (13%), water management (10%), and water quality (6%) are the most common (AWRA 1999). Watershed management is not listed as an "expertise code" on the AWRA membership application. The AWRA does not provide any certification similar to some other professional societies (Soil Science Society of America, Soil and Water Conservation Society, Society of American Foresters, American Institute of Hydrology, etc.). However, AWRA is currently sponsoring a national dialog on concerning the need for professional watershed management certification (Ditschman 1999, Seaburn 1999, Pawlukiewicz and Norton 1999, Witter et al. 1999).

Both the American Society of Civil Engineers (ASCE) and the American Society of Agricultural Engineers (ASAE) recognize the importance of watershed management within the engineering profession (ASAE 1999, ASCE 1999). ASAE has a Soil and Water Division within its professional structure, and the ASCE has a Water Resources Engineering Division and a Water Resources Planning and Management Division. These divisions of ASCE sponsor a major watershed management symposium every 5 years. The next symposium, "Watershed Management 2000: Science and Engineering Technology for the New Millennium", June 2000, contains 22 topic areas that relate to watershed management (ASCE 1999).

The support provided by these organizations is important to the practice of watershed management. However, debate remains about the need to organize a professional society, or some other form of organization, that focuses its institutional mission solely on watershed management and watershed management practices.

Soliciting Input

A questionnaire was available to the conference participants, soliciting their thoughts on the need to identify watershed management as a separate profession or heighten the visibility of watershed management as a land management discipline. These participants, representing international, national, and regional perspectives, were a diverse group of researchers, managers, administrators, and other public appreciative of the contributions that watershed management has made to land stewardship in the past, demonstrated in this conference, and anticipated in the future.

Some key questions asked were:

1. Does watershed management need a heightened level of recognition as a separate land management profession?
2. If so, are watershed management professionals adequately supported by existing societies and organizations?
3. What professional organizations do you belong to?
4. What could these organizations do to improve their support to watershed management professionals?
5. Would you be willing to support a separate organization called the Watershed Management Society?
6. What type of publications should a separate watershed management organization support (e.g., newsletters, specialty papers, proceedings, journal, etc.)?
7. Should a separate watershed management organization provide a certification service?

Future Follow-Up and Recommendations

A summary of responses to this questionnaire will be available to the participants, and published on the University of Arizona's Watershed Management web site (UA 1999). The authors will develop a follow-up paper for publication in a widely distributed professional journal. Future actions could include examination of the possibilities of establishing a separate watershed management society, participating the AWRA's watershed management professional certification dialog, or encouraging other land management professional societies (ARMS, ASCE, SAF, SRM, SWCS, SWS, etc.) to become more active in the area of watershed management professional development and support. The authors encourage readers to examine the current discussions going on within the AWRA (Ditschman 1999, Seaburn 1999, Pawlukiewicz and Norton 1999, Witter et al. 1999).

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RMRS
ROCKY MOUNTAIN RESEARCH STATION

The Rocky Mountain Research Station develops scientific information and technology to improve management, protection, and use of the forests and rangelands. Research is designed to meet the needs of National Forest managers, Federal and State agencies, public and private organizations, academic institutions, industry, and individuals.

Studies accelerate solutions to problems involving ecosystems, range, forests, water, recreation, fire, resource inventory, land reclamation, community sustainability, forest engineering technology, multiple use economics, wildlife and fish habitat, and forest insects and diseases. Studies are conducted cooperatively, and applications may be found worldwide.

Research Locations

Flagstaff, Arizona
Fort Collins, Colorado*
Boise, Idaho
Moscow, Idaho
Bozeman, Montana
Missoula, Montana
Lincoln, Nebraska
Reno, Nevada
Albuquerque, New Mexico
Rapid City, South Dakota
Logan, Utah
Ogden, Utah
Provo, Utah
Laramie, Wyoming

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