United States
Department of
Agriculture

Forest Service

Pacific Northwest
Forest and Range
Experiment Station

General Technical
Report
PNW-180
April 1985

Proceedings of a Workshop on Slope Stability: Problems and Solutions in Forest Management

This file was created by scanning the printed publication. Mis-scans identified by the software have been corrected; however, some errors may remain.

Papers were prepared in camera-ready form for printing by the authors, who are therefore responsible for the content and accuracy. Opinions expressed may not necessarily reflect the position of the U.S. Department of Agriculture.

The use of trade, firm, or corporation names in this publication is for the information and convenience of the reader. Such use does not constitute an official endorsement or approval by the U.S. Department of Agriculture of any product or service to the exclusion of others that may be suitable.

Proceedings of a Workshop on Slope Stability: Problems and Solutions in Forest Management

Seattle, Washington
February 6–8, 1984

Doug Swanston
Technical Editor

Sponsored by:
USDA Forest Service
University of Washington,
College of Forest Resources
Oregon State University,
College of Forestry

Published by:
U.S. Department of Agriculture, Forest Service,
Pacific Northwest Forest and Range Experiment Station,
Portland, Oregon
General Technical Report PNW-180
April 1985

CONTENTS

Page

FOREWORD -- Douglas N. Swanston iv

KEYNOTE ADDRESS

Landslides on Steep Forested Terrain: The Problem and Resource Management Implications . . . .
F. Dale Robertson

EXTENT OF PROBLEM

Survey of Slope Stability Problems on Forest Lands in the West 5
Edward R. Burroughs, Jr.

Factors Influencing the Stability of Slopes 17
R. C. Sidle

Landslide Damage to the Forest Environment 26
George W. Brown

CURRENT TECHNIQUES FOR PROBLEM SOLVING

Pitfalls in the Strict Reliance on Expert Opinion in Assessing Stability Hazard . . 30
James A. McNutt and Dale McGreer

Subjective Techniques for Identification and Hazard Assessment of Unstable Terrain . 36
Dale Wilson

The Engineering Approach to Landslide Risk Analysis 43
W. L. Schroeder

Computer-based Landslide Delineation and Risk Assessment Procedures for Management Planning 51
Tim J. Ward

PRACTICAL FIELD APPLICATION OF AVAILABLE METHODOLOGIES

A Serendipitous Integration of Research with Management Needs--The British Columbia Fish/Forestry Interaction Program 58
V. A. Poulin

Harvest Planning and Layout on Steep Terrain--The Siuslaw Model 64
George Bush

Use of Soils and Geomorphic Information for Road Location and Timber Management in the Oregon Coast Ranges 68
Byron R. Thomas

Road Location in Sensitive Watersheds: An Industry Perspective 78
S. H. Duncan

Landslide disaster Assessment in the Wasatch Range 81
Paul Winkelaar

Applications of Geotechnical Data to Forest Management 87
Tom Reilly and Bill Powell

A Complete Three-level Approach for Analyzing Landslides on Forest Lands 94
Rodney W. Prellwitz

Page

PANEL DISCUSSIONS: NEEDS AND LIMITATIONS FOR EFFECTIVE LAND MANAGEMENT RISK ASSESSMENT OF POTENTIALLY UNSTABLE TERRAIN

Opening address: Decisionmaking in the Presence of Risk 99
Stefan D. Bloomfield

Panel 1—Comments by Practicing Land Managers on the Question: What Levels of Political/Social Influence on Risk are Appropriate in Forest Land Management Decisionmaking?

Dan Bigger 105

Paul Swateck 106

R. T. Bailey 107

John T. Drake 109

Neil Skill 109

Panel 2--Comments by Practicing Land Managers on the Question: How Do the Concepts of Risk Influence Field Decisions?

Soteco Muniz 110

Leo W. Wilson. 111

Melvin L. Kessel 112

Joseph H. Harn 112

Kenneth D. Weyers 113

Panel 3--Comments by Practicing Land Managers on the Question: Given the Social-Political Constraints Imposed on the Land Manager and Levels of Risk Currently Acceptable, What Information and Levels of Application are Needed for Improved Land Management Decisionmaking?

W. W. Bourgeois 114

Dick Olsen 116

Dale J. McGreer 117

Michael J. Cook 118

Ted, Stubblefield 118

WORKSHOP SUMMARY

Status of Enowledge--Reliability of Techniques--Direction for Improved Decisionmaking
Jeff Sirmon 120

METRIC EQUIVALENTS 122

FOREWORD

Forest and related resource management in mountainous areas of the western United States, Canada, and Alaska is severely restricted by unstable'terrain that is susceptible to soil movement varying from surface creep to catastrophic landslides. Management practices that might trigger or increase such disturbance are increasingly subject to public scrutiny.

Land managment planning as required by the Resources Planning Act (RPA) (PL93-378), the National Forest Management Act (NFMA)(PL94-588), the Resource Conservation Act (RCA) (PL95-192) and other Federal and State laws requires that soil stability receive strong consideration in long-range-plans. Accordingly, planners have a critical need for the best possible information on soil stability and risk of landslides, and potential impacts on other resources.

Much research and development work has been done in the West by public agencies, industry, and universities on the causes, effects, prevention, and impacts of soil movement. The largest project of this nature has been the USDA Forest Service's Interstation Soil Mass Movement Research Program which was begun in 1972. This effort is being conducted by threewestern Forest Service Experiment Stations (Pacific Southwest, Pacific Northwest, and Intermountain Forest and Range Experiment Stations) working in close cooperation with the western Regions of the Forest Service, the Bureau of Land Management, western States, universities, and others concerned with slope stability problems. Since the program began, more than 100 technical reports have been produced, and land managers and researchers have made significant progress in applying the information in the field. In February 1984 a workshop on "Slope stability: problems and solutions in forest management" was held at the Univeristy of Washington, Seattle, and was designed to give high-level administrators, decisionmakers, and planners a current perspective on the status of these research and administrative studies, key findings, and how new information is being applied.

Publication of the proceedings of this workshop accomplishes two primary purposes. The first is to bringing together in coherent form, and from as wide a range of experience as possible, information on resources and techniques useful to the land manager who must identify, assess, and mitigate the risk of soil mass movements from steep, forested terrain. The second is to define managerial risk and provide a forum for the expression by land managers of views on the concepts of risk in forest land management decisionmaking. Foremost among these views are the perceived needs, in terms of data and techniques, for effective risk assessment given current social and political constraints.

The concepts, techniques, and applications presented constitute some of the best and most successful approaches currently being applied by specialists and land management decisionmakers. They are, by no means, the only viable approaches to assessment and management of this difficult terrain. After all, there is no single "best approach" applicable under all conditions. Laird managers are encouraged to consult soils, hydrology, and geotechnical specialists with specific local knowledge and experience for guidance in applying these or similar approaches.

KEYNOTE ADDRESS

LANDSLIDES ON STEEP FORESTED TERRAIN: THE PROBLEM AND RESOURCE MANAGEMENT IMPLICATIONS

F. Dale Robertson

INTRODUCTION

I always look forward to escaping the Washington, D.C., environment and appreciate the opportunity to return to the Pacific Northwest where the real action in forestry is.

It was a little over 10 years ago, when I was a brand new Forest Supervisor at the Siuslaw National Forest, that I first faced the challenge of trying to practice forestry on unstable terrain. I remember arriving in November 1973, and it was raining as usual. In that month we set an all-time record in Corvallis, Oregon, of 20 inches of rain. At that time, it seemed to me that the soil started to slip the moment I arrived. During that first winter we had a lot of landslides, slumps, and debris flows in the forest.

As most of you probably know, the Siuslaw National Forest is located in the Coast Range of Oregon. It has some of the most productive timber-growing land in the world, as well as some of the most productive streams for anadromous fish. Unfortunately, the Siuslaw has a lot of especially steep, unstable country, which creates the potential for a basic conflict between two very valuable and important resources — timber and fish.

By winter 1973, the controversy over timber harvesting and road building practices had built up to the point where the Oregon Wildlife Commission and the fisheries interests were no longer willing to let existing management practices continue unchallenged. In analyzing the situation, the Siuslaw National Forest staff basically agreed with many of the concerns expressed by the Oregon Wildlife Commission and decided that some change in management practices was in order. The Forest initiated an effort to bring state-of-the-art knowledge and technical expertise to bear on the Siuslaw problem. This effort also highlighted the weaknesses in the knowledge and helped focus the objectives of the newly formed Forest Service Mass Soil Movement Research Program. This was when I first met a young scientist, Doug Swanston, who came to Corvallis to help me out with my problem. It's times like this when land managers really learn to fully appreciate their colleagues in research.

Purposes of Workshop

Unlike Doug, who is still making a career out of landslides and mass soil movements, I've gone on to other things. Because of my experience at the Siuslaw, though, I've retained a high interest in slope stability; but my knowledge of the subject is really about 5 years out of date. I am looking forward to participating in this workshop, just to see how much progress has been made over the past 5–10 years.

F. DALE ROBERTSON is Associate Chief of the Forest Service, U. S. Department of Agriculture, Washington, D.C.

I think everyone has learned a lot more about slope stability since my time at the Siuslaw. Research has given us a better understanding of the mechanics of slides--of how they're triggered and how they progress. Research has also developed better assessment procedures and predictive techniques that can help to identify unstable ground and areas and situations where there is high risk of soil movement. In the next 3 days we will be talking about what is known as a result of research and identifying high-priority areas where more research is needed. Feedback is needed from the land .manager on where the research program should be headed.

We have a lot more experience, too. Faced with decisions in steep, forested terrain, many land managers have taken research information and developed their own field techniques for assessing landslide hazards and risks. Look around; assembled in this room are probably more than 2,500 years of collective experience in unstable terrain — so another important purpose of this workshop is to let us share what has been learned in those years through experience and sometimes through painful trial and error.

Just to keep things in perspective, I think we should keep in mind that this problem is old and widespread, The problems of unstable terrain are not confined to the Pacific Northwest, but occur in most states and provinces,--in fact, all over the world. Last year there were mudflows in Utah that threatened Salt Lake City and other communities along the Wasatch Front. In 1981 and 1982 there were mudflows near San Francisco and at other places along the California coast. In Fairfax County, Virginia, there's a strong county ordinance controlling construction on unstable lands. One house near where I live was completely demolished when it suddenly slipped several feet downhill.

Landslides aren't new, either. In Lebanon, many centuries ago, the Phoenicians cut the cedar forests and then had to build rock-walled erosion terraces to keep the soils from slipping down the mountains.

Austria has had an active landslide control program for 100 years. There is also unstable terrain in the European Alps, in New Zealand, and in Japan. I visited Japan 3 years ago, and was shown some landslide-prone areas that reminded me of the Siuslaw country. The Japanese have put a lot of effort into building concrete structures in headwalls and other slide-prone areas to prevent landslides. This was a costly program, and the Japanese foresters weren't too sure about its effectiveness. So this is not a problem peculiar to the United States. It may seem that way at times, but colleagues around the world are also worrying about landslides.

The Nature of the Problem

Practicing forestry in steep, unstable country is one of the most challenging jobs land managers face. It is a problem that will never be completely solved, because we are up against a pretty formidable opponent--the laws of nature dealing with basic geological processes.

Those of us in Washington, D.C., sometimes get an exaggerated view of our power and influence, but we still know we can't repeal or modify the basic laws of nature--although there have been times that we have been accused of trying to do so. Rather, we have to live with the laws of nature, and strive to gain a better understanding of what is possible and how to better integrate land management actions into the the natural scheme of things. This is true whether we're dealing with logging and roadbuilding in steep and unstable country, building permanent structures in floodplains, or locating subdivisions in. fuel types subject to periodic and catastrophic fires. When these sorts of things are done, eventually that 50- or 100-year flood, fire, or storm will catch up with all the past bad decisions or miscalculations.

Rising Resource Values Add to Difficulties

Making things more difficult for forest managers are the rising resource values, which make it much more costly to ignore or stay out of the higher risk areas. In the Forest Service, wise predecessors tended to bypass the tougher areas and moved-on to the next ridge or drainage where it was safer to operate.

With the present restrictions on entering many of the roadless areas in the forests and having already harvested much of the timber in the more easily operated areas, we no longer have the luxury of our predecessors. We have to reconsider the "once-or-twice-passed-over" areas for development activities. Fortunately, we have more research results and better technology to deal with the problem than our predecessors ever considered possible. In many other ways, however, things aren't so easy. Public concern and-pressures are greater and environmental standards and expectations are higher. The importance of water quality and anadromous fisheries are better recognized. We have to make tougher decisions about these areas of unstable terrain. Do we forego the resources within them or do we build roads, harvest the timber, use the other resources, and accept the risks?

The Manager Must Assume Some Risks

Those are basic questions and we can't just ignore them. Where the resource values warrant, we have to be cautious in taking calculated risks, yet still make judgement calls based on everything we know. And there is some probability of failure. We should understand that now and then our activities will accelerate or trigger soil movement. But how do we estimate the probability of failure? How do we measure the risks? How do we decide when to go into an area with unstable terrain, and when not to?

Let me make one thing clear before I go on: My job as keynoter is to raise questions for others to answer, not to answer them myself. And I'm thankful for that. In the past I've had to make decisions about managing unstable terrain. And my point is that when we build a road or harvest the timber in unstable areas we should know the risks we are taking in terms of both economic and environmental values.

We Must Know What We Are Doing

It all comes down to knowing what we're doing instead of guessing at it--and this is a case where research and land management must go hand-in-hand. With knowledge developed through research, managers should be able to consider development activities in higher risk areas with greater confidence, We must watch out for dangers of overconfidence, however, where our push to manage resources in unstable areas gets ahead of what we truly know about them. When that happens it's the forestry equivalent to "Russian roulette," where the only uncertainty is not whether, but when, we'll lose, In unstable areas there is no substitute for knowing what we're doing.

What we are engaged in is a perpetual duel — the efforts of human minds and human skills to contend with the basic natural processes of a continually changing earth. That means each function is important and that more is required of everyone in that flow of information, from the researcher who is studying slope stability and landslide processes, to the manager who has to decide how to manage the land and where to get the resources, and the on-the-ground, practicing technician who knows the terrain and how to apply all the knowledge. In reality, we're no stronger than our weakest link.

Challenge to Research

Research has made great strides in recent years, but for all we've learned in the past we need to learn still more. Most specifically, we need more engineering research, better designs for forest roads and other structures in critical unstable areas. We also need to improve our techniques of risk assessment and we need better quantification of downslope damage when the slope fails.

Research has done a lot to help us evaluate risks and to capably take on reasonable risks that were foolish to assume a decade ago; but we need to continually shove back those limits, with research showing us the way. Part of the purpose of this workshop is to assess where we are and to identify our highest priority research needs.

Challenge to Land Managers

In the final analysis, though, it comes down to the land managers who have to make the judgement calls about what will be done, All of the research knowledge in the world is useless at that point unless the managers know how to use it and know the terrain they are working with.

Managers have to know how to use the information that research produces, One reason why we are having this workshop is because of the inadequate extension job - the insufficient transfer of knowledge--in slope stability work. There's been a good flow of slope stability information coming out of research--and the inter-Station slope stability research program has been especially productive — but research results need to be translated into practical guidelines for land managers.

That said, let me set out a few points about what I think land managers need to do in managing unstable country. First--as they say in one advertisement I've seen—we have to recognize that "there are no easy answers, only intelligent choices" in working with unstable terrain, We need to make intelligent choices and ask for help by reaching out for the best experience and expertise available. At the Siuslaw we faced very difficult decisions concerning high timber values and the immensely important anadromous fisheries resource, And so we called in some of the best experts we could find. Doug Swanston came in to help. We brought in experts from the regional office, a biologist from the wildlife commission, and a hydrologist, a soil scientist, and engineers from the Siuslaw National Forest staff. They spent 6 months working with us on our slope stability problems, and several of these people are here today. We made some informed, intelligent choices about what we do, and we reduced the potential for future problems.

My second point about the challenge to land managers is that there is no substitute for knowing the ground. The people on the ground are the first line of prevention if they know what areas are risky and under what circumstances--and after they've been through slumps and slides and creeps and flows, they can tell you a lot about how to avert them.

In meetings like this we sometimes tend to overlook the importance of the on-the-ground practicing technician--the people who actually locate and design the roads and timber sales. There is just no substitute for people who have the experience that comes from living with the problem for 5 years or more and who have developed a special sense or "feel" for the land and what you can or cannot do with it--though they still have to supplement that knowledge with the latest scientific techniques,

Much of what I've said here may remind you of that recruiting ad for the Army. The problems of unstable terrain require that everyone involved "be all that they can be." They require that researchers be productive and working on the highest priority problems; that land managers be wise and sensitive to both economic and environmental values and that the on-the-ground practicing technicians know the land and apply all there is to know from research and from experience. We have to be willing to take reasonable, calculated risks while doing our best to mitigate any resulting damage.

My final point, though, is that sometimes our best won't be quite good enough; and in those instances we have to be willing to admit it. It's sometimes tough to do that--to admit that despite everything we know or could economically do to mitigate the risks, we still couldn't build a road or develop the resources in an area without the soil slumping or land sliding. But when that's the case we need to back away. We need to remember that the soil is our most fundamental resource. It may have taken many thousands of years to put a foot of soil on a forested slope and it is unwise to lose it in a year.

SUMMARY

Let me close by summarizing some of my conclusions, based on my experience in trying to practice forestry in steep, unstable country:

1. In spite of our cadre of very competent, hard-working scientists, there is no "miracle" out there waiting to be discovered that will solve the problem. Likewise, there is no "magic" or "heroic action" out there just waiting for a brave, courageous land manager to come along to take bold action.

2. I don't think it's realistic to accept the view expressed by some people that we should be overly cautious and back away or delay management activities on millions of acres of forest land until research provides the basis for risk-free decisions. That is not realistic and will never happen.

3. I do accept the view that progress comes slowly and, I hope, cumulatively over time based on hard work, good judgement, and experience by everyone involved--researchers, land managers, technical specialists, and on-the-ground practicing technicians.

I think we're at a point where pooling our knowledge and experience has the biggest payoff of anything we could do--and that is the primary purpose of this workshop. It must not stop here this week, however. The acceleration of technology tranfer over the next few years probably will have the largest payoff in term of results on the ground.

I know you're going to have a successful workshop, but this workshop should be viewed only as a beginning.

SURVEY OF SLOPE STABILITY PROBLEMS ON FOREST LANDS IN THE WEST

Edward R. Burroughs, Jr.

ABSTRACT: Within the region west of central Montana and north of San Francisco, the intersection of areas with high hazard levels for natural landslides, important fishery-water resources and major levels of management activity represent areas with a large potential for environmental damage as a result of timber harvest. The magnitude and frequency of slope stability problems increases from east to west and from south to north. The percentage of land in the Northern, Intermountain, Pacific Northwest and Pacific Southwest Regions with a high potential for mass failures ranges from 10 to 12 percent. This percentage at the forest level ranges from 0 to 45 percent. Road construction costs per mile increase by a factor of about 4 from south Idaho to Washington and Oregon. Annual road maintenance costs can increase by a factor of 13 in areas with a high potential for road cut failures. Intensive slope stability surveys can be used to identify timber harvest sites within a larger area generally classified as unstable.

INTRODUCTION

The Pacific Northwest States are blessed with climate and soils that produce abundant forests, clear streams, and important habitat for anadromous and resident fishes. Unfortunately, the climate, geology, and topography frequently produce sites with a high potential for landslides. The risk of damage to fisheries and water quality by landslides caused by timber harvesting and road construction is one of the most serious problems facing land managers in the Pacific Northwest.

The quality of fisheries and water is a very sensitive issue in the northwestern United States, and the public frequently questions the impact of Federal timber sales. Many management decisions regarding road location and design and timber sale layout hinge directly on the potential effect on the fishery-water resource. This paper will describe the magnitude, intensity, and distribution of slope stability problems within the northwestern United States. The impact of slope instability on road construction and road maintenance costs will also be discussed. The area of consideration is western Montana and northern Idaho (USDA Forest Service, Northern Region); western Wyoming, southern Idaho, Utah, and Nevada (Intermountain Region); northern California (northern part of the Pacific Southwest Region); and Oregon and Washington (Pacific Northwest Region).

LOCATION OF SLOPE STABILITY PROBLEMS IN THE WEST

Areas with a high potential for mass failure are the result of interactions between parent

EDWARD R. BURROUGHS, JR., is a research engineer at the USDA Forest Service, Intermountain Forest and Range Experiment Station, Forestry Sciences Laboratory, Montana State University, Bozeman, Montana.

Figure 1.--Geologic landslide hazards west-wide.

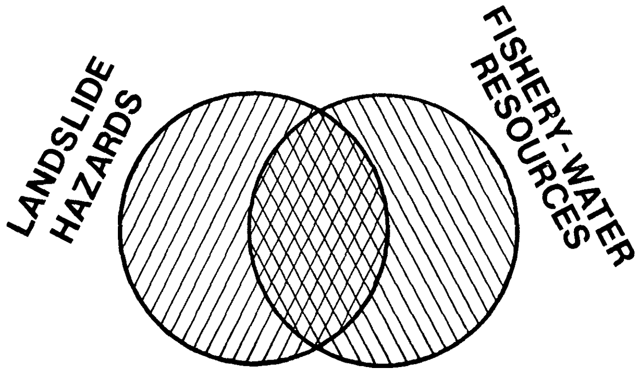


Figure 2a.—Intersection of natural landslide hazard areas and fishery–water resources.

material, topography, and climate. The methodology used to describe stability problems was to consult geologic reports and maps on a West–wide, Regional, Forest, and in some cases, District and project scale to determine the location of intrinsically unstable parent materials. These included deeply weathered sedimentary formations, granitic batholiths, weathered metamorphics, and weathered intrusive and extrusive volcanic materials. Extensive areas of particularly steep topography, regardless of parent material, were also identified as having a high potential for mass failure.

The effect of climate was introduced by mapping the distribution of annual precipitation 20 inches or greater. I assumed that at least this amount would be required to generate enough subsurface water to create instability by increasing pore water pressure. Although 20 inches annual precipitation is quite low for the West Coast, the 20–inch limit is necessary on a West–wide basis to include areas in Idaho and Utah that are known to be unstable. The intersection of significant annual precipitation, unstable geologic materials, and steep topography locates areas with a natural, or geologic landslide hazard. Figure 1 shows these areas on a West–wide basis.

The fishery resource provides a good indicator of the risk of environmental damage from landslides, not only because of the fishery value, but because this resource is intimately involved with water quality. The location of significant fishery habitat is used throughout this report as an indicator of fishery-water resources at risk from mass failures.

Figure 2a illustrates the intersection of natural landslide hazard areas and areas with significant fishery–water resources. The area within the intersection represents the potential for damage to this resource from naturally occurring landslides. Land management activities, principally road construction, oil and gas exploration, and timber harvest, can increase the frequency of landslide occurrence far above the natural, or geologic rate. Figure 2b shows the intersection of areas with a natural landslide hazard, areas with a significant fishery–water resource, and areas with land management activities. The central portion represents areas with the potential for damage to the fishery–water resource as a result of land management–induced landslides.

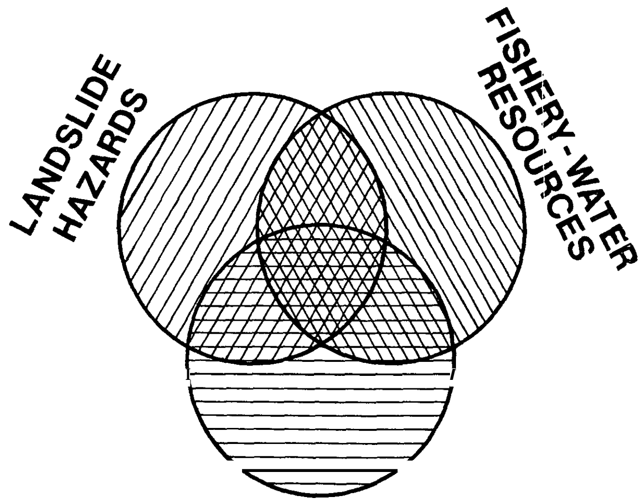


Figure 2b.—Intersection of natural landslide hazard areas, fishery–water resources, and land management activities.

The intensity of land management activity on western forest lands is indicated by the annual timber harvest volume in millions of board feet (MMBF). Timber harvest incorporates both the harvest activity and timber access, usually road construction. Data on timber harvest volume, miles of road construction, and road costs for 1979 were collected from National Forests in the various Regions. The year 1979 was selected because thereafter a recession reduced timber harvesting activity.

National Forest timber harvest volume for each Region was divided into three classes, high, medium, and low, to indicate three levels of activity. Intersections of natural landslide hazard, significant fishery–water resources, and National Forests in the three timber harvest; volume classes are shown for the Regions.

NORTHERN REGION (REGION 1)

Total areas with stability problems within each Region cannot be determined accurately from Regional data because each National Forest has its own criteria for defining, inventorying, and reporting lands in this category. Also, many Forest plans are not yet complete, and the completed plans will include more accurate data than is now available. The most common denominator for comparing stability problems among Regions is to total all lands in each Region classified as either "Marginal,"

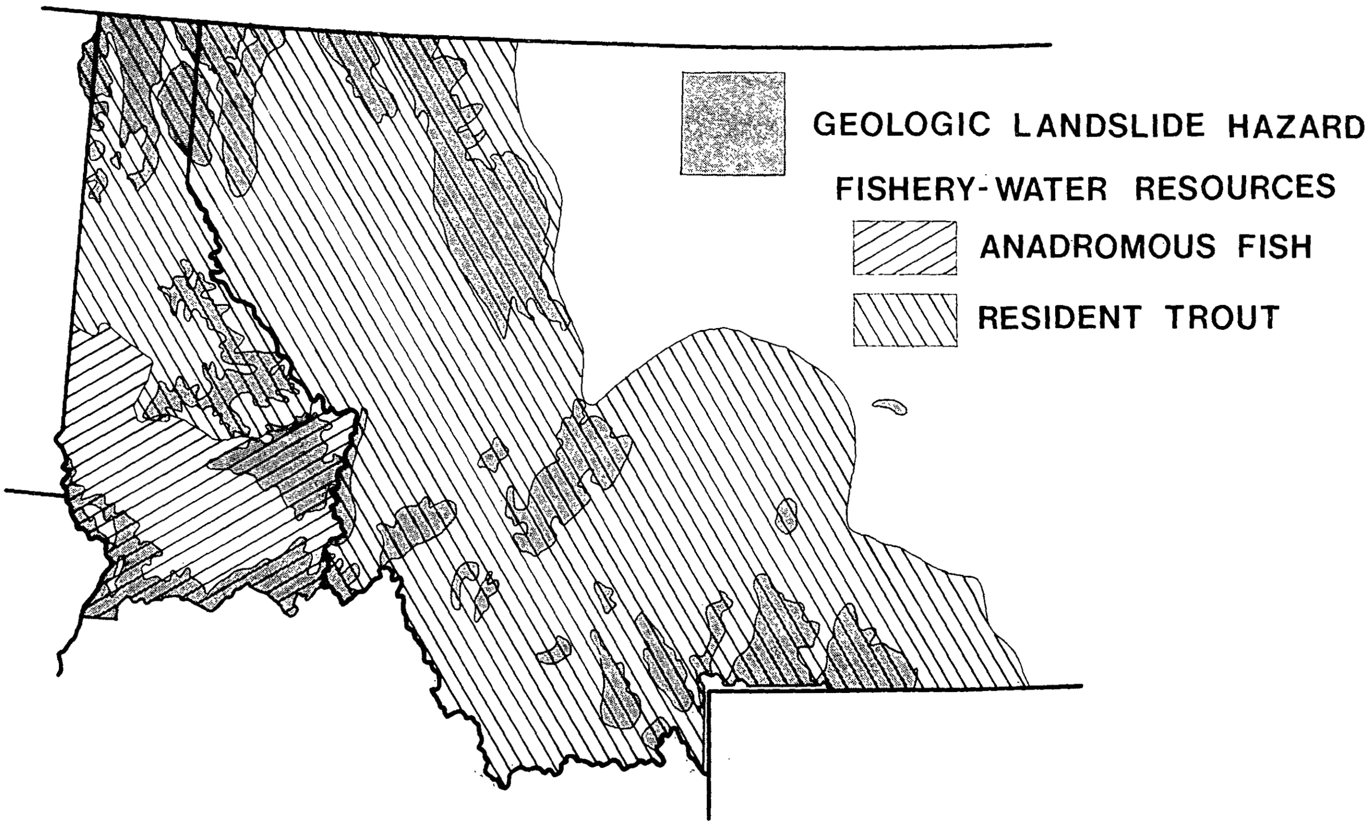


Figure 3a.--Region 1. Landslide hazards and fishery–water resources.

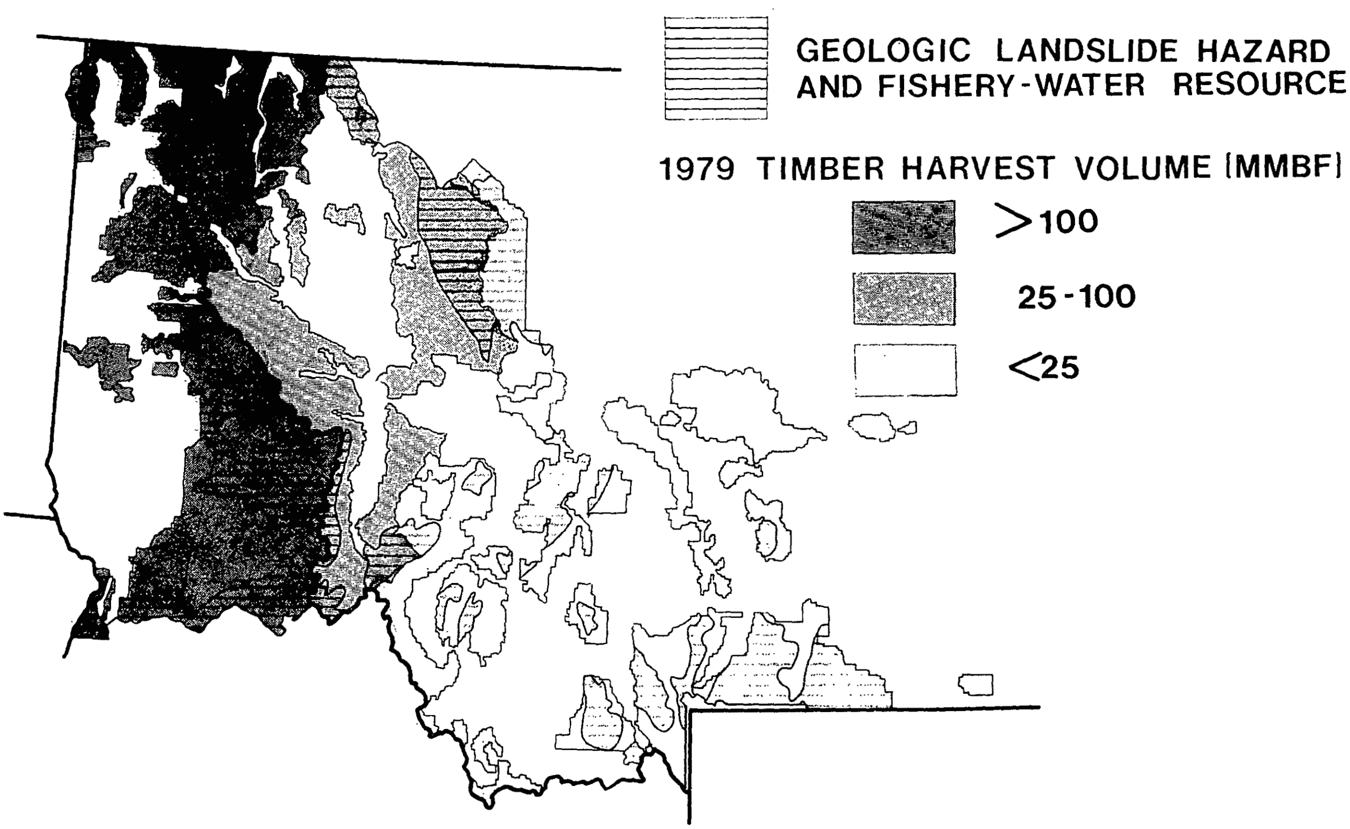


Figure 3b.--Region 1. Natural landslide hazard areas, fishery–water resources, and National Forest lands by timber harvest classes.

"Marginal-Unstable," "Unaccessible," "Inoperable," or "Steep Slope Lands." This total for each Region will be designated as the "High Potential" in this report. Region 1 has 10.3 percent of its lands in the "High Potential" category.

Figure 3a shows the habitat for anadromous and resident trout plus the landslide hazard areas for Region 1. The intersection of these areas represents the potential for damage to fishery-water resources from natural landslides. This intersection is overlaid in figure 3b with the timber harvest volumes of National Forest lands. Timber harvest volumes are divided into three activity classes to show how much of each Forest has a significant landslide hazard. This figure also shows those areas with a potential for management-induced landslide damage to fishery-water resources.

INTERMOUNTAIN REGION (REGION 4)

High-potential lands in Region 4 occupy 17.7 percent of the total forest lands. This estimate may be high because the Region's definition of marginal lands includes some "steep lands" and lands with unmarketable species and other economic problems, A more reasonable, though strictly subjective, estimate would be that 12 percent of the Region's lands have a significant potential for mass failure. Figure 4a shows that many of the geologic hazards and habitat for anadromous fish and most resident trout are concentrated in southern Idaho in six National Forests: the Boise, Challis, Payette, Salmon, Sawtooth, and Targhee. High potential lands for these Forests are 56.5 percent of the total high-potential lands in Region 4. Figure 4b shows those Forests with significant slope stability problems.

PACIFIC SOUTHWEST REGION (REGION 5)

Figure 5a shows fish habitat and natural geologic hazard areas for the northern part of Region 5. The Region provided information on four National Forests in northern California: the Klamath, Six Rivers, Shasta-Trinity, and Mendmino. Areas classified as "Marginal-Unstable" for these four Forests totaled 1.2 percent of National Forest lands. These data were taken from current, approved timber management plans developed in 1971-74 (exception is data from 1983 Mendocino plan), and do not include unaccessible or inoperable lands that may also have a high potental for mass failure. According to the Region, "the areas of forest land classified as unaccessible, inoperable, or marginal-unstable are being determined in conjunction with the current land management planning efforts by the Forests... The marginal acres from these Timber Mangement Plans will probably greatly increase when the new Land Management Plans are completed,.. In general, lands falling under these three Classifications [unaccessible, inoperable, marginal-unstable] will vary between 8 to 20 percent of the total acres on any particular forest." If it is assumed that. these three classifications represent high-potential areas, then 8 to 20 percent for any of these four Forests is reasonable. Figure 5b shows slope stability problems on Forest lands in northern California.

PACIFIC NORTHWEST REGION (REGION 6)

The best general description of the situation in Region 6 is contained in a 1979 document prepared for the Regional Forester by Robert Meurisse, regional soils scientist. "Unstable soils are common in Region 6. About 11 percent (2,712,000 acres) of the Region has soils that are moderately unstable or unstable.,[1/] They have important implications for the development of forest resources. Some of the most unstable areas are presently being developed or will. be within the next 10 years. Unstable soils are among the most productive in the Region... Some have as high as 100 MBF/acre. These soils are widely distributed throughout the Region, but are dominantly on the Western Cascades and Coast Range. Some of the most extensive acreages are in watersheds with high value anadromous fisheries, in municipal supply watersheds, upstream from reservoirs, and in areas of high visual resource quality." Figure 6a shows the location of geologic hazard areas and important fish habitat in the Region, and figure 6b shows those Forests with slope stability problems.

GENERAL REGIONAL SUMMARY

West-wide data indicate that the magnitude and intensity of slope stability problems increases from east to west and from south to north. The total percentage of land in each of the Regions with a high potential for slope stability problems ranges from about 10 to 12 percent. This percentage at the Forest level ranges from 6 to over 45 percent, depending upon whether the Forest is at the drier (eastern or southern) or wetter (western or northern) side of the region.

Figure 7 shows the location of National Forest lands with a potential for damage to fishery-water resources as a result of management-induced landslides. The darkest tones in the figure represent the greatest potential for damage within each Region based on timber harvest classes. Figure 7 is a summary of figures 3b, 4b, 5b, and 6b, and represents the situation on National Forest lands within each Region. Because of the increased intensity and severity of stability problems from east to west, areas with high potential for damage in Regions 1 and 4 are probably equivalent to a moderate potential in Regions 5 and 6. On the basis of my

---

1/ Only tracts of 5,000 acres, or larger, have been considered. Additional acreage is found in smaller, isolated tracts.

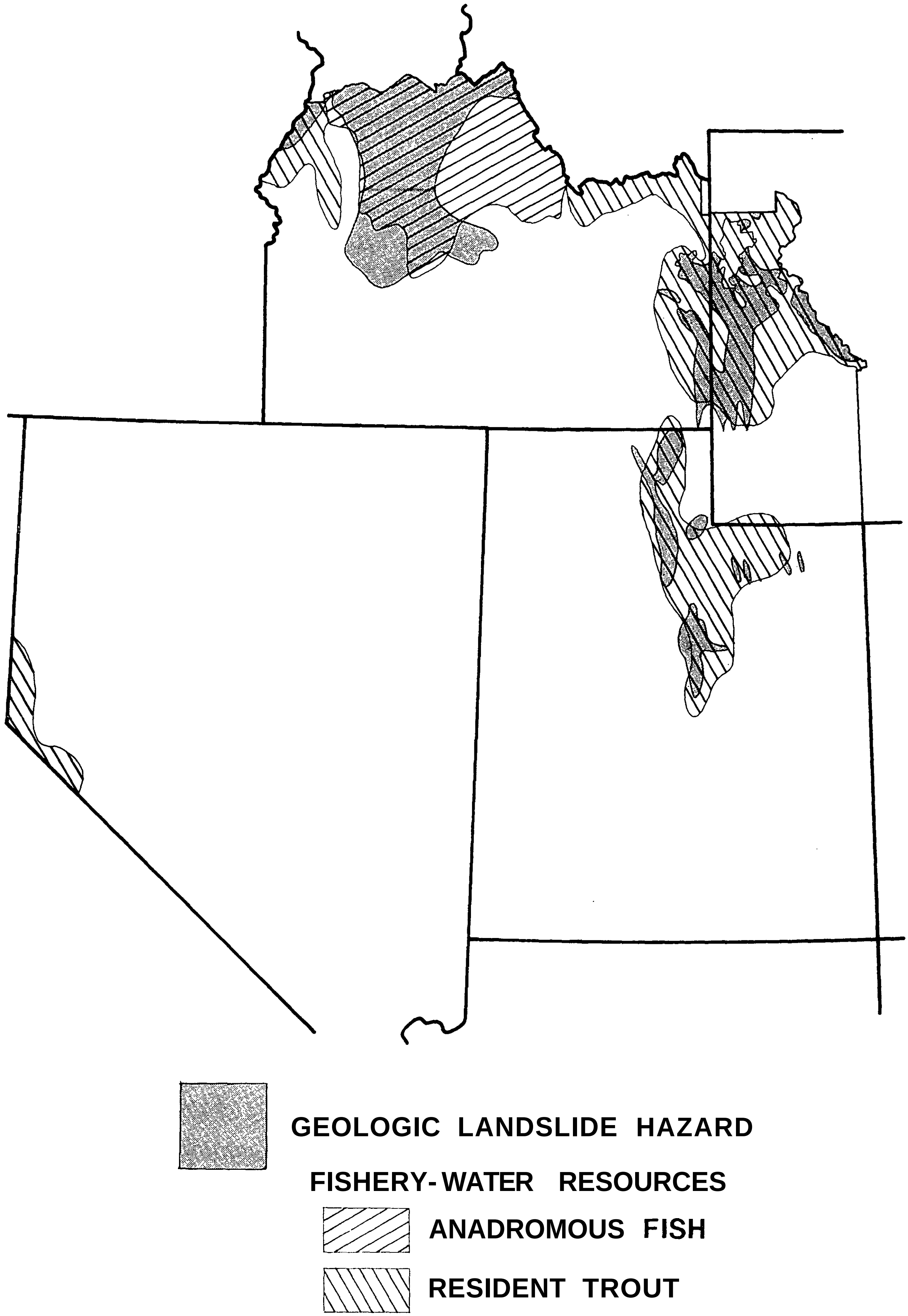


Figure 4a.--Region 4. Landslide hazards and fishery-water resources.

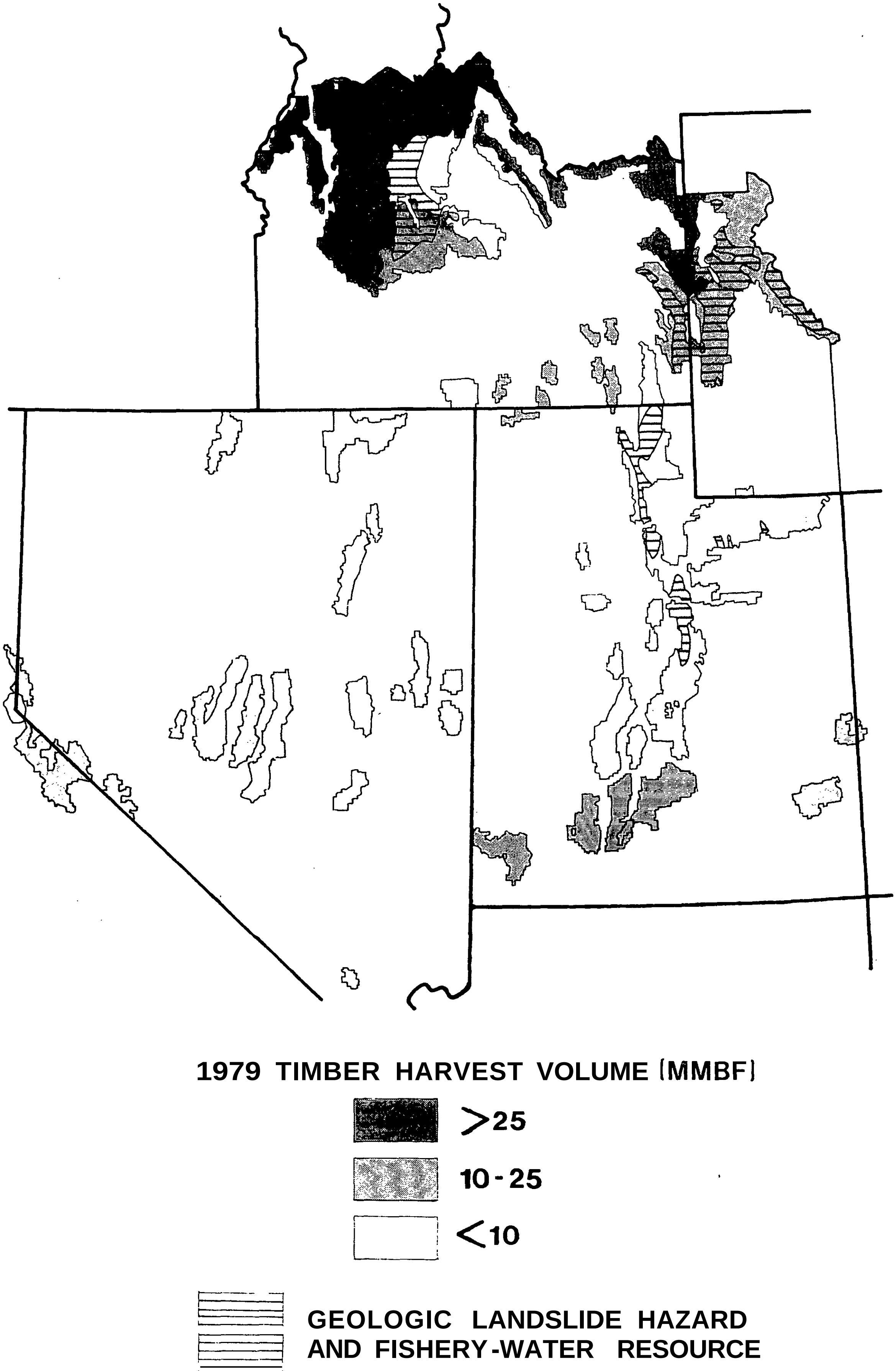


Figure 4b.—Region 4. Natural landslide hazard areas, fishery–water resources, and National Forest lands by timber harvest classes.

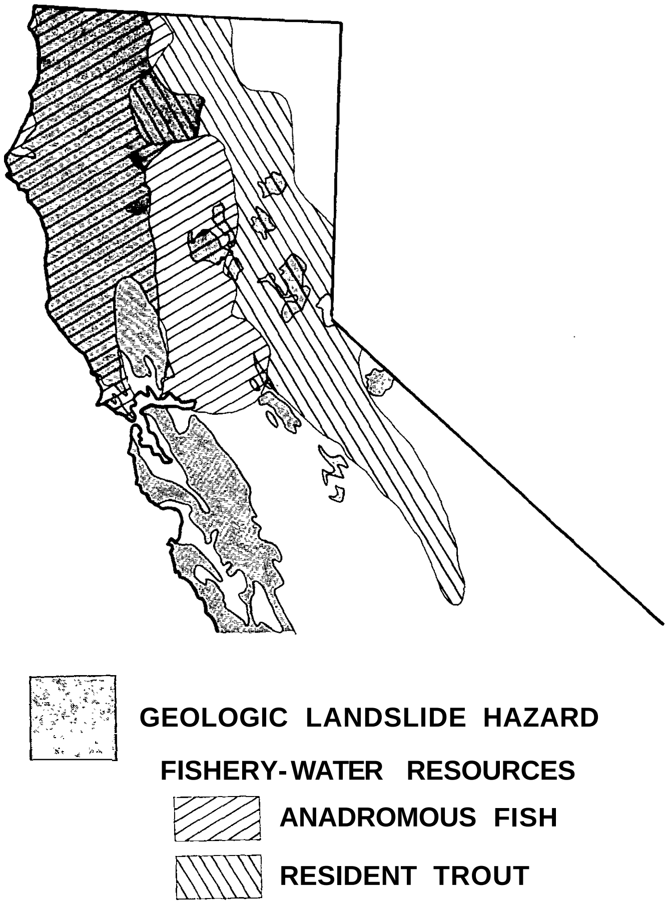


Figure 5a.--Region 5. Landslide hazards and fishery–water resources.

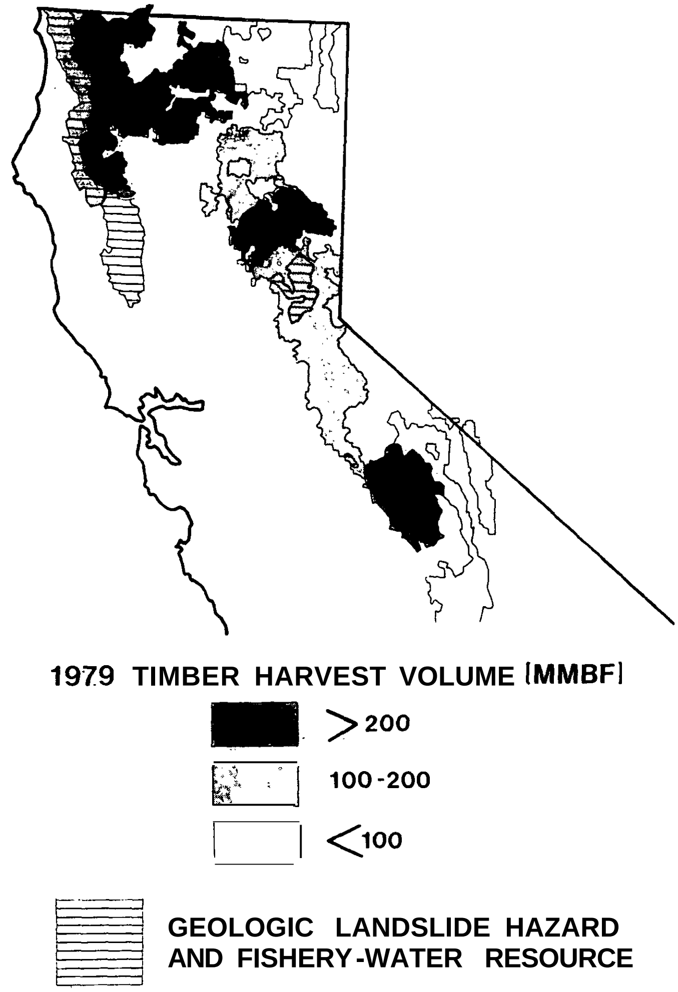


Figure 5b.--Region 5. Natural landslide hazard areas, fishery–water resources, and National Forest lands by timber harvest classes.

own West–wide observations, I have ranked the relative stability on National Forest lands across the four Regions with a four–level rating system as shown in figure 8.

ROAD CONSTRUCTION RELATED TO SLOPE STABILITY

As the stability problems become more extensive and more severe from south to north and from east to west, road construction costs increase accordingly. These increased costs are in response to the need to maintain the annual cut and provide environmental protection under increasingly difficult conditions.

Road construction costs in two National Forests illustrate the differences between the east and west sides of Region 1. The Gallatin National Forest, east of the Continental Divide, built 7.6 miles at $39,921 per mile in 1979. The Clearwater National Forest, on the west side, built 43.3 miles per year in 1979–80 at an average cost of $61,690 per mile. Using these figures, the miles of construction increased by a factor of 6 and the cost per mile increased by a factor of 1.6 from east to west. Region 4 road costs for southern Idaho in 1979 ranged from about $22,000 per mile for the Targhee National Forest to about $50,000 for the Boise and Payette. Average new road construction in the Klamath, Six Rivers, Shasta–Trinity, and Mendocino Forests in Region 5 in 1979 was 46.3 miles per Forest at a cost of $44,487 per mile. Road construction in 1979 in Region 6, west of the Cascades, averaged $124,000 per mile. Costs were about $41,000 in the Umpqua National Forest, $92,000 in the Siuslaw, $150,000 in the Willamette, $160,000 in the Mt. Hood, $123,000 in the Gifford Pinchot, and $177,800 in the Olympic.

An engineer from Region 6 explained that the easily accessible terrain has been developed. The remaining undeveloped country has much steeper slopes (100–percent slopes are not uncommon) and requires more blasting, and 5- to 6–foot stumps increase clearing costs. Endhaul of excavated material is very expensive but is required on steep slopes to avoid sidecast. More endhaul, steeper slopes, and more blasting were also cited as reasons for increased road costs from east to west in Region 1.

Within most Forests, the engineers, planners, and resource specialists usually act as a team to examine alternate routes for road locations to

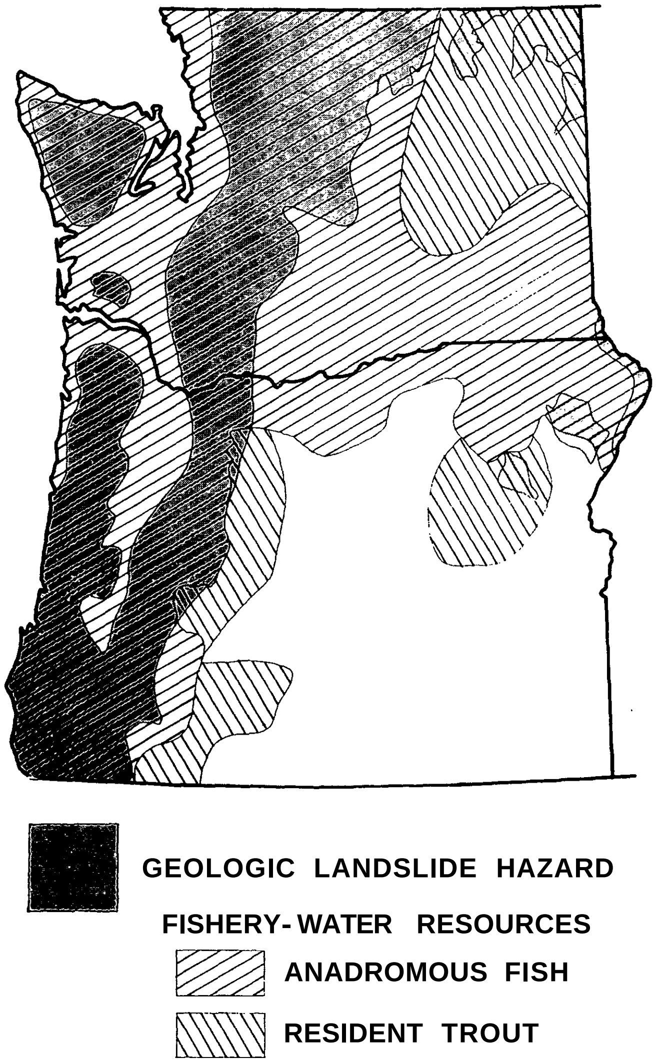


Figure 6a.--Region 6. Landslide hazards and fishery-water resources.

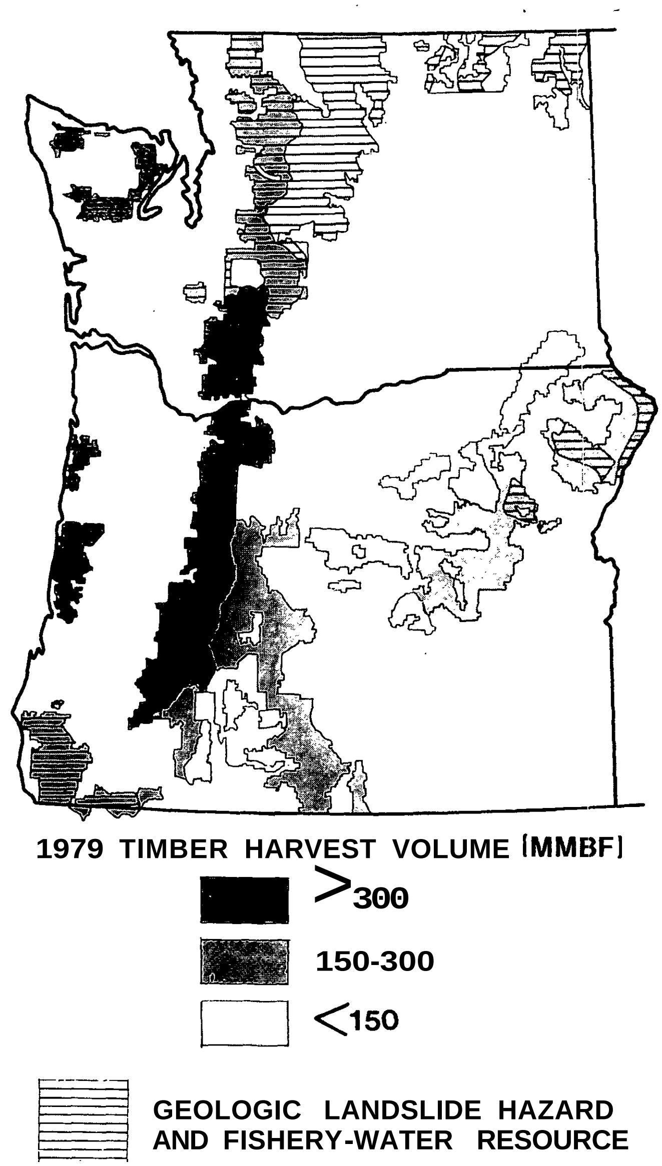
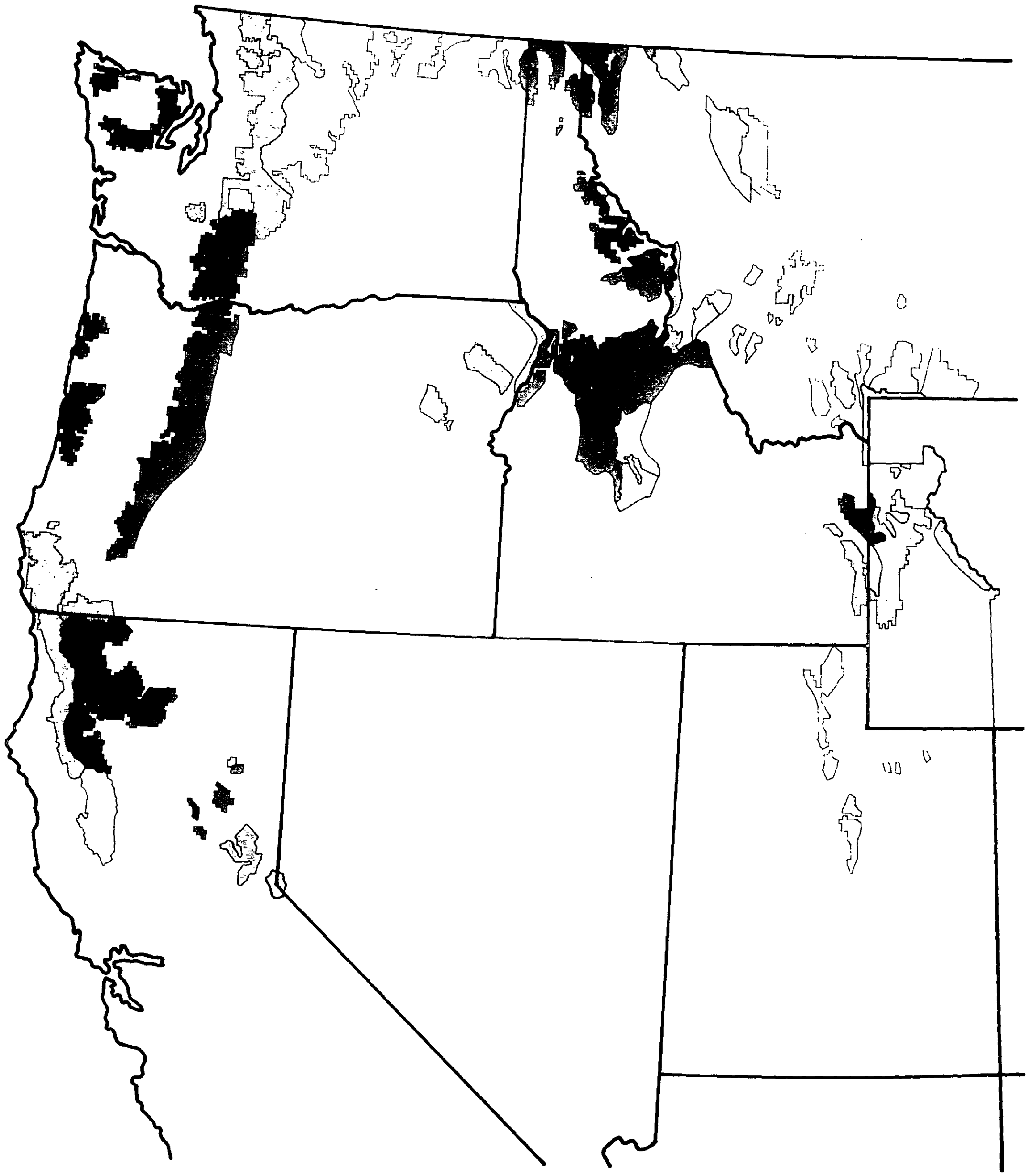


Figure 6b.--Region 6. Natural landslide hazard areas, fishery-water resources, and National Forest lands by timber harvest classes.

determine which will provide the most environmental protection for the least cost. A numerical example of the evaluation of alternate road locations was provided by Edward Butler (engineer) and Dale Wilson (soil scientist) of the Clearwater National Forest, Region 1. This Forest uses a computer program to determine road costs as a function of road specifications, topography, and distance through land type units. Each land type is characterized as to sideslope, degree-of dissection, percent rippable rock, soil depth, mass failure costs, and slope stabilization class (for protection against surface erosion). Cost estimates are developed using these characteristics as variables, except for the cost of mass failures, in which case a cost per mile is estimated. The mass failure cost reflects techniques that must be used to prevent mass failures. Road cost per mile for each land type is the sum of the costs for each characteristic. Road costs per mile can increase by a factor of about 3, depending upon characteristics of the land type involved and the mass failure hazard.

ROAD MAINTENANCE COSTS RELATED TO SLOPE STABILITY

Little information is available on increased road maintenance costs attributable to slope stability problems because of a lack of reporting procedures within and among Regions. Available data provides some insight into this subject. Robert Meurisse, Region 6 soils scientist, estimates that road maintenance costs increase 50 to 100 percent in areas with stability problems. The most detailed information was provided by Larry Rich, Region 6 Engineering, on volumes of slide material removed from roads after the winter of 1981-82. The average slide volume removed from each of six westside forests was 26,385 yd^3. If we assign a unit cost of $4.50 per yard, the average removal cost per westside Forest was $118,730. For three Forests, east of the Cascades, the comparable average volumes and costs are 1,961 yd3 and $8,825. These figures



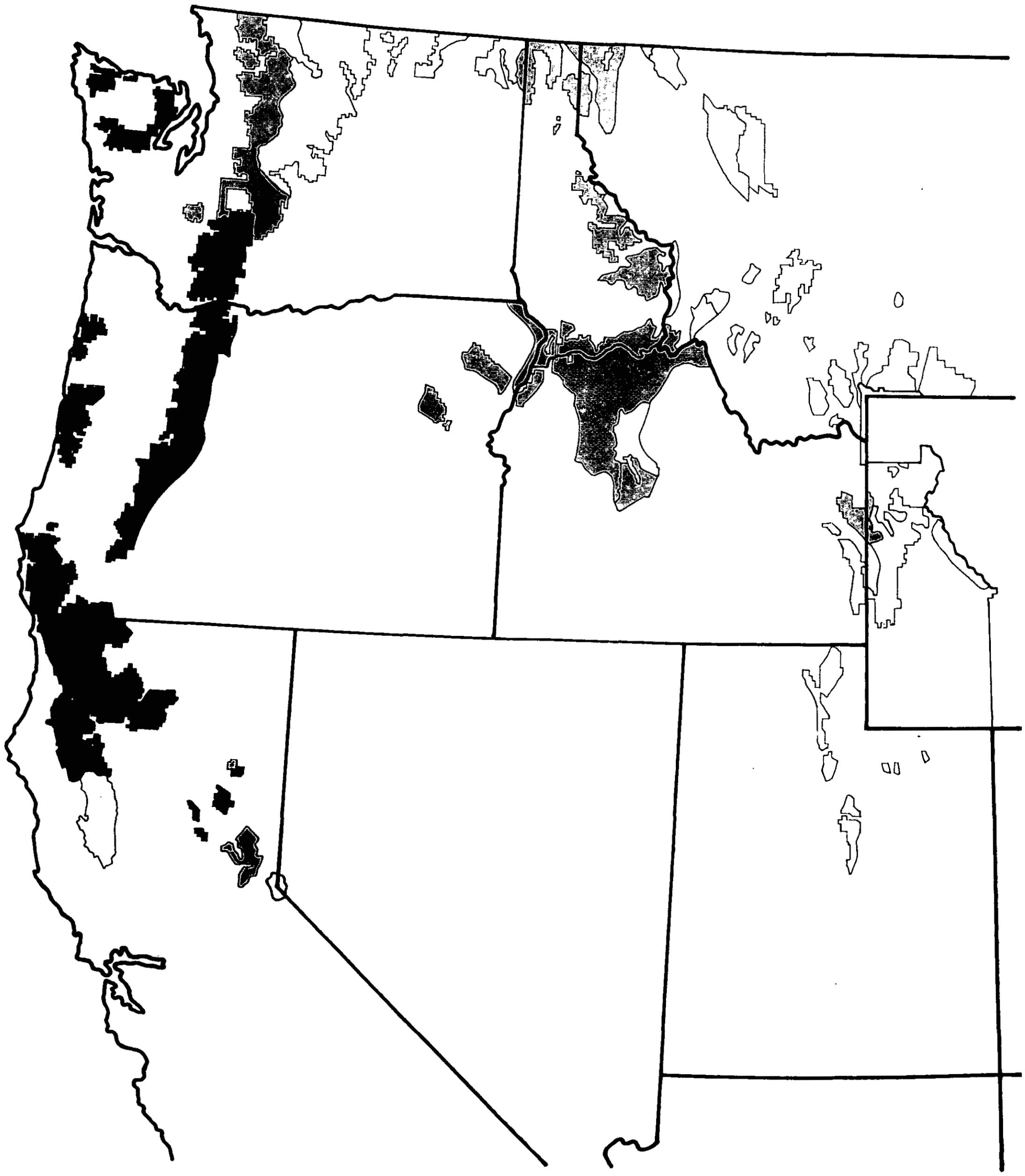
REGIONAL MAPS

FISHERY AND WATER RESOURCES AT RISK FROM MANAGEMENT-INDUCED LANDSLIDES

LEVELS OF TIMBER HARVEST

- HIGH
- MODERATE
- LOW

Figure 7.—Regional distribution of National Forest lands with potential for landslide damage to fishery-water resources as a result of timber harvest activity.



WESTWIDE SUMMARY OF REGIONAL MAPS

FISHERY AND WATER RESOURCES AT RISK FROM MANAGEMENT-INDUCED LANDSLIDES

LEVELS OF TIMBER HARVEST

- I. HIGH
- II.
- III.
- IV. LOW

Figure 8.--West-wide summary of National Forest lands with a potential for landslide damage to fishery-water resources as a result of timber harvest activity.

refer to cut slope failures that deposit material on the road surface. Slide removal costs for slide-prone westside Forests are about 13 times that for the more stable eastside Forests.

The Eugene District of the Bureau of Land Management, U.S. Department of the Interior, in western Oregon faces increased road maintenance costs caused by cutslope failures. The average volume removed annually from 1979-82 was 42,419 yds over 600 miles of road. About 13 percent of this volume was mass failure of the road cut slope (14,140 yd^3), while the remainder was minor "sluff" or dry ravel. About 20 percent of the mass failure volume (2,828 yd^3) reaches a culvert and was deposited in a stream.[2/] If we assign $4.50 per yd^3 for slide removal, then the 80 percent of the material remaining on the road costs the Eugene District $50,904 per year to remove.

Landslides, particularly those that involve the fill slope and the road surface, are difficult and expensive to repair and stabilize. Repair of fill failures is often hasty and accomplished by dumping loose material into the gap to bring the road back to grade--this may be repeated several times a year. Landslides may require engineered structures or augered-in perforated pipe to provide support and reduce pore water pressures to prevent repeated failure. Meurisse reports the average cost of stabilizing three slides in the Siskiyou National Forest was $100,000. Average annual repair costs for landslide damage in the Clearwater (1974-76) was $55,800, and landslide stabilization costs for 1974 were $1,100,000.

One of the best, although expensive, methods to prevent fill failures on existing roads is to remove sidecast material that shows signs of instability. The Siuslaw National Forest began a "Sidecast Pullback" program in 1974 to correct problems caused by mass failures in "uncompacted fill deposited on an unprepared side slope." The problem was compounded by the decay of roots that anchored stumps to the slope when these stumps were covered by fill. With time, organic material decayed, fills settled, and slides were generated by the hydraulic and gravitational forces acting on the unstable material. Debris torrents of several hundred cubic yards are sometimes triggered by the failure of a small amount of unstable sidecast material." Since 1974, about 45,000 yd^3 of sidecast have been removed from 120 high-priority sites at a cost of $94,000.[3/] In 1980, the program was evaluated and the management team decided to continue this work. The magnitude of the unstable sidecast problem is indicated by their estimate that 250,000 yd^3 could be removed in the Siuslaw at a cost of over $1,000,000.

2/ Personal communication with James McLaughlin, soils scientist, Eugene District.

SLOPE STABILITY LIMITATIONS ON DEVELOPMENT

A distinction must be noted between areas classified as having: (a) high potential for mass failure; and (b) areas actually withdrawn from the timber base because of stability-related problems. In the first category, some lands may be routinely developed, using intensive investigations and precautions for environmental protection. Other areas in this category may be deferred for later development in the hope that improved technology may reduce the risk of environmental damage. There is some concern that development on deferred areas may be hindered by development on areas with fewer problems.

Areas actually withdrawn from the timber base are the "hard core" areas wherein no improvement in technology is likely to add to the timber base. Improved methods for identifying and evaluating slope instability may increase the amount of lands classified as unsuited for timber production. But more importantly, such advances in knowledge will provide the technical basis for sound, defensible management on lands with a high potential for mass failures. Improved road construction technology, including better stabilization techniques, will undoubtedly reduce the risk of environmental damage when development does proceed in unstable areas.

3/ Siuslaw National Forest Staff Report on file at Siuslaw National Forest Supervisor's Office, Corvallis, Oregon 97330.

FACTORS INFLUENCING THE STABILITY OF SLOPES

R. C. Sidle

ABSTRACT: Important geologic factors and soil properties influencing the stability of slopes include strength and structure of rock material, bedding sequences, slope gradient, landform shape, soil depth, soil strength, and clay mineralogy. Shallow, rapid failures, such as debris avalanches, are often initiated by extensive pore water pressure buildup within the soil mantle resulting from high-intensity or long-duration storms. Acceleration or initiation of deep-seated, soil mass movements (for example earthflows) may result from a gradual accumulation of seasonal rainfall. Rate of water movement into and through unstable landforms is critical in determining groundwater conditions and can be greatly influenced by the extent and continuity of soil macropores. The influence of plant rooting strength on slope stability is most apparent where extensive clearcutting or vegetation conversion has occurred. Other land management practices, such as road building and residential development, may cause mass failures by overloading or undercutting unstable slopes and by concentrating surface and subsurface water.

INTRODUCTION

Natural factors influencing the stability of forested hillslopes can be catagorized into five process-related areas: (1) geologic/geomorphic factors, (2) soil properties, (3) hydrologic factors, (4) vegetative factors, and (5) seismicity. The importance of most of these factors can be modified by forest management activities; however, the scope of this paper will deal more directly with specific natural factors and processes involved in landslide initiation. It is essential that land managers understand the basic processes controlling slope stability before site-specific prediction, avoidance, and ameliorative measures are applied.

R. C. SIDLE is research soil scientist/hydrologist with the Forestry Sciences Laboratory, USDA Forest Service, Pacific Northwest Forest and Range Experiment Station at Juneau, Alaska.

GEOLOGIC/GEOMORPHIC FACTORS

Influence of Rock Composition and Structure

Geologic factors predisposing certain terrain to soil mass movement include weak or soft rock composition, undesirable structure, and unfavorable bedding sequences. Throughout North America there are numerous examples of particular types of soil mass movement characteristically associated with certain rock or weathered regolith material. These include large earthflows associated with the Franciscan sedimentary assemblage of northern California; volcaniclastic rocks of the western side of the Cascade Range and the Columbia River Gorge; rotational failures associated with weathered shales and siltstones of north-central Texas and the northern Oregon coast, and debris avalanches associated with competent sandstone and compact glacial till in the mountains of coastal Oregon and Alaska, respectively.

Weak rock types reflect the extent of weathering as well as the relative strength of the geologic material. In high rainfall areas, sedimentary and volcaniclastic rocks may weather into deep, clay-rich soils that arc susceptible to deep-seated soil creep and earthflows. Such soil mass movements are typical on slopes of the northern California Coast Range and the western side of the Cascade Range. Kelsey (1978) estimates that approximately 10 percent of the Franciscan melange in the northern California Coast Range is comprised of active earthflow terrain. Along the western side of the Cascade Range in Oregon, soil mass movements occur much more frequently in areas of predominantly altered volcaniclastic rocks (tuffs and breccias) at elevations below 900–7000 m than in areas comprised of unaltered lava flows (basalt and andesite) at higher elevations (Dyrness 1967, Swanson and Dyrness 1975). Soil mass movement over a 25-year period in the unstable volcaniclastic terrain was 2.8 times higher for deforested areas compared to forested sites, indicating the stabilizing effect of vegetation on this weak rock. In both the Cascade Range in Oregon and the northern California Coast Range, stability problems associated with weak rocks are exacerbated by crustal deformation and unfavorable geologic structure.

The influence of rock structures (bedding planes, folds, joints, faults, etc.) is an important factor in the stability of natural hillslopes. Downslope dipping planes between certain sedimentary and volcanic rocks of different competence or alteration, as well as joints and fractures oriented in the same direction, may likely impede vertical infiltration and root penetration, thus acting as potential failure planes. Horizontal or cross-dip bedding may provide natural buttresses that may actually increase the stability of slopes (Swanston 1978). Fault zones often contain fractured, crushed, or partly metamorphosed rocks resulting from stress relief and intrusion of igneous or ultramafic rocks during geologic uplift. The inherent geologic weakness of these zones is further enhanced by deep percolation of water into the bedrock and subsequent chemical weathering of mantle material into clay-rich soil which is susceptible to slump-earthflow type of failures.

Other geologic situations that are susceptible to soil mass movement include most shallow soil mantles over relatively impermeable rocks on steep slopes and resistant volcanic flow rocks overlying clay-rich rocks. Crystalline igneous and metamorphic rocks and competent sedimentary rocks often occur in mountainous terrain and, for these situations, overlying soils may be poorly attached to bedrock. Translational sliding of the whole soil mantle over the underlying rock in debris slides-debris avalanches is a common feature of such areas (for example, British Columbia, O'Loughlin 1972; coastal Alaska, Swanston 1974; the Appalachians, Bogucki 1976, Eschner and Patric 1982, Woodruff 1971; and Adirondacks, Bogucki 1977). Bedding and jointing in hard sedimentary rocks may permit better attachment of soil to the underlying rocks than that frequently found with more massive igneous and metamorphic rocks. Clay layers located at the soil-bedrock interface may provide an especially susceptible surface for sliding-type failures (O'Loughlin and Pearce 1976). In areas where resistant flow rocks (for example, basalt) overlie incompetent, clay-rich, volcaniclastic rocks, large-scale soil creep, earthflows and slumps can develop. Examples of such situations include soil creep and slump-earthflows along the Columbia Gorge in Oregon and Washington (Palmer 1977), along the western side of the Cascade Range of southern Oregon (Swanson and Swanston 1977), and along the eastern side of the Oregon Coast Range (Beaulieu 1974, Swanston 1978). Slumps and earthflows occurring in such terrain typically have steep headwall scarps (Swanson and James 1975).

Shallow landslides are common in western North America where mountains have undergone natural steepening by tectonic uplift and glaciation. Although slope gradient can be closely related to shallow mass movement processes in certain areas (for example, Ballard and Willington 1975, Lohnes and Handy 1968, Swanston 1974), it is difficult to make generalizations based on these localized relationships because of other complicating geologic, climatic, and land-use factors. The concept of a threshold angle of slope steepness is largely based on observations of shallow landslides on particular soil-rock types and has worked well as a predictive tool for debris avalanche risk evaluation in specific areas. In hillslopes with developing (for example, recently glaciated) or changing (for example, active soil creep) soil mantles, identification of high-risk landslide areas must take into account soil mantle thickness as well as rock and soil properties and slope steepness.

A lower limit of slope gradient for various soil mass movements is difficult to specify and wide variations in typical gradients for these processes are apparent (fig. 1). Although generalizations are difficult to make, many slopes over 25° are probably subject to rapid soil mass movement, especially if the soil mantle is poorly bound to the underlying rocks (Sidle and others, in press). Most slopes over 35° are subject to soil mass movement (if soil is present). Slower processes, such as slumps and earthflows, initiate on slopes as gentle as 4–20°. Soil creep has been measured on slopes as gentle as 1.3° (Finlayson 1981); however, certain sites may require gradients as steep as 25° before measurable creep occurs (Burroughs and others 1976). Specialized failures, such as lateral spreads or flow in quick clays, can occur on nearly level slopes.

Slope Shape

Slope shape is important in determining the distribution of soil water in unstable landscapes. Convex slopes disperse subsurface water and tend to be more stable than concave slopes which concentrate subsurface water into small areas of the slope. The frequent association of shallow-rapid landslides with hillslope depressions and V-notch gullies is, therefore, not surprising. Following failure, these depressions gradually fill in by localized sloughing around the headwall, soil creep, and movement of organic debris and surficial material from above (Dietrich and Dunne 1978, Lehre 1981). Soil in hillslope depressions, consequently, may often be much thicker than that in intervening minor ridges, increasing the likelihood of additional failure. Repetition of failure occurs when the depressions become sufficiently overloaded with mineral and organic debris coupled with an episodic storm or snowmelt. The frequency of intermittent failure in these depressions is on the order of tens to hundreds of years depending on rates of fill in and process linkages involved at particular sites.

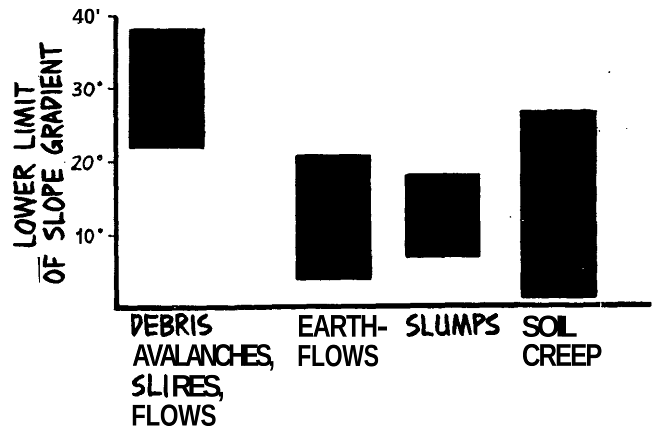


Figure 1.--Lower limit of slope gradient, generally measured in a representative portion of the scouring or active movement zone, for various soil mass movements (after Sidle and others 1984).

SOIL PROPERTIES

Engineering Properties Of Soils

Soil shear strength (s), which quantitatively describes the resistance of a soil to failure, is generally considered to be a function of normal stress on the slip surface (p), cohesion (c'), and internal angle of friction (Ø'). Normal stress is influenced by the unit weight or density of the soil at field moisture content, soil depth, and slope gradient. Pore water pressure (μ) at the failure surface decreases the normal stress to an effective normal stress (p') by acting as a buoyant force. Infiltrating water can generate unstable conditions on hillslopes by increasing the weight of the soil mantle and by eventually increasing pore water pressures.

Cohesion is directly related to the plastic nature of soils. Noncohesive soils are essentially nonplastic. Cohesive soils have high clay content and are characteristic of deep-seated soil creep and slump-earthflow mass movements. Cohesion in these fine-grained soils is a function of moisture content. Cohesion increases slightly with increasing moisture and then decreases rapidly as moisture content is further increased. The point at which cohesive forces are greatest generally corresponds to the minim moisture content at which the soil can be deformed without rupture (that is, the plastic limit). Rogers and Selby (1980) indicate that the cohesion component of two landslide soils (clay and silty clay textures) decreased 18 and 70 percent respectively, following saturation. In field soils, cohesion is supplemented by the contribution of rooting strength (c_r); the sum of these is called total cohesion ($c + c_r$). Aggregation in the soil matrix reflects cohesive forces, but aggregation may increase interlocking, which increases the friction angle (Ø).

Internal angle of friction (Ø) represents the degree of interlocking of individual grains or aggregates and is influenced by the shape, roundness, size, and packing arrangement of these particles. Angular particles have a larger Ø than rounded particles because of their greater interlocking capabilities. True cohesionless soils, such as sands, form a single-grained structure with their shear strength mainly dependent on intergranular friction and on grain interlocking. Aggregated soils may exhibit cohesionless behavior in that aggregates act as individual grains. Yee and Harr (1977) found that aggregation in two essentially cohesionless soils was largely responsible for their relatively high 0 values (40-41°). Compaction of soil materials increases Ø by rearranging particles into a tighter packing configuration.

Chemical/Mineralogical Properties

The influence of clay mineralogy on certain physical and engineering soil properties is an important consideration in the stability of cohesive soils. However, unlike certain physical parameters (for example, subsurface water, slope gradient), mineralogical and chemical properties are normally not solely responsible for slope failure, but rather act synergistically with other destabilizing factors.

Because of their swelling characteristics, smectite clays (for example, montmorillonite, beidellite) are associated with a number of mass soil movement landforms. Smectites have been found to be major constituents in deep-seated mass soil movements, such as earthflows in the Cascade Range in Oregon (Paeth and others 1971, Taskey 1977) and southwestern Pennsylvania (Ciolkosz and others 1979) and deep soil creep in California (Fleming and Johnson 1975). Soils high in montmorillonite have been associated with bentonite debris flows in northern Alaska (Anderson and others 1969) and landslides in Wyoming (Booy and Kerr 1973) and Montana (Klages and Hsieh 1975).

Kaolinite, a nonswelling clay, tends to be a component of more stable soils along the western side of the Cascade Range in Oregon (Paeth and others 1971, Taskey 1977) and in California (Borchardt 1976). Halloysite, a clay with similar mineralogy to kaolinite, has a tubular structure that allows the incorporation of interlayer water into the clay lattice. Unstable slopes have been associated with the hydrated form of halloysite in the Cascade Range in Oregon (Taskey 1977) and Oregon Coast Range (Istok and Harward 1982).

The hydrous mica (for example, illite, vermiculite) and smectite clays both tend to occur in the so-called quick clays of Canada and Scandinavia (Kerr 1963, Rosenquist 1953). Quick clay behavior involves a sudden structural alteration from a fairly stable, brittle solid to a liquid of negligible strength. Quick clays can suddenly turn to liquid when vibrated by such energy sources as an earthquake or blasting. One explanation of this rapid loss of strength is the extensive leaching of salt water cations, which ultimately reduces interparticle bonding in the quick clay matrix (Kaze and Moum 1973, Rosenquist 1953). Many quick clays were deposited in marine or brackish environments and thus developed a dispersed structure rich in sodium and other cations (Yatsu 1967). As these areas rose above sea level following glaciation, some adsorbed cations were leached out of the clays decreasing the ionic strength and changing the chemistry of the pore water. The lower cation concentration within the soil matrix coupled with naturally high water content (often exceeding the liquid limit), makes quick clays highly unstable (Eden and Mitchell 1970). Smalley (1976) emphasizes that quick clay behavior can also occur in soils composed of the primary mineral particles (as opposed to true clays), in which case the rapid loss of strength may be related more to fracturing of interparticle cementing material (for example, iron oxides, calcium carbonate, silica) during disruptions than to the long-term cation leaching phenomena observed in marine clays. Disruption of cementation appears to be a greater cause of liquefaction in the Canadian quick clays than in the Scandinavian materials (Eden and Mitchell 1970, Smalley 1976).

Earthflows in the Cascade Range and Coast Range of Oregon have been related to the presence of amorphous clays (Istok and Harward 1982, Taskey and others 1978). The instability of these amorphous clays was partially attributed to their high water-holding capacities. The water could presumably be released following disturbance, accounting for the fluid behavior of earthflows.

HYDROLOGIC FACTORS

Factors influencing Groundwater Levels

Hydrologic processes influencing the stability of hillslopes are largely dependent upon the incident rainfall or snowmelt regime, the rate of water entry or recharge into the soil mantle, the transmission rate of water within the soil mantle, and evapotranspiration. The general rainfall or snowmelt rates in undisturbed forested areas rarely generate extensive overland flow over large areas. Saturated or nearly saturated soils in valley bottoms or in isolated hillside locations may experience overland flow during storms. In general, however, the dominant mechanism of downslope water movement is by transmission within the soil mantle.. The relative rates of recharge, transmission, and evapotranspiration determine the transient level of groundwater occurring in hillslope soils and thus influence their stability during rainstorms or snowmelt.

Recharge of soil water is the result of water entering the soil and is influenced by vegetative cover, cultural practices, and landscape shape, as well as soil physical properties affecting water movement. Soil water recharge can be greatly influenced by soil layering or the presence of a shallow water table. Downward progress of the wetting front may be greatly impeded when it encounters a layer of considerably lower permeability or other changes in texture or structure. The same effect occurs when infiltrating water reaches a perched water table. Tension cracks, which develop around the headwalls and flanks of potential slope failures, provide a rapid recharge route for water into the soil mantle. Vegetation and ground cover generally enhance soil water recharge. Forest soils typically have high recharge rates because of their thick, permeable organic horizons. Cultural practices such as road building, logging, and burning can significantly reduce soil water recharge.

The discharge rate of water from unstable soil mantles is probably the most significant hydrologic factor affecting soil mass movement. If subsurface flow rate is less than infiltrating rainfall or snowmelt rates for extended periods of time, a perched goundwater table will form within the soil mantle. The height, and persistence of the perched water table depends largely on rainfall or snowmelt intensity and duration, infiltration rate at the site, slope gradient, and subsurface flow rate within the soil mantle. Because the infiltration rate often does not limit recharge of unstable slopes, the subsurface flow rate becomes the controlling hydrologic variable during many rainfall or snowmelt periods.

Large, interconnected soil pores (that is, macropores, soil pipes) provide important passageways for transport of subsurface water in hillslope soil mantles (Jones 1971, Whipkey 1965). Although piping networks are believed to be somewhat interconnected over large areas (Pond 1971), small breaks in this network would create potential sites of extensive positive pore water pressure buildup as the surrounding soil would have a much lower permeability. Tsukamoto and others (1982) cited pipeflow as a primary contributing factor in debris slide initiation in small hillslope basins in Japan. Extensive but discontinuous piping networks have been found in earthflow landforms and are believed to accelerate movement by allowing excessive pore water pressures to build up (Blong and Dunkerly

1976). In such slow mass movements, it is conceivable that the size and extent of pipes, as well as their degree of interconnection, could change over short periods of time.

Evapotranspiration influences, soil water recharge and subsurface flow and, thus, may affect slope stability through either transpiration or interception (depending on vegetative characteristics), seasonal distribution of precipitation, and timing of transpiration relative to precipitation. Deciduous vegetation in climates with fall or winter rainfall maxima will have the least stabilizing influence upon the soil mantle because interception and transpiration are minimal during the extended periods of recharge and saturation. In similar climates evaporation of intercepted rainfall from conifer canopies is one of the few pathways of diverting incident rainfall away from unstable slopes. Colder, higher, snowfall areas, where soil mass movements are intiated by snowmelt, may experience similar ameliorative effects by long-term evaporation of snow from conifer canopies.

Because most shallow rapid mass movements occur during extended rainfall or snowmelt periods, evapotranspiration is unlikely to be a major controlling factor except during the first large rainstorm of the season (Megahan 1983). Increased evapotranspiration may help to reduce the movement rate of deep-seated soil creep and earthflows. Conifers on slopes affected by these movement types will have beneficial effect, compared to other types of vegetation, by extending the period of low soil moisture, by drying the soil to a greater depth during low-rainfall seasons than would occur with shallow-rooted vegetation, and by delaying and extending the period during which recharge takes place.

Groundwater-Slope Stability Relationships

Although implicit relationships have been developed between storm characteristics and landslide occurrence in certain areas of North America (for example, Nielsen and others 1976), only a few studies have investigated the response of shallow grounwater in unstable slopes during storms. Megahan (1983) related peak piezometric rise in two small drainages in the Idaho batholith to snowmelt rate. Nearly total saturation of the soil mantle was reached during a high snowmelt season. Pierson (1980) found complete saturation of the oil mantle along the lower axes of several hillslope depressions in the Oregon Coast Range during a winter storm with an estimated return period of 3 to 4 years. Piezometric head decreased in the upslope direction at most sites. Harr (1977) observed completely saturated conditions at the foot of slightly convex, unstable slopes during moderate winter storms (return periods <1.5 years) in the Cascade Range in Oregon. Isolated regions of partial saturation at the surface soil-subsoil boundary were detected in midslope and upslope locations. Sidle and Swanston (1981) and Sidle

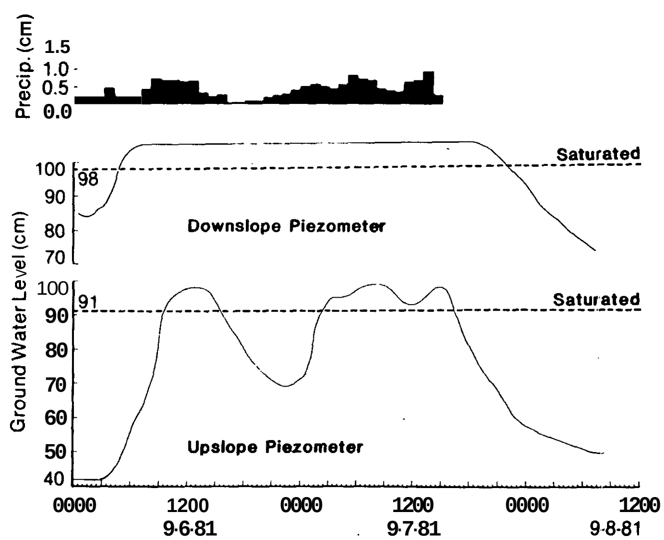


Figure 2.-Groundwater response in two portions of an unstable hillslope depression during a storm of moderate intensity, Kennel Creek, Chichagof Island, Alaska.

(1982) found artesian conditions occurring during major storms at various slope positions in the trough of a hillslope depression. Data from these heavily instrumented depressions suggest; that in such areas where convergent flow dominates, groundwater peaks may occur simultaneously in the upper and lower portionsof the slope, although maximum groundwater peaks may dissipate more quickly in the upper slope locations (fig. 2). In calculating soil shear strength for such sites, the most important hydrologic parameter is the maximum piezometric response (even if only shortterm). Data for shallow soils (<1 m) suggest that nearly saturated to artesian conditions may be necessary to induce slope failure (O'Loughlin and Pearce 1976; Sidle 1982, Sidle and Swanston 1981, 1982).

Shallow-rapid soil mass movements generally respond to individual storm or snowmelt events, and deep-seated earthflows and soil creep are more influenced by seasonal rainfall,. Studies in the Pacific Northwest and northern California indicate that soil creep occurs at rates <1 to >100 mm/yr with movement concentrated during the rainy season (Swanson and Swanston 1977; Swanston 1981). Movement of deep-seated failures is generally slow early in the wet season, while the soil mantle is recharging, and later becomes more responsive to rainfall inputs (Swanson and Swanston 1977).

VEGETATIVE FACTORS

Influence Of Roots On Slope Stability

Plant root systems contribute to the stability of hillslopes in several ways. Roots add strength to the soil by vertically anchoring through the soil mantle into fractured bedrockor other more stable substrate. This mechanism is only effective in stabilizing relatively **thin** soils (that is, <1 m), such as those found on steep, dissected slopes of coastal British Columbia and Alaska. Dense networks of medium- and small-sized roots reinforce the upper soil layer so that it acts as a membrane to provide lateral strength and increased slope stability (O'Loughlin 1981). The combined effect of this "membrane strength" and vertical anchoring is evidenced by the location of landslide planes just beneath the zone of dense root networks on deforested slopes. Swanson and Swanston (1977) suggest lateral root reinforcing across planes of weakness (for example, headwalls and tension cracks around earthflows) may also be important in providing stability to deeper soils prone to creep and earthflow movement. Larger structural roots in the vicinity of individual trees can provide buttressing or soil arching action between trunks, depending upon tree spacing (Gray and Megahan 1981). This buttressing mechanism is only important in stabilizing thin soil mantles prone to debris slides and avalanches.

Effect Of Root Deterioration

The deterioration of tree roots following timber harvesting is believed to be an important mechanism reducing the stability of steep slopes with shallow soils. Studies in various areas have shown an increased frequency of shallow landslides occurring 3 to 10 years after logging; the period of minimum stability during residual root decay and subsequent regeneration (Bishop and Stevens 1964, Megahan and others 1978). Following this susceptible period of minimum soil strength, regeneration generally improves the stability of the slope (fig. 3).

When roots fail during landsliding they more commonly fail in tension rather than in shear (Gray and Megahan 1981, O'Loughlin and others 1982). Studies indicate that root tensile strength following tree cutting declines in an exponential manner over a period of several years (Burroughs and Thomas 1977, O'Loughlin and Watson 1979). Ziemer and Swanston (1978) found an increase in average root strength of Sitka spruce and western hemlock 4 to 6 years after tree removal associated with residual, strong, resinous roots. This would not increase the overall soil strength, however,, because most nonresinuous roots had completely decayed.

The type of vegetation occupying a hillslope can influence the relative rooting contribution to soil strength. In general, root strength tests indicate that coastal Douglas-fir and western red cedar roots are stonger than western hemlock roots, which in turn are stronger than Sitka spruce roots. Living conifer roots tend to be weaker than similar-sized hardwood roots. Studies indicate that certain hardwood shrubs that are often suppressed or killed by herbicides or slash burning following logging, have rooting systems of comparable strength to overstory species (Ziemer 1981, Ziemer and Swanston 1977).

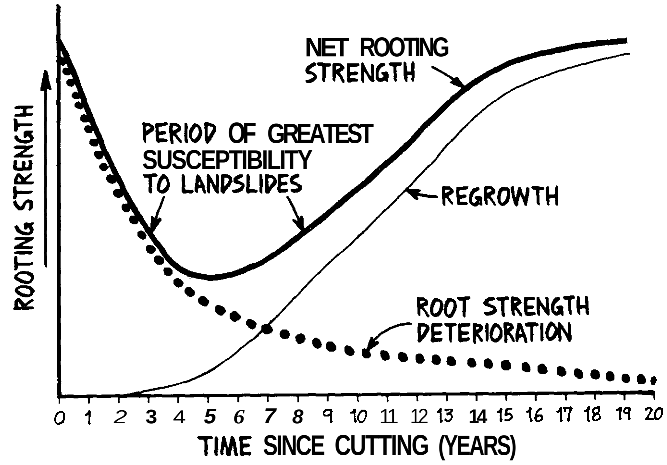


Figure 3.--Hypothetical curves indicating root strength deterioration following timber harvesting, rooting strength of regenerating site vegetation, and net rooting strength. Period of minim rooting strength is noted approximately 3-8 years following logging.

Root systems of different species also decay at different rates following vegetation removal. Burroughs and Thomas (1977) found that although coastal Douglas-fir roots are stronger than those of the Rocky Mountain variety, they decay much faster after cutting. Sitka spruce roots decay more rapidly than do hemlock roots (Ziemer and Swanston 1977). The rate of root decay following timber harvesting, as well as the amount of shrub cover left on the site, can greatly modify the timing and extent of the minimum stability period shown in figure 3.

SEISMICITY

In seismically active regions, moderate to large magnitude earthquakes have generated sufficient ground motion to initiate failures on slopes that exist in an already delicate state of balance. Some of the largest and most devastating landslides in recent history have been triggered by major earthquakes. The effectiveness of earthquakes in triggering landslides and the distance at which earthquakes can cause failures depends on many factors including the stability of the potential slide masses, vegetation, land use, the orientation of potential failures in relation to the earthquake epicenter, and direction of seismic wave propagatior, earthquake magnitude, focal depth, seismic wave attenuation, and aftershock distribution (Voight and Pariseau 1978). In summarizing landslide data from 40 worldwide earthquakes, Keefer (in press) indicates that the area affected by landslides is directly proportional to earthquake magnitude, increasing from 0 km^2 at M = 4.0 to approximately 500,000 km^2 at M = 9.2. Rock falls, rock slides, soil falls, and disrupted soil slides can be triggered by the weakest seismic activity. Deep-seated slumps and earthflows are generally initiated by stronger (and probably longer duration) seismic activity.

Lateral spreads, debris Flows, and subaqueous landslides require the greatest earthquake magnitudes.

SUMMARY

Many of the natural factors influencing the stability of slopes may act synergistically to initiate or accelerate soil mass movements. For example, steep slopes with thin, cohesionless soils, underlain by impermeable rock or compact till may exist in a state of marginal stability until a major storm generates extensive pore water pressures within the soil mantle. The subsequent failure of such sites, typical of shallow-rapid failures in the coastal Pacific Northwest, is a testimony to the interaction of unfavorable geomorphic, soil, and hydrologic conditions. In other similar areas, the triggering mechanism for slope failure may be a moderate-sized earthquake.

The influence of vegetation on slope stability is most apparent in situations where vegetative cover has been drastically modified (that is, clearcutting, conversion of forest or brush land to pasture and crop land). In conjunction with natural factors such as extended rainfall or earthquakes, other land management practices predispose marginally stable hillslopes to landslides. Roadbuilding decreases slope stability by mechanically steepening or overloading slopes, undercutting unstable toeslopes, and concentrating drainage water onto unstable slopes. Residential development on forested or brushland hillslopes causes similar instability problems, with the additional destabilizing factor of widespread vegetation removal.

Responsible land management must evaluate the inherent slope stability risk associated with these intensive and extensive land uses. Risk analysis involves consideration of both natural and land use factors predisposing slopes to failure. Some factors, such as soil strength and slope gradient, can be measured or estimated. Effect of vegetation removal or conversion can be estimated from empirical studies of rooting strength decay. Other factors, such as groundwater, are dependent on probabilistic events. Thus, certain risk analyses (that is, for shallow, rapid failures) must not only estimate or measure natural or management-related factors, but also superimpose the probability of a threshold storm occurring.

LITERATURE CITED

Anderson, D. M.; Reynolds, R. C.; Brown, J. Bentonite debris flows in northern Alaska. Science. 164: 173–174; 1969.

Ballard, T. M.; Willington, R. P. Slope instability in relation to timber harvesting in the Chilliwack Provincial Forest. The Forestry Chronicle. 51(1):59-62; 1975.

Beaulieu, J. D. Geologic hazards of the Bull Run watershed, Multnomah and Clackamas Counties, Oregon. Oregon Department of Geology and Mineral Industries Bulletin 82: 77pp.; 1974.

Bishop, D. M.; Stevens, M. E. Landslides on logged areas in southeast Alaska. Res. Pap. NOR-1. Juneau, AK: U.S. Department of Agriculture, Forest Service, Northern Forest Experiment Station; 1964. 18p.

Blong, R. J.; Dunkerley, D. L. Landslides in the Razorback area, New South Wales, Australia. Geografiska Annaler. 58A:139-147; 1976.

Bogucki, D. J. Debris slides in the Mt. Le Conte area, Great Smoky Mountains National Park, USA. Geografiska Annaler. 3A:179-191; 1976.

Bogucki, D. J. Debris slide hazards in the Adirondack Province of New York State. Environmental Geology. 1:317-328; 1977.

Booy, E. ; Kerr, P. F. Mineralogy of some "bentonites" involved in slope failures in Wyoming. In: Proc., 22 Clay minerals conference; 1973 October 7–11 Banff, Alberta. Banff, Alberta: University of Alberta Press; 1973: 63 p.

Borchardt, G. A. Clay mineralogy and slope stability. California Division of Mines and Geology Special Report; 1976. 41p.

Burroughs, E. R.; Chalfant, G. R.; Townsend, M. A. Slope stability in road construction, U.S. Department of Interior, Bureau of Land Management, Oregon Office, Portland Oregon; 1976. 102 p.

Burroughs, E. R.; Thomas, B. R. Declining root strength in Douglas-fir after failing as a factor in slope stability. Res. Pap., INT-190. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountian Forest and Range Experiment Station; 1977. 27 p.

Ciolkosz, E. J. ; Petersen, G. W. ; Cunningham, R. L. Landslide-prone soils of southwestern Pennsylvania. Soil Science. 128(6):348-352, 1979.

Dietrich, W. E.: Dunne, T. Sediment budget for a small catchment in mountainous terrain. Zeitschrift fur Geomorphologie Supplement band. 29:191–206; 1978.

Dyrness, C. T. Mass soil movements in the H. J. Andrews Experimental Forest. Res. Pap. PNW-42. Portland, OR: U.S. Department of Agriculture Forest Service, Pacific Northwest Forest and Range Experiment Station; 1967. 13 p.

Eden, W. J.; Mitchell, R. J. The mechanics of landslides in Leda Clay. Canadian Geotechnical Journal. 7:285-296; 1970.

Eschner, A. R.; Patric, J. H. Debris avalanches in eastern upland forests. Journal of Forestry. 80:343-347; 1982.

Finlayson, B. Field measurements of soil creep. Earth Surface Processes and Landforms. 6:35–48; 1981.

Fleming, R. W. ; Johnson, A. M. Rates of seasonal creep of silty clay soil. Quarterly Journal of Engineering Geology. 8(1):1-29; 1975.

Gray, D. H. ; Megahan, W. F. Forest vegetation removal and slope stability in the Idaho Batholith. Res. Pap. INT-271. Ogden, UT: U.S. Department of Agriculture Forest Service, Intermountain Forest and Range Experiment Station; 1981. 23 p.

Harr, R. D. Water flux in soil and subsoil on a steep forested slope. Journal of Hydrology. 33:37–58; 1977.

Istok, J. D.; Harward, M. E. Clay mineralogy in relation to landscape instability in the Coast Range of Oregon. Soil Science Society of America Journal. 46(6):1326-1331; 1982.

Jones, A. Soil piping and stream channel initiation. Water Resources Research. 7(3):602-610; 1971.

Kazi, A.; Moum, J. Effect of leaching on the fabric of normally consolidated marine clays. In: Proceedings, International Symposium on Soil Structure; Gothenburg, Sweden. Gothenburg, Sweden: 1973: 137-152.

Keefer, D. K. Landslides caused by earthquakes Geological Society of America Bulletin. 95; (in press).

Kelsey, H. M. Earthflows in Franciscan melange, Van Duzen River Basin, California. Geology. 6:361-364; 1978.

Kerr, P. F. Quick clay. Scientific American. 209(5):132-142; 1963.

Klages, M. G. ; Hsieh, Y. P. Suspended,solids carried by the Gallatin River of southwestern Montana: II. Using mineralogy for inferring sources. Journal of Environmental Quality. 4(1)68-73; 1975.

Lehre, A. K. Sediment budget of a small California Coast Range drainage basin. In: Davies Timothy R. H. and Pearce, Andrew J., eds. Proceedings of a symposium on erosion and sediment transport in Pacific Rim steeplands. 1981 January; Christchurch, New Zealand. Paris: International Association of Hydrological Sciences. Publication 132; 1981: 123–139.

Lohnes, R. A. ; Handy, R. L. Slope angles in friable loess. Journal Geology. 76(3):247–258; 1968.

Megahan, W. F. Hydrologic effects of clearcutting and wildfire on steep granitic slopes in Idaho. Water Resources Research. 19(3);811-819; 1983.

Megahan, W. F.; Day, N. F.; Bliss, T. M. Landslide occurrence in the western and central Northern Rocky Mountain Physiographic Province in Idaho. In: Youngberg, C. T., ed. Proceedings 5th North American forest soils conference; 1978, August; Fort Collins, Colorado. Fort Collins, Colorado: Colorado State University Press; 1978: 116–139.

Nielsen, T. H.; Taylor; F. A.; Dean, R. M. Natural conditions that control landsliding in the San Francisco Bay region--an analysis based on data from the 1968–69 and 1972-73 rainy seasons. U.S. Geological Survey Bulletin 1424. Washington, DC: U.S. Department of Interior, Geological Survey; 1976. 35 p.

O'Loughlin, C. L. The stability of steepland forest soils in the Coast Mountains, Southwest British Columbia. Vancouver, BC: University of British Columbia; 1972. 141 p. Ph.D. dissertation.

O'Loughlin, C. L. Tree roots-and slope stability. In: What's new in forest research. Forest Research Institute Publication 104. Rotorua, New Zealand. New Zealand Forest Service; 1981. 4 p.

O'Loughlin, C. L.; Pearce, A, J. Influence of Cenozoic geology on mass movement and sediment yield response to forest removal, north Westland, New Zealand. Bulletin of the International Association of Engineering Geology. 14:41-46; 1976.

O'Loughlin, C. L.; Rowe, L. K.; Pearce, A. J. Exceptional storm influences on slope erosion and sediment yields in small forest catchments, north Westland, New Zealand. In: Proceedings of National Symposium on Forest Hydrology; Melborne, Australia. Melborne, Australia: 1982 May 11-13; Australia Institution of Engineers, Australia Publication; 1982:84-91.

O'Loughlin, C. L.; Watson, A. J. Root wood strength deterioration in radiata pine after clearfelling. New Zealand Journal of Forestry Science. 9(3):284-293; 1979.

Paeth, R. C.; Harward, M. E.; Knox, E. G.; Dyrness, C. T. Factors affecting mass movement of four soils in the Western Cascades of Oregon. Soil Science Society of America Proceedings. 35(6):943-947; 1971.

Palmer, L. Large landslides of the Columbia River Gorge, Oregon and Washington. In: Coates, D. R., ed. Reviews in the engineering geology; Vol. III - Landslides. Boulder, Colorado. Geological Society of America; 1977: 69–83.

Pierson, T. C. Piezometric response to rainstorms in forested hillslope drainage depressions. Journal of Hydrology (New Zealand). 19(1): 1–10; 1980.

Pond, S. F. Qualitative investigation into the nature and distribution of flow processes in Nant Gerig. In: Subsurface Hydrology, Rep. 28. Wallingford, England: Institute of Hydrology; 1971.

Rogers, N. W.; Selby, M. J. Mechanisms of shallow translational landsliding during summer rainstorms, North Island, New Zealand. Geografiska Annaler. 62A:11–21; 1980.

Rosenquist, I. T. Sensitivity of Norwegian quick clays. Geotechnique. 3:195-200; 1953.

Sidle, R. C. Ground water influences on slope stability. In: Agronomy Abstracts: American Society of Agronomy; 1982: 272.

Sidle, R. C.; Pearce, A. J.; O'Loughlin, C. L. Soil Mass Movement: Influence of Natural Factors and Land Use. American Geophysical Union, Water Resources Monograph; (in press).

Sidle, R. C.; Swanston, D. N. Storm characteristics affecting piezometric rise in unstable hillslopes of southeast Alaska. EOS 62:856; 1981.

Sidle, R. C.; Swanston, D. N. Analysis of a small debris slide in coastal Alaska. Canadian Geotechnical Journal. 19:167–174; 1982.

Smalley, I. Factors relating to the landslide process in Canadian quick clays. Earth Surface Processes. 1:163-172, 1976.

Swanson, F. J.; Dyrness, C. T. Impact of clearcutting and road construction on soil erosion by landslides in the western Cascade Range, Oregon. Geology. 3(7):393-396, 1975.

Swanson, F. J.; James, M. E. Geology and geomorphology of the H. J. Andrews Experimental Forest, western Cascades, Oregon. Res. Pap. PNW-188. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station; 1975. 14 p.

Swanson, F. J.; Swanston, D. N. Complex mass-movement terrains in the western Cascade Range, Oregon. In: Coates, D. R., ed. Reviews in engineering geology; Vol. 111-Landslides. Boulder, CO: Geological Society of America; 1977; 69–83.

Swanston, D. N. The forest ecosystem of southeast Alaska. 5. Soil mass movement. General Technical Report PNW-17, Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station; 1974. 22 p.

Swanston, D. N. Effect of geology on soil mass movement activity in the Pacific Northwest, In: Youngberg, C. T., ed. Forest Soils and land use: Proceedings, 5th North American forest soils conference; 1978 August; Fort Collins Colorado. Fort Collins, Colorado. Colorado State University Press; 1978: 89–115.

Swanston, D. N. Creep and earthflow erosion from undisturbed and management impacted slopes in the coast and Cascade Ranges of the Pacific Northwest, U.S.A. In: Davis, Timothy R. H. and Pearce, Andrew J., eds. Proceedings of a symposium on erosion and sediment transport in Pacific rim steeplands. 1981 January; Christchurch, New Zealand. Paris: International Association of Hydrological Science. Publication 132; 1981: 76–94.

Taskey, R. D. Relationship of clay mineralogy to landscape stability in western Oregon. Corvallis, OR: Oregon State University; 1977. 223 p. Ph.D dissertation.

Taskey, R. D.; Harward, M. E.; Youngberg, C. T. Relationship of clay minerology to landscape stability, In: Youngberg, C. T., ed. Forest Soils and land Use: Proceedings of 5th North American forest soils conference: 1978 August; Fort Collins, Colorado. Fort Collins, Colorado,, Colorado State University Press; 1978: 140-164.

Tsukamoto, Y.; Ohta, T.; Noguchi, H. Hydrological and geanorphological studies of debris slides,on forested hillslopes in Japan. In: Recent developments in the explanation.and prediction of erosion and sediment yield. International Association of Hydrological Sciences. Publication 137; 1982: 89–98.

Voight, B.; Pariseau, W. G. Rockslides and avalanches—an introduction. In: Voight, B. ed. Rockslides and avalanches. Chapter I--Natural phenomena. Developments in Geotechnical Engineering. Vol. 14A. Amsterdam: Elsevier Publishing Co.; 1978: 1-67.

Whipkey, R. Z. Subsurface stormflow from forested slopes. Bulletin International Association of Scientific Hydrology. 10(3):74-85, 1965.

Woodruff, J. F. Debris avalanches as an erosional agent in the Appalachian Mountains. Journal. of Geography. 70:399–406, 1971.

Yatsu, E.. Some problems on mass movements. Geografiska Annaler. 49A:396–401, 1967.

Yee, C. S.; Harr, R. D. Influence of soil aggregation on slope stability in the Oregon Coast Ranges. Environmental Geology. 1:367-377, 1977.

Ziemer, R. R. Roots and the stability of forested slopes. In: Davies, Timothy R. H. and Pearce, Andrew J., eds. Proceedings of a symposium on erosion and sediment transport in Pacific rim steeplands. 1981 January; Christchurch, New Zealand. Paris: International Association of Hydrological Sciences. Publication 132; 1981: 343–357.

Ziemer, R. R.; Swanston, D. N. Root strength changes after logging in southeast Alaska. Res. Note PNW-306. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station; 1977. 10 p.

LANDSLIDE DAMAGE TO THE FOREST ENVIRONMENT

George W. Brown

ABSTRACT: Damage from landslides is a central issue facing land managers today. Landslides may damage site productivity, water quality, anadromous fish habitat, and roads and structures, but it is often difficult to determine the extent and duration of the damage. The reason is that landslide impacts vary widely depending on location of the landslide with respect to valued resources, time, and size of the event. Damage is almost impossible to predict and warrants additional research, especially in today's political environment.

INTRODUCTION

Damage from landslides is a central issue facing land managers today. What has been damaged, by how much, and by whom are important questions many of you have had to address. And if you have become involved in a controversy about landslides, you know that these questions are not easy to answer, especially those that attempt to separate natural landslides from those caused by human activities. Thus, before we examine specific ways in which landslides produce environmental damage, same general points about such damage are in order.

1. Webster defines damage as "loss resulting from injury." Landslides produce noticeable changes in the forest environment, but "losses" and "injury" are often very difficult to quantify. For example, subtle changes in the quality of anadromous fish habitat may require special study to detect.
2. Time is an important variable when considering damage, In the shortterm, landslides can destroy bridges, roads, home sites, and fish habitat. In the longterm or geologic time scale, landslides may be viewed as a more normal part of the earth's natural land-forming process or even as a positive contribution to the environment. Today's landslide material will become gravel or beach sand 1,200 years hence.
3. Damage caused by landslides is usually a function of the size and location of the event. Small landslides in areas far removed from human habitation or important spawning sites may produce no "loss" or "injury." Landslide numbers or frequency are not necessarily good indicators of damage.
4. In a legal sense, damage and negligence are separate issues. Parties damaged by landslides originating on an Owner's land upstream may petition the court for reparation regardless of findings of negligence. Negligent landowners are subject to additional punative damages. In this paper, I will deal only with the damages that landslides produce. Landowner action that may constitute negligenee is beyond the scope of my assignment.

I will address four physical aspects of the environment that may be damaged by landslides: site productivity, water quality, anadromous fish habitat, and roads and structures. No attempt will be made to distinguish the effects of natural and human-caused landslides.

SITE PRODUCTIVITY

Little documentation has been done on how

GEORGE W. BROWN is Chairman, Department of Forest Engineering, Oregon State University, Corvallis, Oregon.

landslides affect site productivity, probably because landslides usually occupy less than 1 percent of the landscape, even in highly unstable areas where clearcutting has been practiced.

Trees grow slower on landslide tracks than on adjacent, undisturbed soil. In the Cascade Range in Oregon, Miles (1983) examined 25 landslide tracks ranging from 6 to 28 years old and compared tree growth, stocking levels, and vegetative cover on them and on adjacent clearcut areas. He found that by 18 years, height growth of Douglas-fir seedlings was reduced by 38 percent, stocking by 25 percent, and volume by 40 percent on the landslide tracks. About 30 percent of the landslide area was nonstockable. Vegetative cover averaged about 51 percent on the landslide areas, but it ranged from 7 to 88 percent. The variability was so great that it masked any predictable recovery trends.

In southeast Alaska, Adams[1/] conducted a similar study on recent tracks left by debris avalanches. He found that soils in the tracks had fewer rooting sites, lower nutrient status, and higher bulk densities than would be expected in undisturbed forest soils. Adams' results help explain the growth reductions reported by Miles for trees growing on landslide tracks.

Thus, trees and other vegetation grow more poorly on landslide tracks than on adjacent soils, but so little work has been done on this topic that prediction of the overall impact of landslides on site productivity is impossible. Fortunately, landslides usually occupy a very small percentage of the landscape. Where they are more frequent, their overall impact on forest productivity could become significant, particularly if site recovery were slow.

WATER QUALITY

Landslides may increase turbidity and sedimentation in streams, rivers, and estuaries. These increases, in turn, reduce the quality of water for aquatic organisms and human consumption. Large landslides scour channel banks and destroy streamside vegetation, thereby exposing previously shaded stream channels to direct sunlight and perhaps increasing water temperature.

The key factor determining the impact of landslides on turbidity is whether slide debris reaches a channel where there is intermittent or perennial streamflow. In Pacific Northwest coastal streams, the turbidity produced by small landslides may be masked by the normally high variation in turbidity or suspended sediment. Furthermore, not all landslides or the sediment they produce reach channels in which water quality is critical for humans or aquatic organisms. Kethcheson and Froehlich (1978) inventoried about 40 slope failures in clearcuttings in the Oregon Coast Range and found that most small debris slides traveled only a short distance; none reached a channel. Other failures scoured first- and second-order channels, but none reached fish-bearing streams.

Such events could, nevertheless, affect sediment and turbidity in streams and estuaries because the scoured channels and debris deposits are sources of sediment immediately available for subsequent erosion. For example, road-related landslides doubled the predicted annual sediment yield for 1 year from a coastal watershed (Brown and Krygier 1971) and increased the mean concentration of suspended sediment during winter storms from less than 100 to nearly 4,000 parts per million in a Cascade Range watershed (Fredriksen 1970). In both examples, turbidity exceeded Oregon's water quality standard for the short period of high runoff during and immediately following storms. An interesting footnote in the coastal study is that coho and cutthroat populations were not affected by this short-term increase in sediment.

Many urban areas in the Pacific Northwest obtain their domestic water from forested watersheds, as do many rural families. Often, chlorination is the only treatment given this water. Normally, this water is so clear that sophisticated filtration systems are not needed. In such circumstances, any suspended sediment caused by landslides will enter the distribution systan and consumers will be forced to use turbid water or find alternative sources. Lawsuits are a likely byproduct.

Fortunately, turbidity produced by landslides is usually short-lived in forest streams. Even in the most extreme events, turbidity usually declines rapidly after rainfall ceases. An important exception is the turbidity resulting from colloidal suspension of clays and runoff in a reservoir. In such cases, water may remain turbid for days or weeks.

Thus, water quality can decline because of landslides. The magnitude and duration of the impact depends upon the size of the slide and how far it travels, whether it enters a stream channel, and the type of soil material it contains. Again, the number of variables involved and the naturally high variability of sediment transported in mountain streams make prediction of damage to water quality very difficult.

ANADROMOUS FISH HABITAT

Landslides have had their greatest impact on forest management by inflicting damage on fish habitat. Directly resulting from such damages, either real or perceived, are recent lawsuits: against the USDA Forest Service and changes in the Oregon Forest Practices Rules. In extreme cases, damage is obvious because spawning gravel

[1/] Personal communication, Paul Adams, Dept. of Forest Engineering, Oregon State University, Corvallis.

is scoured to bedrock or buried beneath mud and debris. In other cases, damage to habitat from landslides may be very difficult to detect and quantify. In all cases, damage to habitat and subsequent impact on fish populations is almost impossible to predict.

Previously cited data from Ketcheson and Froehlich (1978) demonstrate that not all slides reach channels and that many of those that do are confined in the upper reaches above channels where fish live or spawn. The good news in these findings is that many of the slides that occur, particularly small ones, may never cause the type of catastrophic damage to channels that many people predicted. The bad news for managers is that much of the habitat damage that may occur from landslides of this type will take a lot of careful study to'detect. For example, the fine sediments produced by such erosion are not always incorporated directly into spawning gravels. Sometimes these sediments rapidly wash through the streams and are deposited in lower river reaches or in estuaries. Incorporation of sediment into spawning gravels is such a complex process that relationships have not yet been defined for linking the quantity of sediment produced to the productivity of a stream reach or spawning site. Part of the complexity stems from the fact that the stream will work on landslide deposits and eventually produce usable habitat. Furthermore, fish have an ability to modify their spawning environment and cleanse spawning gravels of intruded sediment. Chinook, for example, can change gravel that is 40 percent fines to 15 percent fines by digging a redd.

Estuarine sedimentation is also very complex, but it has the potential for significant damage. Most of the commercial fish and shellfish along the coast spend a portion of their life cycle in the estuary and are highly dependent on the top 2 to 30 cm of the estuary bottom for food. Sedimentation can upset their food chain, though to what degree is uncertain.

Also uncertain is how fast coarse material from landslides move downstream or what effect they have on quality of spawning gravel. We know that coarse materials move more slowly than fines and that their greatest impact may be on channel morphology. Altering channel characteristics may, in turn, have an important effect on the amount and quality of available rearing habitat. In some cases, the effect of introduced coarse material is very negative, but in streams that are gravel-poor, coarse material from landslides may enhance the quality of spawning gravel. In other cases, the change in stream morphology may change the mix of species, but not the biomass of fish. For example, more riffles and less pools would favor chinook and steelhead at the expense of coho. Both cases are good examples of the difficulty in making damage assessments.

Large landslides from clearcuttings or roads may greatly alter anadromous fish habitat. But many of the small slides more common to forested terrain either do not reach streams or are confined in upper reaches above fish habitat. The impact, if any, may be very difficult to detect, and in some cases, may even be positive. Estuarine habitat may be as important to fish as upstream sites, but understanding of the estuary system is so limited that assessing and predicting damage to it is nearly impossible. Landslides can damage anadromous fish habitat, but the relationships are often very complex. Managers must recognize that factors such as characteristics of the landslide, topography and the affected stream channel combine to produce a given impact. Research is a long way from unravelling these complex relationships. At least we now know that simple correlations between road mileage or acres harvested and stream damage are not useful as predictive tools.

ROADS AND STRUCTURES

Landslides frequently damage roads and bridges in the forest, and large landslides may even reach valleys where people live and farm. Damage to structures is often easily quantifiable in economic terms. Rothacher and Glazebrook (1968) noted that roads were involved in over 60 percent of all damage reports made by national forests after the 1964 floods and that most of this damage was related to landslides. Total damage to roads and bridges from these floods was $12,500,000 (in 1968 dollars). Other damages are less easily quantified. For example, losses of human life, of fertile farm land buried under debris, and of access to a road system out of service are very difficult to express economically. But regardless of how difficult it is to quantify such damages to the social fabric, they are among the most visable impacts of landslides.

The most important aspect of such damage is that it is likely to increase from both natural and human caused events. Road systems, bridges, and home sites are all increasing in the forest. The Forest Service adds about 6400 km. of new road each year to its 496,000 km. system. Other agencies and forest industries also continue to expand their transportation networks; much of the new construction is in the most difficult terrain. Continued expansion of these large networks of forest roads means that maintenance problems and costs are also increasing.

Residential encroachment on land heretofore considered as forest or agricultural fringe is a growing problem for forest managers. A typical tenure pattern in the West is federal or industrial ownership of the hillslopes with the valley bottoms owned by small farmers or ranchers. Valley lands once dedicated to agriculture are increasingly subject to subdivision and ownership by part-time ranchers who then establish homesites. Such homesites are typically on a bench or knoll at the mouth of a draw; the knoll provides elevation above the valley floor and, usually, a small creek for domestic water. This ideal location is, unfortunately, likely to be a debris fan formed by old landslides. Any subsequent landslide, natural or otherwise, may jeopardize the homeowner or, at a minim, the water supply. Legal actions to recover damages are likely to follow. And even natural slides from timbered areas may figure in legal suits if property damage results. While education and more sophisticated zoning are probably the long-term solutions to these problems, managers must be sensitive to the short-run impacts and be prepared to use special, more costly, road construction and harvesting techniques for lands upslope from residential property.

Damages to roads and structures are highly visable, fairly easy to quantify, and may result in legal action by damaged parties. Furthermore, such damage is likely to climb as roads are pushed into increasingly difficult terrain and as residential development continues on forest margins. Because of the hazards involved, managers may find it increasingly necessary to use more expensive types of road construction.

CONCLUSIONS

Environmental damage is a central issue in the present controversy about landslides and forest practices. It is also one of the most complex parts of the controversy because losses are often difficult to quantify and almost impossible to predict. Those who manage our national forests must realize that research is a long way from developing the quantitative relationships needed to help relate harvesting and road construction to landslides and thence to environmental damage or loss. And the answers are not likely to be forthcoming until a national commitment is made to determine those relationships.

Do landslides produce environmental damage? They certainly do. But predicting or quantifying how much, where it occurs, and how long it lasts is often beyond our present capability.

LITERATURE CITED

Brown, G.W.; Krygier, J.T. Clearcut logging and sediment production in the Oregon Coast Range. Water Resources Research. 7(5):1189-1199; 1971.

Fredriksen, R.L. Erosion and sedimentation following road construction and timber harvest on three small western Oregon watersheds. Res. Pap. PNW-104 Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station; 1970. 15 p.

Ketcheson, G.; Froehlich, H.A. Hydrologic factors and environmental impacts of mass soil movements in the Oregon Coast Range. Rep. WRRI-56. Corvallis, OR: Water Resources Research Institute, Oregon State University; 1978. 94 p.

Miles, D.W.R. Impact of landslide erosion on the growth and vegetation in the western Oregon Cascades. Corvallis, OR: Oregon State University; 1983. M.S. thesis. 46 p.

Rothacher, J.S.; Glazebrook, T.B. Flood damage in the national forests of Region 6. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station; 1968. 20 p.

PITFALLS IN THE STRICT RELIANCE ON EXPERT OPINION IN ASSESSING SLOPE STABILITY HAZARD

James A. McNutt and Dale McGreer

Abstract: A Bayesian/Delphi analysis of slope stability hazards was performed based on intensive and statistically structured surveys of expert opinions from 35 soils, hydrology and geology specialists. While theoretically sound, and with potential for practical application, the process revealed several potential weaknesses of relying on expert opinion. Major problems were associated with the natural tendency for experts to dwell on sites which failed, rather than those which did not. Additionally, experts had difficulties conceptualizing how seemingly small numerical estimates of probability of failure can translate into very large numbers of failures when applied to large land areas and through time. The authors conclude that if these tendencies exist during a structured research interview, they are also likely to occur while assessing hazards for planning or during field hazard assessments.

INTRODUCTION

Contrary to what we'd like to believe,...most invention comes from the "wrong" person in the "wrong" place in the "wrong" specialty at the "wrong" time, not to mention in conjunction with the "wrong" problem.

This paraphrase of Thomas J. Peters, (1983), author of *In Search of Excellence*, in his review of the mythology of innovation is startlingly counter-intuitive. However, historical studies of scientific discovery clearly illustrate that this is indeed the way of the world. Thomas Kuhn (1970), in his *Structure of Scientific Revolution*, documents that throughout time, groups of trained experts have consistently focused so narrowly that they fail to see or accept major new discoveries.

Galileo, a non-astronomer, is now famous for his astronomical observations; Louis Pasteur, a chemist, is now acclaimed as the father of modern day sterilization theories for the medical profession. Yet, while both of these gentlemen made brilliant advances outside their areas of specialty, the specialists inside those areas could not or would not accept these discoveries.

And the problem continues today. Jewkes, Sawers and Stillerman (1969), in their *The Sources of Invention* reviewed nearly 60 major 20th century inventions, of which at least 80% were discovered by the wrong people in the wrong place. For example, Kodachrome film was invented by two musicians, and a watchmaker discovered the process for continuous casting of steel.

Also important is Thomas Kuhn's observation, that even when new discoveries are accepted by experts, poor vision about the simplest

---

JAMES A. McNUTT is presently with Container Corporation of America, Chicago, Illinois. He was formerly a hydrologist with the Potlatch Corporation, Lewiston, Idaho. DALE J. McGREER is a forester with the Potlatch Corporation, Lewiston, Idaho.

applications with the most potential often lag the initial acceptance by a quarter of a century or more. For example, Thomas Alva Edison observed that the primary application of incandescent lighting would be aboard Ocean going vessels where the then existing open flame gas or oil burning lights were exceedingly hazardous. Similarly, the British Secretary of War, a highly trained military tactician, noted in 1910 that "we do not consider that the aeroplane will be of any use for war purposes."

THE PITFALLS

This may seem like a strange way to introduce slope stability hazard analysis. However, a broad review of a slope stability research project we undertook in the late 1970's (McNutt, 1976; McNutt and McGreer, 1981) reveals several pitfalls mentioned in this introduction. These pitfalls must be taken into account, both by the specialists who are charged with advancing the technology of slope stablity hazard analysis, and by the resource managers who must manage lands, hazards, and resources. Our research indicated

> Many slope stability experts have expertise which is narrowly focused to given hydrological and geological provinces.
>
> Because of narrow focus, many experts, at least intially, have a difficult time understanding and accepting new approaches which could lead to practical and beneficial applications.
>
> Experts are often so close to the problems at hand that they frequently fail to recognize the real world potential of new analytical methods, especially if these methods are developed external to their particular specialty.
>
> Slope stability experts' focus is primarily directed at the study of actual slope failure events and the associated site and climatic conditions. As a consequence of this narrow focus, the experts often fail to extrapolate their knowledge correctly to the forest as a whole, in changing conditions over long time horizons.

THE PROBLEM

The major challenge facing slope stability specialists is to develop reliable techniques for assessing slope stability hazards under any set of specific conditions. This requires identification of cause and effect relationships between variables which are numerous, interrelated, and multi-dimensioned. Dealing with these relationships is a monumental task. Natural variations of slope, soil, geologic, hydrologic and vegetative variables, and man initiated activities are tremendous and collectively generate literally an infinite number of unique conditions.

Available historical data bases which would allow correlation of cause and effect relationships are inconsistently structured. Consequently they are only marginally useful for developing models that predict slope stability hazards. New quantitative knowledge of slope stability experts is quite good and growing every year. In essence, these circumstances "promote" the classic conditions for application of predictive techniques based on Bayesian/Delphi probability theories: the approach we used in our research.

Simply put, Bayesian/Delphi theories applied to slope stability hazard analysis convert experts' qualitative opinions into quantitative estimates of how often different variables, taken one at a time, are associated with a slope failure event (Delphi techniques). For slope stability problems, this process is greatly complicated by the need to consider physical and hydrological systems over time. With this as the general background, a research project based on Bayesian/Delphi analysis of expert opinions, was outlined to estimate probabilities of slope failures under any specific set of site conditions.

THE MODEL

Initially a few key on-site variables affecting mass failures were selected. This variable set was simplified, as illustrated in Table 1, to include four factors associated with natural landscapes; degree of slope, slope form, bedding plane angle, and soil type. Land management factors were limited to road standards, road age, timber age, logging method, and silvicultural method. Four categories of mass failure were defined; debris avalanche/flows and slump/earthflows (non-road related failures), road damage failures and off-road failures (which are road related by definition).

The second step was to obtain the relative probability of each failure type across each variable state. These probabilities were generated through intensive surveys of 35 soils, hydrology, and geology specialists. The respondents' experience with slope stability problems ranged from 4 to 35 years. Interview booklets were mailed to each expert prior to the interviews which were conducted primarily by phone.

These specialists were asked a series of questions that related a specific type of mass failure event to all variable states, one variable at a time. Only two variable state choices were included within each question in order to force the interviewed expert to focus only on the relative likelihood between the two choices posed. Using slope steepness and debris avalanche as an illustration:

Table 1--Variables Affecting Mass Failures Used Within the Inventory[1/]

Natural Landscape Factors	Road Related Factors	Harvest Related Factors
Slope percent	Road standards	Timber age
Slope form	Road age	Logging method
Bedding plane angle		Silvicultural method
Soil type		

1/ Each variable type was subdivided into a few discreet variable states. For example, four slope percent classes were defined: 0–20, 21–50, 51–70 and 71+.

Assume: a) You have $1,000 to wager for each question.

b) A debris avalanche/flow has just occurred on an acre of forest land.

Then, as a typical example, experts were asked to supply wager amounts to the following "paired" statements:

1. I wager $300 the acre of forest affected was on a slope of 51-70%, and I wager $700 it was on one greater than 71%.

2. I wager $10 the acre of forest affected was on a slope of 0-20%, and I wager $990 it was greater than 71%.

3. I wager $150 the acre of forest affected was on a slope of 21-50%, and I wager $850 it was one greater than 71%.

Each of these questions is related to the 71+% slope class. The relative probability for each slope class can then be computed based on the fact that given the condition that a debris avalanche/flow has occurred, the sum of the probabilities that an avalanche occurred associated with each class must equal one. simple arithmetic is then used to calculate the probability for each slope class. For this example response, when a debris avalanche occurs, the probability distribution that it will occur on either a 0-20%, 21-50%, 51-70% or 71±% slope class is respectively: .006, .110, .267 and .623. These are called conditional probabilities; that is, these are the probabilities of a debris avalanche having affected each slope class given the assumption that an avalanche has occurred.

Using the interview results, probability distributions were generated in the same manner for all other variables. Once the distributions for each variable were obtained, the probability for a combination of variables which collectively describe a particular site could be computed.

To this point, the technique generates "conditional" probability tables-tables of probability based on the assumption that an event has occurred. These conditional probabilities then must be adjusted to generate the actual probability that a mass failure will occur within a specified area. To accomplish this, the experts were asked, given an assumed hydrologic event of a given return interval, to estimate across all site conditions what the probability of either nothing or a slope failure event occurred. The product of the conditional probabilities multiplied by these event probabilities are called average event probabilities for a specific hydrologic condition.

The interview process provided data necessary to define the rate of mass failure occurrence by type, following harvest, and through the life of a timber rotation, and likewise following road construction. These data allow calculation of the rate of mass failure per acre or per road mile for specific periods of time and for each site by management regime. As an example, the natural hazard of failure was calculated for a 1,000 acre undeveloped site with shallow non-cohesive soils on normal slopes of 50-70% and where the bedrock dips steeply with the slope. This natural hazard can then be compared to the hazard following construction of 10 miles of unsurfaced secondary roads and following clearcutting by highlead. From start to finish, the calculations require nine steps, which are not reviewed in this discussion. The results are what are of interest, and they are shown in Table 2.

Summarizing the 1,000 acre example for this site, prior to management, an average annual rate of 0.023 slumps per year and 0.078 debris avalanches per year are expected. Clearcutting added an average of 0.07 slumps and 0.44 debris avalanches per year. Construction of 10 miles of forest road added an average hazard of 0.76 road mass failures and 0.58 road damage mass failures.

A major concern is: how reliable are these subjectively derived mass failure/storm event conditional probabilities. In order to gain some insight on this question, the subjectively derived probabilities for the complete survey were compared with the composite results of 9 widely separated studies reported within recent literature. The frequencies reported within the literature were examined on a per year, per acre basis for debris avalanches and slump earthflows as well as for off-road and road damage failures. Table 3 compares the rates of mass failure

Table 2--Example of Results Produced through the Mass Failure Hazard Index Prediction System

NATURAL CONDITION

Event	Natural Site Conditional Probability	Average Annual Event Probability	Expected # of Events/1000 Acres-Year
Nothing	.640	0.99966	999.901
Debris Avalanche	.262	0.00019	0.078
Slump Earthflow	.098		0.023
	E = 1.0	E = 1.0	E = 1.0

CONDITION FOLLOWING HARVEST

Event	Conditional Probability Following Harvest	Average Annual Event Probability	Expected # of Events/1000 Acres-Year
Nothing	.2312	.99966	999.39
Debris Avalanche	.6341	.00019	0.52
Slump Earthflow	.1347	0.00015	0.09
	E = 1.0	E = 1.0	E = 1.0

CONDITION FOLLOWING ROAD CONSTRUCTION

Event	Conditional Probability Following Road Construction	Average Annual Event Probability	# of Events Per Year Per 10 Miles of Road
Nothing	.1451	.9502	8.66
Off Road Failure	.4536	.0267	0.76
Road Damage Failure	.4013	.0231	0.58
	E = 1.0	E = 1.0	E = 1.0

Table 3--Comparison of Survey Results to Nine Reports Within the Literature[1]

	Event	Event Frequencies Per Acre Per Year: From Survey	From Literature
Slope Events	Debris Avalanche	1.89×10^{-4}	0.57×10^{-4}
	Slump - Earthflow	1.51×10^{-4}	0.35×10^{-4}
Road Events	Off-Road	2.67×10^{-2}	1.98×10^{-2}
	Road Damage	2.31×10^{-2}	4.45×10^{-2}
	Total Road	4.98×10^{-2}	6.43×10^{-2}

1/ Bishop and Stevens, 1964. Dryness, 1967; Rice, Corbett and Bailey, 1969; O'Loughlin, 1971; Coleman, 1973; Fiksdal, 1974a, b; Morrison, 1975; Swanson and Dryness, 1975.

derived from the literature to the rates of failure predicted by the survey results using the Mass Failure Hazard Index Prediction System.

The technique is flexible. Hazards for different sites at any stage of management can be compared. Incremental hazards of various management options, such as type and degree of roading and harvesting, can be compared on a site-specific basis over time; and probabilities of mass failure can be computed by period of time following road construction and harvesting. Of most importance, the variable sets are not closed; variables can be discarded or added.

As an alternative, tables generated by survey can be replaced with actual data gathered for a given geographic area-like the Idaho Batholith, the Oregon Coast, the California redwood region, or anywhere else. The technique provides a statistically valid means of correlating mass failures with landtype inventories.

LIMITATIONS WITH RELIANCE ON EXPERT OPINION

The modeling process is theoretically sound. the mathematics reduce to simple arithmetic. There is no searching for data in the literature that might fit a hypothesis, no fitting of curves to data or mathematical interpretation of processes. Essentially, the process should yield results which are as good as the judgement of the experts interviewed. However, by interviewing, analyzing the results, and reinterviewing, certain problems with modeling and expert opinion emerged. Some of these problems appear to apply to reliance on expert opinion in general.

One problem was that it is very difficult for most of us to think in several dimensions simultaneously. The interviewed experts were asked to think in terms of mathematical probabilities, to think about physical landscapes, to consider the effect of hydrologic events of large magnitude but rare occurrence, to think about large areas and long lengths of time. That is indeed difficult, and precisely the problem confronting all of us when asked to assess the risk, or results, of a management action.

A second problem was that nearly all the interviewed experts initially overestimated probabilities of failure. Estimates were not uncommon that were two, three, or even four magnitudes of order greater than the highest rates reported within the literature. There may be several reasons for this type of initial response.

First, experts in slope stability tend to spend a lot of time visiting, studying, and thinking about specific sites which have failed. What is not thought so much about are all the areas, miles of road, and years, where and when failures have not occurred. This phenomena may be something that is inherent in human nature. How many times have you spent half the day driving to the site of a mass failure and spent the rest of the day driving back-driving back over all the sites which did not fail?

Second, thinking in terms of very small probabilities is quite difficult. Consequently, great care needed to be used on "how" questions were asked. When the first interview was conducted in 1975, "wagers" were limited to $1,000. Even when an interviewed expert felt that there was a very low probability of failure for a given described situation, for instance on an acre of ground in a year's time, he was likely to wager two or three dollars. But even that is a probability of 0.02 or 0.03. Applied to a thousand similar acres, this translates to 20 to 30 failures. Applied to 100 years, it is 2,000 to 3,000 failures.

Part of this problem was solved by changing the wager to $100,000 when interviewing in 1980. But even so, the problem persisted. Great difficulty existed in visualizing how estimated probabilities of failure, which seemed very small, translated into very high rates of failure when applied to large areas over long periods of time.

This continuing problem was dealt with by trying to ensure'during the early stages of an interview that the interviewed experts recognized what their probability estimates meant when extrapolated. As as example, an interviewed expert's estimate would be replied to by saying "your estimate of probability would translate into 1,200 failures per 1,000 acres in 10 years. Given that, would you like to change your bet?" In many cases they did. And then the interviews slowed way down as the experts began to conceptualize the probabilistic relationships through time and space: that is, to think in several dimensions simultaneously.

Even then, and sometimes even after revising initial estimates downwards by orders of magnitude, several interviewed experts phoned back hours or days later, asking to redo the interview. This was most common with those who had conducted an actual mass failure inventory and had compared their survey results with their field data. Without exception, the revisions were for lower estimates of risk.

That type of re-evaluation and revision was one of the most fascinating aspects of the modeling process: some of the experts learned something about their approach to qualitatively assessing slope hazard conditions and changed it.

CONCLUSIONS

While experts, like many of us, face real limitations in adapting perceptions on a given problem, in this study, many-probably most-did. The more deeply you are involved in a problem, adapting to new concepts will often be more difficult. However, in this case the experts with the broadest geographic experience, and experts who had conducted inventories, most often changed their thinking. Yet this evolutionary process ultimately required restructuring the general approach and five years of time. A key observation is that expert opinions on slope stability, while well-founded in experience and knowledge, may be unintentionally biased due to the problem of conentrating on sites which have failed, while not paying enough attention to those which did not. To managers seeking the advise of experts, as they should, you are urged to question expert opinions. But be cautious of bogging down in details. Step back and make sure you are satisfied that the opinion makes good sense in the broad context of your experience. Keep in mind that if an expert tends to overestimate risk of failure in a structured research interview, he is likely to also do so when evaluating the risk of management action at a specific site on the ground. For all of us who are experts, sound advice is to constantly remind ourselves to keep open minds. Assuredly, as our base of experience changes, our everyday concepts of problems and solutions will also change: sometimes dramatically.

LITERATURE CITED

Bishop, Daniel M.; Stevens, Mervin E. Landslides on logged areas in southeast Alaska. Research

Paper NOR-1. Juneau, Alaska: U.S. Department of Agriculture, Forest Service, Northern Forest and Range Experiment Station; 1964. 18 p.

Coleman, Steven M. The history of mass movement processes in the Redwood Creek basin, Humboldt County, California. University Park, Pennsylvania: Penn State University; 1973. M.S. thesis. 151 p.

Dyrness, C.T. Mass soil movements on the H.J. Andrews Experimental Forest. Research Paper PNW-42. Portland, Oregon: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station; 1967. 12 p.

Fiksdal, Allen J. A landslide survey of the Stequaleho Creek watershed and upper Clearwater River area. Olympia, Washington: Washington State Department of Natural Resources; 1974a. 19 p.

Fiksdal, Allen J. A landslide survey of the upper clearwater and Solleks River area, Jefferson County. Olympia, Washington: Washington State Department of Natural Resources; 1974b. 6 p.

Jewkes, John; Sawers, David; Stillerman, Richard. The sources of invention. 2d ed. London. MacMillan; 1969. 372 p.

Kuhn, Thomas. The structure of scientific revolution. 2d ed. Chicago, Ill. University of Chicago Press; 1970. 1,972 p.

McNutt, James A. A stochastic analysis of erosion and economic impacts associated with timber harvests and forest roads. Corvallis, Oregon: Oregon State University; 1976. Ph.D. dissertation. 206 p.

McNutt, James A.; McGreer, Dale J. Mass failure hazard index system. In: Research on the effects of mass wasting of forest lands on water quality and the impact of sediment on aquatic organisms. Technical Bulletin Number 344. New York, N.Y.: National Council of the Paper Industry for Air and Stream Improvement; 1981. p. 17-32.

Morrison, Peter H. Ecological and geomorphological consequences of mass movements in the Alder Creek watershed and implications of forest land management. Eugene, Oregon: University of Oregon; 1975. B.A. thesis, 102 p.

O'Loughlin, Colin L. An investigation of the stability of the steepland forest soils in the Coast Mountains, southwest British Columbia. Vancouver, B.C.: University of British Columbia; 1971. Ph.D. dissertation. 147 p.

Peters, Thomas J. The mythology of innovation, or a skunkworks pale, part I. Palo Alto, California: Stanford Magazine, Summer issue; 1983. pp. 13 - 21.

Rice, R.M.; Corbett, E.S.; Bailey, R.G. Soil slips related to vegetation, topography and soil in southern California. Water Resources Research 5(3):647-659; 1969.

Swanson, Fred J.; Dyrness, C.T. Impact of clearcutting and road construction on soil erosion by landslides in the western Cascade Range, Oregon. Geology 3(7):393-396; 1975.

SUBJECTIVE TECHNIQUE3 FOR IDENTIFICATION. AND HAZARD ASSESSMENT OF UNSTABLE TERRAIN

Dale Wilson

ABSTRACT: The key to any subjective mapping system designed to interpret slope stability is that the mapping system must be capable of extrapolating limited research data to a variety of landscapes based on observable characteristics of those landscapes. One of the most readily available and easily implemented methods is the historic approach using dominant geomorphic erosion processes.

The mapping system should be designed with definite interpretation objectives. If mapping units are to be used in land management planning, an interdisciplinary effort will be necessary for mapping unit design. Mapping units should be designed to enable data to be correlated with physical characteristics of the mapping unit. A mapping system based on dominant geomorphic erosion processes will allow mappers to stratify the base erosion rate over the landscape. Research and local data is then used to define relative risk of accelerated erosion resulting from various management practices.

Slope stability data used in water resource interpretations requires that the slopes' efficiency in delivering eroded material into live streams as sediment be considered in mapping unit design. This enables specialists to systematically predict the effect of management alternatives on water resources over time.

INTRODUCTION

This paper presents an approach to slope stability analysis that the Clearwater National Forest in northern Idaho has used to progress from specialist opinion to a documented decision-making tool. The result is a model which can be used to compare the stabilities of different watersheds and predict their response to various management alternatives. Variations of this type of approach are used widely by USDA Forest Service land managers in the western United States.

During the late 1960's roads were built in large areas of the Clearwater National Forest to gain access to diseased and dying timber. Much of the timber was harvested on steep, unstable slopes and many stability problems were encountered. Road-related landslides were the main stability concern as they interrupted road use and were expensive to repair. They also caused widespread and severe water resource damage. During this same period the Forest Service initiated intensive land management planning on all its lands. A major objective of the planning process was to assess slope stability and resultant environmental consequences of forest management practices.

A classification scheme was needed that divided a

DALE WILSON is a soil scientist with the U.S. Department of Agriculture, Forest Service, Clearwater National Forest, Orofino, Idaho.

heterogenous landscape into units which responded similarly to various management practices with regard to engineering, watershed, and silviculture. Interdisciplinary requirements of the classification scheme resulted in an inventory that uses landform, geologic parent material, soils, and vegetative habitat types as mapping unit criteria.

Slope stability evaluation for mapping units uses the analysis of the dominant geomorphic erosion processes that control or have controlled the formation of landforms in the area. The intensity of the erosion processes is stratified using landform and parent material characteristics. The end product is a geomorphic process or erosion model for a large landscape such as a national forest. Mapping units are placed into categories that reflect the relative erosion rates. This enables the base erosion rate to be distributed over the landscape. The relative risk of resource damage is determined by assessing how different management practices will accelerate the base erosion rate. The stronger the historic evidence of recent slope instability, the greater the risk of management activities accelerating the instability.

This method is mostly subjective and is based on local observation and experience. An important factor is the ability of the mapper to extrapolate research findings from outside the area and adapt them to meet local conditions. The accuracy of this method depends on the experience of the mapper and that person's ability to make subjective observations and associations.

THE CLEARWATER APPROACH

In the Clearwater National Forest, landslides can be placed into two major classes: (1) rotational mass wasting (slumps, earthflows), and (2) debris avalanches and flows. Landform and parent material characteristics used to rate rotational mass stability are:

1. Incidence of subsurface water concentration (this is a prerequisite and must be present to evaluate other characteristics). Concave stream headlands and long, steep, dissected slopes are most likely to have subsurface water concentrations.

2. Depth of mantle. Deep mantles can concentrate larger quantities of ground water increasing the potential for deep-seated rotational failures.

3. Soil mantle characteristics. Soil texture classifications are used because of their correlation with soil shear strength. Silty-clay loam textures have the least shear strength and coarse, sandy textures have the greatest shear strength.

4. Parent material type and degree of weathering. Strongly weathered materials are subject to more mantle instability than weakly weathered materials; this is especially true if the material contains large amounts of mica. Debris avalanches and flows occur in very different types of terrain. They consist of rapid releases of accumulated debris in steep draws and concave headlands. Slope characteristics used to rate these processes are:

1. Slope gradient. For this gravity-related process, the steeper the slope the more likely the process is to occur.

2. Potential of the slope to undergo dry surface creep. Creep provides a source of accumulation or buildup of unstable material. Loose, coarse-textured soils are most susceptible.

3. Visual evidence of past debris avalanches. This is reflected in scarred dissections on the slope and fans and cones along the lower margins of the slope.

The preceeding factors are evaluated and a relative rating of mass instability is given to each mapping unit. Risk of failure is presented to the manager only as relative hazard classes. True or acceptable risks are not defined. The manager must depend on specialists for recommendations in determining whether or not the risk is acceptable in order to achieve specific management goals.

DOCUMENTATION

A method readily available to a manager for documenting (or at least better defining) landslide hazard potential is to monitor actual landslides. More than 700 landslides of 10 cubic yards or more, which occurred on system roads in the Clearwater National Forest, were inventoried in 1974, 1975, and 1976. The project was done in cooperation with the Intermountain Forest and Range Experiment Station. Data was taken by a team of engineering, geology, and soils graduate students. Inventory data taken included type and size of failure; management history of the slope; road design, size, and type; and various mantle and landform characteristics. The data were analyzed (Megahan and others 1978) to determine the relationships between landslides and mapping unit properties. The relationship between mapping unit properties and landslide potential is displayed in tables 1 and 2. (Wilson and others 1983).

These data enable a further definition of relative potential for landslide occurrence but do not express numerical probability of failure for the hazard class. For example, the Clearwater landslide data showed that between 60 and 80 percent of landslides that occurred between 1974 and 1976 were on mapping units containing less than 10 percent of the total road mileage. Other mapping units accounted for less than 5 percent of the landslides but contained 40 percent of the road mileage.

Table 1.--Landtype properties used to rate slump-earthflow (rotational failure) mass wasting potential

Hazard rating	Low		Moderate				High				Very High	
Slope gradient	40%	40-60+%	<40%		4040%	60+%	40-60%		60+%		60+%	
Dissection	yes dry	no	yes wet	yes	yes	yes/no	yes wet	yes	no	yes	yes	yes wet
Soil texture[1/]	var.	SL & LS	var.	var.	SL & LS	var.	var.	SL & heavier	var,	SL & LS	SL & heavier	var.
Regolith depth	var.	>60 inches	>60 inches	>60 inches	>60 inches	>60 inches	>60 inches	>60 inches	>60 inches	>60 inches	>60 inches	>60 inches
Presence of mica	var.	no	var.	yes	no	no	var.	yes	var.	no	yes	var.

1/ SL = silty loam; LS = loamy silt

Table 2--Landtype properties used to rate debris avalanche (planar failure) potential

Hazard rating	Low		Moderate		High	
Slope gradient	< 40%	40-60%	40-60%	60% +	60% +	60% +
Slope shape	Variable	Convex	Convex and Straight	Concave and Straight	Concave	Straight
Soil[1/] texture	Variable	CL & SIL	SL & LS	SIL & L	SL & LS	SL & LS
Occurrence of old slide scars	Rare	Rare	Common	Common	Frequent	Frequent

1/ CL = clay; SIL = silt; SL = silty loam; LS = loamy silt; L = loam

I consider this type of project to be one of the most beneficial ways to obtain data for evaluating the potential for landslide Occurrence in an area where little or no local slope stability information is available to the specialist or manager. The cost of inventorying landslides on an area such as a national forest would be between $8,000 and $12,000 per year.

EVALUATION

Results of the Clearwater landslide study were immediately used in transportation planning and in road location, design, and construction. Landslide preventative measures sometimes included avoidance of road construction on mapping units that had the highest potential for landslide occurrence; and in the use of nonstandard construction methods such as full benching and end hauling of excavated material for use on roads constructed in more stable areas. Prior to 1975, the Forest was averaging over 200 road-related landslides per year, So far there have been less than ten road-related landslides per year on roads located, designed, and constructed since 1975.

Another method for evaluating the potential for landslide Occurrence is through the use of the infinite slope equation in conjunction with characteristics of various mapping units. This again enables the specialist and manager to establish the relative stability of various mapping units by establishing a relative stability index. It must be kept in mind, however, that most landslides are associated with relatively small inclusions in larger mapping units. It is therefore a requirement that the frequency of occurrence of these inclusions be a mapping unit characteristic.

The major limitation of the above methods is that they provide a rating based on an average

Table 3--Nature and amount of disturbance by landtypes for alternative timber harvest access routes

Option	Road length	Road subgrade width	Side slope	Calculated area disturbed by road or cutting unit area	Landtype	Type of road prism
	Miles	Feet	Percent	Acres		
1	1.0	15	25	2.4	22-G03	Balanced
	1.0	15	25	2.4	22-G03	Balanced
	0.5	15	70	1.4	61-G08	Full bench
	1.0	15	50	4.1	60-G11	Balanced
				100	22-G03	
				125	23-G03	
2	1.5	15	25	3.7	22-G03	Balanced
	1.0	15	25	2.4	22-G03	Balanced
	1.0	15	40	3.2	32-G02	Balanced
				100	22-G03	
				125	22-G03	

relative potential for landslide Occurrence for the entire area. This can be used only at the planning level. Onsite geotechnical investigation is required to determine the probability of a slope being unstable at a given site.

Analysis of slope stability as a factor in water resource management involves the additional estimation of the delivery potential of the eroded material to a live stream. A systematic analysis of sediment produced in a watershed serves as a method for estimating the role of slope stability in creating a potential for watershed damage. Wilson and others (1982) developed such a model for estimating eroded material delivered to live streams as sediment. The historic erosion approach is used to determine the natural erosion rates of mapping units. Erosion rates of all the mapping units within a watershed are then weighted according to the percentage of the watershed that they occupy. This enables the specialist to compare the relative erosion hazard from landslides for various mapping units ahd management practices. An example of the results of this kind of analysis are shown in table 3.

Coefficients can also be developed for the acceleration of sediment production for various management practices on each mapping unit. Data used to develop the coefficients should come from research conducted in areas that most closely represent the area analzed. Sediment data from research watersheds may meet most of the needs. In the case of the Clearwater National Forest, most of the data came from work in the Idaho Batholith (Megahan and Kid 1972a, 1972b; Megahan 1975, 1978). Results will enable the specialist to estimate the total sediment expected over time; for example, from construction of a mile of road in various mapping units. Sediment derived from all processes, not just landslides, should be represented.

Continued monitoring of sediment production in local watersheds subjected to a variety of management practices will improve the accuracy of predicting the response to local conditions. Local data also enables the specialist to predict the amounts of sediment that watersheds with various degrees of stability can tolerate without sustaining channel deterioration. This can be accomplished by monitoring sediment in several watersheds having a wide range of stability indices and management activities.

Using 28 watersheds with 4 to 10 years of monitoring data on drainages that have experienced various levels of development, the Clearwater National Forest methodology has shown the error in long-term sediment production estimates. These errors are on the order of plus or minus 15 percent in 64 percent of the watersheds. Three additional watersheds have errors of 100 percent or more and were not included in the statistics. Two of the watersheds are dominated by ancient landslide mapping units. Ancient landslides are extremely variable and unpredictable without onsite survey data.

Example of Model Application

The following hypothetical, simplified example of the application of these subjective analysis porcedures has been developed using a representative watershed situation and landtypes found in the Clearwater National Forest. A 1,000 acre watershed is defined that was formed on an old erosion surface by incision of a major drainage system (fig. 1). Elevations range from 4,000 to 4,900 ft. The bedrock underlying the watershed is granitic. Five different landtypes are identified.

Two options are considered in this example; each require 3.5 miles of road construction in 1982

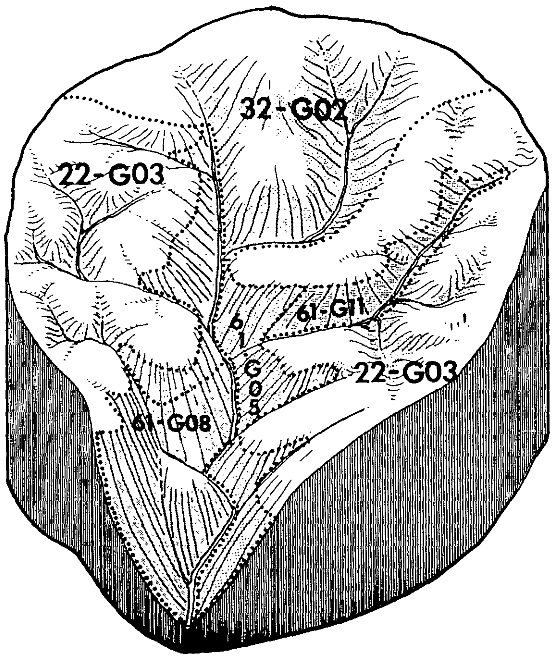


Figure 1.—Mapping units (landtypes) for a hypothetical 1000 acre watershed.

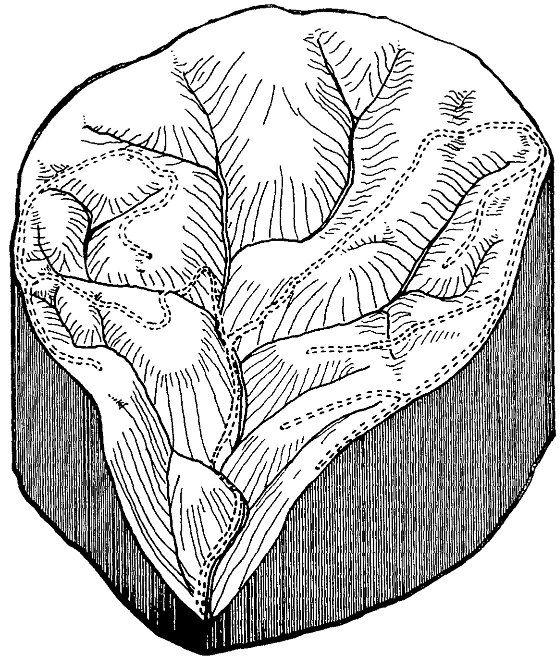


Figure 2.—Road and cutting unit locations for option 1 on the hypothetical watershed.

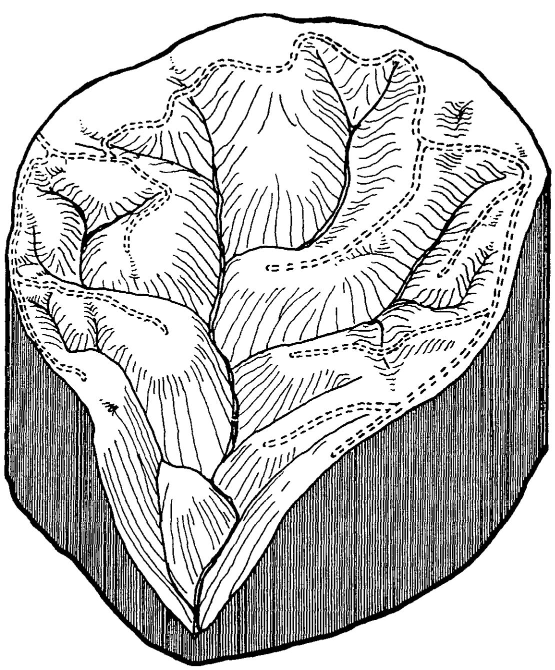


Figure 3.—Road and cutting unit locations for option 2 on the hypothetical watershed.

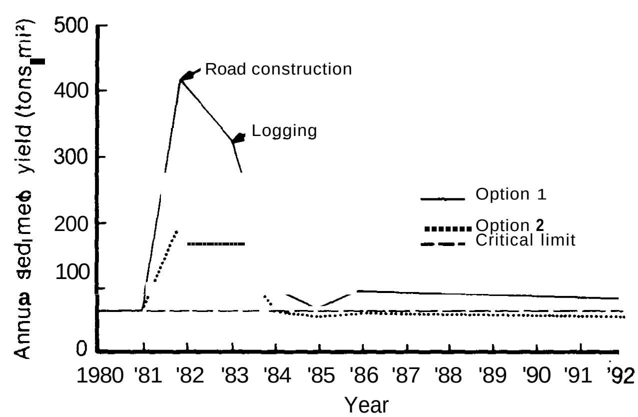


Figure 4.—Percentage change in sediment yields for alternative road and logging practices.

and the logging of 225 acres of timber by using clearcutting and tractor skidding in 1983. Option 1 (fig. 2) accesses the area from bottom of the watershed and crosses steep, high erosion hazard breaklands. Option 2 (fig. 3) provides access from the top of the watershed and crosses a lower erosion hazard terrain. The amount and type of disturbances by landtypes are given in table 3.

The data in the example were analyzed for a 10-year period following disturbance (fig. 4). The time dependence of the sediment responses was apparent. Sediment yields increased in 1981 in response to road construction. Rates decreased in 1982; but at a lesser rate than 1983 because of the 1982 logging activities. Additional decreases in sediment yield occurred over time but recovery to predisturbance levels was slow because of long-term erosion of roadcuts.

Figure 4 shows the percentage increase of sediment over undisturbed levels for the two management alternatives. The critical limit line represents the amount of measured sediment in other watersheds with similar natural stabilities that caused net channel changes and sediment deposition over a period of 5 years. Option 2 is clearly preferred over option 1 in terms of total increase in sediment production over time. Other considerations may be important, however: the nature of the beneficial uses of the water, the value of the water resource, the juxtaposition of development within this watershed over time and space with development of other watersheds in the area, and natural variability.

APPLICATION

This model has been used as a management tool for resource planning since 1976 with satisfactory results. The model has been continually revised and updated as local sediment monitoring data becomes available. It is used only as a tool, though, not as decision criteria; and it is always used with other information and professional judgment.

The model offers the manager three major advantages: it ties slope stability to sediment and water resource values; it analyzes the watershed as a system; and it analyzes the cumulated effects of past management in relation to potential effects of future management. The model is now being used in conjunction with a fisheries biomass model to predict the effect of management activities on fisheries productivity.

Without local quantitative data this procedure is empirical and as such has limited application elsewhere; however, the principals and procedures involved can be extrapolated anywhere. An analysis procedure of this type can be designed for use in areas with minimal local erosion and sedimentation information using the basic principals described to define relative erosion hazard ratings. The evaluation may then be used to design erosion and sediment monitoring programs that serve to document and increase the accuracy of prediction procedures. This enables the extrapolation of the data to other watersheds with similar natural and management-induced erosion rates. Basic mapping unit requirements for implementing a systematic watershed sediment analysis are:

1. The dominant landforming and erosional processes of an area must be recognized.

2. The relative role of processes must be understood.

3. Mapping units must be designed to rate the dominant erosion processes.

4. Mapping units must be designed using criteria essential for making interpretations of sediment delivery efficiency from slopes.

5. The watershed system must be limited in sediment supply in the natural state.

LITERATURE CITED

Megahan, Walter F. Sedimentation in relation to logging activities in the mountains of central Idaho. In: Present perspective technology for predicting sediment yields and sources: Proceedings, Sediment-yield workshop. U.S. Department of Agriculture Sediment Laboratory; 1972 November 28-30; Oxford, MS. Washington, D.C.: U.S. Department of Agriculture Research Service ARS-S-40, 1975: 74-82.

Megahan, Walter F. Erosion processes on granitic road fills in central Idaho. Soil Science Society of America Journal. 42(2):350-357; 1978.

Megahan, Walter F.; Day, N.F.; Bliss, T. M. Landslide Occurrence in the western and central northern rocky mountain physiographic province in Idaho. In: Youngberg, Chester T., ed. Forest soils and land use: Proceedings, Fifth North American forest soils conference; 1978 August; Fort Collins, CO. Fort Collins, CO: Colorado State University Press; 1978: 116-139.

Megahan, Walter F.; Kidd, Walter J. Effects of logging and logging roads on erosion and sediment deposition from steep terrain. Journal of Forestry 70: 136-141; 1972a.

Megahan, Walter F.; Kidd, Walter J. Effects of logging roads on sedimient production rates in the Idaho Batholith. Res. Pap. INT-156. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station; 1972b. 14p.

Wilson, Dale; Coyner, Jack; Deckart, Thomas. Land system inventory of the Clearwater National Forest. Orofino, ID: U.S. Department of Agriculture, Forest Service, Clearwater National Forest; 1983. 400 p.

Wilson, Dale; Patten, Rick; Megahan, Walter F. Systematic watershed analysis procedure for the Clearwater National Forest. In: Leachates: Terrain Analysis. Transportation Research Board Special Publication 892. Washington, DC: National Academy of Science, Transportation Research Board; 1982: p. 50-56.

THE ENGINEERING APPROACH TO LANDSLIDE RISK ANALYSIS

W. L. Schroeder

ABSTRACT: Approaches to evaluation of landslide risk may be grouped in two broad categories. Inductive evaluation of risk is based largely on experience and generally arises from a process of logical reasoning, based on observations. In the case of landslides, physical conditions where there is a concern for sliding are compared to those where landslides are known to have Occurred, and appropriate conclusions are drawn. Deductive approaches begin with the acquisition of certain quantifiable information and result in predictions, based on that information and analytical models, of a certain outcome. In this sense, deductive approaches to landslide risk evaluation are largely analytical or theoretical. The true engineering approach includes elements of both of these processes. Landslide risk analysis is a perfect example of the need to employ both inductive "judgment" and deductive "analysis" for effective decision making. Probability concepts, are used in the paper to make this point.

INTRODUCTION

Geologists and civil engineers spring from diverse educational backgrounds. Over the past 50 years, the related professions of engineering geology and geotechnical engineering have emerged (figure 1). The geologist primarily uses inductive reasoning and observes processes such as landslides and the related physical features and draws conclusions concerning the likelihood that these processes may occur in similar settings in the future. Such conclusions are qualitative and expressed descriptively. The civil engineer operates using deductive logic and analyzes the landslide process to obtain numerical answers and to draw quantitative conclusions. The apparent precision of this numerical answer lends it believability and, in some quarters, infallibility.

The engineering geologist and the geotechnical engineer occupy a gray area in which geological and engineering skills overlap. My perspective is that of geotechnical engineer, and my task is to explain the analytic approach to landslide risk analysis. There are shortcomings, however, in the analytical view of what is certainly a complex natural phenomenon. After presenting this approach, I will discuss these shortcomings and offer a true engineering approach that incorporates certain skills from the science of geology.

LANDSLIDE MECHANISMS AND MECHANICS

Varnes (1978) provides a classification for various types of earth movements. Every type can be analyzed quantitatively to predict if it may happen or, if it has happened, whether it will continue. Engineers focus their attention largely on earth movements classed as slides.

W. L. SCHROEDER is assistant dean, Research and Graduate Studies, Oregon State University, Engineering Experiment Station, Corvallis, Oregon.

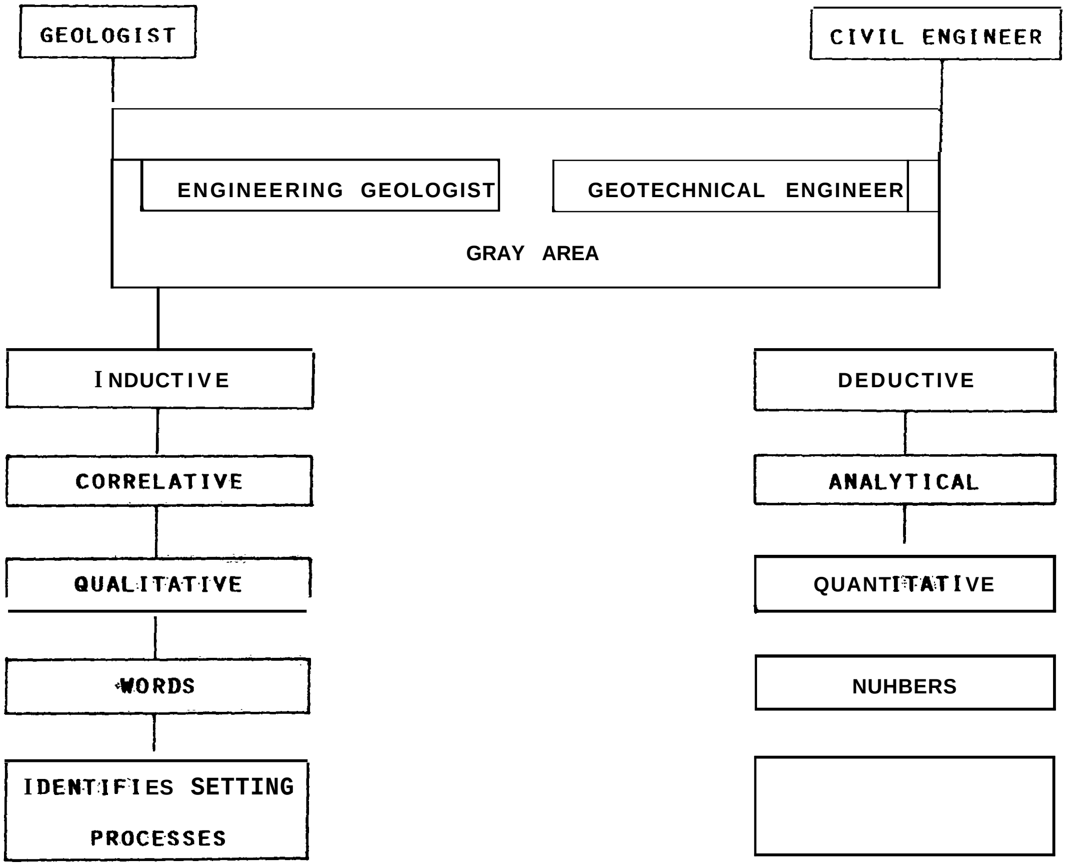


Figure 1.—Description of earth science and engineering professionals.

Mass movements in the forest setting nearly all begin with a rotational or translational slide.

Landslides start when stresses exceed soil strength, The factor of safety (ratio of strength to stresses) is a convenient way to express relative stability, If the factor of safety exceeds one, the slope is stable. A computed factor of safety that is less than one indicates that a slope should fail.

Landslides have length, width, and depth. Slopes are analyzed using the forces on a potentially failing mass. Usually, a section of the potentially failing mass with unit width and actual length and depth is considered. Figure 2 shows a section illustrating potential rotational (ab) and translational (ac) failure surfaces.

Geometric, geologic, and hydrologic factors govern the behavior of slopes. Topography determines the upper boundary of a sliding mass. A sliding surface determines the lower boundary. The sliding surface is known only if the slide has already occurred or an adequate drilling or instrumentation program has been implemented. The possibility of a landslide can be assessed by determining which of many possible sliding surfaces has the lowest factor of safety. If the possibility of sliding along a particular geologic discontinuity is to be evaluated, the critical failure surface may be defined in advance. Geologic factors that must be known include soil weight or density, and strength, Shearing strength, S, may be thought of as the unit resistance between soil layers sliding on one another. It is characterized by the Mohr-Coulomb equation,

$$S = c' + (p - \mu)\tan \phi' \qquad (1)$$

where c' is cohesion, p is normal stress, μ is the water pressure on the potential failure surface, and ϕ' is the angle of internal friction. Cohesion is the strength which exists without any normal pressure. The other component of strength arises from friction between soil grains. Without normal pressure, no frictional strength exists. The tangent of the angle of internal friction may be considered as a coefficient of friction. Hydrologic factors such as rainfall, snowmelt, infiltration, and permeability determine the effects of water on landslides. These factors determine the water pressure, μ, on the failure surface. Water also influences apparent cohesion that exists in moist soils. Of all the factors that influence landslides, the most difficult to determine is water pressure. Actual pore water pressures are hardly ever known.

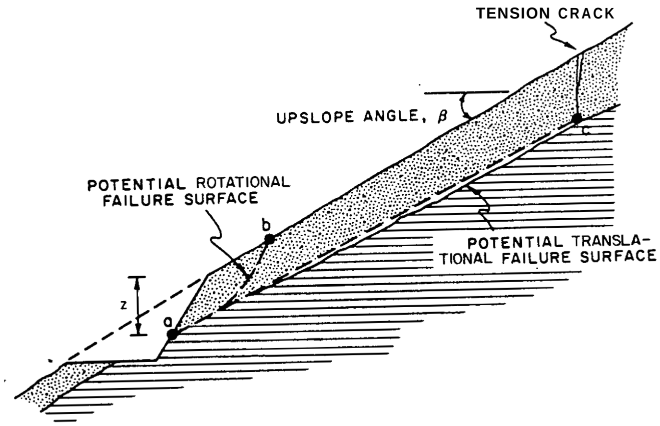


Figure 2.--Section through slope illustrating potential failure surfaces.

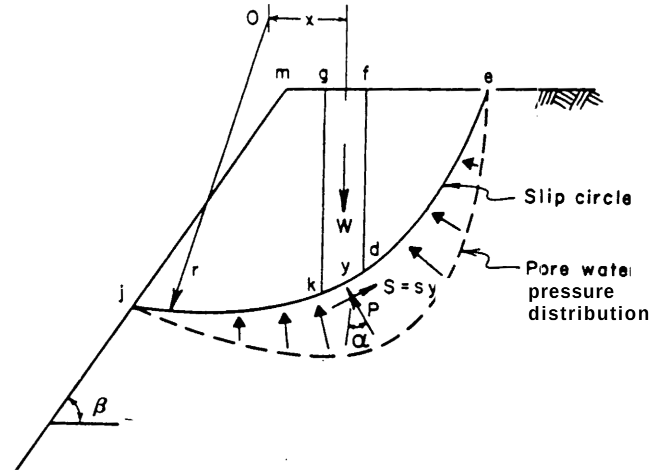


Figure 3.--Slide mechanism with rotational failure surface.

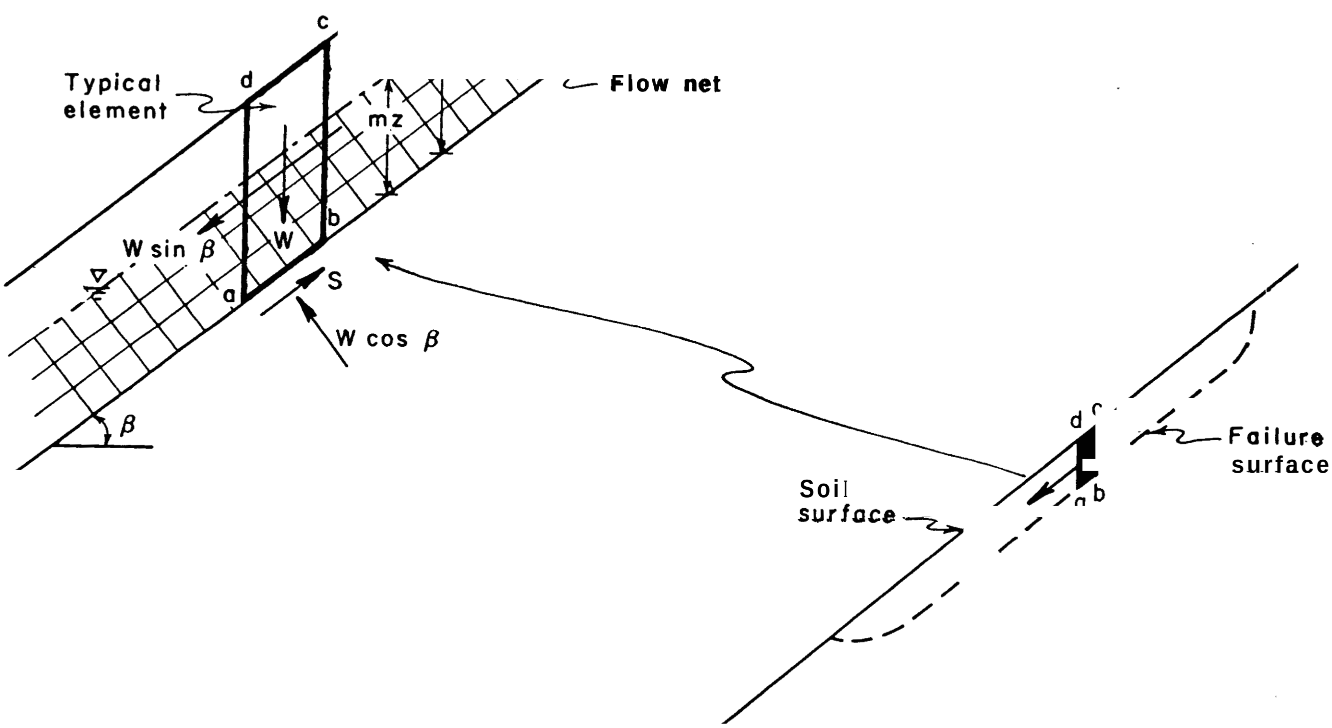


Figure 4.--Slide mechanism with translational failure surface.

Rotational Slides

Arc surfaces (see je, fig. 3) are characteristic of slides in cohesive soils. The mass, ejm, is considered to be of unit width. A typical slice of the potential sliding mass, dfgk, is illustrated. The sliding mass is divided into a number of such slices for analysis. the mass is considered to rotate about O, at radius r. The forces on each slice include the slice weight, W, and the strength at its base, S. The weight, as determined by soil density and slice dimensions, creates a moment, Wx, about O. The unit strength, S, is calculated from equation (1). The normal force, P, is determined by taking that component of weight perpendicular to kd. The sum of the moments tending to create the failure is designated $\sum Wx$, and those tending to resist failure as $\sum Sr$. The ratio of the resisting moments to the driving moments is the factor of safety, FS:

$$FS = \frac{r}{\sum Wx} \sum c'y' + (P - \mu y) \tan Ø' \qquad (2)$$

Translational Slides

Figure 4 **shows** a failure parallel **to** the topographic surface and the detail of forces on a typical slice from the sliding **mass.** Such slides are characteristic of cohesionless soils or of cohesive soils in which a weak soil plane exists. Because every slice, such as abcd, is considered to be the same, only those forces operating on one slice need to be considered. Such failures are referred to as infinite slope or long slope failures. Forces downslope are compared to those upslope to determine the factor of safety. The forces upslope are determined by computing the shearing strength (S) from equation (1) on the failure surface, ab. **Downslope** driving forces are calculated from the slice weight and slope angle. The factor of safety is:

$$FS = \frac{c'}{\gamma z \cos\beta \sin\beta} + \frac{\gamma - m\gamma_w}{\tan\beta} \frac{\tan Ø'}{\tan\beta}, \qquad (3)$$

in which β is the gradient of the failure surface, γ is the unit weight of soil, γ_w is the unit weight of water, and m is the ratio of water depth to soil depth, z.

SHORTCOMINGS OF LANDSLIDE ANALYSIS

Soil strength at lateral boundaries resists movement in a landslide. Because these forces are not accounted for in the usual two-dimensional analysis, the factor of safety is usually underestimated. Aside from this shortcoming, available methods of slope analysis are reliable. Cost and time limitations, however, usually limit **our** knowledge of input data. Therefore, in natural slopes where geologic conditions are nearly always complex, where ground water conditions are seldom reliably known, and where even the topography must be

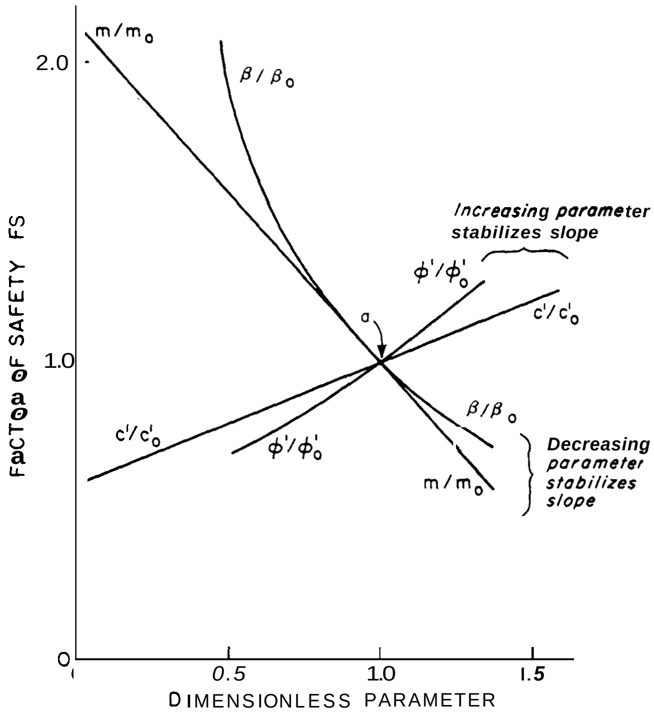


Figure 5.–Sensitivity diagram for **longslope** failure.

approximated for analysis, engineering analysis can never be considered to have great precision.

Consider a **long slope** with β (gradient of the failure surface) = 20°, z (vertical distance from ground surface to failure plane) = 2.4 m (7.9 ft), γ (unit weight of the slide material) = 1.5 Mg/m3 (95.5 pcf), Ø' (angle of internal friction) = 32°, and c' (cohesion) = 5kN/m2 (104.4 psf). Consider also that the ground water level is at the surface so that m = 1. From equation (3), the factor of safety of this hypothetical **slope** is one. We can now examine the influence of poorly defined input parameters by assigning different assumed values to the above quantities. The originally assumed values are assigned the subscript,, o, and newly assumed parameters no subscript. Repeated calculations with equation (3) produce the sensitivity diagram shown in figure 5. From figure 5, an increase in Ø' or c' results in an increase in the factor of safety. Increasing the water level parameter, m, or the slope angle, β, results in a lower factor of safety. Point (a) represents the factor of safety of the slope if all input parameters are known accurately. Figure 5, then, shows the consequences of variable natural conditions or poor input in the analysis. For instance, if all input is perfect except for m, and it is assumed that m_o = 1 when for real conditions m = 0.5, the factor of safety of the hypothetical **slope** is not 1 but 1.6. The difference in water depths for these cases is only 1.2 m (4 ft), but this modest difference

Table 1—Soil Properties for Oregon and Washington Coastal Ranges (from Schroeder and Alto 1983)

Parameter	Value
Mean angle of internal friction, $\phi'_{ave.}$	35.4°
Standard deviation, angle of internal friction, $\sigma_{\phi'}$	4.6°
Cohesion, where present, c'	6.86 kN/m^2 (143.3 psf)
Mean saturated unit weight, $\gamma_{ave.}$	1.82 Mg/m^3 (116.06 pcf)

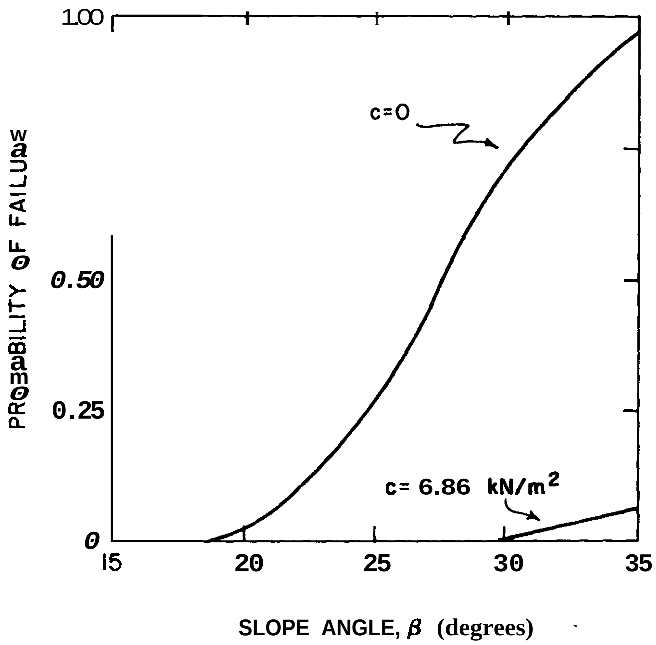


Figure 6.—Probability of failure for hypothetical slopes in the Coast Ranges in Oregon and Washington (see text for conditions).

significantly alters the computed safety factor. As a further example, consider the data of Yee (1975), who showed that the capillary tension of about 0.6 m (2 ft) of water, which exists in most Oregon Coast Range soils during periods of low rainfall produces an apparent cohesion of about 4.6 kN/m^2 (95 psf), approximately equal to the cohesion used in constructing the sensitivity diagram. A rise in ground water level of 0.6 m (2 ft) would destroy this apparent cohesion. According to figure 5, the factor of safety of the slope would drop from 1 to about 0.6, and the slope should certainly fail. Illustrations like this show that erroneous input can have a dramatic influence on the outcome of analysis for stability. In practice, there are limits on our ability to obtain this input. Therefore, engineering analysis for slope stability seldom produces precise answers.

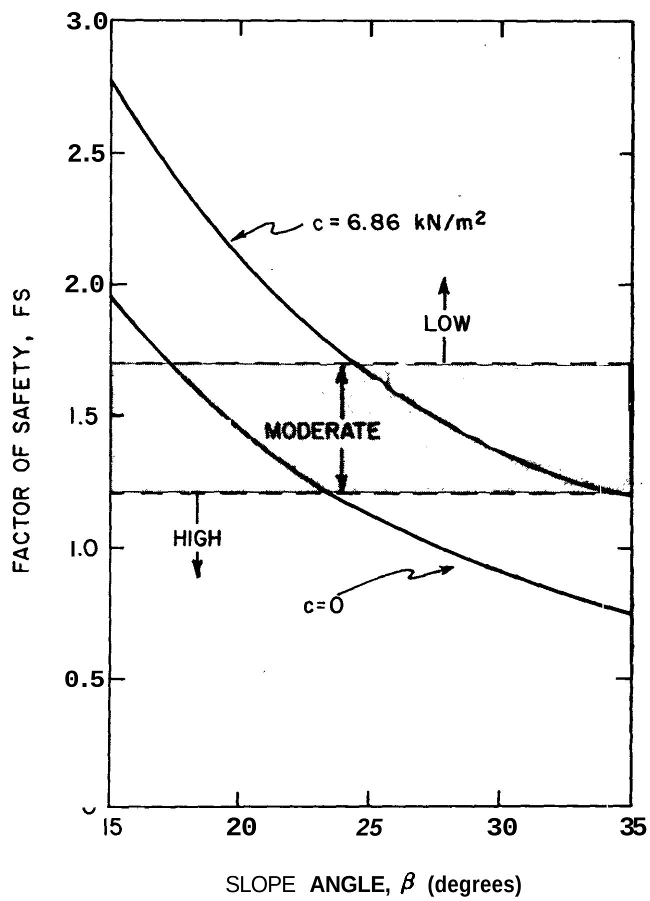


Figure 7.—Calculated factor of safety for hypothetical slopes in the Coast Ranges in Oregon and Washington (see text for conditions).

In evaluating the stability of slopes, an engineer must decide on an acceptable calculated factor of safety. This decision requires judgment. It is generally accepted that a reasonable factor of safety is 1.5, but, if little effort is to be expended to define input, the factor of safety should be higher.

Table 2--Summary of landslide risk assessment[1/]

Indicator	Slope 20°	25°	30°	35°
Calculated mean factor of safety	1.440	1.124	0.906	0.748
Probability of failure	0.024	0.260	0.729	0.976
Relative risk category	Low	Moderate	High	Very high
Observed slide activity	None	Dormant	Dormant	Active

1/ Data on which factor of safety and probability calculations were based.
Mean soil properties: $\phi' = 35.4°$, $c' = 0$, $\gamma = 1.82 Mg/m^3$ (116.06 pcf).
Mean soil depth: $z = 1.83$ m (6.0 ft).
Mean water depth: $mz = 0.92$ m (3.0 ft); $m = 0.5$.

PROBABILISTIC APPROACHES

In nature, soil conditions are never uniform. Schroeder and Alto (1983) have shown, for instance, that the population of strength parameters for soils in the Oregon and Washington Coast Ranges is normally distributed, with properties shown in table 1. Recent approaches to engineering analysis of slopes can use such data to express the reliability of safety factor calculations.

From table 1 and equation (3), the factor of safety in a long slope with $z = 1.83$ m (6 ft), $m = 0.5$, and $c' = 6.86$ kN/m^2 (143.3 psf) is:

$$FS = \frac{0.206}{\cos\beta \sin\beta} + 0.731 \frac{\tan\phi'}{\tan\beta} \qquad (4)$$

If we follow the approach of McGuffey, and others (1981) and consider the variability of the shear strength parameter, ϕ', noted in table 1, the expected value of the factor of safety (mean value) is:

$$E(FS) = \frac{0.206}{\cos\beta \sin\beta} + \frac{0.524}{\tan\beta} \qquad (5)$$

If $c' = 0$, the first term in equation (5) is lost. The standard deviation of the distribution of safety factor with or without cohesion, c', is

$$\sigma_{FS} = \frac{0.089}{\tan\beta} \qquad (6)$$

The probability of a slope failure is the probability that the factor of safety will be less than one. It can be computed for the mean and standard deviation from standard probability tables (Brownlee 1965) as:

$$P\{FS<1\} = P\{1\} = \Phi[u] = \Phi\left[\frac{FS-E(FS)}{\sigma_{FS}}\right] = \Phi\left[\frac{1-E(FS)}{\sigma_{FS}}\right] \qquad (7)$$

Results of these computations are summarized in figure 6, which shows that the probability of failure for cohesive slopes as steep as 35° is quite low (that is, < 0.07). The mean value of $\phi' = 35.4°$ would have given FS = 1.18 for a 35° slope. If there is no cohesion, the probability of failure is much larger. With probabilistic analysis, the engineer can judge the acceptability of a finite probability of failure instead of the adequacy of a calculated factor of safety.

Calculated factors of safety for our example problem for soils having $\phi' = 35.4°$ are presented in figure 7. Often, engineers assume that "high" risk of failure corresponds to calculated factors of safety below 1.2 and that "low" risk corresponds to calculated factors of safety above 1.7. For the cohesive case, from figure 7 we see that a "high" risk occurs for $\beta > 34.5°$ and a "low" risk exists for $\beta < 24.5°$. The "high" risk, according to figure 6, corresponds to a probability of about 0.06 or 6 percent. The "low" risk is very small. But for the noncohesive case, the "high" risk ($\beta > 23.5°$) probability is about 18 percent. Identical factors of safety may represent different risk levels.

The foregoing illustrates probabilistic analysis in which one parameter is variable. In reality, all parameters in equation (3) are variable. That variability may be quantified if adequate data are available, and a similar, but more complex, derivation of the risk of failure can be made. Wu and Swanston (1980) discuss this procedure. Although probabilistic methods allow engineers to quantify risk more clearly than does the factor of safety approach, they do not tell us what an acceptable risk level is. That decision must still be based on judgment.

TRUE ENGINEERING ANALYSIS

The process of assessing risk according to the true engineering approach is illustrated in figure 8. The proper use of this process requires considerable time and resources. Judgmental decisions are made at every step, and the outcome of the analysis depends on these judgments.

Suppose that the risk of landslides in a watershed in the central Oregon Coast Range have to be evaluated. Topographic maps are available, and a geologic reconnaissance has been completed. Areas with active and dormant landslides have been identified, and the mean soil depth over the watershed has been determined to be 1.83 m (6.0 ft). Stability when seepage is at mid-depth in the soil profile is to be considered. Soil conditions determined by Schroeder and Alto (1983) are applicable, and the soils are cohesionless. Analyses for the factor of safety and probability of failure yield the results indicated in table 2.

We may also assign relative risk by drawing the inductive conclusion that landslides will occur again where they have happened before. In table 2, for instance, the areas of active landsliding are identified as very high risk areas. This criterion overrides those based on stability calculations. To use the results in table 2, an engineer would first refer to areas mapped by the geologist as having active or dormant landslides and judge, without recourse to analysis, that these areas would have more than a low probability of future failure. The inductive process could by itself lead to an assignment of relative risk. On the other hand, the hypothetical watershed may-show no signs of past landslide activity. In that case, there is no basis for drawing conclusions concerning risk in different areas of the watershed except a deductive analysis. Risk level is then based on factor of safety and probabilistic determination. In the best of all situations, of course, adequate data are available for both the deductive and inductive processes to work.

SUMMARY

Either inductive or deductive approaches, or preferably both, can be used to assess landslide risk. Often the former is the geologist's exclusively, and the latter is the engineer's. Without judgment, the deductive approach, is, in reality, no more than analysis. True engineering involves judgment. Whether analysis be based on discrete landslide modeling or probability concepts, the current state of the art in engineering requires reliance on inductive reasoning and analysis tempered with judgment. This is particularly true when area-wide studies of landslide risk are required. It is, therefore, not appropriate to assign these duties to persons who are not familiar with the limitations of the analytical methods available to the engineer.

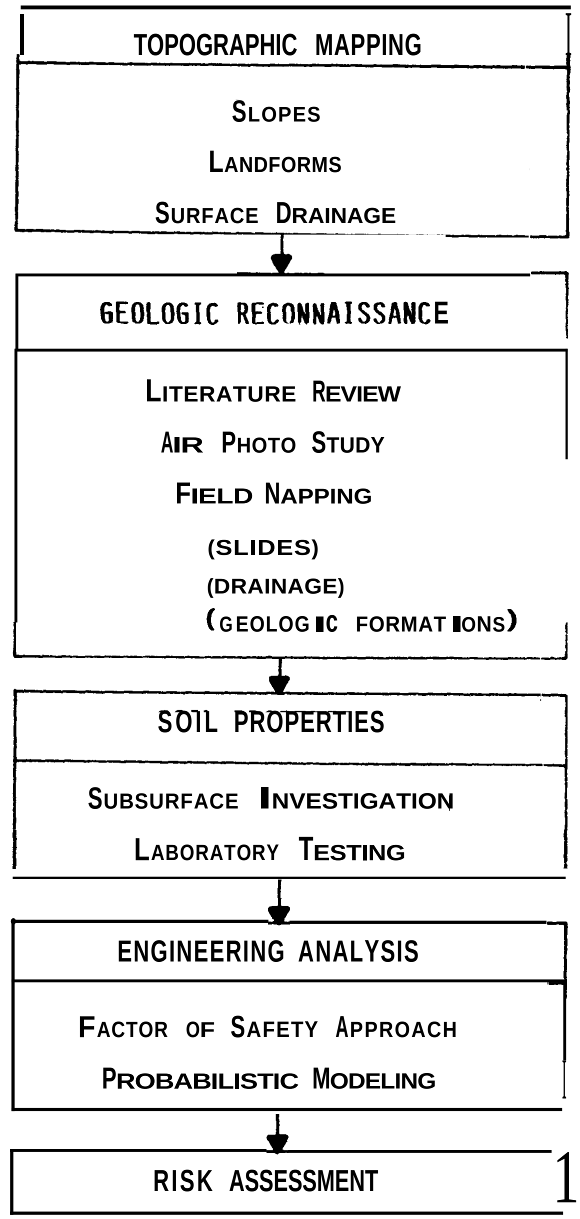


Figure 8.--Methodology for landslide risk assessment using the true engineering approach.

LITERATURE CITED

Brownlee, K. A. Statistical theory and methodology in science and engineering 2d. ed New York: Wiley; 1965. 590 p.

McGuffey, V.; Iori, J.; Kyfor, Z; Athanasiou-Grivas, D. Use of point estimates for probability moments in geotechnical engineering. In: Frost action and risk assessment in soil mechanics. Rep. 809. Washington, DC: Transportation Research Board, National Academy of Sciences; 1981: 60-64.

Schroeder, W. L.; Alto, J. V. Soil 'properties for slope stability analysis; Oregon and Washington coastal mountains. Forest Science. 29(4):823-833; 1983.

Varnes, D. J. Slope movement types and processes. In: Landslides, analysis and control; Transportation Research Board Special Report 176. Washington, D.C.: Transportation Research Board, National Acadamy of Sciences; 1978: 12-33.

Wu, T. H.; Swanston, D.N. Risk of landslides in shallow soils and its relation to clearcutting in southeast Alaska. Forest Science. 29(3):495-510; 1980.

Yee, C. S. Soil and hydrologic factors affecting stability of natural slopes in the Oregon Coast Range. Corvallis, OR: Oregon State University; 1975. Ph.D. dissertation. 204 p.

COMPUTER-EASED

LANDSLIDE DELINEATION AND RISK ASSESSMENT PROCEDURES FOR MANAGEMENT PLANNING

Tim J. Ward

ABSTRACT: This paper explores what computer-based tools are available to the planner/manager. Concepts and principals are discussed, and an application of one method is described.

The primary emphasis is on the merging of theoretical concepts with computer-aided decisionmaking. The factor-of-safety approach for delineating hazardous slopes is used as the basis for many types of decisionmaking processes. Low factor-of-safety values are unsafe and therefore delinate hazardous areas. The factor of safety can also be used as an indicator of landslide risk or of the probability that a slope failure might occur given the uncertainty of the controlling variables. Forecasts of the direction this approach will take in the future are presented.

INTRODUCTION

Effective management of watersheds requires careful planning based on the best information available. The final management decision or recommendation must be made by the planner or planning team from technical input and experience. The mangement planning function is, therefore, a combination of technical expertise and information and the experience of the planners involved. This combination of qualities can be cast in quantitative terms so that it can be made transferable between individuals through the use of computer modeling.

TIM J. WARD is an associate professor of civil and geological engineering at New Mexico State University, Las Cruces, New Mexico.

The Modeling Game

Computer usage in management planning has become both a boon and a bane. One negative aspect is that sometimes the computer generated results form some "model" of the forest system and are used as the ends themselves. This is an incorrect approach to management planning. Instead, computer models (i.e., mathematical abstractions of real physical processes), should be viewed and used as a means to an end. Recently, a forest management project in New Mexico was discontinued because the computer results were erroneous and this was not detected soon enough to make necessary changes. It was only after the numbers (results) were compared with physical reality that someone discovered that the model had a higher harvest than there were trees!

Although these observations are rather negative, do not construe them to be anticomputer-based modeling. In fact, use of the computer has greatly enhanced the management planning function in that a large number of potential scenarios can be analyzed in a relatively short time. The scenarios can provide a matrix of outcomes upon which further analyses can be conducted. One aspect of developing numerous scenario results is that one can start to believe that the watershed or landscape will respond as the model indicates. In truth, the results are how the model responds, hopefully as a relative representation of the true physical world. Just as with arcade games, it is easy for the unseasoned modeler to become enthralled by the "modeling games" and not recognize when the results and reality no longer coincide.

The power and pervasiveness of computer-aided decisionmaking in management planning requires that the managers/planners have an idea what models are available and if they truly meet the perceived needs. There are models for timber growth and harvesting, for animal population dynamics, for watershed rainfall-snowmelt-runoff-sediment yield prediction, and for landslide delineation and risk assessment (as this paper explores). Not only are there different types of models for different aspects of the planning function, but there are different levels of model sophistication. These range from computerized curve fitting through those detailing the basic physics of the important processes. Although more sophisticated, these last types provide the best answers relative to forest management planning. One of these models is presented here to acquaint the reader with modeling.

LANDSLIDE DELINEATION: A PHYSICALLY-BASED APPROACH

General Methodologies

The concept of landslide delineation, or more properly landslide potential delination, comes from the recognition that landslides occur (usually) when slopes are relatively steep, the ground is "weak," and water is present. There have been numerous approaches developed for delineation of potential landslide areas including on-ground monitoring, remote sensing techniques, factor overlay methods, statistical models, and geotechnical process models. Many of these approaches are discussed in Schuster and Krizek (1978).

The most common delineation method used is factor overlay of a combination of landslide producing elements. Krynine and Jud (1957) note that landslides occur in a regional framework such that certain factors common to a region contribute to land sliding. Baker and Chieruzzi (1959) expand this concept to develop a physiographic classification of landslide hazards based on topography, erosional development, and associated rock types. Blanc and Cleveland (1968) were among the first to attempt to delineate landslide areas by use of selected factors. Evans and Grey[1/] present a methodology for mud slide risk delineation in southern Ventura County, California. Cleveland (1971) summarizes and presents factors importan in regional landslide prediction. The approach described by Nilsen and Brabb (1973) and the Committee on Methodologies for Predicting Mudflc Areas (1982) also follow a systematic methodolog using landslide factors. In this overlay approach, certain factors related to landslide occurrence are individually delineated. For example, if landslides occur where steep slopes, weak earth materials, and water are all coincident, then these factors should be used as slope stability indicators. Areas where factors coincide can then be classified as a high hazard potential (Simons and Ward 1976). Although not explicitly stated in delineation schemes, this idea is the basis for most techniques.

Another type of landslide hazard delineation methodology is based on geotechnical models. One such approach has been developed (Ward 1976; Ward and others 1980, 1982) and can be used as a framework for other approaches (e.g., Edil and Schultz 1983).

Framework for the Computer-Based Approach

Current delineation techniques utilizing geotechnical models are available for a wide range of conditions. A basic framework for all types of models should include:

1. The pertinent mathematical equations(s).

2. A method for converting topographic, vegetative, water, and soil-geologic information into a digitized form suitable for the mathematical equations(s).

3. An interactive feature that allows the manager/planner to engage in "what-if" games.

4. A meaningful output feature or display that is easily understood.

The approach of Ward (1976) and Ward and others (1982) is designed to meet these criteria. In the Ward approach or model, a simplified infinite slope factor-of-safety equation is used to determine the ratio between the resisting factors preventing landslides and the driving factors creating landslides. The equation was cast in probabilistic terms so that a mean factor of safety (FS) and a standard deviation (or a variance, VAR[FS]) could be computed. The basic equations were:

[1/] J. R. Evans and C. H. Grey. Analysis of landslide risk in southern Ventura County, California. Unpublished report prepared for the U. S. Department of Housing and Urban Development. On File at the California Division of Mines and Geology, Sacramento, California.

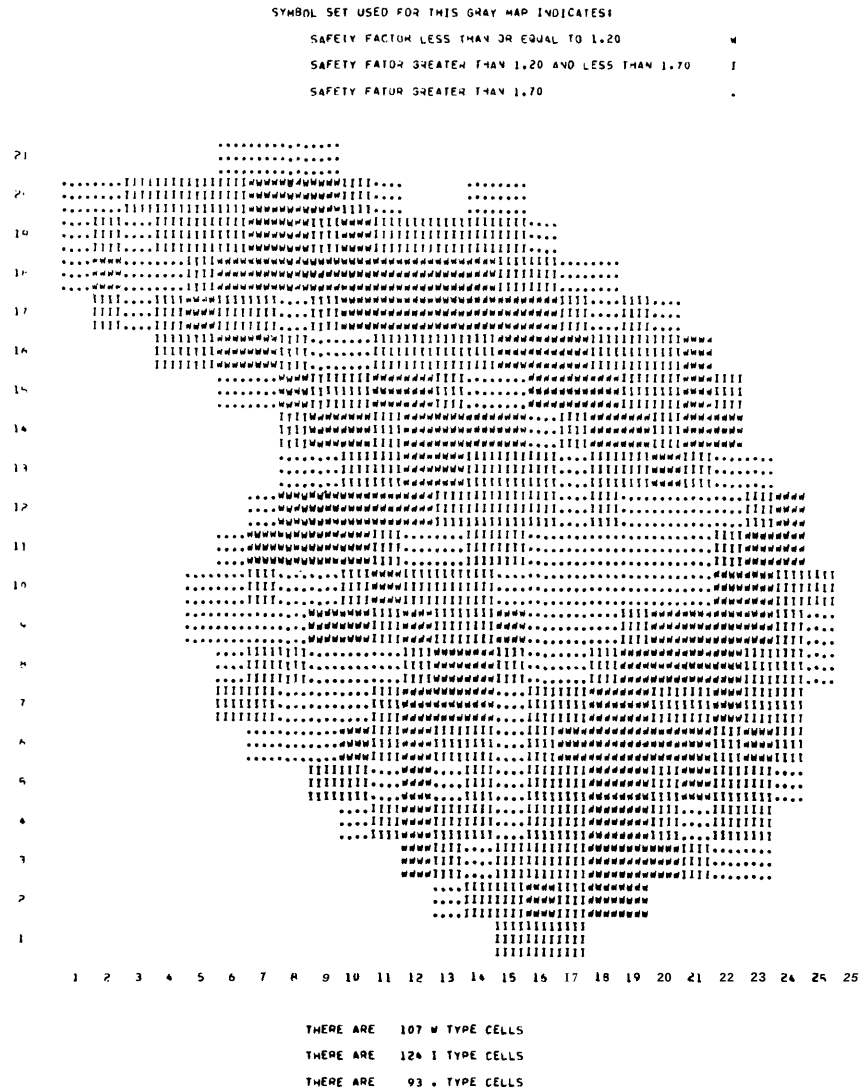


Figure 1.—Gray area or print density map of **Starfish** Creek, Alaska, showing baseline factor-of-safety conditions (undisturbed).

$$FS = L1\,(c_s + c_r) + L2\,(\tan \emptyset) \qquad (1)$$

and

$$VAR(FS) = L1^2\,(c_s + c_r) + L2^2\,(\tan \emptyset); \qquad (2)$$

where

c_s = soil cohesion,
c_r = "cohesion" added by roots,
$\tan \emptyset$ = soil internal friction angle, and
L1, L2 = variables containing terms for soil weight and depth, water effects, vegetation, and slope inclination.

From these equations, the **FS** value could be ranked according to some hazard classification. The probability of a landslide occurrence was cast in terms of the variability of the c_s, c_r, and tan 0 values while the L1 and L2 were fixed. The probability of a landslide, then, is the chance that all the factors exist that would lead to a failure; whereas potential is the determination that factors exist that tend toward (or away from) failure. Edil and Schultz (1983) indicate that hazard zoning based on the probability determination contains more information than just the potential.

Data Needs

A strength of the approach just discussed is also a weakness—data. The geotechnical model requires an estimate of soil parameters, vegetation and topography. This information can be determined from tables presented by Ward

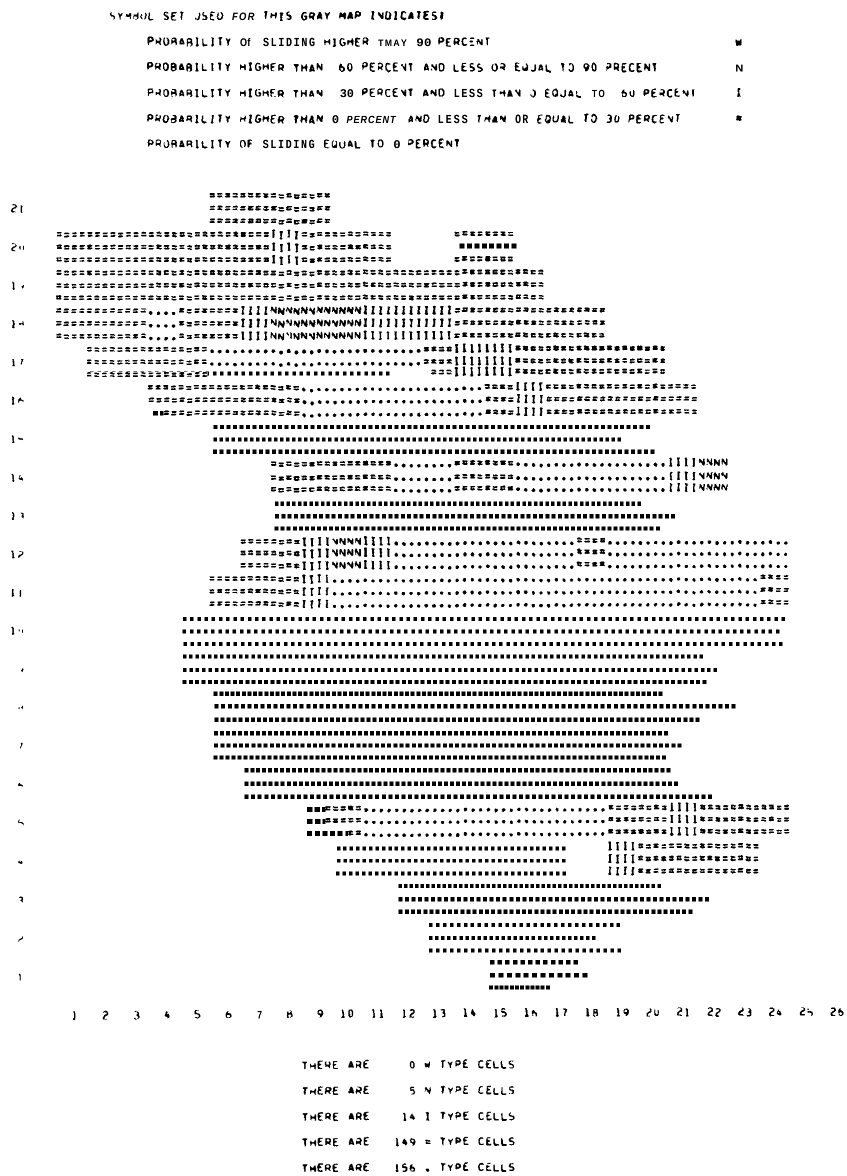


Figure 2.—Gray area or print density map of Starfish Creek, Alaska, showing baseline probability of failure conditions (undisturbed).

(1976) or Campbell and Ward[2/]. Data entry is tedious but is assisted by software packages that arrange the information into a usable form. In this approach the data (parameters, slope, etc) are assigned to a predetermined rectangular grid that is overlaid on the watershed of interest. This grid can vary in size, but larger grids mean more averaging of data and smaller grids mean more intense data requirements. In general, the approach is well suited for land management applications in that each grid cell can be assigned a potential or probability value.

The original approach was not designed with an interactive capability. Instead single data files (or if necessary, multiple data files) could be edited by the user and the model executed again. Interactive computing using a virtual machine concept has negated the need for a truly interactive program.

Display

The results of the geotechnical modeling approach should be displayed in a form that is easy to use. Tables of numbers are tables of numbers. For more impact, nothing ia better than a visual display. When the watershed or landscape is

---

[2/] Campbell, R. E.; Ward, T. J. The LSMAP methodology and uses guide for delineating potential landslides. unpublished manuscript. USDA Forest Service, Rocky Mountain Forest and Range Experiment Station. 1982.

Figure 3.—Gray area or print density map of Starfish Creek, Alaska, showing changes in factors-of-safety resulting from 100 percent reduction in timber density (entire area clearcut).

analyzed using a cellular approach, the cells can be ranked and then printed (on paper or on a CTR) as a print density map with the high potential (or probability) cells shaded more strikingly than the other, lower potential, cells.

Example

An example of the geotechnical approach was presented by Ward and others (1980, 1982). The methodology was initially tested on a forested watershed in the Cascade Range in Oregon (Simons and others 1978), and has been applied in the Coast Range of Oregon (Ward and others 1980). The example is for a basin located in the northern portion of Chichagof Island, southeast Alaska, and is referred to as Starfish Creek. The basin was segmented into 324 10-acre cells, and information from the USDA Forest Service, Alaska Region, Integrated Resource Inventory, was utilized to produce vegetation and soil maps that were grouped into seven soil types and six vegetation types.

Groundwater levels were arbitrarily fixed at 1 and 2 feet, and timber removal at baseline (no removal), 30 percent, 50 percent and 70 percent canopy cover removal, and clearcut conditions. Root strength in the cut portions was reduced to 20 percent of the assumed original value to represent root decay with time (4-5 years).

The results for the baseline and clearcut conditions and 1-foot ground-water level are shown in figures 1-4 as factor of safety (FS) and probability gray-area maps. The darker shades of gray (print density) on those maps indicate more hazardous cells than do lighter shades of gray.

Information presented in the figures can aid planning. For example, the hazardous cells caused by clearcutting can be detected, and areas delineated as unstable can be avoided, another cutting scheme applied, or further investigation initiated.

Figure 4.—Gray area or print density map of Starfish Creek, Alaska, showing changes in probability of failure resulting from 100 percent reduction in timber density (entire area clearcut).

WHAT NEXT?

A phrase for the 1980's is "management technology." What this means is use of the new technologies for the enhancement of management productivity. The concept extends to management planning in that the management planning function will incorporate many of the rapidly appearing technologies. A prime example is the microcomputer. This sleek looking, ergonomic device is changing the way business is done. Such a device, when properly configured, can be used to:

1. Access data on landforms, soils, and vegetation from centralized data banks.

2. Search for references on the area being studied.

3. Accept and store data from field or office test instruments.

4. Load data to a larger, faster computer for processing, then retrieve the results.

5. Process the what-if questions and display the results on the CRT or in print form.

6. Set up summary tables showing results.

7. Act as a word processor to type the planning report.

8. Send the report to a central location.

It is evident from the above limited list that the new technologies will extend the present landslide delineation and risk assessment procedures beyond printing a few maps to a total computer-integrated management planning basis.

CONCLUSIONS

Past and present research has produced numerous techniques to aid in management planning. These techniques often take the form of computer based models of a forest system.. When used as an aid the results from such models can be quite helpful. Care should be taken, however, to see that knowledgeable people have the responsibility of applying the model and interpreting the results. The future of such aids is positive. As the computer based methodologies gain wider use, they will become (or be made) more user friendly and less susceptible to misinterpretation.

REFERENCES

Baker, R. F. and Chieruzzi, R. Regional concept of landslide occurence. Highway Research Board Bulletin No. 216: 1-17; 1959.

Blanc, R. P.; Cleveland, G. B. Natural slope stability as related to geology, San Clemente Area, Orange and San Diego Counties, California. Spec. Rep. 98. Sacramento, CA: California Division of Mines and Geology; 1968. 19 p.

Committee on Methodologies for Predicting Mudflow Areas, R. H. Campbell, Chairman. Selecting a methodology for delineating mudslide hazard areas for the National Flood Insurance Program. Washington D. C.: National Academy of Sciences, National Research Council; 1982. 35 p.

Cleveland, G. B. Regional landslide prediction. Open File Release 72-73 Sacramento, CA: California Division of Mines and Geology; 1971. 33 p.

Edil, T. B.; Schultz, M. N. Landslide hazard potential determination along a shoreline segment. Engineering Geology 19(3): 159-177; 1983.

Krynine, D. P.; Judd, W. R. Principles of engineering geology and geotechnics. New York: McGraw-Hill; 1957. 730 p.

Nilsen, T. H.; Brabb, E. E. Current slope-stability studies in the San Francisco Bay region. Journal of Research, United States Geological Survey; 1(4): 431-437; 1973.

Schuster, R. L.; Krizek, R. J., eds. Landslide-Analysis and Control. Transportation Research Board Special Report 176. Washington D. C.: National Academy of Sciences; 1978. 234 p.

Simons, D. B,; Ward, T. J. Landslide potential delineation. Fort Collins, CO: Colorado State University, Civil Engineering Department; 1976. 183 p.

Simons, D. B.; Ward, T. J.; Li, R. M. Mapping of potential landslide areas in terms of slope stability. Fort Collins, CO: Colorado State University, Civil Engineering Department; 1978. 75 p.

Ward, T. J. Factor of safety approach to landslide potential delineation. Fort Collins, CO: Colorado State University, Civil Engineering Department; 1976. 119 p. Ph.D. dissertation.

Ward, T. J.; Li, R. M.; Simons, D. B. Mapping landslide hazards in forest watersheds. American Society of Civil Engineering 108 (GT 12): 319-324. 1982.

Ward, T. J.; Simons, D. B.; Li, R. M; Gemma, R. A. Application of a landslide delineation methodology to selected forested sites in the Pacific Northwest and coastal Alaska. Fort Collins, CO: Colorado State University, Civil Engineering Department; 1980. 145 p.

A SERENDIPITOUS INTEGRATION OF RESEARCH WITH MANAGEMENT NEEDS: THE BRITISH COLUMBIA FISH/FORESTRY INTERACTION PROGRAM

V, A. Poulin

ABSTRACT: Research in the Fish/Forestry Interaction Program was initiated in 1981 by the British Columbia Ministry of Forests, British Columbia Ministry of Environment, and Canada Department of Fisheries and Oceans as a positive action toward resolution of conflicts concerning steep-slope logging and integrated management of fish and forest resources on the Queen Charlotte Islands. The overall objectives of the program are directed at understanding harvest impacts on fisheries habitat and forest sites, minimizing logging-induced slope instability through the use of alternate logging methods, and mitigating damage caused by landslides using stream and forest site rehabilitation techniques. The program consists of four component research projects, which are being carried out in phases over a 5 year period. The research components are closely integrated within two broad categories of study: (1) impact studies that document the fish habitat damage and loss in forest site productivity caused by soil mass movements; and (2) prescriptive studies that assess the suitability of alternative techniques for reducing slope instability caused by logging and rehabilitation of stream and forest sites following damage by landslides.

INTRODUCTION

Several months ago Doug Swanston called and asked if I would accept an invitation to talk at this conference about the Fish/Forestry Interaction Program. I was not only delighted by the invitation but very pleased to have the opportunity to talk to such a large and diverse audience.

Everything was fine until Doug suggested the title for my talk: "A Serendipitous Integration of Research With Management Needs." When he asked over the phone how that sounded, I said "great," not wanting to reveal my ignorance. I hadn't the faintest idea what the word "serendipitous" meant.

Who had ever heard of Horace Walpole - an English novelist who about the time of the American Revolution coined the term "serendipity" to describe a faculty possessed by the heroes in a Persian fairy tale called, "Three Princes of Serendip." This faculty was the apparent aptitude for making fortunate discoveries quite by accident. In a colloquial sense we're now using the word "serendipity" to express a happy, symbiotic relationship.

In actual fact, the Fish/Forestry Interaction Program originally set out to study the effects of mass wasting--landslides, debris torrents, and so on on fish habitat--and accidently came upon a fortunate discovery: how to fund, staff, and maintain a comprehensive and integrated research

V. A. POULIN is contract program manager, Fish/Forestry Interaction Program, V. A. Poulin and Associates Ltd., Vancouver, British Columbia.

program in an era of government cutbacks. A difficult task even in the best of times.

Much of what has been and will be said during the conference will point to the need for further work—be it basic research or technology transfer. In any event? perhaps decisions will be made to initiate additional studies and steps will be taken to seek the funding for these projects. I feel the integrated approach our program has taken may interest you and could serve as a role model for efficient use of your research dollars and existing expertise.

This conference has been designed to give us a fresh perspective on the status of research and new findings. Our program is still in the midst of data collection and analysis and, therefore, conclusions are still to come. I would like to explain the purpose of the program and give you some idea of the problems being addressed and the information being collected.

THE RESOURCE

The Queen Charlotte Islands are located off the northwest coast of British Columbia. The islands have a land area of about 10,000 km^2 and were extensively glaciated during the last glacial period. Rainfall varies considerably from west to east, ranging from over 4,500 mm in western fiords to 1,200 mm on the eastern slopes. Steepening of mountain slopes through glaciation, and erosion and weathering of bedrock and glacial deposits are major factors that have resulted in mass wasting being the dominant geomorphic process on the islands.

The predominant timber species are Sitka spruce, western hemlock and western red cedar. In recent years, the Queen Charlotte land base has contributed in excess of 3 percent of the total Provincial harvest on approximately 1.7 percent of the Provincial land base. The Queen Charlotte Islands are extremely productive, and in bottomland areas growth in excess of 1 m annually in height is common. The principal silviculture system used is progressive clearcutting followed by natural regeneration and, in some areas, commercial planting.

Of some 350 streams on the islands, 200 are known to contribute to commercial fish production. Total salmon escapement is estimated at roughly 1 million annually. In relation to the rest of the Province, the Queen Charlotte Islands contribute substantially to the overall escapement by providing spawning area for about 13 percent of the total. Coho salmon, a species that resides in Queen Charlotte streams for one or more years, accounts for nearly 18 percent of the total estimated Provincial coho escapement.

Of the three principal species present, pink salmon are by far the most abundant. The Queen Charlotte Islands also support some of British Columbia's finest steelhead and cutthroat trout fishing. Although most major sport fishing streams are large systems, not directly affected by landslides, many of the smaller, first order streams contribute to trout production.

THE ISSUES

Slope stability problems are not unique to logging on the Queen Charlotte Islands. Owing to a combination of steep slopes, highly erosive bedrock, shallow soils, and high rainfall, natural failures are common and reoccurring.

It wasn't until the late 1960's when most of the bottom land timber was depleted that logging began on steep sidehills and soil stability problems were recognized as a serious concern. Steep sidehill yarding introduced the widespread use of unimproved, midslope roads, most of which were constructed using tractors. Many of these areas are now very active and are a chronic source of sediment and debris to streams.

In autumn of 1978 attention throughout Canada was focused on the Queen Charlotte Islands and its slope stability problems. A major rainstorm hit that caused extensive damage and mass wasting throughout the islands. The storm touched off a series of slides in a logged area overlooking Rennell Sound on the west coast depositing sediment and debris into an important spawning stream for pink salmon. A public outcry, mainly from local environmental groups, followed; they demanded logging be curtailed in sensitive terrain. A serious jurisdictional dispute between the Provincial and federal agencies concerning responsibility for habitat protection also arose out of that event.

The outcome of the situation at Rennel Sound was an agreement between the three agencies--Ministry of Forests, Ministry of Environment, and Canada Department of Fisheries and Oceans--to establish a cooperative framework for dealing with steep-slope logging problems. Part of this resolution was an agreement to undertake a joint interdisciplinary study aimed at applied problem solving.

A task force was established, to aid in developing the research priorities. This task force concluded that:

1. Mass wasting was a natural process on the Queen Charlottes Islands and could be seriously accelerated with existing logging and road construction practices; and

2. On some sites accelerated mass wasting did cause severe and persistent loss to forest productivity and fish habitat.

Echoing similar issues that have been voiced throughout the Pacific Northwest, the task force was particularly concerned that information such as effects of siltation on fish was relatively well documented, but that at the time fisheries biologists had little knowledge of the effects of landslides on fish habitat, and certainly less information on rehabilitating sites damaged by slides. Foresters were equally unsure of the risk of causing a landslide and-how to prevent future landslides.

In light of these concerns, the task force recommended the research program focus on four major objectives:

1. Provide documentation on the extent and severity of mass wasting and assess impacts on fish habitat and forest sites,
2. Investigate the feasibility of rehabilitating stream and forest sites damaged by landslides,
3. Assess the use of alternative silvicultural treatments for maintaining and improving slope stability by establishing and maintaining thrifty root systems; and,
4. Investigate the feasibility and success of reducing logging-induced failures through the use of alternative logging methods such as skylines, helicopters, and logging planning,

PROGRAM TIMING

The above objectives drive the Fish/Forestry Interaction program, The early expectations were to conduct a 3-year study, but it soon became apparent that this was not enough time given delays in staffing and inexperience in dealing with slope stability issues. We were able to extend the program to cover a 5-year period, which began in 1981.

The work undertaken in the first year was largely directed toward completing a study design, obtaining staff, and initiating background data collection. The second and third years have been directed at extensive field studies. During the remaining two years studies will be concluded and reports written.

PROGRAM ORGANIZATION AND FUNDING

The program is funded by the British Columbia Ministry of Forests, the Fish and Wildlife Branch of the British Columbia Ministry of Environment, and the Canada Department of Fisheries and Oceans. The Canadian Forestry Service, Pacific Forest Research Centre, and the Forest Engineering Research Institute of Canada provide additional support. Total expenditures over the 5-year period will amount to $1.45 million excluding the support provided by participating agencies through seconded salaries and some overhead.

The success of the program to date has hinged largely on the original commitment of the three lead agencies to stress slope stability issues and to prioritize research in the area of applied problem solving. By pooling the resources and undertaking this study, the program has drawn together senior representatives of the agencies in a manner that also provides dialogue and common understanding of research results. It further ensures that senior administrators know the options available and make management decisions based on current knowledge.

The program is organized on the basis of:

1. An executive-level steering committee,
2. A technical advisory committee,
3. A contract program manager
4. A scientific advisory panel; and,
5. Contract and agency project leaders.

The single most important element of the organization structure is the steering committee. The committee consists of senior executives for the Provincial government, the Canadian Government, and industry, This group is the driving force behind the program and is committed to an integrated approach to resolve slope stability problems, The committee meets on an average of once every 4 to 6 months to provide overall policy direction to and monitor progress.

The technical advisory committee is the working arm of the steering committee and consists of district managers and senior researchers from the sponsoring agencies. The canmittee provides technical direction, reviews working plans and reports, and approves budgets.

Regardless of program size, few integrated studies have the luxury of having internationally renown experts on staff. The FisWForestry Interaction Program has asked a group of recognized scientists to help provide advice on project study design and to serve as reviewers for program publications. This group has met yearly with the research team and several scientists have participated in field workshops on the Queen Charlotte Islands. Members of this committe include scientists from British Columbia, Washington, and Alaska.

An advantage of this organizational structure is that project management and many senior project leaders are contract personnel and not part of any agency. As the contract program manager, this gives me the flexibility to cross agency boundaries and cut through administrative detail. I have full fiscal control over the program and administer all contracts and disbursements. This enables me to direct and administer the program on a day-to-day basis with little interference.

As an independent manager, I have the latitude to approach any viable source to gain support for the program. The program has been able to sponsor job creation (volunteer) projects, for example, that have made several labor-intensive studies possible at no cost to the program. In addition, all of the drafting and much of the office support services have been provided free through this job creation approach.

The project leaders report directly to the program manager and because of the flexibility of the program in attracting support, 11 separate studies have been initiated that have involved 14 project leaders. Our project leaders have included:

- researchers from two Provincial ministries,

- post-graduate, students,
- senior researchers from industry, and
- contract Fish/Forestry Interaction Program (FFIP) staff.

STATUS OF RESEARCH

To stay within the theme of the conference, I would like to review the studies we have initiated and discuss the nature of the information we are collecting and hope to provide. Up to now our research goals have focused on three major tasks:

1. Developing an understanding of the problem by describing the extent and severity of mass wasting on the islands and the link to timber harvest operations.

2. Assessing the impacts of landslides on streams and forest sites

3. Investigating alternative harvesting systems to minimize logging related mass wasting and to develop restorative techniques to mitigate landslide damage.

DEFINING THE PROBLEM

When the program first began in 1981 there was little data to express the magnitude of the problem. Two studies were undertaken to assess the extent and severity of mass wasting on the Queen Charlotte Islands and relation of mass wasting occurrence to land use. The studies were done at two scales:

1. An overview by the Canadian Forest Service using high-altitude, aerial photographs, and

2. A detailed photogrammetric analysis using large-scale, 1:10,000 aerial photographs from 27 drainage basins.

Results of the slide studies point out that the logging-related slides that kicked off the original conflict at Rennell Sound were not an isolated problem. Using 1:50,000 aerial photographs, about 8,000 slope failures have been identified across the Queen Charlotte Islands (Gimbarzevsky 1983). Given the scale of the photography, this is considered a conservative measure. This study further points out that significant landslide activity (greater than 1 failure/km^2 has occurred on nearly 31 percent of the total land area of the islands. Put another way, it suggests that nearly one-third of the island land area is subject to mass wasting.

To develop an understanding of the relationship of logging land use to the occurrence of slides, 27 study basins were examined using 1:10,000 aerial photographs. Results of this study suggest that landslide frequency in the logged portions of the basins is approximately 10.7 failures/km^2 as compared to 2.8 failures/km^2 in unlogged terrain (Rood, in preparation).[1/] This is about a fourfold increase in frequency of failures attributable to logging. The combined data from logged and unlogged areas gives an average frequency of 4.4 failures/km^2 for the study basins. Measurements derived from this photographic analysis indicate approximately 1.89 ha. of bare mineral soil is exposed in logged terrain, as compared to 0.7 ha in unlogged areas.

Sediment volumes produced by landsliding were also estimated from measurements on aerial photographs to help establish the relationship between logging activity on the slope and damage to downstream resources. These data, suggest there is a quadrupling of absolwte sediment yield due to logging (see footnote 1). If these data take into account the different ages of slides in logged vs unlogged terrain, the increase in debris yield jumps to 20 times the undisturbed rate.

Slides observed in logged areas were categorized as to point of initiation in an attempt to determine the relationship of failures to specific land use. Results of this analysis suggested that gullies and roads accounted for approximately 70 percent of the failures in logged areas. These failures delivered an estimated 87 percent of the released sediment to streams. Logging roads and logged gullies are clearly major sources of mass wasted debris on Queen Charlotte Islands.

Another major question the program is addressing is what happens to the sediment after it enters the stream channel. Two post-graduate students are examining the characteristics of channels to describe the movement and storage of eroded material in streams and the effects of the eroded material on channel morphology. Other studies are underway to examine stream flow responses to rainfall and to examine the fate of fine sediments introduced into streams.

IMPACT STUDIES

A major part of the Fish/Forestry Interaction Program is directed at the effects of mass wasting on fisheries habitat. Over the past two field seasons, staff scientists have begun studies in some 44 streams. The study streams represent a range of logged and unlogged systems, from those that have a high frequency of mass wasting to those with no mass wasting.

Field studies undertaken in the study streams have quantified the effects of mass wasting on fish habitat — as expressed by changes in pool to riffle configuration, amount of large organic debris, gravel composition, and gravel

---

1/ Ken Rood, Fish/Forestry Interaction Program and Department of Geology, University of British Columbia, Vancouver, British Columbia. Manuscript in preparation.

stability. Within most of the study streams, information describing the distribution and abundance of fish habitat was collected to examine the relationship of fish densities to amount and quality of available habitat, The fisheries data is still undergoing analysis and results are unavailable.

Outcomes of the fisheries studies will provide information on amount of habitat lost from mass wasting and will document changes in habitat conditions that influence success of fish rearing and egg incubation. Recently initiated fishery studies are examining juvenile salmonid overwinter survival in streams damaged by landslides. These data will assist in defining losses in production attributed to mass wasting.

For the past two summers, the Canadian Forest Service has been investigating the rate and pattern of vegetation succession on slides to ascertain the implications on forest growth (Smith, and others 1983). To date, 45 slides ranging in age from 1 to 125 years have been sampled.

As with other data, the extreme variability in the terrain conditions has made clear trends difficult to distinguish; however, several general facts have emerged. It takes three to four times as long for a slide surface to reach 80 percent cover as it does for a clearcut logged area. A logged area on the Queen Charlotte Islands, for example, will usually reach 80 percent cover in 26 years as compared to 85 years on adjacent slide terrain. When a slide is treated separately, however, the figures change, The upper one-third of a slide barely reaches 80 percent cover in about 100 years; in the lower one-third that level is reached in just 30 years, or close to the average in logged areas,

Red alder appears to be the greatest single determinant in vegetation succession on most slides. When alder occurs in high densities, such as the lower one-third of slides on low-elevation sites, it dominates other vegetation for 30 or 40 years. After that, alder begins to deteriorate, allowing conifers--but often sparsely stocked conifers--to attain an increasing share of the canopy.

In areas where alder hasn't become established, such as high-elevation sites and in the upper portion of slides, conifers — particularly Sitka spruce and western hemlock--dominate. These patterns of the successional forest growth suggest that while acceptable revegetation is obtainable on the lower one-third of slides, these sites still fall behind vegetation establishment in clearcut units. The middle to upper parts appear to remain open to surface erosion and gullying for considerable time.

PRESCRIPTIVE STUDIES

Field studies are being conducted by the Forest Engineering Institute of Canada to determine how best to log the Queen Charlotte Islands to reduce landslide impact using new or traditional systems and to develop logging planning techniques for marginally stable terrain. Studies to date have primarily been reviews of alternative yarding systems and have provided background field data on logging planning. Field studies this past summer have been directed at examining the effectiveness of skyline systems for logging in gullies. In addition, approximately 100 landslides included in the aerial photography surveys were examined by logging engineers to establish cause and effect relationships,,

A literature review of hillslope restoration practices is being done to suggest management techniques for the Queen Charlotte Islands,, Budget limitations have not permitted pilot studies, yet a small, slide revegetation project was initiated this spring involving the planting of some nine different varieties of shrubs to obtain an indication of their suitability for revegetating slide and browse damaged areas.

A review of short- and long-term silvicultural options for improving slope stability following logging is underway. It is hoped this work will identify possible techniques for improving slope stability and culminate in field research.

An important aspect of the FisWForestry Interaction Program studies is determining how to restore streams damaged by slides. The several projects undertaken include examining the use of steel gabions to improve salmon spawning areas, and replacing log debris in streams to develop rearing habitat. Three gabion barriers were placed in a stream in the islands by using heavy equipment and hand labor. Our initial impression of the structures is that they are costly but may be effective in increasing fry survival. The study needs to be completed this winter to evaluate costs and benefits.

Our other study involved the replacement of 25 pieces of log debris in a stream heavily damaged by a debris torrent. The objective of the project was to determine if simple log placements in a stream could speed natural recovery of a stream following a torrent. Preliminary observations of scour pools created over the past winter suggest habitat complexity is increasing, and a definite pattern of increased pool area and meander length is emerging. The use of log barriers appears to be a promising technique that is much less expensive than artificial structures such as gabions.

CONCLUSION

The FisWForestry Interaction Program is compiling a significant data base on the Queen Charlotte islands that will enable managers to better understand the risk associated with steep-slope logging and effects on streams and forest areas.

The final results of the program will provide a clearer picture of the link between downstream channel responses and logging and help determine where and how to log marginally stable terrain within some level of acceptable environmental risk. An important task is working with industry and other user groups to ensure that the results of the program help to better manage the forest base.

The most important point I can convey to this audience is that joint ventures between cooperative agencies do work and work extremely effectively.

LITERATURE CITED

Gimbarzevsky, P. Regional overview of mass wasting on the Queen Charlotte Islands. FisWForestry Interaction Program WP 3/83. Vancouver, BC: Fish/Forestry Interaction Program; 1983. 34 pp.

Smith, R. B.; Commandeur, P. R; Ryan, M. Natural revegetation, soil development and forest growth on the Queen Charlotte Islands. Fish/Forestry Interaction Program WP 7/83. Vancouver, BC: Fish/Forestry Interaction Program; 1983.- 46 p.

HARVEST PLANNING AND LAYOUT ON STEEP TERRAIN—THE SIUSLAW MODEL

George Bush

ABSTRACT: In the early 1970's, the Oregon Wildlife Commission and several other special interest groups openly charged the Siuslaw National Forest with causing significant damage to fish and water resources as a result of harvesting of unstable slopes. Without local research data or any dependable theoretical models to apply to the problem, the Forest launched into one of the most intensive empirical modeling efforts ever made on unstable lands. The method used was based on the premise that inventoried landslides associated with specific management impacts on lands with carefully defined physical characteristics can be depended upon to occur in the future, providing management impacts and climatic parameters are similar,

INTRODUCTION

The United States Federal District Court in Eugene, Oregon will soon rule on the case of the National Wildlife Federation vs. USDA Forest Service (Mapleton Ranger District). The substantive issue in that case centers around the impacts of timber management on slope stability and ultimately on fish, water, and soil resources. The Forest's ability to prevent unlawful mangement-associated landslide damage was challenged. Part of the answer to that challenge was a display of modeled projections of landslide damage. The Forest argued that the data showed present and future reductions in impacts from what has been experienced, and that the damage would not be major. The Siuslaw's sophisticated modeling of future consequences of accelerated landslides is central to the defense of existing and planned timber harvest activities.

GEORGE BUSH is a soil scientist with the U.S. Department of Agriculture, Forest Service, Siuslaw National Forest, Corvallis, Oregon.

The real importance of this case is not just the ruling itself, but the apparent effect that legal recourse by dissatisfied interest groups will have on the Forest Service's attitude and approach to slope stability problems, Managers of unstable lands can no longer wait for perfect methods to analyze the problem and, of course, ignoring the problem is not an option.

This paper outlines the Siuslaw National Forest's approach to understanding and coming to grips with management effects on slope stability and the resulting impacts on Forest resources. The method is straight forward and simple, and very quickly provides basic answers to basic problems. The method is not entirely accurate, but can be very precise; and, in my view, precision is the most important element in comparative analysis of alternative actions. Other modeling methods may be used in conjunction with this one to increase accuracy, but the time to start modeling is now. The Siuslaw's method may be the best way to gain quick and defensible information on management-related impacts to unstable lands.

HISTORY

The Siuslaw National Forest went from knowing nothing, to suspecting something, to systematically analyzing evidence of landslide impacts over 11 years, Energy for doing something finally came from direct confrontation with the Oregon Wildlife Commission in May 1974. That was a period which I suspect Dale Robertson will not soon forget. As Forest Supervisor, Dale and his staff brought the Forest out of the dilemma in which it found itself by guaranteeing committment to solve the management problems on unstable lands that concerned the Wildlife Commission. The Siuslaw National Forest responded in this way for two reasons: first, sufficient external pressure was exerted on the status quo; and second, strong, focused leadership both then and now has demonstrated that only strong solutions to resource damage are acceptable regardless of the effects on the status quo, including timber targets.

First priority after setting the objective was proper staffing to attack the problem. Several soil, water, and fish specialists arrived and began working on finding ways to (1) understand, (2) display, and (3) mitigate or prevent the management impacts on slope stabilty and associated resource damage. No realistic theoretical models existed, so the empirical approach that uses evidence of past management effects began to develop,

METHOD

The method developed was based on the logic that landslide processes accelerated by particular management activities on carefully defined landforms will accelerate in the future at a similar rate providing the management impacts and climatic parameters are similar. If there is any segment of history which repeats itself in a regular way, it is the reaction of geomorphic processes' to environmental changes. By merely recording landslide rates associated with current management impacts without attempting to understand the interaction of the myriad of variables that caused them (as theoretical models attempt to do), the empirical modeler can effectively predict future landslide rates while avoiding some of the pitfalls of having a less than perfect understanding of all the processes involved.

Much of the data necessary to understand and display the effects that harvest and road construction activities have on slope stability already existed when the modeling effort began. It had unknowingly been recorded on resource aerial photos. A prototype aerial photo inventory of landslides visible in clearcuttings on 1972 resource photos was made in 1975. The first approach used the existing Soil Resource Inventory mapping and stability interpretations[1/] as a tool to begin to organize the landscape into high-risk and low-risk components. Each landtype delineation defined significant geologic and soil patterns that were linked intuitively to relative erosion potential. These qualitative interpretations of relative risk of landslides following clearcutting later proved to be accurate for all but a few of the more subtly unstable landtypes. This high level of accuracy was no accident. The risk analysis by the soil mappers was baaed on a basic understanding of geomorphic processes. The major difference between what the soil survey people did in making their interpretations and what the Siuslaw National Forest staff specialists have done since is systematization of the landscape and hazard rating processes, and utilization of more site specific data on landslide rates than had originally been accessible.

This first landslide survey, then, was used to determine the number of landslides per unit area clearcut in the most unstable lands on the "high risk" or most unstable landtypes. Average volume of landslides was determined by measuring length and width on the photos and assuming an average depth. A relative comparison of increased landslide rates within clearcuttings was made between alternative harvest schedules and levels of mitigation and prevention techniques in the 1978 Ten Year Timber Resource Plan[2/]. Road slides were initially ignored in the inventory and modeling process for two reasons. First, road slides had received intense interest for several years, and pressure to change had resulted in significant changes in design, location, and maintenance. The Forest felt it was correct in solving or mitigating road slides. Second, clearcut harvest-associated slides was a new concept to most of the Forest management team, who required the majority of available time to understand the magnitude of the problem and the potential for prevention or mitigation.

LANDSLIDE PREVENTION

Knowing expected landslide frequency per acre clearcut is only half the information needed to make planning decisions. The planner must also know how prevention or mitigation techniques will affect decisions about land allocation and harvest scheduling.

1/ Legard, Harold; Meyer, LeRoy; Badura, George; Boyer, Don. 1974. Soil Resource Inventory, Siuslaw National Forest, U.S. Department of Agriculture Forest Service, Pacific Northwest Region, Copy on file at Siuslaw National Forest, Corvallis, Oregon.

2/ 1978 10 Year Timber Resource Plan, Siuslaw National Forest, U.S. Department of Agriculture Forest Service, Pacific Northwest Region. Copy on file at Siuslaw National Forest, Corvallis, Oregon.

Predicting the reduction of accelerated landslides in clearcut units has been a major part of the modeling program at the Siuslaw, Landslide prevention techniques, whether for roads or timber harvest, are based on the premise that loss of internal soil strength resulting from management activity increases the potential for erosion (landslides).

In clearcuttings, loss of root strength is the major factor influencing accelerated landslide rates, Therefore, leaving the vegetation undisturbed on those sites most likely to require the added strength of the root system to prevent slope failure is the only practical way to reduce clearcutting-associated landslides, The Siuslaw landslide model predicts the reduction in accelerated slides by estimating the future effectiveness of vegetation leave areas in preventing landslides, Theoretically, if all sites that would fail because of lost root strength were left uncut, no accelerated slides would occur. Implementation of such a perfect program is clearly not possible. Several factors, including identifying and locating unstable sites, and logging, fire, and wind damage to vegetation leave areas reduce the implementation efficiency of the leave areas. Some percentage of accelerated slides occur regardless of best intentions, Reliable modeling of reduction of landslides by leaving unstable areas uncut requires an estimation of the influence these factors have on reducing the effectiveness of leave areas.

Estimation of efficiency of vegetation leave areas has been one of the weakest parts of our modeling process. Without much experience in using vegetation leave areas on unstable sites, there is little practical evidence to rely on. The only short-term solution has been to use professional judgment of field personnel to estimate the probabilities that leave areas will be effective. The estimates for each factor when multiplied together has resulted in approximately 50 percent efficiency for vegetation leave areas. Specialists applying this technique feel this is very conservative, but only several years actual experience with leave areas will provide us with an accurate accounting of the effectiveness of this practice. Putting off implementation until better information was available would result in no use at all. Only practical, on-the-job use of vegetation leave areas on unstable sites will ever lead to understanding their value. I wish more Forests would attempt to use the leave area concept so the knowledge would be strengthened and broadened. The trade off in timber harvest potential where leave areas are used is obvious: every acre left uncut to prevent landslides is removed from the productive timber base. Using the landslide model as a tool to project acres of vegetation leave areas necessary to meet minim resource protection requirements, we are projecting approximately 15 percent of the productive base allocated to no harvest.

EFFECTS ON OTHER RESOURCES

During the early stages of the modeling process, the effects landslides had on other resources including water, fish, and soil productivity were not clearly understood. The effects on fish habitat were estimated in a primitive model that predicted changes in fish habitat because of management accelerated landslides, The model assumed the major impacts of landslides to fish habitat were reduction in quantity of habitat (number of usable and accessible miles of stream) and amount of sediment in excess of natural or background levels, This model, too, had its greatest value in making comparative analyses, Fish habitat, as it was perceived in 1978, was compared, on an index scale, to habitat associated with several alternative management scenarios through 1988. A truely accurate accounting of sediment and other instream effects of landslides was, and is, too elusive to worry about, at least in these early stages of developing slope stability and fish habitat models.

The present generation of modeling has been geared to improving the accuracy of the assumptions used in the landslide and fish habitat models to increase the accuracy of our perceptions of the apparent effects forest management had on slope stablity and ultimately on the fishery resources. By periodic on-the-ground monitoring of landslides on a sample basis, improving the geomorphic classification of the landscape, and doing yearly landslide surveys, we are hoping to better shape our concepts of such things as:

1. Relative importance of road associated slides and clearcutting associated slides;

2. Percentage of landslides contributing to instream sediment;

3. Percentage of slides blocking fish passage;

4. Percentage of slides scouring fish-bearing streams;

5. Variations in landslide frequency resulting from different storm intensities;

6. Variations in landslide frequency between areas which are geomorphically different; and

7. Actual effectiveness of vegetation leave areas for preventing clearcut harvest associated slides.

Random sampling of fish-bearing streams and specific research information on the importance of sediment, organic debris, and fish blockage have also fine tuned the precision of the fish habitat index scale. The assumptions are now more defensible and the relative importance of the various effects of accelerated landslides has been clarified. Predictions of absolute changes in habitat and fish production are still lacking.

APPLICATION TO PLANNING

A fundamental improvement in the application of the Siuslaw slope stability and fish habitat modeling techniques has been the continuing development of the land systems inventory. It is patterned after the system developed by USDA Forest Service in the Northern and Intermountain Regions. The system we use allows for a hierarchial organization of lands according to similarities in climate, bedrock, dominant erasion processes, landform, soil, and vegetation. The existing Soil Resource Inventory landtypes mentioned earlier have been grouped within the hierarchy to clarify the relative amounts of high- and low-risk lands between major portions of the Forest that have basic geomorphic and management opportunity differences. The system also groups areas similar in fish habitat potential and hydrologic response. Without a solid land systems inventory, landslide surveys and models made from them have limited value in the planning process. Generalization of gross averages of accelerated landslide rates across the Forest is too broad for even forest-wide planning because it masks important local differences. On the other hand, landslide data for each individual landtype is far too specific to be effectively used for most levels of planning.

I stress planning applications for this sort of modeling for several reasons. On-site decisions about management on unstable lands cannot be made with data that does not account for microsite variations. Project or on-site decisions about slope stability always must be made with that magical combination of theory, on-site stability indicators, and undefinable vibrations that cane up through the soles of the feet of any qualified slope stability expert.

Empirical modeling of landslides is most successful when important measurable effects of management activities and variations in climate are understood. We are very far from having that sort of knowledge. As the planning cycle repeats itself, monitoring of project implementation efficiency and effects of projects on slope stability is accomplished, and better information on climatic variables becomes available, the precision of the predicted impacts will become better and better. Without a start, even with the meager data available, improvement is a meaningless word. Modeling involves risk, regardless of the technique, but there is greater risk if modeling is not done.

It seems there are three ingredients necessary to successfully develop an effective model of management effects on slope stability: (1) pressure to work on the problem, (2) a way to work on the problem, and (3) committment to work on the problem. The first is painfully here; the second you are hearing about at this symposium; the committment must come through you.

USES OF SOILS, VEGETATION AND GEOMORPHIC INFORMATION FOR ROAD LOCATION AND TIMBER MANAGEMENT IN THE OREGON COAST RANGES

Byron R. Thomas

ABSTRACT: Five major factors affecting slope stability are soil shear strength, soil depth, slope gradient, soil water, and root strength.

Soil shear strength is best determined by engineering tests conducted in the laboratory; however, it may be estimated in the field by using soil survey information in conjunction with conversion charts or by back calculation. Soil depth and slope gradient are determined directly by field measurements or interpretation. Soil water depth may be measured, modeled, or inferred from soil properties and geomorphic location. Root strength is inferred from research data correlating root decay over time since trees were felled.

At a qualitative level, some very effective assessments of occurrence or importance of these factors can be made by careful field observation and the use of aerial photos. Vegetative indicators provide many clues to soil wetness and incipient failures. These include Occurrence of hydrophytic species and tipped or "crazy" trees. Bedrock topography that concentrates ground water may be readily identified in the field or with stereo pairs of photos. Geologic features such as fault zones or formations with known zones of weaknesses provide important information about stability to field personnel.

INTRODUCTION

A common type of landslide in Oregon's Coast Range is the debris avalanche or infinite slope failure. Working knowledge of factors contributing to instability and on-site clues for potential landslides is required by those laying out and designing roads and timber sales if these types of problems are to be minimized.

BYRON R. THOMAS is Principal soil scientist with the U. S. Department of the Interior, Bureau of Land Management, Oregon Office, Portland, Oregon.

FACTOR ASSESSMENT

To effectively evaluate slope stability, a person needs background information about geology, climate, and soils in the area of interest. For example, geological and soil properties greatly influence soil mantle stability. The failure surface commonly occurs at the soil-bedrock interface or within the soil mantle. Soil shear strength cannot usually be determined accurately without testing. Test results may be extrapolated, however, to areas of similar geology and soils for the purpose of evaluating potential landslide areas. Technical papers and books describe procedures to estimate soil parameters for nonplastic soils. Another empirical method is to measure appropriate factors from existing landslides and solve a mathematical equation for shear strength.

Soil water is often the critical key to instability. Landslides occur most often during periods of intense rainfall or rapid snow melt. The reason for this is that water within the soil accumulates over the bedrock surface, or other impermeable boundaries, in hillslope hollows. The result is that the pores in the soil become full and provide an uplifing force on the soil mass as a result of the buoyancy effect. This uplifting force becomes greater as more water accumulates in the soil. This saturated mass is more easily pulled downslope by the forces of gravity.

Many times areas subjected to soil water accumulations may be identified in the field by occurrence of hydrophytic vegetation, soil characteristics, and geomorphic position.

Importance of roots in mantle stability has received considerable attention. It is generally accepted that a network of roots strengthens the soil mantle just as reinforcing bars strengthen concrete. Larger roots also function as piles when they penetrate into cracks in bedrock. When these piles are close enough, they also function to strengthen the slope by preventing soil from sliding between them. Studies have shown that landslide frequency often increases 2 to 8 years after trees are cut. This is the time frame in which smaller tree roots decay and weaken. Decaying roots per se cannot be observed. An inference may be made from time since felling when related to other factors that influence landslides. Conceptually, if soils stay in place in areas that should be unstable or should have already failed, then root strength may be the factor holding the soil mantle in place. Root strength decline should also be considered when portions of clearcut units start failing.

FIELD INDICATIONS

The following photographs show examples of clues to instability that may be observed in the field. An important item to keep in mind is that there are usually multiple clues to potentially unstable areas, Each picture and caption focuses on one clue.

Figure 1.--Seeps and springs. Standing water on the soil surface demonstrates that soil water is at or above the ground level. The entire soil profile is considered to be saturated for purposes of calculating mantle stability.

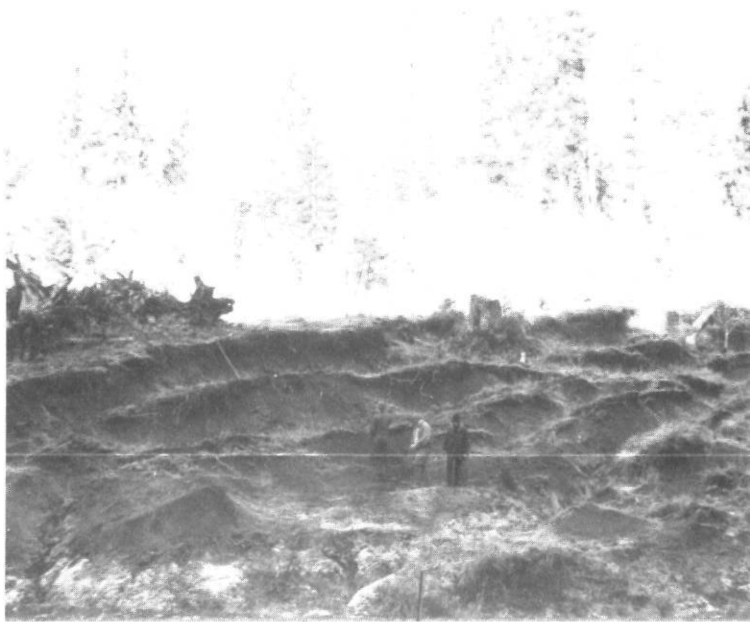


Figure 2.--Presence of hydrophytes (upper left). Hydrophytes indicate high levels of soil water. Hydrophytic species need to be defined locally. For example, a dense stand of sword-fern may denote wet conditions for some geographical areas and not others.

Figure 3.--Msadows (upper right). Natural meadows may be a clue to instability due to soil wetness. One should especially be concerned with those occurring on slopes surrounded by coniferous trees.

Figure 4.--Black soil surface (lower left). Importance of a thick, very dark colored, soil surface needs to be determined locally. These types of surface soils may or may not be important when looking for clues to soil wetness. The black surface is a result of incorporating large amounts of organic matter. A high soil moisture regime is conducive to high vegetative production.

Figure 5.--Gleyed or mottled soil. A gleyed soil exhibits gray or bluish colors because iron is reduced chemically. A high water table usually occurs continuously or for long periods of time annually in gleyed soils.

Mottled soils are similar to gleyed soils except water is thought to rise and fall several times annually. Rising and falling water tables create alternate reduction and oxidation of soil iron. Mottles are characterized by splotches or streaks of gray, red, orange, or yellow. Height of the highest mottle is assumed to indicate the highest annual water table rise. Mottled colors are not continuous in soil, but are quite distinctive.

Figure 6.--Sag ponds. Sag ponds, like seeps and springs, indicate concentrations of water at the ground surface. Sag ponds are created when the hillside slides downslope, rotates outward, and leaves a depression between slump material and the scarp, or back edge, of the failure surface.

Figure 7.--Piping. Water piping from a road cut or structure shows that free flowing water is being concentrated along open pore spaces within the soil mantle or road prism material. This may indicate the presence of a water table at least as high as the point of exit. It may also indicate a confined zone of concentrated flow under substantial hydrostatic head.

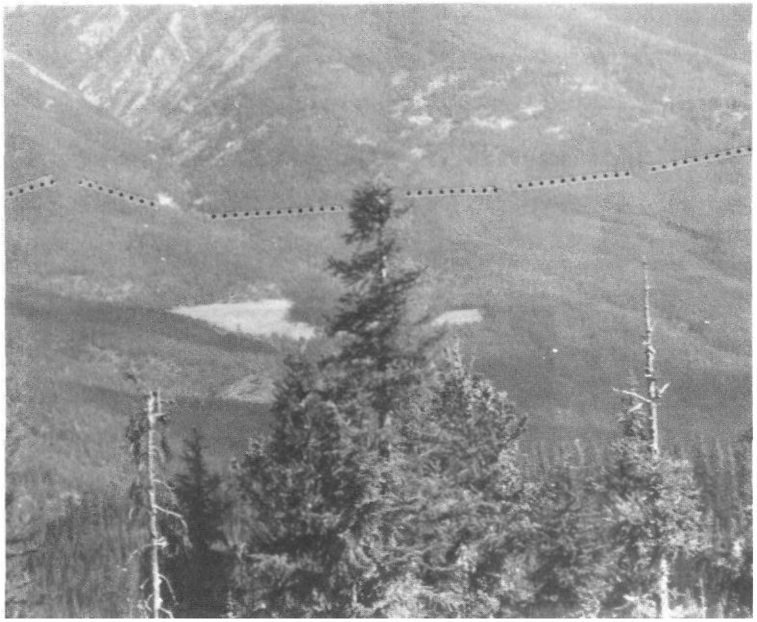


Figure 8.--Fault zones (upper left). Faulting causes bedrock to break and shear, which results in a weakened zone (see dotted line). These weakened zones are often areas of concentrated subsurface water movement and are the source of slope failures, especially when disturbed by road construction. It is not uncommon for the entire road prism to fail.

Figure 9.--Pockets of colluvium (upper right). Competent bedrock is absent in pockets of colluvial material. These "pockets" accumulate ground water from adjacent areas as well as material from soil creep. The surface depression is the only clue to such a situation during field reconnaissance. Not all depressions denote such a situation. Geophysical exploration (seismograph) aids in quantifying subsurface conditions.

Figure 10.--Conglomerates (lower left). Serious stability problems, especially after road construction, occur in conglomerate bedrock in parts of Oregon's Coast Range. Road cuts and fills may slump away. Steep slopes are not a prerequisite for movement in these materials. Not all conglomerates are unstable.

Figure 11.--Tipped, jackstrawed, or crazy trees (upper left). Tipped trees provide solid clues that the mantle is presently moving or has moved during their lifetime. Of course, disturbing an actively moving mantle is risky.

Figure 12.--Curved tree butts (upper right). This clue has to be tempered by additional investigation or knowledge of the area. Butts of young trees also become curved from snow creep. Curved butts in conjunction with other clues or geomorphic location provide a helpful index to stability.

Figure 13.--Tension cracks (lower left). Tension cracks provide physical evidence the soil mantle has slipped and a failure plane has been established. Proceed with extreme caution.

Figure 14.--Hummocky surfaces (upper left). An irregular, hummocky surface shows that the soil mantle has been undergoing forces which cause deformity and movement. These are risky locations for roads without proper investigations and design for the situation.

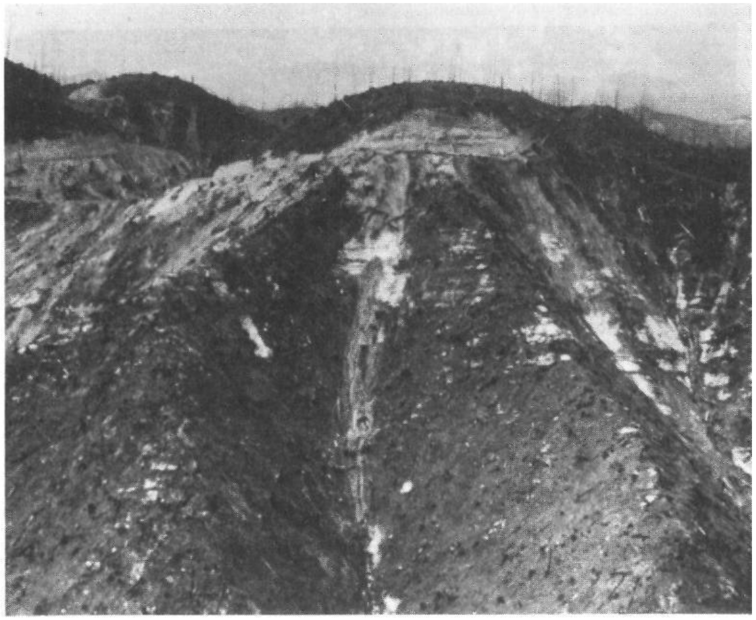
Figure 15.--Terracettes (upper right). Terracettes are a series of multiple failures. Older terracettes usually have more gentle scarps because the raw, exposed edges have fallen. Again, the clue denotes active movement.

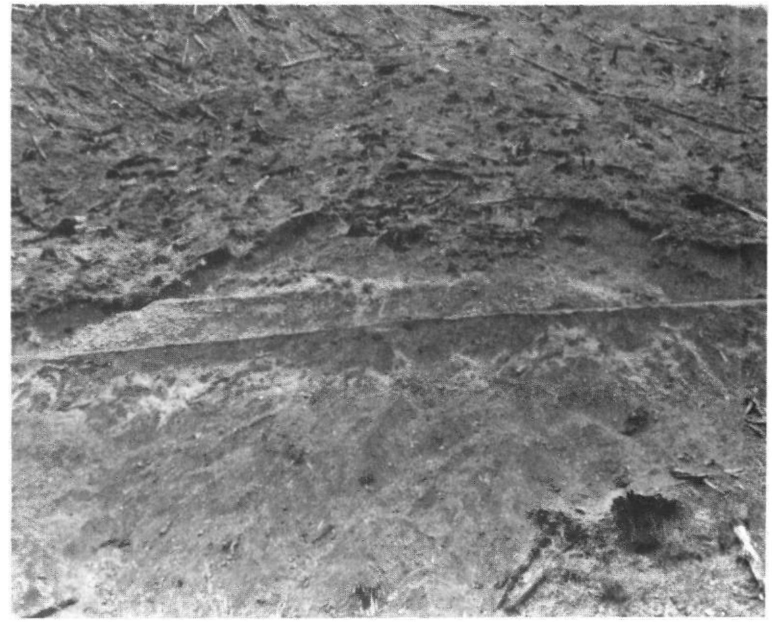
Figure 16.--Streambank overhang (lower left). The item to watch for is the difference between streambank overhang caused by lateral stream movement and soil mantle that is sliding or creeping downhill into the stream. Differentiation between the two at a local site may not be possible. One needs to look at the overall area, particularly upslope. Other clues associated with instability are usually present.

Figure 17.--Downslope depressions or pockets of residual soil resulting from weathering in multiple joints (upper left). (A similar depression is shown in figure 9). Genesis of the two may be different but the surface configuration is about the same. The major item to be aware of is that a depression on a sideslope may indicate a pocket of transported or weathered material. The pocket accumulates ground water, weathers faster, and may lack competent bedrock near the surface.

Figure 18.--Spoon-shaped depression (upper right). It is common for earth flows to be associated with a spoon-shaped depression. Subsidence occurs as the material flows downslope. These areas commonly are acres in size.

Figure 19.--Bedding planes parallel to surface (lower left). Bedding planes parallel to a sloping soil surface are oriented during uplifting of the bedrock. This surface provides a sloping interface of soil and seepage water on top of, and within, bedrock.





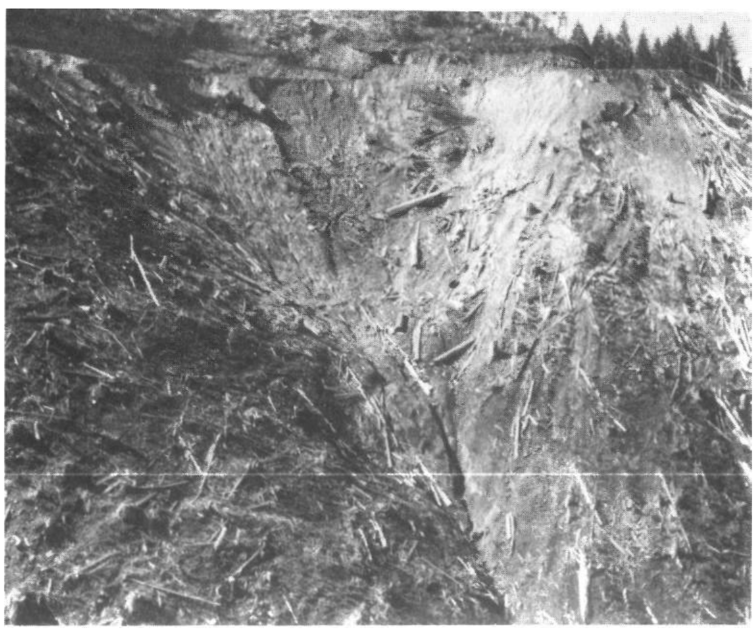


Figure 20.--Very steep slopes (upper left). Some slopes are so steep that soil material is at a critical balance Disturbance by fire, road construction, or logging may cause the mantle to slide. Bedrock is commonly exposed in such areas.

Figure 21.--Old slumps (upper right). Many old slumps have stabilized over geologic time. Removing the toe of these slumps, as shown in the figure, often results in reactivating movement.

Figure 22.--Drainage headwalls (lower left). This figure shows a classic situation where sidecasting in a steep headwall resulted in a slide. Headwalls are very sensitive because of their steepness and ground water concentrations. One would not want to place crossdrain culverts in such positions nor sidecast common material during road construction. Note the backslope has also failed.

Figure 23.--Failure from accelerated weathering of soil material. Natural weathering of the bedrock does not occur at a uniform rate across a slope. Some spots are weaker (fault zones for example) and form a depression where ground water accumulates. These processes hasten weathering and usually form incipient drainages. Over geologic time, weathered material (soil) or colluvium will slide or wash out. The light areas along the channel in this photo are exposed bedrock surfaces from which soil has been removed by slumping. Note accumulations of soil and debris in the channel bottom. This figure shows how areas shown in figures 9 and 17 look after failure. A "slickrock chute" remains after soil material is removed.

Figure 24.--Land overhang. It is not uncommon for landings to be constructed in such a manner as to have sidecast material form very steep slopes. This is a poor construction practice. This problem is often compounded by piling cull material on the edge. The edge of the landing can fail causing damage on and off site.

ACKNOWLEDGMENT

The author is indebted to Dr. Edward R. Burroughs of the USDA Forest Service, Intermountain Forest and Range Experiment Station, Bozeman, Montana, and various Bureau of Land Management soil scientists working in the Coast Range of Oregon for providing many of the pictures;

ROAD LOCATION IN SENSITIVE WATERSHEDS:

AN INDUSTRY PERSPECTIVE

S. H. Duncan

ABSTRACT: The identification of potentially unstable areas for road location and harvest planning in sensitive watersheds can be done at three levels of resolution. The broadest level involves the use of soil survey or geologic maps and is useful in general identification of particularly sensitive areas. Once the sensitive areas are identified, the second level of resolution recognizes individual landscape units and notes particular slope stability charcteristics as the basis for general management recommendations. The third level must be accomplished on site at the time of road and landing location. At this point, fairly specific construction recommendations can be outlined.

INTRODUCTION

Stability of forest land is a highly valued condition. If all the land were stable, forest practice activities could be pursued with little concern for slope failures. Unfortunately, this is not the case. A large enough portion of Pacific Northwest forest lands are of sufficiently low inherent stability to warrant concern. Although instability of forest slopes has received considerable research attention, most of the studies have emphasized how human activities influence the integrity of the slope and affect mass wasting processes and soil loss. Far less research has been devoted to examining cost effective ways to manage lands of questionable stability. Because of this it is difficult to assess the effectiveness of specific harvesting and road building techniques that have potential as economically and environmentally sound management alternatives. Even less effort has been given to technology transfer and development of credibility with the field engineer or forest manager.

The prudent forest manager knows where the most productive lands are located, how much area is in each site class, and the species compositon of the forest stands on those lands. Because of the interaction of forest management activities with other resources, the forest manager must also be cognizant of unstable lands and the potential environmental and economic risks they pose, and be able to implement realistic management alternatives.

The purpose of this paper is to review a method for identifying unstable lands and implementing suitable technology on them. Emphasis is placed on interaction with individuals, from the tree farm manager to the equipment operator, to develop confidence in current technology and the awareness necessary in economically sound and environmentally effective forest land management. Considerations for future slope stability research and technology tranfer are also discussed.

S. H. DUNCAN is an environmental geologist at the Weyerhaeuser Company Technology Center, Tacoma, Washington.

TERRAIN CLASSIFICATION

Three levels of terrain classification are beneficial in identifling areas of varying slope instability for harvest unit planning: (1) identification of key soil and lithologic units; (2) identification of specific geomorphic units, which can be assigned relative stability classes; and (3) site-specific identification of potential slope instability along a proposed road location line.

Various terrain classification schemes have been used to identify areas of relative slope stability conditions. Quite often slope stability considerations have been secondary or have been made to fit an inventory system designed for another purpose. The most widely used medium of this type is the soil survey. Although seldom specific enough for detailed identification of slope instability, a soil inventory can furnish useful information on local lithology, soil physical characteristics, and geomorphic units. Broad levels of slope. stability can be assigned to these soil inventories, making them useful for broad planning purposes.

The next level of resolution is a more detailed inventory at a scale compatible with local forest or timber sale planning. Such an inventory should identify microgeomorphic units or hill-slope elements (such as concave pockets, seepage areas, and rock outcrops), and local slope gradient. Thus delineated, these terrain units can be assigned relative slope stability designations. When combined with a topographic map, this inventory becomes the basic planning tool for the logging engineer.

Bourgeois (1978) described a terrain inventory system designed specifically for slope stability purposes. Used in western British Columbia, the system incorporates both soils and geomorphic units to which five slope stability classes are assigned and guidelines to minimize environmental impacts are proposed.

Similar systems are in use by governmental and state agencies, but all lack the site specificity often required by the field engineer. Although uniformly desirable, accurate on-site identification of potential stability conditions along a road location line often depend on the specific training of the road location engineer. At Weyerhaeuser Company, a checklist of topographic, soil, climatic, hydrologic, and geologic factors similar to that proposed by Swanston and Swanson (1980) in the WRENS document was developed to assist in on-site identification of potential problems. While far from a prediction system, it enables the road location engineer to consider slope elements and slope-forming processes, thus examining the hill slope differently than he normally would. Once identified, a suspected problem site can be avoided, an extraordinary design implemented, or further study done to assess management alternatives.

Detailed investigations of slope instability are both timeconsuming and costly and can be limited to highly sensitive sites identified in the first level of slope stability identification discussed above.

For the purpose of this discussion, a sensitive area or site is defined as a site consisting of soil and geologic units that are naturally susceptible to slippage where damage to a public resource or private property could occur. This greatly reduces the area of land that seed be considered, even though other lands may be classed as sensitive for different reasons.

Many sites that fit the above definition are already known from past experience; if not, an interpretation by someone trained in soil and geology may be required, What is important is that broad slope stability classifications and accompanying "fit-everywhere" interpretations are avoided. They are often as much in error as they are correct and frequently result in unnecessary and costly practices.

IMPLEMENTATION OF TECHNOLOGY

Sensitive area identification, soil and geomorphic mapping, planning, and just plain "geologizing" by technical experts is of little value unless the technology is implemented. The most important part of implementing slope stability technology in forest management is to work with individual managers, engineers, and foremen to develop an awareness and ability to recognize: (1) if a problem exists; (2) if a need for a different approach exists; and (3) where to go for assistance. At the same time a confidence in and acceptance of geotechnical information must be established, Educational seminars and field workshops are important first steps in accomplishing this task, as are field guides and other aids; but if at all possible, a close working relationship with a geotechnician **should** be established.

Once the need for the slope stability information at a particular site is recognized and a plan developed, the next problem facing the geotechnician is recommending practices that represent cost-effective alternatives. At this point there is a problem. While most geotechnicians have the ability to identify potentially unstable sites, to define the type of problem that is likely to occur with sane accuracy, and even to suggest some possible design solutions, there is little factual data on cost-effective design and construction techniques for low-volume forest roads. On sane sites there is no easy solution; whatever is done simply costs money. At other sites problems can often be avoided by maintaining a flexible design arid construction policy whereby the road is tailored to fit specific slope conditions. For a flexible design and construction policy to be effective, there must be a high level of awareness and flexibility on the part of the construction foreman, project engineer, and specific regulatory agency.

The value of high individual awareness is possibly most evident in the area of road maintenance. After examining large numbers of road-related slope failures in the Pacific Northwest, it is evident that the largest single cause is lack of adequate storm water control. The USDA Forest Service has a storm watch program in many forest districts where critical areas are patrolled to ensure continuing operation of drainage structures. Weyerhaeuser Company initiated a forestry road maintenance program several years ago whereby special budget appropriations are made for maintenance and repair of the nonoperating road net. Both of these programs have greatly reduced the incidence of storm water-induced road failures, but more needs to be done. Road maintenance is a never-ending and costly proposition and, like slope stability, is most beneficial when emphasis is concentrated in sensitve areas.

A LOOK AT THE FUTURE

Up to this point the forest industry has been concerned with locating, designing, and constructing roads to serve as transportation routes for harvest of the old-growth forest, Operating in this environment affords more flexibility in road expenditures than is possible in harvest or thinning operations in the second-growth forest. Although much of the second-growth ready for harvesting now and within the next decade is located on lower elevation lands, many of these sites are highly productive and have their own particular slope stability problems. The primary road systems are usually in place, but many are old railroad routes that often require considerable reconstruction. In some cases construction of additional secondary systems is required for the roads to be compatible with modern raw material handling techniques.

Although the same principles and practices currently used to identify areas of potential slope instability will suffice for second-rotation management, the real challenge is in the development of construction and harvesting technology compatible with economic and environmental constraints, and the effective implementation of this technology in the field.

There is, and will continue to be, a need for development of site-specific slope stabilty assessment methods that the field engineer can apply during road location and construction. Although present use of such methods usually requires a person with specific training in earth sciences, the methods are not as successful as they might be if applied by the field engineer. It is necessary to continue to work on development of techniques that allow the engineer to assign site-specific indices of relative stability along a proposed road location line.

Research into ways to construct roads on lands of inherent instability in an economically and environmentally effective manner would be welcomed by forest managers. Before more research dollars are committed to new methods we should "dust off" existing technology and if applicable, scale it to the environment of the low-volume road. Whatever technology is developed it must be introduced in a form palatable to the intended user and confidence must be established in its effectiveness, Specific technologies are often introduced to the user via the regulatory process, Experience has shown that technology transmitted by regulation will most likely not be effectively utilized and may, in fact, create skepticism and disbelief in what may be a sound practice. Most important, those who work in applied technology, and especially the inexact geological sciences, must stress personal contact to develop credibility with field and management personnel.

LITERATURE CITED

Bourgeois, W. W. Timber harvesting activities on steep Vancouver Island terrain. In: Youngberg, C.T., ed. Forest soils and land use: Proceedings of the Fifth North American Forest Soils Conference; 1978 August; Fort Collins, CO. Fort Collins, CO: Colorado State University; 1978: 393-409.

Swanston, D. N, Swanson F. Chapter V, Soil mass movement. In: An approach to water resources evaluation of non-point silvicultural sources.EPA-600/8-80-012. Athens, GA: U.S. Environmental Protection Agency; 1980: 49p.

LANDSLIDE DISASTER ASSESSMENT IN THE WASATCH RANGE

Paul Winkelaar

ABSTRACT: During spring 1983, extensive flooding from snowmelt occurred along the western slopes of the Wasatch Range in Utah causing widespread damage in the major population areas around Salt Lake City. Historically, damaging floods in this locality have occurred during isolated and intense summer thunderstorms. In contrast, the floods of 1983 were caused by wet periods that saturated the soils in autumn 1982 followed by heavy winter snow, a prolonged cold spring and sudden high temperatures in May 1983 that produced rapid snowmelt. This is a new phenomena.

USDA Forest Service specialists on three separate advisory teams made helicopter reconnaissance flights twice daily for 3 weeks to map slides and mud flows, and to identify current or potential problems for downstream areas. The teams analyzed data from the reconnaissance flights and from ground operations, developed inundation hazard maps of flood plain areas likely to be affected, and transmitted this information daily to county administrators so appropriate measures could be taken to provide for public safety and to minimize property damage.

INTRODUCTION

During spring 1983 extensive flooding from snowmelt occurred along the west side of the Wasatch Range in Utah. Numerous debris flows and debris floods resulted from the many landslides on the steep hill slopes along the canyons, and caused approximately $300 million in damage.

The Forest Supervisor of the Wasatch-Cache National Forest, Salt Lake City, mobilized technical specialists in three separate teams to provide assistance to local governments and officials in Davis, Utah, and Salt Lake counties, Utah, and in Uinta County, Wyoming. The role of the Davis County team is explored in this paper. The area discussed is the flood area along the Wasatch Range between Mill Creek Canyon and Hobbs Canyon (fig. 1). The towns affected were Layton, Fruit Heights, Kaysville, Farmington, Bountiful, Woods Cross, North Salt Lake, and Centerville,

Approximately 100 landslides that occurred in 22 canyons were monitored and mapped during the two helicopter flights per day between May 29 and June 16, 1983. During the summer months following the floods many landslides were checked and soils examined in the field in an on-going soil survey of the area.

HISTORY OF FLOODING IN DAVIS COUNTY

Davis County pioneers began to establish homes and farms along the steep mountains of the Wasatch Range in 1847. After years of

PAUL WINKELAAR is a soil scientist with the USDA Forest Service, Intermountain Region, Wasatch-Cache National Forest, Salt Lake City, Utah.

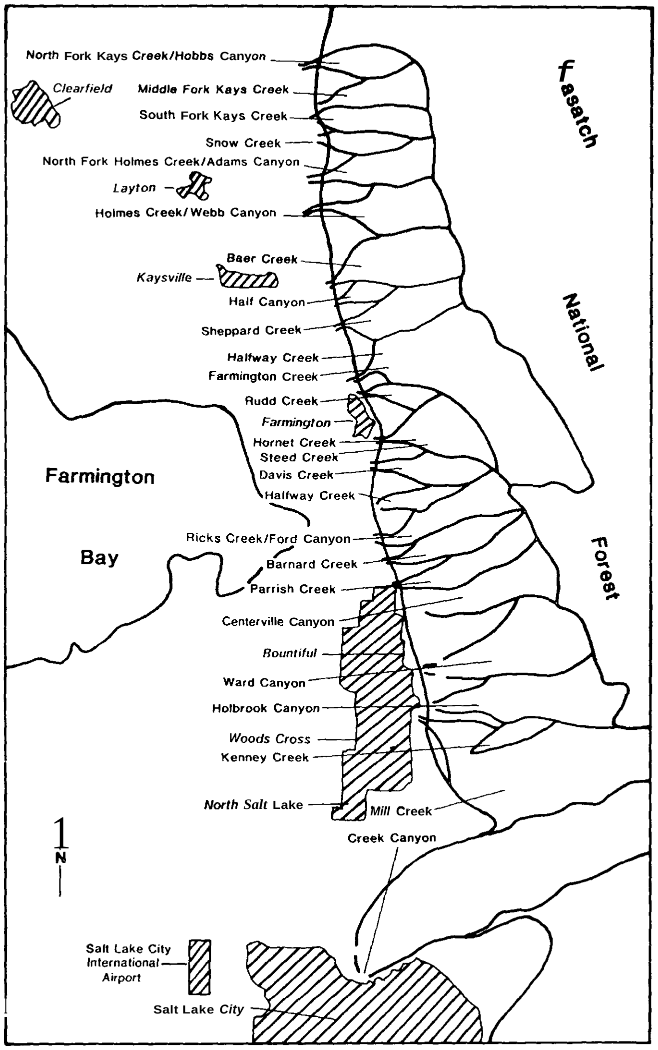


Figure 1.— Planimetric map of the western edge of the Wasatch Range, Utah, between Mills Creek Canyon and Hobbs Canyon showing the area subject to flooding in spring 1983 (Federal Emergency Management Agency, 1983).

overgrazing and frequent fires, the upper watersheds were devoid of vegetation and rains from intense summer thunderstorms produced repeated floods at the canyon mouths. Major floods occurred in 1878, 1901, and 1906, and became more intense and damaging in 1912, 1918, 1923, and 1930.

A flood control commission was established after 1930. This appointed commission recommended a program of increased fire protection, restricted grazing, contour trenching, and reseeding and planting to restore the surface cover in the watersheds. Debris basins were designed to trap sediment from the canyons. As the vegetative cover reestablished, the runnoff from intense summer storms became less damaging, and housing developments replaced fruit orchards and farms at the canyon mouths.

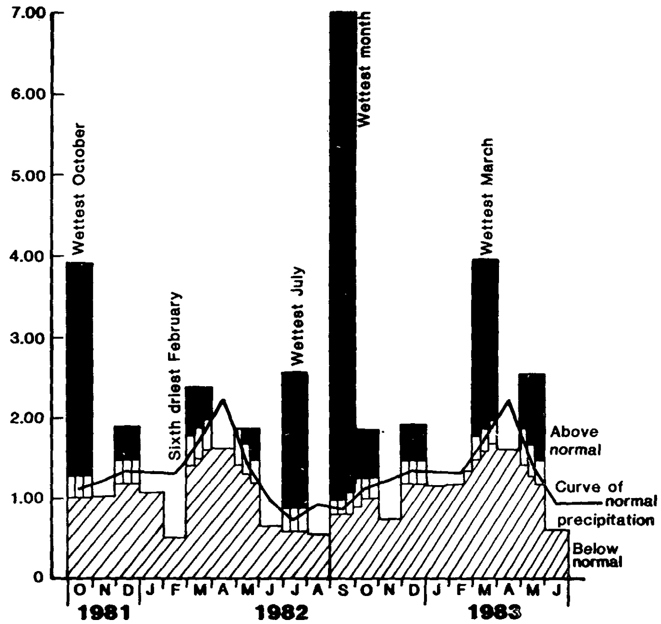


Figure 2.—Monthly precipitation record from the Salt Lake City International Airport for the period of October 1981 through June 1983. The 30-year normal precipitation curve is shown by the solid line. Note that for the 21-month period, four monthly precipitation records are set, October 1981, July 1982, September 1982, and March 1983 (National Weather Service, 1983).

RECENT EVENTS

The mudflows and debris floods in Davis County in spring 1983 were very different from the events of the 1920's and 1930's. The early events were caused by human activities at high elevations in the upper portion of watersheds. The spring 1983 flooding was a natural event and occurred on low to mid elevations within the watersheds. The contour trenches at the upper elevations continue to protect the communities along the range from the intense summer thunderstorms.

As a result of the spring 1983 flooding, there has been a significant change in the Forest Service role in managing the Davis County watersheds. In the past 40 years efforts have focused on fire suppression, maintenance of contour trenches,, and the protection of the watersheds from grazing. In spring 1983, Forest Service specialists were directed by the Forest Supervisor to assist the Davis County Emergency Services. Daily flights were made of the watersheds in a Forest Service helicopter to monitor and identify new landslide activity and to evaluate hazards. The Forest Service also provided technical information to the Federal Emergency Management Agency for their assessment of future mudflow and flood risk potential. This information will continue to be made available to Davis County as it is needed to protect life and property.

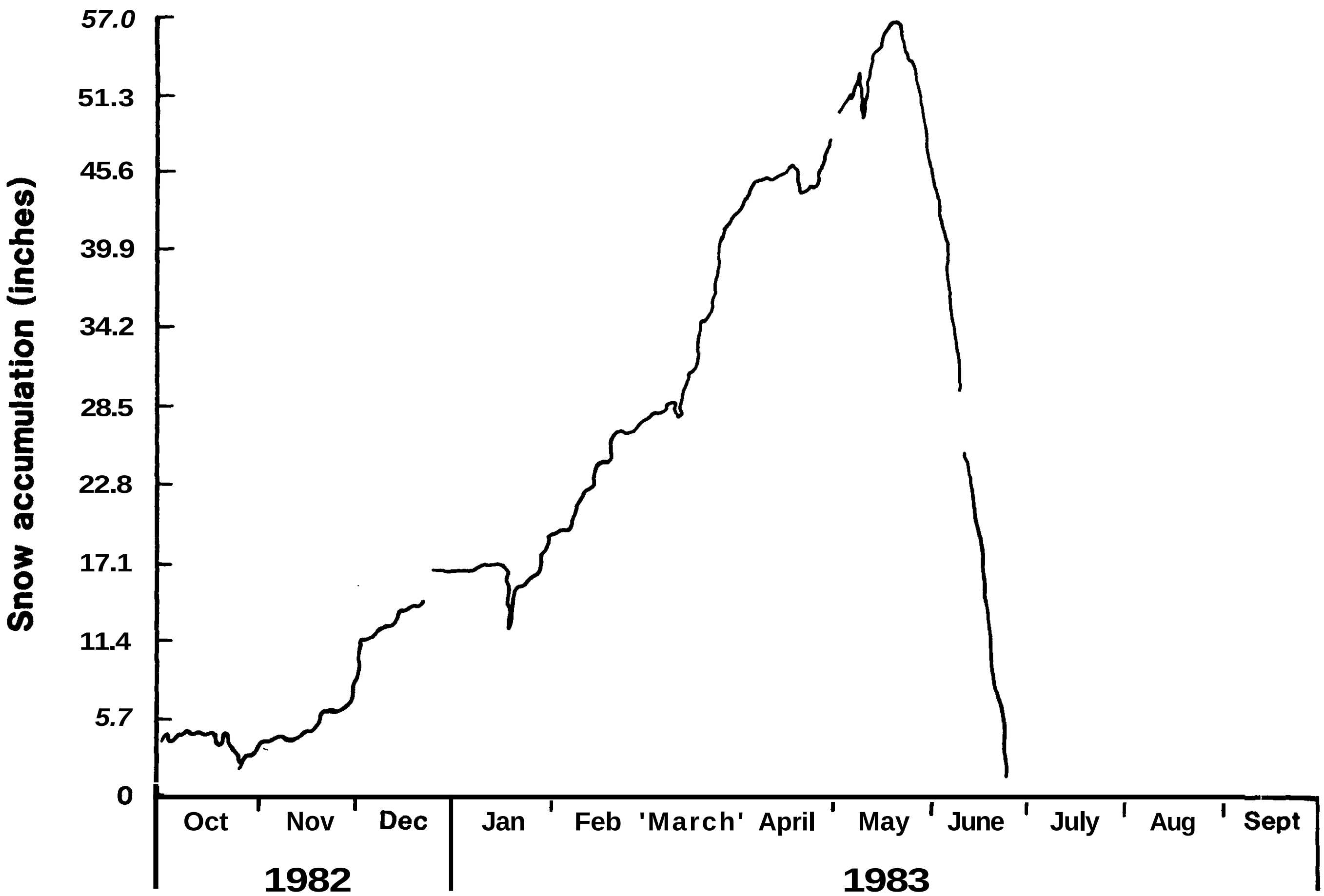


Figure 3.—Snow accumulation (water equivalent) at the 8,010-foot elevation in Farmington Canyon, Utah, for the 1983 water year (October 1982 to September 1983). Snow continued to fall through the middle of May, peaking on May 19. This is about 1 1/2 months past the normal peak around April 1 (National Weather Service, 1983).

CONDITIONS LEADING TO THE 1983 DISASTER

The severely unstable soil conditions that prevailed along the Wasatch Range from April through June 1983 began in the water year of 1981-1982.[1] It was the wettest year in over 100 years of record in the Salt Lake Valley (Kaliser, 1983; National Weather Service 1983). Annual precipitation was 10 inches above the 30-year normal. For the 21-month period from October 1981 through June 1983, four monthly precipitation records were set: October 1981, July 1982, September 1982, and March 1983 (fig. 2). The one "century storm" that saturated the soils in autumn fell in the later part of September with rainfall ranging from 11 to 13 inches across the Wasatch Range.

The heavy winter snow of 1982-1983 compounded the problem (fig. 3). The snow continued to fall through the middle of May, in fact peaking at this time. This is about 1-1/2 months later than the normal snowfall peak around April 1. A 20-inch snowfall at Alta, Utah on May 19, 1983, elevated the winter snowfall there to a record 805 inches. It was estimated that there was from 40 to 60 inches of water in the snowpack at about the 8,000-foot elevation.

Between May 27 and May 31, temperatures rose into the 80's and lower 90's (°F). This accelerated the rapid runoff from the snowpack. During the week following the Memorial Day weekend, moderate or heavy thunderstorms aggravated, the already serious situation.

MAJOR EVENTS IN THE WASATCH RANGE IN DAVIS COUNTY

May 25, 1983 Centerville Creek spilled over its banks.

May 26, 1983 Sudden hot weather initiated the crisis. Flooding began in Salt Lake City. Slides occurred in Big Cottonwood Canyon.

May 27, 1983 Mill Creek flooded in West Bountiful along the Union Pacific

[1] A water year begins in October.

tracks and on 5th Street South. Flood waters cut a hole 60 feet wide and 20 feet deep in Bountiful's Lakeview Drive. Nursing homes evacuated as water broke through dikes and crashed against buildings.

May 28, 1983 Barnard and Ricks Creeks flooded, and damaged homes in Centerville. Water from Barton Creek finished washing out Lakeview Drive and broke sewer lines in Bountiful. Homes and businesses along Stone Creek were also flooded.

May 29, 1983 A mudslide down Bigler Creek took out 30 yards of road in Farmington Canyon.

May 30, 1983 A 20-foot-high mudflow descended on Farmington. Mud covered a 9-block area and 250 people were evacuated. Twelve homes were damaged and six destroyed. Lagoon resort was forced to close by the threat of the mudslide.

May 31, 1983 The Interstate-15 frontage road west of Centerville was forced to close. Water from Rick's Creek in Centerville caused a pond to break out of its banks, sending a flood of water through the Willow Creek subdivision. Water and mud cascaded down Stone, Barton, and Mill Creeks in Bountiful inundating 250 homes with a pudding-like mud. Three homes were destroyed, 11 had major damage and 450 people were evacuated. A second mudslide out of Rudd Canyon in Farmington demolished some homes and damaged others forcing the evacuation of many residents. Stone Creek in Bountiful swept 1,800 gallons of tranformer oil containing toxic PCB into a basement.

June 1, 1983 A 25-foot wall of water rushed out of Stone Creek forcing the evacuation of hundreds of families. Several families in Fruit Heights area were forced to evacuate because of a slide threat.

June 7, 1983 A large slide slowly started moving down Coldwater Creek Canyon into North Ogden forcing evacuations.

LANDSLIDE CHARACTERISTICS

An oblique sketch of a typical debris flow from a steep canyon wall in the Wasatch Range is shown in figure 4. The geology of the Wasatch Range in Davis County is dominated by the Farmington complex. The gneiss and schist that constitute most .of this unit have been extensively weathered resulting in coarse-grained granular soils that include zones of silt and clay. Most of the landslides that were mobilized as debris flows failed at the base of the coarse- and medium-textured soil at the rock interface,

Many slides also showed positive pore pressure zones in their headwalls which was caused by greatly increased amounts of groundwater from rapid snowmelt. After failure, excess water continued to flow freely from the headwalls and formed surface streams, a phenomenon that could be readily observed during the reconnaissance flights. In summer many landslide headwalls were still seeping in these positive pore pressure zones.

Following initial failure, many landslide zones developed cracks above the headwalls, and many detached soil masses consequently remain on the slope. These areas, in particular, were monitored and checked daily. Such areas could, if mobilized, produce debris slides and jams and cause the dangerous, damaging surges of debris flows or debris floods in the stream channels.

Most of the landslides developed on north- and south-facing slopes, with a few on upper west-facing slopes. The canyon terrain is very steep with slope ranges between 60 to 90 percent.

The vegetation is mainly stands of maple, scrub oak, and aspen with open areas of grass-sage-shrubs on south-facing slopes. Dense stands of Douglas-fir and small stands of aspen are on the north-facing slopes. Most slides occurred in the wetter aspen stands.

The landscape is one of an extended prominant mountain ridge that trends in a north-south direction with numerous, steeply incised canyons running east and west. The elevation on the ridge tops ranges from 10,000 to 11,000 feet, with the lowest elevations at the mouth of canyons between 5,000 and 6,000 feet. Many subdivisions and housing developments have been built on the old alluvial debris fans that developed over time below the canyon mouths. It is in these areas that much of the damage to homes and property occurred.

RESOURCE TECHNICAL TEAM ACTIONS

In response to this urban flooding and landslide damage, an interagency resource technical advisory team was formulated by the State of Utah, Utah Geological and Mineral Agency, Davis County commissioners, and the Wasatch-Cache National Forest supervisor. In Davis County, the resource technical advisory team consisted of four Forest Service employees--two regional office geotechnical people, one regional office hydrologist, and one forest soil scientist; one state geologist; the Davis County engineer; and the county water quality specialist. The state geologist headed the team. The team operated out of the Emergency Operations Center located in the Davis County library in Farmington. The situation called for aerial reconnaissance of the

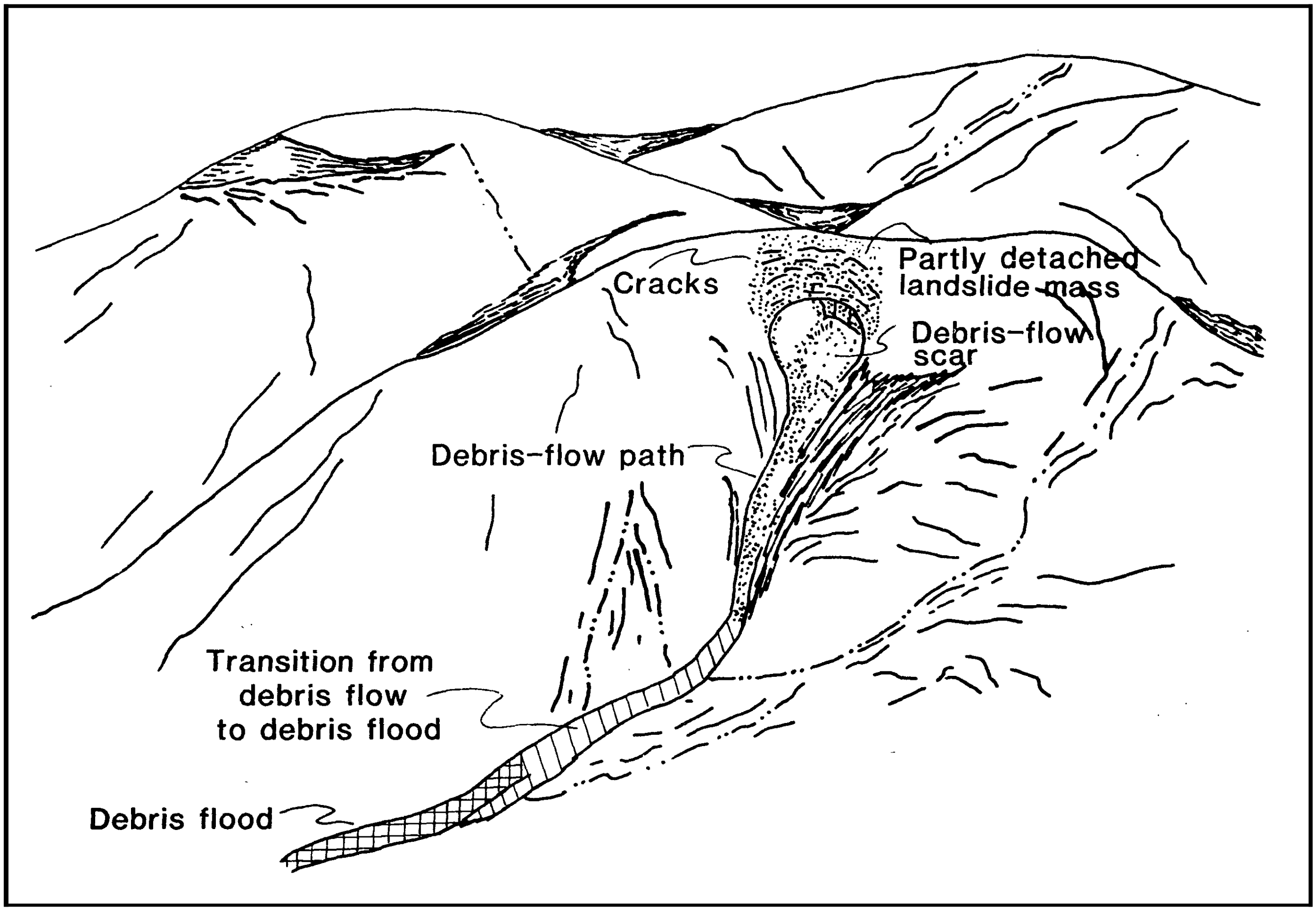


Figure 4.—Oblique sketch of a typical debris flow from a canyon wall showing the transition from a debris flow to a debris flood in the main stream channel.

canyons by helicopter twice a day. Each day the forest engineer, acting as the flood boss, received a comprehensive report of the flood and landslide conditions as observed during the flights. A large room was used solely by the committee members with maps (scaled at 1 inch to 200 feet) hung on the walls. These maps, provided by the County Planning Department, became the base maps for the rapid preparation of potential inundation or damage area maps by the county engineer and forest soil scientist. The maps outlined first- and second-alert zones where flooding could be expected. As quickly as these maps could be completed, they were dispatched to the respective mayors. Priority of preparation was assigned based on the canyon hazard ratings. These hazard ratings were determined for all Davis County drainages and were based on observations made during aerial reconnaissance. To minimize property damage, the information obtained during these reconnaissance flights was transmitted daily to the county administration so appropriate planning and action could be implemented; i.e., where to build dikes, sand bag walls, monitor mud or debris flows, place equipment and personnel, and construct diversion channels.

This technical team functioned for a period of 3 weeks. Its final action was the release on June 21 of a canyon rating list that apprised local governments of the relative degree of hazard existent in the canyons at the time. Local officials were also warned that high-intensity summer storms were capable of creating debris flows in these canyons because unstable slopes with partly detached soils existed.

The Davis County Technical Committee may well serve as a model for dealing with similar crises in the future.

MONITORING TECHNIQUES

Two techniques were used by the technical specialists to map landslides.

1. Preliminary reconnaissance mapping was done on 1:24,000, black and white aerial photographs taken in 1980. Erasable grease pencils were used to draw maps on the aerial photos. These aerial photos were matched and joined with all the drainages outlined in blue; the names of the canyons and streams were included.

2. Mapping was also done from a helicopter with all features transferred directly to 1:40,000 water rights contour maps. Because the maps clearly and accurately show the elevations, they

became an excellent tool to verify location in the canyon by checking positions with the altimeter in the helicopter. Because the forest is completely mapped at this scale, this will be the preferred method for the future, Another advantage to this approach is that personnel not familiar with aerial photo interpretation can easily use these maps.

When flying the reconnaissance flights, careful observation was essential. It was particularily important that accurate notes be kept on all features that might indicate existing or potential risk of debris flows and floods reaching the canyon mouths. These included:

1. Presence, growth, and appearance of ground displacement cracks. An accurate count was essential to judge additional movement that could create mudflows.

2. Amount of water entering the slides either through positive pore pressure zones or from interrupted stream channels emptying the snowmelt waters in the slide.

3. Color of the floodwater. Muddy water often indicated the presence of debris jams.

4. Sudden changes in the depth or amount of floodwater in the channel.

5. Size and amount of partly detached landslides perched on the steep hills and canyon sides. These partly detached masses appeared to be the most likely sources for debris flows in the future.

6. Presence of debris jams in the stream channels. Jams were usually caused by dislodged trees entering the stream channel or by landslide deposits occupying the canyon bottom.

7. It was often observed that the landslide activity followed the snowline by approximately 2 days; that is, the saturated soils would crack and slide 2 days after the snowline retreated to a higher elevation. Snowlines were mapped at intervals when it became apparent that sliding activity would increase. In severe cases, cracks would be apparent in the snow.

ADDITIONAL DATA NEEDS

The following data needs were identified by the Federal Emergency Management Agency team (FEMA) based on the data collected on the potential for debris floods along the Wasatch Range (Federal Emergency Management Agency, 1983; Wieczorek and others, 1983). The team consisted of four geologists from the U.S. Geological Survey, Menlo Park, California and an engineer from the Los Angeles County Flood Control District, Los Angeles, California. These professionals had considerable experience in evaluating flood potentials based on their work in Southern California, an area that is plagued by landslides and flooding.

1. Relationships between rainfall (or snowmelt), ground-water levels, and landslide movement. Such relationships would permit prediction of timing of debris flows. Real-time prediction and warnings could then be made based on telemetered information on rainfall, ground-water level or ground movement.

2. Stability of the partly detached landslides,, Are these masses in fact significantly less stable than nearby hillslopes, and how long will they remain so? These questions should be approached through detailed, site-specific studies including stability analyses of the landslides.

3. The process of transformation from landslide to debris flow. Understanding developed through such study could help evaluate the potential for debris flow of the partly detached landslides,

4. Incorporation of channel materials by debris flow. Possible variations in materials available for incorporation is one of the major uncertainties of our analysis.

5. The transition from debris flow to debris flood. Understanding of this transition would permit more accurate prediction of the nature of flow from canyon mouths.

6. Factors that control debris-flow runout. Understanding of runout would help in predicting those areas likely to be affected beyond canyon mouths.

7. Recurrence of debris floods and debris flows at canyon mouths. Systematic field investigation and dating of deposits would help define the potential frequency of events from each canyon.

LITERATURE CITED

Kaliser, Bruce N. Wasatch Front debris flows and the Davis County experience. Utah Geological and Mineral Survey Notes. 17(2):3-8; 1983.

Federal Emergency Management Agency. Intergovernmental hazard mitigation report for the State of Utah in response to the April 30, 1983 disaster declaration. FEMA Report 680-DR-Utah; August 1, 1983; Salt Lake City, Utah. Washington D.C.: U. S. Government Printing Office; 1983: 17 p.

National Weather Service. Storm report on Utah's spring floods of 1983. Salt Lake City, UT: National Oceanic and Atmospheric Administration, Colorado Basin Forecast Center; 1983. 1 p.

Wieczorek, G. F.; Ellen, Stephen; Lips, E. W.; Cannon, S. H. Potential for debris flows and debris floods along the Wasatch Front between Salt Lake City and Willard, Utah, and measures for their mitigation. Open-file Report 83-635. Menlo Park, CA: Department of the Interior, Geological Survey; 1983. 79 p.

APPLICATIONS OF GEOTECHNICAL DATA TO FOREST MANAGEMENT

Tom Reilly and Bill Powell

ABSTRACT: Prior to **1980,** geotechnical and geologic data were gathered on a project basis in the Gifford Pinchot National Forest in southern Washington. After conducting a study of costs and related benefits, the Forest management personnel approved on a Forest–wide basis the development of Geologic Resource Data (GRD) by the geotechnical group. The initial data collection **was** completed in **1982** at a total cost of approximately $200,000. This investment has already been recouped in cost savings associated with **rock** resource management and has provided the Forest with a more effective approach to stability-associated problems in planning and project implementation. As part of the GRD, Geological Resources and Condition Maps (GRC) were constructed to assist management with Geotechnical information. Generally, all existing landslides were classified into seven different categories, based on process of failure, and mapped along with engineering and geological information relating to existing **soil** and rock conditions. The GRC does not always provide a final answer to Forest and timber sale planners, but will provide information to make decisions when further geotechnical analysis or investigation might be economically warranted. The development of Geologic Resource Data (GRD) and Geologic Resources and Conditions (GRC) maps provide the Forest geotechnical group with a tool to promote involvement in the planning process at the earliest stages. With this involvement the geotechnical personnel can establish the priority of the various stability problems on a Forest–wide basis and schedule field investigations in a more systematic manner. The GRD was designed to be updated, as project work and **more** detailed stability studies are completed, each update improving the accuracy and reliability of information.

INTR :TI(

Starting in **1980** the Gifford Pinchot National Forest geotechnical group embarked upon a geologic data collecting process referred to as the Geologic Resource Data (GRD). Initially, information was gathered over a 2–year period on a Forest-wide basis. Most of the data collection was completed during the **1981** field season. In **1982,** primarily for support. to transportation planning, the GRD data **was** analyzed and portrayed on a single map--Geologic Resources and Conditions (GRC). The data base **was** set up to have application and benefits to **USDA** Forest Service programs, and the information has been tested on land management planning, area and timber sale planning, and project site investigations. The results have greatly exceeded original expectations; and because the resource data **was** meant to be continually

TOM REILLY is an engineering geologist with the USDA Forest Service, Pacific Northwest Region, Gifford Pinchot National Forest, at Vancouver, Washington.

BILL POWELL is Regional Geotechnical engineer with the **USDA** Forest Service, Alaska Region at Juneau, Alaska.

updated, the information will be progressively more effective in the future.

The Gifford Pinchot National Forest is not considered the most unstable Forest in the Pacific Northwest Region, but the type of failures, the geologic conditions, and frequency of failures vary considerably throughout the Forest,, The GRD was designed to have many uses, and one use of primary importance is application for slope stability assessment. This report will primarily address slope stability; but the reader should be aware that, the system was predicated on many other technical applications and has wide application at the Forest and project levels.

DEFINING THE NEED AND SUPPORT TO DEVELOP THE RESOURCE DATA

Since the Gifford Pinchot Geotechnical group leadership was centrally organized in 1975, the need for collecting and interpreting geologic data has been increasingly evident. Some of the main reasons are:

1. Simplified, geologic conditions have consistencies and inconsistencies that can be measured and projected over an area between locations. This information can be related to engineering characteristics including slope stability. This type of analysis was occasionally used by the Forest geotechnical group on smaller, defined areas. It appeared that if similar information were available on a Forest-wide basis, there would be more precise information on which to make stability predictions with limited additional field work at the planning stage.

2. The Forest had geotechnical specialists with many years of experience working in defined areas, It would take years for a new person to gain this field experience. A data base would be a method to display, store, and update engineering geology information on a continual basis and provide new personnel with information in an understandable form.

3. Prior to 1980, project and area transportation planning was a function of the Ranger District and geotechnical services were provided by the engineering staff. Geotechnical personnel worked on a request basis and program effectiveness varied, depending on the individuals involved. Some planners requested assistance on every project and some planners did not request any assistance. The geotechnical group not only felt that a data base would improve the recommendations and increase the visibility of useful available data, but would provide a method of establishing the priority of the stability work Forest-wide. The geotechnical group would also have backup information to support their decisions.

In spite of the obvious benefits that could be derived from a GRD, there was reluctance by management to support the expenditure. The estimated initial cost was $200,000 over a 2-year period, and the program would set a precedent of establishing a geologic data base over an entire National Forest. The Forest already had a soils resource inventory, so the need for a geologic data base was not obvious. A considerable amount of time was spent discussing the potential dollar savings and value of a GRD before management would approved the expenditure, In 1980 the Forest was forming a interdisciplinary team to complete the Forest Land Management Plan to the standards of the National Forest Management Act. The GRD information could be used effectively in completing this plan. Finally,. just prior to the 1980 field season, the geotechnical group obtained approval to proceed with gathering the field data.

DEVELOPMENT OF THE DATA BASE

Prior to the GRD program, geologic inventory and analysis were carried out on a project basis, and project files were the only means of "storing" geologic data. There was no long-term system to store and retrieve geologic data that could prove useful to planning efforts or future project work, and there was little opportunity to break out of the "project mode."

The formulation of the GRD program was envisioned as an opportunity to develop a system for providing data for National Forest planning, The system could be structured to serve as a repository of all geologic data and should prove invaluable to second-order plans and future project work. With a long-term goal in mind, considerable thought was given not only to immediate planning needs but long-term usefulness of the data. The GRD system and method were developed to be uniform throughout the Forest; to be sustained and enhanced by additions of new data; to act as the starting point or base for future geologic investigations; and to be the repository for newly acquired geologic data, The basic effort was to gather technical data and to distill it to be both understandable and usable by nontechnical planners and Forest managers. Yet, the data also had to be technically sound to make engineering and other resource recommendations.

Considerable teamwork and discussion were needed to reach consensus on the type of data to be gathered. Short- and long-term usefulness of the data and potential applications had to be considered and technically sound but understandable terminology, and graphic display symbols had to be devised. The Forest Geologist, with assistance from engineering zone geotechnical personnel, formulated guidelines for the types and levels of data to be gathered. Map and file systems were developed to ensure uniformity. Data were gathered for defined land areas called Total Resource Information (TRI) compartments. There are 254 of these land areas, each averaging approximately 6,500 acres, comprising the Forest land base. The TRI system consists of subsystems of layered resource displays and data files for each TRI compartment map. There are currently 13 other resource inventories (timber, wildlife, transportation, etc.) mapped and displayed in the TRI system. Most field information was obtained by driving Forest roads; driving had to be supplemented in some areas by walking. Temporary employees were hired to gather the data under the immediate supervision of zone geotechnical personnel, with overall direction and review by the Forest geologist. Figure 1 outlines the inventory process.

The GRD was founded on the principle that data gathered must have application and benefit to Forest Service programs. It was set up to gather and display data at a general level of resolution for long-range plans, and to be ground reviewed and further classified at a more intensive level for area and project planning. The process was not envisioned to result in a classic academic geologic map filled with jargon and difficult to interpret. Materials were classified and assessed, based on physical characteristics and response to modification by management activities. Slopes were evaluated not merely to classify as stable or unstable, but features were classified by type of process or mechanism of failure, which allows future prediction of response to modification. Conditions existing on unstable slopes have been compared to those conditions on similar slopes where failure has not yet occurred in order to further understand the mechanism of failure and predict failure potential.

To the engineering geologist, all landslides are not alike. Each landslide responds differently to management activities depending on physical conditions and processes. Many managers wondered why such a data base was necessary in light of the existing Soil Resource Inventory, but the soil inventory was not as comprehensive in evaluating slope stability and lacked sufficient detail for making quantitative predictions and recommendations.

Because geologists in the Forest Service are involved in both surface and subsurface resources, conditions and processes, the data was displayed in two layers. Accordingly, the GRD is structured by TRI compartiints in two overlays: rock and surficial materials. Figure 2 outlines the content of the overlays.

The entire Forest has been mapped and bedrock units designated. Bedrock units are defined as rock masses of similar origin (igneous extrusive and intrusive, pyroclastic, sedimentary, and metamorphic) mapped at a scale of 4 inches to 1 mile and are distinguished by a numerical system. The primary basis for bedrock unit designation is rock origin, but all bedrock units have also been classified according to the Unified Rock Classification System. This system (developed by Doug Williamson, engineering geologist, Willamette National Forest) provides a reliable method of assessing rock mass engineering characteristics and physical parameters necessary to predict rock quality, stability, and response to management activity.

1. OFFICE PREPARATION - Compile onto base map

AIR PHOTO INTERPRETATION
SOIL RESOURCE INVENTORY (SRI) REVIEW
PROJECT FILE REVIEW
MATERIALS SOURCE FILE REVIEW (quarry files)
PUBLISHED GEOLOGIC LITERATURE REVIEW

2. FIELD WORK - Verify accumulated data - "ground truth"

ESTABLISH DATA POINTS AND MILEPOST LOG
MEASURE AND CLASSIFY MATERIALS AND STABILITY FEATURES
PHOTOGRAPH AND SAMPLE
ESTABLISH BEDROCK UNITS
VERIFY BOUNDARIES AND CONTACTS
REVIEW MATERIALS SOUHCE DATA AT THE SITE

3. COMPILATION

ORGANIZE AND SUMMARIZE TRI COMPARTMENT DATA PRIOR TO OFFICE PREPARATION FOR NEXT COMPARTMENT

Figurel—The Geologic Resource. Data (GRD) collection process.

1. ROCK OVERLAY

- BEDROCK UNITS
- MATERIALS SOURCES BY CATEGORY
- BEDROCK STRUCTURE
- AREAS OF ROCK OUTCROP AND TALUS
- GEOLOGIC POINTS OF INTEREST

2. SURFICIAL OVERLAY

- MASS MOVEMENT FEATURES BY CATEGORY
- AREAS OF MAPPABLE GROUNDWATER OCCURRENCE
- SIGNIFICANT MAPPABLE TRANSPORTED SOIL DEPOSITS

Figure 2--Content of Geologic Resource Data (GRD) overlays.

Mass movement is a sensitive natural process that human activities can accelerate or decelerate; with a potential for adverse effects to the environment. Activities such as timber harvest, road construction, or facility placement can initiate or accelerate mass movement, often with catastrophic results.

Mass movement can be decelerated through intervention, but often this requires costly engineering techniques. Confirmed or suspected areas of unstable ground may or may not tolerate management activity depending on specific site conditions. The GRD displays known and inferred areas of unstable slopes throughout the National Forest as a first approximation of potential problems. This display serves as the basis for planning future fieldwork to verify the nature of the problem and to recommend specific mitigation measures. Based on the information gathered, accurate predictions can be made on the potential impacts from road construction and timber harvest using predictive computer modeling techniques. Results of predictive modeling of slope stability is only as accurate as the data used to define the physical conditions of the site, such as soil and rock engineering characteristics. Without an adequate data base, the use of these techniques is limited.

Seven categories of mass movement or instability have been mapped and displayed in the GRD, each category distinguishable by Roman numerals. These categories were developed to differentiate process or mechanism of failure and are described in figure 3. The areal extent of the feature is mapped and displayed, and the feature is classified as to mechanism of failure. When reviewed in the field, additional geologic and engineering information is gathered on soil, rock, and groundwater conditions for future application. Aside from adverse resource impacts such as water quality degradation, some slope failures have long-term impacts on site productivity.

DEVELOPING MAPS OF GEOLOGIC RESOURCES AND CONDITIONS

After the GRD was completed, the technical data needed to be distilled and synthesized to provide a user-friendly, simply structured, yet technically sound, end product for use by nontechnical planners for National Forest and area planning. This led to the development of the Geologic Resource and Conditions Maps (GRC).

The Geologic Resources and Conditions Maps are built through analysis and synthesis of the Geologic Resource Data of rock and surficial layers. Geologic resources and conditions are defined consistent with national and Forest criteria, and are shown in figure 4. The relationship between GRD, GRC, and subsequent field work is displayed in figure 5.

Each map delineates Geologic Materials Units (GMU), each distinguished by symbol, which consist of deep soil deposits (greater than 15 feet) residual soil deposits, transported soil deposits and bedrock. Delineation of a soil GMU vs. a rock GMU is dependent upon relative depth of soil--the dominant geologic condition of that particular area. For example, if the soil depth is estimated at 20 feet, the physical properties of the soil and the surficial processes are the dominant geologic condition for that particular area, and the underlying bedrock is subordinant in importance. If by chance bedrock information is required for a soil-based GMU, it can be obtained from GRD rock overlays. In most instances, the GMU boundaries correspond with bedrock unit boundaries. The GMU is used as the framework to provide interpretations as to geologic resources and conditions (such as slope stability) for the discrete Forest land area. The specific content of GRC maps is described in figure 6. Figure 7 is an example of the typical information contained in a GRC map margin, and figure 8 displays the standard map legend.

I. SLIDES
- ROTATIONAL AND/OR TRANSLATIONAL FAILURES
- SOIL/BEDROCK OR BOTH TYPES OF MATERIAL
- ACTIVE OR PAST ACTIVE (CURRENTLY STABLE)

II. FLOWS
- DEBRIS SLIDES, DEBRIS FLOWS, DEBRIS AVALANCHE
- TERM APPLIED DEPENDS ON WATER CONTENT. MOBILITY, AND CHARACTER OF MOVEMENT
- SOIL PARTLY OR COWLETELY DECOWOSED BEDROCK OR COMBINATION

III. ROCKFALL/TALUS
- TOPPLING AND FALLING OF FAILURES IN ROCK

IV. AVALANCHE
- SEASONAL AREAS OF SNOW/ICE MOVEMENT
- OFTEN ACCOMPANIED BY ROCK, SOIL, AND ORGANIC DEBRIS

V. SIDECAST FAILURE (INITIATED BY ROAD CONSTRUCTION)
- CONSTRUCTION WASTE END DUMPED OR LOOSELY PLACED ON SLOPES EXCEEDING 55 PERCENT WITH RESULTANT FAILURE

VI. FILL FAILURE (ROAD FILL)
- FILL PLACED ON SLOPES LESS THAN 55 PERCENT WITH RESULTANT FAILURE

VII. CUTSLDPE FAILURE (ORIGINATING AT A ROAD)
- CUTSLOPES EXHIBITING EXCESSIVE RAVEL OR MASS FAILURE

Figure 3--Soil mass movement categories mapped and displayed in the Geologic Resource Data (GRD) process.

GEOLOGIC RESOURCES
- EARTH CONSTRUCTION MATERIALS
- GROUNDWATER
- UNDERGROUND SPACE (I.E., CAVES)
- GEOLOGIC POINTS OF INTEREST (EXAMPLES OF UNIQUE OR SPECTACULAR FEATURES DEPICTING GEOLOGIC PROCESSES OR PHENOMNA OF THE EARTH'S EVOLUTION; I.E. , VOLCANIC OR GLACIAL LANDFORMS),

GEOLOGIC CONDITIONS
FEATURES OR PROCESSES THAT AFFECT THE SAFETY, COST, OR FEASIBILITY OF RESOURCE MANAGEMENT ACTIVITIES AND DEVELOPMENT
- ROCK OUTCROP AND TALUS
- MASS MOVEMENT (INCLUDING ROCKFALL AND AVALANCHE AREAS)
- MAPPABLE WET AREAS (SPRINGS AND POORLY DRAINED GROUND)

NOTE: MANY OF THESE GEOLOGIC CONDITIONS ARE SOMETIMES REFERRED TO AS "GEOLOGIC HAZARDS." THIS HAS BEEN AVOIDED BECAUSE OF THEIR SUBJECTIVE NATURE, WHICH IMPLIES HAZARDS TO PEOPLE OR STRUCTURES. THE CONDITIONS COULD POSE HAZARDS IF NOT AVOIDED, BUT ARE NOT HAZARDS IN THEMSELVES.

Figure 4--Criteria used to define units on Geologic Resources and Conditions (GRC) maps.

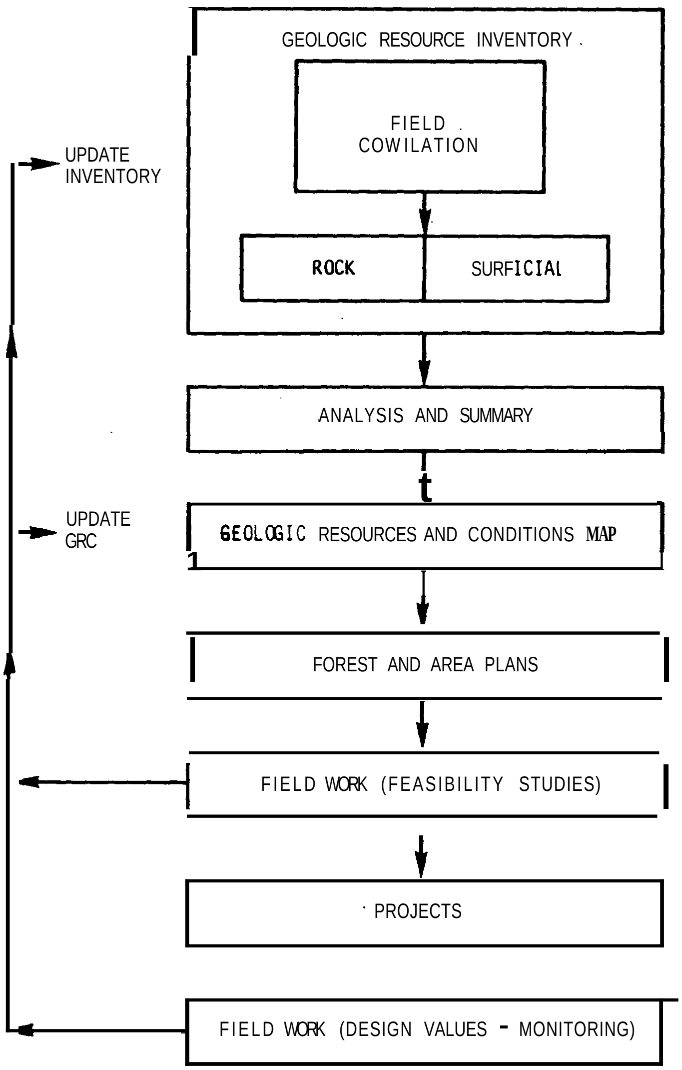


Figure 5—Relationship between GRD, GRC and project planning and design.

- TOPOGRAPHIC BASE MAP 4" = 1 MILE SCALE (TRI COMPARTMENTS)
- GEOLOGIC MATERIALS UNITS (BASED ON RESIDUAL [PARTLY OR CORLETELY DECOMPOSED ROCK] OR TRANSPORTED SOIL DEPOSITS, OR BEDROCK UNIT BOUNDARIES) AND DESCRIPTION
- GEOLOGIC RESOURCES AND CONDITIONS BY SYMBOL
- MATERIALS SOURCE SUMMARY TABLE
- SPECIAL CONSIDERATIONS (POTENTIAL GEOLOGIC CONSTRAINTS OR OPPORTUNITIES) FOR EACH GMU
- TRI COMPARTMENT SUMMARY
  - AREA GEOLOGICAL SETTING AND ORIGIN
  - SOIL/ROCK MATERIALS PROPERTIES
  - SLOPE STABILITY FACTORS
  - GEOLOGIC RESOURCE INFORMATION
  - SPECIAL CONSIDERATIONS FOR THE OVERALL COWARTMENT

Figure 6--Specific content of Geologic Resources and Conditions (GRC) maps.

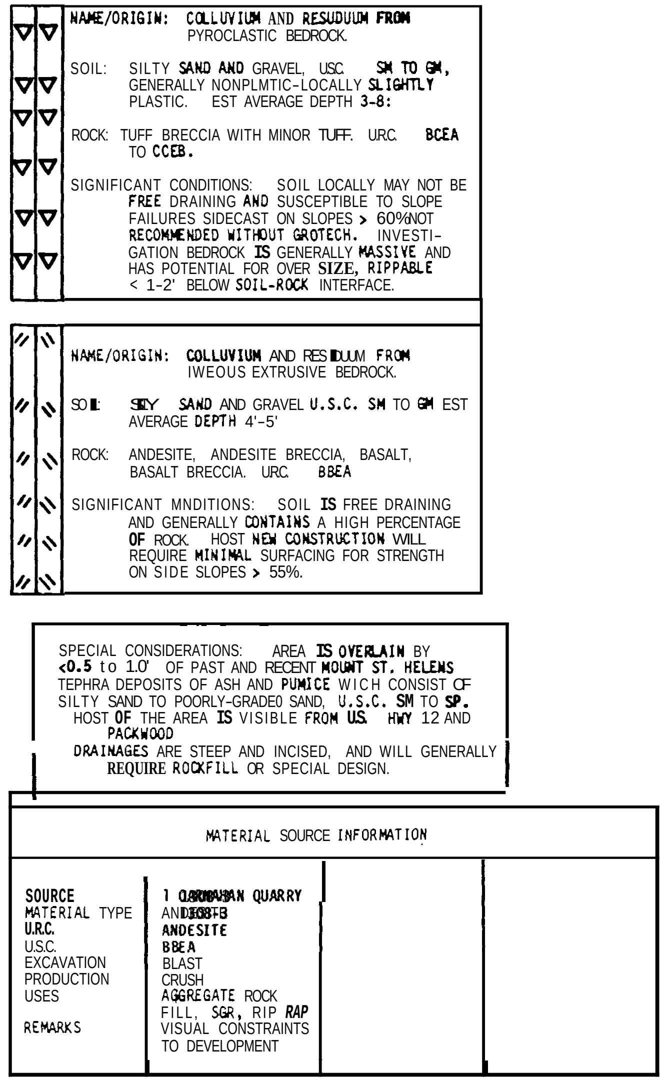


Figure 7–An example of typical information contained in a GRC map margin.

APPLICATIONS OF GRC MAPS

The GRC maps have many applications to Forest resource management activities. One such application is in the planning and design of' timber sales.

The Timber Sale Gate System is a planning process used at the Gifford Pinchot National Forest and developed to systematically gather and evaluate pertinent data that ultimately affects the location and layout of future timber sales. The gate system has six steps, each defining data collection and analysis required prior to moving to the next step in the process. Each gate is of increasing specificity. The gate system serves as the framework to coordinate input by all resource specialities.

Geologic Resources and Conditions Maps display basic geologic reconnaissance-level data that designate geologic factors affecting land

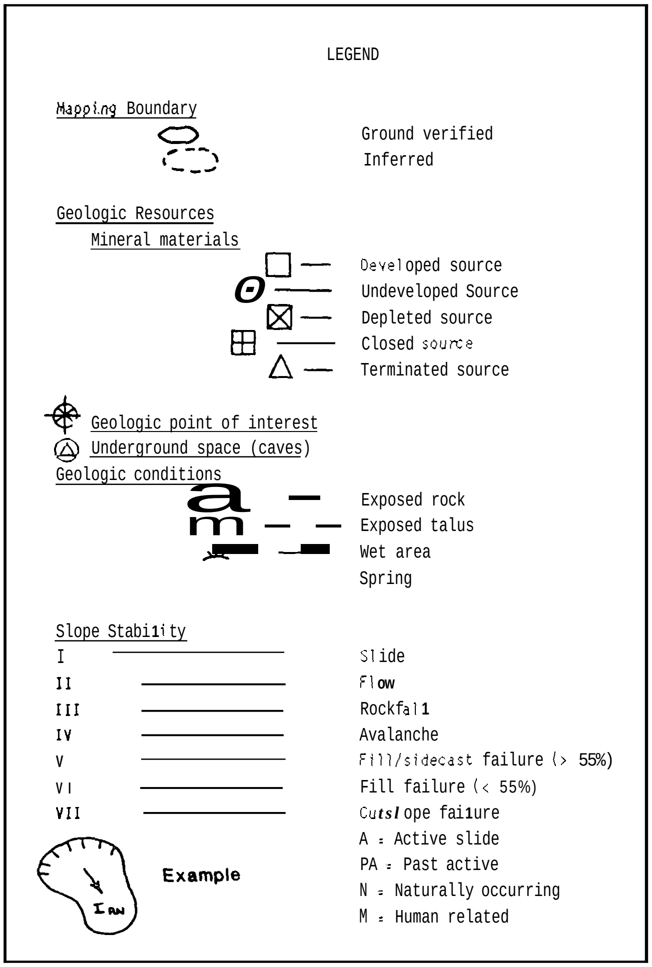


Figure 8--Standard legend used on GRC maps.

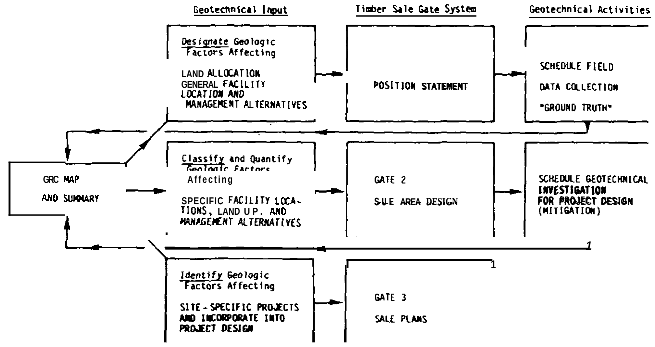


Figure 9—Relationship between GRC maps and the timber sale gate system.

1. Recreation--Geologic resource data (points of interest for interpretive programs; groundwater information for recreation sites)
2. Timber--Geologic materials units probably correlate with site productivity
3. Water and Soil--Forest soil scientists currently utilizing GRC maps in project evaluation; of proving useful for preliminary evaluation of potential hydroelectric permit applications
4. Minerals and Geology--Estimating potential impact from mineral resource evaluation and exploration; common variety mineral materials sources located on GRC maps
5. Lands--Potential use of GRC maps to evaluate relative value of geologic resources in National Forest land considered for sale or exchange.

Figure 10--Potential applications of GRD and GRC data to other resource programs.

allocation, general facility locations, and management alternatives. GRC maps, including the respective TRI compartment summaries properly interpreted by a geology or geotechnical specialist, provide invaluable data for the planner to develop initial land constraints or opportunities. They also supply critical elements to sale implementation which are part of the position statement (gate 1 of the Timber Sale Gate System). This leads to scheduling of field data collection to verify potential problems identified on the GRC before completion of sale area design (gate 2). GRC maps allow for initial gate 1 input, then serve to provide a basis to schedule further classification and quantification of geologic factors as they affect specific facility locations or land use and management decisions necessary for gate 2, sale area design. GRC maps provide an ideal and extremely useful tool to identify concerns regarding slope stability (as well as other geologic factors) at the earliest planning stages (gate 1), to verify in the field the condition during sale area design (gate 2), and to mitigate potential adverse environmental impacts during project design (gate 3). Figure 9 displays the relationship between GRC and the gate system.

In applying the gate system, planners obtain resource data from existing inventories found in TRI with very little field work at gate 1. Prior to formulation of the CRC, it was difficult to provide geologic data at this vital initial step in the planning process.

By no means is the application of Geologic Resources and Conditions Maps limited to timber sale support. Figure 10 displays potential application of this data to other resource programs.

The policy at the Gifford Pinchot National Forest, as stated by the Forest Supervisor, is that TRI is the official Forest data base and will be utilized as such by all resource specialists. When evaluating the best place to put Geologic Resources and Conditions data in TRI, it was decided to create a new subsystem because the GRC is unlike any found in existing subsystems.

A user's manual, Geologic Resources and Conditions Subsystem Guide, has been written to explain sources of information, reliability, subsystem structure, significance of data, and application to resource management activities,[1/].

During 1983, the GRC maps were used in the development of several area plans that the Forest was converting from sale planning to larger planning areas with defined boundaries. The GRC maps were found to be beneficial in assessing the planning alternatives. Specific landslide problems are identified and low intensity field investigations are conducted mutually with transportation planners and geotechnical personnel to provide realistic costs to select the least costly road construction alternatives. During the same 1983 field season, three quarries were found using the GRD in areas of known rock shortages. These quarries have long-term benefits of several million dollars based on reduced costs for hauling, and the timber sales assigned for the initial entries will more than pay for the entire expenditures for the GRD.

Usually by the time specific site information is needed for design, the geotechnical specialists are familiar with the field conditions. They have completed the GRD and GRC maps and have been in the field where problems are anticipated in area planning. The priority levels for field investigations are determined on a Forest-wide basis, and the designers usually know ahead of time how much field data they will need. At the start of each field season the geotechnical group has a realistic work plan with backup information, which is reviewed by the Forest engineer to determine staff and budget needs.

In conjunction with the GRD, a study is being conducted in which existing slides are investigated to determine measurable factors causing failure. This information should improve ability of the geotechnical group to make evaluations in the planning stage.

The GRD was set up to assign several different levels of confirmation depending on whether the information was obtained by physical measurements in the field or projected. When field work is conducted methods are developed to recycle this information in the GRD. The information on the GRD will be continually updated and consequently more accurate.

SUMMARY

The GRD and GRC concepts has proven to have many benefits. Besides being tools to improve the technical adequacy of geotechnical information, they also provide a basis for early involvement in forest timber sale programs. The work is done in a more systematic manner which should result in reductions in overall construction cost and resource damage. On the Gifford Pinchot National Forest, there has already been enough cost savings resulting from their use to pay for the initial cost. With the GRD set up to be continually updated as project site investigations are completed, they will only become more useful in the future.

1/ Geologic Resources and Conditions Subsystem Guide, on file at the USDA Forest Service, Gifford Pinchot National Forest Supervisors Office, Vancouver, Washington.

A COMPLETE THREE-LEVEL APPROACH FOR ANALYZING LANDSLIDES ON FOREST LANDS

Rodney W. Prellwitz

ABSTRACT: Land managers need a uniform and effective system for predicting landslide potential on forested slopes. No single geotechnical or statistical method is appropriate for all types of decisions. The USDA Forest Service in cooperation with the University of Idaho is therefore developing a system suited to three levels of application:

Level I. Resource allocation--provide managers with an overview of landslide potential adequate for developmental planning.

Level 11. Project planning--predict response of slide-prone areas to various harvesting systems and transportation routes.

Level III. Critical site stabilization-evaluate stabilization techniques at critical sites before and after construction.

The proposed system incorporates geotechnical analyses, statistical analyses, and landslide inventories. Implementation is currently handicapped by inadequate data storage techniques and by the lack of methodology to measure and predict timber management impact on the two most dynamic variables: concentration of ground water and strength of tree roots.

INTRODUCTION

Resource management activities on many forest lands can accelerate mass erosion and cause significant degradation of water quality, fisheries, and esthetics. For successful management of forest lands an accurate assessment of the landslide hazard must support management decisions. The slope stability analysis technique, the data required for analysis, and the effort to acquire that data must be tailored to the specific decisionmaker's needs.

MANAGEMENT COMPLEXITY

The management of lands that have a high landslide potential is inherently complex, not only because of the nature of the interacting natural processes and management activities, but also because of the variety of specialists who must to some extent understand slope failure processes if they are to contribute to the total stabilization effort (fig. 1). Considerable overlap and interaction between members of key

RODNEY W. PRELLWITZ is a Research Engineer with the USDA Forest Service, Intermountain Forest and Range Experiment Station at Missoula, Montana.

disciplines must be coordinated.

There are also several levels of intensity at which members of different disciplines must deal with the slope stability problems. For example, the resource planner must be able to recognize high-hazard areas, but only on a broad, general scale. The road locator must be able to recognize potentially unstable areas along proposed routes to minimize problems through optimum alignment. The engineer must be able to use soil mechanics in devising measures to prevent or correct failures of road cuts or fills.

CURRENT MANAGEMENT PRACTICES

Current management practices for dealing with landslides vary from forest to forest. Hazard analysis and treatment will usually follow at least one of the following patterns:

1. No formal analysis during the planning phase; the prudent land manager establishes a moratorium or reduces development in areas with landslide potential.

2. Landslide hazards are evaluated during the planning phase, using subjective ratings developed locally for identified landforms. Moratorium or reduced development may be exercised on landforms where landslides have resulted from road construction or timber harvest.

3. During the development phase, road locators or specialists may recognize slide-prone areas and use such knowledge in selecting the proposed route.

4. Following development, a detailed slope stability analysis is employed in correcting road-related landslides — without feedback into the planning phase.

Seldom do we find the proper slope stability analysis supporting decisions at all levels of management. This is mainly because there is no comprehensive system for evaluating landslide hazards.

IDEALIZED LANDSLIDE EVALUATION SYSTEM

Land mangers need a hazard evaluation system that begins early in the resource planning phase, follows through into the project development phase, and feeds information back to the planning phase to improve future analyses (fig. 2). The selection of technique should be commensurate with the level of management decision. The system should begin with a simple analysis that requires generally available resource inventory data for the planning phase and that becomes more complex and requires more exact data as the intended use demands greater accuracy.

Three levels of analysis complexity and supporting data are visualized for the system as

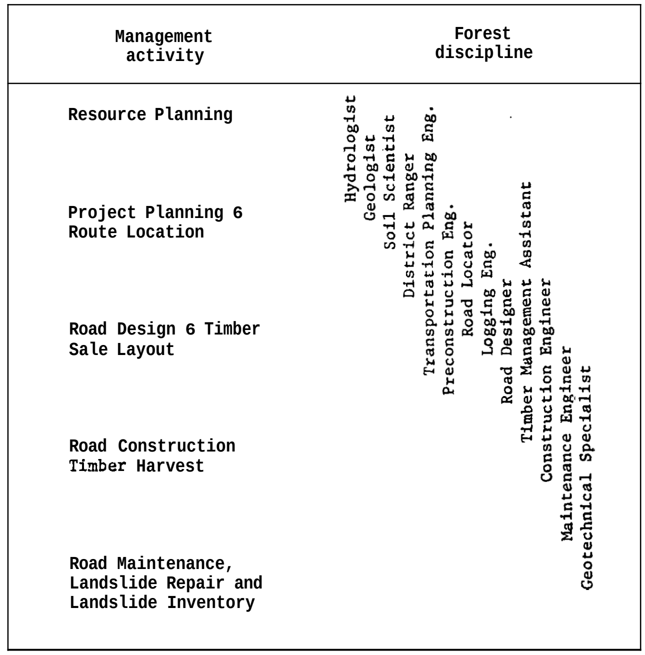


Figure 1.—Specialists involved in managing unstable forested lands.

outlined in figure 3. A more detailed description and a typical problem are given in an earlier publication (Prellwitz and others, in press). The application of the system is as follows:

Level I: Resource allocation.—Stability analysis delineates areas susceptible to landslides on a broad scale to alert the land manager to land units of greatest hazard intensity. The number and magnitude of landslides resulting from resource development can be predicted through statistical correlation to the landslide inventory.

Level II: Project planning.—Added complexity provides information to many additional users. The severity of instability can be more accurately assessed as local "islands of instability" and are identified through reconnaissance. Decisions can be made to limit development or to continue into the Level III phase based on an improved assessment of magnitude and intensity of probable failures. Timber harvest techniques and alternate route locations can be more closely evaluated. Perhaps the most important use is to isolate the critical sites along the selected routes for Level III analysis.

Level III: Critical site stabilization.—An analysis of increased complexity to facilitate the selection and design of road stabilization measures includes an analysis of stability—probability of failure—construction cost of all alternatives. Rock buttresses, drilled-in parallel drains, interceptor drainage trenches, retaining walls and changes in alignment, can all be compared and evaluated in conjunction with current management constraints.

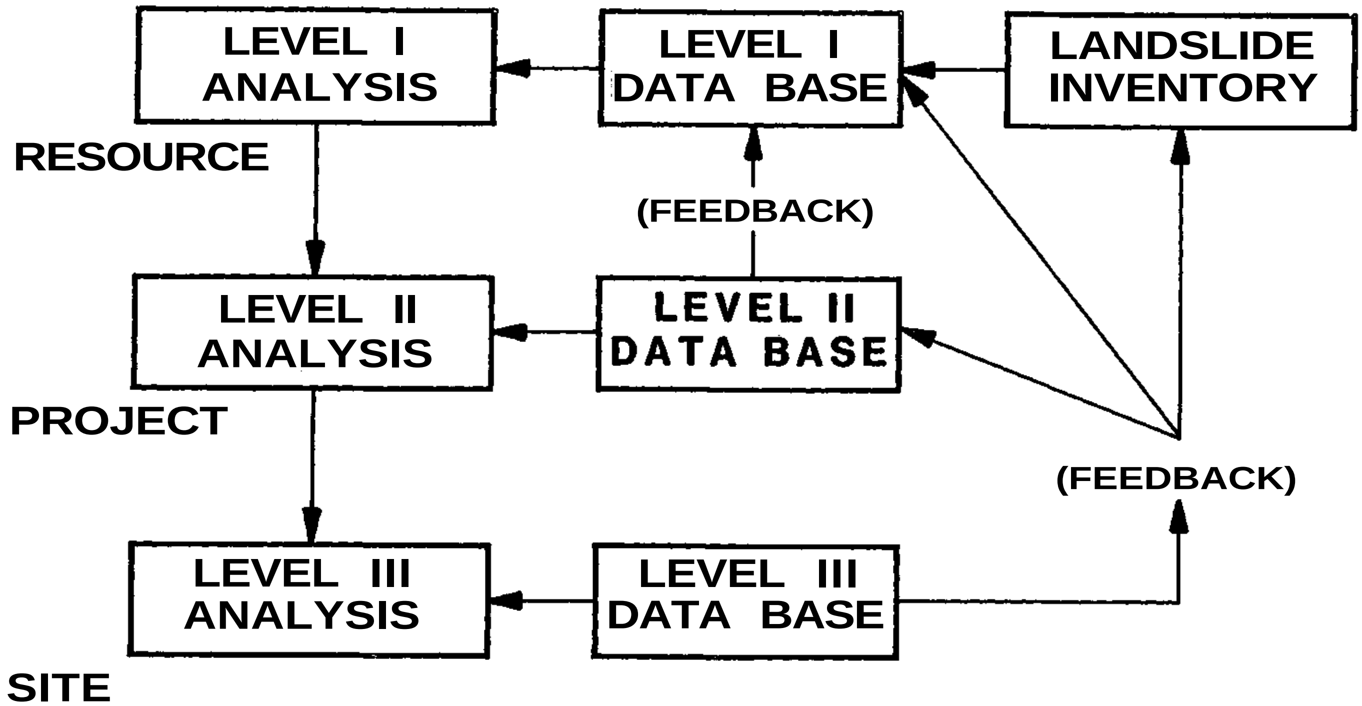


Figure 2.—Idealized three-level slope stability analysis.

Management activity	Analysis complexity level	Stability analysis Level 1	Stability analysis Level 2	Stability analysis Level 3	Base map Level 1	Base map Level 2	Base map Level 3	Input data base Level 1	Input data base Level 2	Input data base Level 3	Output Level 1	Output Level 2	Output Level 3
RESOURCE PLANNING	LEVEL 1 Resource Management	Infinite Slope			Resource Map Approx. scale l"=2000 ft.			Resource Inventory, broad characterization of soil strength parameters, available landslide inventory			Hazard map overlay with factor of safety and probability of landslide		
PROJECT PLANNING S, ROUTE LOCATION	LEVEL 2 Project Planning 6. Design		Infinite Slope and Critical Height			Project Map Approx. scale l"=500 ft.			Blowup of level 1 map, additional input from route and timber reconnaissance, improved estimate of soil strength parameters, improved ground water prediction from response model, improved prediction of subsurface profile			Same as level 1 but more detailed showing local "islands" of instability. Unstable road cut and fill slopes on proposed routes	
ROAD DESIGN & TIMBER SALE LAYOUT	LEVEL 3 Critical Site Analysis			Method of Slices			Site Map and Stability Cross Sections Approx. scale l"=20 ft to 100 ft.			Blowup of level 2 map, additional input from road survey, improved data from geophysical investigation, possible drilling of critical sites, refined ground water response analysis, refined soil parameter analysis			Same as level 2 of critical area, 3-D displays, critical cross section, input for stability analysis, results of stability analysis, relative cost comparison of stabilization techniques
ROAD CONSTRUCTION & TIMBER HARVEST													
ROAD MAINTENANCE, LANDSLIDE REPAIR AND LANDSLIDE INVENTORY													

Figure 3.—Idealized landslide evaluation system-soil mantle failures.

IMPLEMENTATION AND RESTRICTIONS

Existing Stability Analyses

Analysis technology is currently available to implement the proposed system. A program developed by Simons and others (1978) for mapping potential landslides is based on an infinite slope analysis and includes options for both "factor of safety against failure" and "probability of landslide occurrence" for a Level I analysis. Stability charts with seepage correction factors are being developed (Prellwitz 1975) and converted to computer programs for a Level II analysis of critical height of typical cut and fill slopes. Geotechnical specialists are using many programs to analyze and correct existing landslides. The most widely used methods can be integrated into one program to cover a variety of analyses of failure surfaces for Level III. Statistical counterparts for the "probability of landslide occurrence" options used in Level I are possible for Levels II and III based on methods currently used in geotechnical engineering (Simons and others 1978; Wyllie and others 1980).

Existing Data Base

Currently the system is handicapped by the limited data available for most forests. Many forest managers have (or are in the process of developing) resource inventory maps for soils, geology, topography, timber type, and other features. These maps could provide the basis for characterizing geotechnical variables to use as a Level I data base. The data base could be upgraded with use (Vita 1982). Statistical analyses used by Simons and others (1978) and DeGraff (1982) will prove invaluable for linking physical factors such as bedrock, aspect, and slope to inventoried landslides. The accuracy of the values assigned for geotechnical variables, analysis models, and the "probability of landslide occurrence" can be tested through association with corresponding physical factors. Currently, only a few forests have landslide inventory data. Geomorphic maps, where available, are based on major physical factors for identifying and assigning values to geotechnical variables.

Methods for Defining Variables

The main restriction to implementing the system is the difficulty in defining certain geotechnical variables. Techniques for determining slope, soil depth, and soil shear strength have progressed to a state where the values and their variance can be used with some degree of confidence. This is not true for the two most dynamic variables: (1) concentration of ground water and (2) strength of tree roots. There are currently no cost-effective methods for measuring or predicting timber management impacts on these two variables.

The part of the soil mantle that can be expected to be below the phreatic surface at any time is perhaps the most dynamic of the variables. It can fluctuate constantly in response to precipitation. Practical and inexpensive methods are needed to develop local correlations between rainfall and snowmelt and the resulting rise in ground water. Although there is general knowledge about tree root strength within the rooted zone, there currently are no practical methods for measuring the effective strength that relates to the stability of the entire slide-prone soil mass. Until these techniques are developed, probable values and analysis sensitivity for these two variables can be estimated through analysis of existing landslides.

SUMMARY AND CONCLUSIONS

The concept for a complete three-level landslide analysis system has been outlined. Important points regarding the system are:

1. Each level of analysis is designed to provide guidance for land management decisions at that level only. Complexity, data required, and accuracy must be commensurate with the nature of the decision.

2. A loop that channels Levels II and III data back into the Level I data base will upgrade the accuracy of future analyses.

3. Although the system is intended for soil mantle failures, it may be applied to rock slope failures by substituting appropriate analysis techniques and data.

4. Analysis techniques are either available or are developable, but are currently little used because of two restrictions:

   a. Lack of a dynamic and easily upgraded data storage system.

   b. Inadequate techniques for measuring and for assessing timber management impact on geotechnical variables, such as concentration of ground water and effective strength of tree roots.

LITURATURE CITED

DeGraff, J. V. Quantitative approaches, to assessing landslide hazard to transportation corridors on a national forest. Transportation Research Record. 892:64-68; 1982.

Prellwitz, R. W. Simplified slope design for low-standard roads in mountainous areas. In: Low volume roads. Transp. Res. Board Spec. Rep. 160. Washington, DC: Transportation Research Board, National Academy of Sciences; 1975: 65–74.

Prellwitz, R. W.; Howard, T. R.; Wilson, W. D. Landslide analysis concepts for management of forest lands on residual and colluvial soils. Transportation Research Record; In press.

Simons, D. B.; Li, R. M.; Ward, T. J. Mapping of potential landslide areas in terms of slope stability, Rep, CER 78-79 DBS-RML-TJW. Fort Collins, CO: Civil Engineering Department, Engineering Research Center, Colorado State University; 1978; 4975 p.

Vita, C. L. A landform-based probabilistic methodology for site characterization. In: Proceedings, 19th annual Idaho Engineering Geology and Soils Engineering symposium; 1982 March 31-April 2; Idaho State University, Pocatello, ID: Idaho Transportation Department, Division of Highways; 1982: 339-354.

Wyllie, D. C.; McCammon, N. R.; Brumund, W. Planning slope stabilization programs using decision analysis. Transportation Research Record. 749:34-39; 1980.

DECISIONMAKING IN THE PRESENCE OF RISK

Stefan D. Bloomfield

ABSTRACT: Any assessment of risk must take into account both the severity of the possible hazard and the specific probability of that hazard occurring. This paper discusses the concepts of risk and introduces several of the different approaches to risk analysis, with particular emphasis on the way in which such analyses affect the ultimate determination of "acceptable risk" in managerial decisionmaking.

INTRODUCTION

Many public policy decisions are made in a context of risk; land management decisions involving the possibility of landslides are just one example. Most published studies analyzing such decisionmaking, quite understandably, focus on decisions having potentially dramatic and large-scale consequences: decisions regarding the siting of nuclear power plants or liquefied natural gas facilities, the effective control of water resources and sources of environmental pollutants, and the regulation of human exposure to carcinogens or other toxic substances. See the end-of-chapter references and the concluding bibliography in Crouch and Wilson (1982).

In many cases, public policy decisionmaking procedures are mandated to include detailed analyses of the risks inherent in the proposal; the risk assessments resulting from such analyses then often play a formal and prominent role in the decision process. Whether or not a formally prescribed, analytical procedure is followed, however, the decisionmaker bears the ultimate responsibility of determining the level of risk acceptable to society commensurate with the benefits to be received. Although this concept of an "acceptable level of risk" often comprises the key issue of debate in many public policy decisions, such a determination must first be preceded by a well-informed analysis of the risk itself. The purpose of this paper is to discuss various of the basic elements in such risk assessments, that managers in the USDA Forest Service might take into account in their landslide related decisionmaking procedures.'

A DEFINITION OF RISK

Before discussing the various factors that might be taken into account in a complete risk assessment, the word "risk" should be defined. Unfortunately, "risk" is often used to represent several different concepts, as can be illustrated by the following three statements:

1. The risk of a landslide at milepost 2 is 1 out of 10 (that is, 10 percent).

2. The risk of a landslide at milepost 2 is that Fish Creek may be blocked.

3. The risk of a landslide at milepost 2 is simply unacceptable.

Statement 1 is a probability estimate that states the likelihood with which a specified

STEFAN D. BLOOMFIELD is a professor, Department of Economics, Oregon State University, Corvallis, Oregon.

event will occur. This probability (that is, the number 0.10) might result from a complex factor-of-safety calculation, or it might derive from an empirical process such as an on-site evaluation by an appropriate specialist. However obtained, the probability estimate alone does not indicate whether the Occurrence of this event is desirable or undesirable, or whether it is benign or severe in its consequences. As such, this statement does not constitute a risk assessment.

Statement 2 is the description of a possible hazard--something that causes danger, peril, or difficulty. The actual occurrence of this hazard may be quite likely or highly improbable. Simply describing such a hazard, however, does not by itself constitute a risk assessment.

Statement 3 is a judgmental assessment of the risk posed by the hazard described in statement 2 when the hazard occurs with the probability given in statement 1. Here we are defining risk as "exposure to the chance of injury or hazard." This definition, therefore, requires that both a hazard and a chance (probability) be specified in order to describe the risk. Thus, any risk assessment must explicitly consider both the severity of the possible hazard and the specific probability of that hazard occuring.

WHAT IS AT RISK?

Most of the literature on landslide management focuses on techniques for estimating the probability of landslides in different types of terrain, and on descriptions of the adverse impacts of such mass land movements. These studies allow the land manager to assess exactly what is at risk in a potential landslide situation. Such elements at risk may include any of the following:

1. Human lives. In risk assessments involving such decisions as the siting of nuclear power plants or the introduction of hazardous substances into the environment, human lives are the paramount element at risk. Historically, in landslide-related management decisions, the danger to human life was not a relevant concern except in isolated cases. As residential construction encroaches on forested lands, however, this may become a decisive factor in many land mangement decisions.

2. Private property. This category includes damage to houses, other privately-owned structures, items of capital equipment, and degradation of farm and grazing lands.

3. Public property. Included here are public roads, bridges, and other structures; economically important public property such as timber stands and waterways; and a wide range of "public goods" in the form of recreational opportunities.

4. The environment. This category provides the major focus of landslide-related, land management decisions, particularly as the decisions pertain to the maintenance of water quality and fish habitat.

5. The organization. One element at risk that is rarely given explicit consideration in land management decisions is the organization itself. In the private sector, of course, the very existence of the business or industry may be at risk of bankruptcy. Although the Forest Service faces no such terminal hazard, the organization is nonetheless at risk in the following areas:

a. Its reputation as an effective and trustworthy manager of public lands may be put in jeopardy.

b. The credibility of its analyses supporting controversial new management initiatives may be lost.

c. The opponents of specific management policies may become increasingly encouraged to pursue legal challenges to contested decisions.

d. It may be forced to cancel activities for which substantial planning resources have already been committed.

6. The job. Another element at risk that is rarely given explicit consideration is the decisionmaker's job. In the private sector, the loss of one's job is an ever-present risk knowingly assumed by management personnel. It is unclear in what sense any analogous situation exists in the Forest Service.

TYPES OF RISK

In estimating the risk to any of the above entities, we must carefully assess the context in which the risk becomes imposed. Four important considerations directly affecting risk assessments in land management decisions are background risks, incremental risks, marginal risks, and differing boundaries of analysis (see Crouch and Wilson 1982, p. 17).

1. Background risk implies recognition of hazards that may exist independently of any management decisions. In the context of slope stability problems, background risk refers to the occurrence of landslides and surface erosion (sometimes in substantial amounts) even in the absence of land management activities. A complete landslide risk assessment will include an estimate of the degree to which various of the entities listed above are already at risk from strict3y natural phenomena.

2. Incremental risk is a measure of the added risk, over and above the background risk, that would be imposed by the alternatives under consideration. In land management decisions, therefore, one would analyze the additional landslide risk resulting from proposed timber-related activities. A key methodological question in such risk assessments is whether the background risk should be "subtracted"--thereby basing the analysis solely on the incremental

risk from specific proposed activities--or whether the total (background plus incremental) risk constitutes a more appropriate basis for the analysis.

3. Marginal risk is a concept that encourages consideration of the cumulative effect of related decisions. In a land management context, rather than ask, What is the risk involved in developing a unit on this watershed?" one would ask, "What is the risk of developing the next unit on this watershed? or the fifth unit on this watershed?" Whereas the risk of an isolated management decision may be calculated to be quite modest, the combined risk of several management activities to a common watershed might very well be found unacceptable.

4. The boundaries of analysis determine how broadly or narrowly focused the risk assessment will be. In addition to having clear direct effects, land management decisions will typically have a wide range of indirect effects. Such secondary and tertiary effects will quite likely impose their own risks, which might appropriately be added to those of the direct decision. As an example, consider the risk to the Forest Service if logging activities on a large watershed were curtailed by court order. A direct result of this decision might be localized unemployment of loggers, drivers, and mill workers, with an associated wider impact on the region's economy. In addition to such direct effects, however, we might imagine several indirect effects on the Forest Service.

a. To achieve the required cut, there may have to be more intensive harvesting on some other watershed, which would result in a higher-than-planned environmental impact in these other areas.

b. The local unemployment might result in significantly increased fishing, hunting, and camping in the forest, with possible adverse impacts on the resources involved (such as from excessive fishing pressure or from forest fires).

The obtaining of the court order might encourage other special interest groups to increase their efforts at litigation and further divert Forest Service resources to respond to such legal challenges.

GROUNDS FOR DISAGREEMENT

Decisionmaking under risk would pose no significant challenge if all parties always agreed on the best alternative, but this is seldom the case. Kleindorfer (1982, p. 183) points out that disagreements among interested parties can arise from either of two basic sources: conflicts of fact or conflicts of values.

Conflicts of Fact.

Because an assessment of risk is based on estimates of the severity and of the probability of various hazards, either estimate can be a source of disagreement.

1. Probability estimates for a hazard such as timber-related landslides may provoke disagreement because different conceptual or mathematical models (such as different factor-of-safety formulas) are being used by the opposing groups, because not all the constants or coefficients for these models are known (and thus require subjective judgement), or because extrapolation from known data points is required (without agreement on the correct methodology for the extrapolation).

2. Severity estimates for a specified hazard may also be subject to disagreement stemming from a lack of sufficient experimentation or scientific observation of the hazard and its associated effects. This may provoke either disputes over the validity or existence of presumed causal connections, or disputes challenging the ultimate severity of the hazard itself.

Conflicts of Values

The values that play the dominant role in most land management decisions involve either threats to the safety and health of humans or possible adverse impacts on the environment. Each of the concerned parties in a decision may view such impacts from a different perspective and with a different set of underlying values and priorities. Although one might hope that continued scientific investigation can resolve many of the conflicts of fact, conflicts based on values will almost certainly remain a critical element of dispute in decisionmaking.

If conflicts of fact reflect disagreement over the question, "Exactly what is the risk?" then conflicts of values motivate the question, "Is the risk worth taking?" To answer this question, it is necessary to identify whose values and priorities are to be decisive. If the central mission of the Forest Service is the effective management of the lands under its jurisdiction, then this requires identifying for whom these lands are being managed. Such a people-oriented perspecitve requires that the previous framework of analysis be restated; the focus of the risk assessment shifts from a concern over what is at risk, to an analysis of who is at risk.

WHO IS AT RISK?

When considering the groups of people at risk in landslide-related land management decisions, the temptation is to limit the analysis to those individuals adversely affected by the destruction of terrain, degraded fish habitat and reduced water quality, and economic displacement resulting from possible landslides. A more comprehensive analysis, however, would equally acknowledge the risks to individuals resulting from policies of restricted harvesting to minimize landslides. The individuals at risk in these land management decisions include the following groups:

1. Local Residents. Some residents of the local area might be at risk from the direct physical effects of a landslide; effects that include damage to privately owned structures and equipment and the effective loss of real property and domestic water supplies,

2. Local Employees. Employment may be temporarily interrupted by physical damage from landslides. A decision to reduce harvesting as a means of landslide control would clearly be much more damaging to the local employment situation, however: individuals would be at risk from a wide range of economic impacts that would affect not only workers directly involved in wood products industries, but ultimately the region's entire retail and service sectors.

3. Recreation Seekers. An entire class of recreation seekers and recreation providers is at risk from loss of fish habitat and forest access that might result from landslide acitvity.

4. Future Generations. One of the most difficult factors to incorporate into risk assessments for land management decisions is the time scale of an adverse impact, Evaluating the **degree** to which future generations, as distinguished from the present population, are at risk requires accurate estimates cf the effective duration of the adverse impact and appropriate incorporation of such information into the risk assesment process, Such analyses are important for decisions in which relatively severe environmental impacts might still be found to be "worth the risk" if the environment were capable of being restored to its previous condition within a relatively short period of time. For example, a potentially severe **loss** of fish habitat might be judged an acceptable risk if it were shown that the habitat and associated fishery would return to its prior condition well within a decade.

Although we have suggested addressing the question "Who is at risk?" as a basic strategy for the assessment of risk,, it is worth emphasizing that risk is a pervasive condition under which we all exist. People are at risk every moment of their lives, not only from possible adverse consequences of their own actions, but also from direct or indirect effects of the decisions of others. Accordingly, it is totally unrealistic to seek a decisionmaking strategy under which individuals are not put at risk. But even if one accepts the premise that putting individuals at risk is an inherent and inescapable element of any decisionmaking, it is important to understand the special factors in public policy decisions that can make risk assessment such a controversial and emotional process.

PSYCHOLOGICAL FACTORS

Many studies have identified factors that appear to affect the public's assessment of risks in public policy decisions; see, for example, Slovic et al. (1980) and Kunreuther (1980). Most such studies, however, have focused on decisions involving potentially dangerous and controversial issues such as the siting of nuclear power plants or liquefied natural gas terminals, the introduction of toxic substances into the environment, or the exposure of individuals to suspected carcinogens. For these decisions, a set of psychological factors has been identified that appear to assume great importance in influencing public decisionmaking. Although the applicability of these factors to landslide-related land mangement decisions is in some cases only marginal, they are worth summarizing here. (For a more complete treatment of this subject, see Lathrop [1982].)

1. Possibility of Catastrophe. What seems to differentiate a catastrophe from other similarly adverse circumstances is some sort of "bunching" of events, whether bunched by cause, by location, by period of time, or by state of nature. For example,, the most severe accident that could conceivably occur at a nuclear power plant might cause the near-simultaneous death of a large number of **people** within an area and would certainly be considered a major catastrophe. Yet more people, by far, die every year from traffic accidents or from the effects of smoking without provoking even a fraction of the public concern aroused by the extraordinarily low probability "catastrophic" hazard. This psychological phenomenon forces public policy decisionmakers to bias risk assessments away from catastrophic events, even though their probabiliy and relative adverse consequences might otherwise qualify them as quite acceptable risks by other societal standards.

2. Considerations of Equity. In public policy decisionmaking, risk assessments can also be stongly influenced by the public's perception of equity in the risk. There are at least two types of equity considerations that might provoke such public concern.

a. Many public policy decisions would cause the risks to be borne by a different segment of the population than would receive the benefits. Such inequity, for example, exists when a power plant located in one populated area sends its generated power to a distant metropolitan region. (One assumes that this distinction becomes less persuasive, however, when the population exposed to the risk voluntarily make their livelihood by virtue of that activity.)

b. A second type of perceived inequity would result from the possible identification, as part of the risk assessment, of specific individuals who will be adversely affected. As an extreme example, a public policy decision that would very likely result in one additional death annually in the local vicinity might still be considered an acceptable risk, whereas a similar decision that would result in the death (with the same high probability) of a single, clearly identified individual would almost certainly be declared unacceptable.

3. Voluntariness of risk. As just suggested, *the* consideration of equity in risk assessments is strongly influenced by perceptions of whether or not the risk is assumed voluntarily. This determination, in turn, is often **closely** linked to the question of necessity of exposure to risk, which defines the degree to which the risk can be considered to be voluntarily assumed by the individuals so exposed.

4. Participation in the decision. It is understandable that the acceptance of risk assessments in public policy decisions often depends on the degree to which affected parties feel they have participated in the decision. The ultimate impact of such participation, however, is often constrained by the range of alternatives available to the decisionmaking authority.

5. Attributability of the risk. A given risk may be more easily tolerated by the public when no specific entity can be identified as the cause of possible adverse impacts. It is easy to imagine a variety of severe environmental disruptions that would be considered unfortunate, but not disastrous, if they were the result of an unforeseen "act of God," but which would prompt cries of outrage and would be charctcrized as total ecological disasters if traceable to specific human interventions.

6. Nonprobabilistic Reasoning. This phrase expresses the tendency of some individuals to forsake probabilistic reasoning altogether in their assessment of certain types of risks, and instead to base the decision solely on descriptions of the maximum potential. hazard irrespective of its probabilty of occurrence. In some cases such behavior may result from an individual's inablity to understand probability estimates or to comprehend adequately the meaning of extremely low probabilities, In other cases, the individual may simply doubt the accuracy of the probability estimates and choose, therefore, to ignore such estimates in analyzing the decision. Another explanation that should not be neglected, however, is that even at extremely small probabilities some hazards may be so dreadful to contemplate that persons so exposed would lead lives of constant fear--even if it were totally irrational to do so. If one accepts the notion that dread constitutes a social cost, then such considerations will inevitably influence public policy risk assessments (see Burness 1981).

7. Familiarity of the risk. The problem of nonprobabilistic dread tends to diminish as the risk becomes more familiar. In many cases the degree of public concern also diminishes. Almost by definition, the most familiar risks will be those that occur the most often, and this brings our discussion back to the first. point mentioned in this section: familiar risks tend not to be considered catastrophic and, at the extreme, simply become part of the background risk that is accepted as a normal part of one's existence. So it is, for example, that traffic fatalities (which claim more than 50,000 lives in this country each year) and smoking (which results in an annual death toll estimated at 150,000 lives) have become such familiar risks as to be virtually ignored in the everyday risk assessments of ordinary citizens.

CONCLUSION

This paper has not attempted to answer the question What specific level of risk is acceptable for landlside-related land management decisions?" nor is it likely that such a question could be answered in any general fashion. It is obvious that public policy decisionmaking; in the presence of risk cannot be treated as a process depending solely on mathematical analyses of risk factors, but must be seen as a process incorporating complex, and often decisive, psychological and political considerations. This paper has focused on various of the nonanalytical elements to which the decisionmaker should be sensitive when assessing risks and presenting potential risks to the public.

There is, of course, the need for managerial understanding of the way in which a mathematical analysis of risk enters into the risk assessment methodology. Several papers' describing specific methodologies for risk assessment appear in Kunreuther and Ley (1982). Of particular interest are descriptions by Mandle and Lathrop (1982) of different types of analyses used in risk assesments for the siting of liquefied natural gas terminals, and an account by Oseredko and others (1982) of the analysis for the routing of a main gas pipeline. An extremely detailed presentation of the mathematical analysis needed to support a major public policy decision (in this case, the siting of nuclear power facilities) is presented by Keeney (1980).

LITERATURE CITED

Burness, S. Risk: accounting for an uncertain future. Natural Resources Journal. 21(3):723-734; 1981.

Crouch, E.; Wilson, R. Risk/benefit analysis. Cambridge, MA: Ballinger Publishing Company; 1982. 218 p.

Keeney, R. Siting energy facilities. New York: Academic Press; 1980. 413 p.

Kleindorfer, P. Group decision making methods for evaluating social and technologicad risks. In: Kunreuther, H.; Ley, L., eds. The risk analysis controversy. Berlin: Springer-Verlag; 1982: 181-194.

Kunreuther, H. Societal decision making for low probability events: descriptive and prescriptive aspects. Working Pap. 80-164. Laxenburg, Austria: International Institute for Applied Systems Analysis; 1980.

Kunreuther, H.; Ley, L. The risk analysis controversy. Berlin: Springer-Verlag; 1982. 236 p.

Lathrop, J. Evaluating technological risk: prescriptive and descriptive perspectives. In: Kunreuther, H. ; Ley, L., eds. The risk analysis controversy. Berlin: Springer-Verlag; 1982: 165-180.

Mandle, C.; Lathrop, L. Comparing risk assesments for liquefied energy gas terminals--some results. In: Kunreuther, H.; Ley, L., eds. The risk analysis controversy, Berlin: Springer-Verlag; 1982: 41-60.

Oseredko, Y.; Larichev, O.; Mechitov, O. Main gas pipeline route selection problems, taking into consideration risk and uncertainty factors. In: Kunreuther, H.; Ley, L., eds. The risk analysis controversy. Berlin: Springer-Verlag; 1982:91-102.

Slovic, P. ; Fishchhoff, B. ; Lichtenstein, S. Facts and fears: understanding perceived risk. In: Schwing, R.; Albers, W. Societal risk assessment: how safe is safe enough? New York: Plenum Press; 1980: 181-214.

PANEL DISCUSSIONS--LIMITATIONS AND NEEDS FOR EFFECTIVE LAND MANAGEMENT RISK ASSESSMENT OF POTENTIALLY UNSTABLE TERRAIN

Question Before Panel 1: What levels of political/social influence on "risk" are appropriate in forest land management decision-making?

Speaker 1: DAN BIGGER—This question is provocative, but difficult to address. The Washington State Department of Natural Resources is concerned, both as a forest land management agency and as a regulatory agency, about unstable forest land. My response to the question involves the department's regulatory role and is guided primarily by the language and purposes of the Washington Forest Practices Act (Chapter 76.09 RCW) and the Forest Practices Rules and Regulations (WAC 222).

The Forest Practices Act defines public resources as water, fish, wildlife, or State and local government capital improvements. All reasonable methods of technology are to be utilized in the protection of forest soils and public resources while recognizing both public and private interests in profitable timber management.

The varied purposes of the Act and regulations require the department to exercise judgment and to specify the preventative or corrective actions or the mitigation measures necessary to minimize damage to public resources. To be effective, the regulations must be administered in a reasonable manner and the department needs the active support and cooperation of forest landowners and timber harvesting operators.

Forest practices that displace significant amounts of soil and rock on unstable slopes are regulated and the department will analyze soils hazards, proposed road construction and timber harvest operations. The department will recommend feasible mitigation measures that may include alternative proposals for roads and harvest methods.

Although not specifically addressed by forest practice regulations, the department will also consider risks to life and property,. cumulative effects of harvesting on-site and off-site, and the political consequences of slope failures. Where the forest practices rules require mitigation of potential damage, but no feasible methods exist, an environmental review process may be required. Where the State Environmental Policy Act (Chapter 43.21 C RCW) and Rules (WAC 197-11) govern, an environmental impact statement may be required and the proposed forest practice is subject to approval or disapproval based on environmental considerations. Environmental considerations include much more than protection of public resources.

There are few tools and limited technology to assess the potential of slope failure on forest lands. Fortunately, Washington has a comprehensive soil survey, and unstable soils have been identified and mapped. Soil interpretations have been developed and field personnel have received introductory training. Some of the problems have been identified, but reliable solutions have not. Regulations, alternatives for road construction and harvest

---

DAN BIGGER is staff forester, Division of Private Forestry and Recreation, Washington State Department of Natural Resources, Olympia, Washington.

methods, and various mitigation methods only help reduce slope failures. There are no guarantees that any of these approaches will be successful, The department and landowners must contend with possible slope failure site by site.

Speaker 2: PAUL SWATECK--The long tradition from which today's conservationist comes stresses stewardship and wise use of natural resources. This immediate generation has responsibility to utilize renewable natural resources in a fashion that passes the resources on to the next generation with productivity unimpaired. Conservationists see a forest as a community of soils, vegetation, animals, air and water — interdependent and linked. Society's responsibility for stewardship reaches beyond human concerns to the protection of the integrity of this community for its own sake.

To a remarkable extent, the public has embraced these conservation values. The statutes in this country require evaluation of potential environmental impacts through the preparation of impact statements, call for multiple use of our forest lands, and regulate activities on both public and private lands to protect public health and prevent nuisance. This society requires reclamation of strip-mined lands. There is a recognized public interest in protecting navigable waters. The states look out for wildlife, Our government operates by a set of administrative procedures that gives the public rights to participate in decisionmaking regarding environmental matters, and a strong network of groups dedicated to the protection of nature try to follow and influence activities affecting their interests.

This is the context in which decisions about forestry operations are made. Assessing the risk of mass failure from roading and timber operations is not just a technical matter to be handled by the engineers. It also needs input from fish and wildlife professionals, from those concerned with water quality, from land use planners,. and from the general public that uses the resources affected. There are social, political, and even ethical considerations beyond the technical dimensions to assessing risk.

It is important to recognize that risk is not just a question of probabilities. The probability of slope instability may be low in absolute terms and still be unacceptable to a party being asked to absorb the impact of failure while deriving no benefit from the activity precipitating the failure. This is to say, there are important distributional dimensions to assessing risk. Too often, interest groups desiring to obtain a benefit for themselves are willing to overlook the problems that fall to others. The problem may be loss of fish spawning beds, decline of water quality, or loss of recreational amenities. Other parties may be commercial fishermen, sportsmen, recreationists, or neighbors. These parties must have access to the risk assessment process and to the making of risk-taking decisions, when they desire it, for their interests to be protected adequately. They need to be assisted by the best technical, and engineering and legal expertise available. Conservationists believe however,. that the assessment is best done as an interdisciplinary exercise and integrate technical, biological, political, social, and ethical considerations.

There are various ways to resolve potential distributional risk problems. The one that is unacceptable to conservationsts is to ignore the risk and let the victims of failure end up bearing the costs of failure. Most situations present a system of potential tradeoffs among the interests involved. If all affected, parties are involved and empowered to affect the outcome, it is often possible to negotiate an acceptable compromise. A set of uniform rules to establish basic protection is desirable to provide a standard of performance for industry and to protect underrepresented interests.

There also needs to be a mechanism for dealing with failure. Repair of problems arising from mass failure can be very expensive. A system of liability for the operator who derives the benefits of the risk-imposing activity and penalties in the event of failure is needed both to pay for rehabilitation and to create an incentive for good performance. Bonding requirements and liability insurance, tied to an improved technology for assessing risks, and proper incentives for good performance are needed to allow the carrying out of risk producing activities acceptably.

Conservationists recognize that natural systems are dynamic. Preservation of the status quo is not natural or even desireable in every instance. Mass failure is a part of the natural cycle of many watersheds. We have found, however, that human activities which accelerate natural geological processes too much can overwhelm natural restorative processes. These activities usually have complex cumulative effects that make it difficult to establish cause-and-effect relationships. Managers need to gain a better understanding not only of the assessment of the risk of mass failure but also to learn more about natural restorative processes and how to conduct repairs when necessary.

Conservationists support this kind of conference. I have been the environmental cochairman of the Western Forest Environment Discussion Group, which has representatives from conservation groups and the timber industry in the Northwest. The group has been involved in a dialog for 7 years. Field trips were conducted

---

PAUL SWATECK was conservation administrator for the Sierra Club in San Francisco from 1975 to 1983, and served as environmental co-chairman of the Western Forest Environmental Discussion Group. He currently resides in Lafayette, California.

in 1980 and 1981 to review mass failure problems and approaches for improving risk assessment technology.

Conservationists want to see the most knowledgeable experts in geology, soils, hydrology, engineering, and other, relevant disciplines meet and learn from one another and improve understanding of the processes involved in mass failure and predictive capabilities. We want to see biologists join in assessing the impacts of mass failure on the streams and rivers and to the wildlife populations. We want this technical information made intelligible and available to the public and government decisionmakers who grant permits for risk-producing roads and timber harvests. We want the public to be involved.

If managers are smart in doing this work, they will preserve the land and soils base, maintain the harvest, reduce avoidable adverse environmental impacts, and reduce conflict.

Speaker 3: R.T. BAILEY--The question of what levels of social/political influence are appropriate in risk decision making on unstable forest terrain must be put in its proper perspective. Many novices in the world of forest land mangement hold the false conviction that nearly all the mountainous forest land in the west is unstable and any management activity will cause landslides and severe erosion. It is therefore important to understand the relative magnitudes of "high-" and "low-risk" terrain.

Over the past few months I have been heavily involved in what is known as the "Mapleton Lawsuit" in which the National Wildlife Federation brought suit against the Mapleton District of the Siuslaw National Forest in the Coast Range of Oregon alleging violation of the National Forest Management Act, Multiple Use Sustained Yield Act, the National Environmental Policy Act and the the Church clearcutting guidelines. The National Wildlife Federation charged that the forest soils of the Mapleton District are among the most erodible in the United States and that unacceptable resource damage to the soils, watersheds, and fish habitat would occur as a direct result of harvesting on unstable, "high-risk" soil types.

Although many acres of forest land in the west are perceived as being "unstable" by the public, in reality only a very small percentage is actually in that category. For example, out of the 16 million acres of commercial forest land in the USDA Forest Service, Pacific Northwest Region (Washington and Oregon), only 184,000 acres are considered unsuitable for timber production because of the potential for irreversible resource damage--only about 1.1 percent. The supposedly erosive Siuslaw National Forest; has only 14 percent of very high risk lands, while only 0.3 percent of the land base is in actual landslide area. Is undue attention given to this issue? Are we as managers putting 95 percent of our effort on only 5 percent of the problems? And even though landslides do occur, are they causing any damage to the water or fish? I don't know the answer to these questions, but even if professional resource managers get most of the criticisms on that 5 percent of the land base, they must not forget the real and difficult problems on other lands as well.

R. T. BAILEY is director of planning and special projects, Industrial Forestry Association, Portland, Oregon.

Risk in Resource Management

Other speakers here have talked quite extensively about what "risk" is and what "instability of slopes" means. What I want to talk about is the importance of protecting assets in the face of uncertainty. Perceptions are sometimes more damaging than any action, particularly with respect to land management. I've beard, seen, and discussed with many people their perceptions of objectives of industrial forest-land owners. To sum it up briefly, the mythical timber baron lives in the public conscience—I might add, in the minds of some of the regulators and public agencies as well.

What does this mean in terms of risk? The perception is that the timber landowners will risk a great deal to be able to supply their mills or markets with wood, regardless of the land management restrictions imposed along the way. After interviewing 8 timber industry executives, I confidently say that' nothing could be further from the truth!

The industrial land manager (or owner) is responsible for a tremendous asset, that, at his disposal, must be managed in a prudent manner or it loses value. The manager has a great interest in preserving the land to grow trees because the product and returns from this asset are the ultimate objective. Landslides are usually not the most productive sites for growing trees. The asset value is the lynch pin upon which all decisions must pivot, but that is not to say that all factors in the decision are monetary. There are a host of factors in each decision regarding unstable land that are not monetary.

The managers want as stable a road as possible—roads require a heavy initial investment which must be protected. Any road that slides because of poor design or maintenance becomes another unnecessary problem to pour more money into. As the past few years have shown, money is scarce.

Where does this leave the manager in terms of risk in decisionmaking? Again, a little perspective is necessary. There is nothing in this world without risk. Just as there's a risk in driving to work each morning so, too, is there risk in building roads and harvesting timber. In the investment world, people are known as "risk takers" or "risk averters"--takers invest more in volatile stocks (new issues, common stock, etc.); averters invest in stable items (municipal bonds, preferred stock, established companies).

Each of us lives in one of these risk classes—some of us prefer higher risks in some things and lower in others. There is no activity or action that is without risk. The cost of a relatively risk-free society would probably exceed the total U.S. Gross National Product. Many in the environmental movement or in Government may prefer that a lower "risk" be taken in resource management activities (for example, large buffers, minimal harvest, lots of mitigations) while at the same time, they may live their lives under a different risk preference. Mr. Swateck, of the Sierra Club, for example, sitting next to me, may prefer a lower risk in resource management, but he also happens to work in San Francisco. You wouldn't get me to live in California along the San Andreas Fault--it is too risky--that place is going to fall into the ocean!

The Forest Service people, State people, and industry people all have (as a class, if you will) a different risk preference that has developed through growth, personal experiences and organizational goals. While some in the public agencies have adopted the "infinite value syndrome" (that is, avoid all risk in certain areas, regardless of the cost), the industrial owner cannot afford that stance. While an agency manager may avoid unstable lands or difficult to reforest lands and remove them from the timber base (with purportedly no cost), the industrial landowner pays taxes each year on those acres, and in addition, has a large initial investment in them. If a reasonable return can be made, it should properly be sought. Thus the attitude shifts to how can these objectives be met. It may cost more and be more "risky" to operate on unstable lands, but a can-do vs. a can't-do attitude prevails. The weighing of social goals, such as wood for markets and homebuilding vs. the amount of risk on the landscape, is always a factor in the back of the decisionmakers mind.

Risk Factors

What are the risks in managing unstable lands? From an industrial perspective, the risks of losing land or roads through poor management decisions not only affect the asset value of land that managers are entrusted with, but may lead to a host of other negative implications that may be more serious, long lasting, and risky than just the physical impacts of a landslide. What I'm talking about is the ever-present risk to industrial landowners of the political reaction. The expense of environmental litigation with the attendant removal or limitations on private property rights is always there as is the ever-present increased regulatory threat. Changing public policy, tax rate determinations and increases, land use zoning, a biased media, and a credibility gap are also important parts of the "risk equation" that the industry operates under. Benefits and costs loom large in each decision, yet the cost factor is not all in dollars.

A potential risk factor that may seem extreme to some of you is the nationalization of timberland, including private lands. A push for timberland nationalization occurred in the early part of the 20th century when there was a strong belief that we were headed for a timber shortage and only nationalization and federal control would solve the problem. In fact, the origins of my organization trace back to this period and an effort at self-policing the industry for proper forest management standards. The National-Tree Farm Program also got started at that time for much the same reason.

So risk takes many forms in the industrial perspective. No one likes to be told what to do, but this is always a threat. The stockholders (investors) of a company are very aware of the implications of mismanagement or increased social and political pressure and they do react by changing their investments.

One final note on unstable lands. It must be remembered that the mountainous regions of the West, indeed everwhere, are a function of uplift and erosion. If a slide occurs on the landscape, there's a good probability that the same land has slid in the past. Thus, the question becomes "how much does land management accelerate landsliding?"

During the Mapleton District lawsuit, several hydrologists commented that while it's entirely probable that management activities may alter the timing of an event and increase erosion rates over a short time period, long-term average rates are not increased or altered at all. Landslides are an event of nature and impacted areas nearly always recover, and while harvest activities may alter the equation a little bit, such activities are not going to overshadow these natural events. The Mount St. Helens eruption, the forest fires around Tillamook, Oregon in the 1930s and the great Pacific Northwest floods of 1964 all remind us of these natural events. In addition, the question of actual, physical, measurable damage must be answered. Landslides occur, but if they did not damage anything, how concerned would we be?

Changing Knowledge

Managers and practitioners are learning more about harvesting and building roads in relatively unstable land. Much effort by both public and private interests has been made to improve our abilities for avoidance and mitigation of unstable terrain. Improved road design and better maintenance programs combined with an ability to identify unstable situations have contributed to less problems for management. Private landowners share, along with the public and public agencies, a land ethic that requires prudence in managing the Nation's timber resource.

While each of us has our particular biases and preferences, we must not misuse science to achieve personal goals. There's already too much of that as the Mapleton suit demonstrates. Science must be kept objective or it helps no one.

Speaker-4: JOHN T. DRAKE--There is no single appropriate level of social or political risk. Risk is always there in varying degrees and often dictated by outside factors. As I see it, an acceptable level of risk is highly dependent on the sensitivity of the area, on resource values, and on the social and political setting. I might also say that from the National Forest perspective, risk varies significantly based on whether an issue is national or local.

There has been considerable discussion on risk during this workshop, but "risk" needs to be broken into components to be understood. Certainly the physical risk or resource risk is something the Forest Service has dealt with for some time. It can be defined reasonably well. Defining the political and social risks is much more difficult, and interrelationship of these two influences complicates precise assessment. I think the most productive approach, so far, has been to try to keep the total physical risk as low as possible while maintaining the economic viability of a project; both of these factors adjusted to reflect the needs and requirements of current political and social concerns.

At the practical level, the forest land manager must handle the existing risk with the given restraints rather than contemplating what is an appropriate level of risk to deal with. I think it is important that practicing forest land managers recognize risk is there; understand the level of risk acceptable under existing physical, social and political constraints; and try to deal with risk in as positive a manner and as early and as openly as possible in the planning process.

Speaker 5: NEIL SKILL—Let me talk to you about the social and political arena the State Department of Forestry operates in when administering the Forestry Practices Act in Oregon.

JOHN T. DRAKE is supervisor, Gallatin National Forest, USDA Forest Service, Bozeman, Montana.

NEIL SKILL is assistant state forester, Oregon State Department of Forestry, Salem, Oregon.

I think that society has come to realize, and experience in management of state lands has shown, that the public welfare cannot be adequately protected by leaving the entire matter of forest managements on private lands to private enterprise. What is needed ideally is the establishment of public policy that will prohibit or reduce the possibility of exhaustion of a particular resource for private economic or limited interest purposes. Such policy should also prohibit significant lowering of our standard of living as we try to use that resource now and in the future. And finally, if there is a potential for exhaustion, the policy should institute controls or remedies now that will prevent exhaustion in the future.

This is a difficult job to accomplish. It is not uncommon for those of us faced with management of state forest lands to resort to some kind of regulation, such as the forestry practices acts that we see in states having a major forest industry. This is done as well at the Federal level; for example, the Federal Water Pollution Control Act, the Clean Air Act, and the Resources Planning Act. Even at the local level there is a trend toward more effective landuse planning by counties and municipalities.

I don't think there has ever been an entirely successful public policy to deal with natural resource protection and allocation, largely because there has never been a clear definition or understanding of what natural resources in the United States ought to be. Managers like to think that economics is a controlling factor in this definition, but actually political, social, and environmental factors may have equal or greater importance depending on individual points of view. From a public agency perspective, there is no choice but to deal with all of these factors in as unbiased a fashion as possible. There is no real separation between economics, politics, and public welfare; all are closely intertwined and all may be in conflict. I suggest that there are four distinct areas of conflict to deal with in any kind of development and administration of public law operating in the area of stability management.

The Role of Government

Over the years of development and administration of the Forestry Practices Act in Oregon, a whole range of people and organizations have attempted to influence the policy-making process. The Oregon Department of Forestry trys to respond to each of the sometimes conflicting needs or demands, but because of the poorly defined grey areas encompassing these various concerns the State must rely heavily on the political process for final formulation of policy decisions.

The Role of Special Interest Groups

Special interest groups perform the very necessary role of bringing various individual points of view together and putting them into some sort of framework understandable by a decisionmaking body. The problem that policy makers on the Board of Forestry face is trying to determine which group's interests are to be sacrificed. In making such determinations, the question of allocation becomes a very real thing that has to be dealt with. Here help is needed from scientists and technical field specialists.

The Role of Science

Science is a tool that managers have tried to use with various levels of success. As in other areas of resource policy, though, managers find that science does not always have the answers that are needed. Management needs basic information, facts, in a format suitable for making effective policy decisions. As we have heard in this workshop, there is good information available but there are still many areas that need work. Many scientists apparently have their own biases and tend to substitute their own objectives and data interpretations for those of society. This just confuses the issue.

Planning for the Future

To develop an effective and evolving resource management policy managers must somehow predict what is going to happen in the future. Herein we have major problems simply because with the existing level of knowledge it is necessary to make vague assumptions and use these to develop methodologies that have not been fully tested. When applying these methodologies, managers are imposing restrictions on the use of resources now to protect the future but without adequate justification. This is a major social-political conflict and much more information is needed to justify the regulatory decisions currently being imposed.

My final answer to this panel question is that there is no appropriate level of political and social influence on risks. In terms of the Oregon Forestry Practices Act, public policy is made by a number of people and groups acting to influence their particular positions or their points of'view. What the Oregon State Department of Forestry has to do is provide every oportunity for people to have access to the decisionmaking process. State, community and public needs and demands must be weighed and the best possible decision made to minimize risk given the existing social and political environment. The agency also needs to maintain a constant search for improved techniques to reduce adverse social and political impacts from policy decisions.

Question Before Panel 2: How do the concepts of risk influence field decisions?

Speaker 1: SOTERO MUNIZ—The question before Panel 2, stated another way, is, how do managers cope with the problem of assessing slope stability risks in their land management decisions? Land managers, by the very nature of their responsibilities, cope with risk assessment daily. Because risks are assessed daily, the skills managers surround themselves with are one expression of the manager's assessment of the risks. For example, a public land manager whose lands are laden with fuel and have a history of wildfire will organize, staff, and budget for the expertise and tools necessary to minimize fire risks and, therefore, losses. Another manager with different combinations of resources will organize, staff, and budget differently, but will concentrate capabilities in those resource areas with the greatest values and subject to the greatest losses; the objective is to minimize risk.

Risk assessments by managers always involve a blending of subjective and objective data from the manager's own expertise, from the scientific disciplines, and from the expertise of the involved staffs.

The points made thus far are that managers assess risks daily and that judgment and decisions depend on the synthesis of the subjective experience, objective data, and analysis.

Managers have extreme difficulty in coping with problems of slope stability if subjective experience is limited and objective data is lacking. Scientists and technical specialists make the manager's job difficult, if not impossible, when the language used is too technical or too specialized and the recommendations are tentative or inconclusive,

One principle purpose of this workshop is to expose managers to relevant, state-of-the-art information about slope stability. This exposure will increase the manager's knowledge and experience and, therefore, improve the decisionmaking process.

If the manager's needs for information on quantifying risks are known, then criteria can be established for organizing the broad and hetrogeneous body of knowledge on slope stability into its most useful form.

I've listed some of the needs and conditions facing managers today in order to clarify what I believe needs to be considered as the concepts of risks and their influence on field decisions are

---

SOTERO MUNIZ is director of engineering, USDA Forest Service, Washington, D.C.

addressed.

1. All managers are implementing cutback management. As a result, managers do not need and cannot accommodate recommendations to:

a. Increase technical staff or

b. Undertake extensive new inventories or land classifications to map unstable terrain.

2. Managers need clear and uniform guidance from higher organizational levels on particular data that is required for slope stability-affected decisions. For example, if higher levels of organization need to know how many acres of land have been subtracted from the productive land base because of slope stability problems, the managers need clear definitions of terms, categories, and direction on how to display the results.

3. Managers need to hare a body of knowledge to assist them in analyzing slope-stability related problems. This knowledge must be made "user friendly" and must synthesize geology, hydrology, pedology, soil mechanics, and risk analysis.

4. Managers need to minimize data collection needs. They therefore need to use, as much as possible, associated data that has been inventoried for other purposes to satisfy slope stability questions.

5. Managers need to know if advanced technology is available to help with slope stability recognition, evaluation, and analysis. If remote sensing, color infrared photography, and associated technologies ere available, managers need guidance on their effectiveness, costs, and availability.

6. Managers also need some guidance on the best source of expertise available. In some instances, this is self-evident — but what does a unit do that may have some problems but no technical experts?

7. Managers need to know what kind of training is needed and available to develop the level of expertise needed for making decisions regarding unstable lands.

I'm not fully conversant with the content of the extensive "Interstation Soil Mass Movement Research Program" begun in 1972. Perhaps some of the managers' needs listed here have already been accommodated. If they haven't, it may be timely to update the needs of managers and adjust future efforts to satisfy these needs.

In conclusion, knowledge and risk are intimately and inversely related. The challenge is to define the affordable boundaries of knowledge needed to manage unstable lands. As these boundaries are narrowed, the managers can continue to be relied on to approach risk-taking situations as directly as they always have, but with more competence and confidence.

Speaker 2: **LEO W. WILSON**—As director of Forestry Practices in the state of Oregon, I deal directly with a unique group of professionals. They are loggers. Somehow in their daily activities they have to make money, and this fact is very influential in their operational decisionmaking. I want to approach the question before this panel from the perspective of such operators.

The Oregon State Department of Forestry deals with over 11,000 operation notices a year, about the same number as the State of Washington. Most of the logs are moved by contract loggers working for private companies and often working on State, private, and public lands. A great many of the things happening to these operators are determined by the Oregon Forestry Practices Act. Operators must comply with the Act and attempt to make money in the process. The biggest single factor facing them is an adequate assessment of risk before they enter unstable pieces of terrain. As a public agency the Oregon State Department of Forestry must assist them as effectively as possible in avoiding trouble. This must be done while recognizing that they are a private enterprise and have to make a profit to stay in business.

A major problem facing these people, particularly in relation to construction of forest roads, is that building roads in unstable terrain is expensive. Engineering design costs are higher in unstable terrain, and full-benching, end-hauling, bin-wall construction, and other mitigation techniques are added expenses. Many times, operators will get into a contract situation where they must have a road from point A to point B to reach the logs and take them to a mill. In the process they may not recognize the risk they are getting into. The geotechnical expertise necessary to design such roads at minimum risk many times is not always available. Managers and specialists with the Oregon State Department of Forestry know that many of the stability problems in Oregon, particularly in the Coast Range, are road related. One of the new rules passed by the Oregon Board of Forestry and promulgated in September 1980 states that operators will minimize road construction. That is fine, that is a very noble goal. But a great many of the needed road systems are planned or constructed to accomodate a particular company's existing logging systems or equipment they have available. To minimize road construction may require shifting to different systems at a tremendous cost to the operator.

Another problem that is a concern when dealing with land owners of smaller parcels and limited capital is that we are going to have some soil mass movement because of natural erosion processes. It is necessary to convince such

---

LEO W. WILSON is director, Forestry Practices, Oregon State Department of Forestry, Salem, Oregon 97310

land owners that some things they do will accelerate the process more than will others and that the increased costs or revenue losses incurred to reduce accelerated soil mass movement are necessary.

Something that is very difficult to deal with in the private sector is the requirement of leaving some ground uncut, or virtually uncut to prevent landslide damage. These problems and the costs of special yarding techniques, debris removal, and relocation of landings to reduce risk constitute major economic burdens on the operator and land owner.

The land owner and operator will become increasingly involved with damage litigation and repair to streams impacted by debris avalanches,

Cost analyses by the operator for many of these practices are going to be very difficult. Conclusive research results that can be applied are not always readily available. The decision on whether or not to log some areas may ultimately be based on whether or not the logs can be obtained elsewhere for less cost.

These are only a few of the factors used to consider risk from harvesting on public and private lands in the State of Oregon. All are important. There are no simple solutions or easy decisions. It costs more money to operate on unstable ground and, as costs increase, each decision becomes more important. When the operational "break-even" point is reached, the decisions become critical. Operating on unstable terrain will require careful planning and careful decisions at every point of the process.

Speaker 3: MELVIN L. KESSEL--Depending on the degree of the predicted risk, decisions are made to defer a project or to proceed with a project and to accept the risk. If the decision is made to proceed, usually every practical means is taken to mitigate the risk to acceptable levels. The perceived acceptable level of risk differs with individuals. Some managers will choose to cut trees while other managers will walk away. Decisionmakers have various comfort levels with risk. One may be very comfortable operating mostly with high-risk decisions; another may want everything guaranteed. There is a pitfall here. In this workshop we saw some formulas on how to determine certain things through engineering. Some managers believe that you can get answers that are either right or wrong from such an approach. I do not believe that. I think you get grey areas that are neither right nor *wrong*, but that provide indications of which direction a decision should go.

Two things managers have to determine are the "comfort level" acceptable to them when they harvest trees and the "comfort level" when they say they can't harvest trees because of unacceptable risk. When making these determinations they must be able to convince their supervisors that assigned targets cannot be met.

The size of a project can influence how much risk a manager is willing to accept. If it is a multimillion dollar project and the impact is $1,000, the managers will probably take the risk. If the project is several thousand dollars and the impact is the same, the risk may not be acceptable. These considerations have to be weighed. Another important factor, which I feel affects how much risk to accept, is how long the risk may last. How quickly will the land heal?

The last thing that I think influences operational decisionmaking is how acceptable will the current decision on risk be in the future? I have been told that sometimes litigation with the Forest Service is like shooting at a moving target. The Forest Service plans things and 6 years later, sees the results. Then the lawsuits are filed for our past decisions. The decisions were initially made based on the best information then available, but things change: Research and experience increases knowledge in the intervening time. We need to be aware of this and take it into account in our decisionmaking process. Listen to the experts. Listen to what they know and don't know so you can make decisions on that basis.

Speaker 4: JOSEPH H. HARN--Land managers are continually confronted with the need to address the question of "risk" for all resources, not just for timber. They must also deal with a high degree of ambiguity. This requires a committment of resources and effort to gain certain types of information necessary for risk assessment. For example, if the manager considers water quality, fisheries aspects and the potential for landslides affecting these resources, there are eight or nine laws which must be dealt with, These laws direct the manager to address and attempt to mitigate or protect all of those resources. With all of these requirements and directions to consider, it is important that the land manager, the decisionmaker, receive the best type of information available to make decisions. Unfortunately, all of the necessary answers are not available. Many of the processes or techniques being used or that have been used in the past give an illusion of accuracy that just isn't there. That illusion of accuracy at times

MELVIN L. KESSEL is district ranger, Mapleton Ranger District, USDA Forest Service, Siuslaw National Forest, Mapleton, Oregon.

JOSEPH H. HARN is director, Fisheries and Wildlife Management, USDA Forest Service, Pacific Southwest Region, San Francisco, California.

has and still does give land managers problems.

As one land manager I know stated "We have much data but little information to work with in developing some of our decisions."

Let's take a look at the thought process a land manager might go through, or should go through, when assessing risk. Number one, the manager needs to identify the potential for instability in any land areas considered for harvest operation. The manager then needs to assess the type of injury or losses that could occur and to whom or to what. Finally, it is necessary to determine the consequences or magnitude of these potential impacts or losses. The questions that might be asked are: Will slope failure lower productivity of the lands? Will slope failure have adverse effects on other resources? Will slope failure lower the value of other investments and improvements or destroy them? These are all questions which must be addressed and put into a context that allows the manager to balance immediate concerns with all other resource values and special interests which may be involved in any project.

There are lots of methods for assessing risk that can be considered by the manager. We are not operating in a vacuum with an absolute lack of knowledge. Much can be learned from past successes and failures. For example, in the Coast Range of northern California where much of my experience has been, there is some 50 years of experience to look at. Inventory systems can also be used to gather more and better information. It has been mentioned during this workshop that geological resource inventories in some National Forests have helped to increase the level of resolution of stability hazards. Finally, management procedures can be developed to assure adequate analysis of potentially high risk areas. These procedures can be used to address and mitigate risks, Let me give you an example. The Six Rivers National Forest in northern California went through such a process. It was determined that most of the damage to water quality and fisheries values caused by mass wasting resulted from failures on slopes of 70 percent gradient or higher. It was also found that by looking at data already in hand, supplemented with information from an available geological resources inventory, that 12 percent of the Forest fell into this high-risk category. About 16 percent of the remaining old-growth forest occurred within this 12 percent. Based on this information, management was able to concentrate existing professional resources and determine where time and financial resources were most needed. This allowed forest managers to concentrate their efforts on a restricted area where very difficult decisions had to be made.

Through the use of resources that are available and analysis of information obtained from past experience, I believe we are making workable decisions today. Unfortunately, precision and accuracy are still lacking. In the future we may be able to take the illusion of accuracy we have today and make it truth.

Speaker 5: **KENNETH** D. WEYERS--There are several points dealing with the concept of risk that I want to put into practical perspective. First, risk is in the eyes of the beholder or manager. The risk could be unplanned expenses; the loss of a facility such as a road, bridge or building; or excessive environmental damage. Risk could also be loss of creditability for you, your organization, your community, or unit. A risk that hasn't yet been mentioned in this workshop, but should be, is personal liability. It has become an issue in a number of recent instances. Finally there is program variability. What is the risk that harvest and road construction plans will change over time, and what will be the cost of these changes? An adequate assessment of risk, whatever the definition, is essential for effective management of forest lands today,, As others have said in this workshop, the easy management decisions have all been made. In sensitive areas, and most areas seem to be sensitive today, there are only two choices. One choice is to go elsewhere. The other choice is to enter the area and do the best possible job of minimizing any current risk given existing economic, social, or political constraints. As a manager, I can tell you that the second choice is the one you will probably be considering.

How do managers cope with slope stability when risk is involved? I can speak knowledgeably only about the Payette National Forest on this process.

The Payette is fortunate in having developed a system that deals with both short- and long-term impacts from forest operations at a level felt to be adequate given current limitations in funds and staffing. The system goes something like this:

A land systems inventory was developed for the entire forest that describes and delimits the physical characteristics of the soil and terrain. Superimposed on this inventory were project level guidelines, which identify high and low cost, and high and low sensitivity areas based on identified economic and environmental values. In addition, the constraints that were necessary to hold risks associated with harvesting to a minimum were modeled constraints over both time and space to evaluate short- and long-term impacts.

While I am impressed with the amount of technology that has been developed, especially as it relates to slope stability aspects, as a manager I cannot ask or let specialists do more then what is needed commensurate with the level of decision to be made. Given current staffing and budget limitations, major undertakings to collect more and better data are not affordable. Specialists who work on the ground, who know the ground, are the key to our risk assessment

---

KENNETH D. WEYERS is supervisor, Payette National Forest, USDA Forest Service, McCall, Idaho.

program. Their professional judgment is where we start. Research and forest specialists must interact as much as possible so that newly developed techniques and data can be more readily transferred to operational personnel.

My concern lies in the needs for the future. It lies in the urgent need for process understanding and methodologies for assessing and managing cumulative effects.

Question Before **Panel 3:** Given **the** social-political constraints imposed on the land manager and levels of risk currently acceptable, what information and levels of application are needed for improved land **management** decisionmaking?

Speaker **1: W. W.** BOURGEOIS–The land manager of today must consider a number of technical and political factors when making decisions. The area being discussed in this workshop is terrain stability but this factor cannot be considered in isolation. All other factors that affect and are affected by terrain stability are integral components of any land management decision. It is this integration that must be considered when addressing the need for: (1) required information and levels of application for improved land management decisionmaking, and (2) the direction of future research and management to accomplish these goals.

INFORMATION NEEDS AND LEVELS OF APPLICATION

In answering the question of information needs and levels of application for improved land management decision-making in unstable terrain, I have made two assumptions:

1. The principal activity for the area is forest management in an integrated resource context and

2. Timber development and harvesting are planned for unstable areas.

The information readily available to land managers varies depending on geographic region and organization. Nevertheless, there are basic units of information required for any logical land management decisionmaking process in potentially unstable terrain.

W. W. BOURGEOIS is manager, Land Use Planning Advisory Team, Woodland Services Division MacMillan Bloedel Limited, Nanaimo, British Columbia.

These units should include:

1. What resource values exist in the area.

2. Terrain stability maps (1:20,000) that identify potential problem areas.

3. A detailed plan for timber development and harvesting.

4. A site-specific assessment of potential problem areas relative to detailed development plans.

5. A detailed, on-site analysis of soil and rock materials.

6. An assessment of possibility of failure.

Identification of the resource values present is essential for any land management decision. The management practices suitable for unstable terrain in areas that include important fisheries, esthetic or domestic water resources would be considerably different than those necessary when the forest resource is the only high-value resource present. Along coastal British Columbia it is not uncommon to have the same constraints imposed on timber development or harvesting in potentially unstable terrain regardless of the value of other resources present. This, in my view, is inflexible land management and must be challenged if the forest industry is to remain viable and practice good integrated resource management.

In most instances terrain and derived stability maps at a scale of 1:20,000 are a sufficient and cost effective way of identifying potential problem areas that must be incorporated into timber development and harvesting plans. The information supplied by these maps allows the engineer to develop plans that incorporate technical limitations of equipment and other potential problems, (for example, windthrow) with planned activities. The maps also identify the terrain areas where detailed on-site assessments are required to clarify and confirm the potential problems associated with timber development and harvesting.

The site-specific assessments that follow detailed planning allow the engineer and terrain specialist to refine the plans and be more confident in predicting the potential terrain stability problems. Such assessments also allow the assignment of a developed, subjective probability of failure to the area and a decision on whether a detailed engineering soil or material analysis is required. This requirenent is expected to be the exception rather than the rule and would usually be associated with very high-value forest or nontimber resources.

It is my opinion that if the land manager is provided with the above resource data and has technical personnel follow the suggested steps the manager will improve the decisions made in unstable terrain. The resources and values have been identified, the potential terrain stability problems associated with planned development and harvesting practices have been highlighted, and the probability of landslides associated with these practices assigned. These factors can then be used by the manager in association with economic and political factors to make the final decision regarding land management.

AREAS FOR RESEARCH

The previous discussion regarding the information needs and levels of application includes a number of instances where subjective assessments are made based on experiences or limited quantitative data. It is my opinion that a terrain classification system such as that developed by the British Columbia Ministry of Environment, used in conjunction with existing research data by a pedologist or geologist experienced in terrain analysis is sufficient to accurately identify potentially unstable terrain. The priority-areas for research information needed for decisionmaking in unstable terrain can be summarized as follows:

1. Long-term assessments of the effects of present and proposed timber development and harvesting techniques on terrain stability.

2. Long-term implications of landslides on nontimber resources.

3. Techniques for rehabilitation of landslides.

4. Logging and silvicultural techniques to enhance or maintain stability in localized areas.

5. Development of logging practices around gullies to minimize the potential and magnitude of landslides.

6. Evaluation of probability of failure incorporating a statistical and geographical approach to assigning probability of failures within a mapping unit.

7. The application of classical, engineering slope-stability models to terrain mapping systems.

The research data and experience presently available provide us with an indication of the effects that our current timber development and harvesting practices have on terrain stability. A degree of subjective assessment is involved, however, and long-term monitoring studies of specific practices would be beneficial to quantify and clarify the expected effects. The practices to be studied should include not only those presently proposed for unstable terrain but also other practices that appear practical and could reduce impacts. I would like to challenge the engineering community to propose new practices for study and to work with the pedologist or geologist in evaluating the impacts of these practices on terrain stability. To date, new or innovative timber development and harvesting practices are rare. Although we do not feel all of the practices proposed by the environmental community are realistic same practices may be applicable and it could be to our benefit to work with such groups to evaluate their ideas.

There are long-term studies being conducted to evaluate the impacts of landslides on nontimber resources in both Canada and the United States. I suggest that more are required and a long-term commitment for support should be obtained from the funding agencies. We are still making decisions on impacts based on inconclusive data. It is my feeling that in many cases the constraints being applied are too restrictive, but this comment is not in all instances based on sound research data.

Where impacts are shown to be significant., alternative methods of rehabilitation either of the landslide or stream need to be evaluated on a cost-benefit basis and within an integrated resource management context, Research into various mitigation and restoration practices, such as the rehabilitation of landslides, needs to be conducted to determine the viability of such practices and the associated costs and benefits.

Frequently managers are in a situation involving terrain where the root deterioration following clearcut logging is expected to decrease the terrain stability to an unacceptable level.. Most commonly, in coastal British Columbia such areas are deferred from harvesting. This action can not only involve loss of forest resource but the activities adjacent to the area can induce windthrow in the deferred area. Methods other than or in conjunction with clearcut logging need to be investigated to determine their effectiveness in maintaining or enhancing the terrain stability.

One of our more problematic landforms is gullied terrain, including areas with single or multiple gullies. Inevitably gully sides are unstable or potentially unstable, and when the adjacent areas are clearcut the timber within the gully is often subject to windthrow. To protect gullies, considerable areas of timber would have to be deferred from harvesting. Consequently, these areas are often harvested with precautions taken to minimize the effects of logging. The manner of harvest and postharvest cleanup needs considerable research to determine the most effective methods to decrease terrain instability and to reduce the windthrow potential.

The present methods used to determine the probability of logging practices inducing landslides tend to be subjective in nature. This approach has not created problems to date; however, more quantitative methods are required to substantiate stability assessments. The development and evaluation of statistical and geographical methods for assigning probabilities of failure within mapping units is one suggested method of improving assessments. The potential for adapting classical engineering slope-stability models to terrain mapping systems should also be evaluated to see if the techniques can improve assessment of landslide porbability. All of these methods should be related to terrain mapping because this technique has been shown to be an effective and practical way of identifying problem areas and potentially unstable terrain.

MANAGEMENT IMPROVEMENT

Improvements in decisionmaking regarding unstable terrain are not restricted to better technical data on forest engineering practices or terrain analyses. Land managers need to institute management policies and systems that better utilize existing and developing information, The areas where I believe improvements can be made are:

1. The availability of rapid and effective analytical methods for use in assessing harvest plans; that is, "computerized planning."
2. The active use of existing methods for long-term planning in unstable areas.
3. The clarification of resource management objectives prior to developing an unstable watershed or area.
4. The strict application of known practices in both identified unstable areas and those where poor practices could create unstable conditions.

The earlier discussion on information needs identified the evaluation of timber development plans relative to terrain data. Commonly the plan most desirable to the forest engineer is not acceptable to the terrain specialist if landslides are to be prevented or minimized. This leads to the need for evaluation of both the feasibility and economics of various possible plans. The failure to have a computerized system whereby evaluations can be made rapidly and effectively usually results in inefficiencies and, frequently, questionable land management decisions. Systems are available that can do these assessments and should be actively used by managers.

Long-term planning or liquidation planning is commonly discounted due to future uncertainties and availability of personnel. Failure to do this type of planning in unstable terrain can increase development and harvesting costs through lack of consideration of potential problems in the future. Given the present cost of road construction one error of this type can easily cover the cost of the planning.

Establishing management objectives for all resources in areas or watersheds with unstable terrain is essential. Without a clear definition of these objectives there is a tendency to practice single rather than integrated resource management. Managers are in an era when forest land managers must understand and address the management objectives of all resources in technical, economic, and political contexts.

There are many road construction and harvesting practices known today that, if strictly applied, will minimize acceleration of landslides in unstable and potentially unstable terrain. You are all familiar with instances where proper installation of culverts and ditches would have prevented landslides. It is all too easy for the engineer to allow a practice to be performed that is cost effective during the construction phase with little regard for future costs. The land manager must insist that proper engineering practices be applied in unstable and potentially unstable terrain. If such practices are consistantly applied, I believe a significant number of landslides can be prevented.

SUMMARY

I have presented to you what I believe to be the information needs and levels of application required for improved land management decisionmaking in areas of unstable terrain. Generally, I believe we have methods available that, when applied with terrain and other resource data, can identify potential problem areas. In the past, subjective assessments of terrain stability have been adequate, but I feel pressures will be applied to develop more quantitative methods. Research into these methods and the long-term impacts of current practices on terrain stability and other resources are required. New techniques for rehabilitating landslides and mitigating the impacts of landslides on forest and other resources are also priority research areas. The instituting of management policies and systems that allow for the rapid evaluation of resource management objectives and plans, and the conscientious application of existing data and methods will improve the quality of land management decisions.

Speaker 2: DICK OLSEN--In western Washington, outside of Forest Service lands, most of the harvesting has been completed in most of the drainages. Our opportunity to plan new entry into drainages is already gone. Managers must focus on fixing past errors and making sure they do not make these same errors in the future as second-growth areas are reentered. Also, existing resources must be managed so that impacts on people and other resources are minimized.

To do this, more information and new ideas are needed to help predict and stabilize soil failures related to roads, midslope harvesting, and Occurrences in gorges and along stream banks. Of prime importance in my District is how to reduce excessive debris loading in stream channels and destructive downstream scouring effects. I also need answers to help predict the occurrence of landslides and reduce the hazard

---

DICK OLSEN is district manager, Washington Department of Natural Resources, Sedro Woolley, Washington.

to life and property downslope from harvest areas.

The answers to some specific questions would greatly assist me in more effective harvest planning and hazard reduction. For example: Does the speed of harvesting effect slope stability? Are there species or planting densities that I can use to reduce the risk of landslides on unstable slopes? I could also use more quantitative information on how water retention and movement through the soil affects the stability within a drainage.

Finally, I see an increasing need for techniques to effectively deal with people living next to and below my management areas. In effect, I need the data and techniques necessary to manage my forest lands with a minimum of increased damage to my neighbors.

Speaker 3: DALE J. McGREER--The panel members addressing needs and priorities for effective stability hazard assessment were asked to answer rather complex questions. Those questions carried the presupposition that social and political constraints are imposed that determine "acceptable" levels of risk and that these are "given." I preface my response to the panel's questions by noting that acceptable levels of risk are not "given." They are not because they can seldom be defined quantitatively. If acceptable levels of risk could be adequately quantified, it would follow that probabilities of mass failure could also be adequately quantified. In reality they seldom are.

Social and political constraints certainly influence a land manager's decisionmaking processes. Such constraints influence attitudes towards acceptable levels of risk but fall short of defining them. Acceptable levels of risk vary with circumstances, physical as well as social, and social attitudes change with time. Ultimately, it is the responsibility of the professional land manager to accept some level of risk, whether the level can be defined or not. The more accurately he can access risk, the more rationally he can make land management decisions. And the manager faced with certain knowledge of risk, but without the means to assess its severity will all too often choose to avoid the risk entirely.

The problem of defining and controlling levels of risk associated with land management actions is at the heart of the questions posed to the panel. The first of the two questions is What information and levels of application are needed for improved land management decisionmaking in areas of unstable terrain?

DALE J. McGREER is forest hydrologist, Potlatch Corporation, Lewiston, Idaho.

To make rational decisions in the face of known unstable terrain, a manager needs to how the probabilities of failure associated with specific management actions. Two types of knowledge may be necessary: (1) rates and types of natural mass failures through time, and (2) probabilities of failures caused by human activities. Such probabilities are most meaningful in the context of probabilities per unit activity and per unit time. A simplified example might be to assess the probability of a debris torrent per mile of road system per year given sidecast tractor construction on 60 to 70 percent slopes. If enough information on probability of failure for this base case can be provided, the next step would be to assess incremental levels of hazard reduction associated with alternative practices.

Another approach to hazard assessment, and one that can be incorporated into the first, is to assess probabilities of failure on a specific site or problem basis; for example, construction across a rocky, steep, spur ridge or through a deeply encised first-order stream.

Assessing probability of failure, given construction without special design features, is the fundamental first step. If the probability of failure with standard practices is judged too high, then the manager needs to evaluate application of specific engineering solutions. Many situations are encountered where proven solutions exist, but they are not known to the technical and administrative personnel that make the decisions on whether or not to proceed. Again, faced with a risk of unknown magnitude, the manager will all too often choose the option carrying no risk. If knowledge of the effectiveness and cost of solutions to specific problems can be provided, the choices broaden considerably.

In answering the second question, "where should research and management be headed to accomplish these goals?" I take the stand that a great deal of information and experience now exists. Needed are concentrated efforts, to collect, analyze, and synthesize existing information and make it available in a straightforward manner that encourages its use by engineers. A great number of surveys have been done on specific forests, ownerships, and geographic areas to define the probabilities of mass failure associated with specific geomorphic characteristics. Some of these surveys provide detailed information on the geomorphic character of the mass failures; the type of landforms, soils, and geologic materials upon which they occurred; and detailed information on associated management practices.

More surveys are needed. But even now it may be possible to calculate probabilities of failure given certain geomorphic characteristics and practices. These calculations would likely take the form of a model. It is doubtful that the model would be highly accurate--which is the common situation for most models now in use in many earth sciences disciplines. Models might well be reliable enough, however, to allow more rational decisionmaking than if they did not exist. A characteristic of many of the recent land management models is that they often make specific areas of knowledge that are currently insufficient painfully evident. They provide information on what types of data are necessary to allow more rational decisionmaking processes. Research can then play a direct, useful role.

Speaker 4: MICHAEL J. COOK--As described during the last 1 1/2 days, there exists a wealth of information and a number of techniques for stability hazard assessment ranging from factors of safety to computer programs capable of producing answers to six decimal points. These techniques, of course, come with the caution, do not use because of limited accuracy. Participants have also been told that over 2,500 years of experience are represented at the workshop. A problem that I see is that we have all that information, all that experience, and all these techniques contained in or being developed at widely scattered places and being dispersed in many unregulated directions.

I get the impression that as managers, using the techniques described in this workshop, we would have about a 1:100 chance of providing the right solution to the right problem: This is not good enough. Engineers, soil scientists, geotechnical specialists and university professors working on this problem, must not lose sight of the fact that they are providing a service to the decisionmaker. Given the existing social and political constraints, the decisionmaker needs to be provided with the most cost-effective and accurate methods of estimating the probability of failure and the extent of damage if the proposed activity is conducted.

The question of where research and management need to be headed is very appropriate at this time. Sharing viewpoints on this question is probably one of the principal values of a workshop like this. I see a real opportunity and an absolute necessity for National Forest administration, research, universities and industry to work together as a cost-effective team that can be utilized to improve techniques for assessing failure potential or damage on lands which are scheduled for entry. A major way that research and operating organizations can assist, is to pull together much of the available information that has been put forth here in the last few days and provide those specialists assisting the land managers with the most up-to-date tools that are available. In other words, I think we need to provide an effective means of transferring this knowledge *among* the different individuals and organizations representing forestry concerns. And we need to listen to the group represented here today, especially the managers, as far as to what they need, where they are headed, and what research can do to provide the assistance they need.

MICHAEL J. COOK is forest engineer, Nez Perce National Forest, USDA Forest Service Northern Region, Grangeville, Idaho 83530.

Speaker 5: TED STUBBLEFIELD--When National Forest management activities are proposed for unstable terrain, the decisionmaker needs to include the following three primary pieces of information in the decision process:

1. The risk of hillslope failure, as a result of the proposed activity. The risk should be expressed in terms of a probability of Occurrence or chance of failure during a specified period of time. For example, the chances of hillslope failure as a result of clearcut "X" or "Y" (or Road "A" or "B") are 10 percent per year for the next 10 years. The degree of accuracy of the estimate also needs to be stated.

2. The consequences of hillslope failure. Hillslope movement may have minor or major consequences depending on numerous factors. The primary consequences that must be considered are:

A. Capital investment damage (roads, bridges, buildings).

B. Site productivity loss (on-site and off-site).

C. Impact on the riparian and aquatic system.

D. Visual impact.

E. Cummulative effects, including long-term management and public concerns.

3. Management options. Spatial positioning of units, harvest methods, silvicultural systems, road location and design, and fuel treatment alternatives must be examined relative to the risks and consequences of hillslope failure. The option of "no treatment or entry" must also be analyzed. Reformulation of the proposed alternative and a new risk assessment may be required.

With the knowledge of the potential risks, consequences and options supplied by staff (specialists), the decisionmaker can then determine whether the risk is acceptable compared to the benefits of the proposed action.

TED STUBBLEFIELD is Forest staff officer, Siskiyou National Forest, USDA Forest Service Pacific Northwest Region, Grants Pass, Oregon.

DIRECTION FOR RESEARCH AND MANAGEMENT

Information available to the decisionmaker can be improved in three significant areas.

1. Analysis of alternative land management prescriptions (research). Much research has focused on the land stability effects of clearcutting as a treatment. More information is needed about other variable harvest intensity prescriptions. For example, how would partial cutting reduce risk of failure (if any)? Similarly, research has pointed to roads as a management activity responsible for most landslides. But what are the specific design factors of National Forest roads that contribute most to road-caused landslides?

2. Determine acceptable thresholds of risk (management). National Forest managers and decisionmakers must improve their ability to state clearly what level of risk they are willing to accept. Management decisions about unstable terrain will continue to be of a subjective nature. But, managers must strive toward a quantitative and factual approach in decisionmaking.

3. Technology transfer. The transfer of knowledge between research and management is of vital importance. For example, research has developed the techniques to determine the risk of failure, but the techniques are not in common practice in the National Forest System. Technology transfer is not a one-way street from research to management, but rather, a three-way sharing of responsibility where the decisionmaker asks the right questions; the scientist develops techniques and makes them available; and the staff (soil scientist, geologist, engineer, hydrologist, etc.) seek the new information and bring it into practice. The process is best served by a continuum of information exchanges, often via workshops.

STATUS OF KNOWLEDGE--

RELIABILITY OF TECHNIQUES--

DIRECTION FOR IMPROVED DECISION MAKING

Jeff Sirmon

STATUS OF KNOWLEDGE

It is clear to me after listening to the presentations and discussions generated by this workshop, that knowledge of the nature, location, and extent of unstable soils is variable in the western U.S. and Canada. Knowledge of specific failure mechanisms and potential impacts on forest resource mangement is even more variable. In the Pacific Northwest Region of the USDA Forest Service, relatively good knowledge of the extent of unstable soils exists on a forest by forest basis. This knowledge has come through a sequence of inventories and special investigations beginning with a mantle stability survey in the early 1960's. This was followed by our soil resource inventories at 1 inch per mile. We have also conducted a number of special soil, geologic, and hydrologic investigations and inventories in some of the critical watersheds in the Region. For example, staff specialists on the Siuslaw, Siskiyou, and Rogue River National Forests in Oregon have developed some fairly sophisticated assessments of landslide risk so that managers can predict with reasonably high accuracy where events might occur and the expected volume of material that would be generated from such failures.

I believe that our biggest knowledge gap is one of determining what the environmental impacts of land failures are on our resources. For example, one of the areas of greatest concern in the Pacific Northwest is the potential effect of landslides on anadromous fisheries. Yet, even our specialists don't have a clear understanding of what the effects of landslides are. Certainly it is generally accepted that when channel scouring occurs there will be at least a temporary loss of spawning and rearing habitat. It is also generally known that debris jams can block fish from passing to large areas of otherwise suitable fish habitat. Recent studies by biologists at the Pacific Northwest Forest and Range Experiment Station suggest that, except for stream blockage, some streams are deficient in large woody debris. Studies addressing this subject, being done by Fred Everest in the Siuslaw National Forest, will be valuable to managers in the future.

Another deficiency is a lack of understanding of the effect of landslides on site productivity of commercial tree species. In many cases, the actual failure area is extremely small and has little direct effect on forest productivity. I don't think we fully understand, however, the soil replacement process. That is, when failures do occur, where does the soil come from and to what extent does this affect overall site potential.

I believe there is also a need to better differentiate between long-term natural erosion rates and those rates affected by management activities in a basin. This would permit managers to do a better job of monitoring to see how well they are doing.

JEFF SIRMON is Regional Forester, USDA Forest Service, Pacific Northwest Region, Portland, Oregon.

Along much of the Pacific coast of the United States, the major road network is in place. For those areas that are as yet unroaded, we have sufficient information to establish potential risk of failure on most of the public lands. On many private lands, this may not be the case. From this general information on relative risk, managers know where to focus most of their attention for site investigations for actual road design. Thus, it seems that managers need to apply the information and techniques that are already available. They also need to do a better job of analyzing the tradeoffs from planned activities. Where managers have major resource conflicts, with high values, there needs to be a better-assessment of the tradeoffs.

Finally, managers also know that it is extremely costly to rehabilitate areas where slides occur and that it is cheaper to prevent failures than to try to rehabilitate.

RELIABILITY OF EXISTING TECHNIQUES

Several speakers have addressed the question of reliability of predicting landslides. It is clear that there are different degrees of reliability depending upon failure mechanisms, level of inventory, types of environment (rock type, soils, climate), and past experience.

For example, there are some geotechnical procedures that are quite accurate for very specific sites. On the other hand, application of such techniques can be unreliable with respect to-an entire drainage system if there isn't a commensurate inventory of the relative hazards and risks of failure. Reliability, therefore, is really a function of the degree of an integrated assessment of a particular basin, and it is critical that a systematic inventory, analysis and monitoring process be in place. Techniques for predicting and preventing major land failures need to be systematized from a broad assessment to site specific locations. For this reason, a truly interdisciplinary approach is needed and should include geologists, soil scientists, hydrologists, fish biologists, and engineers, together with silviculturists, logging specialists, and others as appropriate.

It may not be necessary to predict every landslide that potentially can occur, but managers, aided by their specialists should be able to predict the major events so that activities in those areas can be avoided or' structures designed to mitigate or prevent landslides from unnecessary occurrence.

IMPROVED DECISIONMAKING

Decisionmaking can be improved by a variety of techniques and methods. Each organization and the levels within an organization make decisions differently.

Decisions related to slope stability require comprehensive-assessments and analysis because the greatest impacts may occur downstream from the intended activity. Activities planned on lower slopes need to be assessed in terms of how such activities might be affected by unstable lands upslope.

Analysis must be truly interdisciplinary, beginning by looking at the nature of the landscape and processes operating on the landscape from a broad view using small-scale photos (1 to 70,000 or smaller depending on the intended activity) and then focusing on site! specific investigations. One example of how this is being done in the Pacific Northwest Region of the Forest Service is that the most severly unstable lands are being identified as unsuited for timber management because of expected irreversible damage to soil productivity or watershed condition in accord with the National Forest Management Act. Then, on those lands that remain in the productive base, a rational decisionmaking process is developed that allows for prediction with an acceptable confidence, or risk, of what the potential impacts will be and what the tradeoffs are, including costs. The decisionmaking process can be improved by applying sound analytical techniques from interdisciplinary functions and by having available the appropriate level of inventory and design specifications for the magnitude of the potential problems and the values at stake.

METRIC EQUIVALENTS

LENGTH

1 inch (in.)	=	25.40 millimeters (mm.)
1 inch (in.)	=	2.54 centimeters (cm.)
1 foot (ft.)	=	30.50 centimeters (cm.)
1 foot (ft.)	=	0.31 meters (m.)
1 yard (yd.)	=	91.40 centimeters (cm.)
1 yard (yd.)	=	0.91 meters (m.)
1 mile (mi.)	=	1609.00 meters (m.)
1 mile (mi.)	=	1.61 kilometers (km.)

MASS

1 pound-mass (lb.)	=	453.60 grams-mass (g.)
1 pound-mass (lb.)	=	0.45 kilograms-mass (kg.)
1 ton-mass (tn.)	=	907.20 kilograms-mass (kg.)
1 ton-mass (tn.)	=	0.91 megagrams-mass (Mg.)

AREA

1 acre (ac.)	=	2.47 hectares (ha.)
1 square inch ($in.^2$)	=	6.47 square centimeters ($cm.^2$)
1 square foot ($ft.^2$)	=	929.00 square centimeters ($cm.^2$)
1 square foot ($ft.^2$)	=	0.09 square centimeters ($cm.^2$)
1 square yard ($yd.^2$)	=	8361.00 square centimeter3 ($cm.^2$)
1 square yard ($yd.^2$)	=	0.84 square meters ($m.^2$)
1 square mile ($mi.^2$)	=	2.54 square kilometers ($km.^2$)
1 square mile ($mi.^2$)	=	254.00 hectares (ha.)

VOLUME

1 cubic inch ($in.^3$)	=	16.39 cubic centimeters (m^3)
1 cubic foot ($ft.^3$)	=	0.03 cubic meters (m^3)
1 cubic yard ($yd.^3$)	=	0.76 cubic meters (m^3)
1000 board feet (BF)	=	5.60 cubic meters (m^3) (Schribner scale)

FORCE

1 pound-force (lb)	=	0.45 kilograms-force (kg.)
1 pound-force (lb)	=	4.45 newtons (N)
1 pound-force (lb)	=	0.0005 megagrams-force (Mg.)
1 ton-force (tn.)	=	0.91 megagrams-force (Mg.)
1 ton-force (tn.)	=	8.89 kilonewtons (kN)

STRESS AND PRESSURE

1 pound-force per square inch (psi)	=	0.07 kilograms per square centimeter (kg/cm^2)
1 pound-force per square inch (psi)	=	6.89 kilopascals (kPa)
1 pound-force per square foot (psf)	=	4.88 kilolgrams-force per square meter (kg/m^2)
1 pound-force per square foot (psf)	=	47.88 pascals (Pa)

DENSITY AND UNIT WEIGHT

1 pound-mass per cubic foot (pcf)	=	0.02 grams-mass per cubic centimeter (g/cm^3)
1 pound-mass per cubic foot (pcf)	=	16.02 kilograms-mass per cubic meter (Kg/m^3)
1 pound-mas per cubic foot (pcf)	=	0.02 megagrams-mass per cubic meter (Mg/m^3)

Swanston, Douglas N., tech. ed. Proceedings of a workshop on slope stability: problems and solutions in forest management. Gen. Tech. Rep. PNW-180. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station; 1985. 122 p.

The workshop provided mid and upper level forest managers and technical specialists with an overview of slop stability problems on forest lands, current state of knowledge, and practical techniques available for problem solving.

Keywords: Slope stability, landslide.

The Forest Service of the U.S. Department of Agriculture is dedicated to the principle of multiple use management of the Nation's forest resources for sustained yields of wood, water, forage, wildlife, and recreation. Through forestry research, cooperation with the States and private forest owners, and management of the National Forests and National Grasslands, it strives – as directed by Congress – to provide increasingly greater service to a growing Nation.

The U.S. Department of Agriculture is an Equal Opportunity Employer. Applicants for all Department programs will be given equal consideration without regard to age, race, color, sex, religion, or national origin.

Pacific Northwest Forest and Range
Experiment Station
319 S.W. Pine St.
P.O. Box 3890
Portland, Oregon 97208