MONTANA STATE UNIVERSITY

Slope stability evaluation for land capability reconnaissance in the Northern Rocky Mountains
by Clifford Montagne

A thesis submitted in partial fulfillment of the requirements for the degree of DOCTOR OF PHILOSOPHY in Crop and Soil Science
Montana State University
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Abstract:
Land planning and use in the United States is becoming more sensitive to the carrying capacity limits of land potential. In the Northern Rocky Mountains, land managers must evaluate vast areas of undeveloped land before committing some of it to irreversible use for recreation development and timber harvest. Landsliding (slope stability) is a major hazard of development in mountain terrain. Engineering slope stability analyses are too sophisticated for use in broad level land systems reconnaissance, so the land manager needs a simple and rapid method to evaluate slope stability.

Environmental features of fifty-five landslides in the Gallatin Canyon area of southwestern Montana are described. The study area is typical of much of the Rocky Mountains in terms of geology, vegetation, hydrology and climate. The landslides are classified by bedrock type and size. Failures occur with decreasing frequency on terrain of Cretaceous, Tertiary volcanic, other Mesozoic and Paleozoic, and Precambrian bedrock.

Larger landslides involve failed incompetent bedrock on gentle slopes with free water and vegetative indicators of free water. They are often relics of glacial and immediately post-glacial time. Smaller landslides involve colluvium on steep slopes without bedrock control and are often associated with roadcuts.

The descriptive term "bedrock control" is proposed to describe influence of bedrock on colluvial hillslope stability. The term "threshold basin" describes relic pre-Tertiary volcanic terrain now being exhumed by landslides and other mass wasting. The ratio of percent of clay to percent coarse fragments indicates surficial material stability. Landslides and highly erodible pinpoint sources account for high Gallatin River sediment turbidity from summer and fall storms.

A reconnaissance slope stability analysis system is developed. Presence of features such as critical slope angle, bedrock type, geologic structure, bedrock control, old landslide terrain, free water, vegetative indicators of moisture, roadcut, oversteepening, till, water impermeable layer, and bedrock weathering or alteration are added to obtain a total score indicative of stability hazard. The multidisciplinary approach to joint land inventory and stability analysis is demonstrated at various scales and levels of intensity.

Gallatin Canyon slope stability hazard and other multidisciplinary information are combined in an Ecological Land Unit map and a Unique and Critical Areas map for communication and general planning.

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by

CLIFFORD MONTAGNE

A thesis submitted in partial fulfillment
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Approved:

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Chairperson, Examining Committee

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Head, Major Department

____
Graduate Dean

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ABSTRACT

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INTRODUCTION

This report examines slope stability in the Northern Rocky Mountains in the context of environmentally sound land planning and use. The introductory section details the background of the need for such a study.

Emergence of an Environmental Land Use Ethic in America

In America, land ownership has been a sacred thing. The frontier ethic gave man absolute dominion over the use of his property.

> From the time of the first settlers man viewed the land and its elements as factors which he must conquer and control in order to survive in the new world. Furthermore, it became more and more important to the individual that he be allowed to own his own piece of land. This feeling combined with the government's need to have land developed for its productive capacity reinforced the concept of private land ownership. In addition, once an individual owned his land he could use it as he wanted. The ethic that evolved in the United States is one that has viewed the ownership and use of a parcel of land as a private matter. (Redding and Parry, 1973)

During the 1800's and early 1900's, formative years of America's environmental consciousness, land was used more or less as individual owners desired. Great tracts of public land became private, and much of the remaining public land was utilized for resource extraction. Patterns of ownership and use were established emphasizing maximum short term economic return. Individual rights to exclusive use of public or private land were held inviolate.

As man populated the continent, some realized the finite size of the natural system and man's dependence on it. The writings and work of individuals such as Thomas Jefferson, George Perkins Marsh, Henry David Thoreau, J. W. Powell, John Muir and Aldo Leopold reminded man of his dependence upon the natural world. George Perkins Marsh, in his classic, Man and Nature (1864), expressed the philosophy that scientific knowledge and a land consciousness should guide land use. In the following century, Aldo Leopold approached land use and conservation from the viewpoint of a forester, game manager, and philosopher.

By the 1960's, land use in the United States had reached the threshold of saturation. Urban and agricultural land was being used at a high level of intensity. Remaining land was being used or considered for resource extraction and production or recreation. Partly because of the near totality of land use, urban environmental problems of air and water pollution and waste disposal became more serious. These problems, coupled with higher levels of general affluence, leisure time, and citizen awareness, initiated new concern for the environment. This led to changes in land use policy and decision making which reflect the beginning emergence of a new land ethic. The requirements of considering short and long term socio-economic and bio-physical environmental effects of land use, the increased level of citizen involvement in the evaluation and decision making processes, and realization of the irreversibility of many land uses are new realities with regard to land utilization. Rapid allocation of undeveloped land is being questioned and the tradition of inviolate private exploitive rights is becoming outmoded.

Ian McHarg, a landscape architect, speaker and writer, is a proponent of "The Ecological View" (McHarg, 1969). With a philosophy similar to Leopold's, McHarg advocates that man's activities and works fit as much as possible with the "real world." He writes that ecologists or natural scientists know the most about the capabilities of the natural system and that maximum long-term benefits and long-term minimum costs are achieved when man's activities "fit" with the ecosystem. McHarg's books, Design With Nature (McHarg, 1969), explains his philosophy and shows examples of applications in which the many facets of a natural ecosystem are combined through the use of transparent overlays to produce an expression of integrated general capability. Design With Nature calls for elaborate ecological inventories and a determination of "ecological carrying capacity" to accompany land planning and allocation.

With the current popularity of the McHargian philosophy and the environmental movement, the meaning of the word "ecology" is becoming increasingly unclear. As the Institute of Ecology (1972) put it;

> Ecology has become a catchword of the seventies representing the movement to clean up our environment. In the process the meaning of the word ecology has become broadened and confused to a point where the study of ecology is often considered synonymous with environmental science. But there is a distinction. Ecology is concerned not only with the environment, but also with the organisms in that environment and their relationships to each other and to their surroundings.

In this report, the words ecology and ecosystem refer to the natural land system and the associated living communities.

Diethelm (1974) defined carrying capacity as:

> ...an evolving cultural model for describing limits for human interaction with natural systems. These limits are empirical and best approximations of landscape resilience. In its simplest form, carrying capacity is an expression of a functional limit between a user and a resource in order to maintain a continually available and healthy supply. More complexly it is a measure of the probable limits of interaction of a group of users in a place or area.

The National Environmental Policy Act of 1969 (NEPA) helped establish policy and guidelines for "ecological" planning. It directs agencies to adopt a systematic multidisciplinary approach to planning, consider the unquantifiable values, and, with impact statements, consider tradeoffs and irreversible commitments (Andrews, 1973). In response to NEPA, the U. S. Environmental Protection Agency recommended a National Land Use Policy with an "ecologically valid land use classification system based on the carrying capacity of the land for certain uses," and implementation of planning by natural ecosystem units (in addition to geographical and political units) (Hansen, 1973).

Concepts and practices of land planning and use continue to grow in the 1970's. The marriage of planning and ecology has produced new concepts such as ecological irreversibility of certain land uses, designation of areas of critical environmental concern (Cooper and Vlasin, 1973), and the realization of limited rather than unlimited carrying capacities of land in America (House and Gerba, 1975). These new developments and technological advances have made new tools available to the land planner. Twiss (1975) lists "...nine approaches to environmental planning." They are all variations of the general theme of multidisciplinary integration of ecological information to obtain the best "fit" between man's needs and the capabilities of the ecosystem.

In America, a changing land use and ownership ethic demands that environmental impacts of irreversible land uses be identified and evaluated. This requires (1) knowledge of the natural and socioeconomic systems, (2) methods for predicting impacts and their tradeoffs, (3) successful communication of information and methodology to the public and decision makers, (4) and methods for implementing environmentally sound land use.

Status of Mountain Lands

Land use. During settlement and development of the West, both mountain lands and the driest, most unproductive, lowland regions were the last to be claimed and exploited. Being isolated, inaccessible, and with few marketable resources other than minerals, mountain lands remained predominately in public ownership. Today, private land consists primarily of mountain valley and meadow land claimed under the Homestead Act (Udall, 1963) and remnants of large land grants to transcontinental railroads. The most "developable" acreage, that in valleys and flat areas, is often owned by individuals because it was the only potentially arable land in the area.

In the Northern Rockies, most mountain land has remained in a near pristine condition. Other than some mining, timber harvest, and grazing, these areas have been used for dispersed "wilderness" recreation. Recently, undeveloped land in the Northern Rockies and the rest of the United States has come under pressure for development. New resource extraction technology (for logging) and a new concept of leisure time has made new land uses popular in mountainous land. In the West, prime sites are being used for developed recreation and second home construction, while large land managing and owning agencies concentrate on developing timber and other resource providing capacities on the rest. Topography restricts most intensive recreation and second home development to valleys and surrounding mountain slopes, but timber production is feasible on a variety of sites. In the multiple use tradition, other land uses such as grazing, water production, wildlife preservation, scientific study, and dispersed "high quality" recreation are also possible uses of land.

Pressure for second home destination resort facilities has led to development in pristine or near-pristine areas such a Lake Tahoe, California; Vail, Colorado; Big Sky of Montana; Steamboat Springs, Colorado; Alta, Utah; Aspen, Colorado; Park City, Utah; Jackson Hole, Wyoming; and proposed developments at Vail-Beaver Creek, Colorado; Ski Yellowstone, Montana; Mineral King, California; and Early Winter, Washington.

Demand for wood products and availability of construction equipment and technology enabling automated timber harvest in rough, remote terrains has made logging feasible in previously untouched areas.

<u>Construction</u>. Historically, the most successful mountain inhabitants have been those who could fit into a delicate and often severe environment. Mountain ecosystems are particularly susceptible to uses and impacts causing danger or loss of environmental quality. Man lives in the mountains at varying habitation densities dependent upon the available level of technology. Many natural systems have been altered by man's ignorant and irresponsible use and have become uninhabitable. Mountain inhabitants of the Alps have developed the land to a high degree while retaining and perhaps enhancing the environmental quality. This is done successfully through a "stewardship" land ownership ethic, governmental control, static density of habitation, and productive non-extractive land usages. Even then, there are natural dangers such as snow avalanches, landslides and floods. In the 1963 Vaiont Dam (Italian Alps) disaster, a landslide was initiated by high reservoir water level. This predictable and avoidable landslide filled the dam causing a flood which killed 2600 people (Kiersch, 1965). In Kansu Province, China, earthquake-triggered landslides in loess killed over 100,000 people (Morton and Streitz, 1972).

Early mountain mining towns in North America suffered snow avalanche, landslide, and flood devastation because of lack of awareness of natural dangers. The mining town of Frank, Alberta, was obliterated in 1903 by a landslide and seventy people were killed (Sharpe, 1938). Gold dredging operation sites are still eyesores and sources of pollution.

The current popularity of recreational and residential mountain land development has focused attention on the environmental problems of mountain land use. Vermont, with interstate highways and ski areas attracting development, enacted an Environmental Control Law listing minimum general environmental standards (Croke, et al., 1972). Other states have since enacted environmental siting legislation which addresses effects of mountain land development.

The Lake Tahoe, California, region was one of the first recreation-residential areas in the mountainous West to be highly developed. As severe bio-physical natural system deterioration set in, the Tahoe Regional Planning Agency was formed to regulate land use. Based on knowledge of the region's environmental systems, the Planning Agency is attempting to preserve minimum environmental standards through enactment of protective ordinances.

In the San Francisco Bay area, residential use of landslide and flood prone land resulted in $25 to $35 million dollars property damage during the winter of 1968-69 (Taylor and Brabb, 1972). The San Francisco Bay Conservation and Development Commission, formed in 1965 to regulate land use, was apparently too late in this instance.

In Colorado, the proposed Marble Ski Area and destination resort will not be constructed. The site was in an area susceptible to landslides, mudflows and floods. The proposed Vail-Beaver Creek Ski Area is undergoing intense scrutiny because of possible bio-physical and socio-economic impacts. In these instances conflicts arise between public interest and private exploitative land rights which may degrade the environment and the quality of surrounding land. Evaluation of the land's carrying capacity and the potential environmental impacts of land use are becoming a necessary and acceptable part of the decision process. This means that land developers and managers (especially of unique and critical land) are being forced to change their attitudes toward unalienable private rights of land use. It is becoming apparent that, in the long run, environmentally sound land use is most economical and in the best interests of the public. This is often not apparent until the natural land system's carrying capacity and its relations to other parts of the system are evaluated.

In compliance with recent legislation and policy, land owning and managing agencies must inventory the bio-physical features of their land and relate them to land use potential so that demands for the wide spectrum of possible uses can be weighed against uses most compatible with the natural environment. A mix of land uses meeting social and economic demands of society which is in harmony with the natural land system is the desired result.

The land owning and managing agencies are faced with the task of performing evaluations of land potential over vast areas in a short time. Usually, the agencies have scarce resources in terms of money and scientific personnel. In addition, while inventories and planning are carried out, "on the line" land managers such as District Forest Rangers must keep up with scheduled timber harvest activities and road construction while also evaluating currently proposed irreversible land uses such as recreation developments.

Those faced with the task of evaluating the Northern Rocky Mountain ecosystem need scientific help. The better the knowledge of the makeup and interrelationships of the various parts of the natural system, the better the inventory, planning, and management will be. Answers to "ecological" questions are often lacking; or else the detailed studies are not available to analyze such questions. In this framework, scientific investigation and problem solving may benefit from an interdisciplinary approach to help understand complex interworkings of the natural systems.

Slope Stability in the Mountain Ecosystem

Because of steep terrain and water availability, landslide or slope stability hazard is usually greatest in the mountains. On a national scale, the Northern and Southern Rocky Mountains have "severe" ratings for landslide hazard (Baker and Chieruzzi, 1955). Landslides are among the most catastrophic and destructive natural events common to mountainous terrain. As more of this terrain is utilized, man's exposure to the hazard becomes greater. Landslides in California will cost an estimated ten billion dollars in the next thirty years if present policies continue (Sorensen, Ericksen, and Mileti, 1975).

This report addresses the need for both stability assessment and methods of multidisciplinary land inventory in the Northern Rocky Mountains. Among seven pressing national landslide research needs listed by the National Science Foundation sponsored Assessment of Research on Natural Hazards Staff are landslide prediction and land use management in hazard areas (Sorensen, Ericksen, and Mileti, 1975). It follows that a slope stability predictive system which can be integrated into natural system land inventory and planning techniques will be useful in the Northern Rocky Mountains.

Factors of Slope Stability and Current Analysis Methods

The following is a general review of landslide and mass movement classification, natural features of landslide prone areas, causes of landslides, and engineering stability analysis.

Classification. There are many classifications for slope mass movement features. As with most natural phenomena, mass movement classifications can not be rigidly adhered to. A particular landslide is often a combination of specific types shown in classification tables. The landslide classification of Varnes (1958) is widely accepted and used. It resembles the earlier classification of Sharpe (1938). The Varnes classification considers two main variables: material type and method of movement (Table 1).

Under method of movement, Varnes considered three main categories: falls, slides, and flows. Falls involve rock or soil which

Table 1

A Simplified Diagram of the Varnes Classification (from Varnes, 1958)

TYPE OF MOVEMENT		TYPE OF MATERIAL			
		BEDROCK		SOILS	
FALLS		ROCKFALL		SOILFALL	
SLIDES	Few units	Rotational SLUMP	Planar BLOCK GLIDE	Planar BLOCK GLIDE	Rotational BLOCK SLUMP
	Many units		ROCKSLIDE	DEBRIS SLIDE	FAILURE BY LATERAL SPREADING
FLOWS		ROCK FRAGMENTS	ALL UNCONSOLIDATED SAND OR SILT	MIXED	MOSTLY PLASTIC
	Dry	ROCK FRAGMENT	SAND RUN LOESS FLOW		
			RAPID EARTHFLOW	DEBRIS AVALANCHE	SLOW EARTHFLOW
	Wet		SAND OR SILT FLOW	DEBRIS FLOW	MUDFLOW
COMPLEX		COMBINATIONS OF MATERIALS OR TYPE OF MOVEMENT			