Bulletin 48

COLORADO LANDSLIDE HAZARD MITIGATION PLAN

Colorado Geological Survey Candace L. Jochim, William P. Rogers

Colorado Division of Disaster Emergency Services John O. Truby, Robert L. Wold, Jr.

University of Colorado Center for Community Development and Design George Weber, Sally P. Brown

Colorado Geological Survey
Department of Natural Resources
Denver, Colorado / 1988

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Colorado Geological Survey
Department of Natural Resources
Denver, Colorado

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ORGANIZATION CONTRIBUTIONS

The **Colorado Geological Survey** prepared chapters two, three, four, five, six, the bibliography, glossary, and appendices one, three, and five; and contributed to chapters one and nine. The **Division of Disaster Emergency Services** prepared chapters one, seven, eight, and nine, and contributed to chapter five and the glossary. The **Center for Community Development and Design** prepared appendices two and four and contributed to chapters five, six, and seven. The Colorado Geological Survey coordinated and formatted the entire text.

FOREWORD

The Federal Emergency Management Agency (FEMA) is pleased to have had the opportunity to sponsor the development of the Landslide Hazard Mitigation Plan by the State of Colorado. Experience in Colorado and elsewhere has shown that it is possible to initiate successful and cost-effective landslide hazard mitigation programs. Appropriately, the prevention and reduction of landslide losses is the principal responsibility of those local governments facing the problem every day. Effective mitigation, however, requires cooperation of federal, state and local governments and the private sector. Losses from landslides can be significantly reduced by such measures as land-use planning and management programs, building codes and practices, engineering techniques for stabilization and control, and monitoring and warning systems. Identification and map portrayal of areas highly susceptible to damaging landslides are first and necessary steps toward loss-reduction.

Successful landslide hazard mitigation must overcome a number of serious obstacles—lack of public recognition and interest in the hazard, funding needed for costly mitigation measures, inadequate leadership, and the lack of widely-accepted procedures for ensuring that community development and redevelopment are compatible with the landslide hazard. The need for action, however, is clear. The currently high losses from landslides will only increase if community development and capital investments continue without recognition of this natural hazard.

Key to any successful community landslide loss-reduction effort is the adoption by local governments of appropriate design, building, and grading codes and land-use planning and management guidelines. Trained people and efficient enforcement of site investigation requirements and grading ordinances are critical elements of any mitigation plan.

The Landslide Hazard Mitigation Plan is designed to take advantage of the opportunities that exist today in Colorado's natural, cultural and political environment; it provides a framework for state and local government action in landslide hazard mitigation. Timely action using the concepts, strategies, and techniques contained in this plan will enable state and local governments to initiate and develop a mitigation process that can materially reduce landslide losses to people, communities, the economy and environment of Colorado. This planning process can also serve as an example to other states and localities dealing with landslide problems.

Arthur J. Zeizel
Project Officer
Federal Emergency Management Agency

PROMULGATION

This plan has been prepared to provide guidance and direction for the implementation of landslide hazard mitigation policies and practices. It is designed to reduce the vulnerability to, and high cost of, landslides threatening and impacting many of Colorado's communities.

All agencies, departments, and individuals who are assigned responsibilities specifically, or by implication in this plan are requested to lend their fullest support to the planning for, and accomplishment of, the tasks and projects set forth in this document.

5/18/88

John P. Byrne, Director
Division of Disaster Emergency Services
Department of Public Safety

5/10/88

John W. Rold, Director
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Department of Natural Resources

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EXECUTIVE SUMMARY

Chapter 1 INTRODUCTION

In Colorado, losses from landsliding have been in the millions of dollars in recent years. In terms of lives, property, and damage to the state's infrastructure, these losses are high enough to significantly impact the state's economy over the short term. If present loss trends continue, expected losses could eventually become high enough to disrupt the state's economic well-being and the quality of life of its citizens. It is estimated that, in a worst case situation, losses from a major landslide event at Dowds Junction could run as high as $1.7 billion. As urbanization and development increase in the mountainous areas of the state, the potential for higher losses also increases.

Of the thousands of landslides in Colorado, at least 49 have been identified as having potential for community impact. Of these, 12 have a very high potential for inflicting serious loss. In addition, the interaction of other geologic hazards, such as seismicity and flooding, together with landsliding increases the overall threat to people, community services, and facilities.

The purpose of this plan is to reduce statewide actual and potential landslide losses by:

- identifying local governmental resources, plans, and programs that can assist in loss reduction,
- identifying unmet local needs that must be addressed to reduce losses,
- identifying and developing state agency capabilities and initiatives that can deal with unmet local needs,
- developing cost-effective mitigation projects that may reasonably be expected to reduce landslide losses,
- educating state and local officials and emergency response personnel on the landslide hazard, and potential methods for loss reduction, and
- establishing means to provide a long-term, continuing governmental process to reduce losses.

Although landslide loss-reduction is primarily a local responsibility, the magnitude of costs may be so great that significant state support is required.

This plan is designed to promote the coordination of loss-reduction efforts by the state and local governments.

Chapter 2 THE LANDSLIDE HAZARD

Local officials and emergency response personnel need to be informed about landslide processes in order to be able to effectively develop and implement landslide hazard mitigation plans and formulate disaster responses. The term "landslide" describes a variety of processes that result in the downward and outward movement of slope-forming materials. Movement occurs by falling, toppling, sliding, spreading, or flowing. Although primarily associated with mountainous regions, landslides can also occur in areas of generally low relief. The various types of landslides can be differentiated by the kinds of material involved and the modes of movement.

Both natural and man-induced changes in the environment can trigger landslides. Human activities affecting landslides are mainly associated with construction and involve changes in slope and in the surface and groundwater regimes. Natural factors that can trigger landsliding include climate changes, weathering processes, and earthquakes.

Chapter 3 VULNERABILITY AND IMPACT

The impacts of landsliding range from the inconvenience of debris cleanup to the life-threatening failure of a landslide-formed dam. The simultaneous or sequential occurrence of other geologic hazards such as flooding or earthquakes with landsliding may produce effects that are different or much greater than those produced by landsliding alone.

Chapter 4 EVALUATING AND COMMUNICATING THE HAZARD

The first step in landslide hazard reduction is the recognition of the presence of, or the potential for, slope movement and the type and causes of movement. Trained professionals can use various methods including map analysis, aerial photography, field reconnaissance, drilling, and instrumentation to detect and monitor landslide movement.

Often individuals or groups do not take mitigative actions because they do not understand what to do, or lack information and training on how to do it. Therefore, once landslide hazard information has been gathered, it must be communicated to planners, decision-makers, emergency response personnel, and the public. Maps are one of the best methods of information transfer available. The three most commonly used types of maps are: landslide inventories, landslide-susceptibility maps, and landslide hazard maps. A wide variety of maps has been prepared for Colorado.

Chapter 5
MITIGATION CONCEPTS AND APPROACHES

The main goals of landslide hazard mitigation are to preserve lives, property, and revenue and to prevent the disruption of critical services and the economy. The three general methods of landslide hazard mitigation are 1) modifying community vulnerability, 2) modifying physical systems, and 3) modifying the consequences of landsliding.

Modifying community vulnerability involves such techniques as avoidance, building and grading codes, land-use regulations and policies, redevelopment restrictions, hazard monitoring and warning systems, and emergency response and disaster preparedness.

Physical modification is undertaken where human occupation of an unstable area already poses a risk, but where measures such as zoning and other land-use regulations are precluded by cost of resettlement, scarcity of land, or historical rights. Physical measures can be directed toward either control and stabilization, or protective functions. Physical mitigation methods used are categorized according to three types of landslide movement. They address 1) slides and slumps, 2) debris flows and debris avalanches, and 3) rockfall. These methods emphasize surface and subsurface drainage, slope stabilization measures such as the construction of buttresses and retaining structures, vegetation and soil hardening measures, and controlling the ways that land is cut, filled, and graded during development.

Modifying the consequences of landsliding consists of methods designed to assist individuals and communities to prepare for, survive, and recover from hazard occurrences. Such methods include increasing public awareness and the redistribution of losses by means of insurance.

When development of potentially hazardous land is proposed, a cost-benefit analysis should be performed to determine if mitigation is justifiable and cost effective. Frequently the costs may outweigh the benefits over the long term.

Chapter 6
THE COLORADO LANDSLIDE PROBLEM

Colorado's vulnerability (exposure) to the landslide hazard is directly related to the location of population centers, land use, emergency preparedness, and efforts to take mitigative action.

In order to design a statewide landslide hazard mitigation plan, select priority projects, and determine unmet local needs, 49 communities and areas at risk were identified in Colorado. Three of these sites provide case studies because they demonstrate 1) the types of landslide hazards that affect Colorado, 2) various levels of government involvement, 3) a variety of potential mitigative actions, and 4) comparability to cases in other states. The three case studies have been analyzed to determine unmet local needs—those landslide problems which are not adequately addressed by the existing mitigation system.

Chapter 7
THE EXISTING APPROACH TO MITIGATION OF LANDSLIDE HAZARDS IN COLORADO

The legal basis authorizing state and local governments to manage landslide hazards in Colorado consists of a range of statutes, executive orders, and interagency memoranda of understanding. Although none address landsliding exclusively, those which promote landslide management activities under provisions addressing geologic (and associated) hazards and emergency preparedness are the most important.

Coping with landsliding in Colorado involves the cooperation of many public and private institutions and all levels of government. Local governments should take a lead role by identifying goals and objectives, controlling land use, providing hazard information and technical assistance, and implementing other strategies as described in this plan. Although state and federal agencies play supporting roles—primarily financial, technical, and administrative—their efforts in supporting and coordinating mitigation actions are particularly important.

The need to develop organizational systems at the state and local levels to deal with landslide mitigation over the long term in a coordinated and systematic manner is clear. Local preparedness efforts should aim at the development of landslide annexes to the Local Emergency Operations Plan (LEOP). Such an annex can provide for timely and effective disaster response and recovery actions by landslide-impacted jurisdictions. A model emergency response annex to the Garfield County Emergency Operations Plan is presented in chapter 7 as an example. This emergency response annex contains within it a special section covering the county mitigation plan.

Chapter 8
PLAN DEVELOPMENT AND ORGANIZATION

The greatest opportunities for reducing landslide losses in Colorado lie in the advancement of state capabilities in emergency management and long-term hazard mitigation. This plan has been organized to be consistent with other state preparedness plans, such as the State Emergency Operations Plan and a variety of other contingency plans. The plan includes a series of steps suitable for adaptation to other state and local preparedness or mitigation plans:

1) identification of vulnerability,
2) identification of potentially impacted sites across the state,
3) assessment of available resources and capabilities of state and local governments and the private sector,
4) determination of shortfalls in state, local, and private capabilities,
5) formulation of goals for the Colorado Landslide Hazard Mitigation Plan,
6) development of a state system to provide long-term, continuing action,
7) translation of technical information to decision-makers, planners, and emergency response personnel, and
8) periodic evaluation and revision of the plan.

For the state to achieve significant long-term savings by means of landslide mitigation, three critical actions important to the implementation of this plan should be taken immediately by state government. The government should:

- establish and develop a landslide hazard mitigation system in state government and maintain this system over the long term
- assist local governments and the private sector to establish and develop landslide mitigation systems and to maintain these systems over the long term
- seek state and federal funding to implement loss-reduction strategies

The mitigation process in Colorado must also consider work that should be performed with respect to existing landslide areas, public education and awareness, improvements in land-use decision making, and unmet local needs.

Chapter 9
IMPLEMENTATION OF THE COLORADO LANDSLIDE HAZARD MITIGATION PLAN

The projects developed in this plan have been divided into three groups, according to level of importance. These groups consist of projects that are 1) critical action projects, 2) secondary action projects—dependent on implementation of the critical action projects, and 3) follow-up projects—projects that require further research or refinement.

The critical action projects call for organizations at the state and local levels to deal with landsliding over the long term and recommend steps to deal with the state's most severe landslide hazards.

The secondary action projects address several of the more serious landslides in the state, public education and awareness, development and exercising of emergency operations plans, improvements in land-use decision making, and a range of structural and nonstructural measures that will reduce potential losses.

The follow-up projects are those that do not require immediate attention and must be examined further to determine their applicability, feasibility and cost-effectiveness.

PART I

SITUATION, PURPOSE, AND SCOPE

This section identifies the landslide hazard and its impact in Colorado, analyzes state and local capabilities to deal with the situation, details available mitigation methods, and promotes planning as a means to deal with the landslide hazard problem.

Chapter 1
INTRODUCTION

BASIS FOR A COLORADO LANDSLIDE HAZARD MITIGATION PLAN

Colorado has a long history of damaging landslide and debris-flow events. The community of Brownville (near Silver Plume) in Clear Creek County was engulfed and destroyed by a series of debris flows in 1912. The town of Marble in Gunnison County was nearly destroyed by debris flows in the 1930s and 1940s. A large landslide in DeBeque Canyon in June of 1924 temporarily blocked the Colorado River and resulted in the forced relocation of a small community, highway, and railroad.

In recent years, losses from landslides have been extremely high. In 1984, 15 Western Slope counties were declared disaster areas by the President due to floods and landslides associated with the spring runoff. More than $6.6 million in federal, state, and local disaster assistance was administered to restore public facilities and services impacted by the disaster. In 1985, floods and landslides again caused $1.4 million in damages in two western counties. An emergency declaration by the Governor authorized $200,000 in emergency repairs from state and local funds. Additionally, millions of dollars in federal emergency highway funds have been committed to repair landslide-damaged highways at Douglas Pass, Muddy Creek and other landslide-prone sites in the western part of the state. In terms of lives, property, and damage to the state's infrastructure (roads, utilities, bridges, and buildings), losses are high enough to significantly impact the state's economy over the short term.

If present loss trends continue, expected losses could eventually become high enough to disrupt the state's economic well-being and the quality of life of its citizens. It is estimated that losses from a major landslide event at Dowds Junction could run as high as $1.7 billion (Minturn Earthflows Task Force, 1985). The potential for higher losses is growing as urbanization and development increase in Colorado's vulnerable mountainous areas. Figure 1 indicates the extent of landsliding in Colorado relative to adjacent states. Most significant landsliding occurs in the mountainous areas in the western two-thirds of the state.

The Landslide Hazard in Colorado

There are thousands of landslides of various ages and degrees of activity in Colorado. A preliminary screening by the Colorado Geological Survey (CGS) has identified 12 large landslides with high potential for very large future losses. Thirty-seven additional areas have been identified that have high potential for future landslide or debris-flow events that could have serious local community impacts. Although few lives have been lost as a result of landsliding, the budgets of the Colorado Department of Highways (CDOH) and many counties and cities have been significantly impacted by costs related to landsliding. Many private industries have also experienced high losses from landslides. These include railroads, mining companies, oil and gas production and transmission companies, and electrical transmission firms. Many individuals have also been seriously affected.

Landsliding in Colorado intensified during the period 1983-1987 as a result of higher than normal annual precipitation in many areas of the state (Figure 2). Although landsliding has always occurred in Colorado, this recent cycle of increased precipitation combined with expanding population growth has increased the likelihood of damage and disaster. Some of the communities and areas believed to be at relatively high risk are listed in Table 8.

Other Hazards Related to Landsliding

Flooding

For many years flooding has been Colorado's most frequent and costly hazard. Landsliding is closely allied to flooding in that both are related to precipitation, runoff, and ground saturation. This was recognized by the Federal Emergency Management Agency (FEMA) and the State of Colorado when specific types of landsliding were integrated into the 1985 *Colorado Flood Hazard Mitigation Plan* (Colorado Water Conservation Board, 1985).

Seismicity

Most of the mountainous areas of Colorado that are vulnerable to landslides also have experienced a moderate level of seismicity in historic times. The coincidence of these hazards has the potential, under certain conditions, of significantly increasing the risk of serious damage.

Dam failure

Failure of man-made dams is also an important hazard in Colorado that may be in part related to landsliding.

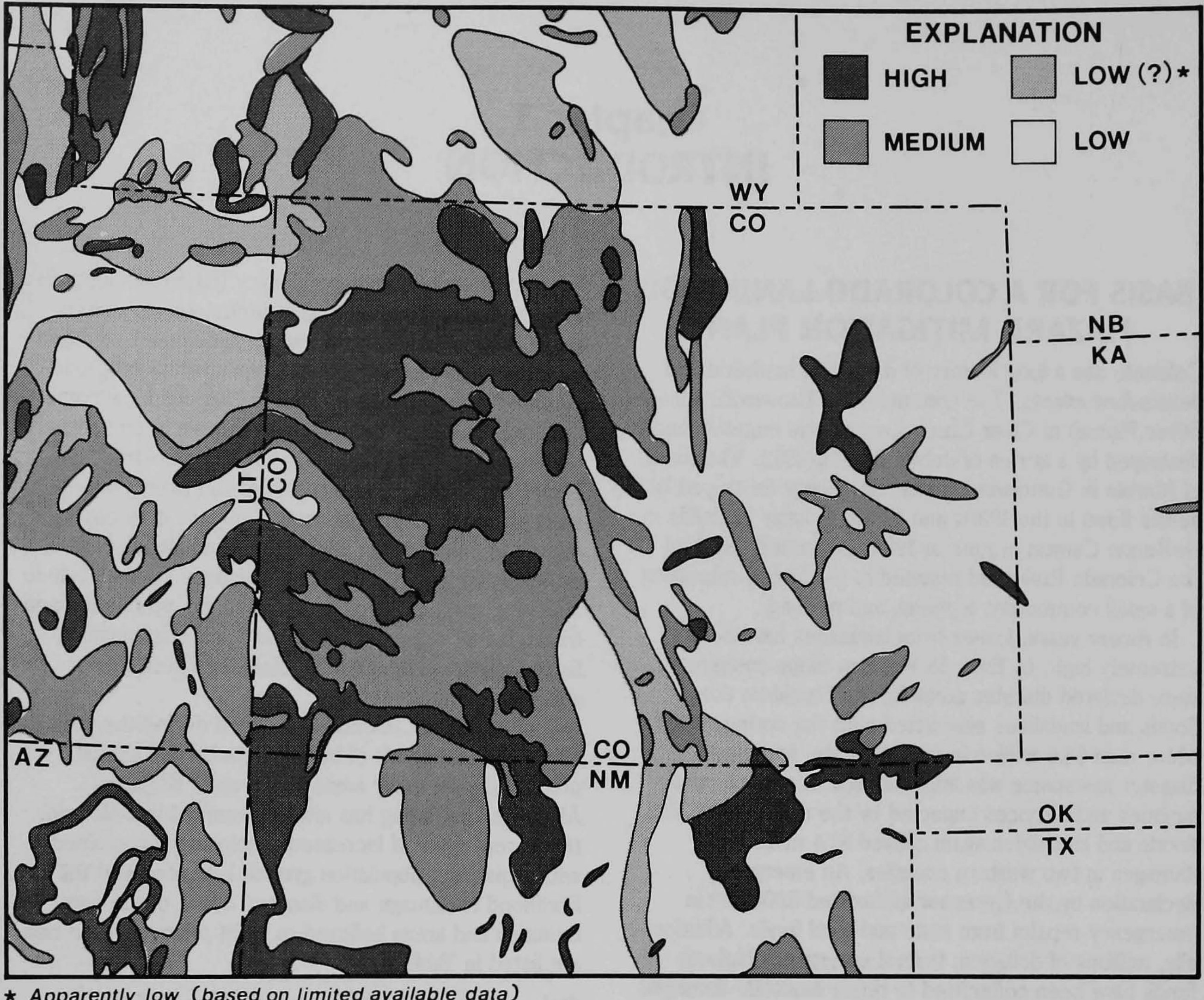


Figure 1. Generalized map showing the relative potential for landsliding in Colorado and surrounding states (Wiggins and others, 1978).

Large landslides may impact dam abutments, block spillways, or lead to overtopping and erosion of a dam or spillway, ultimately leading to dam failure. Since Colorado has 586 "high" and "moderate" hazard dams (defined according to the anticipated number of lives lost and damage caused if the dam failed), the possibility that landslides can contribute to dam failure is very real.

The Need for Planning

Landsliding occurs in every state in the nation, producing significant impacts on the economies of more than half the states (Committee on Ground Failure Hazards, 1985). While landslides can and do occur as specific local events, as much as one-third of the nation's annual landslide loss is associated with major statewide or regional landslide disasters resulting from heavy rains or snowmelt.

> Landsliding of this sort often extends beyond the boundaries of any single state or local governmental entity. Because of this, and because effective measures for reducing landslide losses require the cooperation of federal, state, local, and private entities, reduction of landslide losses should be viewed as a national goal requiring national leadership
> (Committee on Ground Failure Hazards, 1985, p. 1).

Olshansky and Rogers (1987, p. 941) emphasize the seriousness of the situation:

> Public policies for reducing landslide hazards and compensating landslide victims are at best piecemeal and poorly coordinated; at worst, they are misguided, unenforced, or nonexistent. Neither legislatures nor the courts have taken a comprehensive approach toward solving this problem.

In Colorado and in the United States as a whole, the need to mitigate the dangers and costs of landsliding is clear. Lessening the impact of these costly events can save many lives and enormous amounts in property values. Successful and cost-effective national landslide

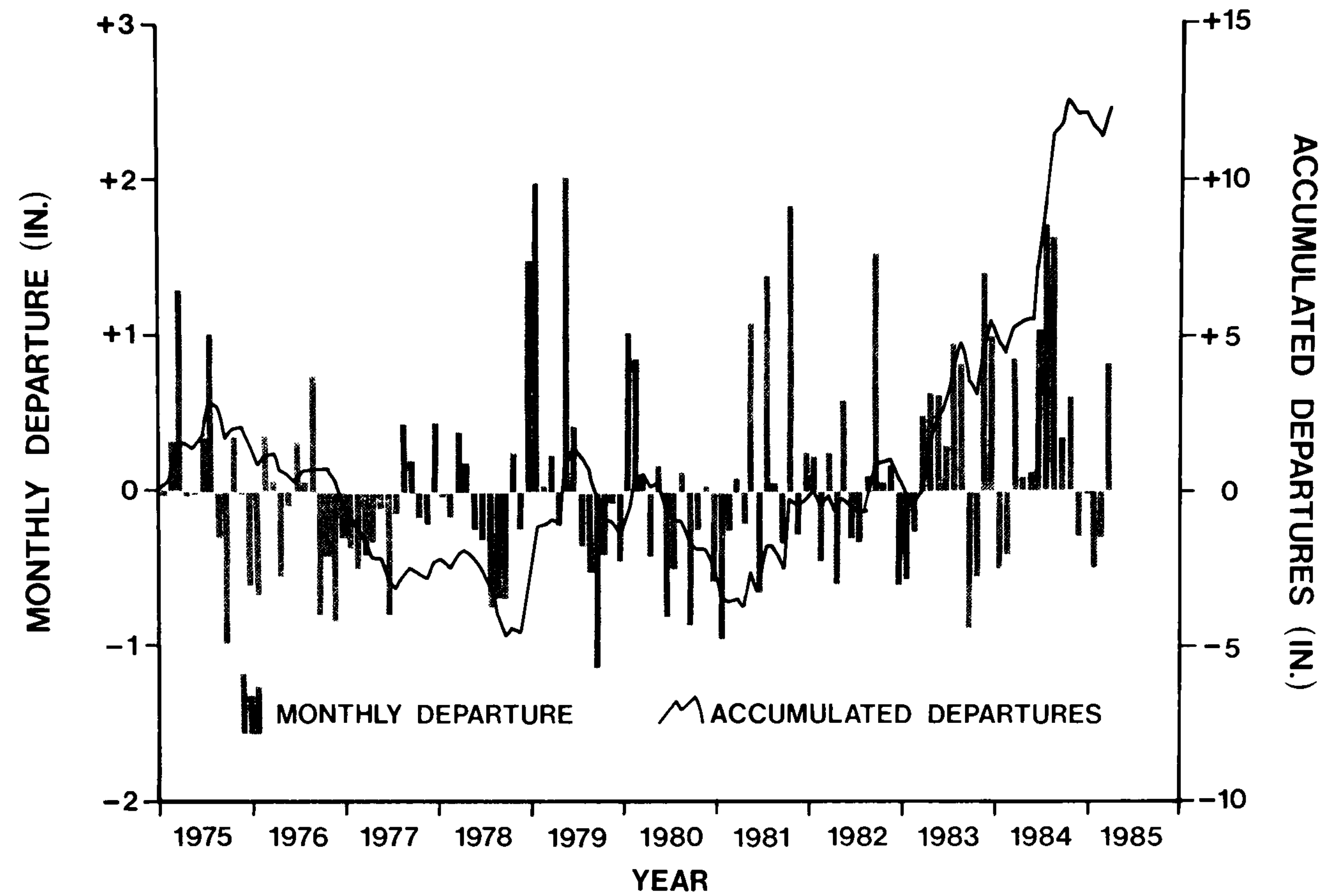


Figure 2. The 1975-1985 monthly and accumulated precipitation departures from the 20-year average for Eagle, Colorado.

mitigation programs have been implemented in Japan and other countries. Based on annual landslide loss figures alone, consideration of such an effort would seem to warrant the attention of political leaders, scientists, engineers, and planners in this country. Although there have been some impressive and successful local demonstrations of landslide hazard mitigation in the United States, information about these activities has not been widely disseminated.

PURPOSE OF THIS LANDSLIDE HAZARD MITIGATION PLAN

The purpose of this mitigation plan is to reduce statewide actual and potential losses from landslides by:

- identifying local governmental strategies, plans, and programs that can assist in loss reduction,
- identifying unmet local needs essential to the loss-reduction process,
- identifying and developing state agency capabilities and initiatives that can deal with unmet local needs,
- developing cost-beneficial state mitigation projects that may reasonably be expected to reduce landslide losses,
- educating state and local officials and emergency response personnel on the landslide hazard and potential methods for loss reduction, and
- establishing means to provide a long-term, continuous governmental process to reduce losses.

SCOPE OF PLAN

This plan recognizes the importance of taking landslide hazards into account in community planning and land-use management, and provides local authorities with a wide range of possible strategies and regulatory approaches for mitigating landslide problems in their communities. Mitigation options are presented in this plan as projects. Implementation costs vary widely. Estimates are provided where possible. Where state and local governments' budgets allow, low cost projects should be undertaken. When costs exceed immediate budget capabilities, projects may have to be implemented in stages over several years, or federal assistance sought.

In view of local government's primary role in managing the use of its land, this state mitigation plan is essentially a support document. It is one of several state mitigation plans now being developed to reduce potential losses from Colorado's most costly threats and potential disasters.

Chapter 2
THE LANDSLIDE HAZARD

In order for local officials and emergency response personnel to correctly formulate and implement landslide hazard emergency response plans, they need to be informed about landslide processes and impacts. To attempt a solution without understanding the problem is inefficient, if not dangerous.

The term "landslide" is used to describe a wide variety of processes that result in the downward and outward movement of slope-forming materials composed of rocks, soils, artificial fill, or a combination of these. The materials may move by: falling, toppling, sliding, spreading, or flowing (U.S. Geological Survey, 1981). The various types of landslides can be differentiated by the kinds of material involved and the mode of movement. A classification system based on these parameters is shown in Figure 3. Other classification systems incorporate additional variables such as the rate of movement and water, air, or ice content of the slide material.

Although landslides are primarily associated with mountainous regions, they can also occur in areas of generally low relief. In these areas landslides occur as cut-and-fill failures (highway and building excavations), river bluff failures, lateral spreading landslides, collapse of mine-waste piles (especially coal), and a wide variety of slope failures associated with quarries and open-pit mines. The most common types of landslides are described below.

TYPES OF LANDSLIDES

Falls

Falls (Figure 4) are abrupt movements of masses of geologic materials that become detached from steep slopes or cliffs. Separation occurs along surfaces such as fractures, joints, and bedding surfaces, and movement occurs by free-fall, bouncing, and rolling. Falls are strongly influenced by gravity, mechanical weathering, and the presence of interstitial water.

Depending on the type of earth materials involved, the result is a rockfall, soilfall, debris fall, earth fall, boulder fall, and so on. All types of falls are promoted by undercutting, differential weathering, excavation, or stream erosion.

Topples

Toppling failures (Figure 5) are distinguished by "the forward rotation of a unit or units about some pivotal point, below or low in the unit, under the action of gravity and forces exerted by adjacent units or by fluids in cracks" (Varnes, 1978, p. 12).

<table>
<tr><th colspan="3" rowspan="3">TYPE OF MOVEMENT</th><th colspan="3">TYPE OF MATERIAL</th></tr>
<tr><th rowspan="2">BEDROCK</th><th colspan="2">ENGINEERING SOILS</th></tr>
<tr><th>Predominantly coarse</th><th>Predominantly fine</th></tr>
<tr><td colspan="3">FALLS</td><td>Rock fall</td><td>Debris fall</td><td>Earth fall</td></tr>
<tr><td colspan="3">TOPPLES</td><td>Rock topple</td><td>Debris topple</td><td>Earth topple</td></tr>
<tr><td rowspan="3">SLIDES</td><td>ROTATIONAL</td><td rowspan="2">FEW UNITS</td><td>Rock slump</td><td>Debris slump</td><td>Earth slump</td></tr>
<tr><td rowspan="2">TRANSLATIONAL</td><td>Rock block slide</td><td>Debris block slide</td><td>Earth block slide</td></tr>
<tr><td>MANY UNITS</td><td>Rock slide</td><td>Debris slide</td><td>Earth slide</td></tr>
<tr><td colspan="3">LATERAL SPREADS</td><td>Rock spread</td><td>Debris spread</td><td>Earth spread</td></tr>
<tr><td colspan="3" rowspan="2">FLOWS</td><td>Rock flow</td><td>Debris flow</td><td>Earth flow</td></tr>
<tr><td>(deep creep)</td><td colspan="2">(soil creep)</td></tr>
<tr><td colspan="3">COMPLEX</td><td colspan="3">Combination of two of more principle types of movement</td></tr>
</table>

Figure 3. Abbreviated version of Varnes' classification of slope movements (Varnes, 1978).

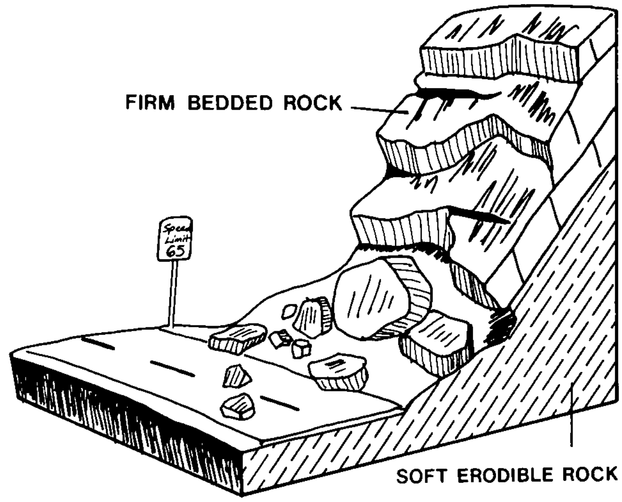


Figure 4. A rockfall.

Slides

Although many types of mass movement are included in the general term "landslide," the more restrictive use of the term refers to only "those mass movements where there is a distinct surface of rupture or zone of weakness which separates the slide material from more stable underlying material" (Rogers and others, 1974, p. 18). The two major types of landslides are rotational slides and translational slides.

Rotational slide

A rotational slide is one in which the surface of rupture is curved concavely upward and the slide movement is more or less rotational about an axis that is parallel across the slope (Figure 6). The scarp formed at the head of the slide may be almost vertical since the movement at that point is almost wholly downward. The toe usually bulges upward, but sometimes flows outward. A "slump" is an example of a small rotational slide (Varnes, 1978; U.S. Geological Survey, 1981, 1982).

Translational slide

In a translational slide, the mass moves out, or down and out along a more or less planar surface and has little rotational movement or backward tilting (Figure 7). The mass commonly slides out on the original ground surface. Such a slide may progress over great areas if conditions are right. The movement of translational slides is commonly controlled by surfaces of weakness such as faults, bedding planes, and variations in shear strength between layers of bedded deposits, or by the contact between firm bedrock and overlying loose soils (Varnes, 1978). Slide material may range from loose unconsolidated soils to extensive slabs of rock.

A block slide is a translational slide in which the moving mass consists of a single unit, or a few closely related units that move downslope as a single unit (Varnes, 1978). If the slide material is a solid block of

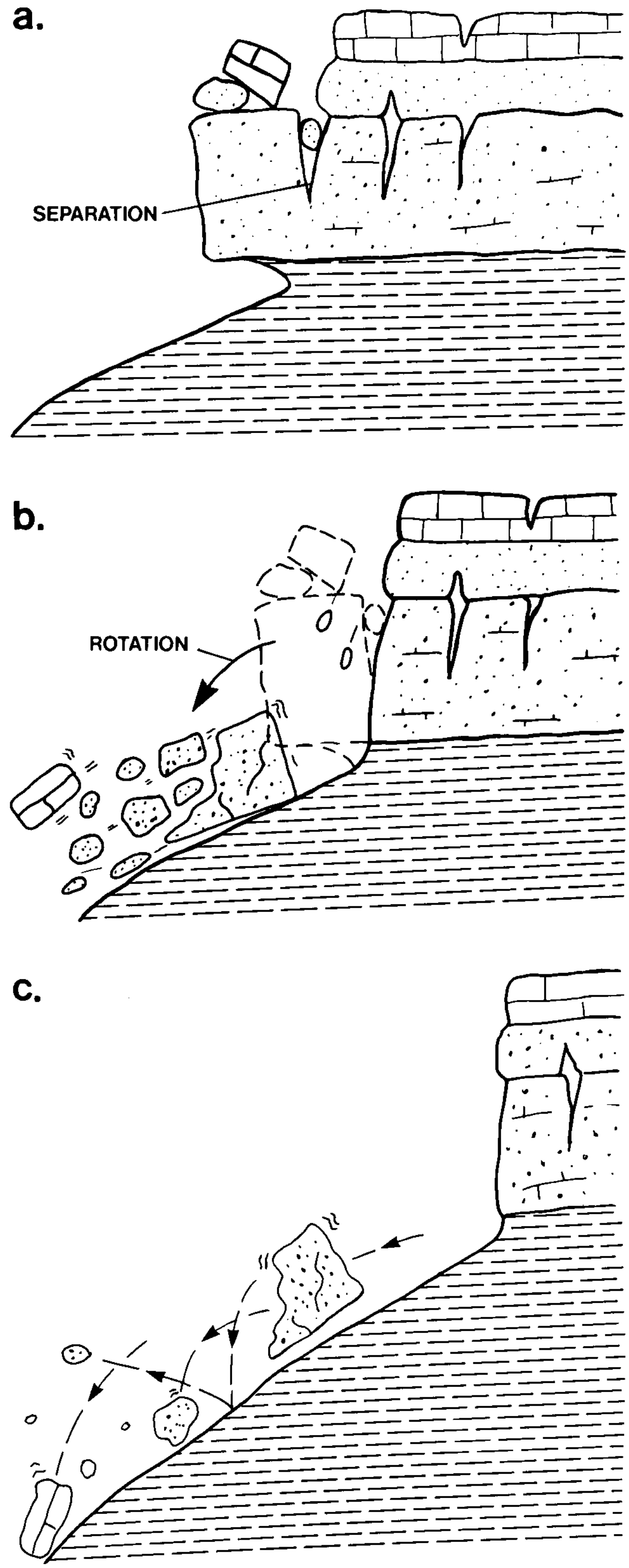


Figure 5. Rocks in the process of toppling: a) separating from the main rock mass and then, b) rotating and falling on the slope below, and c) after breaking into fragments, bounding down the hillside.

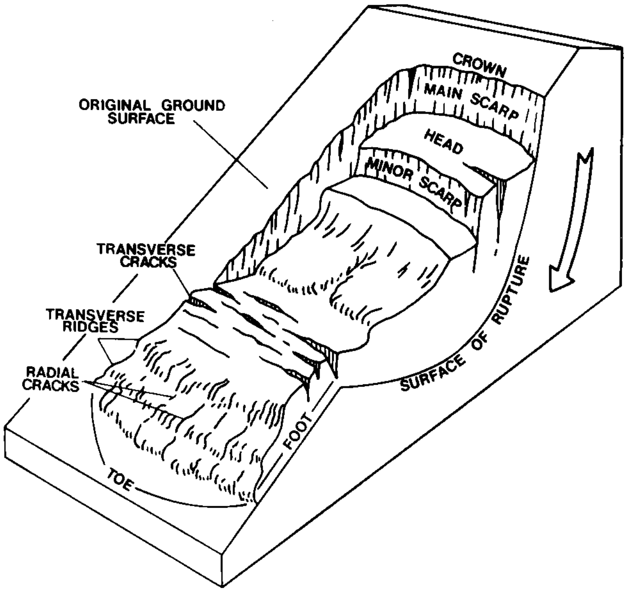


Figure 6. A rotational landslide (modified from Varnes, 1978).

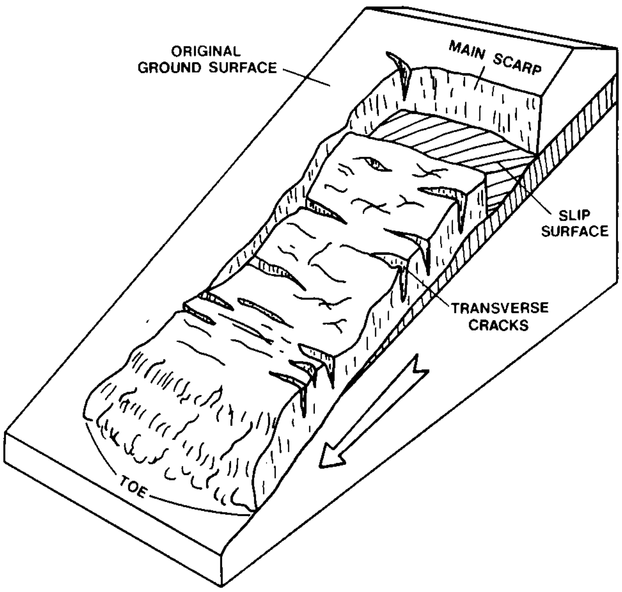


Figure 7. A translational landslide.

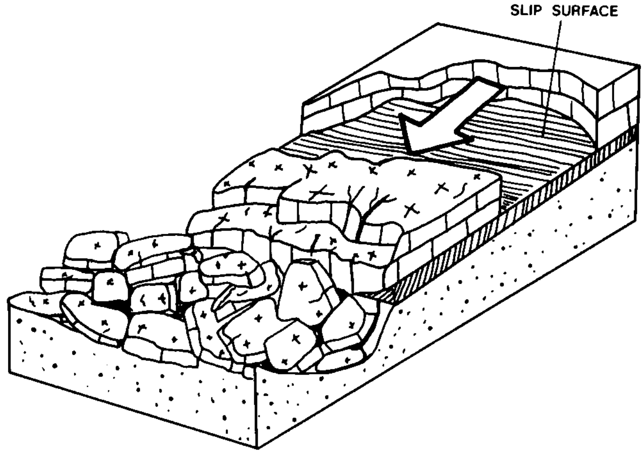


Figure 8. A block slide.

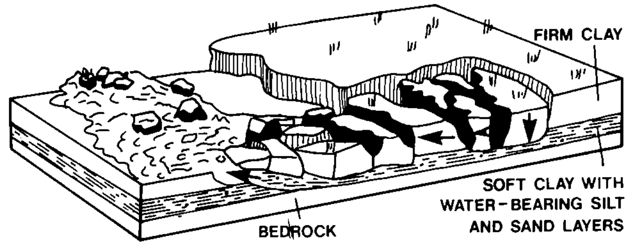


Figure 9. A lateral spread.

bedrock, it is a "rock block slide" (Figure 8). If, however, the rock material is broken, but still slides along a distinct surface of failure, it is a "rockslide."

Lateral Spreads

Lateral spreads (Figure 9) are distinctive because they usually occur on very gentle slopes (between 0.5 and 5.0%). According to Varnes (1978, p. 14), "the dominant mode of movement is lateral extension accommodated by shear or tensile fractures." The failure is caused by liquefaction, the process whereby saturated, loose, cohesionless sediments (usually sands and silts) are transformed from a solid into a liquefied state. Failure is usually triggered by rapid ground motion such as that experienced during an earthquake, but can also be artificially induced.

When coherent material, either bedrock or soil, rests on materials that liquefy, the upper units may undergo fracturing and extension and may then subside, translate, rotate, disintegrate, or liquefy and flow. Lateral spreading in fine-grained materials on shallow slopes is usually progressive. The failure starts suddenly in a small area and spreads rapidly. Often the initial failure is a slump, but in some materials movement occurs for no apparent reason (Varnes, 1978).

Flows

Creep

Creep is the imperceptibly slow, steady, downward movement of slope-forming soil or rock. Movement is caused by shear stress sufficient to produce permanent deformation, but too small to produce shear failure (American Geological Institute, 1974). Hansen (1984) distinguishes three types of creep: 1) seasonal, where movement is within the depth of soil affected by seasonal changes in soil moisture and soil temperature, 2) continuous, where shear stress exceeds the strength of the material, and 3) progressive, where slopes are reaching the point of failure by other mass movements.

Creep is indicated by curved tree trunks, bent fences or retaining walls, tilted poles or fences, and small soil ripples or ridges (Figure 10).

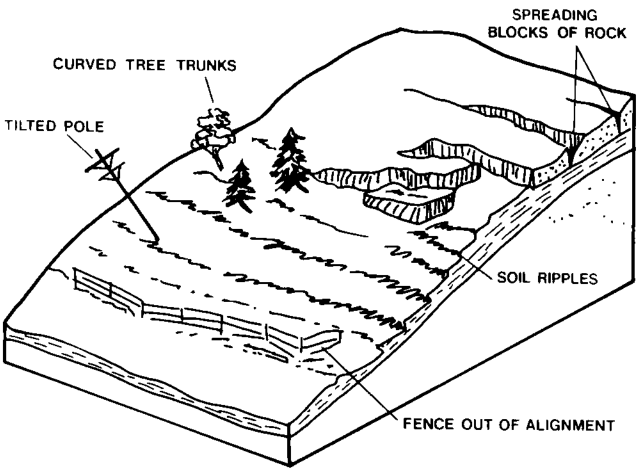


Figure 10. Creep, or the imperceptible slow movement of shallow surficial soils. The process is reflected in the tilting of telephone and power poles, fences out of alignment, curved tree trunks, and a ribbed appearance of the slope due to soil ripples.

Debris flow

A debris flow is a form of rapid mass movement in which loose soils, rocks, and organic matter combine with entrained air and water to form a slurry that then flows downslope. Generally speaking, five conditions must be present for a debris flow to occur: 1) steep slopes, 2) loose rock and soil materials, 3) clay minerals, 4) saturated soils, and 5) rainfall- or snowmelt-generated runoff of sufficient intensity and duration to initiate slope movement.

Debris-flow areas are associated with steep gullies. Individual debris flows can usually be identified by the presence of debris fans at their termini (Figure 11).

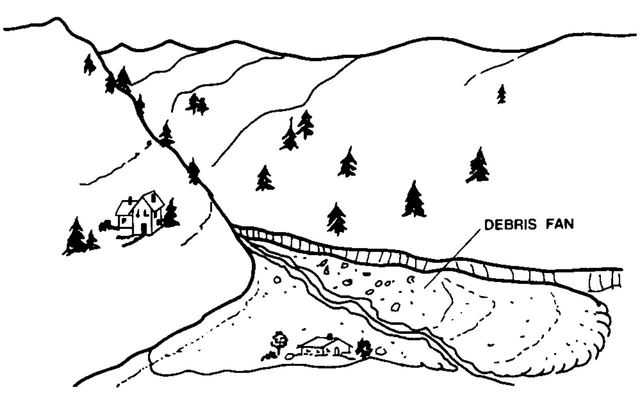


Figure 11. Debris fan formed by debris flows.

Debris avalanche

Varnes (1978, p. 18) classifies the debris avalanche as a variety of very rapid to extremely rapid debris flow. In comparing debris avalanches to debris flows he says:

> In debris avalanches, progressive failure is more rapid, and the whole mass, either because it is quite wet or because it is on a steep slope, liquefies, at least in part, flows, and tumbles downward, commonly along a stream channel, and may advance well beyond the foot of the slope. Debris avalanches are generally long and narrow and often leave a serrate or V-shaped scar tapering uphill at the head, . . . in contrast to the horseshoe-shaped scarp of a slump.

Earthflow

Earthflows have a characteristic "hourglass" shape (Figure 12). A bowl or depression forms at the head where the slope material liquefies and runs out. The flow itself is elongated and usually channelized and spread out at the toe. Flows generally occur in fine-grained materials or clay-bearing rocks on moderate slopes and under saturated conditions. However, dry flows of granular material are also possible.

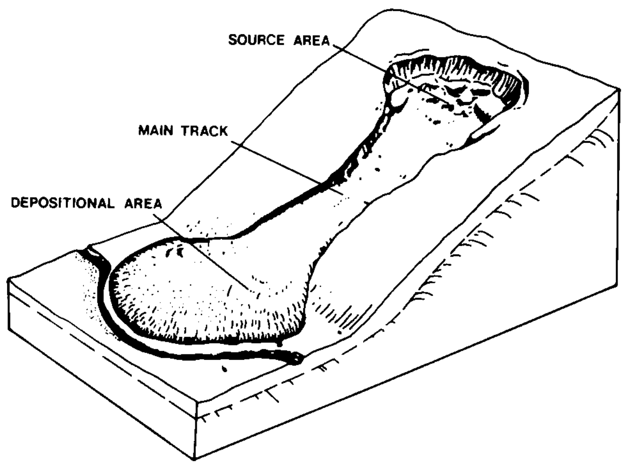


Figure 12. An earthflow (modified from Varnes, 1978).

Mudflow

A mudflow is "an earthflow consisting of material that is wet enough to flow rapidly and that contains at least 50 percent sand-, silt-, and clay-sized particles" (Varnes, 1978, p. 18).

HUMAN ACTIVITIES AND NATURAL FACTORS TRIGGERING LANDSLIDES

Both natural and man-induced changes in the environment can trigger landslides. The geologic history, as well as activities associated with human occupation, directly determines, or contributes to the conditions that lead to slope failure. The basic causes of slope instability are fairly well known, based on a large number of well-documented case studies. The cause can be inherent in the composition or structure of the rock or soil; variable, such as changes in ground-water level; transient, such as seismic activity; or due to new environmental conditions, such as those imposed by construction activity (Varnes and the IAEG, 1984).

Human Activities

Human activities triggering landslides are mainly associated with construction and involve changes in slope and in the surface-water and ground-water regimes. Changes in slope result from terracing for agriculture, cut-and-fill for highways, the construction of buildings and railroads, and mining operations. If these activities are ill-conceived, or improperly designed or constructed, they can increase slope angle, decrease toe or lateral support, or load the head of a landslide. Changes in irrigation or surface runoff can cause changes in surface drainage and can increase erosion or contribute to loading a slope or raising the ground-water table. The ground-water table can also be raised by waste water effluent from leach fields or cesspools, leaking swimming pools or ponds, and irrigation or conveyance of irrigation water. A high ground-water level results in increased pore pressure and decreased shear strength, thus facilitating slope failure. Conversely, the lowering of the ground-water table as a result of rapid drawdown by water supply wells, or the lowering of a lake or reservoir, can also cause slope failure as the buoyancy provided by the water decreases and seepage gradients are steepened.

Vibrations from manufacturing or construction machinery, blasting, and traffic can also trigger landslides in rare instances.

Natural Factors

There are a number of natural factors that can cause slope failure. Some of these, such as long-term or cyclic climate changes, are indiscernible without instrumentation and/or long-term record-keeping.

Climate

Long-term climate changes can have a significant impact on slope stability. An overall decrease in precipitation results in a lowering of the water table, as well as a decrease in the weight of the soil mass, solution of materials, and freeze-thaw activity. An increase in precipitation or ground saturation will raise the level of the ground-water table, reduce shear strength, increase the weight of the soil mass, and may increase erosion and freeze-thaw activity. Periodic high intensity precipitation can also significantly impact slope stability.

Erosion

Erosion by intermittent running water (gullying), streams, rivers, waves or currents, wind, and ice removes toe and lateral slope support.

Weathering

Weathering is the natural process of rock deterioration which produces weak, landslide-prone materials. It is caused by the chemical action of air, water, plants, and bacteria, the physical action caused by changes in temperature (expansion and shrinkage), the freeze-thaw cycle, and the burrowing activity of animals.

Earthquakes

Earthquakes not only trigger landslides but, over time, the fault activity associated with them can create steep and potentially unstable slopes.

Chapter 3
VULNERABILITY AND IMPACT

VULNERABILITY

Vulnerability is the susceptibility or exposure to injury or loss from a hazard. People, structures, community infrastructure (transportation systems, water supply, communications, and electricity), and social systems are all potentially vulnerable.

Colorado's vulnerability to the landslide hazard is largely a consequence of the increasing expansion of commercial and residential development onto steep or unstable terrain that is prone to landsliding. Before resources are invested in hazard mitigation measures, the social and economic costs and impacts associated with landsliding need to be determined and put into perspective.

The first step in determining the overall vulnerability of the state to landslide hazard is the identification of communities, areas, and facilities at risk (for Colorado see chapter 6).

POTENTIAL IMPACTS OF LANDSLIDES ON PEOPLE AND PROPERTY

Once the vulnerability of various communities, areas, and facilities to landsliding has been determined, site-specific evaluations of the potential impacts of landsliding should be performed. **Impact** is the effect of the occurrence of the hazard on people and the infrastructure. Significance is a quantification of the major social and economic elements impacted. Table 1 reflects the types of impacts that can result from landsliding and their consequences in estimated order of increasing significance.

INTERRELATIONSHIP OF LANDSLIDING WITH OTHER NATURAL HAZARDS (THE MULTIHAZARD CONCEPT)

Natural hazards often occur simultaneously or, in some cases, one hazard triggers another. For example, an earthquake may trigger a landslide, which in turn may block a valley causing upstream flooding. Different hazards may also occur at the same time as the result of a common cause. For example, heavy precipitation or rapid snowmelt can cause debris flows and flooding to occur in the same area.

The simultaneous or sequential occurrence of interactive hazards may produce cumulative effects that differ significantly from those expected from any single one of the component hazards.

Landsliding as Related to Dam Safety

The safety of a dam can be severely compromised by the occurrence of landsliding upstream from the dam, or on slopes bordering the dam's reservoir or abutments. Possible impacts include 1) the formation of wave surges that can overtop the dam, 2) increased sedimentation, and 3) dam failure.

Flood surges can be generated either by the sudden detachment of large masses of earth into the reservoir, or by the formation and subsequent failure of a landslide dam across a tributary stream channel. Waves formed by such failures can overtop the dam and cause downstream flooding without actually causing dam failure.

Landsliding into upstream areas or reservoirs can greatly increase the amount of sediment that is deposited in the reservoir, ultimately reducing storage capacity. This increases the likelihood that the dam will be overtopped during periods of excessive runoff, causing downstream flooding. Sedimentation can also damage pumps and water intake valves.

Actual dam failure could be caused by landsliding at or near the abutments or in the embankments of earthen dams.

Rapid changes in the water level of reservoirs can also trigger landslides. When the water level in the reservoir is lowered, the subsequent loss of support provided by the water and increased seepage pressure can initiate sliding. Alternately, the increase in saturation caused by rising water can trigger landslides on slopes bordering the reservoir.

Landsliding as Related to Flooding

Landsliding and flooding are closely allied because both are related to precipitation, runoff, and ground saturation. In addition, debris flows usually occur in small, steep stream channels and are often mistaken for floods. In fact, these events frequently occur simultaneously in the same area and in some cases grade into each other.

Landslides and debris flows can cause flooding by forming landslide dams that block valleys and stream channels, allowing large amounts of water to back-up. This causes backwater flooding and, if the dam breaks,

Table 1. Relationship between potential landslide impacts, social and economic elements impacted, and their significance.

INCONVENIENT → (INCREASING SIGNIFICANCE) ↓

POTENTIAL LANDSLIDE IMPACTS	MAJOR SOCIAL AND ECONOMIC ELEMENTS IMPACTED			
	LIVES	PROPERTY	SERVICES	REVENUE
DEBRIS CLEAN UP Local or small debris flows, landslides, and rockfalls that spill onto roads and streets are relatively easy to clean up and are therefore mostly a costly nuisance. However, repeated road clean up over the years plus the undocumented expense of clean up and landscaping repair costs to homeowners can result in a significant long-term expenditure of funds.		■		
ROAD/RAILROAD/BRIDGE DAMAGED (BUT PASSABLE) If transportation corridors are damaged but passable, they will not prevent the flow of traffic. They may, however, result in delays and restrict some sizes/weights of vehicles. They may also be dangerous in view of the potential for sudden collapse.		■		
LOSS OF CROPS OR FOREST RESOURCES Agricultural crops can be destroyed by 1) surface dislocation, 2) burial, and 3) water loss due to disruption of irrigation ditch water supply. Timber crops can be lost through 1) surface disruption, 2) removal or burial by debris flows.		■		■
IRRIGATION DITCH DAMAGE Damaged irrigation ditches result in 1) loss of revenue because crops cannot be irrigated, 2) loss of service to property owners receiving water from ditch, 3) costs to repair ditch, and 4) if flow is not cut off, water will saturate slope even further, increasing landslide damage and extending it to nearby roads and/or property.		■	■	■
INCREASED SEDIMENTATION Landslides and debris flows into streams or rivers add vast quantities of sediment to the water system. This can 1) silt up reservoirs, resulting in loss of storage capacity, 2) cause damage to pumps for water intake, 3) diminish water quality for drinking, 4) kill fish and fish eggs, and destroy fishing areas (resulting in loss of revenue), 5) cause degradation in crop land when silt decreases permeability, and 6) add enough bulk to the stream flow to cause catastrophic flooding.		■	■	■
ROAD/RAILROAD/BRIDGE BLOCKAGE (TOTAL) Total blockage will prevent traffic flow and affect 1) workers' ability to commute, 2) access of emergency vehicles, and 3) the normal flow of commerce. Blockage time may range from short interruptions to long-term or permanent stoppage. In addition, pieces of a bridge may eventually cause channel blockage and result in backwater flooding.		■	■	■
COMMUNICATIONS OUT (INABILITY TO CALL FOR AID IN CASE OF EMERGENCY)	■	■	■	■

Table 1. (Cont.)

POTENTIAL LANDSLIDE IMPACTS	LIVES	PROPERTY	SERVICES	REVENUE
RAPID DESTRUCTION OF TRANSPORTATION CORRIDORS If roads, railroads, or bridges are destroyed quickly, effects include all of those listed above for those facilities, plus possible loss of life if destruction occurs during use.	■	■	■	■
DAMAGE TO UNDERGROUND AND SURFACE MINING FACILITIES Ground surface dislocation can impact both surface and subsurface mining operations by 1) affecting the working surface, 2) blocking entry ways, 3) disrupting haulage roads, adits, air shafts, etc., 4) collapsing the mine, and 5) causing cessation of supply of needed mineral fuels.	■	■	■	■
UTILITY DAMAGE (SEWER, WATER, POWER, GAS PIPELINES) Utility damage can cause 1) loss of life due to the explosion of gas lines, 2) loss of service, 3) loss of revenue, 4) costs of repair, and 5) potential health risks resulting from sewage system breaks.	■	■	■	■
GROUND SURFACE AND STRUCTURE DISLOCATION/ DISRUPTION Such dislocation can cause 1) utility damage, 2) crop damage, 3) irrigation ditch damage, 4) road blockage, 5) bridge destruction, 6) loss of life, 7) loss of service, 8) loss of revenue, 9) toxic waste hazards if it involves chemical storage tanks, or fire/ explosion hazards if it involves gas or liquid energy fuels, and 10) damage and destruction of buildings (residential and commercial).	■	■	■	■
DEBRIS BURIAL OF STRUCTURES Structure burial is usually the result of debris flows, earthflows, or translational landslides. These events can strike either with great speed and force, or by slow engulfment. Can cause loss of life, property, services, and revenue.	■	■	■	■
LANDSLIDE DAM WITH BACKWATER FLOODING The formation of an earth dam by landsliding can result in 1) upstream flooding; lake formation inundating valuable crop, range, or recreation areas; structure flooding, 2) blocking of transportation routes, thus affecting commerce, tourism, and emergency vehicle access, 3) loss of revenue due to decreased tourism, impeded access to local businesses, and diminished tax revenues from flooded lands, and 4) interruption of communication and utility services.	■	■	■	■
FAILURE OF A LANDSLIDE DAM WITH DOWNSTREAM FLOODING A landslide dam break could result in catastrophic flooding downstream with possible loss of life and extensive property destruction.	■	■	■	■

MAJOR SOCIAL AND ECONOMIC ELEMENTS IMPACTED

(INCREASING SIGNIFICANCE) → CATASTROPHIC downstream flooding. Also, soil and debris from landslides can "bulk" or add volume to otherwise normal stream flow or cause channel blockages and diversions creating flood conditions. Finally, landslides can negate the protective functions of a dam by reducing reservoir capacity and creating surge waves that can overtop a dam, resulting in downstream flooding (as mentioned above).

In turn, flooding can cause landsliding. Erosion, due to rapidly moving flood waters, often undercuts slopes or cliffs. Once support is removed from the base of saturated slopes, landsliding often ensues.

Examples of interrelated landslide/flood events in Colorado occurred:

- in Larimer County, 1976: the mountain torrent flood in the Big Thompson Canyon;
- in Ouray (Ouray County), 1981 and 1982: debris flows in the creeks feeding into the Uncompahgre River (Canyon, Cascade, Portland, etc.) and flooding in the Uncompahgre River itself;
- in Telluride (San Miguel County), 1914 and 1969: debris flows in Coronet Creek and flooding in the San Miguel River;
- near Lake City (Hinsdale County): Lake San Cristobal was formed in prehistoric time when a large earthflow (the Slumgullion) dammed the Lake Fork of the Gunnison River. The landslide dam held, and the lake was formed.

Landsliding as Related to Seismic Activity

Most of the mountainous areas of Colorado that are vulnerable to landslides have also experienced moderate levels of seismicity in historic times. Recent studies by the Colorado Geological Survey indicate that the potential for earthquakes in the state is even greater than previously suspected. The occurrence of earthquakes in landslide-prone areas greatly increases the likelihood that landslides will occur and amplifies the risk of serious damage to a level considerably higher than if the processes occurred separately. Comparison of Kirkham and Rogers' 1987 map of historic earthquake intensities (Figure 13) with Wiggins' 1978 map of landslide potential (Figure 1) emphasizes the relationship between landslide-prone and earthquake-prone areas in Colorado.

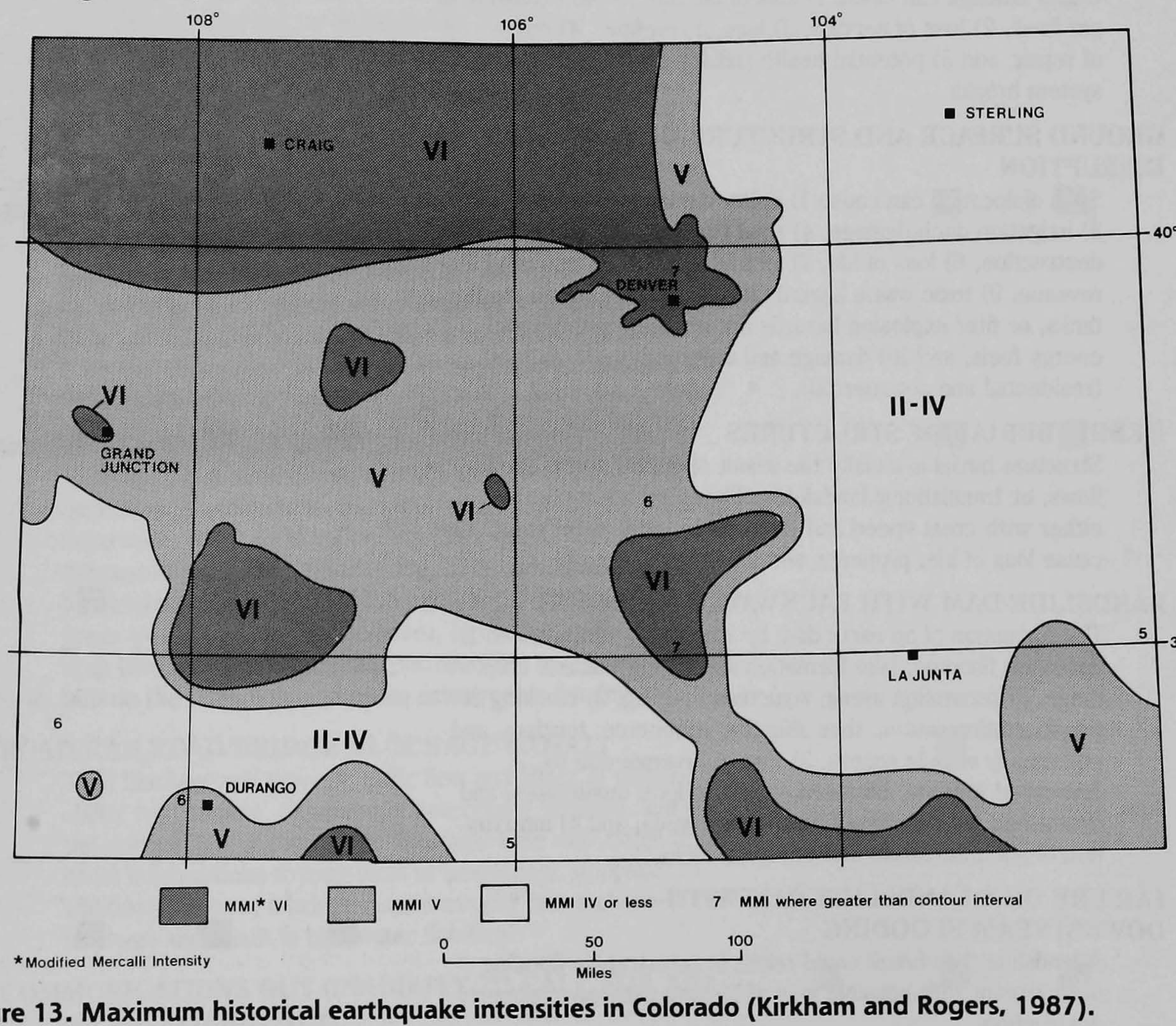


Figure 13. Maximum historical earthquake intensities in Colorado (Kirkham and Rogers, 1987).

Chapter 4
EVALUATING AND COMMUNICATING THE HAZARD

METHODS OF LANDSLIDE EVALUATION AND ANALYSIS

Recognition of the presence of active or potential slope movement, and the type and causes of the movement, is essential to landslide mitigation. Recognition depends on an accurate evaluation of the geology, hydrogeology, landforms, and interrelated factors such as environmental conditions and human activities. Only trained professionals should conduct such evaluations. However, because local governments may need to contract for such services, they should be aware of the techniques available and their advantages and limitations.

Techniques for recognizing the presence or potential development of landslides include:

- map analysis
- analysis of aerial photography and imagery
- field reconnaissance
- aerial reconnaissance
- drilling
- geophysical studies
- computerized landslide terrain analysis
- instrumentation

Summaries of these techniques are presented below, and more detailed discussions are included in Appendix 1.

Map Analysis

Map analysis is usually one of the first steps in a landslide investigation. Maps that can be used include geologic, topographic, soils, and geomorphic. Using knowledge of geologic materials and processes, a trained person can obtain a general idea of landslide susceptibility from such maps.

Analysis of Aerial Photography and Imagery

Aerial photography is a rapid and valuable technique for identifying landslides, because it provides a three-dimensional overview of the terrain and indicates human activities as well as much geologic information. In addition, the availability of many types of aerial imagery (satellite, infrared, radar, etc.) make this a very versatile technique.

Field Reconnaissance

Many of the more subtle signs of slope movement cannot be identified on maps or photographs. Indeed, if an area is heavily forested or has been urbanized, even major features may not be evident. Furthermore, landslide features change over time on an active slide. Thus, field reconnaissance is necessary to verify or detect many landslide features.

Aerial Reconnaissance

Low-level flights in helicopters or small aircraft can be used to obtain a rapid and direct overview of a site.

Drilling

At most sites, drilling is necessary to determine the depth to the slip surface and thus the thickness and geometry of the landslide mass, the water table level, and the amount of disruption of the landslide materials. It can also provide samples for age-dating and testing the engineering properties of landslide materials. Finally, drilling is needed for installation of some monitoring instruments and hydrologic observation wells.

Geophysical Studies

Geophysical techniques (the study of changes in the earth's gravitational and electrical fields, or measurement of induced seismic behavior) can be used to determine some subsurface characteristics such as the depth to bedrock, zones of saturation, and sometimes the ground-water table. In some instances these methods can be used in lieu of drilling. Monitoring of natural acoustic emissions from moving soil or rock has also been used in landslide studies.

Computerized Landslide Terrain Analysis

In recent years computer modeling of landslides has been used to determine the volume of a landslide mass and changes in surface expression and cross section over time. This information is useful in calculating the potential for stream blockage, cost of landslide removal (based on cubic yards), and type and mechanism of movement. Very promising methods are being developed to utilize digital elevation models (DEMs) for rapid evaluation of areas for susceptibility to landslide/debris-flow events (Filson, 1987; Ellen and Mark, 1988). Computers are also used to perform complex stability analyses. Software programs for these studies are readily available for personal computers.

Instrumentation

Instruments such as inclinometers, strain meters, tiltmeters, and piezometers can be used to determine the mechanics of landslide movement and to warn against impending slope failure.

ANTICIPATING THE LANDSLIDE HAZARD

One of the main principles of geology is that the past is the key to the future. In evaluating the landslide hazard this means that natural slope failures in the future will probably occur as a result of the same types of geologic, geomorphic, and hydrologic situations that have led to past and present slope failures. Based on this assumption, it is possible to estimate the types, frequency of occurrence, extent, and consequences of slope failures that may occur in the future. However, the absence of past failures in a specific area does not preclude future failures. Man-induced conditions such as changes in the natural topography or hydrologic conditions can create or increase the susceptibility to slope failure (Varnes and the IAEG, 1984).

In order to predict landslide hazards in an area, the conditions and processes that promote instability must first be identified and their relative contribution to slope failure hazard estimated, if possible. Despite significant improvements over the past 20 years in the analysis and understanding of landslide processes, experts remain unable to accurately predict times and locations of specific landslide incidents. However, useful conclusions concerning **increased probability** of landsliding can be drawn by combining geological analyses with knowledge of short- and long-term meteorological conditions. Current technology enables persons monitoring earth movements to define those areas most susceptible to landsliding and to issue "alerts" covering time spans of hours to days when meteorological conditions known to increase or initiate certain types of landslides occur. Alerts covering longer periods of time become proportionately less reliable.

In summary, current technology only permits the alerting of the affected public of the increased probability of landslides in certain areas; unequivocal, site-specific predictions are presently not possible.

COMMUNICATING LANDSLIDE HAZARD INFORMATION

A major part of an effective landslide hazard mitigation program must be dedicated to the communication and use of the technical information obtained from the other parts of the program. Often individuals or groups do not take mitigative actions because they do not understand what to do, or lack education on how to do it. The mitigation and/or avoidance of landslide hazards and the reduction of landslide losses require that the appropriate information be communicated to, and effectively used by, planners, decision-makers, and emergency response personnel.

The effective use of landslide information to reduce danger, damages, or other losses depends not only on the efforts of the producers of the information, but also on 1) the users' interest, capabilities, and experience in hazard-related activities, 2) the existence of enabling legislation authorizing and funding federal, state, and local hazard-reduction activities, 3) the availability of adequate, detailed information in a readily usable and understandable form, and 4) the use of good information communication techniques. Unless technical studies are specifically tailored, information may be used only by engineers and geologists or may be misused or not used at all in the decision making process.

Users of Landslide Hazard Information

Among the potential users of landslide hazard information are people at national, state, regional, and community levels in both the public and private sectors. Three general categories can be identified: 1) scientists and engineers who use the information directly, 2) planners and decision-makers who consider hazards among other land-use and development criteria, and 3) interested citizens, educators, and others with little or no technical expertise. These people differ widely in the kinds of information they need **and in their capabilities to use that information.** Examples of potential users are listed in Table 2.

Table 2. Potential users of landslide hazard information.

CITY, COUNTY, AND AREA-WIDE GOVERNMENT USERS
City and county building, engineering, zoning, safety, and environmental health departments
City and county offices of emergency services
County tax assessors
Local government geologists
Mayors, county commissioners, and city council members
Multicounty (regional) planning, development, and emergency preparedness agencies
Municipal engineers, planners, and administrators
Police, fire, and sheriff's departments
Public works departments
Road departments

Table 2. (Cont.)

School districts
Special districts (water, sanitation, urban drainage)

COLORADO STATE GOVERNMENT USERS

Attorney General's Office
Department of Administration
  State Buildings Division
Department of Health
Department of Highways
Department of Local Affairs
Department of Military Affairs
  Colorado National Guard
Department of Natural Resources
  Geological Survey
  State Engineer's Office
  Water Conservation Board
Department of Public Safety
  Division of Disaster Emergency Services
Department of Revenue
Governor's Office
  State Planning and Budgeting Office

FEDERAL GOVERNMENT USERS

Department of Agriculture
  Farmers Home Administration
  Forest Service
  Soil Conservation Service
Department of the Army
  Army Corps of Engineers
Department of Commerce
  National Bureau of Standards
  National Oceanic and Atmospheric Agency
Department of Energy
Department of Housing and Urban Development
  Federal Housing Administration
Department of the Interior
  Bureau of Land Management
  Bureau of Reclamation
  Geological Survey
  National Park Service
Department of Transportation
  Federal Highway Administration
Environmental Protection Agency
Federal Emergency Management Agency
General Services Administration
Members of Congress and their staffs
Nuclear Regulatory Commission
Small Business Administration

PRIVATE, CORPORATE, AND QUASI-PUBLIC USERS

Civic and voluntary groups
Concerned citizens, homeowners associations
Construction companies
Consulting planners, geologists, architects, and engineers
Economic development committees
Extractive, manufacturing, and processing industries
Financial and insuring institutions
Landowners, developers, and real-estate persons
News media
Utility and transmission companies
University departments (including geology, civil engineering, architecture, urban and regional planning, and environmental studies departments)

While some state agencies have professional planners, engineers, or geologists on their staffs and are able to make their own interpretations from available hazard information, few cities and counties in Colorado have staff members who have had training in earth sciences or engineering. Specialists from the state or federal governments who are skilled in the translation of technical data for users can assist local agencies, but are often not readily available. Therefore, the most effective use of landslide information by city or county staffs is achieved when maps are provided that indicate the location, severity, and recurrence of the hazards.

Available Maps and Reports

Many maps and reports, ranging from highly technical to more popular types, are available. These include technical reports of landslide processes, specific event damage reports, landslide inventory and hazard maps, and directories of natural-hazard data. Examples of various landslide hazard maps and reports available for Colorado are given in Table 3.

Table 3. Examples of landslide/debris-flow hazard maps and reports for Colorado.

Map Showing Landslides and Areas Susceptible to Landsliding in the Morrison Quadrangle, Jefferson County, Colorado (Scott, 1972)
Engineering Geologic Factors of the Marble Area, Gunnison County, Colorado (Rogers and Rold, 1972)
Map Showing Landslides in the Golden Quadrangle, Jefferson County, Colorado (Simpson, 1973)
Geologic Hazards Map, Dolores, Montezuma County, Colorado (Soule, 1975)
Preliminary Map of Landslide Deposits in Colorado (Colton and others, 1976)
Geologic Hazards, Geomorphic Features, and Land-Use Implications in the Area of the 1976 Big Thompson Flood, Larimer County, Colorado (Soule and others, 1976)

Table 3. (Cont.)

Geologic Hazards in the Crested Butte-Gunnison Area, Gunnison County, Colorado (Soule, 1976)
Geologic Hazards of the Glenwood Springs Metropolitan Area, Garfield County, Colorado (Lincoln-DeVore, 1978)
Reconnaissance Geology and Geologic Hazards Maps of the Canon City 7½ Minute Quadrangle, Colorado (Beach, 1983)
Debris-Flow Hazard in the Immediate Vicinity of Ouray, Colorado (Jochim, 1986)
Surficial-Geologic and Slope Stability Study of the Douglas Pass Region, Colorado (Stover, 1986)
Surficial-Geologic Map of the Muddy Creek Landslide Complex, Gunnison County, Colorado, April 15, 1986 (Stover, 1986)

Sources of Landslide Hazard Information

Some of the organizations that produce or provide landslide hazard information are listed in Table 4.

Table 4. Examples of producers and providers of landslide-hazard information.

American Institute of Professional Geologists
American Society of Civil Engineers
Association of Engineering Geologists, Rocky Mountain Section
Colorado Department of Highways
Colorado Geological Survey
County extension agents
Denver Museum of Natural History
Educators (university, college, high school)
Hazard researchers, interpreters, and mappers
International Conference of Building Officials (Hazard Committee, Colorado Chapter)
Journalists, commentators, editors, and other news professionals
Local seismic safety advisory groups
National Governor's Association
Natural Hazards Research and Applications Information Center, University of Colorado
Public information offices (federal and state)
U.S. Army Corps of Engineers
U.S. Bureau of Land Management
U.S. Forest Service
U.S. Geological Survey
U.S. Soil Conservation Service

PRESENTING LANDSLIDE HAZARD INFORMATION BY MEANS OF MAPS

Maps are a useful and convenient method of presenting information on landslide hazards. They can present many kinds and combinations of information at different levels of detail. When used in conjunction with land-use maps, they are a valuable planning tool. Leighton (1976) suggests a three-stage approach to landslide hazard mapping. The first stage is regional or reconnaissance mapping, which synthesizes available data and identifies general problem areas. This small-scale mapping is usually performed by a state or federal geological survey. The next stage is community-level mapping, a more detailed surface and subsurface mapping program in complex problem areas. Finally, detailed site-specific large-scale maps are prepared. This three-stage approach to mapping provides a quick initial approximation of the general distribution of hazardous areas and a basis for conducting additional studies to quantify the extent of the hazard. If resources are limited, it may be more prudent to bypass regional mapping and concentrate on studying known areas of concern.

Regional Mapping

Regional or reconnaissance mapping supplies basic data for regional planning, for conducting more detailed studies at the community and site-specific levels, and for setting priorities for future mapping.

These maps are usually simple inventory maps and are directed primarily toward the identification and delineation of broad landslide problem areas and the conditions under which they occur. They concentrate on those geologic units or environments in which landslides have already occurred and in which additional movements are most likely. Such mapping relies heavily on photogeology (the geologic interpretation of aerial photography), reconnaissance field mapping, and the collection and synthesis of all available pertinent geologic data (Leighton, 1976).

Regional maps are most often prepared at a scale of 1:24,000, because high-quality U.S. Geological Survey topographic base maps at this scale are widely available and aerial photos are commonly of a comparable scale. Other scales commonly used include 1:50,000 (county series), 1:100,000 (30 x 60 min.), and 1:250,000 (1° x 2° quad.).

Community-Level Mapping

Community-level mapping identifies the three-dimensional limits of landslides as well as causative factors. Suggestions concerning land use, zoning, and building, as well as recommendations for future site-specific investigations are also made at this stage. Investigations should include subsurface exploratory work in order to produce a large-scale map with cross sections (Leighton, 1976). Map scales at this level vary from 1:1,000 to 1:10,000.

Site-Specific Mapping

Site-specific mapping is concerned with the identification, analysis, and solution of actual site-specific problems. It is usually undertaken by private consultants for owners who propose site development and involves a detailed drilling program with downhole logging, sampling, and laboratory analysis in order to procure the necessary information for design and construction (Leighton, 1976). Map scales vary, but are usually not larger than 1'' = 50'.

Types of Maps

The three types of landslide maps most useful to planners and the general public are 1) landslide inventories, 2) landslide-susceptibility maps, and 3) landslide hazard maps.

Landslide inventories

Inventories identify areas that appear to have failed by landslide processes, including debris flows and cut-and-fill failures. The level of detail of these maps ranges from simple reconnaissance inventories that only delineate broad areas where landsliding appears to have occurred (Figure 14) to complex inventories that depict and classify each landslide and show scarps, zones of depletion and accumulation, active versus inactive slides, geological age, rate of movement, and other pertinent data on depth and kind of materials involved in sliding (U.S. Geological Survey, 1981; Brabb, 1984).

Because simple inventories may be prepared mainly by interpreting aerial photographs, they can be put together in a short time at a relatively low cost.

Simple inventories give an overview of the landslide hazard in an area and delineate areas where more detailed studies should be conducted. Detailed inventories provide a better understanding of the different landslide processes operating in an area and can be used to regulate or prevent development in landslide areas and to aid the design of remedial measures (U.S. Geological Survey, 1981). They also provide a good basis for the preparation of derivative maps such as slope stability, landslide hazard, and land use.

Landslide-susceptibility maps

A landslide-susceptibility map goes beyond an inventory map and depicts areas that have the potential for landsliding (Figure 15). These areas are determined by correlating some of the principal factors that contribute to landsliding, such as steep slopes, weak geologic units that lose strength when saturated, and poorly drained rock or soil, with the past distribution of landslides. These maps indicate only the relative stability of slopes; they do not make absolute predictions (U.S. Geological Survey, 1981; Brabb, 1984).

Landslide-susceptibility maps can be considered derivatives of landslide inventory maps because the in-

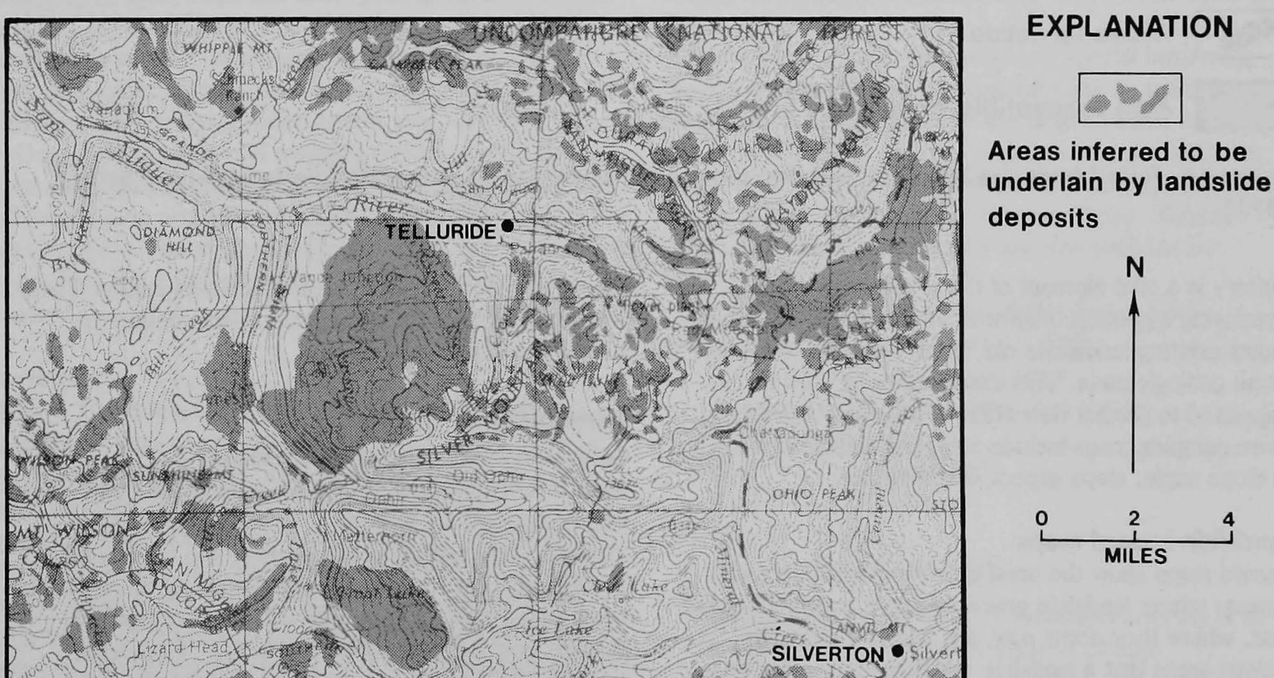


Figure 14. Detail from the landslide inventory map of the Durango 1° x 2° quadrangle, Colorado (Colton and others, 1975).

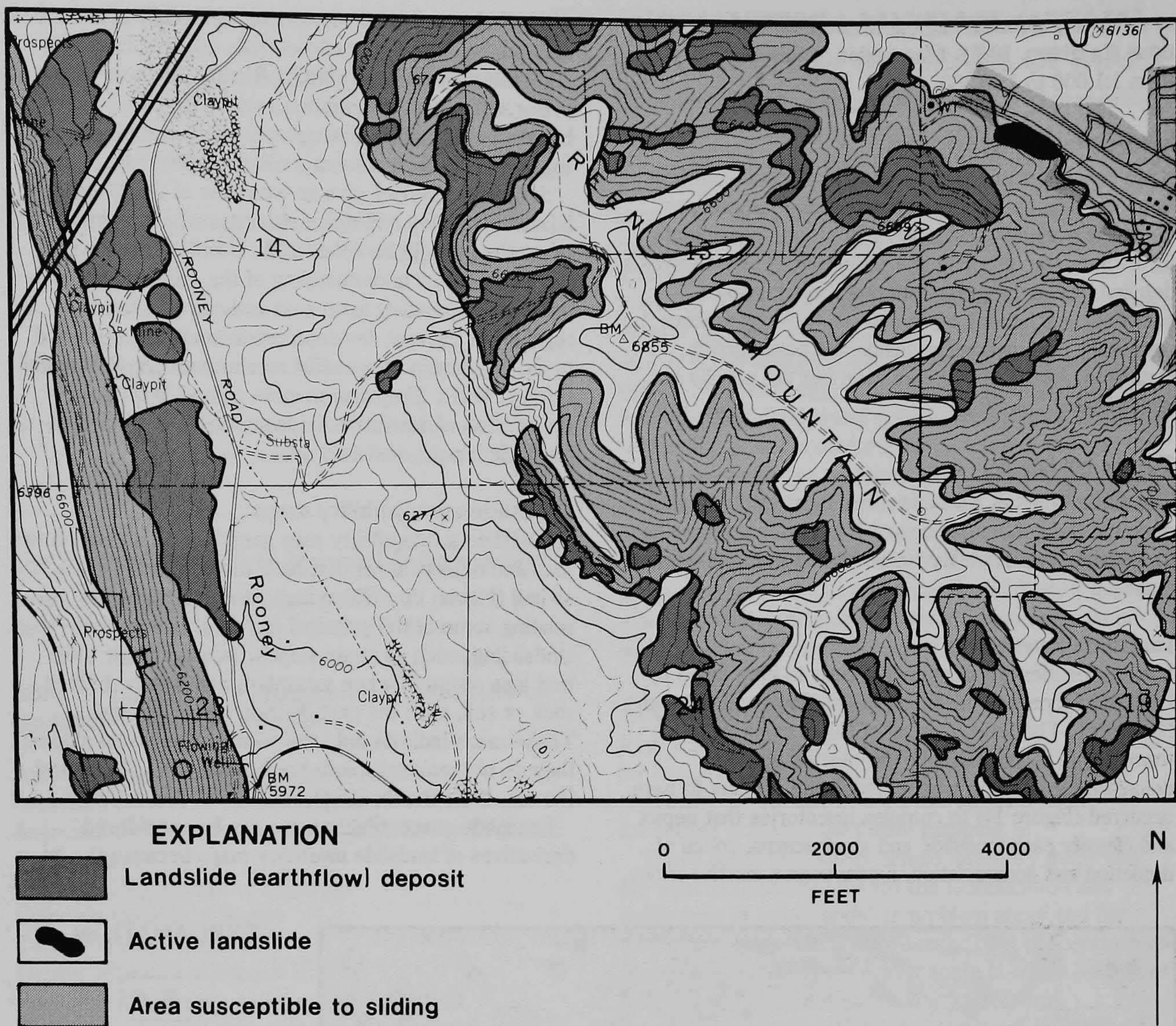


Figure 15. Detail from the Morrison quadrangle folio showing areas susceptible to landsliding (Scott, 1972).

ventory is a vital element of the preparation process. Overlaying a geologic map with an inventory map which shows existing landslides can identify specific landslide-prone geologic units. This information can then be extrapolated to predict new areas of potential landsliding. More complex maps include additional information such as slope angle, slope aspect, and drainage.

Landslide hazard maps

Hazard maps show the areal extent of threatening processes: where landslide processes have occurred in the past, where they occur now, and the probability in various areas that a landslide will occur in the future (Figure 16). For a given area, they contain detailed information on the types of landslides, extent of slope subject to failure, probable maximum extent of ground movement, and the probable frequency of failure. These maps can be used to predict the relative degree of hazard in a landslide area.

Mapping in Colorado

Selection of map scale and format

Map scale and format should be determined by the level of detail necessary to depict the particular problem area, the land use being considered, and data being presented. However, other factors such as the availability of funds, staff, or time may actually have more influence over the final product. The U.S. Geological Survey (1982, p. 21) notes that all landslide hazard maps "are a compromise between detail and reliability and the difficulty and cost of preparation."

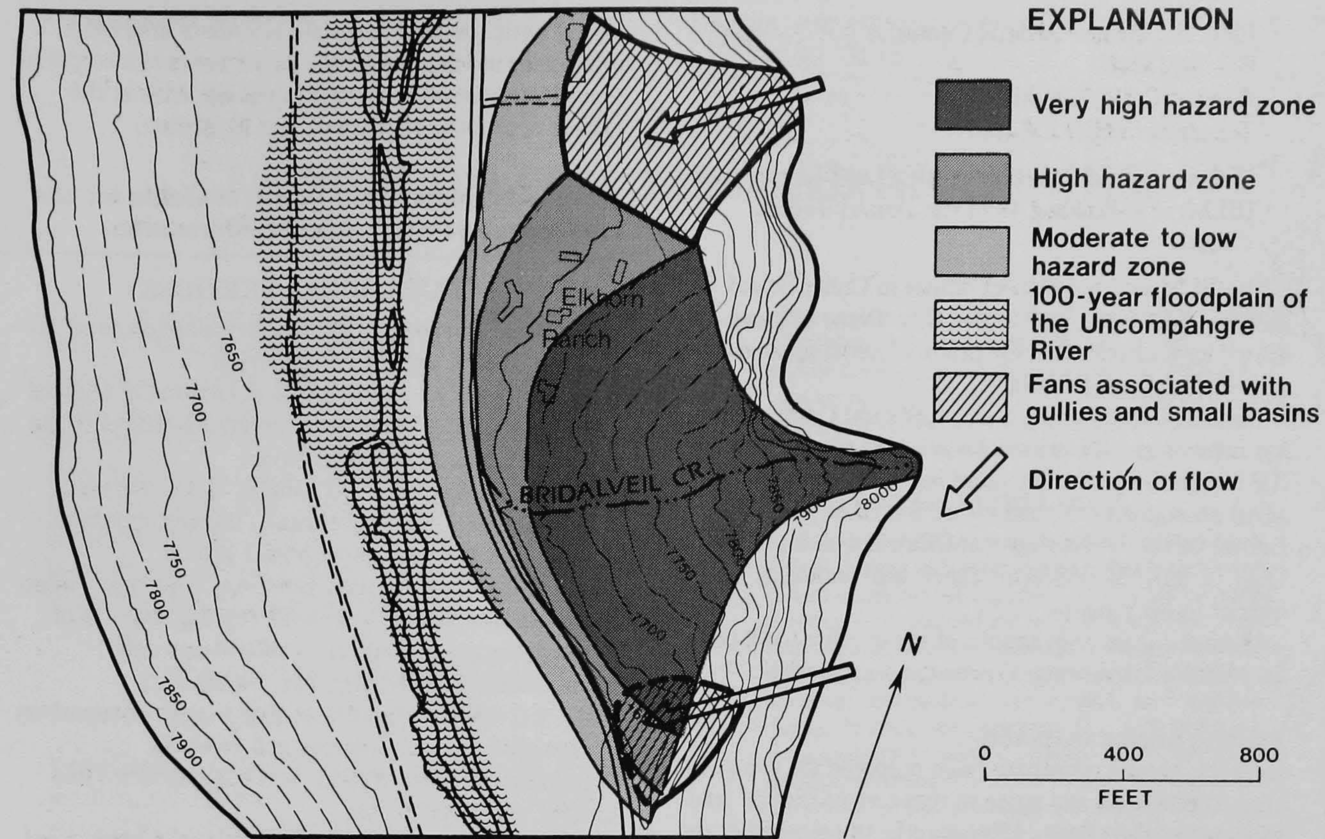


Figure 16. Detail from the Colorado Geological Survey map showing generalized hazard zones for debris fans in the Ouray, Colorado area (Jochim, 1986).

Map scale should be consistent with standard topographic base maps and aerial photographs. Creating maps at scales different from existing maps requires the meticulous transfer of topographic and geologic information from other maps—thus consuming a great deal of time and money and possibly introducing serious errors.

One of the most useful mapping techniques for planners and public officials is the superposition of landslide information on orthophotographic base maps or aerial photographs. The ability to identify actual land or man-made features heightens awareness of the landslide hazard.

Base maps

A base map is necessary to undertake environmental geology or land-use planning investigations. Topographic maps are the best base maps for most purposes. They show contour lines, slope, relief, and landform characteristics, as well as roads, buildings, and other cultural features. The most common and highest quality topographic maps of Colorado are those published and sold by the U.S. Geological Survey. Very high quality 7½ minute (1:24,000) maps and (1:50,000) county series maps have been made of the entire state. U.S. Geological Survey maps also come in other scales: 1:62,500 quadrangles; 1:100,000 (30 x 60 min.) quadrangles; and 1:250,000 (1° x 2°) sheets. A 1:500,000 topographic-political map of the entire state is also available.

There may be cases that require a special base map. In such instances, aerial photographs can be used to prepare a topographic map at any desired scale, detail, and accuracy. Black-and-white photo coverage exists for nearly all of Colorado and is available from public agencies or private photogrammetric consultants. Natural color and infrared photography are also available for some areas.

For more information on the availability of aerial photography for Colorado contact either:

Rocky Mountain Mapping Center
National Cartographic Information Center
U.S. Geological Survey
Mail Stop 504, Box 25046
Denver Federal Center
Denver, CO 80225
Telephone: (303) 236-5829

Walk-in service for the U.S. Geological Survey is in Building 25 of the Denver Federal Center.

or

Division of Technical Services (D-435)
Bureau of Land Management

Bldg. 50, Denver Federal Center
P.O. Box 25047
Denver, CO 80225-0047
Telephone: (303) 236-7991

Walk-in service for the Bureau of Land Management (BLM) is in Building 46 of the Denver Federal Center.

The BLM also has district offices in Craig, Grand Junction, Montrose, and Canon City. Some of these offices have indexes and file prints of aerial photography available for their districts.

The BLM office at the Denver Federal Center also has indexes and file prints of some U.S. Forest Service (USFS) photography. For more information on USFS aerial photography contact either the BLM office in Denver or the USFS Regional Office in Salt Lake City, Utah, at (801) 524-5856, or check with individual USFS district forest rangers.

In most cases, photographs at these offices will only be available for viewing. Copies can be ordered.

Existing hazard mapping

Geologic hazard maps have been prepared for many areas of the state and some of these maps include landslides and debris flows. Most have been prepared at the 1:24,000 scale. Because a comprehensive list of maps does not exist, county planning offices should be contacted to determine the availability of local maps.

Information Transfer

Once information users (Table 2) and their needs have been identified, potential reduction techniques determined (Chapter 5), and usable and understandable information prepared, the next goal is the transference of the information to the users.

Methods for obtaining and communicating landslide information are listed in Table 5 under the headings of educational, advisory, and review services. These methods should be used by any landslide information collection, interpretation, and transferral program designed for planners and decision-makers. Some of these services are provided through universities, state agencies, map sales offices, geologic inquiries staffs, and public inquiries offices, and in the course of ordinary day-to-day contacts with the public by the producers of landslide hazard information. In addition, many research workers have provided such services on a limited and informal basis. Federal and state scientists involved in urban area studies frequently assist users in interpretation of information and government agencies in the review of proposed programs and legislation.

Table 5. Examples of resources available for obtaining/transferring landslide information.

EDUCATIONAL SERVICES

- Universities and their extension divisions; courses, lectures, books, and display materials
- Guest speakers and participants at lectures in regional and community educational programs related to the application of hazard information
- Seminars, conferences, workshops, short courses, technology utilization sessions, training symposia, and other discussions with user groups
- Oral briefings, newsletters, seminars, map-type "interpretive inventories," open-file reports, reports of cooperating agencies, and "official-use only" materials (released via news media)
- Radio and television programs that explain or report on hazard-reduction programs and products
- Meetings with local, district, and state agencies and their governing bodies
- Field trips to potentially hazardous sites by state, local, or federal agencies, and professional societies.

ADVISORY SERVICES

- Annotated and indexed bibliographies of hazard information and lists of pertinent reference materials
- Local, state, and federal policies, procedures, ordinances, statutes, and regulations that cite or make other use of hazards information
- Hazards information incorporated into local, state, and federal studies and plans
- User guides relating to earth-hazards processes, mapping, and hazard-reduction techniques

REVIEW SERVICES

- Review of proposed programs for collecting and interpreting hazard information.
- Review of local, state, and federal policies, administrative procedures, and legislative analyses that have a direct effect on hazard information.
- Review of studies and plans based on hazard information.

Chapter 5
MITIGATION CONCEPTS AND APPROACHES

The main goals of landslide hazard mitigation are to preserve lives, property, and revenue and to prevent the disruption of critical services and the economy. These goals are accomplished by reducing the frequency of occurrence and the extent and severity of landslides, and by redistributing social and economic impacts when landsliding does occur. Three general methods used to accomplish these goals are 1) modification of community vulnerability, 2) modification of the physical system, and 3) modification of the consequences.

MODIFYING COMMUNITY VULNERABILITY

Vulnerability to landslide hazards is a function of a site's location, type of activity, and frequency of landslide events. Thus, the vulnerability of human life, activity, and property to landsliding can be lowered by restricting, prohibiting, or imposing conditions on hazard-zone activity. Local governments can accomplish this by adopting grading and building codes, land-use regulations and policies, redevelopment restrictions, hazard-monitoring and warning systems, and emergency preparedness programs.

Land-use regulations and policies are most economical and effective if enacted prior to development. However, when potentially hazardous land is privately owned with the expectation of relatively intense development and use, or in communities where land optimally suited for development is in short supply, there is strong motivation to use the land intensively. Land-use regulations must be balanced against economic considerations, political pressures, and historical rights. However, if construction is allowed to occur in a hazardous area, there is a moral and legal obligation to disclose the hazard to future owners and occupants.

Avoidance

Reducing Losses from Landsliding in the United States by the National Research Council's Committee on Ground Failure Hazards, (1985, p. 15) discusses avoidance and building codes:

> **Avoidance** involves eliminating or restricting development in landslide-prone terrain. While total avoidance, i.e., a total prohibition on the use of landslide-prone lands, is not possible it is feasible to use these lands in a way that minimizes landslide losses. Thus, it is possible to use such land for recreational open spaces, watersheds, agriculture, and other activities for which the loss in the event of a landslide will be small. It is even possible to allow low-intensity physical development in such areas if appropriate precautions are taken. The principal issue [leading to controversy] in programs of avoidance is the lowering of land values associated with designation as a landslide-prone area.

Building and Grading Codes

> **Design, building, and grading codes** are regulatory tools available to local government agencies for achieving desired design and building practices. They can be applied to both new construction and preexisting buildings. In rare cases, such as those involving large offshore structures, the effect of landslides can be considered explicitly as part of the design, and the facility can be built to resist landslide damage. In some cases, existing structures in landslide-prone areas can be modified to be more accommodating to landslide movement. The extent to which this is successful depends on the type of landsliding to which the structure is exposed. Facilities other than buildings (e.g., gas pipelines and water mains) can also be designed to tolerate ground movement. Codes and regulations governing grading and excavation can reduce the likelihood that construction of buildings and highways will increase the degree to which a location is prone to landslides. Various codes that have been developed for federal, state, and local implementation can be used as models for landslide-damage mitigation. A fundamental concern with design and building codes is their enforcement in a uniform and equitable way.

Land-Use Regulations

Various types of land-use regulations and development policies can be used to reduce landslide hazards. These methods are often the most economical and the most effective regulatory means for local governments. Types of regulations include hillside-development regulations, zoning, subdivision ordinances, rebuilding moratoriums, and abatement districts. These and other landslide management techniques are listed in Table 6 and discussed in detail in Appendix 2. Responsibility for their implementation resides primarily with local governments, with some involvement of state and federal governments and the private sector.

Table 6. Landslide-management techniques modifying vulnerability to landslides.

REGULATIONS

State
- Designation of areas of state interest
- Siting and construction standards for water and

Table 6. (Cont.)

waste-water facilities
- Model regulations

County and Municipal
- Zoning ordinances
- Slide-prone area ordinances
- Hillside development ordinances
  - Density provisions
  - Soil overlay provisions
  - Guiding principles
  - Grading regulations
- Abatement districts
- Subdivision regulations
- Building codes
- Grading codes
- Site investigation requirements
- Restrictive covenants
- Sanitary system codes
- Geological hazard overlay zones

LAND USE
- Appropriate agricultural practices
- Vegetation requirements
- Public nuisance abatement ordinances
- Nonconforming-use regulations
- Acquisition of open space
- Design, location, and relocation of public facilities

EMERGENCY PREPAREDNESS AND DISASTER ASSISTANCE
- Planning and preparation
- Warning systems
- Emergency response operations
- Rehabilitation and recovery
- Post-hazard mitigation

OTHER METHODS
- Dissemination of public information
- Landslide mapping
- Recording and disclosing hazards
- Financing policies
- Higher homeowners insurance rates
- Conditions on federal disaster aid
- Landslide insurance
- Special assessment districts and tax adjustments
- Tort liability

The Effect of Supreme Court Decisions on Land-Use Regulations

In 1987, the U.S. Supreme Court decided three cases (Keystone Bituminous Coal Association v. DeBenedicts [Keystone]; Nollan v. California Coastal Commission [Nollan]; and First Evangelical Lutheran Church of Glendale v. Los Angeles [Lutherglen]) in which land-use regulations were alleged to be a taking of property. Two of these dealt with regulations regarding specific hazards—subsidence and flooding. These cases were widely and erroneously perceived as significantly limiting the ability of state and local governments to regulate land uses. In fact, however, they did not reverse a long trend of Supreme Court rulings that have upheld highly restrictive regulations where issues of public health and safety or prevention of nuisance were involved (Kusler and Thomas, 1987).

Kusler and Thomas have summarized the three cases and cited the following as lessons to be learned from these and other Supreme Court and lower court decisions (Kusler and Thomas, 1987, p. 3):

- Regulation adopted for valid public purposes and with an adequate basis in fact may substantially reduce land values without effecting a "taking." Hazard-reduction regulations have universally been upheld as serving valid public purposes.
- The impact of regulations must be evaluated for an entire piece of property (not just one portion) to determine whether a taking has occurred. This means that hazard-related setbacks which affect only portions of a property are quite clearly not a taking.
- Public safety and prevention of nuisance is a paramount concern of government and no landowner has a property right to threaten public safety or cause nuisances. Control or abatement of even existing uses has often been sustained to achieve these objectives.
- Regulations are a taking only if they deny all use or all economic use of an entire property, including reasonable "investment-backed expectations." Even then, regulations may be valid under certain circumstances where the only economic uses are nuisance-like.

They conclude that most hazard-related regulations will not be held as a taking of property. When deciding whether to adopt performance-oriented hazard regulations, such as building codes, floodway restrictions, and grading codes, the alternative of nonregulation, with its potential resulting damages, should be assessed and compared. Governments are increasingly being held to account for actions, or inactions, which increase hazards.

Kusler and Thomas (1987, p. 3) recommend the following precautions when adopting regulations in order to avoid a taking:

1) Provide a variance, or "special permit" procedure in regulations, since such provisions are very rarely held to be a "taking" on their face, and they provide the regulatory agency with the opportunity to deal with extreme hardships.
2) Emphasize health and safety considerations, and the prevention of nuisances, in your regulations and in your written findings for individual permit denials. Regulatory actions closely tied to these objectives are rarely held a "taking."
3) Link your regulations with national and state-wide programs such as the National Flood Insurance Program. Courts have been particularly willing to sustain such regulations.

4) Apply large lot zoning (two-ten acres) to area-wide land use restriction where appropriate or possible, since courts have held that regulations which permit some reasonable use on an entire property do not constitute a "taking."
5) Document with particular care the need for the regulations, and the reasons for your permit denials, in urban or other settings where land values are very high.
6) Encourage pre-application meetings by permittees so that mutually acceptable project designs can be formulated.
7) Apply your regulations in a consistent and equitable manner. Maximize the opportunity for notice and public hearing.
8) If you adopt a moratorium, do so for a fixed period and make sure that a) the reasons for it are clear and legitimate, and b) there is a viable variance procedure.
9) Coordinate regulatory, tax, and public works policies to ensure that the fiscal burden on landowners for community services is consistent with permitted uses.
10) Apply, in extreme circumstances, transferable development rights to help relieve the burden on landowners.
11) Use acquisition rather then regulation where active public use is needed for land, or where a single landowner or group of landowners must bear disproportionate burdens for the public good.

Emergency Preparedness

Emergency preparedness has the following general goals:

- protect life, health, and safety,
- minimize property damage and disruption of community activities to the degree practicable,
- re-establish critical facilities and services, and
- provide relief to disaster victims.

An effective emergency response has the following stages:

- planning and preparation,
- warning,
- emergency operations including evacuation,
- rehabilitation/recovery, and
- post-disaster evaluation and mitigation of future events.

Emergency planning and preparation consist of identifying potential problems, determining the required actions and parties responsible for implementing them, and ensuring the readiness of necessary equipment, supplies, and facilities. An important aspect of preparation is a public education and information campaign informing citizens of their potential exposure, types of warnings to be issued, probable evacuation time available, and appropriate actions to be taken.

A warning system may include the monitoring of conditions (e.g., snowpack, storm development) with potential for causing a catastrophic event or the placement of signs instructing people within a potentially hazardous area of proper procedures (Figure 17). Automatic sensors, located within landslide-prone areas, with effective linkages to a central communication warning facility and, thence, to individuals with disaster-management responsibilities, are also sometimes used. Warning systems can be permanent or temporary—used only while physical mitigation methods are being designed and built.

Emergency operations include evacuation, shelter and care, clean up, and provision of essential services and activities. Subsequently, during the rehabilitation/recovery stage, the actual response is evaluated and planning and preparation activities are modified accordingly.

An emergency preparedness system can be an effective tool for protecting inhabitants of landslide-hazard areas. However, it is limited in its ability to protect property and facilities at risk.

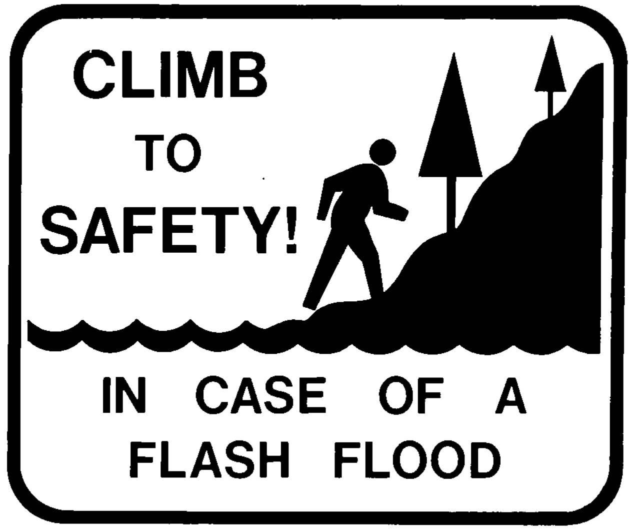


Figure 17. Sign placed in some of the hazardous mountain canyon areas of Colorado.

MODIFYING THE PHYSICAL SYSTEM

Physical modification can be undertaken in unstable areas where human occupation already poses a risk, but where measures such as zoning are precluded by the cost of resettlement, value or scarcity of land, or historical rights. Physical measures can attempt to either control and stabilize the hazard or protect persons and property at risk.

It is not possible, feasible, or even necessarily desirable to prevent all slope movements. Furthermore, it may not be economically feasible to undertake physical modifications in some landslide areas. Where land is scarce, however, investment in mitigation may increase land value.

Landslide control structures may be costly and usually require considerable lead time for project planning and design, land acquisition, permitting, and construction. Such structures may also have environmental and socioeconomic impacts.

Precautions Concerning Reliance on Physical Methods

Although physical techniques may be the only means for protecting existing land uses in hazard areas, sole reliance on them may create a false sense of security. An event of greater severity than that for which the project was designed may occur, or a structure may fail due to aging, changing conditions, or inadequate design. The result could be catastrophic if the hazard zone has been developed intensively.

Design Considerations and Physical Mitigation Methods

When designing control measures, it is essential to look well beyond the landslide mass itself. A translational slide may spread over great distances if the bedrock surface is sufficiently inclined and the shear resistance along the surface remains lower than the driving force. Debris flows can frequently be better controlled if mitigation efforts concentrate on stabilizing the source area. An understanding of the geological processes and the surface and ground-water regimes, under both natural and human-imposed conditions, is essential to any mitigation planning.

Some factors that determine the choice of physical mitigation are:

- type of movement (e.g., fall, slide, avalanche, flow),
- kinds of materials involved (rock, soil, debris),
- size, location, depth of failure,
- process that initiated movement,
- people, place(s) or thing(s) affected by failure,
- potential for enlargement (certain types of failures [e.g., debris flows, translational slides] will enlarge during excavation),
- availability of resources (funding, labor force, materials),
- accessibility and space available for physical mitigation,
- danger to people,
- property ownership and liability.

The physical mitigation of landslides usually consists of a combination of methods. Drainage is used most often; slope modification by cut and fill and/or buttresses is the second most often used method. These are also, in general, the least expensive methods.

The various types of physical mitigation methods are listed in Table 7. Descriptions of these methods are provided in Appendix 3.

Table 7. Physical mitigation methods.

PHYSICAL MITIGATION METHODS FOR SLIDES AND SLUMPS

1. Drainage
   a. Surface drainage
      1) ditches
      2) regrading
      3) surface sealing
   b. Subsurface drainage
      1) horizontal drains
      2) vertical drains/wells
      3) trench drains/interceptors, cut-off drains/counterforts
      4) drainage galleries or tunnels
      5) blanket drains
      6) electro-osmosis
      7) blasting
      8) subsurface barriers
2. Excavation or regrading of the slope
   a. Total removal of landslide mass
   b. Regrading of the slope
   c. Excavation to unload the upper part of the landslide
   d. Excavation and replacement of the toe of the landslide with other materials
3. Restraining structures
   a. Retaining walls
   b. Piles
   c. Buttresses and counterweight fills
   d. Tie rods and anchors
   e. Rock bolts/anchors/dowels
4. Vegetation
5. Soil hardening
   a. Chemical treatment
   b. Freezing
   c. Thermal treatment
   d. Grouting

PHYSICAL MITIGATION METHODS FOR DEBRIS FLOWS AND DEBRIS AVALANCHES

1. Source-area stabilization
   a. Check dams
   b. Revegetation
2. Energy dissipation and flow control
   a. Check dams
   b. Deflection walls
   c. Debris basins
   d. Debris fences
   e. Deflection dams
   f. Channelization

Table 7. (Cont.)

3. Direct protection
   a. Impact spreading walls
   b. Stem walls
   c. Vegetation barriers

PHYSICAL MITIGATION METHODS FOR ROCKFALLS

1. Stabilization
   a. Excavation
   b. Benching
   c. Scaling and trimming
   d. Rock bolts/anchors/dowels
   e. Chains and cables
   f. Anchored mesh nets
   g. Shotcrete
   h. Buttresses
   i. Drainage
   j. Dentition
2. Protection
   a. Rock-trap ditches
   b. Catch nets and fences
   c. Catch walls
   d. Rock sheds or tunnels

MODIFYING THE CONSEQUENCES OF LANDSLIDING

Modification of the consequences of landsliding involves assisting individuals and communities in preparing to survive and recover from hazard occurrences. This includes determining liability, increasing public awareness by information dissemination and disclosure, and redistributing economic losses over time and among a larger segment of society through insurance. Insurance, tax adjustments, assessment districts and tort liability are explained in greater detail in Appendix 2.

Liability

The consequences of landsliding on individuals and governments can include liability for losses generated by these events. Thus, homeowners, builders, developers, architects, engineers, governmental entities and many others are threatened with increased liability. The threat of litigation may act as a deterrent to poor quality geologic or engineering reports, improper design, poor construction, improper grading, faulty hillside maintenance practices, and governmental approval of plans for development of hazardous sites.

Establishing liability is the legal means developed by society to recover damages, such as bodily injury, medical expenses, death, emotional stress, and economic loss, resulting from the improper activities of another.

Sutter and Hecht (1974), supplemented by McGuire (1985), list six types of lawsuits that are brought by injured parties against those responsible for their losses:

1) **Fraud** - a former owner purposely advises a purchaser that a house is "in perfect condition" when, in fact, cracks (caused by recent ground failure) have been disguised by repair and fresh paint.
2) **Negligence** - an owner changes the natural drainage of his land causing a landslide on adjacent property.
3) **Strict Liability** - a developer and seller of lots improperly cuts, fills, and/or compacts earth to create a building site.
4) **Breach of Warranty** - parties to a real estate sales agreement insert a false guarantee of soil and geologic stability.
5) **Failure to Comply with Regulations** - a developer or subdivider fails to perform the geologic investigations required by a state statute or local ordinance, or fails to carry out recommendations.
6) **Public Negligence** - a city grading or building inspector fails to perform periodic inspections of lot grading or building construction to ensure that the work complies with the municipal code.

A seventh can be added:

7) **Professional Negligence** - an engineering geologist and/or geotechnical engineer fails to recognize a hazard or to follow good practice, makes an error, or omits vital data.

As people settle and develop in closer proximity to existing or potential landslide areas, the premise that a hazard is an "act of God" is becoming unacceptable as a defense against liability. As our understanding of natural processes and disasters increases, the conditions under which such events occur are more easily traced to specific actions and actors. The work of the Association of Bay Area Governments (1984) on the liability of businesses and industries for earthquake hazards and losses is applicable to landslides, particularly those triggered by seismic events. The Association concludes that the legal defense that an earthquake is an "act of God" may only work in two very limited situations where the event:

1) was of such type or size as to be unforeseeable and the business did not act negligently with respect to dealing with a foreseeable event; and
2) was foreseeable, and the defendant took all reasonable actions to prevent harm, but nonetheless damage still occurred.

According to Tank (1983), "Recent court decisions have identified the developer or his consultants as primarily responsible for damage due to land failure."

The overall consequences of these decisions to individuals, professionals, and governments are illustrated by a recent earthmoving damage case. In this case, "The California Court of Appeals First District . . . has held that it is the duty of a real-estate broker selling a house to conduct a reasonably competent and diligent inspection of the property and disclose to the buyer any defects revealed by the inspection" (Kockelman, 1986, p. 38).

In view of the many elements of society that can be held liable following a landslide, it is logical that this liability be perceived as a significant threat and serve as an incentive to take mitigative action. As the public becomes more aware of the landslide hazard and the resulting consequences, the chances are increased that individuals and governments will take positive action to prevent excessive exposure to liability.

Information Dissemination

Most important in instituting an active mitigation program is the heightening of public awareness about the problem. There is an inconsistency of information and hazard awareness among the public and in local governments across the state. Many people are unaware that they live where natural disasters could destroy or damage their homes. Many governments are unaware that landslides threaten roads, bridges, utilities, and buildings. In addition, few, if any, legal and statutory mechanisms guarantee the transmission of known hazard information to prospective buyers, and even if owners have access to hazard information, renters are not necessarily informed of a hazard threatening their lives and personal property. Compounding the problem, land-use planning and building-permit agencies serving the public do not always act upon such information even when they have it. Furthermore, it is unlikely that cities or counties will be found liable for landslide damages that result from planning decisions, as long as they make those decisions taking all available information into account. Finally, even if the information is gathered, made understandable to the lay person, and disseminated to the community, citizens may not incorporate the information into their actions (Olshansky and Rogers, 1987).

However, information about landsliding as a hazard becomes a powerful determinant of the choice of means to mitigate landslide impacts. Private lending and insurance have been identified as two important means of impact modification (Olshansky and Rogers, 1987).

Financial Aid

Federal and state financial assistance

Kockelman (1986, p. 37) states:

> Federal and state programs that provide grants, loans, loan guarantees, tax credits, tax deductions, depreciation allowances, insurance, revenue sharing, or other financial assistance have a tremendous effect on public and private development. Obviously, the enabling legislation for these programs can be amended by the U.S. Congress or state legislatures to provide for site investigations in landslide areas, avoidance of hazardous areas, or stabilization of slopes.
>
> Less popular among elected officials, but equally effective, are financial "disincentives" which act as deterrents to the use and development of hazardous areas. A "disincentive" could reduce the federal share of a grant if the facility to be funded were to be located in a landslide area. For example, the U.S. Congress . . . introduced provisions into the *Flood Disaster Protection Act* of 1973 for withholding federal benefits from flood-prone communities that chose not to participate in the National Flood Insurance Program. In providing loans and grants for disaster recovery, the U.S. Congress . . . requires local and state governments to evaluate and mitigate hazards.

Landslide mitigation as a condition of disaster aid

Nationally, landslide damage costs governments hundreds of millions of dollars per year. Governments pay for disasters through direct assistance, tax deductions for property losses, and low-cost loans for recovery. Over the years, the state and federal government shares of all post-disaster recovery costs has risen sharply. The Colorado Disaster Act of 1973 and the Federal Disaster Relief Act of 1974 (Public Law 93-288) address this increasing burden by attaching hazard-reduction conditions to disaster aid. Section 406 of Public Law 93-288 was enacted in 1974 to encourage identification, evaluation, and mitigation of hazards at all levels of government. The requirements of Section 406 are triggered by a major disaster or emergency declared by the President and apply to all types of declared emergencies and disasters. A hazard mitigation clause is incorporated into the Federal Emergency Management Agency (FEMA)/state agreement for disaster assistance, thereby establishing the identification of hazards and the evaluation of hazard mitigation opportunities as a condition for receiving federal assistance.

FEMA is responsible for administering the Section 406 requirements and has prepared implementing regulations (44 CFR 205, Subpart M) that spell out federal, state, and local responsibilities under Section 406. Under the regulation a state hazard mitigation coordinator is designated by a governor's authorized representative to prepare a hazard-mitigation plan and to ensure its implementation. The state may establish a group of individuals from state and local agencies to assist in preparing the "406 plan," which must be completed and submitted to FEMA within 180 days after the Presidential disaster or emergency declaration (FEMA, 1986).

THE COST-BENEFIT OF MITIGATION

Costs of Landsliding

The Committee on Ground Failure Hazards (1985) estimates that economic losses of at least $1 to $2 billion and 25 to 50 deaths occur each year in the United States as a result of landsliding. Economic losses include direct and indirect costs. Schuster and Fleming (1986, p. 12) define direct costs as "the costs of replacement, repair, or maintenance due to damage to installations or property within the boundaries of the responsible landslide." They list indirect costs as:

1) reduced real-estate values in areas threatened by landslides,
2) loss of productivity of agricultural or forest lands,
3) loss of agricultural or industrial productivity as a result of damage to land or facilities or interruption of transportation systems,
4) loss of tax revenues on properties devalued as a result of landslides,
5) costs of measures to prevent or mitigate additional landslide damage,
6) adverse effects on water quality in streams and irrigation facilities outside the landslide limits,
7) secondary physical effects, such as landslide-caused flooding, for which the costs are both direct and indirect, and
8) loss of human productivity due to injury or death.

In addition, there are intangible costs such as stress, reduced quality of life, and the destruction of personal possessions with only sentimental value. Because costs of indirect and intangible losses are difficult or impossible to calculate, they are often undervalued or ignored.

The rising event-specific and cumulative costs of landsliding are a direct consequence of the increasing vulnerability of populations to the hazard. In most regions, the overall rate of occurrence and severity of naturally-caused landslides has not increased. What has increased is the extent of human occupation of marginal lands and the impact of human activities on the environment. Increasingly, hazard-mitigation techniques are being used to overcome objections to development of marginal land.

When extensive development of marginal or potentially hazardous land is proposed, a cost-benefit analysis should be performed to determine if mitigation is justifiable and cost effective. Frequently, when an accounting is made of the potential costs and benefits of development in a hazardous area, the costs may outweigh the benefits over the long term. The cost of mitigation should be considerably less than, or at least equal to the total value of the property to be protected. However, in cases of existing development, where human lives are threatened, strict economic considerations may have to be ignored.

Petak and Atkisson (1982, p. 171) use "break-even" damage rates to identify projects where mitigation might be considered feasible. They list the following five values as necessary for determination of the break-even rate:

1) the initial cost of the mitigation;
2) the annual expected loss reduction associated with the mitigation;
3) the period of time over which costs are to be amortized and loss reductions are to be experienced;
4) the total estimated loss reduction that will be produced by the mitigation over the lifetimes of buildings on areas to which the mitigation is applied; [and]
5) either the discount rate that is applied to building-life loss reductions, or the building life accumulated annual amortized costs of the mitigation at a specified interest rate.

Economic Payoffs from Landslide Hazard Mitigation

Studies have been conducted to estimate the potential savings when measures to minimize the effects of landsliding are applied. One early study by Alfors, Burnett, and Gay (1973) attempted to forecast the potential costs of landslide hazards in California for the period 1970-2000 and the effects of applying mitigation measures. Under the conditions of applying all feasible measures at state-of-the-art (for the 1970s) levels, there was a 90 percent reduction in losses for a benefit/cost ratio of 8.7:1, or $8.7 saved for every $1 spent. Other studies by Leighton (1976) have shown higher ratios. The benefit/cost ratio becomes better as the property becomes more hazardous and/or the density of the threatened population/structures becomes greater.

Cost-Benefit Analysis

This method is used by engineers, economists, and planners to evaluate the feasibility of urban drainage and flood control projects, but can be used equally well for any contemplated project using structural methods. A cost-benefit analysis enables engineers and/or planners to make rational choices among structural alternatives by determining whether, over the life of a structure, the value of the property and/or lives and/or services protected is equal to or greater than the cost of the structure.

First, objectives must be determined. Examples of objectives are to:

- reduce damage and maintenance requirements to public and private property and facilities,
- enhance the value of land and other property in the area,
- reduce threat to life,
- reduce public inconvenience,
- reduce traffic hazards, and
- enhance emergency vehicle movement.

A benefit is provided when any one of the objectives is met. Benefits are usually classified as tangible or intangible depending on the extent to which they can be measured in monetary units.

Since it is difficult or impossible to quantify intangible benefits and even many of the tangible benefits, it is recommended that the tangible benefits quantified for landslides include mainly 1) minimization of property damage 2) minimization of maintenance costs, and 3) preservation of life (lawsuits have been filed and won in wrongful-death cases on the basis of potential lifetime earnings).

For more information on how to prepare a cost-benefit analysis, see the Urban Drainage and Flood Control District report (1977).

For more information on how to prepare a cost-benefit analysis, see the report *Feasibility evaluation: methodology for evaluation of feasibility* by the Multi-jurisdictional Drainage and Flood Control District, Denver, CO (1977).

Chapter 6
THE COLORADO LANDSLIDE PROBLEM

This chapter deals with the determination of Colorado's most vulnerable communities and areas. It provides the information necessary to design a statewide mitigation plan, select priority projects, and determine unmet local needs.

VULNERABLE COMMUNITIES, AREAS, AND FACILITIES IN COLORADO

Table 8 is a selected list of the areas in the state where landslides have the most serious or immediate potential impacts on communities, transportation corridors, life lines, or the economy. Figure 18 shows the locations of these sites.

Three of the sites were chosen as case studies because they demonstrate the types of landslide hazards that affect this state, different levels of government and private involvement, and a variety of mitigative action. They can also be compared to similar cases in other states. These case studies are summarized in this chapter and discussed in detail in Appendix 5.

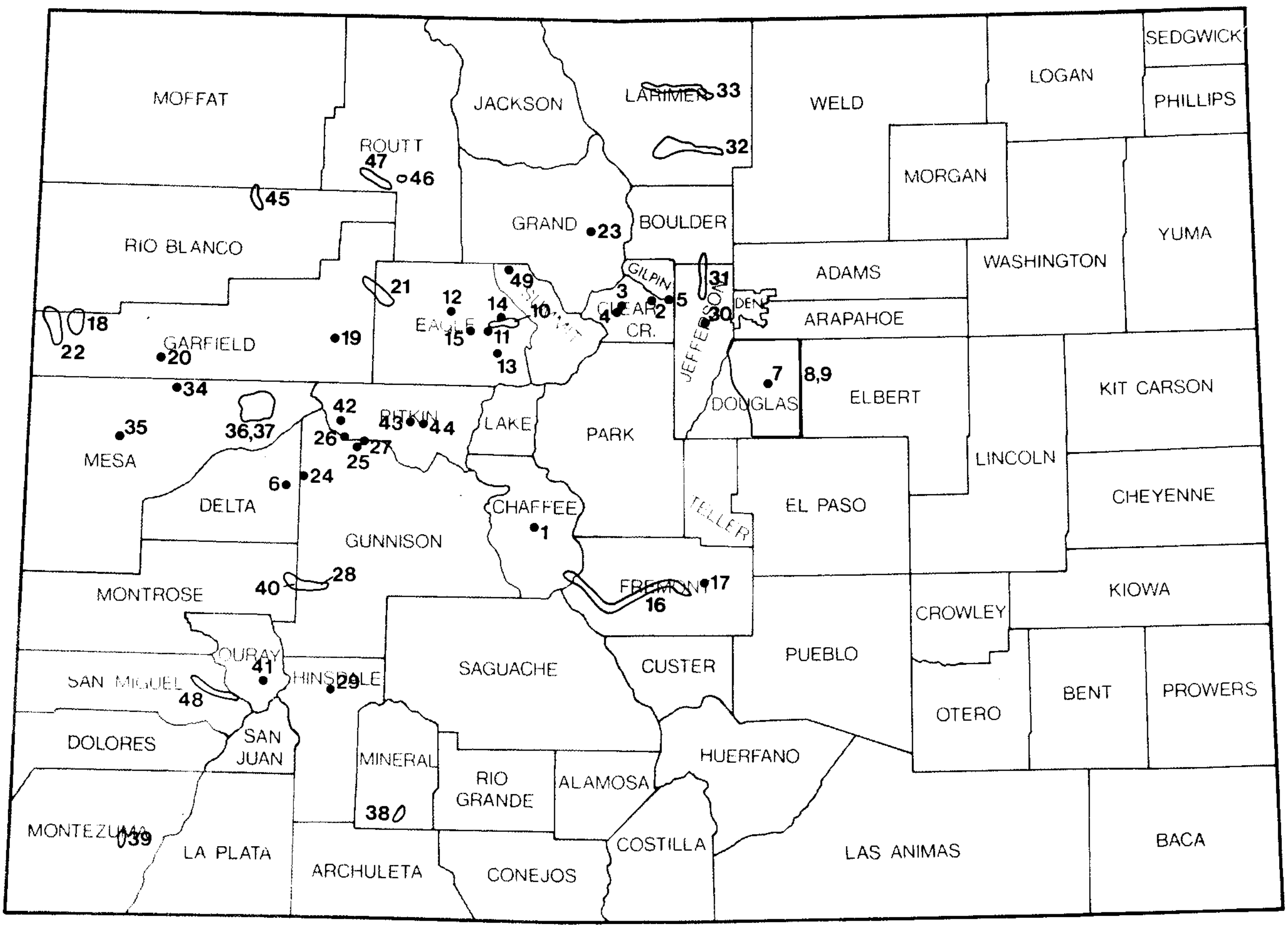


Figure 18. Index map for the 49 vulnerable communities, areas, and facilities in Colorado listed in Table 8.

Table 8. Vulnerable communities, areas, and facilities in Colorado.

COUNTY	MAP NO.	COMMUNITY/AREA	TYPE OF LANDSLIDE	FACILITIES AT RISK	MITIGATION ACTIVITY
Chaffee	1	Chalk Creek area, vicinity of Mount Princeton Hot Springs	Debris flows and rockfall	Residential and commercial properties, new subdivision areas, summer youth camps, roads, and fishery intake	In 1985 a debris-slide dam was inspected to determine if flash-flood hazard existed. There was none.
Clear Creek	2	Idaho Springs	Debris flows and rockfall	Residential and commercial properties, streets, and other public facilities	Hazard mapping done for town in 1975 by CGS.
	3	Georgetown and vicinity	Debris flows, rockfall and landslides	Residential and commercial properties, streets, and other public facilities	Plans prepared to monitor large rockfall blocks with EDM arrays by CGS.
	4	Silver Plume	Rockfall	Commercial buildings and Post Office	USGS vibration monitoring done during blasting nearby, 1984; discontinued.
	5	Junction of U.S. Hwy. 6 and St. Hwy. 119 (Junction Slide)	Large rock slide along metamorphic rock foliation planes. Intermittent movement during last 10 years	Highway, bridges, and tunnel	Monitoring to be initiated and detailed field study to be performed in 1987-88 by CGS.
Delta	6	Fire Mountain Ditch	Landslide	Several hundred feet of ditch and St. Hwy. 133	Repairs made to ditch. St. Hwy. 133 still threatened. Drilling project begun by CDOH.
Douglas	7	Castle Rock	Toppling failures of cliffs	Residential areas	Local planners advised of dangers. Detailed site reviews required of developers.
	8	Steep mesa sideslopes throughout Douglas County	Debris flows, rockfall, debris avalanches	Residential and other properties, numerous undeveloped subdivision lots	Hazard maps by CGS distributed to county and city officials with the recommendation that detailed site reviews be required of developers.

Table 8. (Cont.)

COUNTY	MAP NO.	COMMUNITY/AREA	TYPE OF LANDSLIDE	FACILITIES AT RISK	MITIGATION ACTIVITY
	9	Localized areas near stream and gully banks	Earthflows	Residential and other properties, numerous undeveloped subdivision lots, roads	Hazard maps by CGS distributed to county and city officials with the recommendation that detailed site reviews be required of developers.
Eagle	10	Vail and adjacent development corridors along Gore Creek and Eagle River	Debris flows, rock falls, and landslides	Residences, commercial properties, municipal facilities: water, power, sewer, streets	Currently no mitigation action; lawsuits being pursued in some cases.
[Case Study No. 1]	11	Dowds Junction and extending approximately one mile each way along the Eagle River	Large earthflows and slope failure complexes	I-70, U.S. Hwys. 6 and 24, mainline of D&RGW Railroad, valley development, and facilities including Minturn and West Vail	EDM monitor system installed. Inclinometers installed; periodic field surveillance conducted.
	12	Along I-70 from the vicinity of Wolcott southwesterly about 1.5 miles to Bellyache Ridge in Eagle County	Very large earthflow and slope failure complex—currently shows continuing movement	I-70, U.S. Hwy. 6, D&RGW Railroad, community of Wolcott	CDOH has done geologic study and periodic repair of damaged I-70 sections. Major hazard evaluation needed.
	13	Red Cliff	Rockfalls, debris avalanches	Residential and commercial property in Red Cliff	Hazard areas mapped (CGS), debris-avalanche study completed. Protective structural design study completed by CGS and others. Construction now completed.
	14	Booth Creek	Rockfalls, debris flows	Residences in Vail and part of municipal water supply	Rockfall hazard evaluated (CGS) and design studies made; at least one protective structure built (private). Mitigation work badly needed.
	15	Beaver Creek	Debris avalanche	Residences	Lawsuit settled out of court.

Table 8. (Cont.)

COUNTY	MAP NO.	COMMUNITY/AREA	TYPE OF LANDSLIDE	FACILITIES AT RISK	MITIGATION ACTIVITY
Fremont	16	Lower reaches and alluvial fans of tributaries to Arkansas River between Salida and Canon City	Debris flows	Highways and county roads, railroad, and existing and potential development lands	Reconnaissance hazard study needed.
	17	Fourmile Creek	Debris flow/ landslide	County road and irrigation ditch	Preliminary analysis by CGS. County road crews and ditch company cleaned up landslide.
Garfield	18	Douglas Pass	Very active multiple earthflows, debris flows and other landslides	St. Hwy. 139 (closed during frequent landslide episodes over the past 10 years), natural gas transmission lines (numerous, multiple breaks in the vicinity)	Regional surficial geology and slope-stability mapping completed by CGS. Hazard analysis of individual landslides affecting St. Hwy. 139 completed by CGS. Mapping distributed to several gas pipeline companies for potential alignment relocation. No significantly safer alignment for highway found without major relocations.
[Case Study No. 2]	19	Glenwood Springs and vicinity	Many small debris-flow basins and subsidence caused by hydrocompaction in older deposits of the fans	Residences, commercial properties, streets and other public facilities	Debris-flow hazard mitigation plan developed but negligible implementation.
	20	Roan Creek	Two earthflows converging from opposite sides of the valley	Farm house, potential damming of Roan Creek	Study in progress by CGS and Colorado School of Mines.
	21	Sweetwater Creek	Debris flows	County road, residences	No new activity.
	22	Douglas Pass-Baxter Pass Region	Landslides	Western Gas supply lines	Extensive geotechnical studies. Monitoring and structural mitigation in progress by company and consultants.

Table 8. (Cont.)

COUNTY	MAP NO.	COMMUNITY/AREA	TYPE OF LANDSLIDE	FACILITIES AT RISK	MITIGATION ACTIVITY
Grand	23	Fraser Canyon (Amtrak slide)	Debris slide	Railroad	Extensive geotechnical studies. Monitoring and structural mitigation in progress by company and consultants.
Gunnison	24	East Muddy Creek, starting about 0.6 mile above Paonia Reservoir	Earthflow and complex slope failures—currently showing considerable movement	St. Hwy. 133, Paonia Reservoir, and downstream communities in Gunnison and Delta Counties	Joint co-op project between CGS, CDOH, and BUREC to monitor and study landslide. Drilling project completed, technical report due in 1988. Ongoing EDM and instrument monitoring. Continuing "creep" on southern landslide during summer of 1987.
	25	Marble and vicinity	Debris flows	Most of town and facilities	Detailed hazard assessment and mapping done in 1972 by CGS.
	26	West side of McClure Pass along Lee Creek	Primarily translational landslides, earthflows	St. Hwy. 133	Very expensive and shortlived reconstruction; future mapping of landslide areas to be done by CGS.
	27	Mount Daly (adjacent to Carbonate Creek north of Marble)	Translational rock slides on sedimentary rock bedding planes moving toward Carbonate Creek	Town of Marble and water intake facility (could contribute to very large debris flow or create a large flood crest if a landslide dam failed. Blockage of Crystal River is also possible)	
	28	St. Hwy. 92 in vicinity of Black Mesa	Multiple landslides	St. Hwy. 92	CDOH repairs on a yearly basis.

Table 8. (Cont.)

COUNTY	MAP NO.	COMMUNITY/AREA	TYPE OF LANDSLIDE	FACILITIES AT RISK	MITIGATION ACTIVITY
Hinsdale	29	North end Lake San Cristobal (Slumgullion landslide)	Giant earthflow (currently shows very significant movement in central part of the flow)	Lake San Cristobal (extreme movement could cause changes of level with effects on residential and commercial properties and St. Hwy. 149)	USGS has set of monitoring monuments in center of active landslide. CDOH monitoring highway across upper toe of landslide. Ongoing geological field study by USGS.
Jefferson	30	Morrison Water Plant	Landslide	Morrison Water Treatment Plant	Upper portion of landslide mass removed.
	31	Golden to Boulder along St. Hwy. 93	Slumps and earthflows	St. Hwy. 93, D&RGW Railroad, and developing residential areas	D&RGW Railroad has done considerable remedial work in this area.
Larimer	32	Tributary streams to Big Thompson River from Loveland to Estes Park	Debris flows	Residential and commercial properties, roads, and other public facilities	Hazard mapping done by CGS in wake of mountain torrent flooding of 1976.
	33	Poudre River Valley between Fort Collins and Rustic	Debris slides	Recreational, residential development areas	No activity.
Mesa	34	DeBeque Canyon (Tunnel Landslide)	Complex landslide involving translational, rotational, and rockfall characteristics (first known movement was a major event in 1924 that changed the course of the river and forced relocation of a community, the railroad, and highway)	I-70 and D&RGW Railroad	CDOH repairs affected highway segment on yearly basis.
[Case Study No. 3]	35	Lamplite Park subdivision (City of Grand Junction)	Complex rotational failures	Several houses and city utilities	Preliminary geologic studies performed. Eight structures removed so far.

Table 8. (Cont.)

COUNTY	MAP NO.	COMMUNITY/AREA	TYPE OF LANDSLIDE	FACILITIES AT RISK	MITIGATION ACTIVITY
	36	Vega Reservoir area	Shallow translational landslides in clayey colluvium and bedrock	Roads, utility lines (small landslide dams would flood residential/agricultural areas and facilities)	Geologic study completed. Landslide age and potential for continued activity evaluated.
	37	Buzzard Creek	Usually thin translational landslides and multiple earthflows	Pipelines and other utilities, some low value buildings	Subject of regional landslide inventory by CGS.
Mineral	38	Wolf Creek	Numerous landslides and debris flows	U.S. Hwy. 160, proposed ski area and attendant development	Clean up as necessary. CDOH has done some experimental berming of landslides.
Montezuma	39	Mesa Verde National Park	Complex landslides at several locations due to massive sandstone ledges that fail and move out on underlying soft shales	Access road to Mesa Verde National Park	Potential severe economic impacts to Cortez area. Reconstruction is costly and alternative routing should be explored. Current annual repair/maintenance costs are very high. Study to identify problems and alternatives badly needed, especially with two proposed new visitor attractions.
Montrose	40	St. Hwy. 92 in vicinity of Black Mesa	Multiple landslides	St. Hwy. 92	Annual clean up.
Ouray	41	Ouray and vicinity	Debris flows	Most of the town, municipal facilities, and potential development lands	$2.4 million spent on flume reconstruction and debris basin.
Pitkin	42	Dutch Creek area west of Redstone	Debris avalanches	Mine surface facilities, roads, and downstream areas	Preliminary hazard assessment to be done by CGS.
	43	Snowmass	Landslides, slumps, and earthflows	Ski lift towers and proposed residential areas	Problems are being studied by consultants.

Table 8. (Cont.)

COUNTY	MAP NO.	COMMUNITY/AREA	TYPE OF LANDSLIDE	FACILITIES AT RISK	MITIGATION ACTIVITY
	44	Aspen Mt.	Translational landslide and debris flows in natural slope-forming materials and old mine dumps.	Southernmost parts of Aspen, ski area	Mapped and instrumented. Monitored during snowmelt-runoff season and after heavy summer precipitation.
Rio Blanco	45	Devil's Hole Gulch	Landslides, debris slides, stream scour/erosion	County roads, oil well pads and oil-field facilities, electrical transmission lines	Reconnaissance mapping and hazard assessment by CGS. Road abandoned by Moffat County.
Routt	46	Oak Creek City Reservoir	Landslide	Reservoir overtopping danger to community	No activity.
	47	Dunkley Pass	Landslides	County road	No activity.
San Miguel	48	Telluride and San Miguel River corridor west to Placerville	Debris flows	Residences, streets, water supply, and potential development lands	New debris-flow incident in April 1987, affecting airport and gravel operation. Preliminary investigation of this event completed by CGS.
Summit	49	Green Mountain Reservoir	Rotational landslide/slope-failure complex (currently showing some movement. Could probably be affected by rapid drawdown of reservoir)	Entire community of Heeney and downstream communities on the Blue River	No activity.

THREE CASE STUDIES OF LANDSLIDING IN COLORADO

Three case studies of landsliding are presented in this plan. They were selected to depict a wide range of potential consequences, probability of occurrence, and amenability to mitigation and follow-up measures. Summaries are presented in this chapter with the detailed studies in Appendix 5.

Dowds Junction

CASE STUDY NUMBER 1
POTENTIALLY CATASTROPHIC LANDSLIDES
(Dowds Junction, Eagle County, Colorado)

Dowds Junction is located in Eagle County, Colorado, at the intersection of U.S. Highways 6 and 24 with Interstate Highway 70 (I-70) (Figure 18). The landslide complex at Dowds Junction includes four distinct landslide areas:

Whiskey Creek, Dowds No. 1, Dowds No. 2, and Meadow Mountain (Figure 19).

This is a very large, old landslide area with an ongoing modern history of small but costly and inconvenient landslide activity. This case study is of special interest because: 1) it exemplifies the worldwide problem of evaluating the probability and potential consequences of major reactivation of extremely large old landslide masses, 2) preliminary analyses of the consequences of potential valley-blocking landslides at this location indicated immense potential damage and disruption to both infrastructure and private property, and 3) the State of Colorado declared a Landslide Alert at this location in 1985, and, as a result, state and local agencies conducted extensive geologic investigations, monitoring, and emergency exercises.

Through the years, a great deal of highway maintenance related indirectly to the old landslides has been required at the Dowds Junction location. The soils in the area are seasonally wet and have low strength in many places. The Meadow Mountain landslide south of Dowds Junction on

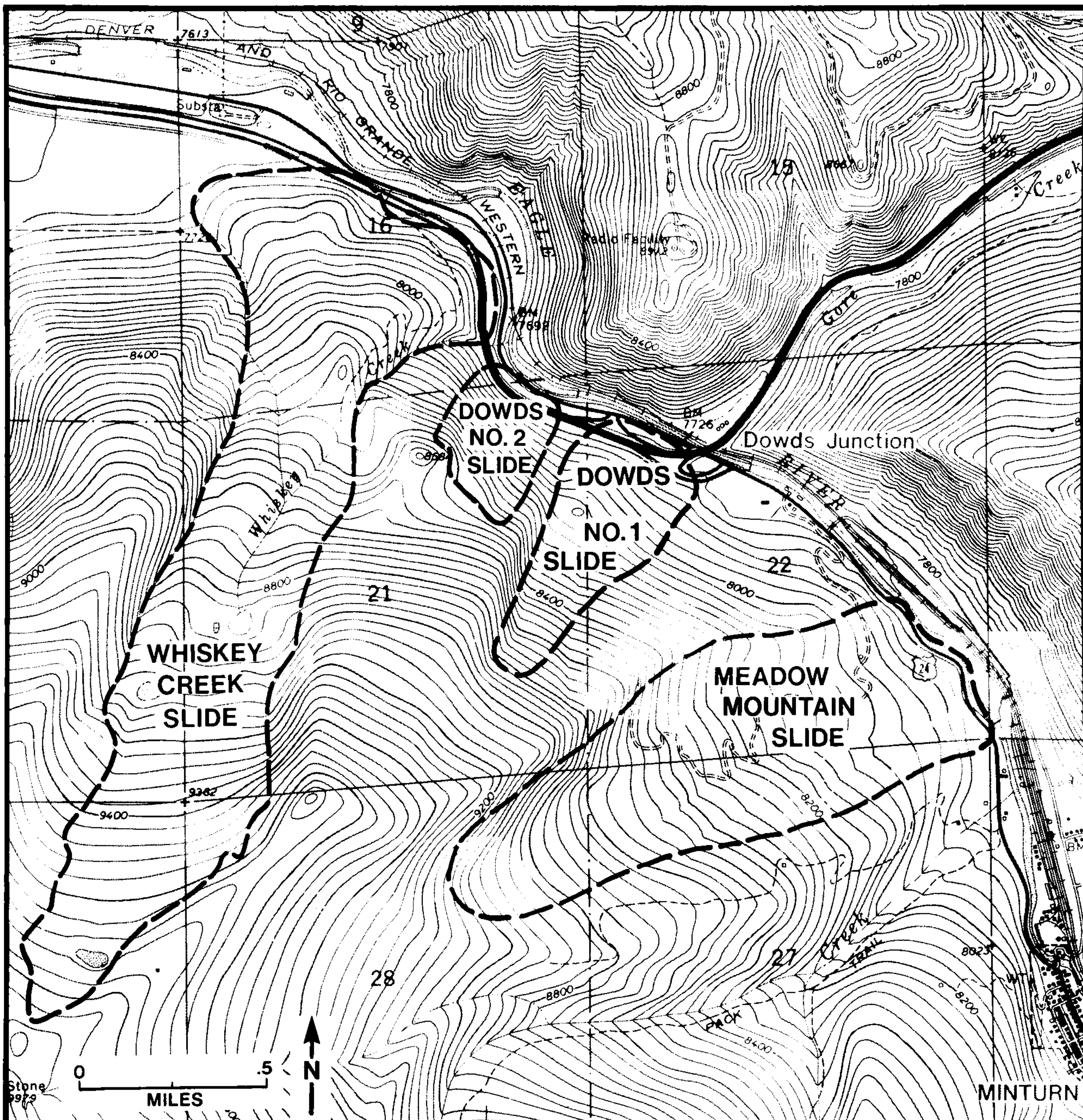


Figure 19. The landslides at Dowds Junction, Colorado (modified from Robinson and Associates, 1975).

U.S. 24 has apparently been active since before construction of that highway in 1930. Repeated patching and overlays on U.S. 24 have resulted in 8 to 10 feet of asphalt in the roadbed.

Formal design studies for I-70 began in the Dowds Junction area in 1963. The old landslides were recognized and methods to allow construction were incorporated into the highway design. However, several problems relating to soils and geology have been experienced since completion of I-70. These include landslides, fill failure, bin-wall distress, and flows of artesian water from the pavement. After the Colorado Department of Highways (CDOH) experienced the partial loss of an approximately 300-foot section of U.S. 24 between Dowds Junction and Minturn in 1985, renewed investigation of the landsliding problem was initiated.

Descriptions of the Four Landslides

Meadow Mountain Landslide

The Meadow Mountain landslide is a compound slope failure consisting of shallow to deep (up to 40 feet) earthflows occurring on the surface of at least three much deeper (90 to 160 feet) translational landslides involving bedrock. The basal surface has numerous bedrock shear zones present above the basal shear. The landslide area covers more than one-half square mile.

Whiskey Creek

The Whiskey Creek landslide probably formed initially as a massive earthflow or a series of earthflows. This landslide is the largest in the area. However, it is also probably the oldest and least active with the exception of the toe of its east lobe, adjacent to I-70.

Dowds No. 1

The lowest part of the Dowds No. 1 landslide is composed of ancient river gravels resting on Minturn Formation bedrock. The gravels represent a former course of the Eagle River and probably are evidence that movement of the upper part of the landslide altered the course of the river, forcing it to the north. This part of the landslide has a long, documented history of slow movement and has damaged I-70, the nearby highway bridge, and its west approach.

The upper half of the landslide shows no evidence of modern movement. It is composed of very large blocky material consisting of arkosic sandstone of the Minturn Formation with individual blocks ranging up to 30 feet in diameter.

Dowds No. 2

This is the smallest landslide in the area. It consists predominantly of large blocky material from the Minturn Formation with a clay and sand matrix. The landslide has been active recently and damaged I-70 in 1983.

Potential Impacts of Landsliding at Dowds Junction

Catastrophic landslide failure in the Dowds Junction area could result in the following impacts: 1) loss of life, 2) significant economic loss, 3) backwater flooding of the towns of Minturn and West Vail if a very large landslide dam should form, and 4) down-valley flooding of portions of the towns and unincorporated communities of Eagle-Vail, Avon, Edwards, Wolcott, Eagle, and Gypsum if there is failure of a dam formed by the landslide.

More than 40 options for mitigation were presented by the 1986 Minturn Earthflows Task Force in response to the range of potential threats posed by the landslides. The analyses were based on possible geologic and hydrologic consequences if major earthflows occur and river damming results. Options included: taking no action, requiring flood insurance, monitoring, regulating development, relocating people and structures, erecting physical structures, establishing drainage control, using anchors, attempting weather modification, and many others (see Appendix 5).

Glenwood Springs

CASE STUDY NUMBER 2 DEBRIS-FLOW HAZARD (Glenwood Springs, Garfield County, Colorado)

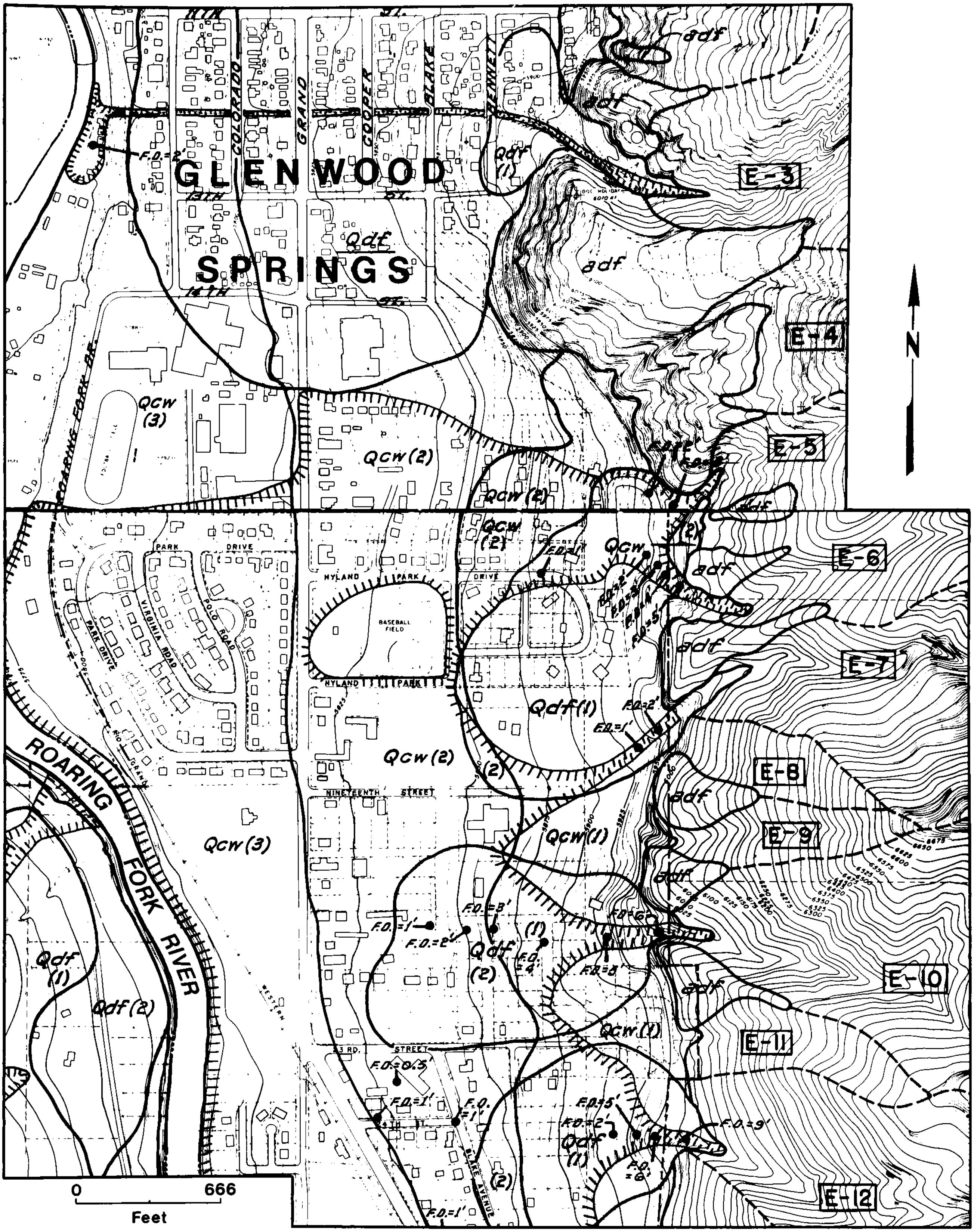
Glenwood Springs is a small mountain city located in a narrow canyon at the junction of the Roaring Fork and Colorado Rivers (Figure 18). It is one of Colorado's older communities and has been affected by debris flows throughout its history. Significant parts of existing development and otherwise attractive potential growth areas are subject to the debris-flow hazard. Glenwood Springs was chosen as a case study because: 1) it typifies the debris-flow hazard that affects dozens of Colorado's mountain communities, 2) the area has been the subject of successively more detailed hazard studies by the Colorado Geological Survey in cooperation with the city and Garfield County over the past 14 years, 3) the excellent information base and relative predictability of hazard zones make a variety of mitigation efforts possible, and 4) there has been recent activity, with debris flows occurring in 1977, 1981, 1984, and 1985.

Although the debris-flow and flooding hazard in Glenwood Springs was recognized early in the city's history, identification and analysis of the source areas were not begun formally until the late 1970s. Most of the city is located on debris fans which have historically been very active (Figure 20). At least 18 major damaging debris-flow episodes have occurred since 1900.

Description of the Debris-Flow Hazard

Debris flows are the most serious type of landslide hazard to affect Glenwood Springs. Debris flows are slurries of rock, soil, organic matter, water, and air that flow rapidly down pre-existing drainage channels until they are deposited in fan-shaped cones where the channels enter the main valley floor. Damage results from impact, burial, and flooding. Debris flows are extremely common in Glenwood Springs and appear to be the predominant form of flood event for most of the smaller watersheds of the region.

The combination of local geology, geography, and climate is responsible for the frequent debris flows at Glenwood



adf,Qdf **Mapped debris fan** **[E-10] Drainage-basin index number**

Figure 20. Mapped debris fans at Glenwood Springs, Colorado (from Lincoln DeVore, 1978).

Springs. The mountain slopes surrounding the city consist of sedimentary rocks whose weathering products are highly susceptible to debris-flow activity. Sudden failure of the accumulations of soil and debris can be triggered by saturation due to snowmelt and torrential rain. Debris fans and aprons are very prone to hydrocompaction and require special drainage and foundations even where not subject to debris flooding.

Impacts of Debris Flows at Glenwood Springs

Direct damages incurred in the debris-flow events of the 1970s and 1980s totaled millions of dollars. Although indirect losses are undocumented, they included loss of tourist trade and fish kills in the Roaring Fork River and other streams.

In 1982 the City of Glenwood Springs contracted for the preparation of an engineering study and control plan for debris flows. Debris-flow basins were ranked in terms of hazard severity, and the hydraulic properties of debris flows and flash floods in selected basins were determined. Conceptual designs of workable alternative control systems for combined debris flow and storm runoff were also formulated. The plan included nonstructural mitigation methods such as zoning and land-use restrictions, flood warning systems, and maintenance programs for channels and debris source areas; and structural methods such as floodproofing of buildings and construction of debris basins and dams, energy dissipators, drop structures, channels, and storm sewers.

Lamplite Park

CASE STUDY NUMBER 3 RIVER BLUFF RETREAT REACTIVATED BY HUMAN ACTIVITY (Lamplite Park subdivision, Grand Junction, Mesa County, Colorado)

Lamplite Park is a subdivision in the City of Grand Junction (Figure 18). Landsliding occurred there after construction activity reactivated an old landslide which had its origin in a river bluff oversteepened by erosion of the Colorado River. Although quite small, this landslide caused severe damage and forced the abandonment of several homes that were only a few years old. This case is of interest because the geologic process of oversteepening and failure of unconsolidated or weak rocks by localized riverine or coastal erosion occurs widely throughout the United States and because full utilization of available geotechnical data would have prevented the severe losses experienced at this site.

The effects of the Lamplite Park landslide were first noticed in the early 1980s, shortly after the housing development was completed. However, aerial photographs indicated that a landslide had existed on the site as early as 1954. Photo analysis also showed that the head scarp had apparently receded about 50 feet between 1954 and 1973. Investigation of the land-use history revealed that the site had been used as a gravel pit, junk yard, and a clean-fill dump prior to development.

When the subdivision was proposed in 1976, the geotechnical report identified the landslide and made several recommendations regarding construction on the site, including avoidance. The main part of the site was developed by 1982. At that time, the property passed to a second developer who built a row of houses on the north side of Santa Clara Avenue in the immediate area of the head scarp (Figure 21). At this time clean-fill dirt was trucked to the site, dumped, and graded to level and extend the backyards of these lots.

Within a year or so of construction, at least two houses began experiencing problems associated with differential movement. By November 1984, these two houses were condemned and the residents had filed lawsuits against the county, city, and individuals involved with the construction. By 1988, eight structures (nine units) had been moved off the site, and one other structure remained condemned.

Description of the Landslide at Lamplite Park

The Lamplite landslide is a complex rotational failure. The slide mass itself is a relatively thin (10 to 20 feet thick) section of the Orchard Mesa terrace gravel deposit. The slip surface is saturated, soft, extremely weathered shale; bedrock is unweathered Mancos Shale. The slip surface is saturated by discharge from a perched water table in the terrace gravels. This causes loss of strength and an increase in hydrostatic pressure.

This was an old metastable landslide that was reactivated in the head scarp area as a direct result of residential development, which caused loading of the top of the landslide and a change in the ground-water regime.

A two-phased geologic investigation determined that the main cause of damage to the houses was failure of the fill material that had been placed out over the head of the old landslide. The fill itself increased the weight on the top of the landslide, while the development on the fill resulted in increased soil moisture. The ultimate result was a reactivation of motion along the original landslide failure surface.

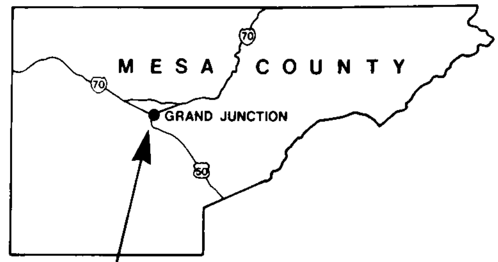
Impacts of the Landslide on the Community

The greatest impact on the community has been the loss of 10 homes (9 structures) located on the landslide. Originally the city-owned and private utilities beneath Santa Clara Avenue were also thought to be at risk. When the houses were occupied, there was a risk of personal injury associated with the possibility of a sudden foundation collapse or explosion of a ruptured gas line caused by the slow deterioration of the bearing support for the buildings and the presence of large open tension cracks.

Stabilization of the upper portion of the landslide was considered and discounted due to the poor benefit/cost ratio between construction cost and the present or anticipated value of the property and improvements. It was concluded there was no cost-effective way to allow long-term continued residential use of the lots north of Santa Clara Avenue east of address 1154.

Mitigation

Remedial actions taken to stabilize the landslide area at Lamplite Park consisted of the removal of 8 of the 12 affected structures, regrading of the ground surface, and the installation of 10 monitoring wells to observe the perched water table and provide an early warning system for future instability that might impact Santa Clara Avenue and the utilities beneath it.



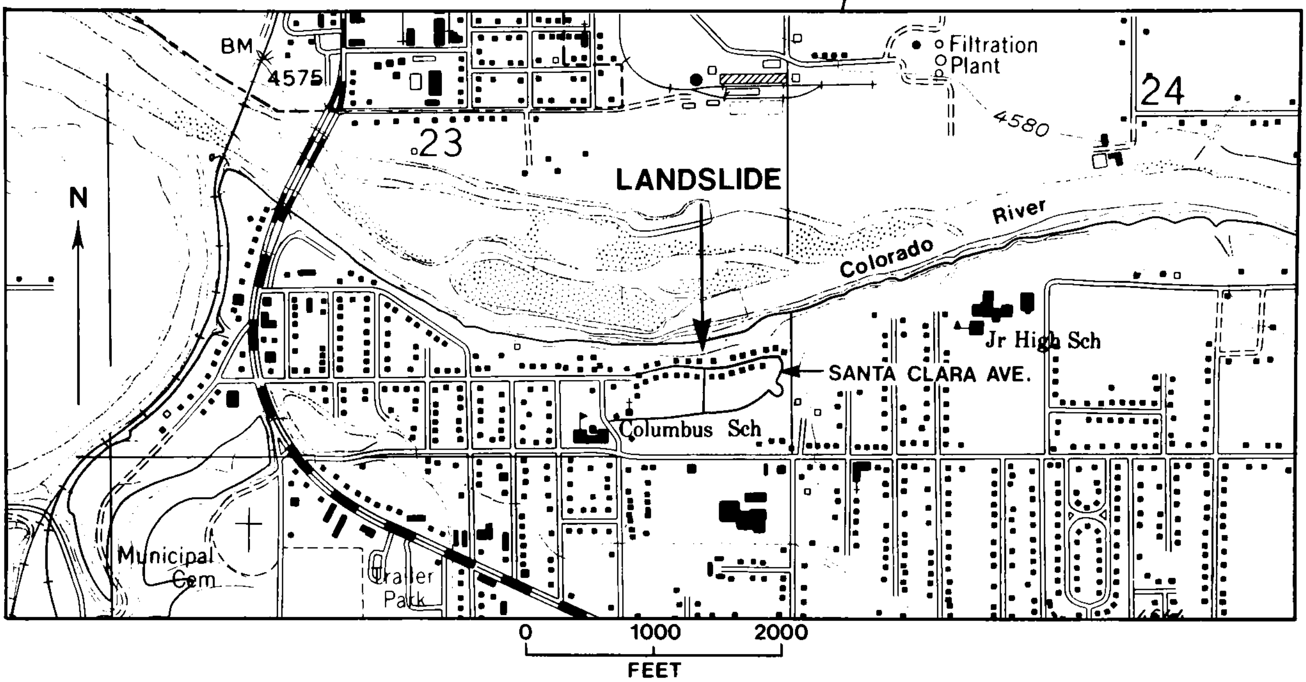


Figure 21. Detail from the Grand Junction 7½ minute quadrangle showing location of Santa Clara Avenue and the Lamplite Park landslide.

ADDRESSING UNMET LOCAL NEEDS

These three case studies provided the basis for formulation of a mitigation assistance strategy by state government. In each case, local entities had expended considerable effort and money in order to mitigate their landslide problems. Yet much still needed to be done, because technical and financial needs often exceeded the capabilities of the impacted communities. Development of the three cases provided opportunities for the identification of available resources and needs that could not be met at the local level. In many cases, the resource shortfalls identified represented substantial obstacles to reducing the impacts of future landslides on people, property, and essential services. The unmet needs typified the problems that face most local governments impacted by landsliding. Thus, once these cases were analyzed, projects could be developed to deal with many high priority local needs.

Unmet needs were identified and prioritized following on-site investigation and analysis. Vulnerable areas were evaluated to determine the potential type and magnitude of impacts. Health and safety, property loss, economic and social disruption were all considered in each situation. Any potential impacts were then aggregated and ranked by priority so that major potential impacts were clearly identified. A portion of the matrix used for this analytical process is offered as an example in Table 9. Next, these high priority potential impacts were listed for each major study site and compared against existing response systems available to local governments. Once this comparison was made, residual needs were then identified (as shown in the right hand column of Table 10) as unmet needs that should be considered by state and federal governments. A portion of this matrix—examining potential "health and safety" impacts for certain specific activities at Glenwood Springs and Dowds Junction—is also provided. When all three case studies had been thoroughly analyzed, a wide range of unmet needs were identified, and the most critical were selected to form the basis for state mitigation-assistance projects. Other less urgent unmet needs and potential projects were identified for later consideration by state agencies.

Table 9. Analysis of potential impacts of landsliding.

<table>
<tr><th rowspan="2">HUMAN ACTIVITIES/ FACILITIES AT RISK</th><th colspan="4">POTENTIAL IMPLICATIONS FOR:</th><th rowspan="2">AGGREGATED POTENTIAL IMPACTS</th></tr>
<tr><th>HEALTH AND SAFETY</th><th>PROPERTY LOSS</th><th>ECONOMIC DISRUPTION</th><th>SOCIAL DISRUPTION</th></tr>
<tr><td colspan="5">MESA COUNTY/GRAND JUNCTION, LAMPLITE PARK SUBDIVISION</td><td rowspan="6">Health and Safety
•Direct impact, burying of people
•Structure collapse
•Natural gas explosion
•Exposure to hazardous materials (e.g. chlorine)
•Disruption of critical services
•Water pollution
•Disrupted access
•Flash flooding

Property Loss
•Residences
•Utility and critical service facilities
•All land uses exposed to secondary flooding

Economic Disruption
•All activity regionally dependent on I-70 corridor
•Activities disrupted due to interruption of critical services
•Resources diverted from productive activity to disaster response
•Major economic loss to commerce and tourism of central and western Colorado

Social Disruption
•Neighborhood and community dissolution
•Disruption of all social activity dependent on I-70</td></tr>
<tr><td>Residential Land Use</td><td>•Risk due to sudden foundation collapse
•Risk due to explosion from gas line rupture
•Risk due to service interruptions
•Risk due to large cracks in ground</td><td>• 12 to 14 homes
•Public and private utility lines</td><td>•Diversion of labor and other resources from productive activities to disaster response.
•Disruption due to service interruptions</td><td>•Disruptions due to disaster response
•Neighborhood dissolution</td></tr>
<tr><td colspan="5">GARFIELD COUNTY/GLENWOOD SPRINGS</td></tr>
<tr><td>Water Treatment Plant
Chlorine Tanks</td><td>•Risk due to direct hazard impact
•Risk due to contact with liquid chlorine
•Risk due to chlorine inhalation
•Risk due to disrupted water supply
•Risk due to surface and ground water deterioration</td><td>•Chlorine tanks and associated facilities</td><td>•Disruption of economic activity dependent on domestic water supply</td><td>•Indirect impacts</td></tr>
<tr><td colspan="5">EAGLE COUNTY/DOWDS JUNCTION</td></tr>
<tr><td>I-70
U.S. Hwys. 6 and 24
D&RGW Railroad</td><td>•Risk due to inundation and burial (pop. at risk = 100)
•Risk due to flooding in Minturn (pop. 1800), West Vail
•Risk due to downstream flash flooding of Eagle, Vail, Avon, Edwards, Wolcott, and Gypsum following landslide-formed earthen dam failure (pop. at risk = 3000)</td><td>•$10 million in private property
•500 structures worth $50 million</td><td>•Loss of transportation corridor
•$40 million diverted to disaster response
•Major economic loss to commerce and tourism of central and western Colorado</td><td>•Major regional social dislocations</td></tr>
</table>

Table 10. Analysis of potential impacts and needs.

LOCATION AND EXAMPLE ACTIVITY	HIGH PRIORITY POTENTIAL IMPACTS (Health & Safety)	EXISTING RESPONSE SYSTEM	UNMET NEEDS LOCAL ACTIONS	UNMET NEEDS STATE AND FEDERAL
GLENWOOD SPRINGS Existing Residential Land Use	•Direct impact •Building collapse •Utility service disruption •Natural gas explosions •Disrupted access •Burial	•Geologic hazard ordinance zones •Debris-flow committee •Nonconforming use ordinance •Condemnation •Emergency operations plan •Enlarged culverts •Inverted street crown •Private berms •City blueline restrictions •Tree planting •Citizen studies of landslide hazard	•Establish open space hazard zones •Purchase easements and rights of way •Install warning system -install automated sensors -establish communications link with weather service •Make minor structural changes -upgrade potentially impacted walls -construct berms -install culverts •Implement local public/private program addressing private structural measures -establish design approval process -specify diversion standards •Educate citizens regarding limitations of structural mechanisms •Further specify risk -count buildings, population; determine assessed valuation -assess potential implications of hazard occurrence •Establish debris-flow destrict •Pursue funding for indentified structural measures •Continue public education and information campaigns •Continue emergency exercises and update emergency plans •Institute debris-flow committee on ongoing basis •Coordinate storm water and drainage system	•Investigate improvements/land use changes in upper basins -tree planting -construction of catchment basins •Clean debris basins •Match funding •Install warning system -install automated sensors -establish communications link with weather service •Provide technical assistance •Provide funding

Table 10. (Cont.)

LOCATION AND EXAMPLE ACTIVITY	HIGH PRIORITY POTENTIAL IMPACTS (Health & Safety)	EXISTING RESPONSE SYSTEM	UNMET NEEDS LOCAL ACTIONS	UNMET NEEDS STATE AND FEDERAL
GLENWOOD SPRINGS				
Water Treatment Plant Chlorine Tanks	•Direct impact •Explosion •Poisonous gas •Water pollution	•Nonconforming use ordinance •Updated emergency (city and county) evacuation plan •Currently developing hazardous substance annex to county emergency operations plan	•Assess potential implications of rupture •Post-disaster mitigation plan •Relocate structures •Institute structural protection •Boil water •Establish alternate treated water supply	•Provide coordination and technical assistance
EAGLE COUNTY/DOWDS JUNCTION				
I-70 U.S. Hwy. 24 U.S. Hwy. 40 D&RGW Railroad Condominiums	•Burial •Direct impact •Upstream flooding •Downstream flash flooding due to failure of landslide-formed dam •Transportation corridor disruption •Communications disruption •Direct impact to utilities and pipelines	•Governmental task force •EDMs (sensors) •Drainage •Technical studies •State response plans •Emergency operations plans and exercises •Snowpack and precipitation monitoring	•Establish land-use regulations •Initiate public awareness campaign (for condominiums) •Establish nonconforming use ordinance •Acquire and relocate endangered structures	•Install additional EDMs •Institute additional structural measures (e.g., tunnels, conduits, toe anchors) •Relocate highway •Provide flood insurance •Continue monitoring precipitation and snowpack •Continue emergency planning and exercises •Coordinate upstream reservoir operations with federal agencies and private dam owners •Promote public education campaigns •Provide state funding for construction •Dewater landslides •Divert river •Analyze significant structural responses •Modify government institutions to respond to the hazard

Chapter 7
THE EXISTING APPROACH TO MITIGATION OF LANDSLIDE HAZARDS IN COLORADO

LAWS AND REGULATIONS

Legal Framework

A range of statutes, executive orders, and interagency memoranda of understanding authorizing state and local initiatives to manage landslide hazards are in effect in Colorado. Although none address landsliding exclusively, those that authorize landslide management activities under provisions addressing geologic and associated hazards and emergency preparedness in general are discussed below.

The Colorado Geological Survey (CGS) within the Colorado Department of Natural Resources is the lead agency in Colorado for handling geologic hazard issues. The CGS was created in 1969. The legislation establishing the CGS was Colorado Revised Statutes (C.R.S.) 34-1-101, et seq. The agency was created in part to address the serious geologic problems associated with rapid development in mountainous regions in the late 1960s.

The legislation establishing CGS outlines its responsibilities and general statutory authority. C.R.S. 34-1-103 states:

> The Colorado Geological Survey shall function to provide assistance to and cooperate with the general public, industries, and agencies of state government...in pursuit of the following objectives...a) To assist, consult with, and advise existing state and local government agencies on geologic problems...c) To conduct studies to develop geological information...g) To evaluate the physical features of Colorado with reference to present and potential human and animal use..., and i) To determine areas of natural geologic hazards that could affect the safety of or economic loss to the citizens of Colorado.

In 1983, the Colorado General Assembly reduced funding for the CGS, making the agency unable to perform many of its statutory functions unless it could obtain funding from other sources.

The following legislation describes the specific functions of the CGS: **House Bill 1041,** C.R.S. 24-65.1-101, et seq., 1974, the "Colorado Land Use Act," involves comprehensive treatment of geologic hazards and charges local governments with legal responsibility for designation and administration of geologically hazardous areas of state interest. The CGS was designated as the lead agency for geologic hazards mapping and for providing technical assistance to local governments in designation and management of geologic hazard areas. The CGS was also charged with preparing and publishing a set of guidelines and model geologic hazard regulations for local governments.

The act defines a geologic hazard as "a geologic phenomenon which is so adverse to past, current, or foreseeable construction or land use as to constitute a significant hazard to public health and safety or to property." The term includes avalanches, landslides, rock falls, mudflows, and unstable or potentially unstable slopes.

Senate Bill 35, C.R.S. 30-28-101, et seq., 1972, concerns the division of land into sites, tracts, or lots, and is often referred to as the "subdivision law." The bill requires that subdivision proposals be evaluated for geologic conditions prior to approval by a county and applies to the division of land into parcels of less than 35 acres within a county.

The provisions of Senate Bill 35 which pertain to geologic hazards are listed below:

- Counties are required to request data, surveys, analysis, and relevant site characteristics, such as topography, streams, lakes, geology, and soil suitability.
- The CGS and other state agencies must evaluate geologic features that have an impact on the proposed use, such subdivision plans being distributed by the Board of County Commissioners.
- Sound planning and engineering requirements must be met before a subdivision may be approved.
- No preliminary or final plats may be approved until hazardous conditions requiring special precautions are identified, and the proposed uses are determined to be compatible with the conditions.

House Bill 1034, C.R.S. 29-20-101, et seq., 1974, is the "Local Government Land Use Control Enabling Act." The act gives authority to local governments to plan and regulate the use of land within their jurisdictions, including regulating development and activities in hazardous areas. The act then allows geologic hazards to be used as a basis for land-use decisions. No requirements or procedures are prescribed for adopting local land-use plans; the only intent was to affirm land-use regulatory authority to local governments.

Senate Bill 13, C.R.S. 6-6.5-101, 1984, relates to geologic hazards in requiring all residential developers to analyze and disclose any potentially hazardous conditions to prospective home buyers. Because the state does not enforce review or require disclosure statements, enforcement of this statute is difficult—usually by threat of litigation for not disclosing known hazardous conditions.

House Bill 1574, C.R.S. 34-1-201, et seq., 1973, requires that all geologic reports required by law be prepared by a "professional geologist." Since there is no formal registration procedure for geologists in Colorado, the law defines a professional geologist as a person who is a graduate of any institution of higher education which is accredited by a regional or national accrediting agency and who has a minimum of 30 semester hours of undergraduate or graduate work in the field of geology. The law also requires that the individual have baccalaureate training in the field of geology with an additional 5 years of geologic experience, counting no more than 2 years of graduate study. Other than these qualifications, the selection of a geologist to prepare geologic reports is left to the discretion of the agency or person contracting the work.

House Bill 1045, C.R.S. 22-32-124 (1), 1984, requires that, prior to the acquisition of land for school buildings sites or construction of any buildings thereon, the board of education must consult with the Colorado Geological Survey regarding potentially swelling soils, mine subsidence, and other geologic hazards and determine the geologic suitability of the site for its proposed use.

ORGANIZATION OF GOVERNMENTAL RESPONSIBILITIES

Coping with landsliding in Colorado involves the cooperation of many public and private institutions and all levels of government: federal, state, regional, county, city, and town. Some of the roles of government in hazard mitigation are listed in Tables 11, 12, and 13.

State and Federal Roles

State and federal government roles in supporting local efforts to respond to landslide hazards are listed in Tables 11 and 12. State and federal activities generally consist of financial, technical, or management assistance in landslide mitigation initiatives. The greater resources of these levels of government are particularly important to small, sparsely populated rural communities where the hazard is prevalent and adequate resources for hazard mitigation and response are lacking.

Table 11. State government roles in landslide hazard mitigation.

- Perform landslide hazard zone and control studies
- Perform geologic investigations and economic and cost-benefit analyses
- Prepare "work programs" and "scopes of work"
- Prescribe standards for surveys, mapping, and engineering for landslide-related studies
- Certify technical accuracy of landslide hazard zone analysis
- Participate in public educational and informational programs regarding landslide hazard and hazard zone management practices
- Coordinate federal assistance programs and landslide-control projects
- Coordinate disaster relief programs
- Seek authorization and funding for federal and state projects and programs
- Coordinate landslide hazard mitigation activities as mandated by a federal disaster declaration
- Plan for emergency preparedness and evacuation activities
- Plan for hazard evaluation and mitigation actions as required by Sec. 406 (Public Law 93-288) of the Disaster Relief Act
- Prescribe standards for state-financed facilities
- Respond to disaster emergencies and perform associated recovery activities

Table 12. Federal government roles in landslide hazard mitigation.

- Perform landslide control feasibility studies
- Research and develop facility design procedures
- Implement relocation and rehabilitation programs
- Provide disaster relief funds
- Provide disaster relief technical and administrative assistance
- Provide technical assistance to states
- Assist with management of publicly owned watersheds to minimize landslide hazards

STATE AND FEDERAL PLANS AND PROGRAMS

State Plans and Programs

As a whole, state government in Colorado plays an extremely important role in the landslide mitigation process. Although no single department has a statutory responsibility to fund mitigation, the Department of Natural Resources and Department of Highways have important programs that directly and indirectly lead to mitigation. For many years, the Colorado Geological Survey (CGS), a division of the Department of Natural Resources, has (within its responsibility for dealing with geologic hazards) provided governmental program leadership. The CGS has played an important role in identifying, mapping, and assessing landslide hazards. Other divisions within the Department of Natural Resources have played supporting roles:

- Colorado Water Conservation Board - oversees flood control and floodplain management programs,
- Division of Water Resources - directs dam safety programs,
- Division of Wildlife - owns and controls a number of properties throughout the state and is responsible for preparing plans to deal with hazards on those properties,
- Division of Parks and Outdoor Recreation - manages parks and other recreational facilities across the state and is responsible for preparing plans to deal with hazards on those properties.

The Department of Highways is involved in the design, construction, and maintenance of highways throughout the state and has programs to deal with landsliding impacts to these highways.

The Department of Public Safety, Division of Disaster Emergency Services, addresses four major aspects of disaster activity: mitigation, response, recovery, and preparedness. The Division coordinates efforts of other agencies of government in disaster/emergency situations.

The Department of Local Affairs, Division of Local Government, manages grant programs that may assist local governments in mitigating landslide hazards. In addition, a number of other state agencies have programs that may support landslide mitigation. A more comprehensive and detailed description of state agency programs is presented in Appendix 4.

Federal Plans and Programs

These are an even broader variety of programs that relate to landslide mitigation within the federal government. Two agencies, the Department of Interior, U.S. Geological Survey (USGS), and the Federal Emergency Management Agency (FEMA), play primary roles. Of particular importance is the USGS' involvement in geologic research, mapping, and geologic hazard warnings and FEMA's overall responsibility for disaster management and hazard mitigation. Appendix 4 contains a comprehensive discussion of the federal programs that support landslide hazard mitigation.

ANALYSIS OF THE STATE'S ORGANIZATIONAL CAPABILITY TO SUPPORT LANDSLIDE MITIGATION

Prior to 1986, state agencies other than the Colorado Geological Survey and the Department of Highways paid little attention to landsliding in Colorado.

In 1986, the Department of Natural Resources chaired the Minturn Earthflows Task Force, which assessed the landslide problem at Dowds Junction and recommended a variety of mitigation actions to be taken by state agencies. The task force was composed of representatives of the Geological Survey, the Water Conservation Board, the Division of Water Resources, the Division of Disaster Emergency Services, and the Department of Highways. Although this effort adequately addressed the situation at Dowds Junction, it was not translated into a statewide program.

Local Government Role

Local governments make most of the decisions affecting vulnerability and response to natural hazards; they are on the front line in the hazard management battle. State and federal government agencies play important, but supporting roles, primarily providing financial, technical, and administrative assistance and coordination.

Local governments may assume a number of landslide hazard management responsibilities, including:

- selecting goals and objectives,
- controlling land use,
- providing information and technical assistance,
- planning, financing, and implementing relatively modest mitigation projects, and
- operating landslide hazard management projects on a day-to-day basis.

Staff and elected officials of local government are usually subjected to diverse and sometimes conflicting pressures regarding community land use and development. Consequently, a model community landslide hazard management planning process should permit citizen participation and review in order to identify and address the perspectives and concerns of various community groups affected by landslide hazards. In addition, local governments must be careful to identify and develop clear goals and specific objectives in their plans.

The State of Colorado has placed the greatest responsibility for land-use planning and hazard control at the local level of government. Local governments are free to draw upon any and all authority delegated by the state, and home-rule cities derive additional authority from their charters. The statutory authority of local governments includes the power to plan, to regulate uses within their boundaries (using zoning, subdivision regulations, "matters of state interest," and the extensive list of powers contained in H.B. 1034), to regulate certain activities outside their jurisdictions, and to contract with other jurisdictions. The establishment of planning commissions and the regulation of subdivisions is optional for municipalities (C.R.S. 31-23-202, 214).

Counties and municipalities have the duty to prepare and adopt comprehensive plans for the physical development of their respective jurisdictions (C.R.S. 30-28-106 and 31-23-206). Establishment of planning commissions and adoption of subdivision regulations have been required of counties since 1972 (C.R.S. 30-28-133). Some of the roles that local government plays in landslide hazard mitigation are shown in Table 13.

Table 13. Local government roles in landslide hazard mitigation.

- Determine local landslide hazard problems and management needs and work with state and federal agencies to develop options to address them
- Transfer landslide hazard information and data to users
- Conduct public education and informational programs on land-use aspects of the landslide hazard zone management program
- Implement a landslide hazard management program
- Institutionalize use of landslide hazard data and information
- Adopt and enforce appropriate land use and land development regulations (based on detailed geologic analyses)
- Monitor changes in unstable slopes and take appropriate action.
- Operate and maintain federally constructed local landslide control or drainage projects
- Share costs with federal and state agencies in landslide hazard studies
- Perform field surveys
- Obtain rights of way and rights of ingress and egress for completion of studies and projects
- Construct street and drainage projects

LOCAL EMERGENCY MANAGEMENT AND MITIGATION

The Colorado Disaster Emergency Act of 1973 established the Division of Disaster Emergency Services (DODES) as the lead agency for coordinating state assistance in disasters and emergencies and sets up guidelines for local governments to follow in meeting the statutory requirements for emergency preparedness. In Colorado, the county is the unit of local government responsible for carrying out emergency management activities, primarily the development and maintenance of all-hazards Local Emergency Operations Plans (LEOPs). While many of the larger incorporated areas in the Denver metropolitan area have their own emergency management agencies, the emergency plans and procedures of most Colorado communities are represented in the county LEOP. This is the case in Mesa County (Grand Junction) and Garfield County (Glenwood Springs), where landslide and debris-flow problems of counties and their municipalities are addressed as hazard-specific annexes to the county LEOPs. The Garfield County landslide annex, or plan, has been included in this chapter as a model for local governments with landslide problems. Emergency management officials in Eagle and Mesa Counties have also pioneered emergency life- and property-saving plans in response to the widespread landslide problems that could potentially impact these counties and their jurisdictions.

Responsibility for the design and implementation of mitigation strategies (aimed at reducing future losses from the hazards identified in the planning process) is generally dispersed throughout local government, where all but the low-cost activities are usually unfunded. Both those strategies accomplished locally and those beyond local capability are identified in the mitigation elements of the landslide annexes to the LEOP. Through this effort, local officials are able to develop a list of needs, unmet locally, to improve public health and safety, as well as to plan for a reliable, coordinated response and recovery when landslide emergencies do occur.

The landslide plans for Mesa, Garfield, and Eagle Counties were developed by local emergency management directors and their planning teams, with technical assistance provided by the CGS and DODES. In recognition of a serious threat to lives and property in each county, the plans are intended to address the unique challenges presented in the planning, response, recovery, and mitigation phases of a landslide disaster, and to provide for effective direction and control, communications, warning, evacuation, sheltering, and public information services by emergency management officials. A "Hazard Analysis" has been developed as part of each plan to assist planners and response authorities by identifying population, structures, and critical facilities/services that are located in areas of greatest risk. The testing of existing plans by means of formal exercises has already begun, and more landslide and debris-flow exercises are planned for each county in the future. Refinements to plans and hazard analyses will be a continuous process as actual needs and community perceptions evolve. Local planning teams recognize that a program of long-term hazard reduction, together with a strong emergency management capability, is necessary to effectively reduce the vulnerability of the subject communities over time. In light of the budget constraints of local governments, particularly in western Colorado, a multi-year plan (usually five years) is followed for funding mitigation projects, filling resource needs, and improving emergency management capabilities in general.

Local Planning Teams

Among the participants on local landslide planning teams in the case study counties are county commissioners, emergency management directors, city/county planners, city/county engineers, building inspectors and road and bridge department personnel. Although the level of planning activity for landslides varies among these counties, each has recognized the threat and, at a minimum, has upgraded emergency plans and preparedness activities with the support of local leadership.

While a significant threat to the public still exists, particularly at Dowds Junction and Glenwood Springs, each county has made some progress toward alleviating the direct threat to life and property. The completion of hazard maps and technical studies, the construction of limited structural protection, restrictions on uses of land (based on detailed geotechnical studies), relocation of vulnerable structures, and the development and exercising of emergency operations plans are among the mitigation successes in these three counties. Local planners rely heavily on hazard maps and detailed geologic and geotechnical information about the threat to assess its extent and plan for the public health and safety needs of a jurisdiction. The technical studies and assistance provided by the CGS have helped to guide local planning and mitigative decision making in each of these counties. In each case, hazard maps have been used in applying zoning, subdivision controls, condemnation notices, nonconforming use restrictions, and other land-use techniques to reduce the vulnerability of some parts of the population to landslides.

Garfield County

Landslides and debris flows occur regularly throughout Garfield County, but the focus of emergency management activities remains at Glenwood Springs, the center of population, tourism, commerce, and government for the county. Hundreds of homes, as well as utilities, businesses, offices, churches, a hospital, a nursing home, and a college campus are potentially at risk due to the periodic debris flows that originate from the 20 or more drainage basins surrounding the city. As at Dowds Junction (discussed below), recommended structural measures to protect existing developments are prohibitively expensive for local (and likely state) government, even though studies indicate that they would yield a substantial degree of protection. The City of Glenwood Springs, however, has attacked the threat on a number of fronts, given the resources at hand, including:

- formation of a debris-flow committee that reviews, prioritizes, and schedules available mitigation opportunities,
- adoption and enforcement of a geologic hazards ordinance that restricts development in identified hazard zones,
- enforcement of city blue line restrictions, which limit the extension of city utilities,
- purchase of easements and rights of way to permit passage of debris flows through suspect areas and restrict growth in known hazardous zones,
- construction of enlarged concrete culverts capable of passing debris flows,
- redesign and construction of one street with an inverted crown to allow debris flows to be carried away from structures (and to permit easy cleaning of debris by street crews),
- revegetation and other floodproofing efforts by affected property owners, and
- construction of berms and deflectors and regular maintenance of structural features by the city and private individuals.

These measures represent only a small portion of the mitigation that can and needs to be done. The construction of arresting and retaining structures and improvements to the storm-water drainage system are expensive, and therefore long-term, efforts. Public awareness and education campaigns must be tempered by the timing of the debris-flow season in the spring and summer months, coincident with the vital tourist season. Public education about debris flows, warning procedures, and home/business protective measures is nonetheless favored by local emergency planners, given the extent of development potentially at risk and the high cost of structural remedies.

Mesa County

Landslides in Mesa County are widespread and impact both unincorporated and incorporated areas, including the City of Grand Junction. The most serious landslide threats exist at the Lamplite Park subdivision in Grand Junction and near the Vega Reservoir in unincorporated Mesa County.

Following identification of the landslide problem at Lamplite Park, the City of Grand Junction appropriated funds for geological studies to determine the extent of the problem and to assess possible solutions. Based on this information, city planners and the chief building official sought to eliminate the risk to the 11 most seriously threatened homes through condemnation (two homes), subdivision controls, and finally relocation. To date, nine of the 13 units have been removed from their foundations and are being relocated to safer sites in the city. Further geological studies are scheduled to assess the risk to the remaining four homes and to the city street and services. The results of these studies will guide decisions regarding the fates of the remaining properties and determine the scope of remedial stabilization work to be completed. The city plans to restrict all activities in this area in the future, possibly donating the land to a conservancy to be used as greenbelt and open space.

In the Vega Reservoir area, shallow landslides have frequently impacted county roads, creating high annual maintenance requirements, and threatening access to a state recreation area at the reservoir. A number of vacation homes at the reservoir have been damaged or destroyed since 1980.

Although the threat of landslide dam formation in Plateau Creek is relatively low, the downstream town of Collbran, in cooperation with the county sheriff and county emergency management agency, has completed a warning and evacuation plan for potential landslide/flash-flood scenarios. A landslide and/or flood emergency in the relatively remote Grand Mesa area of

Mesa County would present a number of unique challenges to emergency officials during the response and recovery phases of a disaster. Due to the shortage of shelters and the potential for whole communities to become isolated, the county LEOP addresses the unique types of resources that would be required to evacuate and protect residents and tourists and restore access to the area. County planners are exploring a number of mitigation alternatives, including redesignation of the zoning along hazardous stretches of Plateau Creek to "no-build." The county has also pursued returning the road to the state, since it provides the only access to the recreation area and the state would be better able to protect and maintain it.

Eagle County

Landslide problems in Eagle County are not limited to Dowds Junction, although this landslide complex has been extensively studied and has gained the attention of state government. The perception of the situation locally is that solutions to the problems at Dowds Junction are beyond the scope of local or even state capabilities. The findings in the Minturn Earthflows Task Force Report generally support this perception. For this reason, and because mostly federal lands are involved and the county's staff is relatively small, county planners have not concentrated on land-use regulations to mitigate the problem. The county emergency management office, however, has been very active in developing and exercising warning and evacuation plans of county and municipal governments. Although Eagle County has exhibited strong capabilities in the area of emergency management, effective mitigation solutions to the problems at Dowds Junction will require the full attention of state and federal government agencies with funding, resources, or expertise in this area. The challenge at Dowds Junction is a clear "pay now or pay later" proposition, and post-disaster recovery costs are sure to be very high.

In addition to detailing the emergency responsibilities of local and state agencies in a major landslide event at Dowds Junction, the county LEOP also establishes a system for monitoring conditions, notifying emergency officials, and warning the public in the event of a serious landslide at any one of the other known problem areas in the county, including parts of Vail, Red Cliff, Beaver Creek, and areas along Sweetwater Creek and the Frying Pan River.

Summary

Direct losses due to landslides in these three counties have been shouldered by federal, state, and local agencies that provide disaster assistance, flood insurance, and highway/road maintenance and repairs. Federal disaster assistance was provided in Mesa, Eagle, and Garfield Counties in 1984, as a result of serious flooding and landslides. State disaster assistance was granted in Mesa and Garfield Counties in 1985, following severe storms and landslides. The major impacts to public services in recent years have been to county roads that service farms, ranches, and recreational and forest lands, including a ski area. The indirect costs of landslides—reduced property values, declines in tourism, and revenue losses—are generally undocumented, but probably exceed the direct costs. Although local emergency management and mitigation efforts have been effective, increased state involvement in landslide mitigation will be necessary to prevent impacts that are statewide in scale.

The local landslide plan that follows is provided as model guidance to emergency officials in other jurisdictions in the development of their plans and procedures regarding landslide hazards.

GARFIELD COUNTY EMERGENCY OPERATIONS PLAN LANDSLIDE/DEBRIS FLOW ANNEX

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I SITUATION

A. Definitions

1. Landslide - the movement of a rigid body of soil or rock along an identifiable surface called a rupture zone. Landslide velocities can range from ten (10) meters per second to one (1) meter per year.
2. Debris Flows - as defined by the Colorado Geological Survey (CGS) are "slurries of rock, soil, organic matter, water, and air that flow rapidly down pre-existing drainage channels until they are deposited in fan shaped cones where the channels enter the main valley floor. Debris flow damages result from impact, burial and flooding."

B. Frequency

1. According to newspaper accounts, 18 debris flows have occurred in Glenwood Springs this century, four of which inundated the downtown district in only a seven-year period (1936-1943).
2. Following an uncommonly heavy thunderstorm on July 24, 1977, the most serious debris flow to hit the city inundated about 200 acres up to 12 feet deep and caused widespread damages. A number of smaller debris flows occurred in the summer and fall of 1981 and again in 1984, with lesser damages.
3. Mud and debris flows are a part of the history of Glenwood Springs. In fact, the central business and residential district is built on the debris fan of Cemetery Hill Gulch and the majority of West Glenwood Springs is also built on outwash.
4. In the winter of 1984-1985, unusually heavy early snowfalls resulted in an increase in landslide activity throughout the county. On May 13, 1985, the Garfield County Commissioners declared a disaster in the county due to damages caused by landslides.

C. Impacts

1. Estimates of damages from the 1977 debris flow disaster range as high as $2 million, although most reports indicate total losses fall somewhere between $500,000 and $1 million. The 1981 debris flows in Glenwood Springs caused approximately $100,000 in damages.
2. Landslides caused approximately $300,000 in damages in 1984, and over $500,000 in damages in unincorporated Garfield County in 1985. In May, 1985, 20 county roads were blocked by landslides, and Baxter Pass had to be closed. In May, 1985, Garfield County also recorded the largest single-event earthflow in Colorado history, a 175-foot-thick mass of debris that was a mile long and 1,000 feet wide on Roan Creek.
3. In addition to direct damages, other economic impacts include loss of tourist trade due to media coverage of events and fish kill in the Roaring Fork River and other streams, although these losses are undocumented.
4. The "hidden" impacts of debris flows are documented in a 1986 report by the Mount Sopris Soil Conservation Board and Marian Smith, "Debris Flow Costs and Inventory of City of Glenwood Springs Area" (Smith, 1986). Some of these impacts are:
   a) trauma, and the stress induced by recurring fears in some residents when thunderstorms occur,
   b) homeowner costs of clean up and repair, including boots, gloves and tools, and damage to furnaces and appliance motors,
   c) the loss of landscaping, acquired over many years and too costly to replace all at once,
   d) irreplaceable personal possessions such as clothes, books, family photos, etc., and
   e) the loss of time that is spent completing repairs and reconstruction.

D. Population at Risk

1. Threat areas identified in this hazard analysis are based on historical frequency and geotechnical studies. This does not imply that damages from future events will be experienced in or confined to the areas identified. In general, although most parts of the city are vulnerable to debris flows, the threat is greatest to people and property on the upper parts of debris fans, with vulnerability decreasing to those lowest on the fans.
2. The primary land use in the most hazard-prone areas is residential, the most vulnerable area being that south of 13th Street and east of Grand Avenue/U.S. Hwy. 82.
3. Extensive development has occurred in West Glenwood Springs in the past few years. No special provisions were included to carry anticipated flows through a shopping center.
4. The Red Mountain area west of the Roaring Fork River and south of the Colorado River is subject to periodic landslide and debris-flow activity, most recently in the spring of 1984, when mud and debris flows resulted in extensive flood-fight and cleanup actions, minor damages, and access problems.
5. At South Canyon near Hell's Gate, a landslide area is located immediately adjacent to Interstate 70 on the north side. This

presents a significant threat to freeway traffic in both directions.

6. A landslide area stretching from Sweetwater Lake to the Eagle County line is characterized by steep slopes on the south side of Sweetwater Creek and numerous streams feeding into the creek. This combination periodically produces landslides into the creek and over the only road into the resort area at Sweetwater Lake.

E. Structures at Risk

1. In Glenwood Springs, structures at risk represent the full range of land uses (residential, commercial, educational, health and medical, and parks and recreational uses).

F. Critical Services and Facilities at Risk

1. Utilities - potential impacts include: a) loss of life due to gas-line breaks and explosions, b) loss of service, c) loss of revenue, and d) cost of repair. Underground utilities are generally more protected, although debris flows are capable of severing below-grade services as well. Utility companies will follow their own emergency SOP's in debris-flow incidents.
   - **a.** Natural gas - potentially at risk are the gas main into town and distribution lines.
   - **b.** Electricity - electrical transmission and distribution lines.
   - **c.** Water - two water storage tanks in eastern part of the city are vulnerable to debris flows. Debris flows into the river and resulting sedimentation problems impact water-treatment equipment and drinking-water quality. Additionally, the City's Red Mountain Water treatment facility and the West Glenwood facility are located in landslide-active areas.
   - **d.** Telephone lines.
2. Roads/Bridges/U.S. Hwy. 82/I-70 - heavy debris removal requirements and potential access problems. The possibility of long detours or isolated groups requiring assistance is a concern.
3. Irrigation ditches.
4. Sedimentation of waterways adversely impacts reservoirs, water systems, cropland and fish habitat.
5. Denver and Rio Grande Western Railroad - railways and depot.

II ASSUMPTIONS

A. Due to the large volume of debris present in the unstable drainage basins surrounding Glenwood Springs, the threat to people, property and essential public services will be a persistent one. Aggravating the problem is the alteration of natural debris fans by the construction of roads, homes, irrigation ditches and businesses (Mears, 1977).

B. Major debris flows are deep enough (5 feet or more) to transport large boulders for long distances at velocities up to 10 to 15 feet/sec. Debris flows can produce impact pressures on exposed structures of 400 to 900 lbs/ft2, potentially destroying structures and causing injuries and loss of life (Mears, 1977).

C. Debris flows can occur in surges (due to repeated formation of debris plugs in the channel resulting in intermittent build up and release of debris and water): individual flows often bypass established channels and change directions unpredictably.

D. Abnormally high snowfalls may cause increased and new movements of large deep landslides. There appears to be a correlation between high precipitation in the fall of the year (before the ground freezes) and increased landslide activity the following spring and early summer.

1. Increased water content within a landslide increases the weight and, therefore, the driving force for landslide movement, as well as reducing the friction and internal strength of the landslide mass.
2. Many heavy snowfalls occur before the ground freezes. As the snow melts at the ground surface, it soaks into the ground and enters fractures in the landslide.
3. A heavy blanket of snow protects the ground surface from early freezing and increases the time for soaking by the melting snow.

E. Since most of the debris fans in Glenwood Springs are highly urbanized and it is not possible to avoid the hazard, a program of structural and nonstructural mitigation must be developed.

F. Structural alternatives are extremely expensive, but may provide the only protection in some areas.

G. Of the 20 or more drainage basins surrounding Glenwood Springs that are capable of producing debris flows, most do not pose an immediate threat to people and improved property. The larger basins, however, present a considerable threat of serious damages and risk to life and will require a host of structural and nonstructural mitigation strategies to alleviate the hazard.

H. Engineering and structural solutions will not completely avoid damages in extraordinary debris-flow/landslide events. Nonstructural measures such as public awareness of the hazard and emergency home-protective measures, together with city/county lifesaving plans and prudent land use management practices, must therefore be exercised in concert with structural protection.

I. Due to the concentrations of debris remaining in the gulches and the continued development of the debris fans, future events will undoubtedly occur, with losses equal to or greater than those already experienced.

J. When a debris-flow/landslide disaster impacts incorporated areas exclusively, the county will assume a support role and activate the County Emergency Operations Center (EOC), emergency plans and incident management functions as necessary.

III PURPOSE

Pursuant to the provisions of Section 24-33.5-707 (8), C.R.S., as amended, the purpose of this portion of the emergency operations plan is to prepare for, respond to, recover from and mitigate the effects of serious landslide/debris-flow incidents in Garfield County. The plan shall identify existing and potential mitigation measures and include, to the extent possible, a schedule for their implementation. All readers are advised to consult their own engineer or advisor for advice concerning the actual existence of any debris-flow path or projected impacts from such a landslide or debris flow.

IV AUTHORITIES

A. Federal

1. Public Law 81-920 (Federal Civil Defense Act of 1950), as amended;
2. Public Law 93-288 (Disaster Relief Act of 1974), as amended.

B. State

1. Colorado Disaster Emergency Act of 1973;
2. Colorado Disaster Emergency Operations Plan of 1987.

C. Local

1. Garfield County Resolution -84-212 establishing a County Emergency Preparedness Office, affirmed by the Board of County Commissioners, October 3, 1984, and renewed annually.
2. Glenwood Springs Ordinance establishing geologic-hazard zones (Ordinance No. 26, 1981).

V CONCEPT OF OPERATIONS

A. General

Since debris flows/landslides occur with little or no warning, departments and organizations with emergency responsibilities must assure that all personnel concerned are familiar with existing plans and are capable of implementing them in a timely manner. The greatest opportunity to protect lives and property lies in the advancement of identified mitigation measures in known hazard areas prior to a disaster.

B. Specific

1. Depending upon the extent of jurisdictional impact, the Board of County Commissioners and/or Mayor will be responsible for the direction and control of emergency operations to include, if necessary, Emergency Operations Center (EOC) activation, disaster declarations, liaison with the Division of Disaster Emergency Services (DODES) and state agencies, organization of personnel, resources and facilities, etc. (see Direction and Control, Annex C of this plan).
2. The Emergency Preparedness Coordinator serves as operations coordinator for the Board of County Commissioners and must stay apprised of the status of the emergency response in all functional areas.
3. The maintenance within the EOC of detailed action logs (date/time, action required, response taken) will protect against liability claims following the disaster.
4. The maintenance within the EOC of detailed financial records, including all commitments of personnel, equipment, and other resources, will assure maximum reimbursement of eligible local emergency expenditures should state or federal disaster assistance become available.
5. The accuracy of damage assessment data compiled in the EOC is essential in determining the availability and level of supplemental disaster assistance.

C. Operational Phases

1. **Readiness** - Notification of an actual or imminent debris-flow/landslide threat may originate from eyewitness reports by the public or from police/public works personnel working in the area. Storm and flood watches and warnings issued by the National Weather Service should alert emergency organizations to the potential for debris-flow/landslide problems and trigger increased surveillance and other preparedness activities. The Emergency Preparedness Coordinator will alert the Board of County

Commissioners of any reported debris flows/landslides and damages, and keep them informed of the situation. The Coordinator will maintain communications with city officials to respond to requests for emergency assistance from the county. The Coordinator will alert heads of departments/organizations of a possible partial or total activation of the EOC. Initial evaluations of the potential threat to life and property should consider potential inundation areas and access problems, warning and evacuation requirements, temporary shelters and safe areas and future resource requirements.

2. **Emergency Response** - Incident Command will be established at or near the threat areas to direct on-site actions and the county/municipal EOC will be established to coordinate off-scene support requirements. The Mayor and/or Board of County Commissioners will assume direction and control and assess the emergency in terms of the need for warning and evacuation, temporary shelter, emergency declarations, public information, etc. All damage assessment information should be forwarded to the County EOC.
3. **Recovery** - Short-term recovery activities include emergency repairs and restoration of essential public services and facilities, provision of emergency services (health, food, shelter, clothing) to disaster victims, debris clearance, damage assessments, and all actions to return the community to normal. Long-term recovery includes the provision of state/federal disaster assistance, revisions to emergency plans, and reducing the vulnerability of citizens to future debris-flow/landslide events through the implementation of structural and nonstructural hazard mitigation solutions.

VI ORGANIZATION

A. The designated debris-flow/landslide response authorities for Garfield County are as follows:
   1. **Unincorporated Areas** - Sheriff
   2. **Incorporated Areas:**
      a. Glenwood Springs: Police Chief
      b. Silt: Mayor
      c. New Castle: Police Chief
      d. Parachute: Police Chief
      e. Rifle: Police Chief
      f. Carbondale: Board of Trustees

B. See Direction and Control, Annex C of this plan. (Note: Where an incident impacts across jurisdictional lines, close coordination of direction and control will be exercised by the responsible on-site official. Any conflicts will be resolved by the Board of Commissioners/Mayor.)

VII SPECIAL RESPONSIBILITIES UNIQUE TO THIS ANNEX

A. **The Board of County Commissioners** is responsible for:
   1. Implementation of the Garfield County Emergency Operations Plan, all or in part, and the direction and control of all County departments before, during, and after a debris-flow/landslide disaster (in support of city officials when impacts are only to incorporated areas of the county).
   2. Establishment of an emergency public information service at the County EOC to provide accurate, up-to-date information to the public, including emergency protective instructions, through all available media (see Public Information Annex of this plan).
   3. Issuance of public proclamations relative to the emergency and evaluation of conditions in terms of the need for a disaster declaration.
   4. Implementation of appropriate mutual aid/interlocal agreements, when necessary.
   5. Establishment of a fiscal policy concerning the expenditure and allocation of funds and a resource priority assignment and allocation policy.

B. **The Emergency Preparedness Coordinator** is responsible for:
   1. Coordination of necessary support requirements and advising elected officials and agency representatives on the current status of response and recovery efforts. The Coordinator must be fully informed on the changing emergency situation and must provide appropriate briefings for government officials.
   2. Activation and staffing of a portion or all of the County EOC, at the direction of the Board of County Commissioners.
   3. Monitoring debris-flow/landslide events with respect to the need to activate the EOC in order to provide for incident management of off-scene support needs (see EOC Standard Operating Procedures).
   4. Establishment of a plan for monitoring and mitigating debris flows and landslides, in coordination with city/county officials.
   5. Maintaining close liaison with emergency response agencies and DODES, particularly during periods of greatest potential threat.
   6. Conduct/coordination of training and exercises regarding the debris-flow/landslide threat, as considered necessary.

7. Dissemination of debris-flow/landslide educational materials to the public to increase awareness of the hazard and to provide information on preparedness and emergency protective measures.
8. Maintenance of Garfield County Emergency Operations Plan, including Debris-Flow/Landslide Annex (review/update/distribute changes).

C. EOC Functions and Responsibilities (Incident Management):
1. Serves as central office for debris-flow/landslide information (maps, damage assessments, geological information) and for the dissemination of situation reports (to DODES).
2. Coordination point for all support activities away from the incident site, to include requesting outside assistance, coordinating force account resources and arranging for the emergency shelter and care of evacuees.
3. Monitoring debris-flow/landslide emergencies with respect to the need for state and federal resources. Requests for supplemental assistance should be channeled through DODES (24-hour emergency line: 279-8855).
4. Public Information functions: 1) maintain government and public awareness of debris-flow/landslide incidents by use of available media (as outlined in the Public Information Annex of this plan), 2) prepare maps reflecting hazard zones, evacuation routes, shelters, and safe areas, 3) brief local media sources on status of emergency relief efforts, and 4) establish a public information center to respond to inquiries from the public, assist in the control of rumors, authenticate information, and ensure the accuracy of shelter and casualty records.
5. Coordination point for compilation of damage assessment figures and preparation of supporting documentation for county requests for state/federal assistance (County Assessor can provide damage assessment assistance). EOC staff will also maintain detailed financial records of all incident-related resource commitments.

D. **The Sheriff/Police Departments** will be responsible for:
1. Issuing warnings and instructions to the public regarding the nature of the debris-flow or landslide emergency and maintaining current information regarding warning and evacuation. Special emphasis will be placed on warning at most exposed buildings/residences as documented in paragraph I-D, Population at Risk.
2. Coordination of search-and-rescue operations and maintenance of law and order within respective jurisdictions.
3. Conducting evacuation activities to include designating and securing evacuation routes, coordinating emergency medical, housing and food resources (with EOC), coordinating transportation resources (with EOC), providing security in shelters and evacuated areas and arranging for evacuation of special populations (e.g., nursing homes, hospitals, elderly, handicapped, disabled and infirm residents, and non-English- speaking groups).
4. The law enforcement agency having jurisdiction shall have responsibility for traffic control (except on highways, where Colorado State Patrol has authority).
5. Assisting in communications between state and local EOC's.

E. **Road and Bridge/Public Works Departments** will be responsible for:
1. Assisting in necessary road closures, detours and establishment of control zones, at the direction of the Police/Sheriff Department.
2. Providing public safety measures including identification and marking of dangerous areas in coordination with Police/Sheriff Departments.
3. Providing for the removal of debris to permit emergency rescue operations and movement of emergency vehicles and supplies.
4. Providing for emergency repairs to streets, roads, public buildings, hospitals, utilities, and other essential services and facilities under established priorities for restoration and continued operation of governmental functions.
5. Providing damage assessment information to EOC staff on roads, buildings, equipment, etc.
6. Maintaining potable water and sewer facilities and equipment.
7. Assisting in provision of transportation for movement of personnel, equipment, and supplies.

F. **County/City Attorney** is responsible for:
1. Being familiar with all local, state, and federal laws applicable to disasters and emergencies.
2. Providing legal advice to the Board of County Commissioners and the Emergency Preparedness Coordinator.

G. **County Health Official/Nurse** is responsible for:
1. Directing and coordinating of emergency medical assistance to persons/families to in-

clude identification and prioritization of health needs and arrangements for resources to meet those needs (coordinate with other medical agencies and inform EOC).
2. Planning for, providing, and supervising nursing services in temporary shelters until relieved by Red Cross or other qualified nurses.
3. Serving as a resource regarding known residents with health/disability problems who would require extra assistance in the event of an evacuation.
4. Identifying potential health hazards throughout the county, including utilities and hazardous materials, and developing procedures to minimize adverse impacts in a debris flow or landslide.
5. Assisting Public Information Officer in preparation of health- oriented public announcement materials (with respect to debris-flow/landslide hazard).

H. **The Social Services Department** is responsible for:
1. In coordination with the local Red Cross representative and Sheriff/Police Chief, selection of temporary shelters to accommodate projected number of evacuees from each identified threat area. Obtain prior approval for the use of each designated shelter.
2. Establishing plans and procedures for mass care and assistance for displaced persons in designated shelters.
3. Assisting in the provision of emergency needs with Red Cross, Salvation Army and other private/volunteer organizations. Coordinate staffing support requirements and procedures for opening shelters.
4. Determining special needs of the handicapped, infirm, and elderly prior to, during, and after a disaster.
5. In coordination with State, implementation of Individual and Family Grant Program following the Presidential declaration of a major disaster (if declared).

I. **Fire Protection Districts** are responsible for:
1. Coordinating and communicating with Incident Commander for assistance in rescue operations, evacuation orders, public warnings, fire security, emergency medical assistance, and other support, as required.

J. **The City Engineer/County Planning Department** is responsible for:
1. In coordination with Colorado Geological Survey, collection and analysis of data on potential debris-flow/landslide threats (Emergency Preparedness Coordinator should be kept informed of significant information).
2. Determining, and providing for in the annual budget, funds required to support monitoring and mitigation measures.

K. **The County Assessor** is responsible for providing information on damages sustained to county/city population, public facilities, utilities, highways, and other resources. This assessment is to be used by all levels of government to assign priorities for assistance and as a basis for declaring a disaster or emergency (see Damage Assessment Annex of this plan).

VIII EXECUTION

A. Monitoring

1. Electronic warning devices that sense movement and transmit warnings are available and have proven successful in other areas with debris-flow and earthflow problems; however, they are expensive and difficult to justify from a cost/benefit standpoint in the short term.
2. In lieu of an electronic early-warning system, the best indicator of potential debris flows is rainfall. The rainstorm that set off the debris flows of July, 1977, produced 1.08 inches of rain, 0.85 inches of which came in only about half an hour (the soil was wet, although not saturated, prior to this storm). According to the CGS, it can be assumed that future rainstorms of similar **intensity** and **duration** would also trigger debris flows; although storms of lesser intensity, and greater probability, may also be capable of producing serious debris- flow events (Mears, 1977).
3. Public education and awareness programs should address the correlation of rainfall to debris flows, home emergency protective measures that can be taken when threatening rainstorms occur, and other debris-flow mitigation steps that property owners can employ in advance of an event.

B. Notification

1. Notification of an actual or imminent debris flow/landslide may originate from the Police/Sheriff Department, public works personnel or private citizens. The appropriate warning/public safety officials should be notified immediately when a threat is indicated. The first responder from the designated response authority should assume incident command (in accordance with Standard Operating Procedures for the

local Incident Command System) and assess the seriousness of the situation with respect to alerting/warning needs. Depending upon the magnitude of the incident, notification should be made to the following officials:

a. Emergency Preparedness 945-9158 (ext. 249)
Coordinator . . . . or 945-2898
b. Mayor, City Hall 945-2575
c. Board of Commissioners 945-9158
d. Additional EOC Staff, as needed:

Glenwood Springs

1. Emergency Calls . 945-6672 or 945-8566
2. City Manager 945-2575
   Home Phone: ____________
3. Public Works 945-6443
   Home Phone: ____________
4. City Attorney 945-2575
   Home Phone: ____________
5. City Engineer 945-2575
   Home Phone: ____________

Garfield County

1. County Attorney 945-9150
   Home Phone: ____________
2. Social Services 945-9191
   Home Phone: ____________
3. Road and Bridge 945-6111
   Home Phone: ____________
4. County Nurse 945-6614
   Home Phone: ____________
5. County Assessor 945-9134
   Home Phone: ____________

DODES

1. 24-hour line 279-8855

C. Warning and Evacuation

1. **Local emergency response agencies** will confirm debris-flow/landslide reports, initiate incident command, consider warning and evacuation requirements, and direct other immediate actions necessary to protect lives and property and keep roads safe and passable. The Incident Commander will authorize and direct precautionary warning and evacuation orders and carry out door-to-door measures. Warning and evacuation plans should be based upon a detailed hazard analysis that determines the most vulnerable areas with respect to suspect drainage basins (see Hazard Analysis).
   Glenwood Springs Police 911 or 945-8566
   Glenwood Springs Fire Chief . . 945-4942
   Garfield County Sheriff 945-9151

2. **Radio stations** will be asked to air a warning to the public that a debris flow/landslide has occurred at **(location)** and, as a result, damages have been sustained at **(roads/river)**, and the public should be advised to stay away from affected areas using **(alternate routes)**. Emergency steps and evacuation instructions should be related. The following is a list of local radio stations.
   KDBL-AM and FM, Rifle 945-0164
   or 625-2299, 625-0810, 625-5325
   KDNK-FM, Carbondale 963-0139
   KGLN-MBS, Glenwood Springs945-6501
   KGMJ-FM, Glenwood Springs,
   Eagle . . . . 945-2938 or 945-1242
   KMTS, Glenwood Springs 945-9124
   (Emergency Broadcast System)
   KQIX Q-FM, Glenwood Springs . . . .
   945-1093
   or 945-7000

3. **Colorado State Patrol (CSP) and Colorado Department of Highways (CDOH)** will be notified of potential impacts to U.S. Hwy. 82 or Interstate 70 and will assess needs for traffic control, road closures, and emergency repairs. Impacts to the railway should be reported to the Denver and Rio Grande Western Railroad. Warning and evacuation considerations should include possibilities of landslide dams forming and associated flooding.
   Colorado State Patrol 945-6198
   Colorado Department of
   Highways . . . . . . 945-7629 or 945-8080
   Denver and Rio Grande Western
   Railroad . . . . 945-5011 or 945-7514

D. EOC Activation - At the direction of the Board, the Coordinator will activate a portion or all of the County EOC (activation of a municipal EOC will be the call of the Town Council, Mayor, or his/her designee). The EOC staff will ascertain the need for an emergency resolution or disaster declaration to trigger mutual aid and supplemental assistance, as well as directing other incident management support functions in support of response and recovery efforts (see EOC functions under "Special Responsibilities" section of this annex). Necessary equipment, materials, and labor for emergency protective measures such as berms, ditches, sandbag channels, culverts, and other diversions will be coordinated by EOC personnel.

EOC Location: Garfield County Courthouse
109 8th Street, Suite 301
Glenwood Springs, Colorado

E. Sheltering - The Shelter Officer, Social Services representative, or other designated EOC staffer will arrange for the opening of predesignated shelters for congregate care (see Shelter Annex of this plan for specific sites and procedures).

F. Other Resources and Services - Transportation resources, medical service telephone lists, utility services, and sources for public- and privately-owned equipment are listed under separate cover in the "Resources Available for Garfield County" booklet.

IX MITIGATION PLAN

A. General - Nonstructural measures generally do not require large capital outlays and often yield the greatest mitigation benefits. Identified nonstructural alternatives should be implemented at the earliest possible opportunity. Nonstructural actions include warning systems, emergency plans, public education, emergency exercises, zoning and land use restrictions, maintenance programs, and floodproofing measures.

Structural measures may be very costly and must be provided for through the budget over a period of years on a priority basis. Structural, or capital, improvements include debris catchment basins, diversions, arresting structures, drop structures and storm sewers.

The larger debris-flow source areas present the most serious threats and will require actions at all levels of government to reduce the risk. Existing development in the smaller watersheds may best be protected by the private actions of the affected property owners.

Strict channelization is *not* a recommended mitigation measure, according to the CGS, because as channels are blocked by debris, subsequent surges will flow in new directions.

B. Existing Measures and Capabilities

1. Nonstructural:

- a. formation and regular meetings of a Debris Flow Committee, which prioritizes needs, makes recommendations and schedules implementation of available alternatives,
- b. adoption of a Geologic Hazards Ordinance (Glenwood Springs Ordinance No. 26, 1981) that restricts development in identified hazard zones,
- c. enforcement of City Blue Line restrictions, which limit the extension of city utilities,
- d. purchase of easements/rights of way to both restrict growth and permit passage of debris flows through suspect areas,
- e. the completion of a 1983 engineering study and control plan that recommended structural mitigation strategies,
- f. the individual floodproofing efforts of affected property owners.

2. Structural:

- a. construction of berms/deflectors and maintenance of structural features by the county/city and private individuals,
- b. construction of enlarged concrete culverts capable of passing debris flows,
- c. redesign and construction of 21st Street in Glenwood Springs with an inverted crown to allow carrying of debris flows away from structures (and to permit easy cleaning of debris by street crews).

C. Recommended Mitigation Activities

1. Nonstructural:

- a. adoption and enforcement of County/City/Town Geologic Hazards Ordinances, grading codes, building codes, development reviews and other land-use measures to restrict development in hazardous areas,
- b. review of existing zoning and land-use restrictions with respect to upholding government's responsibility for promoting public health, safety, and welfare,
- c. restrict development or reconstruction of disaster damaged properties in developed areas following future debris flows or landslides. In undeveloped areas of the city and county, reclassification of debris fans to "no-build zones" is the most cost-effective mitigation solution, if a method for public purchase of such lands can be developed so that private interests are properly compensated,
- d. formation of a "debris-flow or landslide district" (with members assessed in proportion to their level of risk) for the purpose of funding mitigation projects under a multi-year, capital improvements approach,
- e. planting of closely-spaced trees, as recommended in the 1977, CGS Report (Mears), is an effective means of stopping boulders and large rocks and slowing erosion (the Soil Conservation Service and Colorado State Forest Service can assist),
- f. ongoing program of floodproofing promotion and regular maintenance of protective features,
- g. pursuing funding of identified mitigation projects through established grant programs (Department of Local Affairs),
- h. developing an electronic, early warning system,
- i. public awareness/education campaigns,
- j. developing, maintaining, coordinating, and exercising emergency operations plans,
- k. adopting an additional ordinance requiring periodic meetings of the debris flow

committee as well as periodic reports on progress to Mayors/City Councils/Board of County Commissioners.

2. **Structural:**
   - **a.** developing a coordinated storm-water drainage system in Glenwood Springs,
   - **b.** structurally reinforced building walls (those facing uphill) capable of withstanding the impacts of 5 to 10 ton boulders transported five or more feet above the ground,
   - **c.** investigating with Colorado Division of Wildlife the construction of ponds in upper basins to help catch runoff in intense storms and also to enhance deer and wildlife habitat (preventing "road kill" when wildlife goes to river),
   - **d.** constructing arresting and retaining structures:
     - debris basins and detention structures
     - cribs and grade-stabilization structures
     - catch fences (steel and concrete)
     - berms and diversions
     - drop structures, hydraulic jumps and other energy dissipators
     - debris deflectors
     - culvert cribs and risers
     - conveyance structures
   - **e.** where feasible, re-route road alignments away from identified landslide areas,
   - **f.** divert runoff away from identified landslide areas and prevent ponding.

NOTE TO READER: This annex would normally include several appendices, maps, a hazard analysis, references, and a list of state and federal assisting agencies. They have not been included because most of the information they contain is provided elsewhere in the Colorado Landslide Hazard Mitigation Plan. Local emergency planners should be aware, however, that this information is integral to emergency plans for any hazard. In particular, the hazard analysis indicates in detail the hazards a community faces, and what parts of the community are vulnerable to those hazards. In Colorado, completion of a hazard analysis is the important first step in the development of state and local emergency operations plans.

9

PART II

CONCEPT OF MITIGATION

This section discusses plan development and organization, and how situational information is applied to achieve the plan's purpose.

Chapter 8
PLAN DEVELOPMENT AND ORGANIZATION

THE PLANNING PROCESS

The greatest opportunities for reducing future landslide losses in Colorado lie in the advancement of state capabilities in two principal areas: emergency management, and long-term hazard mitigation. The emergency management responsibilities of state government in landslide disasters are addressed in the State Emergency Operations Plan (SEOP). A proposed program for long-term landslide hazard reduction is set forth in the Colorado Landslide Hazard Mitigation Plan.

A series of sequential steps has been followed in the development of this hazard mitigation plan. These steps are basic to mitigation planning for other hazards in the state and are adaptable to the development of future hazard-specific mitigation plans. These planning steps are as follows:

1) Identification of landslide hazards in the state and an assessment of the vulnerability of people and property to the hazards, based on existing data and additional scientific and engineering studies. This **hazard analysis** defines the landslide problem and is the starting point for both the emergency management and long-term mitigation of the state's landslide hazards.
2) Identification of potentially impacted sites across the state; and determination of specific impacts for these sites.
3) Assessment of available resources and the capabilities of local governments, state government, and the private sector to deal with the potential landslide impacts identified in the hazard analysis.
4) Determination of shortfalls (unmet needs) in local, state, and private capabilities to deal with the landslide hazard. The identification of shortfalls at each level of government allows federal and state agencies to apply technical and financial assistance, when available, toward projects that can best contribute to the reduction of future losses.
5) Formulation of goals and objectives for the Colorado Landslide Hazard Mitigation Plan, based on the assessment of vulnerabilities and capabilities and the development of cost-effective strategies and projects, using known mitigation techniques that best achieve the goals and objectives identified.
6) Establishment of a permanent **state natural hazards mitigation system** to (1) focus the attention of government on landslides and other hazards, (2) prioritize strategies and projects, (3) promote implementation of strategies and projects, and (4) secure and direct funding. This proposed permanent mitigation system would be guided by this and other state hazard mitigation plans.
7) Translation of technical information to users such as decision-makers, community planners, and emergency management officials (usually in the form of maps and explanatory texts).
8) Evaluation and modification of this plan and the planning process, based on regular reviews, identification of new landslide threats, actual landslide disasters, or emergency field exercises of local and state emergency operations plans.

This planning process is consistent with that followed in the development of other state hazard mitigation plans, such as the *Colorado Flood Hazard Mitigation Plan* (Colorado Water Conservation Board, 1985), which recommends strategies and projects for reducing the vulnerability of Colorado communities to flood hazards. As new mitigation plans are developed to address other natural and man-made hazards in the state, this ''family'' of hazard mitigation plans will serve as an ongoing resource for the proposed permanent state natural hazards mitigation organization.

An incentive for having hazard-specific state mitigation plans is the fact that, in presidentially declared disasters, the preparation of a state plan that identifies and evaluates hazard mitigation opportunities is mandated by Section 406 of the Disaster Relief Act (Public Law 93-288) as a condition of receiving federal disaster assistance.

ISSUES CRITICAL TO THE IMPLEMENTATION OF THIS PLAN

In order to implement the range of actions necessary to reduce Colorado's vulnerability to future landslide losses, significant adjustments to current state and local procedures for accomplishing mitigation goals must be made. This plan has identified a significant statewide landslide problem, the consequences of which are high annual public costs with the potential for major economic impacts and possible deaths in the event of a catastrophic landslide disaster. The case studies and other research associated with this plan also provide evidence that, in view of very scarce mitigation resources, state government must be better prepared to identify new landslide hazards, to warn citizens of them, to identify viable mitigation options, and to initiate or assist in mitigative action. The following three efforts are fundamental to the successful implementation of this plan and must be taken in order to yield long-term savings:

1) Establish, implement, and maintain a permanent natural hazards mitigation system in state government to effect landslide hazard mitigation.
2) Assist local governments and the private sector in establishing landslide mitigation and emergency response systems and in maintaining these systems over the long term.
3) Seek state and federal funding where required to implement loss-reduction strategies and projects.

System Development in State Government

The goal of the state landslide mitigation organization is to coordinate the resources of state, local and federal agencies with landslide hazard mitigation responsibilities and authorities. In order to establish and maintain such a system, a number of actions will be required:

1) A preliminary identification of major landslide threats to the state has been included in Chapter 6. As these threats intensify, or as new threats develop, earth movements and potential impacts should be monitored, analyzed, and reported expeditiously to the hazard mitigation organization. Particular attention should be paid to preventing highway loss or damage, formation of life-threatening landslide dams, disruption of the state's environment and opportunities for recreation and tourism, and interruption of utility services.
2) Means must be developed to evaluate and prioritize risks in order to focus mitigation efforts on areas of critical needs and risks.
3) Means must be developed to trigger governmental action on a site- and problem-specific basis, both in terms of public warnings and credible information to stimulate resource allocation where needed.
4) A decision making process dedicated to landslide mitigation must be instituted so that information is gathered and assessed, options are identified and evaluated, decisions are made, and requirements for action are passed to interagency working groups for implementation.
5) The interagency project control system must manage key subsystems including disaster preparedness, emergency response, and implementation of structural and nonstructural mitigation measures. It should also relate to the efforts of existing management systems: geologic (including earthquake), flood plain, and dam safety.

System Development in Local Governments and the Private Sector

Local governments must also institute a range of measures to ensure the safe, orderly development of their own jurisdictions in accordance with local goals and resources. State government assistance cannot effectively support local needs if primary action is not taken at the local level. Local governments assume a number of landslide hazard management responsibilities, including: 1) selecting goals and objectives, 2) controlling land use, 3) providing information and technical assistance, 4) planning, financing, and implementing relatively modest mitigation projects, and 5) operating landslide hazard management projects on a day to day basis.

In order to establish and maintain a viable system for landslide mitigation at the local level, the following issues should be addressed in local government jurisdictions where landsliding is occurring or is likely to occur:

1) A warning and evacuation system to enhance preparedness, provide for emergency public information, and ensure a timely and effective emergency response to landslide events should be written as an annex to the local emergency operations plan (this plan should be exercised regularly).
2) Local jurisdictions should develop a system to identify needs, assess risks, and establish policy for resource prioritization and allocation. Resource inventories should consider not only local public resources but also those available commercially, from other local jurisdictions, from professional associations, from volunteer groups, from the private sector, and from state and federal governments.
3) Regular meetings of local landslide mitigation planning committees should be conducted to prioritize needs, make recommendations, and schedule implementation of available options. These groups should then identify and monitor needs that cannot be met locally. These unmet needs, or shortfalls, provide a "wish list" of projects and resources that can be prioritized and funded locally over time, or reported to the state landslide mitigation organization for possible state action.
4) The private sector should undertake the decision making processes described above in items 1, 2, and 3 so that businesses can assess their own

needs, institute their own mitigation and employee safety programs, identify critical unmet needs, and report these needs to local and state governments. Areas of greatest interest to the private sector are telecommunications, electric power, petroleum, railroads, highways, bridges, infrastructure supporting the recreation industry, and the production and storage of toxic and hazardous substances. Private sector resources, through careful planning and coordination, can be utilized to improve the overall capability of a community to deal with its landslide hazards.

5) In order to protect existing development and discourage or restrict future development in landslide-prone areas, local planning departments and committees must be knowledgeable of, and capable of implementing, the full range of possible mitigation strategies available for reducing landslide hazards in their communities. A comprehensive local hazard mitigation program should be based on community consensus, developed in local planning committees with citizen support and involvement, and conform to local goals and objectives, budget constraints, and politics.

State and Federal Funding for Landslide Mitigation Projects

Although funds for the implementation of most projects recommended in this plan are not currently available, an ongoing and aggressive search for funding sources will be a major role of the state natural hazards mitigation organization. State and federal support should be obtained immediately for those projects that address landslides where potentially catastrophic or serious economic impacts have been identified. At the Dowds Junction landslide complex, a full-scale, constantly monitored warning system needs to be established to ensure adequate warnings to the public and to trigger the state government emergency response system. Further engineering studies are needed to determine the most cost-effective means of averting the possible formation of a landslide dam that could cut off I-70 and the railroad at Dowds Junction. State agencies should continue efforts to design and complete the low-cost projects identified in the Governor's Minturn Earthflows Task Force study of 1986.

Many other landslides in Colorado continue to cause damages, strain public resources, and/or pose the threat of escalating losses. Future landslide occurrences could present new and larger threats and require immediate actions by state, and possibly federal, agencies. In addition to the Dowds Junction landslides, tax dollars are committed annually at East Muddy Creek near Paonia Reservoir, areas of Mesa County, areas of Garfield County, areas of Mesa Verde National Park, and areas of central Eagle County including Vail, Red Cliff, and Beaver Creek. Alternatives to mitigate new and existing threats in these and other areas will be considered by the state natural hazards mitigation organization, as imminent emergency conditions are identified.

PART III

IMPLEMENTATION

This section presents a series of strategies and projects, which should be implemented in order to deal with the landslide hazards impacting Colorado. Most significant is the effort to adjust the organization of state government to better respond to, and mitigate, the landslide problem.

Chapter 9
IMPLEMENTATION OF THE COLORADO LANDSLIDE HAZARD MITIGATION PLAN

Unless a program of long-term landslide hazard mitigation is adopted and implemented, landsliding in Colorado will continue to impose a considerable drain on the available resources of state and local governments. The potential for very large and destructive landslides has been demonstrated in the frequent landslide activity of the past few years. Those landslides preliminarily judged to be most threatening to lives, property, infrastructure, or state/regional economic well-being should be studied and monitored to determine the best ways to limit future losses. Many landslides that currently require extraordinary commitments of emergency highway maintenance funds could eventually require even broader government involvement and much higher expenditures. In most cases, technical studies support the position that money and effort dedicated now to landslide hazard mitigation will prevent much higher costs later.

GENERAL STRATEGIES

Fundamental to a mitigation program is the establishment of a system for landslide mitigation management at the state and local levels. A permanent state system must be established in order to effect mitigation projects which are needed but cannot be accomplished locally. This system must be initiated rapidly, so that:

- existing hazardous conditions are dealt with expeditiously,
- new landslide hazards are assessed and prioritized,
- new options are developed and evaluated,
- interagency technical advice and mitigative action can be coordinated,
- priorities are established for high- and moderate-risk situations,
- decisions are made and funding obtained and spread over a period of time that is commensurate with state fiscal capabilities,
- feedback is evaluated and needed program adjustments made, and
- a systematic approach to mitigation is established.

Local jurisdictions should institute mitigation programs that coordinate landslide hazard information and mitigation needs with state government and the private sector. Local systems should be able to effectively employ state assistance and be ready to take on new problems as solutions to old problems are found. Local mitigation plans should be in place so that work on mitigation projects can begin as soon as funds become available. In addition, detailed plans and cost estimates are frequently required of local applicants for state and federal funding assistance. Many local governments are currently taking steps to reduce landslide vulnerability, but more systematic and coordinated efforts for the long term are urgently needed. Effective local systems are important to state mitigation strategies because they provide direction for state action. Local leadership must choose and develop their own systems and strategies, but a range of recommendations to local governments is offered in the projects that follow in this chapter and in Appendix 3.

STRATEGY IMPLEMENTATION

Implementation of the landslide hazard mitigation strategies recommended for Colorado in this plan can be achieved by three sets of projects:

1) **Critical Action Projects** are those projects that require the immediate attention of state and local governments in order to establish a permanent and coordinated natural hazards mitigation system in Colorado.
2) **Secondary Action Projects** are equally important, but dependant upon the institution of the state mitigation organization established by the preceding group of projects.
3) **Follow-up Projects** are those that will require some further research, analysis, and refinement.

Critical Action Projects

The ''critical action'' projects formally address landslide hazard mitigation in Colorado through the establishment of a State Natural Hazards Mitigation Council with interagency working groups, and the development of local approaches for reducing landslide hazards. These projects have been developed to respond to the ''critical issues'' posed in Chapter 8. These projects also recognize that the state system must first address the more immediate threats presented by landslides with potential for catastrophic losses in lives and property, as well as potentially massive indirect economic impacts. The Governor's Minturn Earthflows Task Force of 1986 proposed several potentially useful approaches, although many require very high capital outlays. Action on many of these possible approaches has not been taken, but the proposed state landslide hazard mitigation organization should encourage further evaluations, firm decisions and funding support.

Secondary Action Projects

The "secondary action" projects are suggested for implementation as soon as a viable interagency state natural hazards mitigation system is in place. These projects deal with actual landslide situations that have not yet reached catastrophic proportions, but will require mitigative actions soon if new and higher losses are to be avoided. These projects also emphasize public education and awareness, the development and exercising of emergency operations plans, land-use policies and procedures, and construction of mitigation works.

Follow-up Projects

Additional suggested projects that do not need immediate attention and that require further refinement constitute the third set of projects.

CREATION OF FUTURE PROJECTS

A continuing analysis of local efforts and important unmet needs must be conducted to deal effectively with residual problems and the future changes that can be expected to occur. This is especially important in a state such as Colorado where the steep terrain and rapidly changing climate can cause local conditions to change overnight. Local jurisdictions should report their accomplishments and important unmet needs to the State Natural Hazards Mitigation Council and new state/local strategies should be developed. A continuing review of Colorado's climatological, geological, and hydrological conditions and available mitigation procedures must be carried on. Finally, in specific cases, the most effective mitigation measures need to be identified, designed, and implemented.

SUGGESTED PROJECTS

More specific recommendations to accomplish the state's landslide hazard mitigation strategies follow in the form of possible projects. Each project includes a brief statement of the problem, a general statement of the recommended solution, a description of short- and long-term initiatives, a designated lead agency, and a preliminary cost estimate, where possible. These projects were developed through a series of discussions with state and local agencies aimed at developing a better hazard mitigation system in Colorado. An effort was made to develop systems that will:

- provide both emergency life saving response and property saving mitigative action,
- distinguish the different responsibilities for assessment and response,
- promote innovative concepts and options involving both structural and nonstructural approaches,
- provide warnings which translate technical data into governmental action, e.g., signs of increasing movement or massive failure should trigger emergency action or timely expenditure of funds,
- be cost effective,
- provide continuing and timely attention to the changing situation,
- encourage timely decision making, and
- be formalized in government rather than adopted ad hoc so that priorities, continuity of action, and visibility over the long term can be achieved.

The projects which follow generally meet the above criteria. If implemented, they should contribute toward an effective and coordinated state/local landslide mitigation system. These projects are not meant to be rigid in content or priority—they can and should be improved upon as the mitigation system develops and new projects should be added as new landslide threats are identified.

CRITICAL ACTION PROJECTS

Project: ESTABLISHMENT OF THE COLORADO NATURAL HAZARDS MITIGATION COUNCIL

Problem: No interagency, interjurisdictional system currently exists within State government to provide a systematic means to mitigate the impacts of natural hazards on Colorado's population. Risks to citizens from Colorado's major hazards are known and annual losses are high. Despite continuous efforts to increase public awareness and governmental capabilities to respond to and recover from hazardous events, loss trends and public vulnerabilities remain high.

Solution: Establish and manage a process for hazard mitigation by development of a council that will encourage effective mitigation through interagency management of hazard specific, cost-beneficial loss reduction projects.

Short-Term Initiative: A mitigation council will be established to manage the various existing strategies and those that will be developed as different hazards impact the state and as needs for mitigation actions arise. The council will integrate and prioritize mitigation needs and strategies to best conform to current and long term conditions. Council composition will include a chairperson appointed by the governor and sufficient members of varying expertise to give the council an interagency, interjurisdictional character. At a minimum, membership will include:

- representatives from the Departments of Natural Resources, Highways, and Public Safety,
- representatives of the Federal Emergency Management Agency (FEMA) and the National Oceanic and Atmospheric Administration (NOAA),
- representatives of the Colorado Municipal League, and Colorado Counties Inc.,

- representatives of the academic and business communities, and
- two elected local officials.

The council will meet approximately once a year. General guidance will be given to a steering committee selected and appointed by the council so that mitigation action will be carried on and coordinated between sessions of the overall council. In general the council will allocate priorities for action to other inter-agency, interjurisdictional working groups that respond to major hazards likely to heavily impact the state. Priorities for action will be allocated on the basis of current or expected losses that can be reduced through mitigation. Local entities will be encouraged to meet their own needs, and state agencies will be encouraged to support high priority needs that cannot be met at the local level.

Long-Term Initiative: The council will provide guidance to local and state agencies as hazardous conditions and mitigation opportunities change or take place. As soon as possible, an executive secretary for the council will be appointed to ensure that regular meetings are called and that overall guidance (as well as steering committee guidance) is forwarded to action agencies. The executive secretary will prepare reports to the governor for the council chairperson. Reports will include progress of projects underway and specific needs that may require executive and legislative support.

Cost: The mitigation council should not require significant funding beyond the allocation of member time and travel expenses.

Lead Agency: Department of Natural Resources.

Project: ESTABLISHMENT OF A STATE AGENCY LANDSLIDE MANAGEMENT SYSTEM

Problem: No interagency system currently exists within state government to provide hazard mitigation in general or landslide loss reduction on a long term basis in particular. There is no systematic interagency provision of timely risk analyses, warnings, option development, or recommendations for mitigation and response action. Although some of these measures are being accomplished at present, the effort is not integrated and coordinated.

Solution: Develop a system of related interagency working groups, managed by state agency personnel, that will stimulate effective mitigative decision-making and resulting project implementation over the long term. This system should provide for state agency control, input of outside expertise, project management, timely warnings to government and the public, and time-phased recommendations for implementation and execution.

Short-Term Initiatives: Establish a mitigation council (all hazards) and the following landslide working groups under council management to provide the planning and action described above:

- Risk/Options Development Working Groups, chaired by an appointee of the Executive Director, Department of Natural Resources.
- Review and Warnings Working Groups, chaired by an appointee of the Governor; appointee to be selected from agencies participating in the mitigation process.
- Implementation Working Groups, chaired by an appointee of the Governor.

The Mitigation Council and the landslide working groups are described in the "projects" which follow; participating agencies are shown in Figure 22. The flow of actions required are shown in Figure 23. This system is established upon receipt of this plan. Working groups will hold organizational meetings one month after receipt of this plan and a preliminary report by each working group covering expected short- and long-term actions will be forwarded in sequence (Risk/Options Development Working Groups to Review and Warnings Working Groups to Implementation Working Groups) to the Governor's office two months after receipt of this plan. Whenever specific warnings or emergency actions are required, working groups will meet as soon as possible. Overall control of the landslide mitigation system will be exercised by the Colorado Mitigation Council. The council will meet periodically to oversee the functioning of all Colorado mitigation systems, including that devoted to landsliding.

Long-Term Initiative: Initially, working groups will meet as frequently as required to stimulate the execution of high priority actions. Later, working groups will meet at least once a year to provide the continuity of action needed to cope with these long-term hazards. Reports will be forwarded to the Colorado Mitigation Council.

Cost: Agencies which have personnel involved with elements of the landslide mitigation system will pay for activities of working group participants including travel. Costs may be considerable during the system's first year but should be minimal thereafter.

Lead Agencies: Lead agencies are prescribed according to statutory roles; working group chairs are appointed as described above.

Project: ESTABLISHMENT OF A RISK/OPTIONS WORKING GROUP

Problem: Currently, no interagency group exists to identify, monitor, and analyze landslide risks to Colorado communities, infrastructure, and facilities across the state; well-defined options to deal with these risks are not systematically developed at the state and local levels.

Solution: Form a working group that will meet on a regular basis (initially on call of the chairperson as needed; later, once a year) to broaden and support the landslide assessment process currently being conducted by the Colorado Geological Survey. Vulnerabilities, risks, potential impacts, local mitigative measures and unmet local needs should also be identified and analyzed systematically. Options for state government to initiate mitigative action should be developed and forwarded through a review group to agencies of government responsible for mitigation action.

Short-Term Initiative: A working group comprised of representatives from pertinent state agencies, as well as some private and academic institutions, should be formed under state leadership to delineate statewide community risks. At a minimum, the following state agencies should be included in this working group: Department of Natural Resources, Colorado Geological Survey, Department of Highways and the Division of Disaster Emergency Services. At the earliest opportunity, the working group should address the list of landslide hazards for community and infrastructure shown in this plan in Table 6.1, further analyze the elements on this list, and develop appropriate mitigation strategies. Potential costs, alternate means of approach, phases for long-term action, and recommended choices should be developed.

Long-Term Initiative: This working group should continue to meet upon the call of the chairperson as needed to stay abreast of changing conditions and to provide a basis for determining appropriate state actions.

Cost: Cost will be borne by participating agencies at an approximate rate of $10,000 the first year and $3,000 for succeeding years; travel costs may be significant.

Lead Agencies: The working group chairperson should be

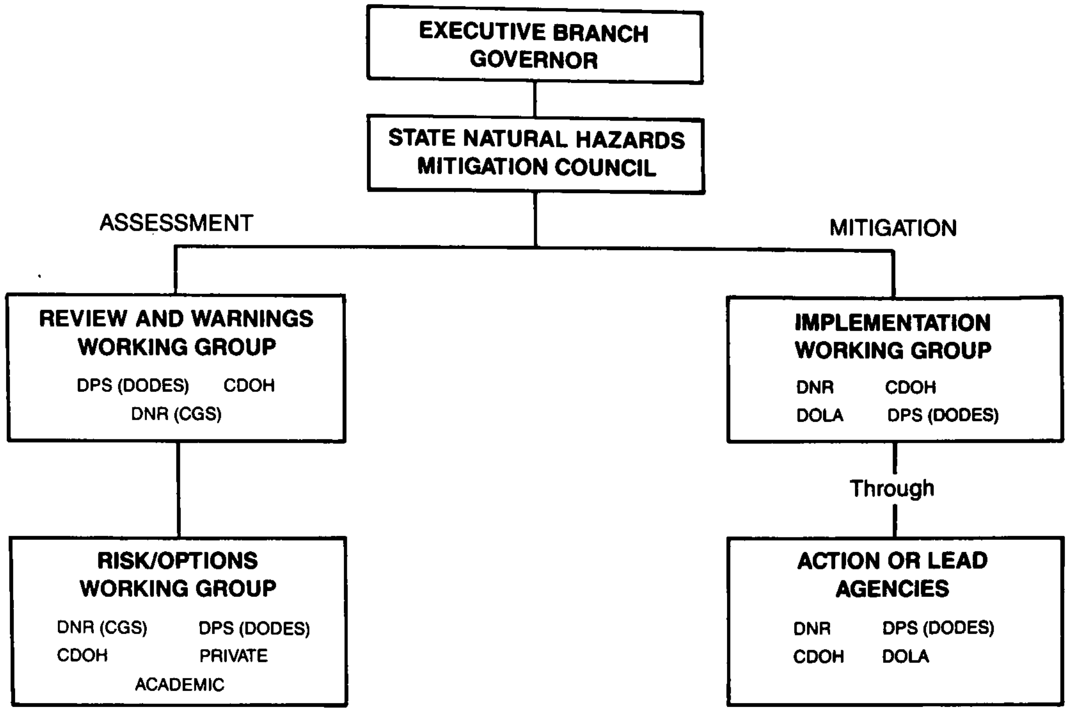

Figure 22. The proposed organization of the Colorado Natural Hazards Mitigation System.

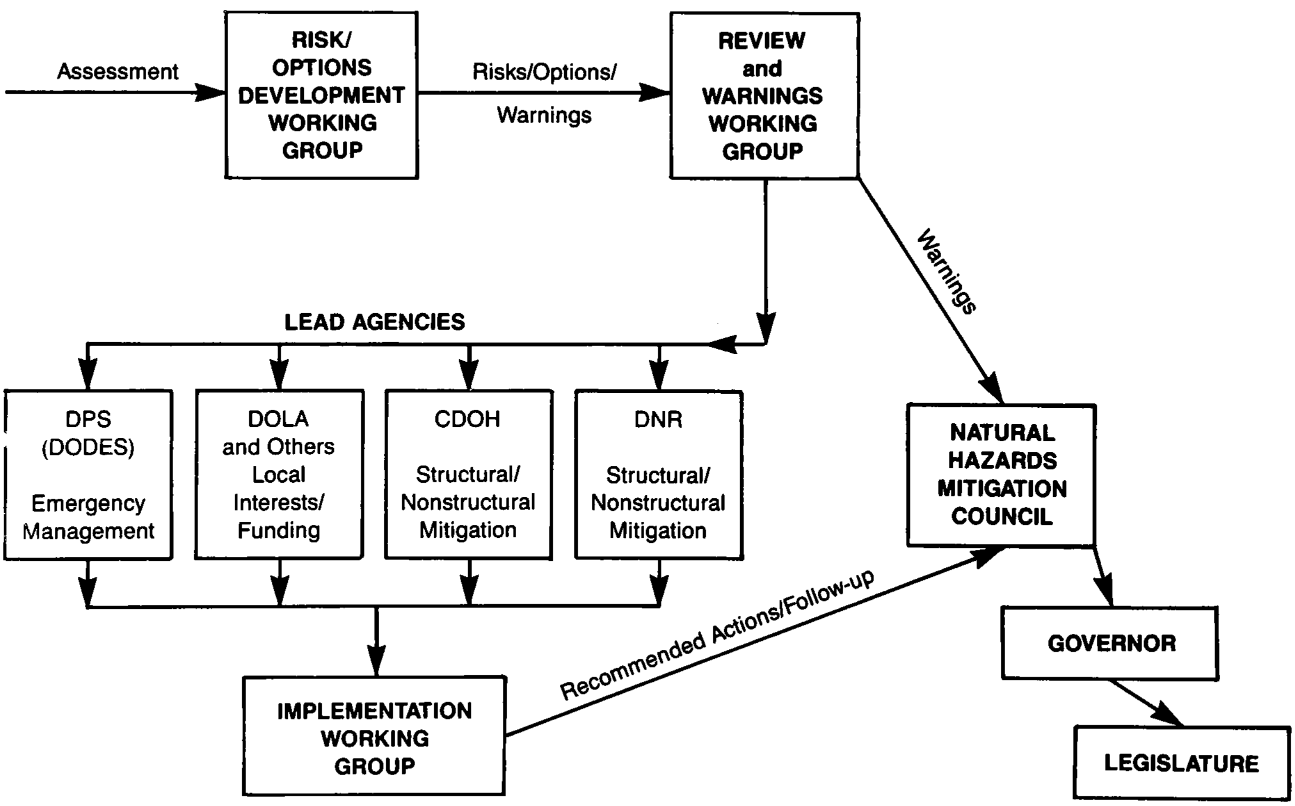

Figure 23. This flow chart represents the general flow of mitigation actions through the Natural Hazards Mitigation System.

appointed by the Executive Director of the Department of Natural Resources; major agencies listed above will supply representatives. The working group will then select other academic and private participants.

Project: ESTABLISHMENT OF A REVIEW AND WARNINGS WORKING GROUP

Problem: Once landslide hazard risks have been identified, there is a need to present to governments and the public warnings that can be easily understood and that permit time for emergency response and mitigative action. Warnings should include probabilistic estimates of time before a catastrophic event is likely and should clearly identify conditions in which lives and property are immediately at stake and mitigative action should be taken. There is also a need to review recommendations presented by the Risk/Options Development Working Group and pass these to responsible agencies of government.

Solution: Establish a working group with review authority over the Risk/Options Development Working Group to review conditions, situations, risks, options, and then make appropriate recommendations and warnings to state government, local governments, and the public. The working group should also review recommendations presented by the Risk/Options Development Working Group and then pass recommended actions to lead state agencies for project decision. This group should be comprised of relatively senior members of CDOH, DNR (CGS), and DPS (DODES).

Short-Term Initiative: The working group should be appointed by departmental/agency executive directors, conduct a short organizational meeting within a month after this plan is received, and then should meet as soon as the Risk/Options Development Working Group has completed analysis of high priority landslide risks and options across the state. Options, priorities, and recommendations should then be forwarded to lead agencies for action.

Long-Term Initiative: This group should meet at least once a year (or more if needed) to review work of the Risk/Options Development Working Group, but if warnings are considered necessary by the Risk/Options Development Working Group, a meeting should be held immediately. Also, a meeting should be held prior to the first meeting of the General Assembly so that timely legislative consideration of lead agency budgets is possible. In its first year of operation, extra meetings should be held as necessary to plan phased projects for major landslide hazards.

Cost: Costs will be borne by participating agencies and should be less than $2000 per agency, per year.

Lead Agency: Participating agencies are Departments of Highways, Natural Resources (CGS), and Public Safety (DODES).

Project: ESTABLISHMENT OF AN IMPLEMENTATION WORKING GROUP

Problem: When landslide risks and options for mitigation are identified, there is a need to decide on the most cost-beneficial projects to be implemented by state or local agencies in order to 1) obtain funding through the regular departmental budgetary process, 2) recommend projects to the Governor for funding when high costs are involved, and 3) implement projects over the long term.

Solution: Establish a working group composed of senior representatives of state agencies involved in landslide mitigation. When lead agencies receive landslide risk analyses, warnings, and option recommendations from the Review and Warnings Working Group, they should identify, develop, and coordinate cost-beneficial projects. They should also provide project management over the long term.

Short-Term Initiative: Lead agencies should develop projects based on their statutory responsibilities and in consideration of available resources. When lead agencies can take immediate or short-term action, they should do so. When lives, property, or critical services are at stake, very high priority should be placed on project initiation and completion. Projects undertaken by lead agencies should be submitted to the Implementation Working Group along with work schedules, costs, and completion dates. When sufficient resources are not available for short-term action, projects should be submitted to the Implementation Working Group for transmittal to the Governor for action or transmittal to the legislature.

Long-Term Initiative: This group should meet whenever warnings indicate the need for short-term action. In any case, the working group should meet at least once a year with one meeting being held prior to the beginning of the General Assembly, so that agencies can include approved options/decisions in annual agency budget requests.

Cost: Costs will be borne by participating agencies; they will amount to approximately $1000 per year for staff work.

Lead Agencies: Participating agencies are Departments of Natural Resources, Local Affairs, Highways, and Public Safety. The working group chairperson will be appointed by the Governor.

Project: DEVELOPMENT OF LOCAL APPROACHES FOR REDUCING LANDSLIDE HAZARDS (Based on Erley and Kockelman, 1981)

Problem: Local planners and decision makers must be aware of the full range of techniques available for reducing landslide hazards in their communities. A combination of the strategies indicated below - one that is tailored to local goals and objectives, conforms to budget constraints, and is politically practical - will best serve landslide hazard mitigation purposes.

Solution: Adopt and institutionalize a comprehensive, multifaceted program of landslide loss reduction that considers all possible strategies and solutions. This program must be based on community consensus, developed in local planning committees with citizen involvement and support.

Short-Term Initiatives:

- Protect existing development in landslide-prone areas through development of emergency warning and evacuation plans, installation of electronic warning systems, and construction of retaining walls, debris basins, drainage features, diversion channels, and other structural engineering solutions.
- Where no other alternative exists to protect lives and property, remove existing development through public acquisition and relocation, application of public nuisance abatement powers, and elimination of nonconforming uses.

Long-Term Initiatives:

- Discourage developers and home buyers from locating structures and buying homes in potentially unstable areas by establishing public information campaigns, issuing public notices, forming special assessment districts, influencing lending policies, requiring real estate disclosure and/or limiting the extension of public utilities and facilities.
- Restrict development in landslide-prone areas through established land-use development regulations, e.g., zoning

unstable areas for open space, agricultural, or recreational uses; limiting development in hillside areas through density regulations; regulating hillside development through subdivision ordinances; and utilizing sanitary regulations to prohibit unsafe development.

Cost: Cost will vary depending on local conditions.

Lead Agency: Local governments.

Project: DEVELOPMENT OF LOCAL EMERGENCY OPERATIONS AND MITIGATION PLANS THAT ADDRESS LANDSLIDE HAZARDS

Problem: In landslide disasters, local government has the responsibility for protecting the lives and welfare of its citizens, protecting public and private property, minimizing overall damages, and managing community recovery efforts. In order to optimize the effectiveness of the (generally limited) available local resources, a well-organized, coordinated, and comprehensive emergency operations plan, understood and accepted by elected officials and response agencies, must be in place to guide government actions before, during, and after serious landslide events.

Solution: A community landslide plan, or annex to the emergency operations plan, must be developed, maintained, and periodically exercised to ensure a coordinated and timely response to landslide disasters. The annex or plan should provide for all possible emergency functions, including warning, evacuation, communications, direction and control, public information, damage assessment, and shelter needs, and should list all resources, public and private, that would be available to respond to and recover from a landslide disaster (including a plan for accessing and returning borrowed assets).

Short-Term Initiatives:

- Based on technical guidance and assistance from CGS and DODES, develop a landslide-specific annex to the comprehensive Emergency Operations Plan that addresses the emergency functions indicated above as well as emergency officials' responsibilities unique to the landslide hazard.
- Encourage broad input from the community in plan development through planning committee and special meetings; coordinate plan with all agencies/individuals with responsibilities under the plan.
- Conduct a table-top exercise of the annex or plan and make further revisions and refinements.

Long-Term Initiatives:

- Gain acceptance of the plan, by promulgation, from elected officials (city and county where necessary) and from all interested citizens.
- Continue coordination with CGS and DODES so that new and changing landslide threats can be addressed; provide for regular update of the plans.
- Conduct full-scale exercises of the landslide annex, and coordinate and provide for training needs identified in exercises.

Cost: Costs for developing, coordinating, and exercising of plans are not high and are assumed by the Colorado Disaster Act of 1973.

Lead Agencies: Local: County emergency management agency.
State: Division of Disaster Emergency Services.

Project: ORGANIZATION OF LOCAL LANDSLIDE PLANNING COMMITTEES

Problem: Local jurisdictions with landslide problems must be organized so that there exists general agreement on:

- the extent of the problem, possible solutions, and remaining needs,
- the goals and objectives of a community landslide mitigation program, and
- the areas and services potentially at greatest risk and therefore in need of immediate attention. A local consensus regarding priority issues is also needed so that state and/or federal assistance (pre- or post-disaster), when available, can be directed where it is most needed and can thus yield maximum local benefits.

Solution: Local landslide planning teams, or committees, should be established and should hold regular meetings in order to review landslide problems, identify all possible solutions, prioritize alternative mitigation strategies, identify sources of funding and assistance, schedule implementation of recommended options, and expose those needs that are beyond local resource capabilities. These committees should be dedicated to a program of long-term hazard reduction, as well as to improving existing emergency management capability. In many jurisdictions, existing emergency planning committees can be expanded to address landslide mitigation concerns. In all cases, representation should include, at a minimum, elected officials, emergency managers and response personnel, planners, engineering and public works personnel, building inspectors, private sector representatives, and interested citizens.

Short-Term Initiatives:

- County emergency management directors should recommend committees; county commissioners should appoint members and chairs.
- Committees should initially review the landslide plan, including mitigation elements and resource listings.
- To solicit citizen involvement, committees should prepare a public information landslide package that provides general information on committee activities and landslide risks.

Long-Term Initiatives:

- County commissioners should adopt a resolution establishing the committee, citing goals and objectives, supporting the concept of mitigation, outlining duties, and mandating regular meetings.
- A reporting system should be established to advise the state mitigation system of local recommendations.

Cost: Costs should be reasonable if initiatives are coordinated with other activities of local government.

Lead Agencies: County Commissioners and County emergency management agency.

Project: PRIVATE SECTOR INVOLVEMENT IN LANDSLIDE MITIGATION

Problem: In landslide disasters, losses to private property frequently exceed public property losses, yet responsibility for planning, response, recovery, and mitigation is generally perceived to be solely a function of government. There are resources in the private sector that, through careful planning and coordination, can be utilized to improve the overall capability of a community to deal with landslide hazards.

Solution: Representatives of private industry, affected property owners, volunteer agencies, and community groups should be routinely included in emergency management discussions, planning team meetings, plan development, resource identification efforts, etc. Businesses potentially vulnerable to landslides should also be encouraged to develop their own internal emergency plans and procedures, conduct emergency response exercises, and sponsor landslide awareness campaigns for employees. Assistance from professional organizations should also be solicited.

Short-Term Initiatives:

- Initiate formal correspondence with all private and community organizations that could potentially contribute to the local mitigation program.
- Invite organizations that are contacted to emergency management meetings, emergency training classes, and emergency response exercises.
- Address meetings of the above groups to promote awareness and public relations.
- Include representatives of the above groups on the local landslide planning committee or form an advisory council as a separate subcommittee.

Long-Term Initiatives:

- Establish a system for routinely updating Emergency Operations Plan "Resource" listings with respect to private resources, in order to establish prearranged agreements on the use of private sector resources in emergency situations; such agreements should cover cost, liability, plans for return of borrowed assets, etc.
- Promote private industry emergency plans, emergency response exercises, and employee awareness campaigns.

Cost: Costs should be reasonable, in view of potential savings.

Lead Agency: County emergency management agency.

Project: ASSESSMENT OF LOCAL RESOURCES AND NEEDS

Problem: Population growth, the pressures of new development, climatic conditions (wet/dry cycles), and actual landslide occurrences all change (and generally expand) a community's vulnerability to the landslide hazard. The resource and management capabilities of local governments are also undergoing changes, though not necessarily in proportion to the changing threat. Local government must understand, in advance of a landslide disaster, the levels at which supplemental emergency assistance will be necessary, and where and how such assistance can be obtained.

Solution: A detailed hazard analysis is an integral component of any local landslide plan, or annex. Since the hazard analysis guides the overall emergency planning process, it must be continually updated to expose new shortfalls and resource needs. Local landslide plans should outline procedures for obtaining supplemental assistance from neighboring jurisdictions (mutual aid agreements, memoranda of understanding) and from state and federal governments. To the extent possible, these annexes should also indicate existing resources and capabilities, and those needs that are beyond the capabilities of local government (unmet needs). Procedures for routine reporting of unmet needs to the state mitigation system should be established.

Short-Term Initiatives:

- Develop, as part of the local landslide plan, a mitigation plan that assesses existing resources and lists those needs that are unmet locally. Unmet needs provide a "wish list" of projects and resources that can be reviewed and prioritized by local planning teams and either funded locally over time or presented to the state mitigation system for consideration by state agencies.
- Identify not only local public resources, but also those available commercially, from other local jurisdictions, from volunteer groups, and from state and federal government.

Long-Term Initiative: Establish procedures for reporting resource needs and shortfalls to the state mitigation system for action by state or state/local agencies (and, in some cases, federal agencies).

Cost: Costs should be reasonable and will be dependent on local conditions.

Lead Agencies: Local: County emergency management agency; Planning/Mitigation Committee.
State: Division of Disaster Emergency Services; State mitigation system.

Project: MONITORING OF EXISTING LANDSLIDES

Problem: There are many metastable landslides, debris flows, and rockfall areas in Colorado that pose a threat to people, communities, and facilities. Continuous monitoring of these areas could prevent disasters and loss of life by providing an early warning of imminent failure.

Solution: The CGS now has most of the necessary equipment to establish and survey fixed monuments on potentially moving areas. The number of monuments and the total number of landslides monitored is restricted by lack of funding. If additional funding were obtained, additional critical landslide areas could be monitored, and the frequency of monitoring increased during critical months of the year.

Short-Term Initiative: Monitor a few potentially serious landslide areas.

Long-Term Initiative: Monitor additional areas and increase the frequency of monitoring of all areas during critical months.

Cost: Capital sufficient to purchase steel-post monuments and pay for travel and staff time involved in installing and surveying monuments.

Lead Agency: Colorado Geological Survey.

Project: MAPPING OF STATE LANDSLIDE AREAS

Problem: Although preliminary landslide maps of Colorado were prepared by the USGS, they are at a scale of 1:250,000. This scale is not sufficiently detailed for land-use planning. Maps prepared on the scale of 1:50,000 (county map series) or 1:24,000 (7.5 min quad.) would be much better suited to land-use planning and hazard assessment.

Solution: The Department of Natural Resources should pursue funding for a program of detailed mapping of landslide, debris flow, and rockfall areas statewide on a priority (need) basis.

Short-Term Initiative: Acquire funding to contract for new aerial photography of *selected* critical areas in the state. With the aid of the photos and field checking, maps should be prepared.

Long-Term Initiative: Acquire recent aerial photography for all critical areas of the state in order to produce suitable landslide maps.

Cost: Approximately $75,000, per year.

Lead Agency: Colorado Geological Survey.

Project: IDENTIFICATION OF LANDSLIDE HAZARDS THROUGH MAPS AND SITE INVESTIGATIONS

Problem: The starting point for emergency management and mitigation planning is the development of maps that identify areas where landslides are likely to occur. Landslide maps are needed by local officials in order to develop emergency operations plans, establish policies for regulating development in hazardous areas, and implement a program of long-term landslide mitigation. Landslide-susceptibility maps also identify the need for additional investigation of site stability.

Solution: The offices of the U.S. Geological Survey and the Colorado Geological Survey in Denver can provide information about maps of a given area. Many areas of Colorado have been mapped for landslide activity.

Short-Term Initiative: To the extent possible, all landslide-prone jurisdictions should establish and maintain a complete set of topographic and geologic maps to assist planners and developers in determining the need for additional soil or geologic investigations for any site proposed for development.

Long-Term Initiatives:

- By local ordinance, when maps indicate a proposed site could be unstable, developers should be required to provide specific information on slope stability and proposed construction practices. (Note: The grading section of the Uniform Building Code provides a good model for development of local standards and regulations.)
- Development in identified landslide areas should be permitted only after completion of detailed site investigations of soils and geology that determine proper grading, excavating and filling during construction and landscaping and drainage procedures after construction.

Cost: Costs should be reasonable.

Lead Agencies: Local planning agencies and committees.
Local engineering departments.
Building inspectors.

SECONDARY ACTION PROJECTS

Project: REGIONAL PRESENTATIONS OF LAND-SLIDE HAZARD INFORMATION TO LOCAL/STATE LEADERSHIP

Problem: An adequate response to Colorado's landslide hazard depends on raising public awareness and obtaining resources. Political support must be developed before required resources can be obtained.

Solution: Develop a landslide hazard presentation and briefing team. Present regional briefings to local leaders—state legislators, county commissioners, community officials. Present a briefing to key legislators including the Joint Budget Committee and staff. Present briefings to annual meetings of Colorado Municipal League, Inc., city/county attorneys, and other relevant associations.

Short-Term Initiatives:

- Presentations will be arranged and managed by the Risk/Options Development Working Group.
- Identify key leadership groups to receive presentations.
- Identify logical geographical regions to be covered by each briefing.
- Develop presentation materials (e.g., state plan, issue briefs, slides, posters, etc.).
- Develop work plan/logistical arrangements for presentations.

Long-Term Initiative: Implement regional presentations (send invitations, reserve meeting sites, make presentations on a regional basis).

Cost: $20,000 per year.

Lead Agency: Department of Natural Resources with support from Division of Disaster Emergency Services and Department of Local Affairs.

Project: CREATION OF A "COLORADO STATE LANDSLIDE INFORMATION CENTER"

Problem: Colorado has many stable, metastable, and active landslides, as well as rockfall and debris-flow areas. Some of these areas have long histories of damaging events. The creation of a computerized data base would allow the systematic accumulation of information on all landslide areas in the state and would aid in predicting future movement and recurrence intervals.

Solution: The CGS now has various software packages and the computer technology to create and maintain such a data base. Funding for staff time to accumulate and input the data is needed.

Short-Term Initiative: Create a data base from the already existing data on major active landslide, debris-flow, and rockfall areas.

Long-Term Initiative: Gather historical data on metastable areas for input into the system.

Cost: Not estimated.

Lead Agency: Colorado Geological Survey.

Project: REGULATION OF DEVELOPMENT IN HAZARDOUS AREAS

Problem: Regulations governing grading and development have not been adopted by many localities. Such regulations have great potential to decrease losses from landsliding.

Solution: Require every county and city to adopt grading, building, subdivision, or other development ordinances regulating development in potential landslide areas.

Short-Term Initiatives:

- Have communities investigate what ordinances would be most effective in regulating development in their particular jurisdiction.
- Identify agencies responsible for reviewing development plans and enforcing ordinances.

Long-Term Initiatives:

- Have identified ordinances adopted by local government.
- Increase local awareness of hazardous building sites within a community to discourage development in those areas.

Cost: $100,000.

Lead Agencies: Local planning commissions, state legislature.

Project: DOCUMENTATION OF SERIOUS GEOLOGIC HAZARD INCIDENTS AND ANNUAL DAMAGE

Problem: Landslides, rockfalls, and debris flows occur throughout the mountain and canyon areas of the state. These events can cause a significant financial impact on individuals, companies, municipalities, and state and federal governments. The total yearly impact for Colorado has never been assessed. Such statistics are needed to estimate the amount of funding that may be needed to maintain, repair, or replace roads and/or facilities; to apply for government disaster aid; and to calculate cost-benefit ratios to determine if proposed mitigation measures are justified.

Solution: The Department of Natural Resources should continue to pursue funding to prepare a summary of incidents and damage costs for Colorado. The summary would list occurrence, location, type of event, cause of event, facilities damaged, and cost of damage and/or repair and replacement. Maps and pictures would also be included.

Short-Term Initiative: Prepare a summary for the years 1984-1987 (the most recent period of above average precipitation and above average damages).

Long-Term Initiative: Prepare yearly summaries.

Cost: Estimated cost for the 1984-1987 summary would be about $15,000 at 1987 costs. Yearly updates could be prepared for about $3,000 for staff time plus $6,000 for small contractual services, arrangements for aerial photography, special instrument rental, etc.

Lead Agency: Colorado Geological Survey in cooperation with Colorado Water Conservation Board, Division of Disaster Emergency Services, and Department of Highways.

Project: EVALUATION OF THE MAGNITUDE OF POTENTIAL LANDSLIDE CATASTROPHES

Problem: There are numerous very large old landslides in Colorado potentially capable of reactivating and blocking valleys or causing other extensive damage. Major past movements of these landslides occurred from tens of years to thousands of years ago. Several of these observed by CGS staff show some evidence of current movement.

Solution: Certain critical old landslides in Colorado need to be studied in detail with follow-up monitoring if the findings warrant it.

Short-Term Initiative: In 1986, the CGS conducted a reconnaissance field and photogeologic check of several large landslides that are currently on a priority list of the Colorado Geological Survey. Several of those landslides found to have the highest potential for significant future movement should be studied in greater detail. Techniques used in advanced studies might include: detailed field mapping, detailed photogeologic mapping, special stereoscopic aerial photography to establish baseline data for future reference, establishment of EDM stations to monitor possible future movements, and, in some special cases, acoustic or satellite monitoring.

Long-Term Initiative: Site-specific or generic worst-case scenarios should be prepared to aid FEMA, DODES, and local governments in response planning and possible preventive mitigation.

Cost: Approximately $55,000 per year for two years, with a carry-on surveillance cost of $20,000 per year for 0.25 FTE and instrumental monitoring costs.

Lead Agency: Colorado Geological Survey.

Project: INVESTIGATION OF VULNERABILITY TO LOSS OF LIFE IN HAZARDOUS CANYONS IN COLORADO

Problem: Increased use of the mountain area canyons of Colorado, both for residential development and recreation, has placed people and human activities in direct conflict with several kinds of active, potentially hazardous geologic processes. The most serious of these processes are those associated with major mountain-torrent floods. A very preliminary evaluation of Colorado canyons susceptible to mountain-torrent floods and related processes indicates that at least 30 such canyons are found along and/or in the Front Range, the most populous area of the state. Many more such canyons exist in the central part of Colorado and in the Western Slope area.

Informal cooperative efforts by both state and federal participants have shown that certain innovative geological studies could greatly improve conventional hydrologic approaches to the evaluation of catastrophic flood risk in canyon areas. Past efforts to obtain USGS funding for a full-scale, cooperative, prototype study have failed because of severe constraints in federal funding.

Solution: The Department of Natural Resources should continue to pursue funding for this project from any potential source.

Short-Term Initiatives:

- Prepare detailed geomorphic and surficial-geologic maps of selected Front Range stream reaches that have the best preserved or most significant evidence of past catastrophic floods.
- Measure and describe particle size, composition, and geomorphic character of selected flood-deposit sequences.
- Determine by geophysical or other appropriate means the available sediment supply in selected watersheds.
- Determine radiocarbon(C^{14}) dates for approximately 50 additional flood-related deposits.

Long-Term Initiative: Publish a series of reports available to the general public on the hazards of mountainous canyons.

Cost: $80,000 per year for 3 years.

Lead Agency: Colorado Geological Survey in cooperation with Colorado Water Conservation Board.

Project: PREPARATION OF A TECHNICAL MANUAL FOR THE STANDARD IDENTIFICATION OF MUDFLOW AND DEBRIS-FLOW HAZARD AREAS

Problem: The CGS and CWCB have enough experience with, and knowledge of, mudflow and debris-flow phenomena to identify vulnerable areas and evaluate hazard potential through more detailed studies. However, while the necessary expertise and legal authority exist, there is no available staff time or funding for preparing the needed site-specific documents.

Solution: Prepare a technical manual to explain and describe the geological process(es), provide detailed information on hazard identification and zonation methodologies, and establish minimum criteria for mudflow and debris-flow hazard studies. Such a document is essential to a statewide approach to emergency response and management of the mudflow and debris-flow hazard. The proposed manual would provide DODES, other state agencies, FEMA, local governments, and private sector professionals with an essential document.

Short-Term Initiative: With adequate funding a staff person could be placed full-time on the project and complete it in one year.

Long-Term Initiative: The manual should be published and distributed to local government and practicing professionals. Strategies for application of the information in geologic hazard mapping and management should be devised and carried out by the state. Full participation of local governments will be essential to program effectiveness.

Cost: Approximately $65,000 at 1987 cost levels.

Lead Agency: Colorado Geological Survey in cooperation with the Colorado Water Conservation Board and Colorado Department of Highways.

Project: ESTABLISHMENT OF EARLY-WARNING SATELLITE-TELEMETRY LANDSLIDE MONITORING SYSTEM

Problem: The Colorado Department of Natural Resources currently has a satellite-telemetry data collection system in place for continuously monitoring critical stream flows and reservoir levels throughout the state. Remote stations continuously transmit real-time data via satellite to computer controlled data processing facilities in Denver. Similar collection and transmission of data from landslide areas is needed.

Solution: Use system described above to monitor large active potentially threatening landslides around the state. Instrumented movement monitoring stations could be established at the landslides to provide data on cumulative movement and rate of creep. This would allow real-time monitoring and data collection on a continuous basis from offices in Denver, and would provide the earliest possible warnings of imminent failure.

Short-Term Initiative: Install monitoring stations on several known large active landslides (Dowds Junction complex, Slumgullion, Muddy Creek). Begin developing data base on seasonal behavior of these landslides in order to develop baseline comparison data with which to gauge future movement rates and processes.

Long-Term Initiative: Install stations at other critical landslide areas.

Cost: $40,000 for three stations (includes instrumentation, installation, and hook-up costs).

Lead Agency: Division of Water Resources with support from Colorado Geological Survey.

Project: PROVISION OF ASSISTANCE TO CITY OF VAIL

Problem: Although the entire incorporated area of Vail has been mapped for hazard zones, which include debris-flow areas, large scale systematic mitigation action has not yet taken place. The lives and homes of residents in debris-flow zones are at risk. Landslides have also impacted development in the Beaver Creek area over the past few years. Thus, a range of high-cost landslide hazards exists in the area, and the state should provide assistance before further large-scale losses occur.

Solution: Landslide and debris-flow problems can be significantly reduced if acceptable legal, administrative, and funding arrangements are made prior to further landsliding.

Short-Term Initiative: Although responsibility for this problem rests with the City of Vail, the state can offer considerable assistance by reviewing various means of mitigation now being considered by the city. Visits by state preparedness planning officials and technical experts should be made as soon as possible to discuss further action by the county and its municipalities as well as state assistance.

Long-Term Initiative: Since further high hazard debris flows are inevitable for central Eagle County, a continuous effort over the long term by the state will be necessary to enhance Vail's image as a well-prepared, safe tourist community. State officials should meet with county and city officials as needed to promote and encourage mitigation programs.

Cost: Visits by a select group of state officials to review local mitigation in progress will cost approximately $1000.

Lead Agency: Department of Natural Resources with support from Division of Disaster Emergency Services.

Project: GEOLOGICAL INVESTIGATION AND MONITORING OF THE GRAND MESA LANDSLIDES

Problem: Several major landslides exist along U.S. Highway 65 across Grand Mesa. These landslides move seasonally and necessitate significant annual highway maintenance. Any of the landslides could move catastrophically, closing U.S. Highway 65 for an extended period of time.

Solution: Perform investigations and develop design solutions for each area. Establish a monitoring program and develop contingency plans for closure. Establish criteria for determining when preventive measures would be appropriate.

Short-Term Initiative: Prepare an inventory and perform investigations. Install monitoring systems. Prepare plans and designs.

Long-Term Initiative: Continue to monitor and review plans periodically.

Cost: $100,000 initially; $5,000 annually.

Lead Agency: Colorado Department of Highways.

Project: REVIEW OF MAJOR LANDSLIDE 2 MILES EAST OF SOMERSET ON U.S. HIGHWAY 133

Problem: Recent highway construction has resulted in various slope stability problems that have been complicated by several years of increased precipitation. One major area has recently shown evidence (heaves and cracks in the new pavement) that it may fail. This landslide could block U.S. 133 entirely and could affect a nearby river channel as well.

Solution: Perform geologic investigations and prepare designs for remedial action. Establish a monitoring system and contingency plans for catastrophic movements. Establish criteria for taking preventive action.

Short-Term Initiative: Perform investigations and prepare designs. Establish a monitoring system. Prepare contingency plans.

Long-Term Initiative: Continue monitoring and keep plans current.

Cost: $65,000 first year; $5,000 subsequent years.

Lead Agency: Colorado Department of Highways.

Project: DEVELOPMENT OF COMPREHENSIVE COST ACCOUNTING FOR GEOLOGIC HAZARD-RELATED EXPENDITURES FOR PUBLIC ROADS IN COLORADO

Problem: Geologic hazards, such as landslides, debris flows, rockfalls, collapsible soils, etc., contribute significantly to the cost of maintaining public highways and other facilities. Also costly are corrective measures that fail or that stabilize but do not remedy a problem.

Solution: Establish a cost recognition system that will allow engineers and administrators to better identify the total annual costs attributable to geologic hazards. This system would be an important tool in planning annual maintenance and construction budgets and in prioritizing work efforts.

Short-Term Initiative: Establish a working group of state and county professionals to develop a cost identification system for accurately isolating costs related to geologic hazards. Develop methods to measure savings that result from more efficient allocations of resources in maintenance of facilities.

Long-Term Initiative: Continue to monitor costs and upgrade the cost accounting system.

Cost: $75,000 for working group effort; $50,000 annually to monitor and update the system and to share utilization techniques with participating agencies.

Lead Agencies: Colorado Department of Highways and Colorado Geological Survey.

Project: TRANSFER OF GEOLOGIC HAZARD TECHNOLOGY

Problem: Geologic hazards cost Colorado taxpayers a substantial sum of money each year. Many hazards continue to exist even after remedial measures have been attempted, compounding the economic drain. Many unsafe conditions are perpetuated through lack of appropriate expertise at the local level.

Solution: Prepare a manual of practice for recognition and remedy of geologic hazards. Establish a training and assistance team to work with private and governmental agencies in ongoing technology transfer and assistance with special problems. This would require 2 FTE positions and overhead support funds.

Short-Term Initiative: Establish a Geologic Hazards Working Group consisting of governmental and private practitioners. Prepare a manual of practice for geologic hazard mitigation. Develop a two-person team, either by rotating existing employees or by creating two new positions, to train and support state, county, and local officials and perhaps some private individuals.

Long-Term Initiative: Continue to update the manual of practice and continue to transfer this information to a variety of users. Through rotation of professionals on the team, additional training benefits would accrue.

Cost: $50,000 for the manual of practice. $100,000 annually to fund the two-person geologic hazards team.

Lead Agencies: Colorado Department of Highways, Colorado Geological Survey.

Project: CREATION OF LANDSLIDE EDUCATIONAL SIGNAGE PROJECT

Problem: Responding to landsliding requires a base of political support and thus a knowledgeable public. Citizens need to be made aware of landslides. One excellent method of education is to point out actual landslides and their impacts to the public.

Solution: Designate selected areas and post signs describing landsliding.

Short-Term Initiatives:

- Identify good examples of various types of landslides occurring along major Colorado highways.
- Assess the potential of sites to become "informative turnout," "rest stop," etc.
- Develop educational signs for installation.
- Incorporate the construction of turnouts, posting of signs, etc., into state highway improvements budget.
- Install signs. Construct pull-offs.

Long-Term Initiative: Maintain the educational project. Modify and improve it as necessary.

Cost: $100,000.

Lead Agency: Department of Natural Resources with support from Colorado Department of Highways.

FOLLOW-UP ACTION PROJECTS

Project: REVIEW OF RESERVOIR SITES FOR LANDSLIDE HAZARDS

Problem: Reservoirs potentially impacted by landsliding present a potential hazard of flash flooding downstream due to overtopping or dam failure. Reservoir sites should be free of significant geologic hazards.

Solution: Review all existing and proposed reservoir sites for geologic hazard implications.

Short-Term Initiatives:

- For new reservoir sites, require proper structural design to reduce risk of failure due to landsliding.
- Require specific review of reservoir site plans for landsliding threats.

Long-Term Initiative: Investigate existing reservoir sites to identify areas particularly hazardous to the public. Request federal assistance in reviewing sites of federal dams.

Cost: $50,000 — State Engineer staff 0.5 FTE, Colorado Geological Survey staff 0.5 FTE.

Lead Agency: Colorado State Engineer.

Project: MAPPING AND REGULATION OF LANDSLIDE AND DEBRIS-FLOW AREAS

Problem: Landslides and debris flows constitute a significant hazard which may be addressed under authority of the National Flood Insurance Program (NFIP).

Solution: Encourage NFIP mapping of debris-flow and mudflow areas and local adoption of and regulation under floodplain management ordinances.

Short-Term Initiatives:

- Identify areas of landslide hazards where landslides and debris-flow and mudflows are potential local problems.
- Investigate techniques that can be adopted under the floodplain management ordinance.
- Lobby FEMA, congressional delegation for appropriate amendments to National Flood Insurance Program; request assistance where mudflows meet National Flood Insurance Program criteria.

Long-Term Initiative: Determine whether landslides and debris flows can be addressed under the NFIP.

Cost: $25,000 (1/4-time geologist).

Lead Agency: Colorado Geological Survey with support from Colorado Water Conservation Board.

Project: HAZARD ASSESSMENT AND MITIGATION FOR COLORADO STATE RESERVOIRS POTENTIALLY VULNERABLE TO LANDSLIDING

Problem: State-owned or operated reservoirs have not been evaluated for susceptibility to landsliding. Corrective measures have not been taken for vulnerable reservoirs.

Solution: Stabilize landslide hazard areas potentially impacting state-owned reservoirs.

Short-Term Initiatives:

- Identify state-owned or operated reservoirs potentially impacted by landsliding.
- Evaluate potential vulnerability of these reservoirs to landsliding.
- Evaluate potential downstream impacts for reservoirs vulnerable to landsliding.
- Prioritize vulnerable reservoirs for mitigation initiatives.
- Identify alternative potential mitigation strategies for each priority reservoir.
- Identify preferred alternative.
- Implement preferred alternative.

Long-Term Initiative: Promulgate and implement regulations pertaining to new reservoirs minimizing vulnerability to landsliding.

Cost: $100,000.

Lead Agency: Colorado State Engineer. Critical support provided by Colorado Geological Survey and Colorado Water Conservation Board.

Project: ASSISTANCE TO RED CLIFF MITIGATION PROJECT

Problem: In the Red Cliff area, 12-14 private residences are directly in the path of two potentially catastrophic debris flow source areas. To date, repeated but minor debris flow/debris avalanche activity has been experienced.

Solution: Structural mitigation has been implemented and emergency life saving and evacuation plans have been developed by the town and Eagle County. Plans should be regularly updated and periodically exercised and training should be provided for emergency officials to ensure timely, coordinated response in the event of future debris flows.

Short-Term Initiatives:

- Continue monitoring, instrumentation, and technical surveillance of debris flow/debris avalanche zones (CGS).
- Continue operation and maintenance of early warning device and expand as necessary.
- Continue public education for residents with respect to warning and evacuation procedures, home safety measures, etc.
- Continue maintenance and, if necessary, expand existing concrete retaining structures and other structural protective measures.

Long-Term Initiative: If future activity increases the threat to homes below suspect area, further protective actions should be immediately implemented, as warranted.

Cost: Not estimated.

Lead Agencies: Eagle County, Town of Red Cliff, Colorado Geological Survey, Division of Disaster Emergency Services, Department of Local Affairs.

Project: ASSISTANCE TO GLENWOOD SPRINGS DEBRIS-FLOW MITIGATION AND EMERGENCY MANAGEMENT PROGRAM

Problem: Debris flows are a part of the history of Glenwood Springs; most of the city is developed on the debris fans of numerous basins capable of producing major debris flows (18 debris flows have occurred this century). Losses due to the 1977 debris flow disaster fell between $500,000 and $1 million. Because most of the debris fans in and around Glenwood Springs are already highly urbanized, a strong, reliable emergency management capability, together with a program of structural and nonstructural mitigation, will be necessary to protect lives and property and reduce losses in future debris flow occurrences.

Solution: Develop an emergency operations plan to protect lives and property from debris flows, periodically exercise the plan, and regularly train emergency management officials with responsibilities under the plan. Equally important is the adoption by city and county officials of a program of long-term hazard mitigation which addresses structural (engineering) protection, land-use planning, floodproofing, emergency management, and formation of an emergency planning team which prioritizes needs, makes recommendations, and schedules implementation of available alternatives.

Short-Term Initiatives:

- Extend and formalize activities of the local debris-flow committee.
- Complete development of county debris-flow annex to Local Emergency Operations Plan and provide for training and exercising of plan elements.
- Promote public education and awareness about debris-flow mitigation including home safety measures, floodproofing, instructions for reinforcing uphill walls, etc.
- Continue blue line restrictions and explore feasibility (and desirability) of purchasing additional easements and rights of way.

Long-Term Initiatives:

- Continue strict enforcement of city geologic hazards ordinance; explore feasibility of adoption by county of a similar ordinance to govern development in unincorporated areas of county with landslide and debris-flow problems.
- Continue strict enforcement of those land-use regulations that restrict development in hazardous areas (building and grading codes, nonconforming uses, development reviews, zoning).
- Provide for construction of recommended structural protective measures (retaining walls, debris basins, stormwater drainage improvements) in multi-year budget program (capital improvements).
- Pursue funds from established grant programs for mitigation projects (Community Development Block Grant and Energy Impact funds - Department of Local Affairs).
- Pursue formation of a ''debris-flow district'' in order to establish a mitigation fund to pay for construction of recommended projects on a continuing basis.
- Explore state assistance for a major project to plant closely spaced trees and other vegetation (recommended by Colorado State Forester) in critical areas.

Cost: Costs should be reasonable in view of current progress.

Lead Agencies: Garfield County, City of Glenwood Springs, Colorado Geological Survey, Division of Disaster Emergency Services, Soil Conservation Service, State Forester, Department of Local Affairs.

Project: MITIGATION OF MESA VERDE ACCESS ROAD LANDSLIDE

Problem: Large-scale landslides continue to force frequent closings of Mesa Verde National Park, a major tourist attraction.

Solution: Major mitigation along the access road should be undertaken to keep the park open; environmental issues should be fully considered when making plans. The National Park Service should develop a landslide mitigation plan and take remedial action.

Short-Term Initiative: The Department of Natural Resources (Parks and Recreation Division) should write a letter for the Governor's signature to the National Park Service to request planning and action as described above.

Long-Term Initiative: A continuous check should be made on progress towards landslide mitigation instituted by the National Park Service; additional requests for action should be submitted if satisfactory progress does not occur.

Cost: $5000.

Lead Agency: Department of Natural Resources.

Project: MITIGATION OF LANDSLIDES IN LAMPLITE PARK SUBDIVISION, GRAND JUNCTION

Problem: Eleven homes in the Lamplite Park Subdivision of Grand Junction are situated at the top of a river bluff on an old rotational landslide. Several of the homes exhibited structural damage beginning in 1985.

Solution: Relocate or remove homes and stabilize river bluff and remaining landslide areas. Determine, through geologic evaluation, the level of risk for the residences across, or south of, Santa Clara Avenue, and for city services in the area (streets, utilities). (Note: Short-term initiatives indicated below are complete or in progress.)

Short-Term Initiatives:

- Complete all necessary geotechnical studies and assessments to determine the level of remaining mitigation requirements, including the need for and magnitude of further slope stabilization efforts (terracing, drainage).
- City building official should evaluate risk of continued occupancy and exercise authority accordingly.
- Develop landslide emergency plan as annex to Mesa County Emergency Operations Plan.

Long-Term Initiatives:

- Remove and relocate eleven homes on north side of Santa Clara Avenue; stabilize slope and rezone area for use as greenbelt/open space.
- Determine level of threat to remaining development at Lamplite Park Subdivision.
- Institutionalize those land-use strategies implemented in response to Lamplite Park subdivision problems to mitigate future landslide hazards in other areas of the city and/or county (e.g., subdivision controls, condemnation, promotion of open space).

Cost: Cost not estimated.

Lead Agencies: City of Grand Junction, Department of Housing and Urban Development, Colorado Geological Survey.

Summary of Action Requirements and Projects By State Agency. The projects shown on previous pages and organized by priority have been grouped below in Table 14 by responsible state agency and project title. Lead agencies should undertake projects as part of the state mitigation system and ensure coordination with local and other state agencies. Projects should be incorporated into state agency budgetary submissions for the next legislative cycle (Fall 1988). When funding cannot be obtained for a project, a report should be submitted to the Implementation Working Group for forwarding to the Governor and for possible submission to the legislature or the federal government. A specific report on progress attained in each project listed in Table 14 below is required for submission to the landslide mitigation system (Implementation Working Group chair).

Table 14. Projects summary.

RESPONSIBLE/LEAD AGENCY	PROJECT TITLE	PRIORITY A,B,C*	SUPPORTING AGENCIES	COMPLETION DATE
LOCAL GOVERNMENT-LOCAL OFFICIALS (All landslide-prone jurisdictions)	1. Development of local approaches for reducing landslide hazards	A	Local planning agencies Local zoning agencies Local engineering departments Local public works departments	
	2. Development of local emergency operations and mitigation plans	A	Local emergency management agency, DODES	
	3. Organization of local landslide planning committees	A	Local emergency management agency	
	4. Private sector involvement in landslide mitigation	A	Local emergency management agency	
	5. Assessment of local resources and needs	A	Local emergency management agency, local planning committees, DODES, CGS	
	6. Identification of landslide hazards through maps and site investigations	A	Local planning agencies Local planning committees Local engineering departments Local building inspectors	
	7. Regulation of development in hazardous areas	B	Local planning commissions State Legislature	
EAGLE COUNTY/ TOWN OF RED CLIFF	8. Assistance to Red Cliff mitigation project, as requested	C	CGS, DODES, Department of Local Affairs	

*Priorities:
A - Critical Action; B - Secondary Action; C - Follow-up Action

Table 14. (Cont.)

RESPONSIBLE/LEAD AGENCY	PROJECT TITLE	PRIORITY A,B,C*	SUPPORTING AGENCIES	COMPLETION DATE
GARFIELD COUNTY/ CITY OF GLENWOOD SPRINGS	9. Assistance to Glenwood Springs debris-flow mitigation and emergency management program, as requested	C	DODES, CGS, SCS, State Forester, Department of Local Affairs	
CITY OF GRAND JUNCTION	10. Lamplite Park Subdivision relocation and landslide stabilization project	C	Mesa County, CGS, HUD	
COLORADO DEPARTMENT OF HIGHWAYS	1. Act as lead agency in projects designated by state landslide mitigation system	A		
	2. Participate in landslide working groups as designated	A		
	3. Transfer of geologic-hazard technology	B	Coordinate with CGS	
	4. Development of comprehensive cost accounting system for geologic hazard-related expenditures on public roads in Colorado	B	CGS	
	5. Geological investigation and monitoring of Grand Mesa landslides	B		
	6. Review of major landslide two miles east of Somerset on U.S. Highway 133	B		
DEPARTMENT OF LOCAL AFFAIRS - DIVISION OF LOCAL GOVERNMENT	1. Act as lead agency in projects designated by state landslide mitigation system	A	Other responsible agencies	
	2. Participate in landslide working groups as designated	A		
	3. Assist local governments in forming landslide mitigation systems and implementing solutions	A		
	4. Provide funds for identified landslide mitigation projects, when feasible	A		
DEPARTMENT OF NATURAL RESOURCES - EXECUTIVE DIRECTOR'S OFFICE	1. Establish Colorado Natural Hazards Mitigation Council	A	Department of Highways, DODES	
	2. Establish Risk/Options Working Group; appoint chair	A	Department of Highways, DNR agencies	
	3. Participate in Review and Warnings Working Group and Implementation Working Group	A	Other state agencies	

Table 14. (Cont.)

RESPONSIBLE/LEAD AGENCY	PROJECT TITLE	PRIORITY A,B,C*	SUPPORTING AGENCIES	COMPLETION DATE
	4. Act as lead agency in projects designated by the state land-slide mitigation system	A	Other state agencies	
	5. Regional presentations of landslide hazard information to local/state leadership	B	DODES, CGS, Department of Local Affairs	
	6. Creation of landslide educational signage project	B	Department of Highways	
	7. Assist Glenwood Springs, upon request	C	Garfield County, CGS	
	8. Mitigation of Mesa Verde access road landslide	C	National Park Service	
	9. Provision of assistance to City of Vail, upon request	C	Eagle County, City of Vail, CGS, DODES	
	10. Assist local governments in Lamplite Park Subdivision mitigation project, upon local government request	C	City of Grand Junction, Mesa County, CGS	
	11. Assist local governments in Red Cliff mitigation project, upon local government request	C	Eagle County, Town of Red Cliff, CGS	
DEPARTMENT OF NATURAL RESOURCES - COLORADO GEOLOGICAL SURVEY	1. Monitoring of existing landslides	A	Department of Highways	
	2. Mapping of state landslide areas	A		
	3. Creation of a "Colorado State Landslide Information Center"	B		
	4. Documentation of serious geologic hazard incidents and annual damage	B		
	5. Evaluation of the magnitude of potential landslide catastrophes	B	Department of Highways, DODES, CWCB	
	6. Investigation of vulnerability to loss of life in hazardous canyons in Colorado	B	CWCB	
	7. Preparation of a technical manual for the standard identification of mudflow and debris-flow hazard areas	B	CWCB, Department of Highways	

Table 14. (Cont.)

RESPONSIBLE/LEAD AGENCY	PROJECT TITLE	PRIORITY A,B,C*	SUPPORTING AGENCIES	COMPLETION DATE
DEPARTMENT OF NATURAL RESOURCES — DIVISION OF WATER RESOURCES	1. Establishment of early-warning satellite-telemetry landslide monitoring system	B	CGS	
	2. Review of reservoir sites for landsliding hazards; state-owned, private	C		
	3. Hazard assessment and mitigation for Colorado state reservoirs potentially vulnerable to landsliding	C	CGS, CWCB	
DEPARTMENT OF PUBLIC SAFETY - DIVISION OF DISASTER EMERGENCY SERVICES	1. Act as lead agency in projects designated by the state landslide mitigation system	A	Other responsible agencies	
	2. Establish a Review and Warnings Working Group; provide chair	A		
	3. Participate in other working groups, as designated	A		
	4. Assist local governments in development of local emergency operations plans that address landslide hazards	A	Local emergency management agencies	
	5. Assist local governments in resource and needs assessments	A	Local agencies	
	6. Assist City of Glenwood Springs and Garfield County in landslide mitigation and emergency management programs, upon request	C		

GLOSSARY

ABBREVIATIONS

BLM	U.S. Bureau of Land Management
BUREC	U.S. Bureau of Reclamation
CCDD	Center for Community Development and Design at the University of Colorado
CDOH	Colorado Department of Highways
CGS	Colorado Geological Survey
CWCB	Colorado Water Conservation Board
DODES	Division of Disaster Emergency Services
DOLA	Department of Local Affairs
DONR	Department of Natural Resources
D&RGW	Denver and Rio Grande Western (Railroad)
FEMA	Federal Emergency Management Agency
FTE	Full-time Employee (or the equivalent number of hours)
SCS	Soil Conservation Service
USFS	U.S. Forest Service
USGS	U.S. Geological Survey

DEFINITIONS

ANNEX
A supplement to a plan that offers detailed guidance, in terms of unique procedures and responsibilities, for a specific hazard (e.g., landslides) or a specific function (e.g., warning).

AVOIDANCE
Refers to the avoidance of a hazard by prohibiting or restricting development in the area where the hazard is likely to occur.

BEDDING SURFACE/PLANE
The interface or surface of separation between two adjacent beds (layers) of sedimentary rock. When the surface is nearly planar, it is called a bedding plane.

BEDROCK
A general term for the solid rock that underlies soil or other unconsolidated superficial material.

BENEFIT/COST RATIO
The estimated amount of reduction in the estimated total amount of losses after the implementation of loss-reduction measures, divided by the cost of applying the measures.

COHESIONLESS
Said of soils whose resistance to internal shear is almost solely dependent on the interparticle friction generated by particles sliding and rolling over each other; versus cohesive soils, which usually contain clays that bond or cement the soil internally.

DESIGN FLOW/EVENT
The size of debris flow or flood used as the basis for designing a mitigation structure.

ELECTRONIC DISTANCE MEASURING (EDM)
EDM instruments utilize either microwaves or lightwaves (laser or infrared) to measure distances between the instrument and a reflector. The EDM unit is attached to or built into a surveying theodolite. The EDM projects several calibrated waves at a reflector positioned at the point of interest and calculates the distance to the reflector by analyzing the returned wavelengths. Distances up to several miles can thus be measured quickly to millimeter accuracy without the need for taping and "chaining" operations.

ELEMENTS AT RISK
The population, properties, economic activities—including public services, at risk in a given area.

EMERGENCY EXERCISE
A simulated activity designed to promote emergency preparedness, test or evaluate emergency operations plans, train personnel in emergency response duties, and demonstrate operational capability.

EMERGENCY OPERATIONS CENTER (EOC)
A pre-designated location from which government leaders can coordinate, direct, and control the response and recovery operations of emergency organizations. A public information office is established in the EOC for purposes of coordinating and authenticating information about the emergency and providing accurate up-to-date instructions and information to the public. The EOC has established means of communicating with response agencies in the field.

FRACTURE
A general term for any break in a rock, whether or not it shows displacement, caused by mechanical failure as a result of stress; includes cracks, joints, faults.

GEOLOGIC HAZARD
A naturally occurring or man-made geologic condition or phenomenon that presents a risk or is a potential danger to life and property.

GEOMORPHOLOGY
The geological study of the configuration and evolution of land forms.

Geomorphic
Of or pertaining to the form of the earth or its surface features.

HYDRAULIC
Moved, operated, or effected by a fluid, especially water.

HYDROCOMPACTION
The process by which dry, unconsolidated earth materials compact or densify, settle, and crack when wetted.

HYDROLOGY
The scientific study of the properties, distribution, and effects of water on the earth's surface, in the soil and underlying rocks, and in the atmosphere.

IMPACT
The effect of the occurrence of a hazard on people and community infrastructure.

INTERSTITIAL WATER
Subsurface water in the voids of a rock; also, pore water.

JOINT
A surface of fracture in a rock without displacement. Usually a plane and often occurring with parallel joints to form a joint set.

LANDSLIDE DAM
An earthen dam created when a landslide completely blocks a valley.

LIQUEFACTION
The transformation of saturated, loosely packed, coarse-grained soils from a solid to a liquid state. The soil grains temporarily lose contact with each other and the particle weight is transferred to the pore water.

LOCAL EMERGENCY OPERATIONS PLAN (LEOP)
A document that identifies the available personnel, facilities, supplies, and other resources in the jurisdiction and states the method or scheme for coordinated actions to be taken in the event of an emergency or disaster. It describes a jurisdiction's emergency organization and its means of coordination with other jurisdictions. It assigns functional responsibilities and details tasks to be carried out for each hazard that could potentially impact people, property, and services.

METASTABLE
Said of a material that is stable in it current condition, but is capable of becoming unstable if disturbed.

MITIGATION
Activities that reduce or eliminate the probability of occurrence of a disaster and/or activities that dissipate or lessen the effects of emergencies or disasters when they do occur.

MUDSLIDE
An imprecise but popular term coined in California, frequently used by laymen and the news media to describe a wide scope of events, ranging from debris-laden floods to landslides. Not technically correct. This term is used in the Housing and Development Act of 1969, which amended the National Flood Insurance Act of 1968.

NONCONFORMING USE
Used to define a land use that exists at the time a zoning ordinance is adopted or amended, but that does not conform to the new ordinance.

PORE PRESSURE (PORE-WATER PRESSURE)
The stress transmitted by the fluid that fills the voids between particles of a soil or rock mass.

PORE WATER
That water residing in the open spaces (pores) between individual grains of sediment. Interstitial water.

RECONNAISSANCE GEOLOGY/MAPPING

A general survey of the geology or specific geologic features of a region, conducted as a preliminary to a more detailed survey.

RELIEF

The elevations or differences in elevation of a land surface.

RISK

The probability of occurrence or expected degree of loss, as a result of exposure to a hazard.

SEDIMENT

Generally refers to unconsolidated materials that originated from weathered rocks and were transported or deposited by air, water, or ice; or that accumulated by chemical or biological precipitation.

SHEAR

The mode of failure of a body or mass whereby the portion of the mass on one side of the surface of failure slides past the portion on the opposite side.

Shear Strength

The internal resistance of a body or mass to shearing.

Shear Surface

Surface along which differential movement has occurred as a result of shear.

STRESS

Force per unit area.

SURFICIAL GEOLOGY

The geology of surficial deposits—soils and bedrock—at the surface of the earth.

TENSILE STRESS

A stress that occurs normal to a plane or failure surface and tends to pull the body apart. Such stresses can produce cracks, fissures, grabens, etc. within a landslide mass.

TOE OF LANDSLIDE

The lower margin of the disturbed material of a landslide pushed over onto the undisturbed slope.

VULNERABILITY

The susceptibility or exposure to injury or loss from a hazard.

WEATHERING

The destructive process by which earth and rock materials exposed to the atmosphere undergo physical disintegration and chemical decomposition resulting in changes in color, texture, composition, or form. Processes may be physical, chemical, or biological.

Differential Weathering

When weathering across a rock face or exposure occurs at different rates; mainly due to variations in the composition and resistance of the rock. This results in an uneven surface with the more resistant material protruding.

Mechanical Weathering

The physical processes by which rocks exposed to the weather change in character, decay, and crumble into soil. Processes include temperature change (expansion and shrinkage), freeze-thaw cycle, and the burrowing activity of animals.

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APPENDIX 1
METHODS OF LANDSLIDE EVALUATION AND ANALYSIS

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MAP ANALYSIS

The analysis of various types of maps is usually one of the first steps in a landslide investigation. Useful maps include topographic, geologic, soils, geomorphic, and miscellaneous engineering maps. Unfortunately, not all of these maps are available for all areas. The information obtainable from a map depends on the type of map, scale, and the detail used in its preparation.

Topographic Maps

Topographic maps show the size, shape, and distribution of features on the surface of the earth. They depict relief, drainage, vegetation, and culture (roads, towns, windmills, etc.). Landslides can sometimes be detected by irregular nonsymmetrical contour patterns with shallow depressions that indicate the hummocky surfaces peculiar to landslide areas, and by contours showing landforms such as debris fans.

Geologic Maps

Types of geologic maps include surficial geology maps, bedrock geology maps, and standard geologic maps depicting both surface and bedrock units. Geologic maps, combined with knowledge of the characteristics of the formations, can be used to determine areas susceptible to landsliding. Surficial geology maps usually show any large landslide deposits in the map area.

Soil Maps

The U.S. Soil Conservation Service has prepared and published soil surveys primarily for the agricultural areas in the United States. These surveys contain information on the engineering properties of the soils, as well as the areal extent and vertical profile for each soil unit. Other information includes depth to water, depth to bedrock, and grain-size distribution. This information can be used to estimate environmental setting and potential stability.

Geomorphic Maps

Geomorphic maps identify landforms and/or geologic processes, and thus can be used to indicate landsliding. However, these maps are not very common.

Miscellaneous Maps

Occasionally special maps prepared for engineering projects are available. These include engineering soil maps, geologic reconnaissance surveys, and site-specific geotechnical investigations.

ANALYSIS OF AERIAL PHOTOGRAPHY

The use of aerial photography has proven to be an effective technique for recognizing and delineating landslides. Aerial photography provides a three-dimensional overview of large areas and allows the viewer to evaluate the interrelations of topography, drainage, surface cover, geologic materials, and human activities (Rib and Liang, 1978). Mapping can be performed directly on the photos, which can then be taken to the site to be checked.

The types of landslide features that can be recognized on aerial photographs include: 1) small isolated ponds, lakes, and other closed depressions, 2) natural springs, 3) abrupt and irregular changes in slope and drainage patterns, 4) hummocky and irregular surfaces, 5) smaller, younger landslide deposits within older and larger landslide deposits, 6) steep scarps at the upper edge of a deposit, 7) irregular soil and vegetation patterns, 8) disturbed vegetation, and 9) interspersed, discontinuous flat areas (U.S. Geological Survey, 1981).

Aerial photographs typically used for landslide studies are panchromatic and infrared black-and-white, natural color, and color infrared. Black-and-white photos are the most common because they are the least expensive. However, natural color photography may be more useful for determining differences in soil moisture content, drainage, and vegetation; and color infrared is especially valuable for locating seepage zones.

The scale of the photography greatly influences the viewer's ability to identify landslides. Small-scale photographs (1:40,000 or smaller) may be necessary to view the full extent of very large landslides. However, small landslides become difficult to see at a scale of 1:75,000. Photographs at scales of 1:4,800 and larger work best on landslides only a few hundred feet wide (Rib and Liang, 1978; U.S. Geological Survey, 1981).

When available, old photos should be compared with recent ones. This can help determine when landsliding began and how it developed over time. Old photos are also essential for areas that have become urbanized and where all, or most, of the features necessary for recognizing landslides have been destroyed by development or covered by vegetation. Also, older photos are very valuable in identifying inactive landslides that have become less obvious with time and erosion.

Types of photographs, scale, coverage, and quality available vary locally. Black-and-white stereo coverage exists for the entire state of Colorado. Natural color and infrared are also available for some areas. Photography is available from the National Cartographic Information Center (NCIC) of the U.S. Geological Survey, Bureau of

Land Management, and U.S. Forest Service, as well as private contractors. Photographs at scales of 1:15,840, 1:40,000, and 1:75,000 are common for Colorado.

FIELD RECONNAISSANCE

An important step in the preliminary investigation of a landslide or landslide-prone area is field reconnaissance. The purpose is to verify the problem that has been identified from analysis of aerial photography, various other remote sensing data, and maps. Many of the features and subtle evidences of slope movement either cannot be identified at the scales of the available photographs, or cannot be seen due to vegetative cover or urbanization. A field survey can detect these features. It is also important to recognize that active slides may change physically over time. A field survey may be able to detect changes that occurred after photos and maps were prepared.

AERIAL RECONNAISSANCE

Because the usefulness of aerial photographs is restricted by scale, lighting, and age, and maps are a product of interpretation, it is useful to view landslide areas first-hand from the air. While field reconnaissance provides many details unobtainable from these other methods, it cannot provide a comprehensive overview. Low-level flights in helicopters or small planes can provide such an overview and can reveal many details of landslide morphology and activity that would otherwise go unnoticed.

GEOPHYSICAL STUDIES

Geophysical methods can be used to determine some subsurface features, such as boundaries between different materials and depth to the zone of saturation, as well as some engineering properties. The techniques used include: 1) electrical resistivity (electric current), 2) seismic methods (shock waves), and 3) gravity (measurements of gravitational force and inferred density).

Electrical Resistivity

Electrical resistivity measurements are made by passing electric current through electrodes placed in the ground and measuring the resistance of the subsurface materials to the current flow. Current flow is dependent on soil moisture and dissolved salts. Thus, this method differentiates between dense rock with few voids and little moisture, and loose materials with high moisture content. The advantage of resistivity is that the instruments are portable and large areas can be covered at a relatively low cost. However, data interpretation is difficult in areas where subsurface formations are not horizontal and/or contrasts in the resistivities of the materials are not sharp (Sowers and Royster, 1978).

Seismic Methods

The seismic refraction and reflection methods are based on the measurement of the rate of passage through the earth of shock waves generated by impact or detonation. The shock waves are reflected or refracted by the formations. Seismic equipment is reasonably portable, and large areas can be covered at a relatively low cost. However, seismic data, like resistivity data, can be difficult to interpret and the technique cannot differentiate softer strata below more rigid ones (Sowers and Royster, 1978).

Gravity

According to Sowers and Royster (1978), measurements of the earth's gravity field can detect areas of low density; and since old landslide debris is usually less dense than the original undisturbed materials, it can be identified. Precise boundaries, however, should be identified by borehole logging.

DRILLING

Drilling, sampling, and correlating the relative data give a good three-dimensional view of subsurface geometry and provide quantitative data on the physical properties of formations, ground-water levels, water chemistry, and thickness of the landslide mass. The layout and spacing of borings depends on what type of information is to be generated. In an area where landslide activity is only suspected, but not yet developed, a gridwork of borings should be used. On an active landslide mass, the borings should be placed in critical areas of interest such as a profile down the center of the landslide, the toe, and the scarp area. Additional borings should be placed outside the landslide area to provide a reference.

Cores and sample borings taken can be used to identify formations, angle of bedding, location of surface of failure, and to provide samples for shear and consolidation tests.

Limitations of a drilling program are cost and the accessibility of drilling sites.

COMPUTERIZED LANDSLIDE TERRAIN ANALYSIS

Computer modeling of landslide masses can be used to determine landslide mass volume and change in topographic expression and cross section over time. Before modeling can be initiated, it is necessary to obtain fixed coordinates on a landslide surface. These can be obtained by a field survey, or can be plotted from low-altitude aerial photographs. The coordinates are then put into a computer program that does three-dimensional modeling. The information generated can be used to calculate potential stream blockage, cost of landslide removal (based on volume of material), and the type and mechanism of slide movement. Comparing different models generated over time can indicate relative movement across the landslide and perhaps can warn of an impending major failure.

Computers are also being used to compile digital landslide inventories, which can then be used in conjunction with other data files. Filson (1987) states:

> Major innovations are occurring in the preparation of susceptibility maps through digital methods and the use of computer-based Geographic Information Systems. Digital data bases with geological, topographic, ground cover, rainfall, and other spatial information are compiled and compared with the digital landslide inventories. Analytical procedures are then used to determine what set of conditions have given rise to landslides in the past and to project which additional regions will be susceptible to landslides in the future. The susceptibility maps are simply "hard copies" of digital files based on these inventories and analytical procedures.

INSTRUMENTATION

Field instrumentation can be used to determine the mechanics of landslide movement, to monitor remedially treated slides for effectiveness, and to warn against imminent slope failure. Instrumentation is commonly used to measure the magnitude, rate, and distribution of movement, and pore-water pressure. Parameters measured and the common types of instruments used and their purpose are listed below. A detailed discussion can be found in Wilson and Mikkelsen (1978) and Franklin (1984).

Movement Monitoring

Monitoring a slope for horizontal and vertical ground movements provides a direct check on stability because large movements are usually preceded by smaller ones. Surveying techniques used to measure movement include:

1) **Electro-optic distance-measuring instrument (EDM)** - This instrument measures distance by reflecting a light beam or laser off a target strategically placed on a slope face. The system is expensive, but very accurate, and can make measurements in relatively inaccessible locations and without interfering with construction activities.
2) **Photogrammetry** - This method compares a sequence of photographs taken over time to indicate movement through changes in surface contours. Accuracy depends on distance between the camera and the ground surface. The technique is good for inaccessible areas.
3) **Measurements of cracks, joints, and faults** - The pattern of tension cracks and their elongation and expansion over time provides information about the mechanism and direction of movement. Portable gauges or stakes and string can be used to measure changes in crack width.
4) **Extensometers and stain meters** - These devices, which are anchored into the soil, measure the increase or decrease in the length of a wire or rod connecting two points of known separation.
5) **Settlement gauges** - Vertical movement is measured by comparing the level of fluid in one end of a "U" tube with the level of fluid in the other end. One end of the tube is placed in a stable instrument house and the other at the potentially unstable crest of the slope.
6) **Inclinometer and tiltmeters** - These instruments measure the change in inclination (or tilt) of a casing in a borehole. They are particularly useful on rotational and translational slides.
7) **Piezometers** - These instruments are used to measure the pore pressure and ground-water level. Types of piezometers include: simple standpipe, pneumatic, electric, and twin tube.

APPENDIX 2
NON-PHYSICAL MITIGATION TECHNIQUES

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INTRODUCTION

The following are mitigation techniques that can be used in landslide management. The information for these techniques was obtained from the most current natural hazard literature available.

The listing for each technique includes the following: a general **description** of the technique, its **components**, a brief outline of the **process** through which a technique is applied, the **participants** in applying the technique, the **advantages** and **disadvantages** of applying the technique, **who benefits** and **who pays** (not only in monetary terms but in terms of aesthetics, health and safety, quality of life, etc.) and an **example** (where available) of a city, county or state currently using the technique.

While several documents were used to obtain information on the techniques, the majority of the information came from Erley and Kockelman (1981), Kockelman (1986), Committee on Ground Failure Hazards (1985), and Olshansky and Rogers (1987).

REGULATIONS

Designation of Geographic Areas of State Interest

Description

Legislation providing for the identification and designation of areas of state concern, including areas subject to natural hazards, and establishment of criteria for their administration.

Components

Enabling legislation, regulations and guidelines governing administration of designated areas, and technical assistance programs.

Process

Local governments initiate the designation process through public notification and hearings, then designate areas of state concern and adopt regulations for their administration. These are subject to approval by the State Land Use Commission. In addition, the State Land Use Commission may request action by local governments. Provisions are included for emergency designation and administration by the governor. Appropriate state agencies (e.g., Geological Survey, Water Conservation Board, Department of Local Affairs) provide technical or financial assistance.

Participants

- state legislature
- state agencies providing technical assistance
- State Land Use Commission
- local governments

Technique advantages

- relatively low cost
- promotes multiple objectives
- may be implemented relatively quickly
- effective indefinitely if adequately enforced
- protects unwary consumers
- flexible

Technique disadvantages

- limits potential loss without protecting existing development
- imposes restrictions on use of land by owners and community
- implementation depends to a large degree on local initiative and cooperation
- implementation depends on aggressive action by State Land Use Commission

Who benefits

- the public, by avoiding costs of future landslides

Who pays

- the public and state and local governments for adoption, administration and technical assistance
- landowners, for opportunities foregone

Example

- Colorado

Siting and Construction Standards for Water and Waste-Water Facilities

Description

State government may specifically prohibit, or permit conditionally, construction of water and waste-water facilities in landslide hazard areas via state regulations establishing siting and construction standards.

Components

Statute identifying general parameters governing water and waste-water facility siting and construction, and mandating development of specific regulations pertaining to the same, and enforcement.

Process

Legislative, regulatory, and enforcement.

Participants

- state legislature
- state agency responsible for permitting water and waste-water facilities
- local, general, and special purpose governments
- private developers

Technique advantages

- low cost
- promotes multiple objectives (e.g., environmental quality, minimizing potential loss and disruption of service)
- may be implemented relatively quickly, particularly if broad encompassing enabling legislation already exists
- effective indefinitely if adequately enforced

Technique disadvantages

- limits potential loss rather than protecting existing development
- imposes restrictions on use of land by owners and community

Who benefits

- the public, by avoiding costs of future landslides
- facility owners, by avoiding future loss and disruption of services from hazard occurrences

Who pays

- landowner bears cost of opportunities foregone
- state and local governments bear cost of adoption and administration

Example

- regulations pertaining to siting and construction of water and waste-water facilities in flood hazard areas are common and could be extended to other hazard types

Model Regulations

Description

Appropriate state agencies can develop standard model regulations governing hazard area land use for use by local governments.

Components

Standard model regulations drafted for adoption and use by local governments. Regulations may be drafted so that pertinent local information may be integrated and the regulation adopted in whole as provided. Resource and explanatory material may be drafted and provided to local communities in support of model regulations.

Process

Interagency technical assistance effort to develop model regulations and supporting material. Outreach and technical assistance effort to local governments.

Participants

- state agencies with missions pertaining to relevant substantive areas including geologic hazards, natural resource management, local government, transportation, health, economic development, and law

Technique advantages

- relatively low cost
- promotes multiple objectives
- may be implemented relatively quickly
- flexible

Technique disadvantages

- local governments may choose not to adopt
- intergovernmental projects are problematic
- adopted regulations generally limit future loss without protecting existing development
- adopted regulations will impose restrictions on use of land by owners and communities

Who benefits

- the public, by avoiding cost of future landslides

Who pays

- state government bears cost of development and technical assistance effort
- local governments bear cost of adoption and administration
- landowners bear cost of opportunities foregone

Example

- Colorado

Zoning Ordinances

Description

The use of police power to regulate the use of private land and the structures thereon, in such a way as to protect the safety, health and general welfare of the public.

Components

Zoning ordinance consisting of maps, accompanied by text describing uses allowed and not allowed in specific zones.

Process
Consists of dividing a community into districts or zones and regulating land use and construction within each district. Districts most compatible with landslide hazard areas are open space, recreation, park, conservancy and agriculture.

Participants
- local planning or zoning office
- planning commission
- zoning board of appeals
- landowners
- courts

Technique advantages
- promotes multiple objectives (e.g., environmental quality, quality of life)
- effective indefinitely if adequately enforced
- protects unwary consumer
- specific uses which may trigger landslides could be prohibited by provisions to district ordinances
- development density in landslide areas can be regulated
- special hillside districts can be created to require that certain lands be left in their natural state or to specify slope percentages suitable for development
- restricts future development of vacant lands in landslide areas

Technique disadvantages
- limits potential loss without protecting existing development
- must not violate state and federal constitutional provisions
- imposes restrictions on use of land by landowners and community
- can be interpreted as exclusionary zoning where very low densities are required
- adequate knowledge of zoning is required

Who benefits
- the public, from reduced risk of health and safety hazards in landslide areas
- the public, from saving the expense of potential landslides
- the public, from expanded scenic views and uses of open space

Who pays
- landowner bears cost of opportunities foregone
- community bears cost of adoption and administration
- builders and developers from loss of profit due to reduced building densities

Example
- San Mateo County, CA

Slide-Prone Area Ordinances

Description
Such ordinances can be used specifically to regulate the use of land in hazardous landslide areas and can supplement the basic use and site development plans of a zoning ordinance.

Components
An ordinance describing how landslide-prone areas can and cannot be developed would be adopted by a local jurisdiction. Maps of landslide areas would be needed.

Process
Landslide-prone areas are identified and the restrictions on their use spelled out in the adopted ordinance. Builders then comply with the restrictions in their development plans.

Participants
- local government
- planning office

Technique advantages
- ordinance can be designed specifically to preserve or prohibit certain land uses
- development densities can be regulated in landslide-prone areas
- low cost
- may be implemented relatively quickly
- effective indefinitely if adequately enforced
- protects unwary consumer
- flexible

Technique disadvantages
- restricts use of land by owners and community
- must not violate state and federal constitutional provisions
- limits future loss without protecting existing development

Who benefits
- the public, by averting cost of potential landslides
- the public, by reducing risk of health and safety hazards on landslide-prone areas

Who pays
- landowner bears cost of opportunities foregone
- community bears cost of adoption and administration
- builders and developers from loss of profit due to reduced building densities

Example
- Portola Valley, CA

Hillside Development Ordinances

Description
A regulation limiting the amount and type of development that may take place on hillside areas. Types of hillside ordinances:
- **slope density** provisions which decrease allowable development densities as slope increases
- **soil overlay provisions** that assign use and density based on soil characteristics in sloped areas
- **guiding principles** which have no precise standards but emphasize case-by-case evaluation based on several specific policies
- **grading regulations**

Components
Regulations limiting the amount and type of development that can take place on hillside areas. Engineering reports concerning where regulations are needed. Proper grading procedures, and correct excavation and fill practices are also necessary.

Process
A geologist or geotechnical engineer makes a judgment as to where slope density and other regulations are needed. A formula needs to be devised for determining the density of development to be permitted for a given degree of slope. Grading procedures, and excavation and fill practices need to be defined in accordance with the ordinance. Builders need to comply with ordinance.

Participants
- local government body to adopt ordinance
- planning and building inspection offices enforce ordinance

Technique advantages
- promotes multiple objectives (e.g., public safety and aesthetic qualities)
- limited development can preserve natural features of hillsides
- low density building reduces danger of slope failure
- may be implemented fairly quickly
- effective indefinitely if adequately enforced
- flexible

Technique disadvantages
- requires technical engineering assistance
- grading and excavation and fill procedures must be defined to make ordinance effective
- imposes restrictions on use of land by owners and community
- must not violate state and federal constitutional provisions
- limits potential loss without protecting existing development

Who benefits
- the public, by maintaining scenic quality of the community
- the public, by averting potential landslides
- the public, by reducing health and safety hazards

Who pays
- landowners bear cost of opportunities foregone
- community bears cost of adoption and administration
- builders or developers from loss of profit due to reduced building densities

Examples
- Palmer Lake, CO
- Manitou Springs, CO
- Colorado Springs, CO
- City of Los Angeles, CA
- Los Angeles County, CA
- Orange County, CA
- Ventura County, CA
- Cincinnati, OH

Abatement Districts

Description
Special assessment districts formed to specifically abate actual or potential landslides.

Components
Must have group of residents in potential landslide area willing to join and fund a district.

Process
District can be initiated by residents or local government. Once established, abatement measures must be determined. District members pool their resources to abate a common geologic hazard.

Participants
- local government
- landowners

Technique advantages
- pools resources of affected landowners to abate a common geologic hazard
- district has power to raise money and implement projects
- can be initiated prior to development of landslide problems
- organized entity has more influence than individuals
- provides government with equitable way to assist in repair of landslide damage to public and private property
- can be used in combination with other techniques to reduce hazards in both new and existing development
- can be tailored to finance preventive measures and to address the particular landslide problems of a district
- can be established to pay for regular maintenance and monitoring actions
- can reduce hazards which predate a grading ordinance

Technique disadvantages
- landslide abatement is expensive
- difficult for large group to reach consensus initially and to find means of financing preliminary investigation prior to district formation
- organized district may facilitate litigation rather than replacing it
- politically complex to form, requiring consensus by property owners and government on financing mechanism
- adequate knowledge is required

Who benefits
- the public, by having private landowners pay for hazard abatement
- private landowners, by having control over decisions made affecting their properties

Who pays
- landowners
- possibly builders, government or neighboring communities, if successful litigation is sought

Examples
- Abalone Cove Landslide Abatement District, CA
- Rancho Palos Verde, Los Angeles County, CA
- Contra Costa County, CA

Subdivision Regulations

Description
Regulates the design and improvement of subdivisions to control development in landslide-prone or other natural hazard areas.

Components
A set of guidelines setting standards for how lands can be subdivided; including such things as width and placement of streets,

infrastructure, and dedication of open space. Zoning and other related regulations need to be designed to support the specific subdivision regulations being used.

Process
Undeveloped land is divided into smaller buildable sites, with blocks, streets, open space and utilities. Landslide areas may be dedicated as open space or public parks and infrastructure and building planned in such a way as to avoid landslide areas.

Participants
- local government
- planning office
- developers and builders

Technique advantages
- promotes multiple objectives (e.g., environmental quality, quality of life)
- low cost
- may be implemented relatively quickly
- effective indefinitely if adequately enforced
- protects unwary consumer
- flexible
- incorporates landslide mitigation measures early in the planning process
- public open space can be created in landslide-prone areas
- requires adherance to grading code

Technique disadvantages
- must not violate state or federal constitutional provisions
- imposes restrictions on use of land by owners and community
- zoning and other related regulations must be designed to support subdivision regulations prior to subdivision approval, extension of utilities, or acceptance of public rights-of-way
- adequate knowledge of regulations is required

Who benefits
- the public, by averting costs of potential landslides
- the public, by reducing health and safety hazards

Who pays
- community bears cost of adoption and administration
- landowners bear cost of opportunities foregone
- builders and developers, in loss of profits due to reduced building densities

Example
- Southwestern Wisconsin Regional Planning Commission
- Colorado

Building Codes

Description
Building codes are developed by governments to regulate construction and the quality of materials being used in structures. Landslides can be considered explicitly in the building design, and the structure can be built to resist landslide damage.

Components
A code defining how building construction should be carried out and with what materials in order to achieve the desired building practices.

Process
A builder must submit construction plans to the local building department to obtain necessary building permits. This process applies to both new and remodeled structures.

Participants
- building department
- builders
- landowners

Technique advantages
- low cost
- promotes multiple objectives (e.g., quality of construction, environmental design)
- may be implemented relatively quickly
- effective indefinitely if adequately enforced
- protects unwary consumer
- can be applied to both new and pre-existing construction
- structures built specifically to resist landslide damage

Technique disadvantages
- must not violate state and federal constitutional provisions
- may impose restrictions on building design
- uniform and equitable enforcement is difficult
- lack of uniform federal code affects the consistency of the quality of the construction throughout the nation
- need more technological data to effectively develop codes

Who benefits
- building owners with a structure that can resist landslide incidents
- the public, by reducing risk of health and safety hazards

Who pays
- community bears cost of administration and enforcement
- builder or owner, in having some features of design dictated by code, and paying fees

Examples
- Los Angeles, CA
- Cincinnati, OH
- Prince Georges County, MD
- Fairfax County, VA

Grading Codes

Description
A grading ordinance regulates the way land is cut and filled, and moved for construction. It is typically part of a community building code.

Components
A code requiring geology or engineering reports which analyze slope stability on proposed building sites; specifications for quantity and quality of fill; site preparation, earthwork, and drainage plans.

Process
Local governments implement grading codes through the building

permit process. Compliance is required as a condition of approval for final building and occupancy permits. Enforcement is carried out by a series of inspections throughout the development. Ordinances are generally accompanied by professional licensing procedures or peer review boards. Subdivision plans must be filed with the planning department so they can be reviewed by the staff to determine compatibility with soil and geologic conditions. When approved the subdivision receives the typical subdivision review, with grading recommendations incorporated into the final report.

Participants
- building or grading inspectors
- geologists to prepare geologic reports on proposed sites
- builders
- city building department
- engineers to prepare grading plans

Technique advantages
- low cost
- effective indefinitely if adequately enforced
- protects unwary consumer
- promotes multiple objectives (e.g., environmental quality, quality of life)
- combines land-use and engineering techniques for landslide reduction
- hillside development costs can be included in purchase price paid by property owner
- system can be self-supporting if funded through development fees

Technique disadvantages
- adequate enforcement and inspection are essential
- requires support of elected officials if inspectors are expected to be firm in making technical decisions in the face of developer resistance
- since engineers' reports vary, local agencies must apply consistent technical review if they expect to establish minimum earthwork standards
- limits potential loss without protecting existing development
- must not violate state and federal constitutional provisions

Who benefits
- the public, by reducing risk of health and safety hazards
- owner of land with structure not susceptible to landslides

Who pays
- community bears costs of administration and enforcement
- landowners may pay extra engineering fees as required by code

Example
- Los Angeles, CA
- Uniform Building Code, Chapter 70

Site Investigation Requirements (soil engineering and geology reports)

Description
Geotechnical reports that cover the character and physical properties of soil deposits; used for structural foundation or for earthwork construction.

Components
A map identifying areas potentially prone to landsliding. A set of standards which soils reports must meet to regulate grading and construction practices.

Process
If a site is known or suspected of being unstable, developers are required to provide information on slope stability and proposed grading procedures.
- if an unstable area is present, the report must assess the short- and long-term stability of the site and possible effects of development on neighboring properties
- final development plans are reviewed for compliance with recommendations of report
- engineer and geologist must inspect work and, on completion, provide a written evaluation to the county: a permit can then be issued

Participants
- city building department and inspectors
- engineers and geologists who prepare reports
- property owner and builder
- planning departments

Technique advantages
- relatively low cost
- may be implemented relatively quickly
- protects unwary consumer
- effective indefinitely if adequately enforced
- case-by-case approach means grading and construction practices are tailored to specific soil and geologic conditions
- uncomplicated for jurisdictions to adopt and administer
- system can be self-supporting through development fees

Technique disadvantages
- must not violate state and federal constitutional provisions
- approach is site-specific so it tends to be piecemeal, ignoring cumulative effect of developing individual parcels
- cannot be specific on requirements because natural soils are not heterogeneous
- must be adequately enforced
- because engineering reports vary, local agencies must apply consistent technical review if they expect to establish minimum earthwork standards

Who benefits
- the public, by reducing risk of health and safety hazards
- landowners, with structure not susceptible to landslides

Who pays
- community bears cost of administration and enforcement
- landowners must pay for engineering reports

Example
- Fairfax County, VA

Restrictive Covenants

Description
A restrictive covenant is a legally binding agreement among participants (e.g., individual owners, developer) in a private

development imposing restrictions and/or conditions on activities, improvements, and other aspects of land use. A restrictive covenant can include provisions restricting and/or imposing conditions on hazard-zone activities.

Component
Legal document.

Process
A legally binding agreement is developed and signed by all participants.

Participants
- developer
- landowners
- homeowners association
- local government
- lawyer

Technique advantages
- low cost
- promotes multiple objectives
- may be implemented relatively quickly, particularly in the case of new developments
- effective indefinitely if adequately enforced
- protects unwary consumers
- flexible

Technique disadvantages
- limits potential loss without protecting existing development
- imposes restrictions on use of land by owners and community

Who benefits
- the public, by avoiding health and economic costs from future landslides

Who pays
- developer and landowners association bear cost of development, implementation, and enforcement
- developer and landowners bear cost of opportunities foregone

Example
- no model example identified in the literature

Sanitary System Codes

Description
Ordinances to regulate or prohibit private sewage disposal systems in landslide-prone areas.

Components
An ordinance detailing what permits are required prior to installing a system, prohibiting systems in certain landslide areas, or requiring that on-site sewage disposal systems in landslide areas be replaced with alternate systems, such as the public sanitary sewage system.

Process
Prior to installing a system in a landslide-prone area, the builder must obtain a permit.

Participants
- local public works department
- builder or property owner
- local and state health departments

Technique advantages
- can prevent health hazards associated with possible contamination of private water supply systems
- helps eliminate problems caused by disruption of private sewage disposal system
- low cost
- may be implemented relatively quickly
- effective indefinitely if adequately enforced
- protects unwary consumer

Technique disadvantages
- limits potential loss without protecting existing development
- imposes restrictions on use of land by owners and community

Who benefits
- the public, by reducing risk of health and safety hazards
- landowners, by installing system that will not trigger landslides

Who pays
- community bears cost of administration and enforcement
- property owner, by possibly needing to invest more money in system

Example
- Southwestern Wisconsin Regional Planning Commission

Geologic Hazard Overlay Zones

Description
A special geologic hazard zone created to prohibit certain uses in areas identified as being potentially dangerous. The restrictions on uses within this zone are in addition to those within the underlying zone.

Components
Uses prohibited within a geologic hazard zone include buildings intended for human occupancy, as well as any land use which significantly increases the geologic hazard danger. County/city personnel may authorize certain provisional uses, such as utilities, roads, fills, or structures for storage and livestock.

Process
Geologic hazard zone boundaries may be determined by use of published geologic hazard mapping and expert witness testimony, and can be adopted by a county-initiated rezoning process. This process obtains full disclosure since the zoning category appears on all property deeds and on maps filed in the related planning departments. During an application to rezone, the zone may be altered or removed if the applicant can prove the following: 1) the hazard as mapped does not actually exist, or 2) the hazard has been successfully mitigated.

Participants
- local zoning office
- local planning department
- property owners

Technique advantages
- geologic expertise can be utilized, while maintaining actual land-use regulation within local governments
- once approved, zones may be modified, but the burden of proof is on the developers to prove the absence of the hazard
- protects unwary consumer
- specific uses which may trigger landslides are prohibited
- restricts future development in landslide areas

Technique disadvantages
- limits potential loss without protecting existing development
- must not violate state and federal constitutional provisions
- imposes restrictions on use of land by landowners and the community
- can create conflicts with existing zoning
- creates mapping problems as to where geologic hazard zones should be drawn, possibly leading to piecemeal zoning
- local government's limited knowledge of geologic hazards may lead to difficulties in handling special circumstances and in verifying the validity of geologic reports supplied by developers

Who benefits
- the public, by reducing landslide risk

Who pays
- local government bears costs of adoption and administration
- landowners bear cost of opportunities foregone
- landowners pay to mitigate the hazard and appeal the geologic hazard zone

Example
- Jefferson County, CO

LAND USE

Appropriate Agricultural Practices

Description
Agricultural practices, such as tree farming (silviculture), pasture improvements, and controlled livestock grazing, which rely on natural precipitation and tend to stabilize soil.

Components
Naturally occurring vegetation, or vegetation suitable for the specific hazard site.

Process
Preserve natural vegetation. Cultivate vegetation appropriate to site-specific conditions.

Participants
- landowners
- community
- appropriate state and federal agencies in supporting functions (e.g., providing plants, performing research identifying appropriate vegetative cover.)

Technique advantages
- promotes multiple values, particularly environmental quality
- inexpensive, relative to other slope stabilization techniques
- initiative required only of landowner, assisted by community and government

Technique disadvantages
- knowledge of appropriate vegetation required
- cooperation and initiative of hazard-area landowner required

Who benefits
- the public and landowners, by avoiding cost of potential landsliding
- the public, from enhanced aesthetics

Who pays
- landowners
- the community
- others bear cost of vegetation and maintenance
- landowners bear cost of opportunities foregone

Example
- no model example identified in literature

Vegetation Requirements

Description
Ordinance requiring that hillsides subject to erosion be planted and irrigated in a manner that prevents landslides.

Components
Landscape requirements are often included in grading ordinances, along with soil reports and permits. Minimum vegetation requirements should be specified for various slope angles.

Process
If included in grading ordinance, landscape plan must be approved prior to permitting; planting takes place after grading.

Participants
- building or grading inspectors
- city building department
- landscape architects
- property owners

Technique advantages
- protects unwary consumer
- promotes multiple objectives (e.g., environmental quality, public safety, aesthetics)
- attempts to control landslide problem in an environmentally sensitive way
- can be applied to new or existing development

Technique disadvantages
- must not violate state and federal constitutional provisions
- imposes restrictions on use of land by owners and community
- must be tailored to specific local conditions
- not always a permanent solution to landslides or erosion

Who benefits
- the public, by reduced risk of health and safety hazards
- the public, by acquiring an aesthetically pleasing landscape design

Who pays
- the public bears cost of administration and enforcement
- landowners bear the cost of investing in plants or irrigation systems

Examples
- Los Angeles City Grading Code, CA
- Orange County, CA

Public Nuisance Abatement Ordinances

Description
A form of police power allowing government to remove structures which interfere with the health, safety, comfort, or convenience of the community.

Components
An ordinance defining what constitutes a public nuisance within a particular community.

Process
Buildings or structures that are structurally unsafe, constitute a fire hazard, are dangerous to human life, constitute a hazard to safety or health and the public welfare by reason of inadequate maintenance, dilapidation, obsolescence, disaster damage, or abandonment can be declared public nuisances and be abated by repair, rehabilitation, demolition or removal.

Participants
- local government
- landowners

Technique advantages
- can permanently remove structures from landslide areas
- no conflict with constitutional provisions
- funding assistance may be available

Technique disadvantages
- can be costly to community
- imposes restrictions on use of land by owners and community

Who benefits
- the public, by reducing risk of health and safety hazard
- the public, by removing nuisance

Who pays
- community bears cost of administration and enforcement

Example
- no model example identified in literature

Nonconforming-Use Regulations

Description
Nonconforming uses are those that exist at the time a zoning ordinance is adopted or amended and do not conform to use restrictions.

Components
An adopted zoning ordinance or amendment defining what uses are nonconforming.

Process
A community adopts a zoning ordinance or amendment and uses that already exist in the zoned area, but do not meet restrictions, are considered nonconforming. The zoning ordinance can provide that nonconforming uses can be continued but not enlarged or extended.

Participants
- city zoning or planning office
- property owners
- local government
- zoning board of appeals

Technique advantages
- protects unwary consumer
- effective indefinitely if adequately enforced
- restricts future and possibly existing uses in landslide areas
- protects public health and safety

Technique disadvantages
- must not violate state and federal constitutional provisions
- imposes restrictions on use of land by owners and community

Who benefits
- the public, by reducing risk of health and safety hazards
- the public, by avoiding expense of potential landslide damage

Who pays
- community bears cost of administration and enforcement
- landowners bear cost of opportunities foregone

Example
- City of Los Angeles, CA

Acquisition of Open Space

Description
The acquiring of land by a government agency to control development in the public interest

Components
The actual purchase of land for public interest. Determination as to how the land will be used.

Process
There are numerous methods for acquiring land: negotiation, condemnation, tax delinquency, default, dedication, donation, easements or exchange. The agency controls development in the public interest.

Participants
- local government
- landowners

Technique advantages
- promotes multiple objectives (e.g., environmental quality, quality of life)
- no conflict with constitutional provisions
- permanent solution
- public use of lands thereafter
- funding assistance may be available

Technique disadvantages
- acquisition may be costly
- open space uses and structures still vulnerable
- sites not always suitable for recreation or wildlife
- may create shortage of land for higher intensity use
- expense for public management

Who benefits
- the public, with more open space

Who pays
- the public bears cost of purchasing land
- the public bears cost of managing the land

Example
- Santa Monica Mountains State Park, Los Angeles, CA

Design, Location, and Relocation of Public Facilities

Description
Public facilities such as municipal water and sewer systems can be designed such that they do not have the capacity to serve urban developments in landslide areas. Community facilities located in landslide areas can be relocated or converted to a use that is less vulnerable to damage.

Components
Policies by local government announcing that they will not authorize, finance, or construct community facilities to service areas subject to landslides. The feasibility of relocating or converting depends on the value of structures, whether they can be successfully reinforced, their potential for triggering landslides, and the degree of citizen concern.

Process
Methods for construction include reinforcement, designing to accommodate displacement, and relocating in areas not subject to landslides.

Participants
- government agencies
- builders and developers
- landowners

Technique advantage
- minimized number of critical facilities at risk

Technique disadvantages
- limits potential loss without protecting existing development
- decreased options for use of land by owners

Who benefits
- the public, by reducing risk of health and safety hazards

Who pays
- developer bears cost of structurally sound building
- landowners bear cost of services foregone

Example
- Los Angeles County (water and gas pipelines), CA

EMERGENCY PREPAREDNESS AND DISASTER ASSISTANCE

Planning and Preparation

Description
Developing information, identifying potential problems and the required actions and responsibilities for accomplishing them, prior to a natural disaster event.

Components
Problems, actions and responsibilities should be documented. The readiness of equipment, supplies and facilities should be ensured.

Process
Once problems, actions and responsibilities are identified, the public should be informed of their potential exposure, warnings to be issued, probable evacuation time available, and appropriate actions to be taken.

Participants
- local, state, and federal governments
- local disaster emergency office

Technique advantages
- protects existing development as well as future development
- planned response is more organized and efficient than spontaneous response
- minimizes property damage and disruption of community activities
- protects life, health, and property

Technique disadvantages
- must be used in combination with other methods
- success depends on adequate warning
- protection of property is limited
- system must be adequately operated and maintained
- public and participants must be informed and cooperative

Who benefits
- government, from more positive, less costly response
- the public, from increased safety

Who pays
- the public bears cost of adoption and administration

Example
- City of Los Angeles, CA (storms and landslides of 1969, 1978, 1980)

Warning Systems

Description
Warning systems may include monitoring of situations (landslides, debris flows) or conditions with potential for causing a severe event (e.g., storm development, snowpack, dam safety) and signs instructing people within the potential hazard area of proper procedures.

Components
Common forms of monitoring are field observation and electrical fences or trip wires, with effective linkages to a central communication warning facility and thence to individuals with disaster management responsibilities.

Process
Sensors are triggered alerting response personnel, who follow emergency operations plans.

Participants
- local and state government
- individuals with monitoring responsibility

Technique advantages
- protects safety of people
- planned response is more organized and efficient than spontaneous response

Technique disadvantages
- must be used in combination with other methods
- does not protect property
- systems must be adequately operated and maintained
- public and participants must be informed and cooperative
- earth movement can happen so rapidly that it can be difficult to design effective warning systems

Who benefits
- government, from more positive, less costly response
- the public, from increased safety

Who pays
- government bears cost of adoption and administration

Examples
- Malibu, Los Angeles County, CA (Big Rock slope failure)
- Red Cliff, CO
- Roan Creek, CO

Emergency Response Operations

Description
Emergency operations include evacuation, shelter, and care, cleanup, and provision of essential services and activities.

Components
A document outlining which agencies or individuals are responsible for carrying out each operation and activity.

Process
Once a warning has been issued, the emergency operations plan goes into effect. The plan is followed until it is determined that a threat no longer exists, at which time rehabilitation and recovery efforts start.

Participants
- local, state, and federal governments
- local individuals with responsibility in emergency operations

Technique advantages
- protects existing development as well as future development
- planned response more organized and efficient than spontaneous response

Technique disadvantages
- must be used in combination with other methods
- success depends on adequate warning
- protection of property is limited
- systems must be adequately operated and maintained
- public and participants must be informed and cooperative

Who benefits
- the public, from more efficient, less costly response
- the public, from increased safety

Who pays
- the public bears cost of adoption and administration

Example
- City and County of Los Angeles, CA

Rehabilitation and Recovery

Description
This stage of disaster response becomes effective when a threat or actual disaster has ended. The work of rebuilding or restabilizing damaged properties or natural features takes place.

Components
Rehabilitation program, procedures, and funding.

Process
An inventory is conducted to determine the extent of damages and the resources available to repair them.

Participants
- local, state, and federal governments

Technique advantage
- planned response is more organized and efficient than spontaneous response

Technique disadvantages
- must be used in combination with other methods
- protection of property is limited
- systems must be adequately operated and maintained
- public and participants must be informed and cooperative

Who benefits
- the public, from rehabilitated properties

Who pays
- the public bears cost of recovery efforts
- governments, through disaster aid

Examples
- Malibu, CA (1980)

Post-Hazard Mitigation

Description
Post-hazard mitigation involves plans and regulations governing rehabilitation of hazardous areas after a natural disaster. Post-hazard mitigation plans and regulations are developed before the hazard occurs. Typically included are provisions for a moratorium

on rebuilding, relocation of destroyed facilities, acquisition of funding for relocation and reconstruction, and post-hazard land use.

Components
Plan, regulations, institutional mechanism for administration, financing scheme.

Process
A plan is developed for post-hazard relocation and reconstruction of damaged facilities, and rehabilitation of the land to appropriate uses. Regulations are implemented governing post-hazard recovery activities.

Participants
- local government
- state and federal governments in supporting roles (technical, management, financial assistance)

Technique advantage
- less costly than continuing to periodically incur losses from hazard occurrence

Technique disadvantages
- limits potential loss without protecting existing development
- implementation may be emotionally difficult for local authorities in the post-hazard recovery period
- imposes restrictions on use of land by owners and community

Who benefits
- the public, by speeding recovery from disaster

Who pays
- local government bears cost of developing and administering plan
- landowners bear cost of opportunities foregone

Example
- Estes Park, Colorado, 1982

OTHER METHODS

Dissemination of Public Information

Description
Information on landslides can be disseminated to the public in an attempt to increase their awareness of the nature of the hazard and what can be done to reduce it.

Components
Detailed landslide information needs to be provided in a readily usable format understandable by non-scientists.

Process
Information can be disseminated through workshops, conferences, newsletters, bulletins, press releases, and erecting signs in hazard areas.

Participants
- geologists
- the public
- media
- educational institutions
- civic organizations
- planners
- all levels of government
- engineers

Technique advantages
- increased public awareness of landslides
- such information can help to better define hazard zones and develop cost-effective engineering solutions
- low cost
- an informed public can create a climate for effective use of hazard information by local government and lawmakers

Technique disadvantages
- appropriate hazard information may not be available
- citizens must be encouraged to incorporate information into their actions
- must be used in combination with other methods
- often requires repeated exposure to be effective
- requires cooperation of all levels of government

Who benefits
- the public, with knowledge to take constructive action to reduce landslide risks in their lives

Who pays
- government bears cost of developing and administering landslide information programs

Examples
- West Virginia
- State of California (select locations)

Landslide Mapping

Description
Landslide mapping involves preparing maps with detailed information on the probable type of landslide, the extent of slope subject to failure, the probable extent of ground movement, and the frequency of slope failure.

Components
Maps at the proper scale for the intended use which can help predict areas where landslides can occur in the future.

Process
Maps are prepared by government agencies or the private sector. Areas where landslides have been identified, inventories of human activity, slope stability analysis and studies of underlying materials all can be included as overlays on landslide maps.

Participants
- U.S. Geological Survey
- state geological survey
- private sector geologists or engineers
- local planning office

Technique advantages
- provides detailed guidance for planners, engineers, and the general public as to the extent and degree of landslide hazards

- can be used to regulate development
- assists in locating and designing structures

Technique disadvantages

- costly in time and money to gather and evaluate the data
- studies require experienced personnel
- there are no universal standards for accuracy, comprehensiveness, scale, symbols, or format; this can lead to variability in final products

Who benefits

- planners, with more detailed information for making recommendations
- builders, from more guidance in building structures outside landslide areas
- the public, from more detailed information on landslide hazard areas

Who pays

- government agencies that must prepare maps
- consultants who must purchase maps according to local regulation

Examples

- California Division of Mines and Geology
- Association of Bay Area Governments (mapped by USGS)
- West Virginia Geological Survey
- Colorado Geological Survey

Recording and Disclosing Hazards

Description

Information concerning hazards on particular properties can be put on public records of land ownership. This provides a means of alerting land purchasers, local assessors and lenders to potential landslide hazards.

Process

Maps of landslide areas are filed with local registrar of deeds, and together with listings of affected subdivisions, entered onto tract indexes. Entries referencing the hazard can then be found on the abstracts of title for the affected properties.

Participants

- registrar of deeds (county clerk)
- landowners
- realtors

Technique advantages

- protects unwary consumer
- low cost
- effective indefinitely if adequately enforced

Technique disadvantages

- imposes restrictions on use of land by owner and community
- must not violate state and federal constitutional provisions
- reduces value of real estate

Who benefits

- home buyers
- the public, by reducing risk of health and safety hazards

Who pays

- landowners bear cost of opportunities foregone
- community bears cost of adoption and administration

Example

- Santa Clara, CA

Financing Policies

Description

Policies adopted by private lenders and government agencies to discourage development in landslide areas by denying building loans or loan insurance.

Components

A policy adopted by private lenders or governmental agencies outlining where and why construction loans or loan insurance will not be approved.

Process

When builders or landowners apply for loans or insurance, the requests would be denied if the properties or structures are found to be in landslide areas. Government agencies can enforce this policy through private lenders, who make most mortgage and construction loans, and who are insured by the government.

Participants

- private lending institutions
- local, state, and federal agencies
- landowners or builders

Technique advantages

- protects unwary consumer
- permanent solution
- effective indefinitely if adequately enforced
- discourages development in landslide areas

Technique disadvantages

- limits potential loss rather than protecting existing development
- must not violate state and federal constitutional provisions
- may create shortage of land required for higher intensity use

Who benefits

- the public, by avoiding the expense of protecting developments in landslide areas
- the public, by reducing risk of health and safety hazards
- private lending institutions, by avoiding making loans in hazardous areas

Who pays

- landowners bear cost of opportunities foregone
- government bears cost of administering and enforcing

Example

- HUD Standards

Higher Homeowners Insurance Rates

Description

Higher homeowners insurance rates can be applied to development in landslide areas to create economic incentives for uses that are less subject to damage.

Components
An insurance policy with high rates reflecting the landslide risk involved. Local land-use planning defining development in landslide areas.

Process
If a property and its structures are found to have a landslide risk, the insurance rate can be set to appropriately reflect this risk.

Participants
- insurance companies
- landowners
- local government

Technique advantages
- discourages development in landslide areas by creating economic disincentives
- protects existing development as well as future development
- redistributes loss among population

Technique disadvantages
- insurance is costly, usually requires government subsidization
- determining risk is difficult with landslides
- government subsidies to landslide damaged properties may lead to undesirable development in landslide areas in anticipation of indemnification of loss
- landslide risk is not uniformly distributed throughout the population making equitable application of insurance difficult

Who benefits
- landowners who are insured
- the public, by reducing their economic burden in responding to landslides

Who pays
- insurance holders
- possibly government and the public, if insurance is subsidized

Examples
- typical homeowners insurance policy

Conditions on Federal Disaster Aid

Description
The federal government requires that hazard mitigation measures be taken by a community as a condition to receiving federal disaster aid.

Components
Federal government pays for disaster through direct assistance, as well as through tax deductions for property losses. The Disaster Relief Act of 1974 attaches hazard reduction conditions to disaster aid in an attempt to decrease the federal burden.

Process
Government can require jurisdictions receiving aid to take steps to evaluate and mitigate natural hazards. These regulations can require local aid recipients to evaluate natural hazards, develop land-use plans and set standards for construction practices.

Participants
- federal agencies coordinated by the Federal Emergency Management Agency (FEMA)
- local government

Technique advantages
- the federal government can require local governments to improve land-use regulations and construction practices
- educates local officials to pursue mitigation that would reduce the cost of future disasters

Technique disadvantages
- difficult to force states to implement plans after disaster aid has been paid
- does not cover all landslides and, as a policy tool, does not in itself encourage landslide hazard reduction
- inequitable in that all taxpayers must share costs that local government might have prevented by stricter hillside development practices
- imposes restrictions on use of land by owners and community

Who benefits
- the community which receives disaster aid
- landowners whose property is repaired by aid assistance

Who pays
- taxpayers
- federal government

Example
- Disaster Relief Act of 1974 (Public Law 93-288)

Landslide Insurance

Description
Insuring residents in landslide areas against damage to their property from landslides.

Components
An insurance policy whose premiums reflect the actual risk of landslide hazards. Local land-use planning guidelines defining development in landslide areas.

Process
Residents in landslide hazard areas would pay insurance rates reflecting risk of landslides and this fund could then compensate landslide victims. To encourage landslide reduction, insurance rates could be based on engineering features and site improvements, as well as the degree of natural hazard.

Participants
- insurance company
- landowner
- local government

Technique advantages
- encourages hazard reduction by property owners
- protects existing as well as future development
- provides for equitable distribution of costs and benefits

- insurers can require risk reduction practices as a condition for insuring property
- depends more on private market and less on regulation than other approaches
- insurance could potentially reduce litigation because private parties would no longer sue to obtain compensation
- could operate along with land-use and grading regulations, each improving the performance of the other in reducing landslides and compensating victims

Technique disadvantages
- landslide probabilities are not evenly distributed which causes concern for government agencies that provide aid as a result of a disaster that might have been prevented
- insured persons may reduce care to their properties, thereby changing the probabilities upon which the premiums were based
- landslides demand unique, frequently expensive solutions for each site
- must be used in combination with other methods

Who benefits
- landowners who are insured
- the public, by reducing their economic burden in responding to landslides

Who pays
- insurance holders
- possibly government, if insurance is subsidized

Examples
- Existing landslide insurance was not identified in the literature, but could be implemented similar to flood insurance
- National Flood Insurance
- Insurance programs in New Zealand
- Insurance programs in France
- Pennsylvania Mine Subsidence Insurance
- Florida Department of Insurance Sinkhole Insurance
- West Virginia Coal-Mine Subsidence Insurance

Special Assessment Districts and Tax Adjustments

Description
Differential tax rates are levied on specific parcels located in hazard zones. Higher rates reflect costs potentially incurred by the community due to future hazard occurrence and should tend to discourage intensive hazard zone land use. Lower rates may be levied for appropriate lower intensity land uses, reflecting the costs of opportunities foregone by the land owner.

Components
Ordinance, assessment rate structure, enforcement.

Process
An appropriate ordinance and assessment rate structure is developed and administered. Low assessment values can be applied to lands left as open space by private owners to provide a property tax rate to compensate for loss of profits that might have been realized through other types of development. Landslide areas that are developed contrary to adopted plans can be assessed and taxed at rates high enough to recover costs of protecting the development by the public. Costs can be assessed in part or in whole against lands that will benefit from construction if the building of public works is necessary for the control or prevention of landslides.

Participants
- local government
- land owners

Technique advantages
- reallocates costs, to some degree, to those responsible for hazard zone activity
- less costly relative to other hazard mitigation techniques, particularly structural ones
- can be tailored to specific properties with the highest risk of landslides so the public as a whole does not have to pay
- can be applied to existing as well as future development

Technique disadvantages
- difficulty of developing viable differential rate structure
- relies on economic incentives to discourage intensive hazard zone use
- empirical evaluation of potential effectiveness not identified

Who benefits
- the community, by avoiding potential loss and obtaining revenues for mitigating hazards
- landowners, by incurring lower tax rates for developing hazardous land less intensively

Who pays
- hazard zone landowners
- community bears cost of adoption and administration

Example
- Ouray, CO

Tort Liability

Description
Governments can be held responsible for public actions that increase landslide hazard.

Components
Common law doctrine has been at least partially abolished in most states, but it is still unlikely that jurisdictions will be found liable for landslide damage resulting from planning decisions, if they are well-reasoned, policy-level decisions, using all available information.

Process
A governmental entity may be sued for actions that cause landslide damage.

Participants
- government entities
- parties affected by landslide damage

Technique advantages
- attempts to hold governmental entities responsible for public actions that increase landslide damage
- provides incentives to minimize landslide hazard incidents

Technique disadvantages

- tort system inadequately deters unsafe action and insufficiently compensates victims
- legal system can be more concerned with finding fault than with compensating victims
- lack of available landslide information presents obstacle to litigation
- dependence on litigation can result in landslide policy that is uncertain and disjointed
- useful only after disaster

Who benefits

- winners of liability litigation
- the public, if reduction in landslide hazards occurs

Who pays

- losers of liability litigation

Example

- Los Angeles County, CA (Portuguese Bend Landslide; Big Rock; Flying Triangle, etc.)

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APPENDIX 3
PHYSICAL MITIGATION METHODS

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PHYSICAL MITIGATION METHODS FOR SLUMPS AND SLIDES

Drainage

"Next to gravity, water is the most important factor in slope instability" (Sowers and Royster, 1978, p. 99), and therefore drainage is probably the most effective method of preventing or slowing slope movement. It also is commonly the most cost effective. Desirable effects of drainage include reducing the weight of the mass tending to move and increasing the strength of slope materials by decreasing hydrostatic pressure. Ideally, water should be intercepted before it enters the landslide mass. This can be accomplished by both surface and subsurface drainage methods.

Surface drainage

Surface drainage should intercept not only surface waters that would flow across the landslide mass itself, but more importantly, waters that could seep into the head scarp and cracks located within the landslide mass and behind the scarp. Ponds located on the landslide mass should also be drained.

Methods used in correcting or improving surface drainage preferably include the use of lined ditches, but unlined ditches may be used if they do not lose excessive amounts of water into the subsurface. Regrading and surface sealing are also used.

Ditches should be designed to intercept surface water from the head of the landslide mass as well as the main mass of the slide and to carry it well away from the slope. They are usually lined with impervious materials to decrease infiltration and resist erosion. In sandy soils, the ditch sides may be protected with asphalt or bitumen. A uniform gradient should be maintained to prevent deposition of material on the bottom of the ditch. Ditches are frequently placed in a herringbone pattern across a slope. However, these systems can cease to function after even slight slope movement causes realignment.

Regrading the surface of a landslide mass can promote drainage by filling unnoticed cracks and eliminating surface depressions that collect water. The finished surface should slope at a gradient of 2% or greater downslope or towards a drainage device.

Surface sealing—treating slopes to decrease infiltration—can promote rapid runoff, reduce erosion, and improve overall slope stability. Methods used include: 1) seeding and sodding, 2) guniting, 3) applying asphalt, bitumen, or waste oil products, 4) asphalt paving, and 5) compacting low-permeability soils.

Subsurface drainage

The most commonly used methods of subsurface drainage are horizontal, vertical, and trench drains. However, there are many other related methods whose effectiveness and frequency of use depend on the local geology and climate conditions.

Horizontal drains are small-diameter gravity-drained wells (Figure 1) drilled into slopes or embankments at a 5 to 10% grade and fitted with perforated drainpipe (usually 2" pvc). Drain length is usually 50 to 500 feet. These drains are most effective if they intercept aquifers, fissures, cracks, or other water-bearing zones.

Drains are usually installed in groups with the initial ones serving as exploratory borings, indicating areas where additional drains should be placed. They are often spaced at intervals of 20 to 50 feet. Horizontal drains can be used advantageously in conjunction with vertical drains, trench drains, or galleries to collect and divert water.

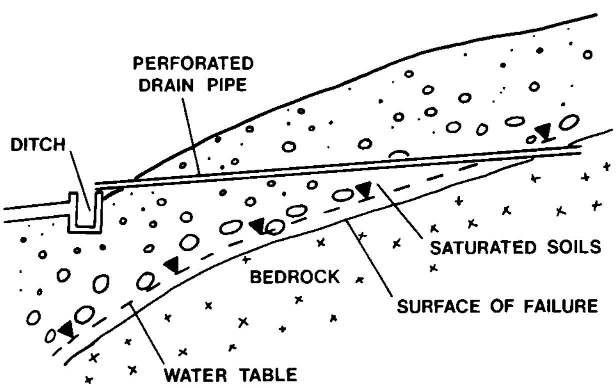

Figure 1. Horizontal drain intercepting the saturated soils above a slip surface.

Vertical drains/wells provide a drainage path between lenses or strata of water-bearing materials that are separated by impervious strata. They are also used to draw down the water table in highly fractured landslide debris. Vertical drains are 2- to 3-foot diameter shafts belled at the bottom. An 8-inch to 12-inch perforated drainpipe is placed in the center and backfilled with coarse pervious material (gravel). The well space around the pipe is then backfilled with finer filter material (sand). Wells may discharge by gravity through horizontal drains or adits, by siphoning, or by pumping. Occasionally, under favorable geologic conditions, they may be discharged into an underlying permeable stratum. They may also be used as relief wells, discharging upwards under artesian conditions.

Trench drains (also called interceptor, cut-off, or counterfort drains) are filled with graded filter material and usually have a perforated drain pipe placed in the bottom. The drains can be aligned directly downslope and fed by shallower cross-slope drains or be placed cross slope. When positioned cross slope, they should be located upslope from the slide mass or shallower than the failure surface. Shallow drains will only catch surface runoff whereas deeper ones, called interceptor or cut-off drains, will also catch ground water. The counterfort drain is an early version of the trench drain and penetrates, or keys into, bedrock beneath a slip surface, providing mechanical buttressing as well as drainage (Hutchinson, 1977).

Drainage galleries or tunnels are large-diameter (commonly about 6 foot) tunnels from which horizontal borings can be drilled deep into the subsurface beneath the slip surfaces of large, deep-seated landslides. They are capable of discharging large amounts of water, particularly when supplemented by borings in the walls, floor, or roof of the gallery. Since they are usually constructed manually, they are expensive and labor-intensive. For maximum efficiency, they should be backfilled with coarse material (a dangerous operation due to the potential collapse of the fill material on the workers).

Blanket drains are used if a surface layer of weak soil is relatively shallow and underlain by stable rock or soil. The most economical treatment is usually to strip off the unsuitable material, emplace a layer or blanket of filter material and drains, and then replace the slope or embankment material with compacted engineered fill (Gedney and Weber, 1978). This method replaces poor quality material, or material weakened due to sliding, and provides material with good drainage characteristics.

Electro-osmosis induces the migration of water out of soil pores by establishing an electric current between electrodes driven into the soil (Root, 1958). A direct current is passed from anodes (pipes) to cathodes (wells) placed at predetermined locations. The water migrates from the anodes to the cathodes and is then removed. This method works best in silts or silty-clay soils.

Blasting to increase drainage is usually used where a relatively shallow mass of cohesive soil is underlain by bedrock or other hard material and the contact between the two is smooth and sloping and forms a potential slip surface. Blasting breaks up this surface, providing a mechanical bond between it and the overlying materials and permitting drainage through the impermeable layer. However, blasting may cause slope movement; fragments from blasting will weather and add to the mass; and a weak zone may eventually develop along the contact due to migration of fine soils and healing (filling-in with fine soils) of the fracture zone.

Subsurface barriers are low-permeability cut-off walls or diversions installed below ground to redirect ground water. They are only effective if used up-slope from a slide mass. Barrier walls include slurry walls, grout curtains, sheet piling, compacted clay barriers, and impermeable membrane walls. This method is most familiar to those dealing with toxic waste containment. These walls differ from trenches in that they frequently are not designed to **capture** and **collect** water, but rather simply to **divert** it. Such barriers may have an adverse effect on adjacent slopes. Therefore, the disposition of the diverted water should be carefully planned.

Excavation or Regrading of the Slope

One of the techniques used for stopping the movement of a landslide is selective unloading of the landslide by the removal or excavation of a quantity of landslide material. The amount of material to be removed and the ideal final slope grade should be determined by stability analyses.

Total removal of slide mass

If slides are relatively shallow and the volume of material is small and/or there is a need for borrow material, it may be feasible to totally remove a slide. Any plan for removal should consider the stability of the area upslope from and lateral to the slide mass. A stability analysis should be performed.

Regrading of the slope

Changing the slope configuration may increase stability. General flattening of a slope can reduce the driving forces and may effectively halt slope movement. Terracing or benching the upper slide area also reduces the impact of surface runoff and erosion by reducing the velocity of the water and providing an area for deposition of eroded soils. Stability analyses should be performed prior to grading.

Excavation to unload the upper part of the slide.

It is sometimes possible to improve the stability of a landslide by removing material at its head. This may eliminate enough of the driving force to bring the moving mass to a state of equilibrium. This method works best if there has not been a total loss of strength in the slide mass or if the land flattens above the landslide. In some instances, the material removed from the head may be placed at the toe, thus serving as a counterweight berm.

Excavation and replacement of the toe

It is sometimes possible to **temporarily** improve the stability of a landslide by removing the most unstable material at the toe and replacing it with a buttress fill or retaining wall. However, extensive toe removal should not be undertaken unless one is prepared to do a great deal of clean up, because excavation at the toe practically guarantees further sliding. In fact, one method of stabilizing a landslide is by successively removing material at the toe causing retrogression of the slide until all unstable material is removed, or its average slope is gentle enough to be readily maintained. This method can be dangerous to construction crews, undependable, and is not generally recommended.

Restraining Structures

Retaining walls

Crib walls, bulkheads, sheet piling, bin walls, gabions, and fabric walls are just some of the various types of walls that have been constructed to restrain unstable soil and rock masses. The success of these structures depends on their ability to resist shear action, overturning, and sliding on or below the base of the structure (Root, 1958). This resistance comes from the design of the walls, as well as systems of tie backs. Retaining walls are usually placed at the toe of a slope that must be undercut. Such walls should include provisions for adequate drainage.

Piles

Piles are large vertical columns emplaced in the subsurface. They are constructed of reinforced concrete, steel, or timber and may be driven or drilled and cast-in-place. The shearing resistance of a soil mass can sometimes be increased by driving piles. A stability analysis is necessary to determine the depth of the failure surface. The piles must extend considerably below the estimated slip surface. The effectiveness of piles can be compromised by movement or flow of soil between and around piles; overturning; shear failure of the piles; or development of a new surface of rupture beneath the pile tips.

Buttresses and counterweight fills

Earth or rock berms installed near the toe of an unstable mass can prevent movement by providing either sufficient dead weight or artificially reinforced restraint. The success of these structures depends on their ability to resist overturning, sliding at or below the structure's base, and internal shearing (Gedney and Weber, 1978).

Tie rods and anchors

Tie rods and anchors can be used to provide the additional resistance necessary to prevent overturning of retaining structures. They usually consist of pre- or post-tensioned cables, steel rods, or wires. They must be securely fastened to the retaining structure and anchored to deadmen placed in the most stable accessible material behind the slide or slump back of the structure (Root, 1958).

Rock bolts/anchors/dowels

These methods are usually used to prevent movement in rocky slopes and rock slides (Figure 2). However, they can also be used on some soil slopes. See "Physical Mitigation Methods for Rockfall."

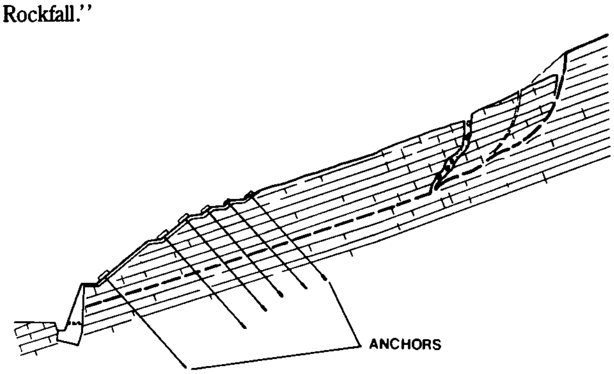

Figure 2. Placement of rock anchors for slope stabilization (modified from Zaruba and Mencl, 1982).

Vegetation

The selective use of vegetation on a slope has several advantages. Ideally, it reduces the amount of water infiltrating into the subsurface by means of interception, evaporation, and evapotranspiration. During periods of precipitation, rain can be directly intercepted by the leaves of trees and evaporate without ever reaching the ground. Much of the moisture that does infiltrate can be removed by evapotranspiration, resulting in a net reduction in pore pressure (Prandini and others, 1977). Vegetation also usually reduces surface infiltration and erosion. However, in the case of highly impermeable clay soils, the root action may actually increase infiltration. Root systems can contribute to stability by binding the surficial soils.

Vegetation is not very useful in arresting either deep-seated slope failures or vigorous erosive action such as that associated with stream and coastal waves. In addition, vegetation may be difficult to establish on some slopes, and is vulnerable to frost heave, trampling, and browsing.

It is possible to combine vegetation with structural methods to control severely eroding and landslide-prone slopes. This should decrease overall costs. Additionally, when plantings are used in the interstices of structural walls such as gabions, they may enhance the appearance (Gray and others, 1980).

Soil Hardening

Chemical treatment

If certain clay minerals such as sodium montmorillonite are present along a slip surface, it is possible to chemically induce a base-exchange reaction, which in turn will increase stability along that surface. One method used is to inject quick lime along the subsurface, or to mix it by machine and spread the material as a compacted fill (Handy and Williams, 1967; Stout, 1977). Other chemicals may also be used to induce ion exchange. The actual chemicals used are determined by the clay mineralogy of the soil to be treated and the ground-water conditions in the landslide mass (Gedney and Weber, 1978).

Freezing

Freezing slopes to attain stability is an unusual method and is rarely used. It is based on the principle that the properties of a saturated soil or rock will be altered if the state of the soil-water phase is changed from liquid to solid (ice). The two main benefits are that the strength of the soil will be increased and ground-water flow may be eliminated. The process involves circulating a coolant through cased boreholes drilled into the unstable mass. Cylinders of frozen soil form around the pipes and eventually coalesce (Attewell and Farmer, 1976). The freezing process is slow and costly, and probably is most useful as a temporary treatment to stabilize a mass long enough to construct more permanent structures.

Thermal treatment

This is the process of stabilizing loess or clay soils by passing hot gases, or burning liquid or gas fuel through a system of tunnels or boreholes. Heating dries the clays, thus increasing strength, and causes structural changes in the clays that reduce the binding capacity for water. In addition, the process evaporates accumulated pore water, increasing the frictional resistance to movement (Beles and Stanculescu, 1958). This process is expensive and is used only in special cases.

Grouting

The purpose of grouting is to either reduce the permeability or compressibility of rocks or soils, or to increase their strength or stability. Grouting is used in landslides to increase shear strength, displace water, and densify soil materials. This is achieved by filling the cavities, fissures, and pore spaces in the rock or soil with a grout. Types of grout include cement, clay, silicates, and organic polymers. The performance of various grouts depends on their particle size, viscosity, and shear strength. The choice of grout and the method of injection are determined by the properties of the ground material (Attewell and Farmer, 1976).

PHYSICAL MITIGATION METHODS FOR DEBRIS FLOWS

The choice of debris-flow mitigation measures depends on where they are to be used in relation to the three zones of debris-flow activity, 1) the source area or zone of degradation and saturation, 2) the zone of acceleration, and 3) the runout zone or zone of accumulation.

The main source area is the watershed or basin at the head of the stream. In this area the accumulation of large amounts of debris is hastened by weathering and erosion. Debris flows may start as small slumps or slides within the basin.

The stream channel is the zone of acceleration. In this area the flow gains speed and energy as it plunges down the channel. The channel may also serve as a source area because the flow can pick up additional debris from the stream bed and the sides of the channel; conversely, it may deposit part of its load in the channel.

The runout zone usually occurs where the stream intersects the valley floor of a larger stream and becomes unconfined, but it can also occur in the channel if the gradient decreases sufficiently at this point. The flow loses momentum, thins, and spreads out. It deposits its load of debris where the gradient decreases, creating a debris fan; or, if still in the channel, a levee or plug.

Mitigation methods used in the source area are aimed at stabilization of the debris. In the zone of acceleration, the goal is to break up the flow and reduce its velocity and destructive energy. In the runout zone, flow control and direct protection are the most effective methods.

Source-Area Stabilization

Check dams

Check dams are usually constructed in a series (Figure 3) and are used to stabilize heavily eroded stream reaches that are contributing to debris flows. According to Eisbacher and Clague (1984), the rising wings of the dams keep the flow of the streams to the center of the channel and prevent lateral and vertical erosion of the stream bed; deposition of sediments behind the dams adds stability to the toes of embankment slopes on the upstream side; the velocity of the water (and thus its erosive power) is

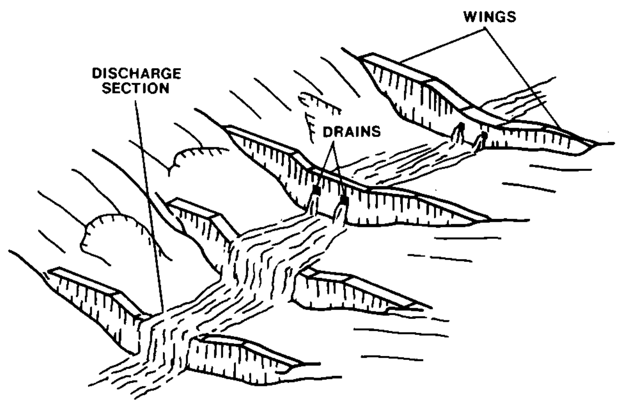

Figure 3. Check dams as they would be arranged in a stream channel to reduce flow velocity and control erosion (modified from Eisbacher and Clague, 1984).

reduced by the stepped channel profile; and the gently curved discharge sections of the dams facilitate unobstructed passage of minor debris floods and flows without endangering the stability of the dam abutments. Dams may be constructed of concrete, masonry, metal-concrete cribs, gabions, or timber. Revegetation of scarred embankments should accompany dam construction.

Revegetation

The majority of the debris mobilized in a debris flow usually originates in the source area; the rest comes from scouring of the stream channel. The availability of debris is dependent on the materials present, weathering, and mechanical erosion. Erosion is accelerated by the absence of vegetation. In some cases, logging or other human activities are responsible for the loss of vegetation. In these instances, revegetation can eventually minimize the amounts of debris available and reduce debris-flow frequency, probability, and volume. However, in other areas, lack of vegetation is due to adverse soil, weather, or altitude conditions, and revegetation is not practical.

Energy Dissipation and Flow Control

Check dams

As described above, these dams (Figure 3) reduce stream velocity and channel the flow to reduce erosion.

Deflection walls

A deflection wall is essentially a vertical retaining wall which is placed at an angle other than 90 degrees to the direction of the slope (Figure 4), thus decreasing the perpendicular component of the impact force, directing debris along the wall, and decreasing the probability that the wall will be overtopped (Hollingsworth and Kovacs, 1981). Care must be taken not to direct debris, and its potential damage, onto or toward other people's property.

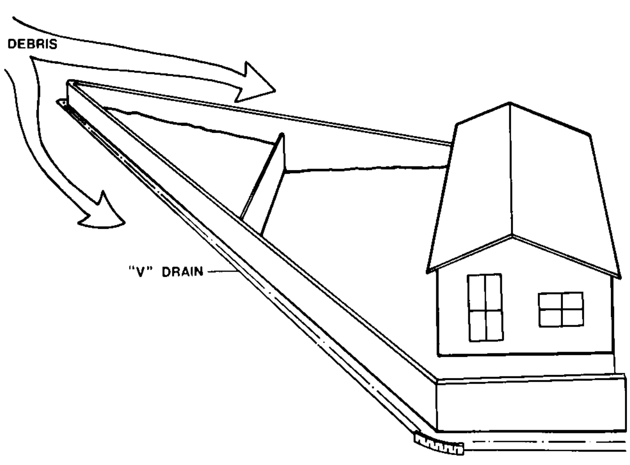

Figure 4. "A"-shaped deflection wall serving as a splitting wedge to deflect debris from the house (modified from Hollingsworth and Kovacs, 1981).

Debris basins

Debris basins or depressions are usually constructed at the mouths of canyons or on the fan to catch any debris that may come down the stream channel. They should be sized for projected design flows.

Debris fences

Debris fences are structures designed to retard the rate at which debris flows move down a slope or channel; to sort out the largest fraction of the debris (the rest passes), which also reduces volume; and to break up the flowing mass (thus reducing its impact). They are usually constructed at the apex of a debris fan or at the base of a steep slope. Materials used include steel, concrete, and masonry. The foundation sills should be keyed into bedrock and anchored since they must withstand the direct impact of debris flows (Figure 5). Openings in such structures should be large enough to permit passage of normal bedload. Also, there should be access to the backside of the fences for maintenance and removal of debris.

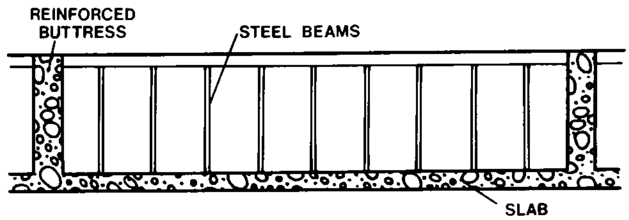

Figure 5. Debris fence (Mears, 1977).

Deflection dams

Deflection dams are large gravity structures built to channel debris flows away from inhabited areas. They are constructed at the apex of a fan and flare out in a gentle arc. Such dams should be sufficiently strong and sufficiently high that they cannot be breached or overtopped. They may be built from coarse debris deposited on the fan, but should be armored to withstand impact and erosion.

Channelization

When streams prone to debris flows and flooding flow through inhabited areas, the only mitigation option available may be channelization (Figure 6). The channel should be sized to carry at least a 100-year event. However, this may not be possible if space is limited due to existing development. Channels are usually constructed of concrete. Sufficient gradient must be maintained to convey design debris flows. Optimally, these structures are used in combination with debris basins and debris fences.

Direct Protection

Impact walls

Impact walls are placed perpendicular to the direction of the slope from which debris flows are anticipated. They are designed to retain and spread any debris coming down the slope. Walls can be constructed of earth, rock, or poured concrete with steel reinforcement. They should be designed to withstand the impact from a projected design flow.

Stem walls

A stem wall is a reinforced footing or retaining wall used to support the main wall of a building. It should extend at least 3 feet above the level of the ground on the side of the building facing upslope. The purpose of a stem wall is to resist the lateral pressures exerted when debris comes to rest against a building.

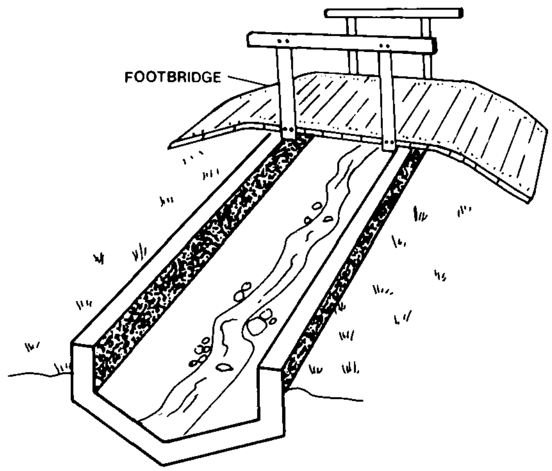

Figure 6. Lined channel to contain and direct debris flow. Foot and traffic bridges should be removable to facilitate debris removal.

Vegetation barriers

Stands of closely spaced trees or patches of shrubs may break up minor debris flows.

PHYSICAL MITIGATION METHODS FOR ROCKFALL

Before designing rockfall mitigation measures, it is necessary to understand the nature of the rockfall problem. The type, size, and shape of the rocks; their method of movement (free fall, bouncing, rolling); and the cause of the rockfall should be determined.

According to Peckover and Kerr (1977), rock instability may be the result of external or internal influences on the slope. External factors include chemical weathering of surface rocks, temperature variations, frost wedging, water running on the surface or stream erosion at the toe of the slope, and prying by the roots of vegetation. Internal factors include residual stresses from geological influences; orientation and spacing of rock defects such as joints, faults, bedding planes, and weak zones; water pressure; broken rock; and disturbance due to heavy blasting during construction.

The two principal methods of dealing with rockfall are stabilization and protection. The purpose of stabilization is to prevent rocks from moving out of place unexpectedly. Protection methods keep the rocks that do move from reaching roads or structures. Designing for rockfall must take into consideration not only the minimum width of the runout zone, but also the angular velocity built up on impact (Ritchie, 1963; Piteau and Peckover, 1978).

Stabilization

Excavation

In order to improve the stability of rock slopes, excavation can be used either to reduce the driving forces contributing to failure or to remove unstable or potentially unstable sections of the slope that may lead to failure (Piteau and Peckover, 1978). Slopes may be modified to better reflect the bedding or joint planes of the rock, flatten the slope, remove individual blocks of rock, increase the setback from structures, emplace drainage ditches, or construct benches below areas of rapidly weathering rock.

Benching

Benches are designed primarily to catch rocks and should be placed below layers of rapidly weathering rock (Figure 7). Because they interrupt and dissipate the energy of surface water flow, they also reduce erosion. Benches should be wide enough to accommodate maintenance equipment. Although benches can serve as access roads and as the basis for a contour drainage system (Fookes and Sweeney, 1976), these are not their primary function and should not influence their location.

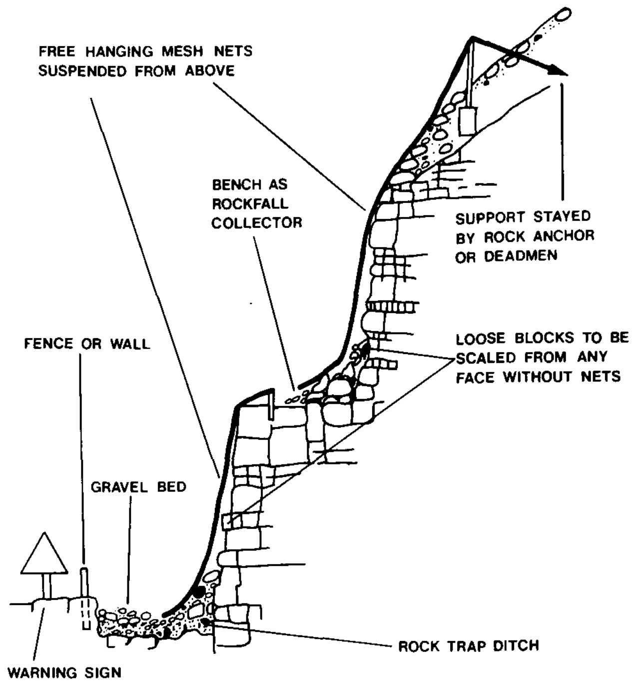

Figure 7. Rockfall control measures (modified from Fookes and Sweeney, 1976).

Scaling and trimming

The removal of loose, overhanging, or protruding blocks is a basic maintenance operation on rock slopes. Scaling is usually done by workers on ropes and is accomplished by using hand pry bars, hydraulic jacks, or explosives. Mechanical scaling equipment is available, but its use is limited by access problems. Trimming involves drilling, blasting, and scaling to remove small ragged areas where repetitive scaling would otherwise be required (Piteau and Peckover, 1978). Nonexplosive demolition agents that expand due to chemical reactions can also be used to remove rocks. Scaling and trimming is most effective and safe if initiated in the spring after the last frost.

Rock bolts/anchors/dowels

Several devices can be used to prevent movement in rocky slopes and to stabilize rock slides and occasionally soil slopes. They work by either increasing shear resistance on potential failure surfaces by forcing them together or by increasing overall strength by tying together a fractured rock mass. A rock bolt is a steel bar which is inserted in a hole drilled in the rock at right angles to the surface of weakness. The end away from the rock face has a wedge or other expansion device that permits it to be firmly anchored in the hole. The projecting end is fitted with a nut and a large washer or plate that bears against the rock surface. The bolt is placed in tension between the anchor and the plate by tightening the nut. This exerts a compressive force on the rock which increases frictional resistance within the rock mass. Unless fully grouted, bolts can lose their tension due to weathering of rock around and under the surface plates. Rock anchors are cables and are usually longer than bolts. They can be prestressed and grouted.

Bolts and anchors (Figure 8) work best in dense, consolidated rocks that are jointed or bedded with the surface of discontinuity inclined in the same direction as the slope (Coates, 1977). The angle of inclination of bolts and anchors should be examined carefully to ensure that, if deformation of the slope occurs, there will be an increase in tension in them, since relaxation may reduce their effectiveness (Zaruba and Mencl, 1982).

Dowels are steel bars grouted into holes drilled normal to the bedding and are unstressed and unanchored. These relatively short bars are used to increase shear resistance and work best to "knit" together medium- to thin-bedded materials (Fookes and Sweeney, 1976).

A "perfobolt" is basically a steel dowel encased within a thin perforated sheet-metal liner filled with low-slump slush grout. The liner is inserted into a hole drilled into the rock and then a steel reinforcement bar is inserted into the liner. This displaces the grout and forces it through the perforations. This forms a bond with the rock (Piteau and Peckover, 1978).

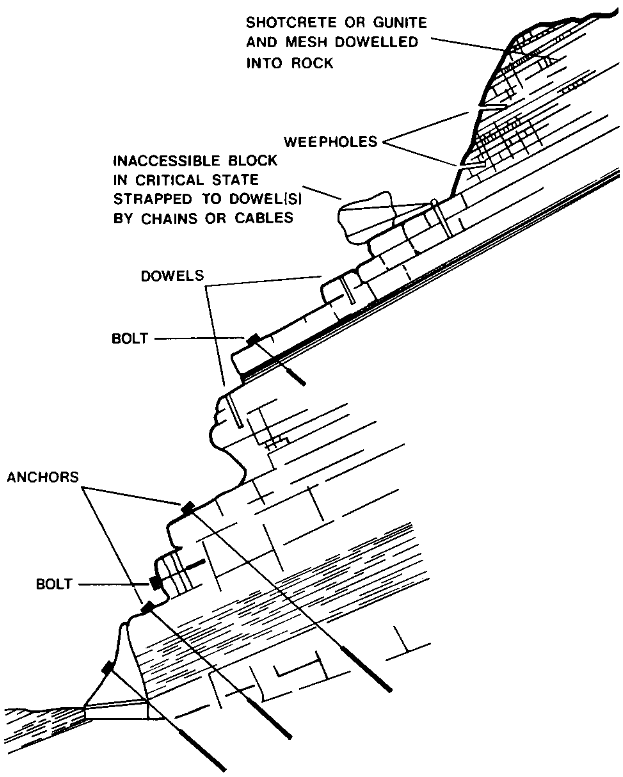

Figure 8. Rockfall control measures (modified from Fookes and Sweeney, 1976).

Chains and cables

Chains and cables may be used to temporarily hold individual blocks until they can be bolted, broken, or hauled away (Figure 8).

Anchored mesh nets

Blankets of wire mesh can be pinned onto the rock surface to prevent small loose rocks from becoming dislodged or, if draped over the surface, to guide falling rock into a ditch or onto a bench (Figure 7). Mesh in combination with both shotcrete and rock bolts provides general reinforcement and surficial support and retards the deleterious effects of weathering (Piteau and Peckover, 1978). Draped mesh can also be used for temporary protection when slopes are being worked on. In these cases, synthetic fiber nets can be used. However, they are vulnerable to being cut by the sharp edges of rocks.

Shotcrete

Applying shotcrete is one of the basic methods for treating unstable sections of rock slope. Shotcrete can be used to minimize weathering of rock surfaces, seal joints, and provide structural support. Shotcrete should be applied on cleaned scaled surfaces, and drainage should be provided (Figure 8). Failures are caused by internal water pressures, frost action, or poor bond with the rock. Shotcrete used in combination with wire mesh and bolts can substantially increase the stability of a slope (Peckover and Kerr, 1977).

Buttresses

Buttresses, bulkheads, and other support structures are used to provide permanent support under large rocks where failure appears imminent or where cracking or vertical displacement appears to be occurring. They are most effective where overhangs have developed and where excavation to remove the overhangs would either be too costly or where removal would release large amounts of material from above.

Drainage

Drainage is a basic stabilization method used for rock slopes. Both surface and subsurface water should be controlled. The methods of surface water control are the same as those used for slumps and slides and include reshaping upper slopes behind the unstable area to control water collection and runoff, providing lined ditches to divert surface flows, and minimizing removal of vegetation.

The purpose of subsurface drainage is to lower the water table, and therefore the hydrostatic pressure. The main method used to accomplish this is a system of drain holes extending behind the critical failure zone.

The effectiveness of drains depends on the size, permeability, transmissibility, and orientation of the discontinuities in the rock. Optimum performance is obtained by designing drain holes to intersect the maximum number of significant discontinuities. If freezing conditions exist, drains should be insulated and outlets kept free of blockage (Peckover and Kerr, 1977; Piteau and Peckover, 1978).

Dentition

Dentition is the process of trimming back beds of soft material between competent beds and packing the slots with bags of filter material followed by a facing of masonry or reinforced concrete. Weep holes are then installed to relieve water pressure (Fookes and Sweeney, 1976). The process is used to prop individual blocks of rock liable to roll, topple, or disintegrate and to underpin overbreak cavities and overhangs.

Protection

Rock-trap ditches

Excavated ditches can be placed at the base of vertical cliffs to catch falling rocks (Figures 7, 9). They should be of adequate depth

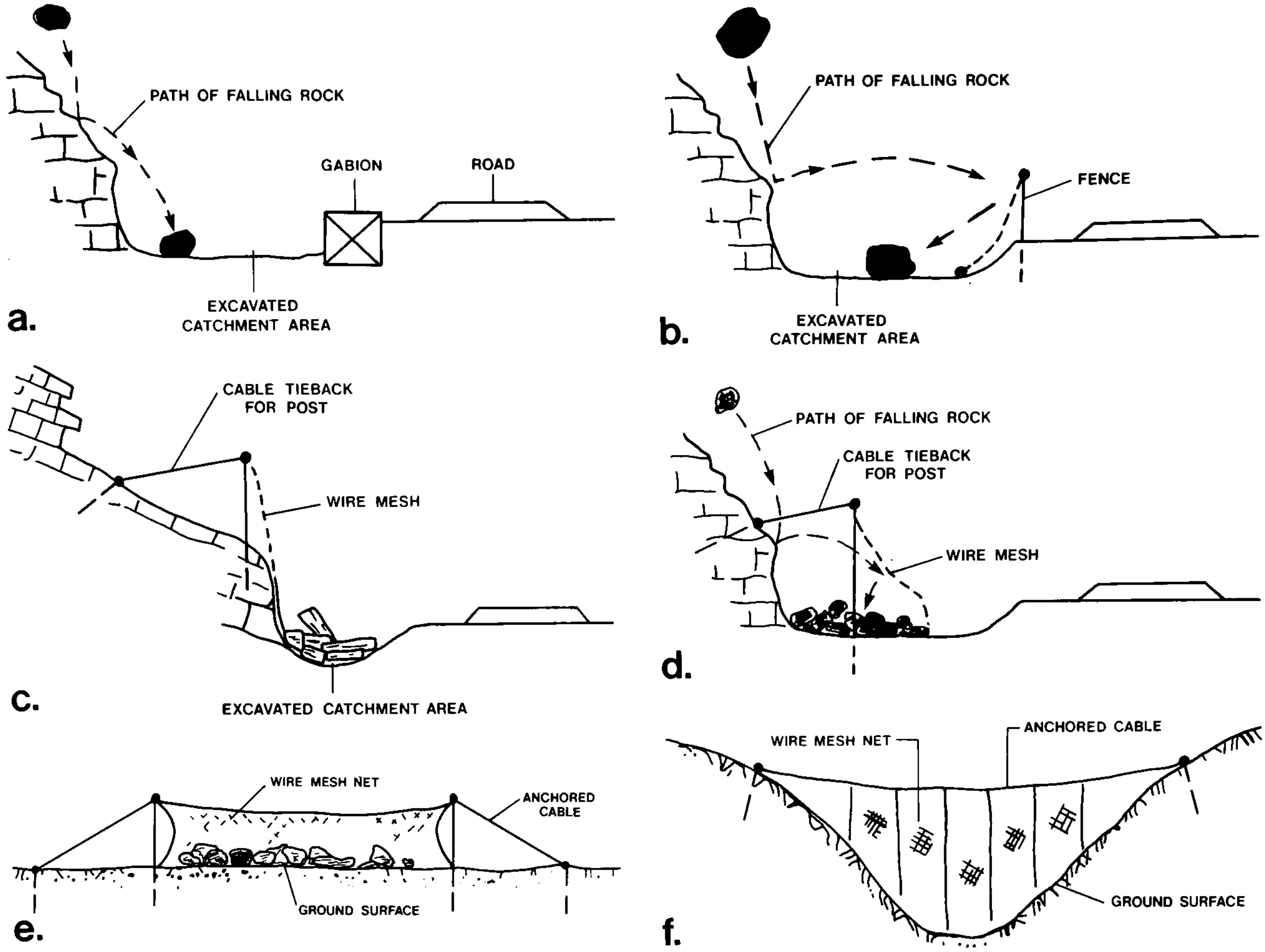

Figure 9. Rockfall control measures (modified from Peckover and Kerr, 1977): a) shaped ditch without catch fence, b) shaped ditch with catch fence, c) catch fence, d) catch fence, e) catch fence across slope, and f) catch net across gully.

and properly shaped to prevent rolling and bouncing rocks from reaching roads or structures. In areas where the ditch width is restricted by lack of space, it may be supplemented by a wall placed on the roadway side. The ditch bottom should be covered with small broken rocks or loose earth to absorb the energy of falling rocks and keep them from bouncing or shattering (Peckover and Kerr, 1977; Piteau and Peckover, 1978). Accumulated rockfall should be removed periodically.

Catch nets and fences

Wire mesh can be hung from a cable anchored to sound rock to form a catch net. Such nets work well when suspended at the lower ends of gullies where they catch rocks bouncing down the slope (Figure 9). The flexible arrangement of cable and net absorbs the energy of the rocks and allows them to fall harmlessly into a ditch or catchment area below. Catch fences also form flexible barriers that dissipate the energy of rapidly moving rocks. Wire mesh is hung on cables supported on posts, or strung between posts or trees. Fences are usually located on the roadway side of the ditch or at the base of a slope, with or without a ditch. They should be located so that accumulated rocks can be easily removed (Piteau and Peckover, 1978).

Catch walls

Catch walls are rigid barrier walls constructed on the roadway side of the rock-trap ditch to catch rolling and bouncing rocks and to increase the storage capacity of the ditch (Figure 7). They can be faced on the upslope side with loose earth to absorb the energy of the falling rocks. In recent years, gabions have been used extensively for this purpose (Figure 9a).

Rock shed or tunnel

When other forms of stabilization and protection are not effective, protective sheds or tunnels may be the only option. These are designed to allow rock to pass harmlessly over a road.

APPENDIX 4
STATE AND FEDERAL AGENCIES WITH LANDSLIDE HAZARD RESPONSIBILITIES AND AUTHORITIES

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STATE GOVERNMENT

Department of Administration (DOA)

The primary involvement of this department in landslide mitigation is in the review of proposed construction of new state buildings, the leasing of office space for state agencies, and in insuring state buildings and property.

Plans for new state buildings must be approved by the State Buildings Division (SBD), Capital Construction and Control Maintenance Section.

State office space acquisition must be approved by DOA. State agencies must indicate if the proposed facility will be exposed to geologic hazards, which could be grounds for rejecting a proposed location.

The Division of Accounts and Controls can provide emergency assistance to state agencies in the event of geologic hazard damage to their buildings. The SBD reviews the proposed repairs.

Department of Corrections (DOC)

DOC's responsibilities include providing facilities and prisoner forces for emergency response, signs identifying hazardous conditions, and industrial capacity for other disaster management related activities.

The Department's Correctional Industries unit makes highway signs. In emergency conditions, warning signs can be designed and constructed.

The Correctional Industries Program has other operations which could be used in hazard management. These include manufacturing, metal fabrication, printing, and shop services. The Industries Division has some limited capability in construction.

Department of Education (DOE)

The Department of Education provides input to 176 local school boards concerning siting of their facilities, including advice regarding geologic hazards. School districts finance facility construction and improvement entirely with locally generated revenue. School districts make many decisions independent of other government agencies, and are exempt from county land-use regulations and building codes. However, school districts must meet state building codes established by the Public Safety Division of the Department of Labor and school sites must be reviewed by the Colorado Geological Survey for geologic hazards under House Bill 1045 (1984), C.R.S. 22-32-124.

The state provides aid to school districts through the School Finance Act of 1973. However, the funds are deposited into the district's general funds and are not earmarked. No conditions are imposed on the state aid. If school districts request advice regarding project finance or architectural design, DOE staff informs them of state requirements pertaining to construction of school facilities in geologic hazard areas.

Although some school districts have prepared emergency plans, many lack them. The state does not require such plans.

Department of Health (DOH)

Hazardous Material and Waste Management Division (HMWMD)

The HMWMD and the Radiation Control Division enforce standards for wastes and radioactive substances. The HMWMD has passed regulations for hazardous waste disposal requiring avoidance of geologic hazard areas.

Water Quality Control Division (WQCD)

The Drinking Water Section of the Water Quality Control Division reviews applications for domestic water supply facilities. All parts of the water supply system up to the plant outlet, with the exception of the intake structures, must be located outside known geologic hazard areas. The DOH has control over the location of water treatment plants themselves but not over the location of distribution facilities.

The role of WQCD in geologic hazard management relating to waste water facilities includes three functions: first, the site application process, during which facility siting considerations are reviewed; second, the construction grant applications process during which an applicant requests federal funding assistance; third, the discharge permit application process. All three processes have potential for identifying and modifying inappropriate land use. WQCD relies on the Colorado Geological Survey to review approximately 150 proposals per year for geologic hazard problems.

The DOH has no authority with regard to sewage collection lines, so development in geologic hazard areas generally is not controlled even when state funding is involved.

The WQCD is sometimes involved in providing emergency help to communities suffering damage from hazard occurrence.

Department of Higher Education (DOHE)

Colorado Climate Center (CCC)

The CCC is a part of Colorado State University at Fort Collins. The center was established in 1974 to provide information and expertise on Colorado's complex climate. Through its threefold program of climate information service, data acquisition and archiving, and climate research, the center responds to climate related problems affecting landsliding.

Colorado Commission on Higher Education (CCHE)

CCHE is the policy coordinating body for the seven boards that administer the State of Colorado's 22 college campuses. CCHE has a process for planning and locating new construction. The Facility Program Plan is referred to other state agencies for review and recommendation. A checklist is used to ensure that either the college or the commission looks at the appropriate geologic hazard issues. The commission tries to assure that Campus Physical Facility Plans are consistent with local plans and with long-range state policies. They are exempt, by law, from local requirements.

Colorado State Forest Service (CSFS)

The CSFS is a branch of Colorado State University located in Fort Collins. CSFS has approximately 88 full-time employees located in 19 field offices throughout Colorado. CSFS responsibilities and capabilities related to natural hazards primarily address wildfire hazards.

CSFS activity related to landsliding includes technical assistance to public and private entities with erosion control and slope stabilization through tree/shrub planting and conservation practices.

In addition, CSFS promotes the Incident Command System (ICS) for managing emergency incidents. The ICS has been used in a variety of incidents and has potential for application to landslide emergencies. CSFS staff are qualified to manage ICS operations and support major emergencies.

The CSFS has several resources potentially available for landslide emergencies, although some services would require landowners to pay or share in the costs of assistance. Personnel and equipment may be loaned to local governments upon request of local officials or the Governor. Seedling trees and shrubs from the CSFS nursery can be provided for emergency revegetation projects. CSFS staff can develop on-site damage surveys as a basis for emergency reseeding and revegetation.

Department of Highways (CDOH)

The CDOH is involved in the design and construction of highways throughout the state. Landslides are frequently associated with construction activity in uneven terrain and may occur during or subsequent to highway construction.

CDOH policy requires evaluation of proposed construction sites for landslide hazards prior to project design. Design standards incorporate measures for avoiding or preventing landslide hazards, including alignment shifts, grade changes, drainage modifications, and special slope designs.

In the event of an impending or actual landslide, the CDOH installs barricades and implements additional traffic control measures as required. Subsequently, the road is repaired and returned to full service as soon as possible. The CDOH does not become involved in landslides occurring outside highway rights-of-way unless they pose a potential highway hazard.

Department of Institutions (DOI)

The DOI manages various facilities including several youth camps, schools, detention centers, the Fort Logan Mental Health Center, the Colorado State Hospital, and three regional centers for the developmentally disabled. In addition, DOI contracts with local agencies to provide services to particular communities.

DOI-supported mental health centers provide counseling services to survivors of disasters. The department also coordinates the work of local agencies and provides counselors serving geologic hazard victims suffering emotional or other mental health problems.

Department of Labor and Employment (DLE)

DLE has jurisdiction over all petroleum product storage tanks. The department's responsibilities include petroleum releases or spills due to geologic hazard induced damage.

Department of Law (DOL)

DOL prepares legal documents for the Division of Disaster Emergency Services (DODES) in support of its emergency functions. DOL prepares Emergency Orders upon request of DODES in order to declare a disaster area.

Department of Local Affairs (DOLA)

Division of Commerce and Economic Development (DCED)

The DCED provides grants for local public facilities through the Impact Assistance Program. Assistance applications are routed through the State Clearinghouse, providing a mechanism for considering potential exposure to geologic hazards.

Division of Local Government (DLG)

The DLG administers grant programs addressing hazard impacts. These include public facility construction grants, funded through the Housing and Urban Development (HUD) Community Development Block Grant Program, and emergency grants or loans for immediate repairs to water and sewer facilities. DLG no longer administers land-use planning grants.

The Sewer Construction Grants Program provides state funding for sewer facility construction. The money is provided by the EPA and administered by the State Health Department. DLG reviews local fiscal capabilities and comments derived from the State Clearinghouse review process. Based on this input, DLG decides whether to issue a certificate of financial need for the community. The certificate is a prerequisite to funding. The process allows DLG to request geologic information and review from the Colorado Geological Survey concerning geologic hazards.

The emergency repair fund may be used to assist needy communities in repairing damaged sewer and water systems. DLG performs a similar financial needs analysis for disaster relief grants in state-declared disasters.

The Technical Assistance Unit interacts with local governments in geologic hazard management through its field representatives.

Land Use Commission (LUC)

One of the responsibilities of the LUC, whose staff resides in the Technical Assistance Unit of the Division of Local Government, is to review rules and regulations used by state agencies implementing Executive Orders pertaining to hazard issues.

Under provisions of House Bill 1041 (1974) the LUC can request a hearing regarding development potentially exposed to natural hazards. However, after the hearing the local jurisdiction can choose not to designate such hazards.

Department of Natural Resources (DNR)

Colorado Geological Survey (CGS)

The CGS has general and specific statutory authority pertaining to geologic hazards under:

- Title 34, Article 1, Colorado Revised Statutes, Colorado Geological Survey (also known as House Bill 1282), Objectives of the Survey-Duties of State Geologist.
- Title 24, Article 65.1, Colorado Revised Statutes (also known as House Bill 1041), Government-State Areas and Activities of State Interest.

Under these titles, the CGS has provided consultation and technical assistance to state and local agencies, mapped geologic hazards, and prepared numerous technical publications. Current budget constraints preclude execution of these responsibilities except when funding can be arranged in advance from the requesting entity.

As a result of budget cuts and the legislature's requirement for state agencies to charge for their services, CGS's ability to perform its historic mission has been severely hampered. However, the agency continues to perform a limited amount of review related to geologic hazards in response to specific requests of other agencies. Review activity includes screening of selected Community Development Block Grant applications, environmental impact statements, sewage treatment plant permit applications, and siting of state facilities. In addition, the CGS reviews subdivision applications under a fee for service arrangement and new school construction, as required by state law.

Colorado Soil Conservation Board (CSCB)

House Bill 1041 (1974) charges the board and the Soil Conservation Districts with assisting local governments in identifying areas vulnerable to natural hazards, including landslides.

Colorado Water Conservation Board (CWCB)

The CWCB was created by the Legislature in 1937 for the general purpose of promoting "the conservation of the waters of the State of Colorado in order to secure the greatest utilization of such waters and the utmost prevention of floods" (*Flood Hazard Mitigation Plan*, Colorado Water Conservation Board, Department of Natural Resources, January 1985). The CWCB is the designated state agency for coordinating the National Flood Insurance Program. The CWCB may become involved in landslide hazards through NFIP activities addressing landslide hazards and in situations where landslide hazards have potential for causing flooding.

Division of Mined Land Reclamation (MLRD)

The MLRD is concerned with landslide hazard only as it relates to operating and reclaiming mines. The interaction of mining and reclamation operations with surface drainage is considered during the mine permit application review process, inspection of ongoing operations, and evaluation of final reclamation. MLRD is concerned with re-establishing stable geomorphic landforms and drainage regimes in all areas of mining. MLRD performs remedial work at old mine sites that includes addressing landslide problems. MLRD's capability to perform its functions has been hampered by legislative budget cuts.

Division of Parks and Outdoor Recreation (DPOR)

DPOR programs in potential hazard areas include recreation development centered on reservoirs, the state trails program, and Land and Water Conservation Fund supported recreational development. In administering these programs there are no established rules or regulations implementing the Governor's Executive Orders regarding hazard zone management.

Division of Water Resources (DWR)

DWR, through its Dam Safety Branch, reviews, approves, and files plans and specifications for dams prior to construction. Finished structures must be approved before storage of water is allowed. The DWR becomes involved with landslide hazards when existing or proposed dam and reservoir sites may be impacted negatively by landslide occurrence.

Division of Wildlife (DOW)

The DOW owns and controls a number of properties throughout the state. They have an ongoing inspection and maintenance program for 74 lakes, 215 wildlife areas and 14 fish hatcheries. The primary involvement of the DOW in landslide hazard management decisions is in the administration and protection of wildlife habitat areas in hazard zones.

Wildlife values can coincide with hazard management values. In some urban or urbanizing areas, protection of undeveloped slopes as wildlife areas preserves land in its undeveloped state, potentially decreasing the probability of landslide occurrence, and certainly limiting the human development that could potentially be damaged in the event of an occurrence.

DOW hazard-related initiatives are constrained by the requirement that land acquisition must be made on the basis of current, rather than potential, wildlife values. Where wildlife value criteria are appropriate, the DOW can assist communities in acquiring hazardous areas for management of wildlife.

State Land Board (SLB)

The SLB administers about 4 million acres of state-owned land. Most of this land is leased for grazing, agricultural crops, and oil development. SLB's primary concern is assuring that, at a minimum, income derived from leased property does not decrease during development, and that the state receives an appropriate share of increased land value.

SLB has begun leasing land in urban or urbanizing areas. Some of this land will include geologic hazard areas. The most likely places for such development will be the Front Range area and the Western Slope energy and recreation development areas. The property leases are long term. Homeowners could own their homes and lease the land upon which they are located.

Proposed developments are reviewed by SLB staff. However, detailed review for subdivision and zoning compliance is the responsibility of the appropriate local jurisdiction. Because local performance standards and review capabilities vary considerably throughout the state, uniformity of geologic hazard management is difficult to achieve.

The SLB is responsible for responding to landslides only if they occur on state-managed land. Response occurs on a case-by-case basis depending on the type of response needed.

Department of Personnel (DOP)

DOP's disaster-related responsibilities pertain to developing personnel resources required for emergency response. Activities include identifying, contacting, and reassigning present state employees with needed skills, as well as, obtaining temporary employees through the normal state personnel selection process.

Department of Public Safety (DPS)

Colorado State Patrol (CSP)

CSP provides assistance during hazard-induced emergencies. CSP's major responsibility is traffic management. During emergencies, the foremost traffic consideration is directing people away from danger, whether by vehicle or by foot. CSP relies on local field staff, including dispatchers, to verify and respond to an emergency. Sixteen dispatch centers are located throughout the state. In emergency situations local officers often assume command. Frequently, local officials (police chiefs, fire chiefs, and mayors) request CSP assistance from the Governor's Office.

Once a geologic hazard event is in progress, or has occurred, the CSP's primary function is instituting a command post for the disaster area. Working in concert with the Department of Military Affairs, the CSP establishes and manages these communications posts.

The CSP assists in identifying victims and in keeping lists of missing persons in natural disasters. This includes handling telephone calls originating nationwide. The Patrol's auto theft unit aids in recovery and identification of hazard-damaged motor vehicles.

Division of Disaster Emergency Services (DODES)

DODES addresses four basic aspects of disaster activity: mitigation, preparedness, response and recovery.

DODES is responsible for coordinating the work of other state agencies in these four areas. The agency's statutory authority is weaker regarding mitigation than regarding the other three areas, although DODES' coordinating role has been strengthened in recent years by a series of Executive Orders. DODES has prepared the Colorado Natural Disaster Emergency Operations Plan identifying specific activities required of state agencies during emergencies. In addition, by Executive Order, DODES has responsibility for supervising and reviewing development of local government preparedness and emergency plans.

When a specific local hazard is known, DODES takes several steps to address the hazard. First, the local preparedness plan is evaluated. Next, the means for providing help are reviewed. DODES coordinates disaster response to an occurrence, including establishing and operating a communications network. Subsequent to the immediate response, DODES assesses the natural occurrence and response and recommends initiatives for preventing or mitigating future losses. Following a disaster declaration, DODES coordinates development of an agreement among involved entities requiring preparation of a mitigation plan.

DODES acts as the conduit for emergency assistance to local governments from the Governor's Office. In the event of a request for assistance DODES:

- assesses damages and local efforts made to repair damages; reviews analysis of the Colorado Department of Local Affairs, Division of Local Government, regarding local capacity to finance recovery efforts,
- recommends appropriate funding for consideration by the Governor; assistance is limited to funding emergency repairs only,
- processes a state-local agreement enabling transfer of funds to the impacted local government,
- performs on-site evaluation of emergency response activities.

The means by which DODES encourages local governments to improve local hazard mitigation programs includes:

- federal pass-through funding,
- state funding assisting local government recovery from a state-declared disaster,
- state law requiring local emergency preparedness plans.

DODES reviews current research in the area of disaster preparedness and recovery to keep the state abreast of recent national and international trends. In addition, DODES has prepared a report entitled *Colorado's Vulnerability to Very High Risk Natural Hazards*, providing a statewide perspective of hazards and preparedness. The report includes consideration of landslide hazards.

Department of Regulatory Agencies (DORA)

General responsibilities of the DORA include:

- coordinating emergency regulation of public utilities within the state,
- assisting in the emergency regulation of industry and commerce within the state,
- promoting the National Flood Insurance Program within political subdivisions and the commercial insurance industry,
- issuing certifications for hazard insurance.

Responsibilities related specifically to hazard management include:

- providing insurance claims information to disaster victims upon request,
- furnishing resource lists of specialized personnel as required under emergency conditions,
- promoting a system for cooperation between professional associations and state disaster/emergency response organizations.

Coordinating responsibilities of the DORA include:

- validating, aggregating, and providing damage assessments concerning private, nonprofit and public utilities to the State Emergency Operations Center in coordination with local governments and related federal agencies,
- providing inspectors to participate in damage assessment of private, nonprofit and public utilities, as required,
- recommending initiatives improving response, relief, and mitigation of a declared disaster to DODES within three months.

Department of Revenue (DOR)

In the event of a natural disaster, the DOR's Motor Vehicle Division responds to authorized requests for aid in identifying disaster victims. Specifically, DOR responds to requests for identification of vehicles involved in the disaster or emergency. Upon application, and when authorized, the department issues disaster identification cards.

In the aftermath of a natural disaster, the DOR's Taxpayer Service Division responds to requests for assistance from individual or corporate taxpayers directly affected by the disaster.

In the event of a natural disaster, the DOR Research and Statistics Section, upon request of state or federal agencies, assesses potential revenue impacts and provides information concerning local financial status in support of disaster assistance eligibility determinations.

Department of Social Services (DOSS)

The DOSS administers the Individual and Family Grant Program, authorized under Section 408 of the Federal Disaster Relief Act of 1974. The program is used following declaration of a major disaster by the President and Governor.

The program assists victims suffering loss in designated disaster areas by providing direct grants up to $5,000 to individuals and families. The grants are 75% federal and 25% state funds. Assistance is permitted for meeting victim's necessary expenses or serious needs for which alternative assistance, including insurance, is unavailable or inadequate. Funds may not be used for non-essential, luxury, or decorative items or services. The executive director of the State Department of Social Services is responsible for administering the program as it applies to both state and county departments of social services.

Department of State (DOSt)

DOSt responsibilities include maintaining records of executive orders, proclamations, etc., supporting continuity of government, or modifying government rules and regulations. DOSt certifies and maintains records concerning private incorporations and formation of governmental entities. DOSt emergency responsibilities pertain primarily to maintaining, protecting, and issuing critical state documents during and subsequent to a major emergency. In addition, DOSt supports DODES in developing interstate agreements for disaster response.

Governor's Office (GOV)

The Governor's Office is responsible for making state disaster declarations, usually upon recommendation of the Division of Disaster Emergency Services (DODES), and in support of a request for a Presidential disaster declaration. The Governor's Office is responsible for managing the state public information program, located in the disaster field office, during the recovery efforts.

Office of State Planning and Budgeting (OSPB)

OSPB manages state funds in the event of a natural disaster. The Governor has the authority to spend amounts that are required, as well as divert individual state agency funds to combat an emergency. OSPB exercises a leading role in identifying, and recommending to the Governor state agency funding contributions for disaster response and assistance.

FEDERAL GOVERNMENT

Department of Agriculture (USDA)

U.S. Forest Service (USFS)

USFS has authority and responsibility to engage in emergency activities on National Forest land. In the event of an emergency, their objectives are to:

- render authorized, timely, physical assistance whenever necessary for the immediate protection of life and property,
- coordinate USFS efforts with those of other agencies engaged in disaster relief,
- assist state and local governments in disaster response efforts upon request.

During emergencies the USFS may implement emergency measures on National Forest land safeguarding life and property downstream from watershed lands suddenly damaged by fire, flood, and other natural disasters. Where natural disasters cover National Forest, as well as, state and/or private lands, the USFS works closely with the relevant parties.

U.S. Soil Conservation Service (SCS)

SCS provides technical assistance in the conservation, development, and productive use of soil and water resources. SCS activities in Colorado include watershed protection, flood protection projects, floodplain management studies, resource conservation and development, emergency watershed protection, conservation technical assistance, soil surveys, snow surveys, and water supply forecasting.

Department of the Army

U.S. Army Corps of Engineers (COE)

The COE has authority to respond to landslides where COE reservoirs or projects have been affected or major flooding has occurred. In the case of landslide-obstructed streamflow, the COE would provide technical assistance to state and local agencies involved in the mitigation activity.

Department of Commerce (DOC)

National Weather Service (NWS)

NWS is responsible for 36 to 48 hour weather forecasting. The agency issues severe-weather warnings and watches regarding conditions that increase the probability of landsliding. In addition, NWS attempts to identify areas prone to landsliding.

Department of The Interior (DOI)

U.S. Bureau of Land Management (BLM)

BLM has district offices located in 11 Western states. Four district offices are located in Colorado. District offices prepare resource management plans for the public lands within the district. The plans include maps and other information identifying and characterizing landslides, debris flows, and unstable soil. Leasing of BLM land to private companies requires preparation of an Environmental Impact Statement detailing how the leasee will manage the identified geologic hazards.

BLM provides technical assistance to other federal, state, and local agencies and is active in post-hazard activities on BLM land.

U.S. Bureau of Reclamation (BUREC)

BUREC develops and administers federal multipurpose water resources developments in 17 Western states. The purposes of the projects are agricultural irrigation, hydroelectric power, municipal and industrial water supply, flood control, fish and wildlife enhancement, recreation, and other natural resource conservation concerns.

BUREC's six regional offices maintain a registry of landslides on and adjacent to all BUREC facilities. The agency performs periodic inspections, instrument surveillance, and site-specific geologic investigations of landslides potentially threatening BUREC facilities. Various levels of risk are assigned each landslide area indicating its potential for causing damage to other potentially vulnerable properties, in addition to BUREC facilities. BUREC designs and implements mitigation measures controlling the landslides and/or minimizing potential damage as required. BUREC assists other federal, state, and local organizations in performing any of the identified services.

U.S. Geological Survey (USGS)

USGS was established by Congress on March 3, 1879 to classify public lands and examine the geological structure, mineral resources, and products of the country. Over the years, other Congressional acts have expanded USGS duties and functions to include geologic and topographic mapping, issuing "Geological Hazard Warnings", and other related functions.

A "Geologic Hazard Warning" is a formal statement by the USGS Director discussing a specific geological condition, process, or potential event presenting a significant public threat to which a timely response is expected. Statements may be issued by responsible officials of other federal, state, or local agencies directing the public to take action based on a "Geologic Hazard Warning".

USGS provides technical assistance and information to states on a case-by-case basis. In addition, the agency consults with state and local governments in assessing geologic hazard situations and recommending mitigation schemes.

National Park Service (NPS)

Each NPS service area conducts a number of activities addressing natural hazards under the direction of the superintendent and chief ranger. Activities include resource surveys as a basis for park management, which in turn include problem identification and recommendations. Potential hazards are identified and relevant public information developed. Each NPS park develops an Emergency Action Plan (EAP) responding to potential natural hazard occurrences within the park. The EAP identifies corresponding responsibilities of NPS personnel, as well as relevant local agencies and resources. NPS uses the Incident Command System (ICS), and serves on the state Incident Management System Board. NPS has authority to assist in disaster response activities on adjacent lands so long as sufficient staff remain in the park to provide emergency response and visitor services there.

Department of Transportation (DOT)

Federal Highway Administration (FHWA)

FHWA provides highway construction grants to the state and administers federal highway construction appropriations. Federal administration and funding requires that highways constructed and maintained with federal money comply with regulations addressing geologic hazard conditions. FHWA provides funding for maintaining and rebuilding federally assisted highway facilities damaged by geologic hazards when required repairs exceed the local financial capabilities. FHWA will assist in surveying roadway damage in geologic hazard areas.

Federal Emergency Management Agency (FEMA)

FEMA was instituted on April 1, 1979 by the President's Reorganization Plan No. 3 of 1978. Several existing federal functions related to natural and human-induced hazards were consolidated under FEMA authority. Colorado is located in FEMA Region VIII which has its central office in the Denver Federal Center.

Disaster Assistance Programs Division (DAP)

DAP is the lead federal agency coordinating the federal emergency response, disaster relief funding, and hazard mitigation planning in the event of a Presidential declaration. DAP coordinates assistance provision and activation of an intergovernmental hazard mitigation team under Public Law 93-288.

Federal funds are provided assisting individuals and state and local governments. State and local assistance is for repair or replacement of public facilities, e.g., roads, buildings. The program requires 25% matching funds from non-federal sources.

DAP promotes hazard mitigation immediately following a disaster through activation of an intergovernmental, interagency hazard mitigation team. The team, comprised of federal, state, and local representatives, surveys the disaster area and identifies opportunities for hazard mitigation. Action recommendations are presented in a report completed within 15 days of the disaster declaration. Follow-up reports are then required at both 90 and 120 days from the declaration date.

Federal Insurance Administration (FIA)

The FIA administers the National Flood Insurance Program that provides federal flood and mudslide insurance. The FIA maps flood hazard areas and provides technical assistance to communities regarding nonstructural flood and mudslide hazard management techniques.

APPENDIX 5
THREE CASE HISTORIES OF LANDSLIDING IN COLORADO

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CASE STUDY NO. 1
POTENTIALLY CATASTROPHIC LANDSLIDES - A CASE HISTORY (DOWDS JUNCTION, EAGLE COUNTY, COLORADO)

Introduction

Dowds Junction is located in Eagle County, Colorado, at the intersection of U.S. Highways 6 and 24 with Interstate Highway 70 (I-70). It is approximately 2 miles west of Vail and 2½ miles north of Minturn near the confluence of Gore Creek and the Eagle River (Figure 1).

The landslide complex includes four distinct landslide areas: Whiskey Creek, Dowds No. 1, Dowds No. 2, and Meadow Mountain (Figure 2).

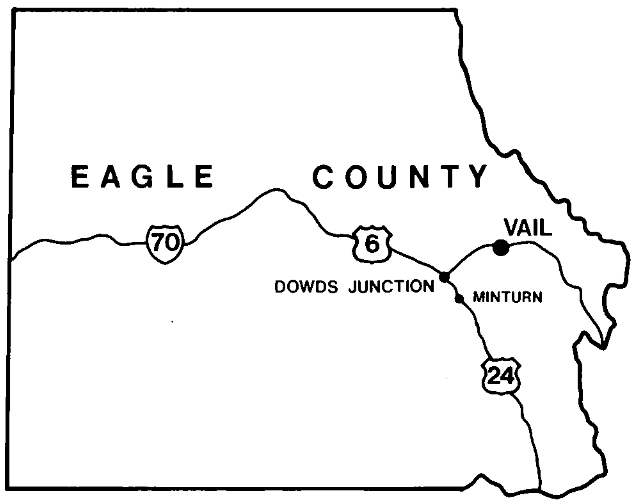


Figure 1. Location map of Dowds Junction.

The Landslide Hazard

The landslides at Dowds Junction are but one of a dozen major landslide areas preliminarily identified in the 1985 *Flood Hazard Mitigation Plan for Colorado.* Through the years, a great deal of highway maintenance related indirectly to the old landslides has been required at the Dowds Junction location. The soils in the area are seasonally wet and have low strengths in many places. The Meadow Mountain landslide south of Dowds Junction on U.S. 24 has apparently been active since before construction of that highway in 1930, and has been the focus of a number of minor grading and leveling projects; especially during snowmelt periods. Repeated patching and overlays on U.S. 24 have resulted in 8 to 10 feet of asphalt in the roadbed.

After the Colorado Department of Highways (CDOH) experienced the partial loss of an approximately 300-foot-long section of U.S. 24 between Dowds Junction and Minturn in late April

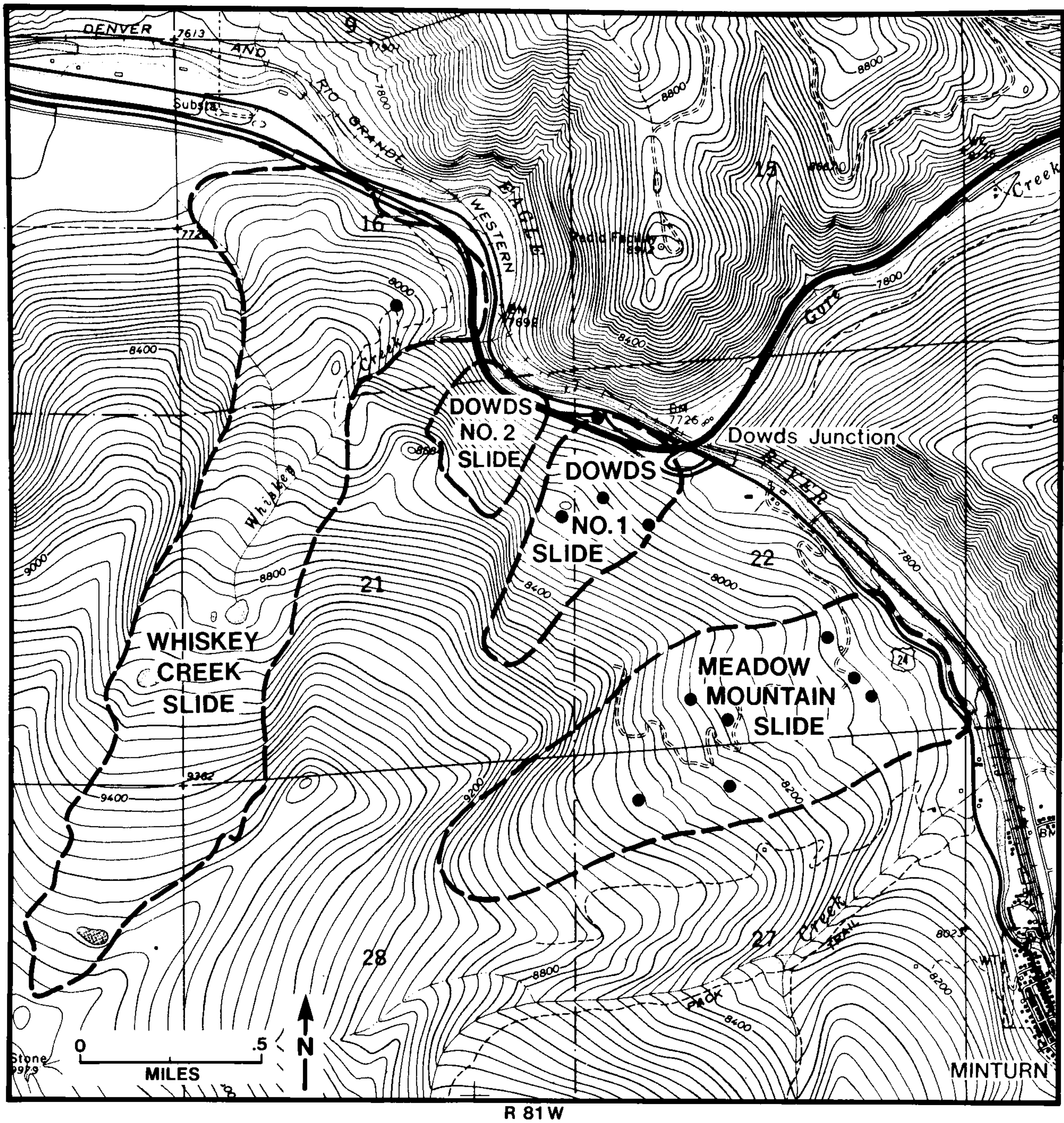


Figure 2. The four landslides at Dowds Junction (modified from Robinson and Associates, 1975).

1985, the Governor formed an interagency Earthflows Task Force to examine the potential consequences of the landsliding at Dowds Junction, and to investigate the range of measures that might be applied to mitigate the potential damages. The CGS and CDOH began a joint study of the Meadow Mountain landslide. The first on-site work was conducted by CDOH. This work consisted of drilling five boreholes, installing 12 electronic distance measuring stations (EDM points), and diverting water by ditching to keep, to the extent possible, snowmelt water out of the landslide. This initial work investigated a relatively small landslide (hereafter referred to as the "highway" landslide) that is in reality a small component of a much larger feature (hereafter referred to as the "intermediate landslide") which is in turn a part of the very large older Meadow Mountain landslide.

The continued instability of road cuts in three other landslides in the general vicinity of Dowds Junction (Dowds No. 1, Dowds No. 2, and Whiskey Creek landslides), which had not previously been carefully monitored and studied by CDOH or CGS, prompted the cooperative study of landslides in the area by the two agencies.

Land-Use and Development History

1963: Formal design studies for I-70 in the Dowds Junction area began in 1963. The K.R. White Company completed geologic studies in 1966 and presented their recommendations in 1967. The old landslides were recognized and methods to allow construction were presented in that report. These recommendations were incorporated into the highway design. A gravel drainage blanket was built under the I-70 embankment in anticipation of roadbed stability problems.

1968: During construction of the I-70 Eagle River bridge in 1968, it was observed that some movement of the landslide was occurring on the south side of the river. The CDOH monitored that area for approximately 5 years by means of a triangulation survey, and observed annual movements of 1/2 to 3 inches per year. Most movement occurred during the snowmelt period. Continuing slow movement was noted in the west abutment, but no serious distress was recorded in the bridge structure or foundation. Formal monitoring was discontinued in about 1975; however, some movement in the roadway west of the bridge continued each year requiring maintenance.

Several problems related to soils and geology have been experienced since completion of the I-70 construction. A cut-slope failure occurred prior to paving and was corrected using a large rock buttress.

1972: Artesian water flow emerged from the pavement during the spring. This was corrected with horizontal drains.

1981: The bin-wall that supports the I-70 fill above the frontage road west of the Dowds Interchange has shown various signs of distress. The fill slope above the bin-wall failed badly enough to require construction of a short wall to maintain the I-70 guardrail in 1981.

1983: Two landslides occurred, blocking I-70 for a few hours. Also, a large fill failure occurred that closed the westbound frontage road for several days.

The period 1983 to 1984 experienced record-breaking precipitation characterized by unusually heavy snowfall in the fall before the ground had frozen. Snow-course measurements for October and November were unusually high for the area. As this heavy snowfall melted, it soaked much more deeply into the ground than later snowfalls after the ground had frozen. Unusually large and more numerous occurrences of freezing ground-water springs issuing from normally dry cliffs, road cuts, and hill slopes were observed in several locations along the I-70 corridor.

1984: The eastbound lane of I-70 and the U.S. 24 interchange were closed in the spring of 1984 by landslide movement during the period of high water saturation.

1985: In March, Eagle County officials and Division of Disaster Emergency Services (DODES) staff expressed concern about the springtime landslide activity occurring in the Dowds Junction area and affecting U.S. 24 and I-70. As a result, the CGS and CDOH formulated a plan for limited but immediate instrumentation with complete detailed geologic evaluation to follow later in 1985. However, increased concern over the similarity of potential landslides in this area to the Thistle Landslide in Utah prompted the CGS to do a brief office study to determine if immediate action was needed. The study documented a trend of steadily increasing soil moisture over the preceding 3 to 4 years in Eagle County. This, and the geologic similarity to Thistle, resulted in the Governor forming an Earthflows Task Force to evaluate and address the Dowds Junction situation. The task force met weekly. Various affected and contributing agencies and individuals were identified and liaison was established. A more aggressive schedule of studying and monitoring the landslides was devised and undertaken, emergency-response plans and exercises were implemented, and various contingencies were considered and discussed. The task force also assisted DODES in planning and carrying out two emergency exercises.

In the fall of 1985 and the winter of 1986, the CGS and the Colorado Water Conservation Board (CWCB), as members of the task force, performed reconnaissance level engineering and geological evaluations of possible options to mitigate the impacts of the landslides. Over 40 options were presented in response to the range of potential threats posed by the landslides. The analyses were based on the possible geologic and hydrologic consequences if major earthflows occurred and river damming resulted.

Descriptions of the Four Landslides

Meadow Mountain

The Meadow Mountain landslide is a compound slope failure consisting of shallow to deep (up to 40 feet) earthflows occurring on the surface of at least three much deeper (90-160 feet) translational landslides involving bedrock. The basal surface has numerous bedrock shear zones present above the basal shear which occurs at different places within the Belden Shale or in the Minturn Formation.

The landslide area covers more than one-half square mile. In the highest parts of the Meadow Mountain landslide, older landslide material is covered by glacial drift, mostly bouldery gravels.

Whiskey Creek

The Whiskey Creek landslide consists predominantly of 1- to 6-inch clasts of mudstone and sandstone in a clayey matrix. The texture indicates that the landslide formed initially as a massive earthflow or a series of earthflows. Ancient stream gravel associated with a distributary channel on an older landslide surface was encountered between a depth of 210 and 215 feet. The landslide is 244 feet deep below the one drill-hole location.

This landslide is the largest in the area. However, it is also probably the oldest and least active with the exception of the toe of its east lobe, adjacent to I-70.

Dowds No. 1

The lowest part of the Dowds No. 1 landslide is composed of ancient river gravels resting on Minturn Formation bedrock. The gravels represent a former course of the Eagle River and probably are evidence that in the past, movement of the upper part of the landslide forced the river to alter its course to the north. Drilling of the toe of this landslide revealed several shear zones including ones at 45 and 75 feet and a basal shear zone at 142-165 feet below ground surface.

The lower part of the landslide has a long documented history of slow movement and has damaged I-70, the nearby highway bridge, and its west approach. Approximately the upper one-half of the landslide shows no evidence of modern movement.

The upper area of the landslide is composed of very large blocky material consisting of arkosic sandstone of the Minturn Formation with individual blocks ranging up to 30 feet in diameter. This blocky material is very permeable and snowmelt water percolates rapidly into the subsurface. The morphology of the ground surface, vegetation changes and types, combined with drilling data and the known history of the landslide indicate continuing, relatively slow modern movement of the lower landslide area.

A scarp within the landslide coincides with a vegetation change from coniferous to deciduous forest. Water was issuing from the ground along this scarp in May 1985. The geology of the landslide in this area is similar to the upper part of the landslide except that the large blocks are absent.

Dowds No. 2

This is the smallest landslide in the area. It consists predominantly of large blocky material from the Minturn Formation with a clay and sand matrix. The landslide has been active recently and damaged I-70 in 1983.

Community Impact

Catastrophic land failure in the Dowds Junction area could result in the following potential impacts:

1) The potential loss of life due to persons being buried by a fast moving landslide. Approximately 100 people are estimated to be at risk.
2) The potential for losses to private property in the landslide area—estimated at over $10 million.
3) The potential economic loss of a significant transportation corridor including I-70, U.S. 6 and 24, and the Denver and Rio Grande Western Railroad. Temporary disruption of this corridor for a 90-day period could result in an economic loss of about $600 million.
4) The potential flooding of the town of Minturn, population 1300, and perhaps a part of West Vail, if flow in the Eagle River is impeded by a Thistle-type landslide dam. With the total submergence of about 500 structures, losses would be at least $50 million.
5) The potential flooding of portions of the towns and unincorporated communities of Eagle-Vail, Avon, Edwards, Wolcott, Eagle, and Gypsum could occur due to a sudden or rapid failure of any dam formed by the landslide. Approximately 3000 people are at risk, and the damages to over 1000 structures could total over a billion dollars.
6) The potential cost of fighting such a disaster—estimated at about $40 million.

Mitigation

The following are the options presented in the 1986 Minturn Earthflows Landslide Task Force report:

Table 1. Proposed mitigation options - Dowds Junction.

OPTION 1: NONSTRUCTURAL SOLUTIONS			
RECOMMENDATION	**TIME FRAME**	**RESPONSIBLE PARTY**	**ESTIMATED COST**
Buy flood insurance in affected areas:	Immediate	Eagle County provide information to local jurisdictions and unincorporated areas. Individuals work with local insurance agents	Average policy about $250 for $50,000 of coverage. $1.7 billion damage potential
Creekside (multi-family housing)	Purchase immediately		—
Mintum	Investigate immediately	Individual decision	—
Downstream along Eagle River	Investigate immediately	Individual decision	—
Other types of insurance	Immediate	Governor request State Insurance Commission to provide information to Eagle County on insurance options	Depends on carrier
Visual inspections	Weekly: April 1 - August 1 (every year)	Joint effort of the CGS, CDOH, and Eagle County Surveyor. System and schedule to be coordinated by the CGS	General Fund; approximately $15,000
Preparation for 1986 EDM Program:			
1. Redrill Whiskey Creek monitoring hole which has been destroyed due to movement	Completed summer 1986	Contract with CDOH	$5,000 (Potential need to cost-share between CDOH, Governor's Emergency Fund, and Eagle County)

Table 1. (Cont.)

RECOMMENDATION	TIME FRAME	RESPONSIBLE PARTY	ESTIMATED COST
2. Drill new hole in Meadow Mountain for depth and volume information	Completed summer 1986	Contract with CDOH	$5,000 (Potential need to cost-share between CDOH, Governor's Emergency Fund, and Eagle County)
1986 EDM Program Option 1:			
Purchase Geodetic Total Station	Purchased summer 1986	Schedule for readings: April - CDOH, May/June - CGS, July - Highways, CGS, or County Surveyor	$10,000 to purchase Station (potential need to cost-share between CDOH, Governor's Emergency Fund, and Eagle County). Less labor intensive than 1985 due to new equipment. Readings would be provided in-kind by indicated agencies
Option 2: Purchase no new equipment - readings done manually which requires dedicated staff time	Read EDM's every other week: April 1-August 1 (or weekly if necessary) in 1986	Contract with either CGS or Eagle County for the readings	$9,500 for labor (potential need to cost-share between CDOH, Governor's Emergency Fund, and Eagle County)
1987 + EDM Program	Reading cycle to be determined based on annual precipitation and interpretation of 1986 data	CDOH, CGS, Eagle County	Depends on actions recommended
Read water levels	Every other week: April 15-August 1	CDOH to take readings; CGS to interpret data	General Fund (cost approximately $250/trip)
Read inclinometer	Every other week: April 15-August 1	CDOH to take readings; CGS to interpret data	General Fund (cost approximately $250/trip)
Cut drain in the marsh area above the landslide	Immediately for one pond	Governor request U.S. Forest Service to dewater pond	$1,000 (?)
	Evaluate the larger area for dewatering next year	U.S. Forest Service	(?)
Monitor precipitation trends	Monthly	State Climatologist in conjunction with the National Weather Service and the U.S. Soil Conservation Service. Information forwarded to Eagle County	Existing agency responsibilities
Monitor snowpack trends	Monthly	U.S. Soil Conservation Service forward data to County	Existing agency responsibility
Monitor run-off	Frequency determined by the CWCB	County take readings as appropriate from stream gauges. Data forwarded to the CWCB	General Fund responsibiltiy of CWCB and Eagle County

Table 1. (Cont.)

RECOMMENDATION	TIME FRAME	RESPONSIBLE PARTY	ESTIMATED COST
Investigate potential reservoir characteristics	Data has been collected. Curves to be developed.	Division of Water Resources and the CWCB prepare area-capacity curves for potential reservoirs caused by the Whiskey Creek/Meadow Mountain landslides	General Fund
Investigate slide characteristics	Drilling and photography has been completed. Analysis to be completed later as necessary. Technical report due July 1, 1986	CGS to prepare report	$15,000 contract from CDOH to CGS
Improve Communications Network:			
Review status of local emergency operations plans for Minturn, West Vail, Avon, Eagle, Gypsum, Vail, and Eagle Counties. Take appropriate action to address planning shortfalls	May 1986-April 1987	DODES with identified local governments	$1500 General Fund
Based on exercises run to date develop a checklist identifying state agency responsibilities and major issues to be addressed by each agency should a major incident actually occur. Encourage preplanning on the part of all agencies concerned	May - June 1986	DODES	$250 General Fund
Conduct a communications exercise to identify needed system improvements and present system shortfalls. Develop actions to be taken and time frame to address each shortfall. Emphasis to be placed on ability to communicate between command and field elements of different levels of government and from different jurisdictions, as well as internal command communications	Fall 1986	DODES-supported by state and local government agencies	$2000 General Fund
Evaluate existing system to disseminate warning information to governmental agencies and the general public. Identify system deficiencies and take action to address them	Summer-fall 1986. Implement actions to correct deficiencies once identified	DODES-supported by state and local government agencies	$2000 General Fund
Determine need for future exercises	January 1987	DODES-in coordination with state and local government agencies	—
Identify training weaknesses which surface during the planning and exercise process. Develop and conduct training to address the identified weaknesses	Continuous process. Initial effort May 1986-April 1987	DODES-all state and local governmental agencies	To be identified

Table 1. (Cont.)

RECOMMENDATION	TIME FRAME	RESPONSIBLE PARTY	ESTIMATED COST
Upgrade status of Eagle County Emergency Preparedness Program to a full-time staff position to manage local planning and exercising	Spring 1986	Eagle County in coordination with DODES	—
Regulate development in the hazard area	Immediately	Eagle County and local jurisdiction responsibility. Technical assistance from CGS	—
Acquire and relocate the vulnerable areas	Discussions in the near term	Colorado Department of Local Affairs and Eagle County develop options for the State Legislature, U.S. Army Corps of Engineers and the Federal Emergency Management Agency	Unknown
Reroute the transportation network	To be addressed at time of landslide based on actual needs for both state and federal highway access	Alternate temporary routes have been identified by responsible parties. CDOH performing maintenance on bridges in the event of rerouting	Unknown but will involve state and federal highway funds
Reroute sewers, etc.	Contingency plans should be developed immediately	DODES to advise responsible parties of potential dangers and encourage their own contingency plans	—
Record expenditures	Ongoing	All parties should maintain records of costs (both special appropriations and ongoing expenditures) for possible federal reimbursement in an emergency	—
Construct landslide deflection structures	Not feasible	—	—
	OPTION 2: STOP IT FROM MOVING		
Cease or reduce irrigation of the landslide	As requested	Division of Water Resources advise owners of situation and necessary actions. CGS to do some preliminary impact analyses in 1986	—
Pump water out of old landslide mass	Preliminary data collected in 1986	CGS collecting preliminary data to be translated into a hydrogeological study and recommendations in 1986	Unknown
Construct drains in landslide	Work begun as needed	CDOH has installed drains under the crib wall of the Dowds No. 2 landslide	General Fund
Control drainage in landslide area	Preliminary data collected in 1986	CGS collecting preliminary data to be translated into a hydrogeological study and recommendations in 1986	General Fund
Channelize the river at the base of the landslide	To be determined	This option may not be necessary; future actions will be based on the results of the buttressing currently underway by CDOH	Unknown
Install toe anchors to stabilize landslide	Currently underway	CDOH	$100,000 General Fund

Table 1. (Cont.)

RECOMMENDATION	TIME FRAME	RESPONSIBLE PARTY	ESTIMATED COST
Stabilize landslide by special chemical treatment	Not practical; technology untested	—	—
Remove unstable landslide material	Inadvisable since sources of movement and interconnection of landslide mass is unknown	—	—
	OPTION 3: DON'T LET IT FLOOD		
Modify weather	Not feasible; technology uncertain	—	—
Divert water from the basin	Immediately. Collect background data and set up diversion agreements. Plan should be activated now	Division of Water Resources collects background data. Division engineer should work with DODES in the development of the plan	General Fund
Release water from upstream reservoirs	Develop procedures and set up agreements immediately	Division of Water Resources, Water Planning Branch, to develop plan. U.S. Army Corps of Engineers will be requested by the Governor to provide technical assistance	—
Store water in upstream reservoirs	Develop procedures now	Division of Water Resources, Water Planning Branch, to develop plan. U.S. Army Corps of Engineers will be requested by the Governor to provide technical assistance	—
Build a new flood control dam	Investigation to be suggested immediately	The state will formally request the proponents of the Homestake II project to include landslide mitigation impacts as part of the evaluation and design of the project. The CWCB and the Division of Water Resources will provide comments	Unknown
Construct pre-landslide outlet works*:			
Option A. Pipeline for water only	Would require several parallel pipes for the required capacity which would be expensive and not multifunctional	—	—
Option B. Three-box culvert for the road, river, and railroad	Would be constructed at two locations: Meadow Mountain and Whiskey Creek. This would be a future action but would require construction before the landslide moves	Best option; however, high front-end cost to all parties	—
Divert river around landslide	Would require construction of a canal and trestle for Whiskey Creek and/or Meadow Mountain landslides	Innovative idea	—

*Recommendation: Feasibility study by engineering firm to evaluate these options as well as the cost to remove the landslide. CDOH would coordinate the preparation of the scope of work. The cost would be about $50,000 from an as yet unknown source.

Table 1. (Cont.)

RECOMMENDATION	OPTION 4: WAIT UNTIL THE LAST MINUTE TIME FRAME	RESPONSIBLE PARTY	ESTIMATED COST
Maintain conveyance capacity of the channel	Interim solution in the event of movement	County/state/U.S. Army Corps of Engineers during emergency	Unknown
Provide seepage path in landslide	Not feasible due to volume involved. Dangerous piping hazards	—	—
Siphon water over landslide	Not feasible; unsuccessful at Thistle, Utah, due to landslide movement and volumes involved	—	—
Pump water over landslide	Not feasible due to the number of pumps required, power needed and the availability of equipment	—	—
Excavate overflow spillway in dam	Preliminary design concept and specifications should be developed for the file	Division of Water Resources to develop preliminary concept and specifications	Unknown; would require supply of polyvinyl chloride fabric to construct spillway
Blast an overflow spillway in the hillside, cut a channel and blow rock over the spillway	Not practical; blasting results may be uncertain	—	—
Cause controlled failure of landslide dam	Best concept after the immediate danger has passed — breaching may be time-consuming and not cost-effective. Negative downstream sediment impacts may occur	—	—

CASE STUDY NO. 2
DEBRIS-FLOW HAZARD - A CASE HISTORY (GLENWOOD SPRINGS, GARFIELD COUNTY, COLORADO)

Introduction

Glenwood Springs is a small mountain-valley city in Garfield County (Figure 3). It is located in a narrow valley at the confluence of the Roaring Fork and Colorado Rivers. At 5800 feet above sea level the city is surrounded by steep slopes and high peaks of the southern Rocky Mountains.

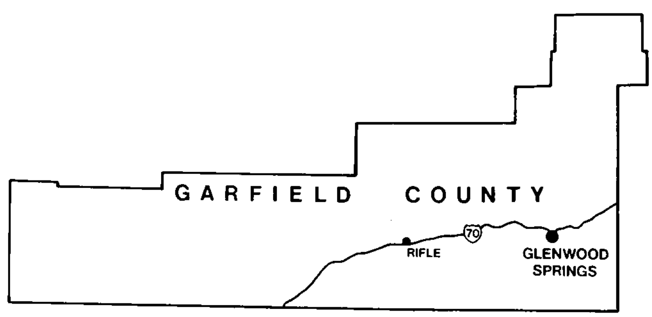


Figure 3. Location map of the City of Glenwood Springs.

The Debris-Flow Hazard

The City of Glenwood Springs is located at the junction of two of western Colorado's most important rivers, the Colorado and the Roaring Fork. Its strategic position as a gateway to the mining camp of Aspen and its hot springs were the most important historical considerations in locating the townsite.

The first recorded debris-flow event in the area occurred just south of the city in 1903. A rainstorm caused mud and rock to cover one of the railroad lines resulting in a wreck that killed a member of the train crew. Numerous events have been reported thereafter.

Awareness of the debris-flow and flooding hazard in Glenwood Springs occurred early in the town's history. However, identification and analysis of the source areas was not begun formally until the late 1970s.

History of Debris-Flow Events

1903: Debris flow south of Glenwood Springs covered railroad track causing train wreck; one killed.

1917: Debris flow in northeastern Glenwood Springs.

1929: Series of summer storms resulting in damage.

1936: In July debris-flow events blocked the highway in Glenwood Canyon at six places. In September, a large "mud flood" damaged the city prompting it to call on the Works Progress Administration (WPA) to build a flood control ditch along Twelfth Street, below Cemetery Gulch.

1937: Much of townsite inundated by debris flow down Cemetery Gulch; mud 2 feet in depth; boulders 2 feet in diameter strewn at intersection of Ninth Street and Grand Avenue.

1938: Twelfth Street ditch was constructed by WPA; the partly completed ditch conveyed a flood in August.

1943: Debris flow in Cemetery Gulch; flow jumped Twelfth Street ditch and damaged town.

1947: Flooding in southern, undeveloped part of town.

1974: Geological hazard reconnaissance study commissioned by CGS: *Roaring Fork and Crystal Valleys—An Environmental and Engineering Geology Study: Eagle, Garfield, Gunnison, and Pitkin Counties, Colorado* (Fox and Associates, 1974).

1977: July 24, a debris flow covers 200 acres of the residential district up to 14 feet deep; damage totals $300,000 to $2 million.

1977: The CGS commissions a report *Debris-flow Hazard Analysis and Mitigation, an Example from Glenwood Springs, Colorado* (Mears, 1977).

1978: The CGS and the planning departments of the City of Glenwood Springs and Garfield County co-fund a study of geologic hazards, *Geologic Hazards of the Glenwood Springs Metropolitan Area - Garfield County, Colorado* (Lincoln DeVore, 1978).

1981: A number of smaller debris flows occurred in the summer and fall.

1982: The city developed a control program to mitigate the problem.

1984/1985: In the winter of 1984/1985, unusually heavy early snowfalls resulted in an increase in landslide activity throughout the county. On May 13, 1985, the Garfield County Commissioners declared a financial disaster due to damages caused by landslides.

Geologic Evaluation

Debris flows are the most serious type of landslide hazard to affect Glenwood Springs. Debris flows are slurries of rock, soil, organic matter, water, and air that flow rapidly (usually) down preexisting drainage channels until they are deposited in fan-shaped cones where the channels enter the main valley floor. Damage results from impact, burial, and flooding. Debris flows are very common in Glenwood Springs and appear to be the dominant form of flood event for most of the smaller watersheds of the region.

Most of the city is located on debris fans (Figure 4). These fans have historically been very active with at least 18 major damaging debris flows occurring after the year 1900.

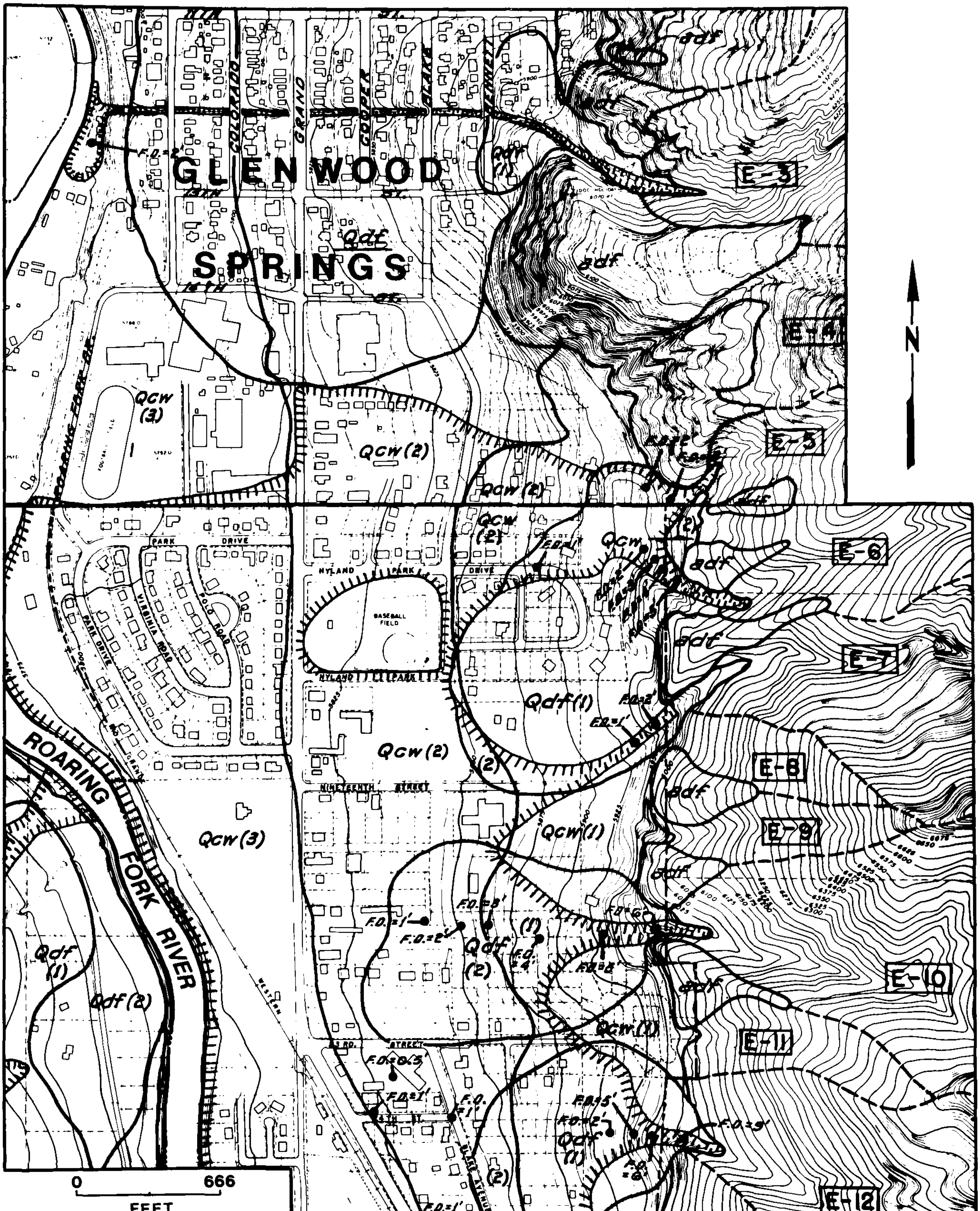
The combination of local geology, geography, and climate is responsible for the frequent debris flows at Glenwood Springs. The mountain slopes surrounding the city consist of sedimentary rocks whose weathering products are highly susceptible to debris-flow activity. The Eagle Valley Evaporite, a thick body of impure gypsum, calcareous sandstone, dark shale, halite, and anhydrite, forms the lower slopes of the valley walls. The Maroon Formation, a thick sequence of red sedimentary rocks which includes shale, siltstone, conglomerate, and thin limestone beds occurs higher on the slopes.

Upon weathering, the Eagle Valley Evaporite forms soils that absorb water easily and change to thick slurries that resemble wet Plaster of Paris. Because of the easy dissolution of the minerals in this formation, outcrops and soils are susceptible to rockfall, bank caving, landsliding and hydrocompaction. Weathered rocks of the Maroon Formation decompose to form accumulations of boulders, rock fragments, and large percentages of sand, silt, and clayey silt. The inherent weakness of the soil and weathered rock forms extensive, marginally stable slopes of talus and colluvial debris that rest on the steep slopes of the unweathered rocks.

Sudden failure of the accumulations of soil and debris can be triggered by wetting due to snowmelt and thunderstorms. Also, debris fans and aprons are very prone to hydrocompaction and require special drainage and foundations even where not subject to debris flooding.

Community Impact

1) Estimates of damages from the 1977 debris-flow disaster range as high as $2 million, although most reports indicate total losses fall somewhere between $500,000 and $1 million. The 1981 debris flows in Glenwood Springs caused approximately $100,000 in damages.
2) Landslides caused approximately $300,000 in damages in 1984, and over $500,000 in damages in unincorporated Garfield County in 1985. In May 1985, 20 county roads were blocked by landslides, and Baxter Pass had to be closed. In May 1985, Garfield County also recorded the largest debris flow in Colorado history, a 175-foot-thick mass of debris that was a mile long and 1,000 feet wide.
3) In addition to direct damages, other economic impacts include loss of tourism, due in part to media coverage of events, and fish kills in the Roaring Fork River and other streams. These losses are undocumented.
4) The "hidden" impacts of debris flows are documented in a 1986 report by Marian Smith and the Mount Sopris Soil Conservation Board, *Debris Flow Costs and Inventory of City of Glenwood Springs Area*. Some of these impacts are:
   a) trauma, and the stress induced by recurring fears in some residents when thunderstorms occur;
   b) homeowner costs of clean up and repair, including boots, gloves and tools, and damage to furnaces and appliance motors;
   c) the loss of landscaping, acquired over many years and too costly to replace all at once; and



adf, Qdf Mapped debris fan E-10 Drainage-basin index number

Figure 4. Debris fans at Glenwood Springs (from Lincoln DeVore, 1978).

d) irreplaceable personal possessions such as books, family photos, etc.

Mitigation

In 1982 the City of Glenwood Springs contracted for the preparation of an engineering study and control plan (ESA Geotechnical Consultants and ARIX, 1982). The four general purposes of the plan were to:

1) develop recommendations for the stabilization of the debris in the gulches and upper basins,
2) locate proposed control facilities and prepare conceptual designs for the facilities,
3) develop an overall stormwater drainage plan and make a conceptual design of that drainage system, and
4) make recommendations and outline a plan for the maintenance of the debris and stormwater facilities.

The actual work plan accomplished the following:

1) debris-flow basins were ranked in terms of hazard severity; the 20 most hazardous basins were selected for detailed analysis;
2) the hydraulic properties of debris flows and flash floods in the selected basins were determined;
3) the relation of debris flows to storm runoff in the selected basins was defined;
4) conceptual designs of workable alternative control systems for combined debris-flow and storm runoff were provided;
5) the results were extrapolated to the remaining basins in the city; and
6) cost estimates and priority ratings for construction of the systems were provided, and maintenance recommendations for operation of those systems were made.

The main emphasis of the report was on those basins which affected public property or large numbers of citizens. These areas would require public action in order to accomplish hazard mitigation. They were ranked in priority according to the magnitude of the hazard, the level of exposure for persons and property, and the practicality of effective mitigation.

The plan included nonstructural methods such as zoning and land-use restrictions, flood-warning systems, and maintenance programs for channels and debris source areas; and structural methods such as floodproofing, debris basins and dams, energy dissipators, drop structures, channels, and storm sewers.

CASE STUDY NO. 3 RIVER BLUFF RETREAT REACTIVATED BY HUMAN ACTIVITY - A CASE HISTORY (LAMPLITE PARK SUBDIVISION, GRAND JUNCTION, MESA COUNTY, COLORADO)

Introduction

The Lamplite Park subdivision is located in Grand Junction, Colorado on a bluff overlooking the Colorado River (Figure 5). This case history demonstrates the types of damages that can occur when a naturally occurring metastable landslide is reactivated by human activities.

The Landslide Hazard

In March of 1985, the State Geologist attended a meeting of the Mesa County Commissioners and staff to discuss geologic

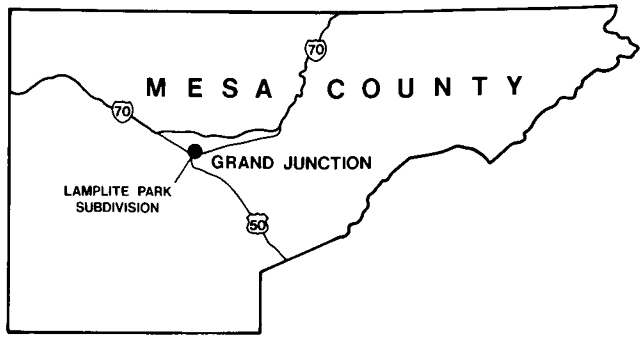


Figure 5. Location map of the Lamplite Park Subdivision.

problems in the county. The meeting included a field inspection of the Lamplite Park Subdivision, a tract of land including 12 structures (14 housing units) that was experiencing "settling" problems. The settling was determined to be the direct result of an active landslide.

Subsequently, a staff geologist at the Colorado Geological Survey (CGS) reviewed aerial photographs on file and confirmed that a landslide had existed on the site as early as 1954. The photo analysis seemed to indicate that the scarp had regressed about 50 feet between 1954 and 1973. However, further investigation revealed that the site had been used as a borrow pit, which may account for the apparently regressing scarp face. It was recommended that a detailed geological investigation be conducted to evaluate the landslide.

Preliminary Geologic Investigation (Phase One)

On October 16, 1985, the City of Grand Junction accepted a proposal from the CGS to conduct a geological investigation and appropriated $16,070 for the project. This study included the review of a soils report prepared originally for the Lamplite Park subdivision by a geotechnical consulting firm, a review of available aerial photography and detailed topography of the vicinity, detailed surficial mapping of the landslide, and a subsurface investigation consisting of drilling and logging six core holes on the landslide mass and excavating a series of three test pits down the slope.

Preliminary Geologic Evaluation

The Lamplite Park landslide was determined to be a complex rotational failure. The slide mass itself was a relatively thin (10 to 20 feet thick) section of unconsolidated muds, clays, sands, and gravels of the Orchard Mesa terrace gravel deposit. The slip surface consisted of saturated, soft, extremely weathered shale. Bedrock was unweathered Mancos Shale and there was a perched water table in the terrace gravels.

This was an old metastable slide that was reactivated in the head scarp area as a direct result of residential development. Development caused the following changes:

1) Loading of the top of the landslide. Topographic comparison of the pre-development and post-development ground-surface configuration suggested that a substantial amount of granular fill material had been placed over the head scarp on top of the upper portion of the landslide mass. This was apparently done to level the backyards of the lots north of Santa Clara Avenue (Figure 6). Assuming that the position of the southernmost tension feature in the soils reflected the approximate original scarp location, the lateral extent of the fill was on the order of 20 to 30 feet. Test-pit data in-

dicated that the fill was at least 12 to 15 feet thick. The fill increased the driving forces on the top of the landslide.

2) Altered ground-water regime. Prior to development this area had a relatively uniform, steeply sloping, exposed surface with no direct irrigation. The landscaping associated with residential development led to the introduction of flat, irrigated lawns and gardens and an irregular distribution of soil moisture caused by the introduction of horizontal impermeable zones (housing and pavement), vertical impermeable zones (foundations), and roof-drain downspout areas. These disturbances in the soil-moisture regime tended to increase the destabilizing effects of excess moisture.
3) Prior to development the area was unshaded and winter moisture accumulation (mostly snowfall) was substantially reduced by evaporation and sublimation. As a result of the shading effect of the one- and two-story structures, placed relatively close together, the amount of moisture which was introduced into the soil was significantly increased with resultant weight and "lubrication" effects.

The overall cumulative effect of the above changes in the metastable equilibrium of the landslide was to reactivate motion or accelerate ongoing motion resulting in dislocation and damage to the development north of Santa Clara Avenue.

Land-Use and Development History

An essential part of the project was determining the land-use history of the site.

Pre-development: Discussions with local residents indicated that the northern portion of the site had probably been used initially as a gravel pit and/or borrow pit and then later possibly as a junk yard. Evidence on site also indicated use as a "clean-fill" dump. The southern portion of the proposed subdivision (behind the scarp) was used for irrigated agriculture.

1976-77: The Lamplite Park subdivision was proposed.

1977: A geotechnical consulting firm prepared the subsurface investigation for the site. The report identified the existing landslide. Its character and anticipated behavior were estimated on the basis of soil borings and a cursory investigation of the landslide itself. Certain general recommendations were made as to appropriate foundation design and site drainage which would be needed to mitigate landslide-related problems if the landslide area was to be developed. The consulting firm also mentioned the option of not building in that area.

197?-1982: A developer/builder subdivided the land and built most of the homes in the subdivision—all south of Santa Clara Avenue (see Figure 6). The northern part of the site, which included the landslide area, was later sold, undeveloped, to another developer. It was not known whether or not the head scarp of the landslide had already been obscured by grading at the time of the sale.

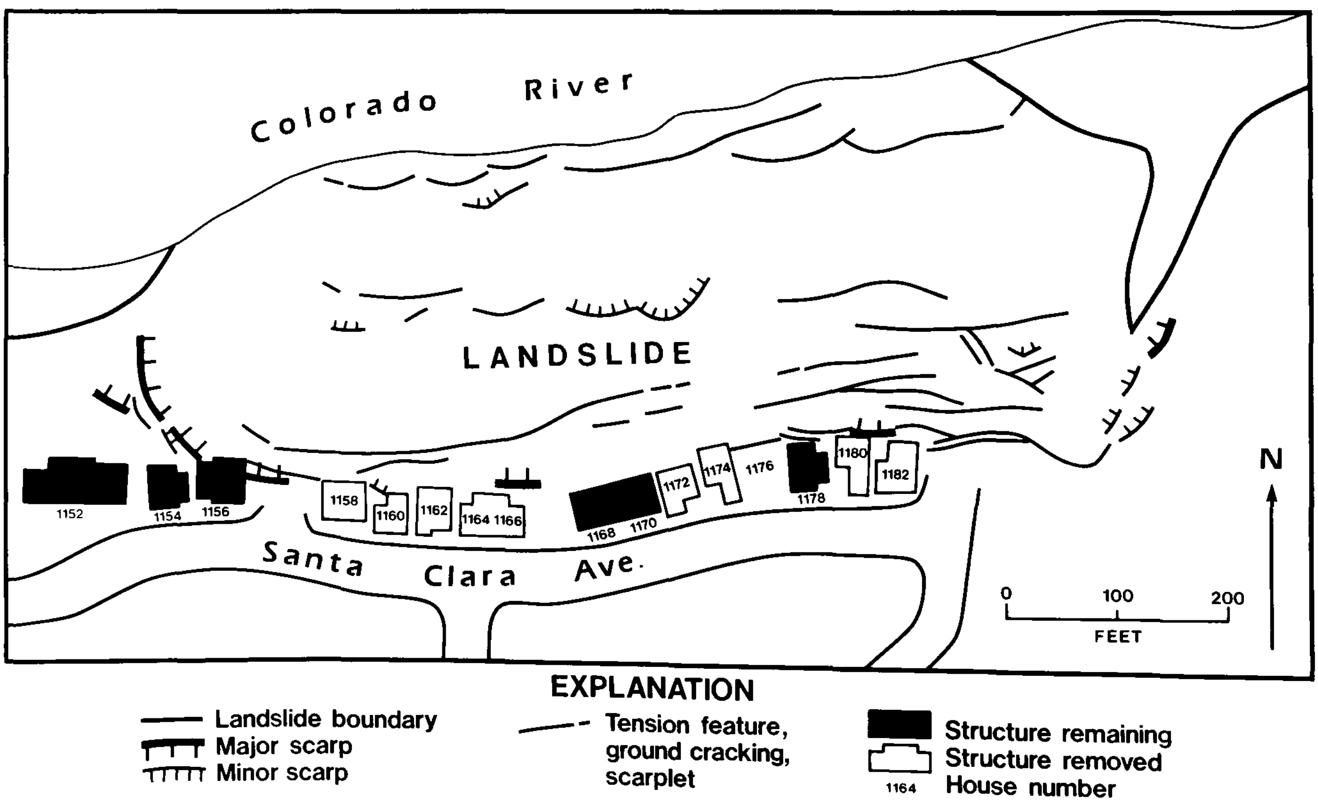


Figure 6. Street map of that portion of the Lamplite Park Subdivision affected by the landslide.

1982-1984: The second developer built a row of houses on the north side of Santa Clara Avenue in the immediate area of the head scarp. During foundation construction, clean-fill dirt was trucked to the site, dumped, and graded to level the backyards of these lots.

Within a year or so after construction at least two houses began experiencing problems associated with differential movement. At 1158 Santa Clara Avenue (Figure 6) the porch separated from the house, was replaced, separated again, and was replaced a second time after replacing the north foundation wall and adding fill dirt to the slope. The house at 1156 Santa Clara Avenue also began to suffer foundation damage.

By November 1984, these two houses had been condemned and the residents had filed lawsuits against the county, city, and individuals involved with the construction.

Proposed Mitigation

Several conceptual engineering solutions oriented toward stabilization of the upper portion of the landslide were explored at a preliminary level and discounted due to the construction costs compared to an assumed present or anticipated value of the property and improvements of approximately $500,000 to $1 million.

Given the state of distress to several of the structures, the anticipated damage to essentially all of them, and the estimated cost of a suggested stabilization plan, it was concluded there was no cost-effective way to allow long-term continued residential use of the lots north of Santa Clara Avenue east of address 1154. This was based primarily on the assumption that the original head scarp lay at the northern limit of the foundations or actually below the structures, essentially precluding any realistic expectation of successful, cost-effective rehabilitation. Furthermore, any structures remaining on the site would interfere with the proposed second phase of the investigation and could severely constrain implementation of any stabilization plan intended to save the street and utilities.

The mitigation plan proposed for this site was two-staged and required a second phase of geological investigation in order to determine the best approach. Additional drilling and trenching were necessary to determine whether the property south of the scarp was distressed.

If the property south of the scarp was not threatened by further landsliding, it was proposed to regrade the slope; unloading the upper landslide area by removing the excess fill wedge from the head of the landslide, decreasing slope angle and improving slope drainage and solar exposure. The installation of a monitoring system set back from the head scarp would serve as an early warning system should retrogressive slope failure begin.

If the area south of the scarp was distressed, it would be necessary to install a drainage gallery and/or cut-off wall to divert subsurface water away from the slope. This would reduce the likelihood of further bluff retreat and tend to stabilize the unconsolidated alluvial materials north of Santa Clara Avenue. The net result of this program would be to minimize the threat of continued slope failure and the resulting loss of the utilities beneath Santa Clara Avenue.

Follow-up Geologic Investigation and Evaluation (Phase Two)

The second phase of the landslide investigation was conducted in early March of 1988. While the evaluation of the data is not yet complete, several noteworthy observations have been made which resolve some of the more important questions left unanswered after phase one. Preliminary opinions can also be made at this point with reasonable surety.

The second phase investigation consisted of four, long, deep, continuous trenches across the projected scarp and fill wedge, one localized excavation to explore a pronounced tensional feature, and ten shallow borings to evaluate the perched water conditions behind the scarp at the terrace gravel-shale contact. These borings were also used to install the monitoring assemblies.

The extensive detailed trenching program permitted by the removal of most of the structures tended to confirm the general assumptions made during phase one as to the nature of the slope failure and its causes.

Based upon the exposures observed in phase two, the site can best be characterized as an uncontrolled fill of an old gravel pit developed in an old landslide deposit of primarily terrace gravel materials.

The physical evidence suggests that the quarrying operations exhumed the original head scarp (main scarp) as materials were removed south of the failure surface. This tends to confirm the earlier photo interpretation.

At least two major episodes of fill placement were involved in achieving the final topographic configuration upon which the houses were built. Construction debris, old abandoned machinery and fairly well decomposed trash were found beneath the older fill. This seems to support the contention that this fill episode occurred sometime ago, perhaps shortly after the quarrying operations. The older fill represents the majority of the total fill both in thickness and volume. The more recent fill material is defined by a markedly coarser grain size, and in some cases, by a very weak, residual organic soil layer at the interface with the older fill.

Essentially undecomposed organic material consisting of buried vegetation and lumber indicate the time of placement of the younger fill to be contemporaneous with the development of the site. The overall contribution of the younger fill to the total fill mass is estimated to be between 15 and 20 percent.

Based on the evidence developed in phase two, it appears that the observed distress to the structures and immediately adjacent ground was caused by failure of the fill material. This failure was the result of a complex combination of several factors: significant increases in soil moisture, loading of the older fill with the younger fill, and reinitiation of motion along the original landslide failure surface below the fill induced by both the increase in moisture and mass surcharge in the upper regions of the landslide.

Remedial measures taken to stabilize the area consist of the removal of 8 of the 12 affected and potentially affected structures, regrading of the ground surface to improve drainage and increase solar exposure, and the installation of 10 monitoring wells.

The monitoring wells were completed as open well piezometer/deformation/extensometer devices to observe the condition of the shallow, perched water table and to provide an "early warning system" with respect to any future instability in the area, which might adversely impact Santa Clara Avenue and the utilities beneath it.

Community Impact

The greatest impact on the community is the loss of 10 homes (nine structures) located on the landslide. One of the remaining structures is condemned and the final disposition of the matter is still unresolved as of April 1988. Destabilization of the top of the landslide resulted in ground displacements of as much as 3 to 4 feet in two years. This displacement caused structural distress to foundations and utility lines. Large, open tension cracks also posed a danger to people and animals.

The risk of serious personal injury was mainly associated with the possibility of a sudden foundation collapse or explosion of a ruptured gas line caused by the slow deterioration of the bearing support for the buildings.

Also considered potentially at risk were the city-owned and private utilities beneath Santa Clara Avenue. Unfortunately, the original scarp had been completely obscured and it was therefore difficult to determine whether the surface distress observed on the site was due to motion along the original scarp, or settlement and failure of the fill wedge placed during overlot grading. If motion had been reinitiated along the main head scarp at its inferred location, it is possible that lateral support behind the scarp would be reduced and a new scarp could form farther to the south, endangering the main utility lines and/or the next row of houses.

Conclusion

As of March, 1988, four of the twelve structures comprising the development remain. The westernmost house (1154) is determined not to be at significant risk due to any anticipated renewed activity of the landslide or fill material. One of the two originally condemned structures (1156) remains on the site. It is still condemned, still at risk and should be removed. The two other structures, one duplex (1168 and 1170) and one detached house (1178), are not condemned and are presently occupied. These buildings are considered to be at risk in the long term though they show no signs of distress at the present.

The physical condition of these remaining structures will be evaluated routinely as part of the overall long-term monitoring program conducted by the City of Grand Junction. Plans to resolve any future problems with the site or these remaining structures have not been formulated at this time.