Text to Accompany

GIS Overview Map of Potential Rapidly Moving Landslide Hazards in Western Oregon

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Cover photos

The pictures show an example of a landslide occurrence and the damage it caused: the Royse residence destroyed in February 1996 by a slide in the Dodson/Warrendale area of the Columbia River Gorge.

Photos courtesy of Kenneth Cruikshank, Portland State University (left), and Dave Wieprecht, U.S. Geological Survey (right).

NOTE

The map of this publication depicts landslide hazard zones on the basis of limited data, as described in the text. It **cannot serve as a substitute for site-specific investigations by qualified practitioners.** At any point, site-specific data may give results that differ from those shown on the map.

The Oregon Department of Geology and Mineral Industries is publishing this study because the information furthers the mission of the Department. To facilitate timely distribution, IMS-22 has not been edited to our usual standards.

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Geographic Information System (GIS) Overview Map of Potential Rapidly Moving Landslides in Western Oregon

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SUMMARY

Landslides are a serious geologic hazard, threatening public safety, natural resources, and infrastructure, and costing millions of dollars for repairs each year in Oregon. This map of areas where rapidly moving landslides pose hazards in western Oregon is part of the State's attempt to protect lives and property.

The overview map delineates zones that are prone to landslide hazards, especially rapidly moving landslides. These zones provide information to local governments about property that might require more site-specific evaluation.

The map is digital and was produced with data at a scale of 1:24,000 (1 in. = 2,000 ft). Therefore, the information provided is appropriate only at that scale or a smaller scale (e.g., 1:48,000) and cannot show greater detail if viewed at any larger scale (e.g., 1:12,000).

Creation of the map involved the use of Geographic Information System (GIS) modeling, checking and calibrating with limited field evaluations, and comparing with historic landslide inventories. The Oregon Department of Geology and Mineral Industries (DOGAMI) worked with the Oregon Department of Forestry (ODF), the Oregon Department of Land Conservation and Development (DLCD), the Earth Systems Institute (ESI), and a number of landslide researchers to compile data and create the map.

The extent and severity of the hazard posed by rapidly moving landslides varies considerably across western Oregon. In general, the most hazardous areas are mountainous terrains—which are usually sparsely populated—especially drainage channels and depositional fans associated with debris flows.

Where hazard areas intersect with human development, use of the map can help to assess the risk and prioritize risk-reduction activities. Various options are available to reduce the risk of landslide losses. Risk-reduction activities can include engineering solutions, public education, warning systems, temporary road closures and evacuation, land use regulation, and many other options. Although this project addresses a range of rapidly moving landslides, this map is not a compilation of all possible landslide hazards.

INTRODUCTION

Landslides are a common occurrence in Oregon. Landslide impacts, such as those shown in Figures 1 and 2, can be devastating to individuals, businesses, and communities, and millions of dollars are spent annually to repair the effects of landslides in Oregon (Wang and others, 2002).

Although landslides occur virtually every year in Oregon, general awareness and recognition of the hazard remains relatively low. The ephemeral nature of landslides, the location of many events in relatively undeveloped areas, and the fact that landslide damages are often quickly repaired contribute to the low awareness. In addition, programmatic recordkeeping of landslide locations is rare, which limits transfers of information generation-to-generation and between technical specialists and the general public.

In an attempt to address the most dangerous landslide hazards more systematically, the Oregon legislature adopted Senate Bill 12 (SB 12) in 1999[1]. SB 12 established Oregon's current state-level policy addressing rapidly moving landslides. The overarching goal of SB 12 was to save lives and reduce future landslide losses.

An important step toward achieving this goal is to systematically characterize the geographic extent and location of the hazard areas. Spatial identification of hazard and risk allows for more informed policies and implementation of strategies to effectively reduce risk.

This report describes the development of a regional hazard map that provides a consistent, first approximation of terrain susceptible to rapidly moving landslides. The digital hazard map is released as a GIS layer that allows for comparisons with other relevant data. The map should serve as a valuable tool for local government planners, transportation officials, foresters, emergency managers, ecologists, public policy makers, and property owners. They can all benefit from a consistent and comprehensive means for identifying hazard zones in which rapidly moving landslides might occur.

The report provides information and background to support the application of the map, including sections on the following topics:

- Characteristics of the types of landslides addressed by the hazard map;
- Methods used to develop the map;
- Important limitations and appropriate uses of the map;
- General strategies for mitigating rapidly-moving landslide hazards; and
- Potential areas for refinement of the map and assessment of other landslide hazards.

The report is not intended to be comprehensive but is meant rather to provide an introduction and overview. The authors have attempted to avoid the use of technical terminology where possible and have included a short glossary of terms (Appendix A). Relevant literature citations throughout the text refer to the list of "References Cited" at the end of the report and provide additional information for interested readers.

[1] Senate Bill 12 is codified as ORS 195.250-195.275, ORS 527.630-527.710 and is available on the web at http://www.leg.state.or.us/99reg/measures/sb0001.dir/sb0012.d.html. Future legislation may change part or all of the statute.

Figure 1. Royse residence in the Dodson/Warrendale area, Columbia River Gorge, affected by landslide in February 1996.

Photo courtesy of Kenneth Cruikshank, Portland State University.

Figure 2. Residences in the Scottsburg area, Douglas County, hit by landslides in November 1996.

Photos courtesy of John Seward, Oregon Department of Forestry.

RAPIDLY MOVING LANDSLIDE HAZARDS

This study focuses on identifying areas subject to landslide hazards. One type, rapidly moving landslides, were singled out primarily because they are the greatest threat to human life and have the potential to cause sudden, catastrophic damage. Mitigation alternatives for these types of landslides are limited, particularly after a structure is sited within a high-hazard zone.

In Oregon, a very common and particularly dangerous type of rapidly moving landslide is a debris flow (commonly referred to as a mudslide). While other types of rapidly moving landslides can also pose serious social and economic hazards, debris flows were the primary focus of SB 12. A major reason for this focus is the fact that the source of debris flows is often far away from their downslope impact areas (in some cases, miles). Seemingly insignificant landslides of 10 cubic yards (about the size of a dump-truck load of material) or less can increase in volume by 100 times or more if conditions are conducive to debris flow formation (Robison and others, 1999; Benda and others, 2000). As these masses move downslope, they can gain significant momentum and wreak havoc on objects in the way, plowing down trees, picking up boulders, and smashing anything else that happens to be in the path. Large debris flows can travel at velocities exceeding 50 mph and are easily capable of flattening homes, crushing cars, and taking the lives of people in their paths.

Although debris flows are the focus of this study, it is important to note that there are many different types of landslides, both slow- and fast-moving. Figure 3 shows a common classification scheme for landslides. All of these landslide types occur in Oregon and can be significant in local areas. Both large earthflows and comparatively small slope failures have caused extensive damage to structures in Oregon and continue to be persistent problems in many areas (Beaulieu and Olmstead, 1999). Rockfalls and rockslides are also common rapidly moving landslides and are particularly dangerous along Oregon highways (Pierson and Van Vickle, 1993).

In addition to debris flows, a few of the other types of fast-moving landslides are implicitly included in the hazard map. For example, some dangerous rockfall and rockslide areas are included on the map. Figure 4 is a photograph of a major rockslide area along Oregon Highway 6 that is highlighted as a hazard on the map.

It is important to note, however, that substantial landslide hazard areas, including those associated with large earthflows in moderately to gently sloping terrain, small slumps, local rockfalls, and large volcanic debris flows (lahars), are neither explicitly nor implicitly addressed in this map product. This does not diminish the importance of these significant hazards; however, they require different types of hazard analyses and warrant further evaluation, as noted in the Map Updates and Future Work section.

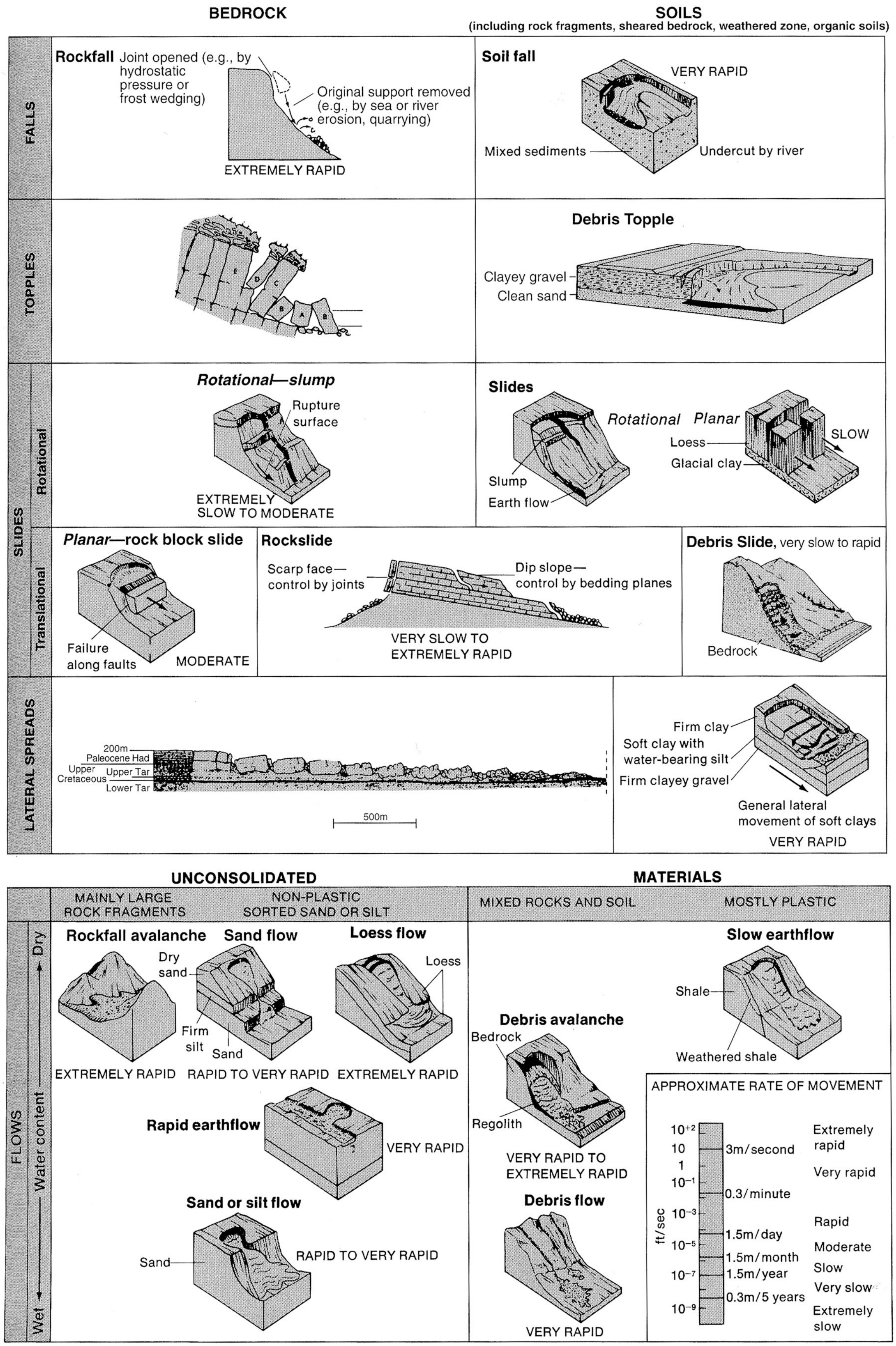


Figure 3. Landslide types. (From Ritter and others, 1995)

Figure 4. Rockslide that occurred along the Wilson River Highway (Hwy 6) in 1991. Though not a debris flow, this hazardous area is identified by the hazard model. (Photo courtesy of Susanne L. D'Agnese, Oregon Department of Transportation)

CHARACTERISTICS OF DEBRIS FLOWS

Debris flows, shown schematically in Figure 5 and by example in Figure 6, consist of water-charged soil, rock, colluvium, and organic material traveling rapidly down steep topography (Johnson, 1984). Debris flows are often triggered by small landslides (Figure 7) that then mobilize and grow to be large flows, entering and scouring stream channels downslope (Figure 8). When momentum is eventually lost, the scoured debris is often deposited as a tangled mass of boulders and woody debris in a matrix of finer sediments and organic material (Figure 9).

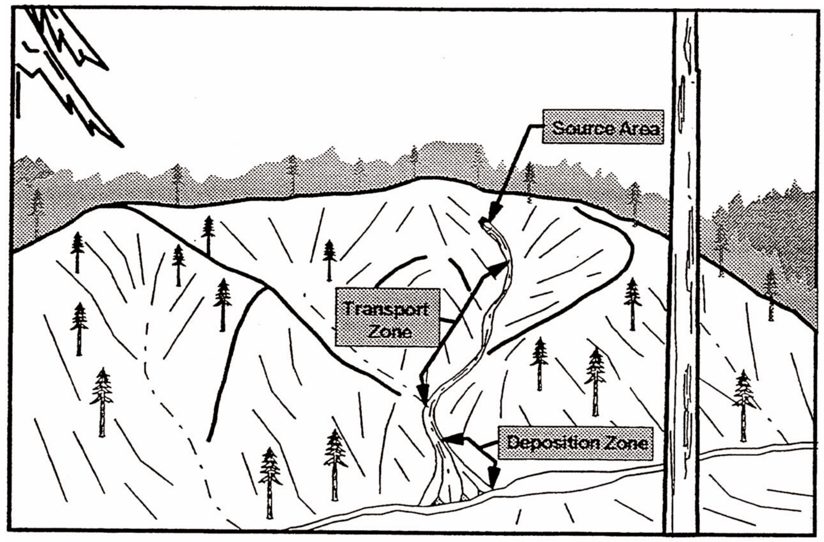


Figure 5. Diagram of a debris flow showing zones of initiation (source areas), transport, and deposition. (From Pyles and others, 1998)

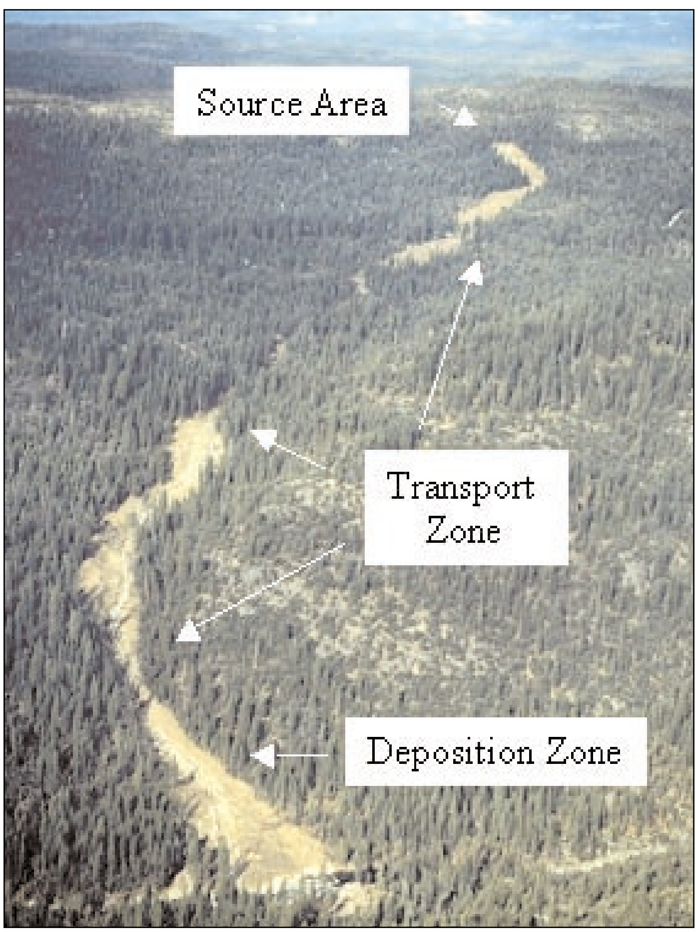


Figure 6. Photo of a debris flow showing zones of initiation, transport, and deposition. (Photo courtesy of U.S. Geological Survey)

Although debris flows can be extremely variable and chaotic, they have some common characteristics. These characteristics form the basis of much of our scientific understanding and provide the keys to identifying and modeling potentially hazardous locations. Before describing the development of the hazard map, therefore, useful background on factors that affect debris flow potential is provided.

For descriptive purposes, it is helpful to segment debris flow paths into areas of initiation, transport, and deposition as shown generally in Figures 5 and 6. Some of the common debris flow causes (termed trigger mechanisms) are outlined below, followed by some of the significant factors affecting debris flow initiation, transport, and deposition. This section provides only a brief overview of the subject.

Trigger Mechanisms

Debris flows can be initiated in marginally stable slopes by a number of natural and unnatural disturbances. Because most steep slopes are near their point

↑ **Figure 7. Small intiating landslide.**

➔ **Figure 8. Scoured transport zone.**

↓ **Figure 9. Tangled debris in deposition zone.**

of equilibrium, failures can be the result of seemingly minor modifications. In a fundamental sense, modifications that lead to failures can be simply grouped into factors that (a) increase the gravity-driven forces acting downslope and (b) reduce the resisting forces acting to keep the slope in place (Figure 10). Multiple factors may be involved in triggering any given debris flow.

Natural events that can induce failures include high-rainfall storms, rapid snow melt, earthquake shaking, breach of landslide or other natural dams, and volcanic eruptions (Wieczorek, 1996). By far the greatest number of debris flows that have occurred in Oregon (at least in historical times) have been associated with severe rainfall and rain-on-snow storm events.

Severe Rain Storms

High-precipitation storms can trigger slope failures through a number of mechanisms. Water infiltration into zones of weakness can trigger failures by (1) reducing the frictional resistance to sliding, (2) increasing pore pressures within a slope mass, and (3) adding weight (through saturation of the soil mass) (Turner and Schuster, 1996). Typically, all three of these mechanisms combine during long-duration, heavy-precipitation storm events to trigger widespread slope stability problems. During three 1996/97 storm events, for example, thousands of landslides (including many debris flows) were triggered throughout western Oregon (Figure 11).

Given the importance of rainfall events for slope failures, it is not surprising that a number of studies have

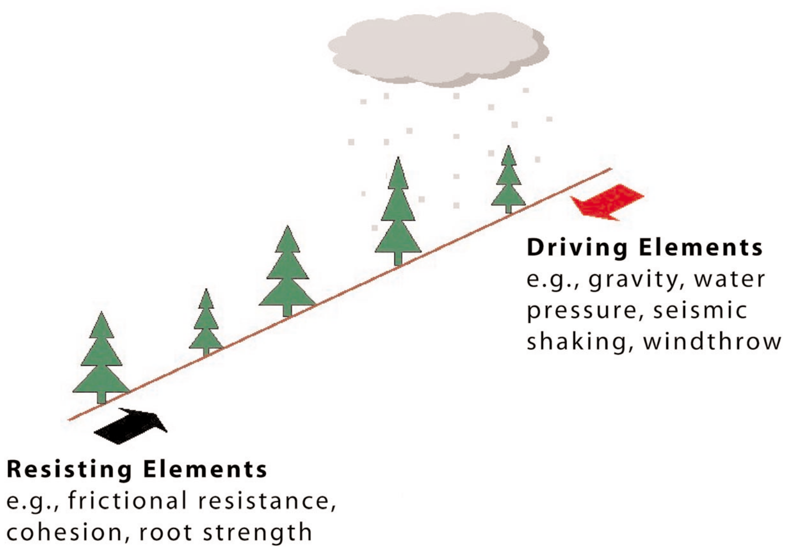


Figure 10. Schematic of a slope, showing driving and resisting elements.

focused on evaluating relationships between storm characteristics and debris flow occurrences (e.g., Campbell, 1975; Crozier and Eyles, 1980; Keefer and others, 1987; Cannon, 1988; Wieczorek and Sarmiento, 1988; Wilson and Wieczorek, 1995; Wilson, 1997; Wiley, 2000). Several of these studies have focused specifically on identifying rainfall thresholds above which landslides (and particularly debris flows) become significantly more widespread and numerous (Keefer and others, 1987; Wilson and Wieczorek, 1995; Wilson, 1997; Wiley, 2000).

One rainfall threshold study that used storm data specifically from the Pacific Northwest was reported by Wiley (2000). This study included evaluations of climatic data in comparison with landslide occurrences recorded for the period of February 1996 through January 1997 and indicated that widespread landslide activity in steep terrain throughout western Oregon is likely to be triggered by rainfall intensity/duration combinations of (a) 40

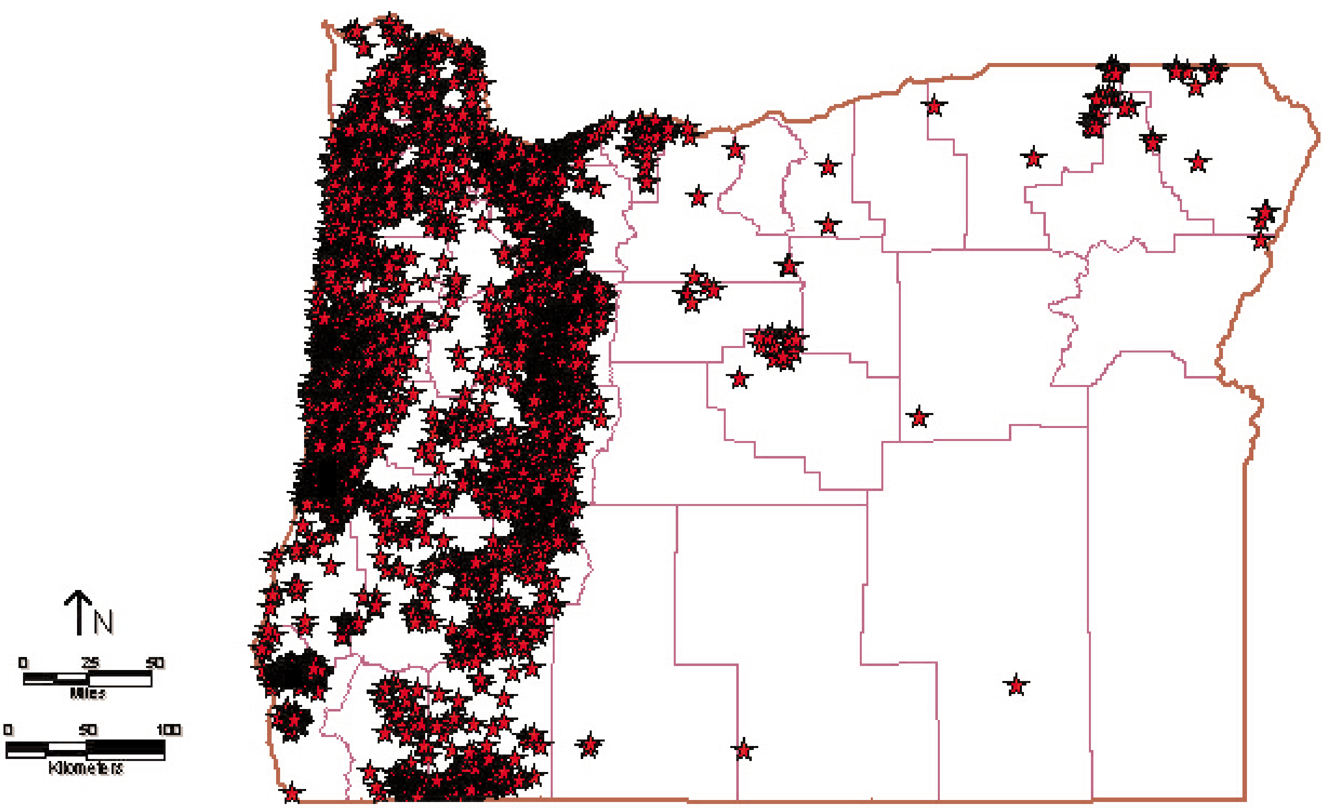


Figure 11. Distribution of the more than 9,500 landslides triggered in Oregon by the storms of 1996-97. (From Hofmeister, 2000)

percent of mean December rainfall in a 24-hour time period, (b) 25 percent of mean December rainfall in a 12-hour period, or (c) 15 percent of mean December rainfall in a 6-hour period. Figure 12 is a map showing the general magnitude of the 24-hour rainfall thresholds in western Oregon. Storms that produce rainfall in excess of these levels are considered to be particularly prone to triggering dangerous landslides.

Slightly more conservative rainfall-threshold criteria are used by the Oregon Department of Forestry (ODF) for the Oregon Debris Flow Warning System (discussed in the Risk Management Strategies section). Thresholds of 3 in. in 12 hours, 4 in. in 24 hours, 5.5 in. in 36 hours, or 7 in. in 48 hours are used by ODF to issue debris flow advisories for forecast storms. As will be discussed in later sections, a number of important variables affect local debris flow occurrences, and no simple criteria can be used to precisely predict debris flows on a regional scale. Nevertheless, rainfall intensity studies and warning systems are important attempts to save lives by providing advance notice of dangerous storms.

Human Actions

While large storms and other natural events beyond our control are often the prime triggers of landslides in the Pacific Northwest, human actions resulting in adverse modifications to the natural environment can also be significant factors in causing and/or exacerbating slope instabilities. Many common artificial alterations to topography make slopes more vulnerable to landslides, and it is important to evaluate how human actions affect slope stability over both the short and the long term.

Modifications that alter the internal

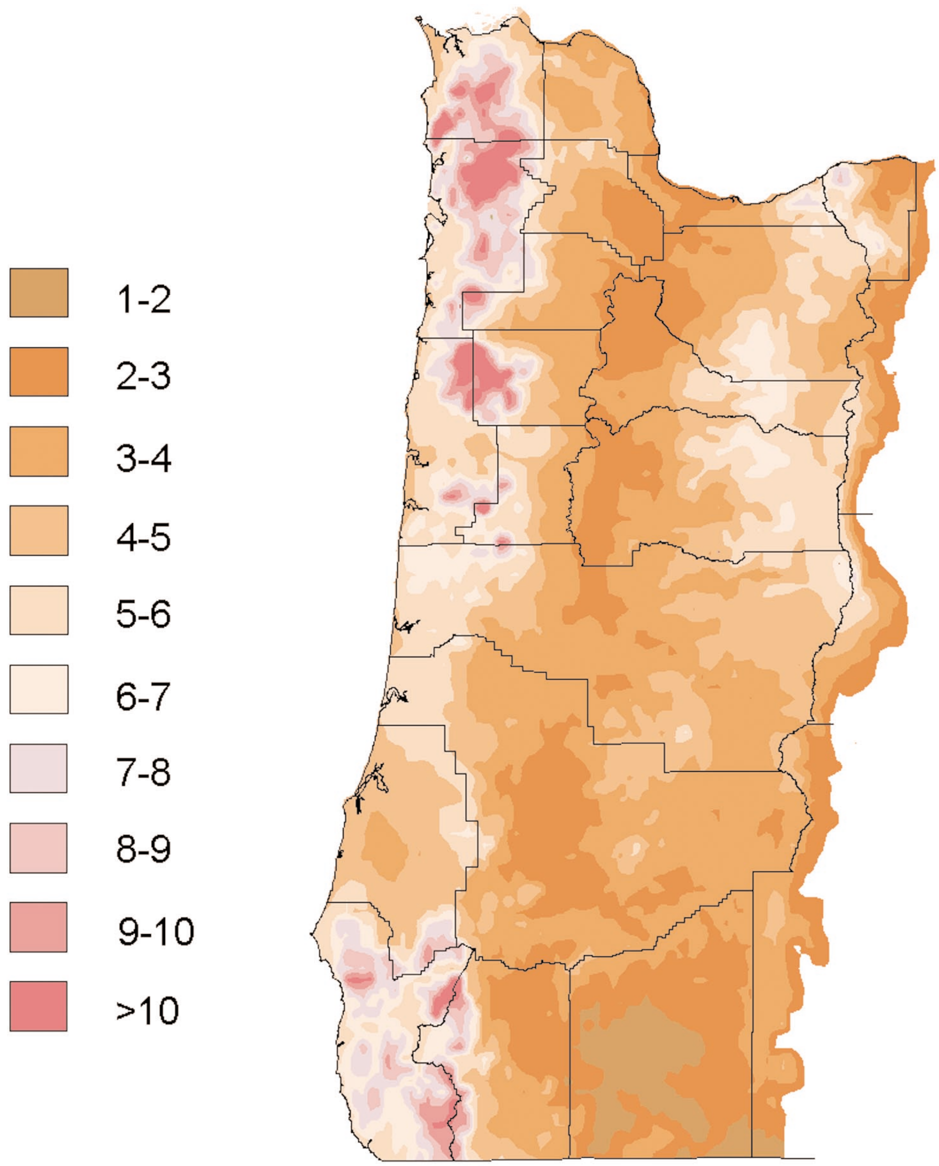


Figure 12. Map of estimated 24-hour rainfall intensity-duration thresholds in western Oregon (measurements in cm). Contours are derived from the Oregon Climate Service data of mean December precipitation. (From Wiley, 2000)

strength of slopes and the flow of water can adversely affect slope stability. Construction of roads, buildings, dams, and other infrastructure typically involves earth movement and redirection of water. For example, surface paving that redirects water to hazardous areas, excavations that remove materials from the base of marginally stable slopes, and removal of vegetation on marginally stable slopes are a few of the more common factors that can increase the likelihood of slope failures.

In forested terrain, logging activities can also have a negative impact (Swanson and Dyrness, 1975; Sidle and others, 1985). Vegetation can stabilize slopes by binding soil masses together with roots and by affecting the distribution and rate of water flow through the system. It is difficult to quantify the effects of vegetation on the stability of a particular slope, but removing vegetation increases susceptibility for slide initiation in most cases (Burroughs and Thomas, 1977; Sidle and others, 1985; Robison and others, 1999). In addition, logging practices that leave loose material in debris flow paths can significantly increase the size and downslope impact of flows.

Redirecting water, excavations, and vegetation removal are only a few of the many actions that can adversely affect the stability of slopes in steep terrain. Other common human actions that can cause or exacerbate slope instability may be loading slopes (e.g., with buildings or equipment), replacing natural materials with lower strength materials (e.g., nonengineered fill), and removing soil reinforcement.[2]

Debris Flow Initiation

The factors mentioned in this section are interrelated. Although other factors can also be critical in evaluating the stability of particular sites, the factors listed below are the most commonly used in landslide hazard modeling efforts. Based on research into these factors, regional and site-specific models have been developed to address potential landslide initiation (e.g., Ward and others, 1978; Burroughs, 1984; Hammond and others, 1992; Montgomery and Dietrich, 1994; Carrara and others, 1997; Fannin and others, 1997; Rollerson and others, 1997; Wilkinson and Fannin, 1997; Pack and others, 1998; Vaugeois and Shaw, 2000; Wu and Abdel-Latif, 2000). Reviews of the various types of initiation hazard modeling approaches are included in Swanson and Dyrness (1975), Sidle and others, 1985, Montgomery and Dietrich (1994), Carrara and others (1997), May (1998), Montgomery and others (2000), and Vaugeois and Shaw (2000).

In addition to triggering mechanisms, a number of related factors must be considered in assessing the potential for debris flow initiation. For regional hazard evaluations in particular, topography and other inherent physical parameters are often the focus, such as slope steepness, landform (concave, convex, planar), rock and soil properties, hydrol-

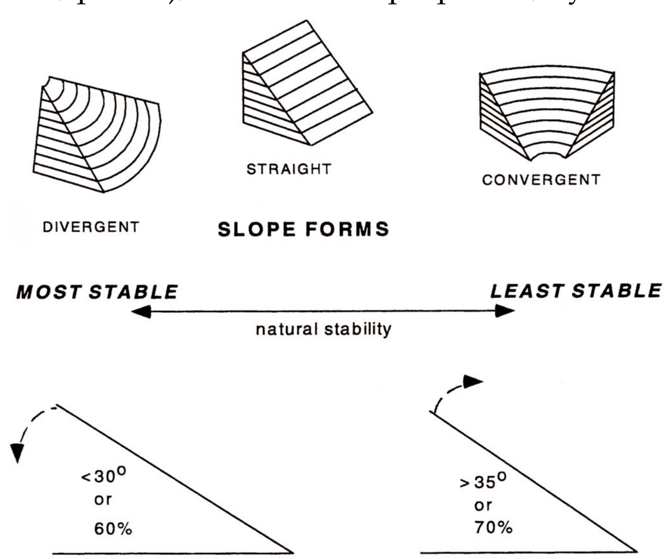


Figure 13. Schematic of divergent, straight, and convergent topography. (From Benda and others, 2000)

[2] More information and detailed descriptions of human effects, triggering mechanisms, and slope stability factors can be found in Turner and Schuster, 1996.

ogy, and type and extent of vegetative cover. Short descriptions and useful references for each of these factors are provided below.

Slope Steepness

Although not all steep slopes are unstable, steeper slopes tend to be less stable, other conditions being equal. Many studies have corroborated and quantified this fundamental tenet (Wieczorek and others, 1988; Millard, 1999; Robison and others, 1999; Vaugeois and Shaw, 2000). For example, in a recent study by ODF, no debris flows in the study areas were initiated on slopes below 40 percent steepness, with slopes measured directly in the field. Most of the landslides were initiated where slope steepness was measured to be over 70 percent (Robison and others, 1999).

Landform

Landform has an impact on slope stability (Figure 13). Sharply convergent (concave) slopes tend to develop thicker soil/colluvial deposits and are locations of concentrated drainage (Dietrich and Dunne, 1978). Many studies report that such locations have higher landslide hazard than straight (planar) and divergent (convex) slope forms (Tsukamoto and others, 1982; Reneau and Dietrich, 1987; Benda and Cundy, 1990; May, 1998; Millard, 1999). While landslides do occur on slopes with no apparent distinctive landform, convergent landforms tend to have a higher landslide occurrence in western North America.

Rock and Soil Properties

Properties of geologic materials can exert important control on the stability of slopes. Rock joints, bedding planes, and other discontinuities typically display lower strength than a continuous rock mass, sometimes lower than the strength of weathered soils. These discontinuities can also affect the flow of water through a slope and can lead to high, localized water pressures. Studies by Swanson and Lienkaemper (1985), Wieczorek and others (1988), Rollerson and others (1997), and Millard (1999) have shown that landslides occur predominantly in certain rock and soil types.

Hydrology

The influence of water in initiating and affecting the geometry of landslides is well documented (Pierson, 1980; Reneau and Dietrich, 1987; Iverson, 2000). As explained in the Trigger Mechanisms section, most debris flows are initiated during or shortly after large storms. Storm runoff can produce substantial erosion and in some cases can be the primary mechanism for initiating a debris flow (Wells, 1987; Cannon, 1997). More commonly, however, subsurface water flow concentrates in marginally stable areas and contributes to debris flow initiation through increased water pressure and saturation of soil horizons (Iverson, 1997). In the long term, water can also contribute to decreased slope stability through natural weathering processes, including both chemical and physical breakdown of rock and soil.

Vegetation

Both vegetative type and cover (how much and where it is located) can significantly affect landslide initiation potential. Many debris flows begin in small, nonvegetated pockets of soil, and substantial research has focused on evaluating the role of vegetation in forestland stability (Burroughs and Thomas, 1977; Dietrich and Dunne, 1978; Ziemer, 1981; Reneau and Dietrich, 1987; Montgomery and others, 2000).

Transport

Since most debris flows begin as relatively small events, the factors that cause these small landslides to become large, rapidly moving debris flows are of critical importance. Essentially, any factor that contributes to developing momentum from the onset of a landslide will contribute to the transport potential. This includes characteristics of the slide mass itself (such as mobility, hydrology, mass composition) and of the travel channel (such as gradient, confinement, roughness, obstructions, junctions). The dominant factors include the presence (or absence) of a steep downslope travel path, the mobility of the initial landslide debris, the availability of additional debris, internal hydrologic characteristics of the slide mass itself, confinement of the channel, and the presence of wood and other organics (Johnson, 1984; Davies, 1997; Iverson and others, 1997).

A steep downslope travel path and the mobility of the initial landslide debris are significant factors affecting the initial stages of debris flow movement (Campbell, 1975; Corominas, 1996). As debris flows travel further downslope, other factors combine to affect the potential for continued travel or loss of momentum and subsequent deposition. The availability of additional debris along the path can lead to extensive increase (bulking) of the slide mass and, if slopes continue to be steep, can greatly increase momentum. Internal hydrologic characteristics of the slide mass also affect its mobility (Ellen and Fleming, 1987; Iverson and LaHusen, 1989; Iverson, 1997).

Confinement is a term that refers to narrow, steep-sided channels for slide-material transport. Debris flows that travel through confined paths tend to travel farther than those on open slopes (Fannin and others, 1997). Concave landforms such as swales, channels, or draws can funnel debris flows and keep their energy from dissipating. Thus, confined stream channels and the outlets of canyons can be particularly dangerous locations during debris flow events.

Wood and other organic materials can substantially affect debris flow behavior and are common in flows in the Pacific Northwest (May, 1998; Johnson and others, 2000). Wood material often accumulates at the front of debris flows and can greatly affect debris flow transport paths and distances. In some cases, when trees are lodged in confined areas, small debris flows can be stopped. In other cases, large pieces of wood can act to increase momentum or function as battering rams along transport paths.

Modeling debris flow transport typically involves the use of simplified rules for determining whether a flow is likely to continue traveling downslope or instead will lose momentum and deposit its mass. These rules are often based on empirical observations of conditions associated with transport on the one hand and deposition on the other. Some models that address debris flow transport include those by Hungr and others (1984), Benda and Cundy (1990), Benda and Dunne (1997), Fannin and others (1997), and Iverson and others (1998).

Deposition

As debris flows eventually lose momentum they form single or multiple deposits. Many of the same factors that affect transport, including channel gradients, channel roughness (or friction), channel confinement, obstructions, channel junctions, and material properties of the flow, determine when and where deposition will occur (Benda and Cundy, 1990; Fannin and Rollerson, 1993). The onset of deposition is controlled by factors that slow down and/or obstruct debris flow movement.

Where channel gradients decrease and flows lose channel confinement, debris flows typically spread out and quickly lose momentum. Once a flow is no longer in steep scour zones, obstructions (including large rocks, levees, standing trees, etc.) can also reduce momentum and cause the flow to cease movement. Very sharp turns in the debris flow path can also cause them to stop (Swanson and Lienkaemper, 1978; Benda and Cundy, 1990).

The characteristics of debris flows in deposition areas are highly variable, particularly when confinement is abruptly lost. The size and material properties of the flow influence the size and shape of its mass over the topography in the deposition zone. Large debris flows with high water content and relatively uniform grain size tend to spread out substantially and form relatively thin and broad deposits (Figure 14). Less saturated debris flows tend to form thicker, shorter deposits (Figure 15). These thicker deposits are more common with open-slope (versus channelized) failures that are not fully saturated (Major, 1997).

Debris flows are often deposited in several surges or pulses of activity (Iverson, 1997; Major, 1997; Mohrig and others, 1998). In some cases, the surges may be attributed to multiple upslope failures initiating the debris flows. In other cases, they are attributable to inherent instability within the moving mass. Subsequent floodwaters, particularly in cases of channelized debris flow deposition, may erode and redistribute the deposited debris (Benda, 1988; Costa, 1988). Under such conditions, a deposit can be created that consists of a sequence from debris flow to hyperconcentrated flow to flood, with gradual transitions. Figure 16 shows a schematic diagram of such an event. The downslope floodwaters are not likely to exert the extreme impact forces of large debris flow surges, but can still be extremely damaging.

From this overview of contributing factors, one can see that predicting and modeling debris flow deposition is a difficult task, particularly for regional applications. Some researchers have focused on this important aspect of landslide hazard assessment, notably Cannon and Savage (1988), Cannon (1989), Ellen and others (1993), Hirano and others (1997), Morgan and others (1997), Nakagawa and Takahashi (1997), Iverson and others (1998), Campbell and Chirico (1999), and Hungr (1999).

Figure 14. Fine-grained fan deposit in the Dodson/Warrendale area.

Figure 15. Unchannelized debris flow deposit.

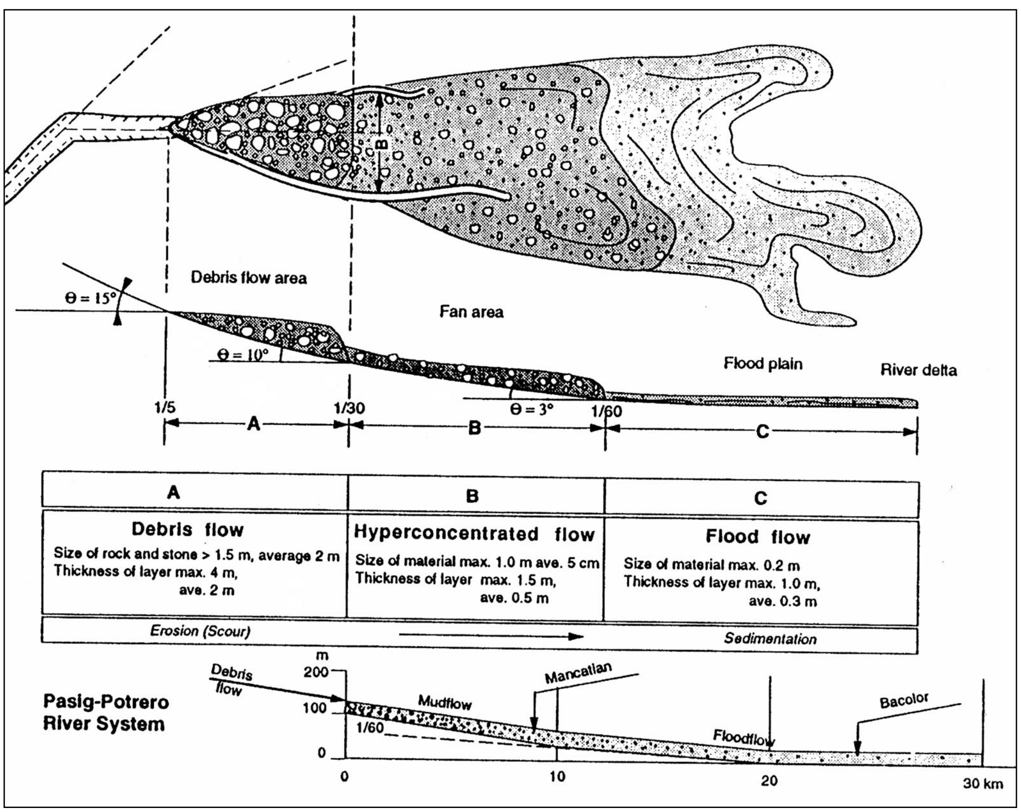


Figure 16. Schematic of transition from debris flow to hyperconcentrated flow to flooding. (From United Nations, 1996)

HAZARD MAPPING OVERVIEW

The debris flow characteristics described in the previous section form the basic information used for various hazard-modeling approaches. In essence, the general objective of hazard modeling is to break a phenomenon down into its governing processes. All modeling is a simplification of reality, but effective models accurately reflect fundamental components of the process being modeled.

For specifically evaluating regional landslide hazards, various qualitative and quantitative tools and modeling approaches are used. Typical methods used to assess debris flow hazards include aerial photo interpretation, landslide inventory comparisons, Geographic Information System (GIS) modeling, and field evaluations. There are significant advantages and also significant limitations to the use of each of these methods of evaluation. For example, aerial photo interpretation can be quite efficient in identifying unstable terrain over large areas, but can miss critical sites because of forest cover or scale limitations. Similarly, GIS modeling is uniquely suited for regional implementation, but applications are dependent on the quality and availability of input data. Field observations and inventory data comparisons can also be limited by scale and access constraints.

The overall objective for this project was to maximize the strengths and minimize the weaknesses of each of these methods to produce the most useful and accurate map possible. We used an iterative process (shown schematically in Figure 17) that included multiple phases of GIS screening, field data collection, inventory comparisons, and peer reviews. Our overall goal was to develop a map that provided the best spatial match with each reliable source of data available on areas of historic occurrence and likely future impact zones. The following sections describe the main procedures used to develop the map.

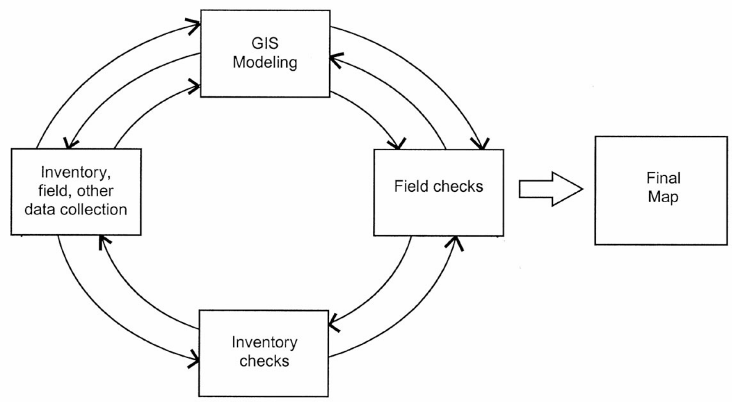


Figure 17. Schematic of the iterative process used to develop the map.

Initial GIS Modeling

The first step was to develop an initial GIS model to serve as a guide for more detailed hazard mapping. The initial modeling was done by ODF and essentially involved highlighting steep slopes based on 30-m U.S. Geological Survey (USGS) Digital Elevation Models (DEMs). ODF completed and released the initial GIS layers in December of 1999.

Targeted Field Investigations

The initial ODF GIS output was used to select areas as targets for field investigations of debris flow transport and runout zones. The primary intent of the initial stage of field investigation was to identify areas where we could use geologic evidence to evaluate the extent of historic deposition. The presence or absence of historic debris flow activity can be valuable for evaluating future hazards because many debris flows occur at, or very near, previous flow sites. A diagram of some of the geomorphologic features that can help identify areas of historic debris flow occurrence is shown in Figure 18.

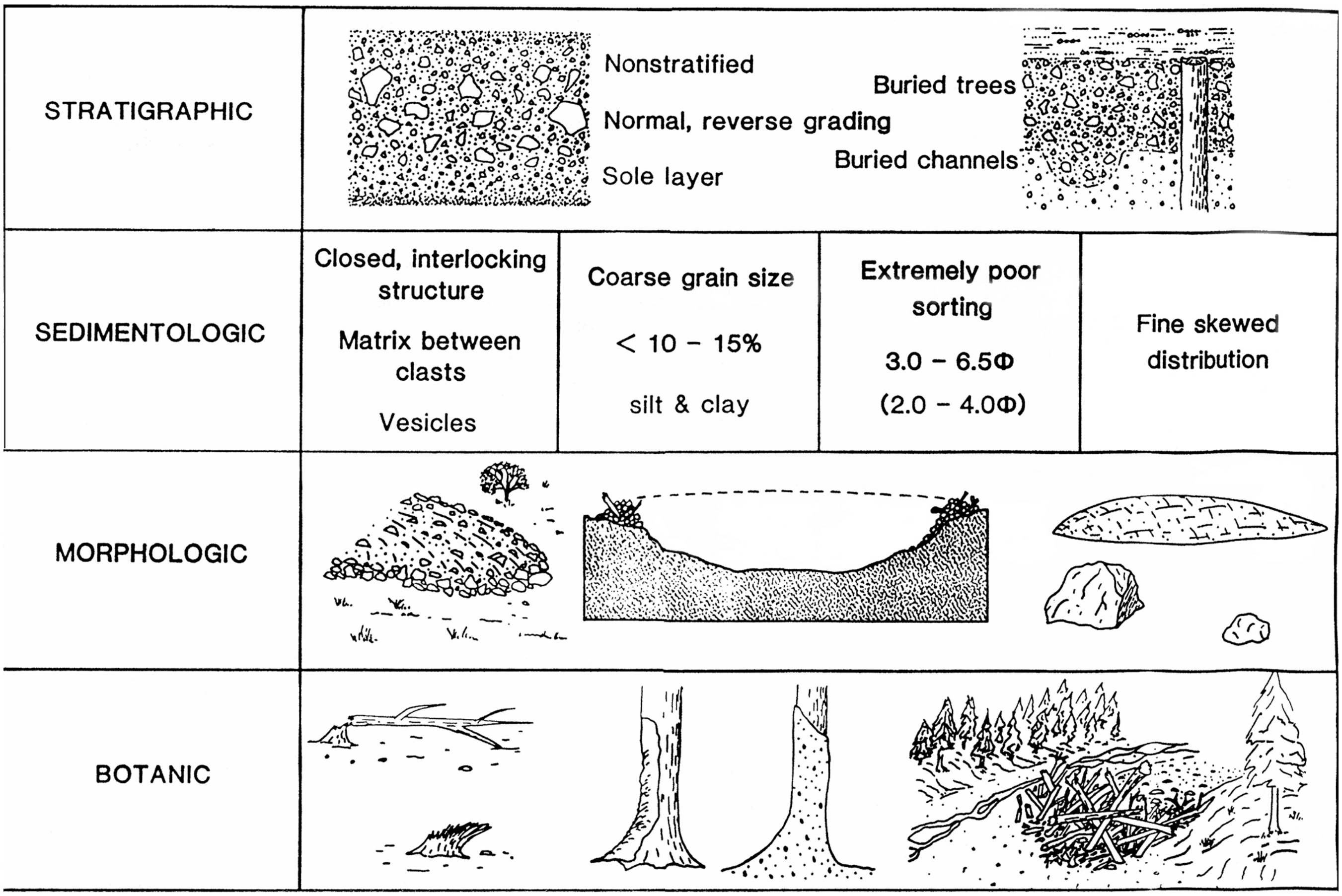


Figure 18. Geomorphic features that can aid in the identification of historic debris flows. (Diagram courtesy of Tom Pierson)

Both the Oregon Departments of Geology and Mineral Industries (DOGAMI) and ODF performed these targeted field investigations. Geographically distributed (and geologically diverse) areas were evaluated as shown in Figure 19. In these areas, reconnaissance-level field investigations were conducted. Where geologic evidence clearly defined the extent of historic debris flow deposits, boundaries were mapped. More commonly, the geologic evidence was discontinuous or otherwise inconclusive. In these cases, field investigations focused on a general rating of terrain for high versus low relative debris flow hazard.

Improved GIS Modeling

During and following the initial field mapping, a variety of GIS models that could aid in the hazard mapping effort were evaluated. Our focus was on identifying a suitable modeling framework to delineate the range of debris flow hazards observed in the field, including initiation, transport, and deposition areas. While numerous models have been developed for evaluating initiation potential, fewer have focused on the transport and deposition hazards—areas that are critical for impact and public safety.

In a general review of modeling approaches and available models, a modeling framework developed by the Earth Systems Institute (ESI) was selected as the starting point . The ESI program uses topographic input data (DEMs) and a suite of rules to model initiation, transport, and deposition zones. In this study, the general three-part framework implemented was as follows:

For initiation, steep slopes are used as the

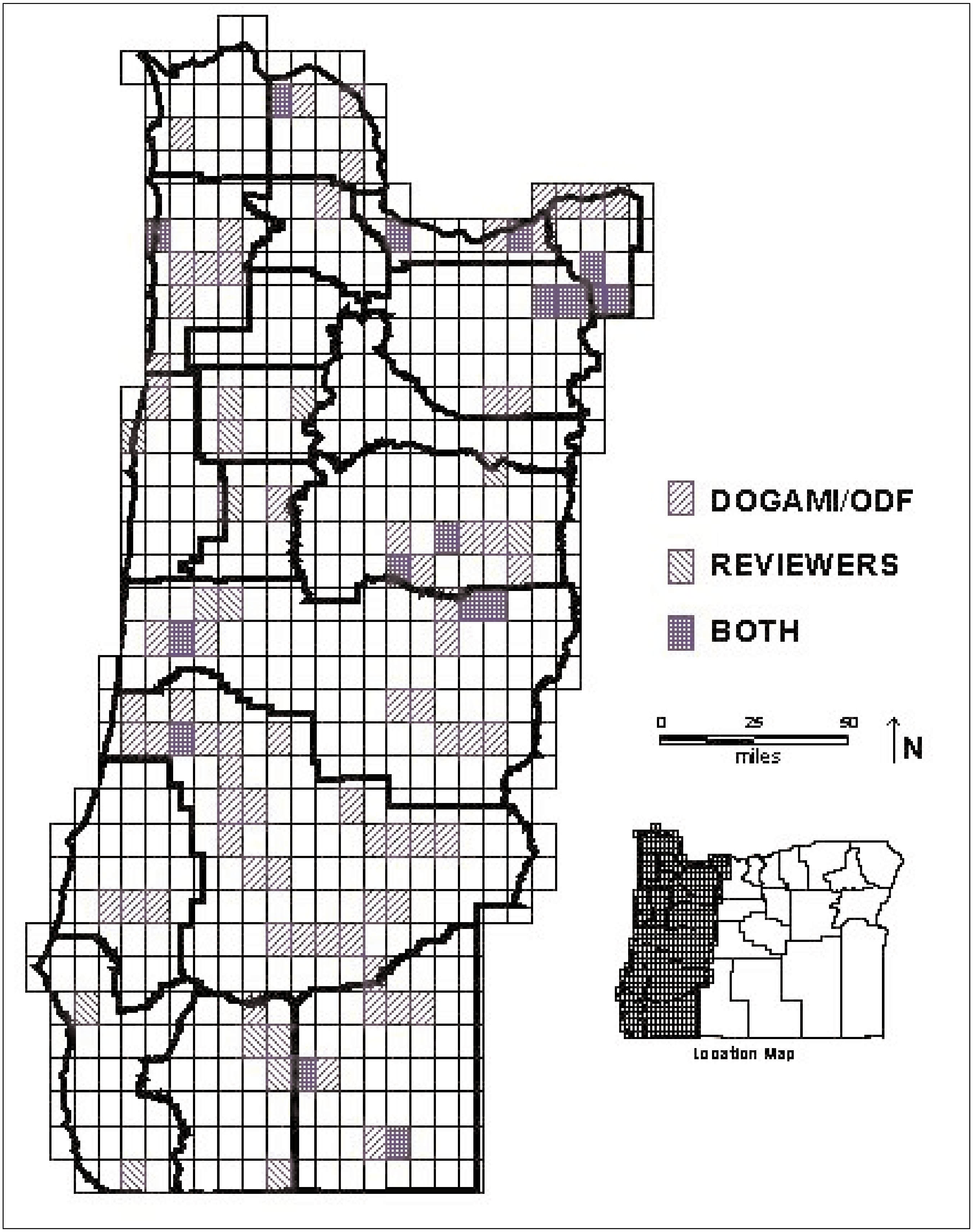


Figure 19. Map showing areas where field investigations were performed for this study. Shading identifies investigators for those 7 1/2-minute topographic quadrangles within which investigated areas were located.

basis for distinguishing potentially unstable sites.[3]

For transport, each potential initiation site (determined by a specified slope threshold) is routed downslope according to rules that incorporate a number of factors, including slope gradients and topographic confinement. If a path is steep, the failure will continue to travel and will accumulate more material. If the path gradient drops substantially and loses confinement, the mass begins to settle as a deposit.

Once deposition begins, a modeling approach developed originally by the USGS for volcanic hazards (Iverson and others, 1998) and adapted for debris flow modeling (Griswold and Iverson, 2002) is used to predict the spread of the accumulated debris.

The input parameters used in the model are summarized in Appendix B, and specifics on the algorithms are described in Miller (2002). Significant advantages of the ESI modeling approach are a straightforward and logical framework, flexible parameter selections to account for varying conditions, and presentation of relative hazard indices. The following sections discuss refinements and calibrations of the model as we made them specifically for this project.

Qualitative and Quantitative Testing

The ESI program immediately produced map results that were a good spatial fit with the field notes and inventory data. However, as with any regional GIS model, it is critical to test and refine the results. In this case, our main objective was to get the best match between the GIS model output, the debris flow inventory data, and our field observations. In fine-tuning the ESI model, we started by testing parameters for use in evaluating initiation susceptibility, then progressed to selecting specific transport and deposition parameters.

[3] The ESI program can implement other proxies for initiation potential such as Shalstab (Montgomery and Dietrich, 1994) or SMORPH (Vaugeois and Shaw, 2000).

Initiation Comparisons

To evaluate and select a model for debris flow initiation potential, we performed a quantitative comparison of a consolidated inventory of debris flow locations and common initiation hazard indices, including slope gradient, topographic convergence, and topographic contributing area. We evaluated the appropriateness of each hazard index by comparing the number of historic landslides to the total area mapped by the hazard selection.[4]

On the basis of the inventory comparisons, slope gradient alone (versus slope plus convergence or slope plus contributing area) was selected as the index for use in the modeling. Slope gradient alone is the simplest of the initiation indices, and the number of landslides identified per mapped area was actually slightly higher than the number captured by the other indices.

A plot of the percentage of landslides in the inventory captured by various slope cutoffs is provided as Figure 20. Also shown is the percentage of the total western Oregon study area covered by each slope value and higher (e.g., 10-m DEM-derived slopes of greater than 50 percent comprise approximately 20 percent of western Oregon). From Figure 20, one can compare various selections of cutoffs in terms of historic debris flows identified versus total areas that would be mapped by the cutoff selections. The three distinct curves labeled 0 m, 15 m, and 31 m represent different buffer spacing selections used to compare debris flow initiation locations to slope values. The purpose of the buffer spacing selections is to address spatial uncertainty in the inventory locations (see, for example, Vaugeois and Shaw, 2000, where a 15 m buffer was used).

[4] Models were compared as to how many landslides the index identified. A model that identifies a high number of landslides in a small mapped hazard area is considered preferable to one that captures fewer landslides in the same amount of hazard area, or requires more mapped area to identify the same number of landslides.

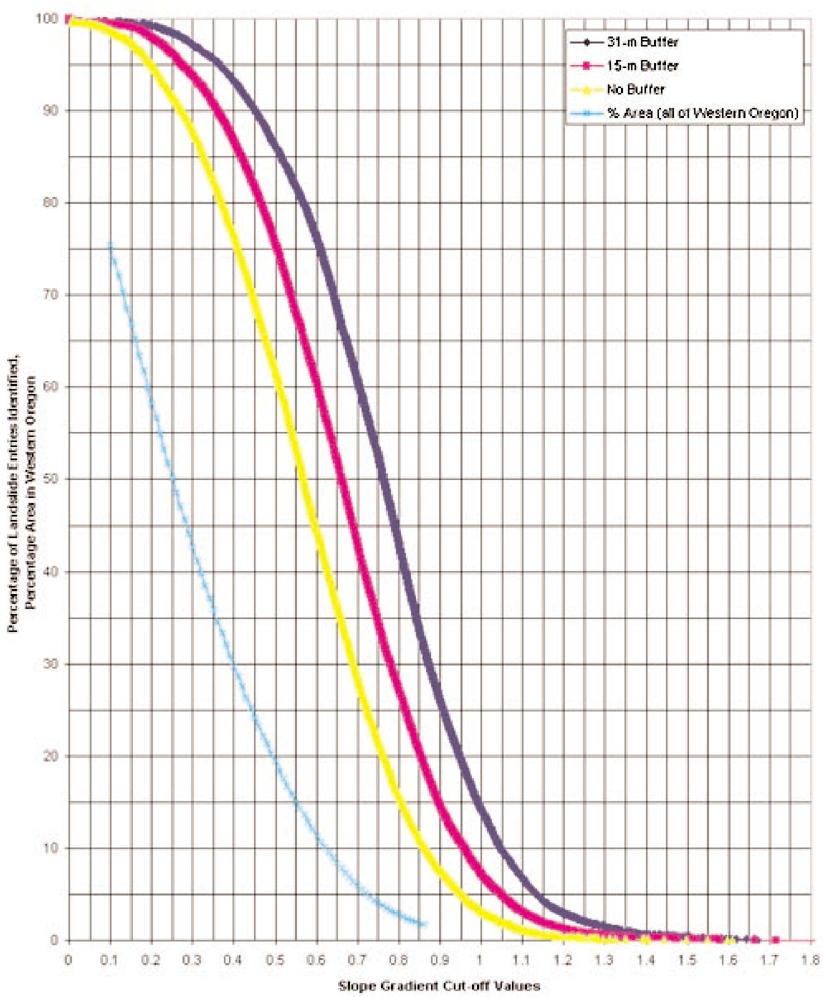


Figure 20. Percentage of landslides identified by various slope threshold selections.

In order to capture a range of 60–85 percent of the known landslide locations, a 10-m DEM-derived slope gradient of 50 percent and higher was selected as the cutoff for defining initiation susceptibility for the overview map. This is a lower threshold than that commonly used for field-based forestry applications, and a higher threshold than commonly used for local government landslide hazard ordinances. It is important to note that the threshold identified for this project was designed to balance the conflicting objectives of identifying as many future debris flow initiation sites as possible while minimizing the area affected. Also, while the hazard specifically targeted was debris flow initiation, other types of landslides can occur, particularly on gentler slopes.

Path and Deposition Comparisons

To test and calibrate the path and deposition parameters, we primarily used comparisons with field observations and inventory data that included transport and deposition zones. We ran the ESI model at various locations throughout the western portion of the state and then compared the outputs to field interpretations. The objective of these comparisons was to find correlations among (a) the hazard areas identified in the GIS outputs, (b) field-identified hazard zones, and (c) debris flow paths identified in a consolidated debris flow inventory.

The variability of debris flow transport and deposition across regional landscapes is well documented (Swanson and Lienkamper, 1985; Millard, 1999). While it was not feasible to calibrate the modeling approach site by site in this study, it was possible to identify generalized relative hazard differences by physiographic region. Based on results from the test sites scattered throughout western Oregon, we selected four generalized provinces with which to separate relative hazard cutoffs. Figure 21 shows the generalized geographic separation. These regions were used to separate the final deposition cutoff selections (as summarized in Table 1) but were not used to modify either the initiation or transport parameters for this map.

Additional Field Checks

As we worked toward achieving high correlation among existing data for our various test sites, we performed additional field checks and sent draft copies of the map to debris flow researchers for field verification. This allowed us to obtain ground observations in areas we could not have otherwise visited due to time and budget constraints. The field reviewers of draft maps are listed in Appendix C. The reviewers evaluated areas based on their particular field expertise, and the geographic distribution of those areas is shown in Figure 19.

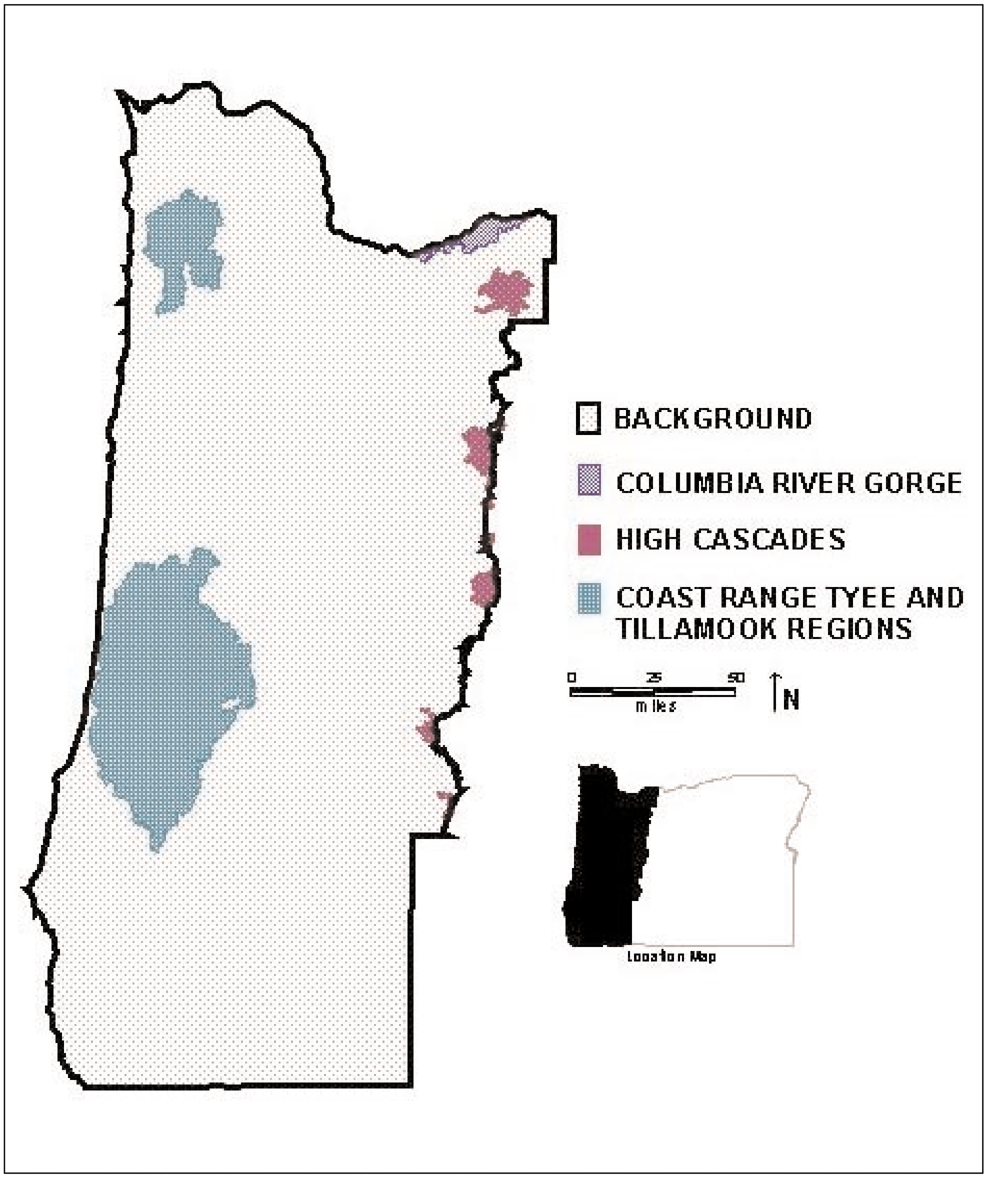


Figure 21. Generalized geographic separation used for selecting deposition hazard cutoff values.

Final Selection of Parameters and Map Generation

We made final refinements based on feedback from the draft map reviewers and then proceeded to process the model for western Oregon. Due to the large amount of data and the detail of the programming operations, the map development necessitated dividing the region into 149 sections. The model was processed on these sections (with 3 to 5 km overlaps to eliminate negative edge effects) and stitched together at the borders.

As a final processing step, the output deposition hazard values were grouped to de-

Table 1. Parameters used for defining deposition hazard zones for the overview map

Geographic Designation	Index Cutoff Selected
Region 1—Background	<100
Region 2—High Cascades	<1000
Region 3—Columbia River Gorge	<500
Region 4—Coast Range Tyee and Tillamook	<50

velop the overview hazard zones as summarized in Table 1. The background cutoff of 100 was applied to the majority of western Oregon and was selected to create a relatively conservative, average-case zone that is intended to encompass the reasonable range of potential impact areas. It will be over-conservative in some case and under-conservative in others. On a regional scale, however, it should effectively serve as a screening tool.

The three other regions (High Cascades, Columbia River Gorge, and Coast Range Tyee and Tillamook) include areas where regional hazard patterns varied markedly from the background case and thus warranted separate treatment. Glacial and volcanic effects can lead to very large debris flows in the High Cascades. The steep, geologically young margin of the Columbia River Gorge on the Oregon side also generates anomalously large events (e.g., Robertson, 1996). And, on the other extreme, the very steep and highly dissected geomorphology of the Coast Range tends to produce frequent slides of smaller magnitude (Swanson and Lienkaemper, 1985).

MAP RESULTS AND DISCUSSION

Figure 22 shows the hazard zone for the City of Salem and the Dodson/Warrendale area in the Columbia River Gorge. As is evident from these two examples, the extent of the hazard area varies substantially across western Oregon, with a large percentage of the Dodson/Warrendale region identified as a hazard and only a small area identified in the southwest corner of the Salem map.

The hazard map zones are stored as digital polygon files in GIS file formats. These digital files can be used as overlays on other relevant map information, such as zoning maps.

It is important to note, however, that the hazard map is intended for use with the 1:24,000-scale USGS topography and stream data. The model was derived from USGS 10-m DEMs, and, therefore, other coverages (particularly stream layers) derived from topography at other scales are unlikely to match.

For higher resolution coverages, the fit may be acceptable in some cases, but any spatial data sets used for decision-making with the map should be thoroughly analyzed for compatibility.

The map is an overview with only two zones: potential hazard or no hazard. A particular map location is simply inside or outside the hazard zone. In reality, the hazard is gradational. The areas of highest hazard are typically near channel mouths or close to the base of very steep slopes (Figure 23). From the outlets of channels and the bases of steep slopes, the hazard typically decreases with distance and with increasing elevation above the source channel. Figure 24 provides an illustration of modeled hazard gradation for a fan complex near Rogue River.

A relative hazard map showing these gradations is in development (Hofmeister and others, in prep).

Areas Affected

While the map covers 19 western Oregon counties (Figure 25), the amount of area impacted in each county varies considerably. Figure 25 includes the percentage area in each county covered by hazard zones. Within counties, much of the hazard area is confined to localized steep areas, mostly on federal, state, and private forestland. For example, 58 percent of Josephine County is included in the overview map, the highest percentage of the 19 western Oregon counties. Although a large portion of that area is steep terrain that is extremely dangerous for debris flows, much of it is sparsely inhabited, publicly owned forestland, where development is not likely. To illustrate this, the breakdown of the

Table 2. Hazard area breakdown by ownership* in Josephine County

Ownership	Percent of total county acreage owned	Percent of owned acreage mapped as potential hazard area	Percent share of total county hazard acreage
USDA Forest Service	39	70	47
US Bureau of Land Management	28	67	33
Private	32	36	19
State land and Oregon Caves Monument	1	67	1

* Ownership data are estimates and were derived from regional GIS layer owner.shp from the Oregon Geospatial Data Clearinghouse, http://www.gis.state.or.us/.

hazard area designation by general land ownership is shown for Josephine County in Table 2. While approximately 68 percent of Josephine County is in the public domain, this accounts for more than 80 percent of the total mapped hazard area in the county. Alternatively, approximately 32 percent of the county is privately owned and accounts for less than 20 percent of the hazard area in the county.

Quantification of Hazard Designations

For application of the map, it is helpful to evaluate how the overview hazard zones quantitatively relate to known occurrences of debris flows. Debris flows often recur at or very near the same locations. Therefore, comparing the map results with information on

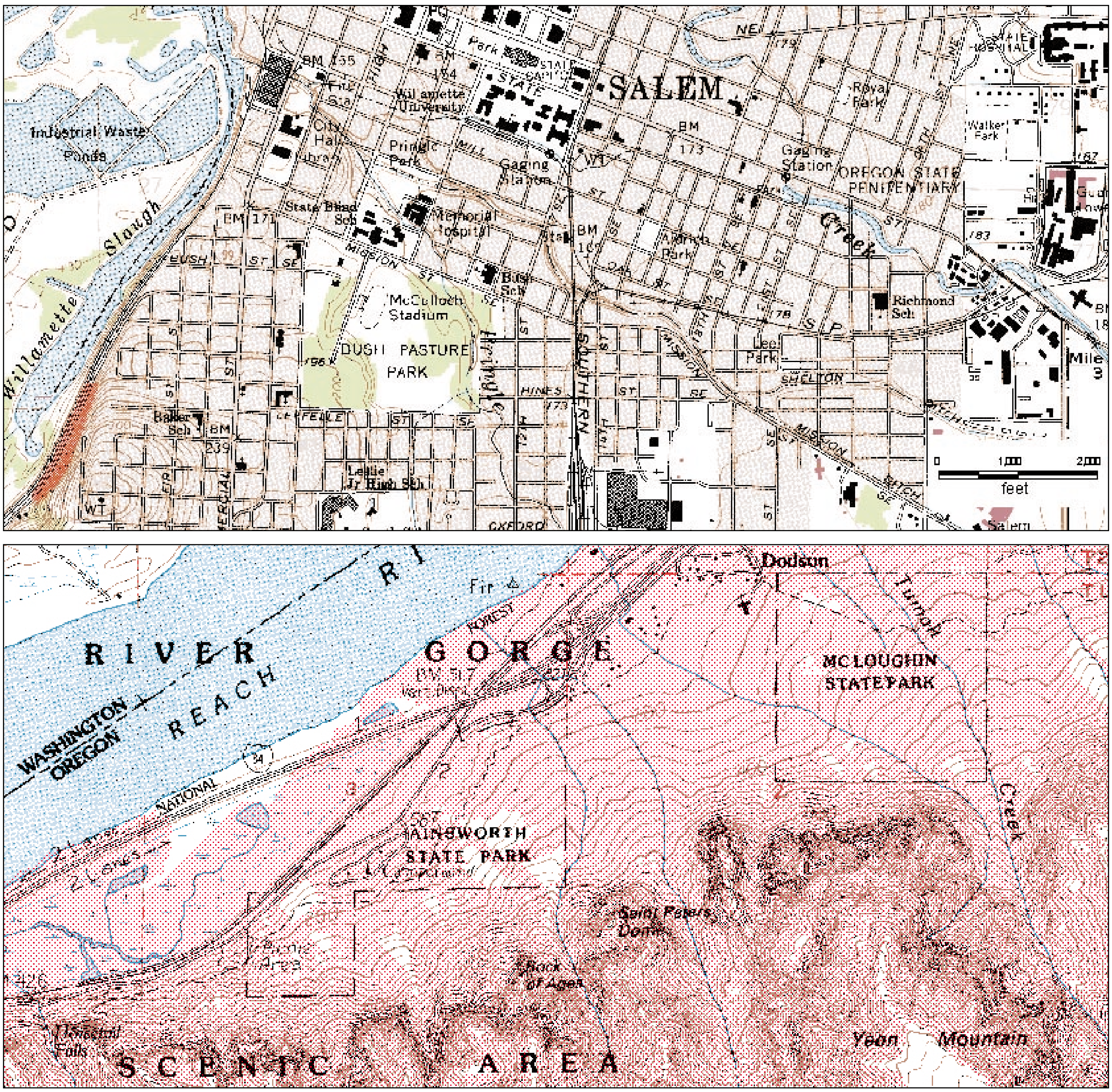


Figure 22. Maps of Salem (above) and the Dodson-Warrendale area, as examples of the mapped hazard areas.

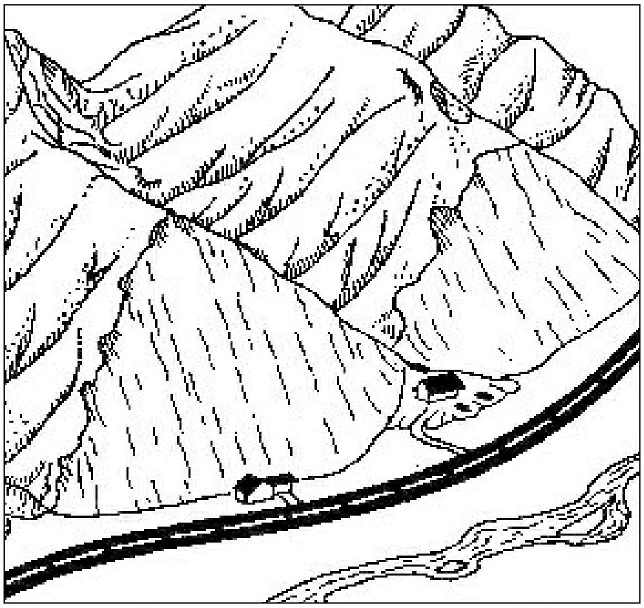


Figure 23. Typical highest hazard home locations: near channel mouths and at the base of very steep slopes. (Illustration courtesy of Oregon Department of Forestry)

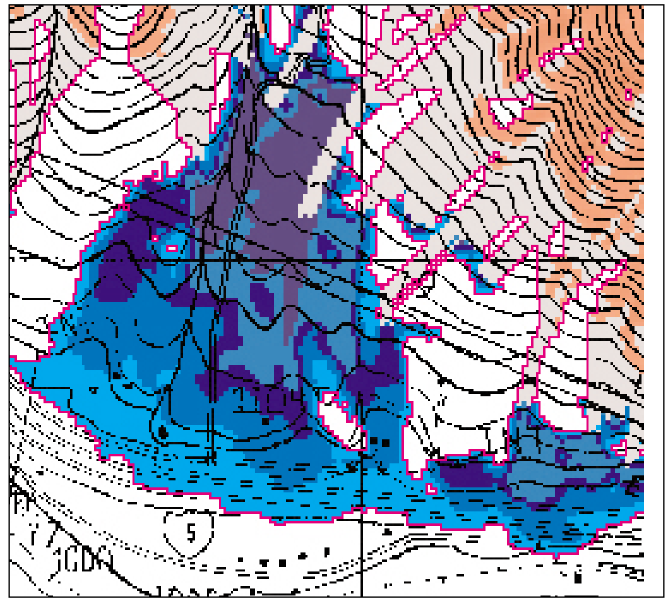


Figure 24. Example of gradation within a hazard zone. Darker shades signify higher relative hazard. Initiation areas are in red; transport areas in gray; and deposition areas in blue.

historical debris flow locations is a useful means of evaluating the reliability of the hazard map. Use of existing inventory data to estimate future landslide hazards leads to capture rates that for the overview map that are expected to be roughly within the ranges summarized in Table 3.

Initiation

For the initiation portion of the model, the estimated performance of the hazard designations is based on the percentage of historic landslides identified by each slope cutoff value in the previously mentioned inventory comparison (Figure 20). Extrapolating these data to future time periods and storms, the slope threshold of 50 percent used for the overview map is roughly estimated to capture between 65 percent and 85 percent of the landslide initiation sites.

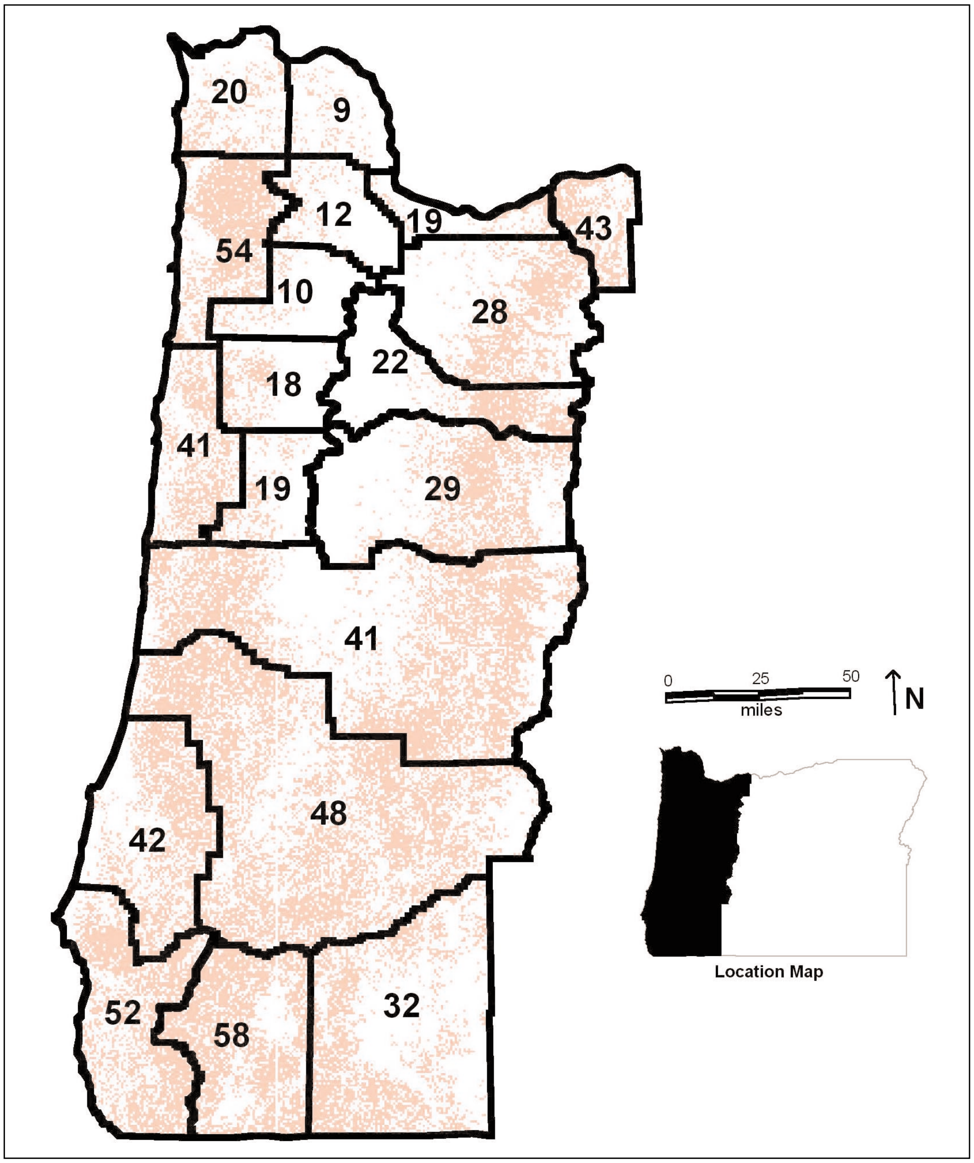
Transport

For transport evaluation, we cannot conduct as detailed a comparison of map areas and lines because of limited path data, and additional spatial uncertainties. In general, however, we expect the capture of debris paths to be similar or better than the initiation areas. We expect this because, within the model (and in reality), slope failures from

Table 3. Summary of predicted capture rates for the hazard areas, by component

Component	Expected capture rate	Basis for prediction
Initiation	65-85% regionally	7,640 historic locations*
Transport	80-95% regionally	Qualitative observations
Deposition	80-95%	4,000+ historic locations*

* Inventory data in Hofmeister (in preparation).



🡐 **Figure 25. The 19 western Oregon counties covered by the hazard map. The numbers are the percentage of that county's area included in the overview hazard area.**

🡓 **Figure 26. Coalescing debris flow sources in Nagasaki, Japan. (From United Nations, 1996)**

multiple sources tend to coalesce into a smaller number of drainage paths (Figure 26). Thus, if steep upslope areas are identified as hazards, and the gradients are sufficient for the model to assume transport, the downslope drainage path will be included as a potential hazard.

Deposition

Similar to the initiation comparison, we compared a consolidated GIS inventory of historic debris flow locations to the hazard output for deposition zones. The overview hazard area captured over 90 percent of the historic deposition locations. This is a particularly rough indicator because of the inherent variability in the deposition hazard, but it is reasonable to expect captures in the range of 80 percent to 95 percent.

Summary

Although each of these quantifications for initiation, transport, and deposition is based on limited data, the comparisons with inventory data are useful for estimating expected performance. As more data are collected, analyzed, and quantified from future events, these estimates can be evaluated further.

LIMITATIONS

The map outputs are intended to be used at a scale of 1:24,000, and the hazard information is stored at the original 10-m DEM spacing. This is a higher level of detail than is often used for regional mapping, but it is not a replacement for site-specific evaluation. Some of the reasons for this critical limitation are worth highlighting.

- *The map is based on coarsely-spaced representations of topography*. 10-m DEM data are the best regional topographic data available with full western Oregon coverage at this time. These DEM inputs do not incorporate changes since the development of the original topographic quadrangle data (in some cases over 20 years ago) and have inherent uncertainties (Holmes and others, 2000). Changes in the DEM—from activities such as grading for development—could affect the hazard mapping in some areas. In addition, local features such as soil strength, hydrology, vegetative cover, geologic discontinuities, unfavorably dipping bedding planes of geologic units, seams of local weakness, and other local slope stability factors that are not incorporated in the map may be critical factors for particular areas. These conditions could not feasibly be assessed at the regional level, yet may be critical for particular sites.
- *Only select areas have been field verified*. As explained in the section Characteristics of Debris Flows, local conditions can greatly affect debris flow hazards. Only a small sampling of areas in western Oregon could feasibly be field-evaluated for this project. Distinctive local conditions will inevitably affect the accuracy of the results in some areas more than others.
- *The hazard itself is characteristically chaotic.* In some cases, debris flows can become tangled in confined channels and avulse (or jump) the confines of the channel and create a new path. Also, debris flow deposition paths will often diverge substantially from one flow to the next. Barring the mapping of huge, overly conservative regional hazard zones, there will always be some level of uncertainty in identifying future impact areas.
- *The map is not currently correlated to recurrence intervals or intensities*. Recurrence intervals are important for the transition from hazard assessment to risk assessment and mitigation (Hungr, 1997) but can vary considerably, depending on local conditions (McCuen and others, 1990; Johnson and others, 2000) and method used (Orme, 1990). Due to a lack of time-sequenced regional data, we have not yet attempted to associate the hazard zones to recurrence intervals or intensities.
- *Unusually large slides may not be adequately captured*. This regional model focuses on medium-scale landslide hazard areas (10-m by 10-m map dimension). Very large slides are difficult to capture at this scale and, in some locations, this model may not identify the full extent of the hazard area. In particular, large volcanic landslides (lahars) and dam-break floods are not addressed in the map. For areas in the Oregon Cascades, lahar and historic glacial dam-break events are identified on existing USGS maps (Scott and others, 1997; Walder and others, 1999; Scott and others, 1999; O'Connor and others, 2001).

We sought to find reasonable agreement among the available sources of data and purposefully selected parameters to capture a high percentage of historic slide locations. It is inevitable, however, that slides will occur outside the hazard areas. While we hope these slides will be small and not adversely impact people or property, it is nonetheless critical to note that *significant impacts outside the mapped zones are inevitable*.

The hazard areas have a relatively high hazard, and are considered more likely to be affected by rapidly moving landslides than other areas. The specific location and timing of events, however, depends on a number of highly localized and variable parameters. The hazard map is a valuable screening tool for identifying high hazard areas. Used in conjunction with site-specific evaluations, the map can be helpful in regional planning and implementation of risk reduction measures.

RISK MANAGEMENT STRATEGIES

The map characterizes potential areas of hazard from rapidly moving landslides. Hazard is a term referring only to the geologic danger. Risk is a term used in the natural sciences to refer to the combination of geologic hazard plus the potential that the geologic hazard will impact something valuable (an individual, a structure, road, fish-bearing stream, etc.). For example, a very high debris flow hazard area may have low risk if it is located in a remote, inaccessible wilderness area. On the other hand, if something of worth is exposed within that same hazard zone, there is a greater inherent risk of damage. Risk, thus, increases with both hazard and the value of objects or people in the potential impact path.

To develop an effective risk management strategy, it is critical to accurately identify both hazard and risk. This map provides information about the extent of rapidly moving landslide hazards. Communities and individuals must assess their own risk by identifying things of value within the hazard areas. For example, a particular community may have two primary hazard areas identified as likely debris flow zones. One area could be a rarely visited park located within the hazard zone. The other area could consist of several blocks of residential and commercial buildings vital to the community's livelihood. In this simplified example, the community would likely choose to make reducing risk in the more developed area a higher priority because of the higher inherent risk to property and lives.

Risk reduction includes a host of actions aimed at reducing the level of risk over both the short and long terms. The hazard map allows for first-step screening of hazard zones and for characterizing the geographic extent of rapidly moving landslide hazards. While this regional tool does not replace site-specific analyses, it does facilitate systematic and consistent evaluations of the geography of the hazard. Follow-up studies can then focus resources on evaluating the specifics of local hazards and assessing the associated local risks (Mears, 1977; Hungr and others, 1984; Hungr, 1997; Rickenmann, 1999).

Once risk is adequately characterized at a site-specific level, risk management strategies can be evaluated. Part of reducing risk is simply avoiding activities that increase susceptibility, such as building roads in potential slide initiation areas, removing vegetation on high-hazard sites, and concentrating drainage into high-hazard areas. Other risk-reduction efforts can focus on reducing either the hazard itself or the exposure (keeping people and structures out of dangerous locations). In general, most risk management strategies can be grouped into (a) planning, policy, and education efforts, and (b) engineered mitigation.

Planning, Policy, and Education Efforts

Debris flow damage to dwellings, business structures, roads and bridges can severely affect an entire community. Mitigation and risk-reduction efforts, therefore, are often most appropriate and effective when multiple parties join forces to ensure broad participation and ongoing commitment. Common debris flow mitigation approaches that can be implemented at both regional and community-specific scales may include information dissemination programs, public policies, warning systems, traffic alerts, and temporary closures (of roads, parks, etc.).

Information Dissemination/Increasing Awareness

The surest way to avoid threats to public safety from dangerous landslides is to limit time spent in locations with such a hazard, especially during periods of extreme rainfall. This can be achieved in some cases simply by increasing awareness of debris flow hazards. Many agencies and organizations provide useful public information to aid in the identi-

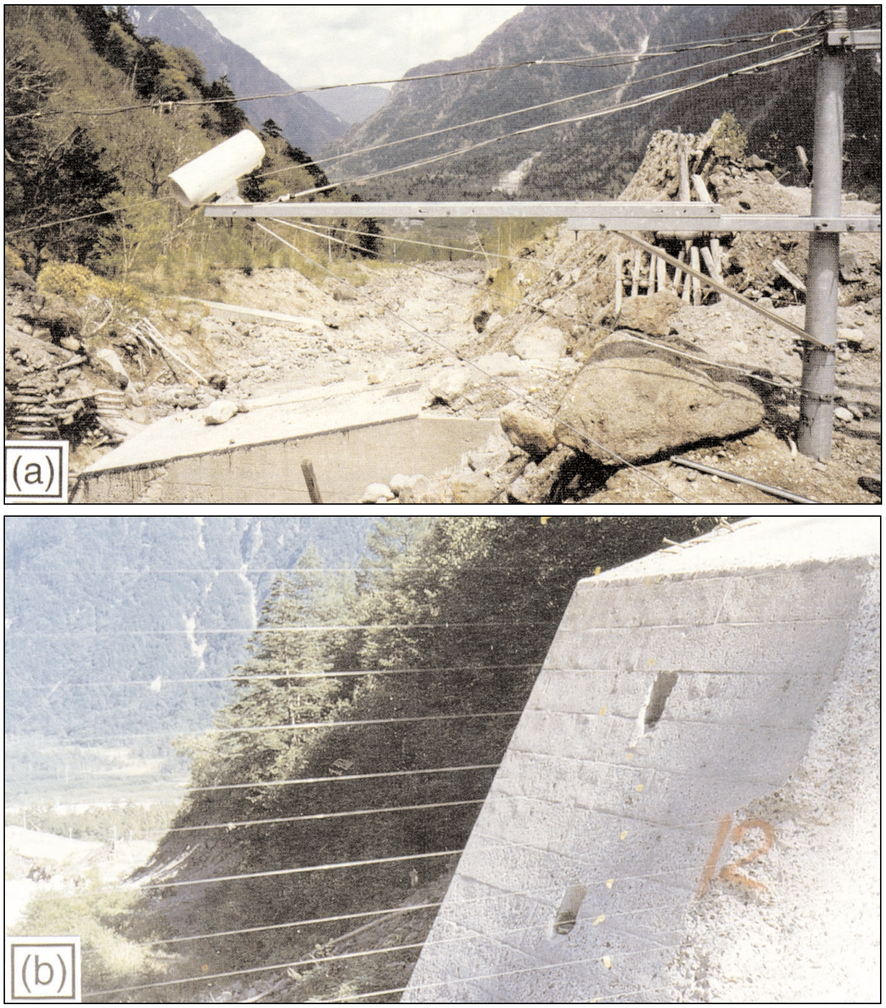


Figure 27. Examples of monitoring devices for debris flow warnings, (a)—a current gage and (b) a wire sensor system. (Photos from United Nations, 1996)

fication and mitigation of natural hazards, and a large body of literature has been developed. The reference list at the end of this paper provides some sources for locating additional information. Particularly valuable debris flow references are Blair and others (1985), Bowles (1985), United Nations (1996), Chen (1997), and Wieczorek and Naeser (2000).

Public Policy Programs

Implementation of public policies, particularly through zoning and land use regulation, is a critical component for long-term risk reduction. The landslide hazard area map can be linked to local planning operations. It can also aid local mitigation efforts such as the establishment of evacuation routes, identification of safe havens prior to large storms, and installment of physical warning devices (Figure 27) such as ground vibration sensors (LaHusen, 1996) and trip wires (Reid and others, 1999).

Another example of a public policy program is the ODF forest practices regulation included in SB 12. Forest practices management efforts tend to focus on limiting the extent of vegetation removal and road construction in high-hazard areas. ODF has recently reevaluated the forest practices rules and will incorporate use of the hazard area map for screening potential downslope risks, including homes and highways that could potentially be impacted by rapidly moving landslides.

Debris Flow Warning Systems

Warnings and advisories are intended to identify the time frame when, and general area where, debris flows are most likely. As discussed in the section on trigger mechanisms, most (but not all) debris flows occur during, or closely after, high-rainfall storm events. The Oregon Debris Flow Warning System[5] has been in place since 1997 and is

[5] More information on the Oregon Debris Flow Warning System is available at: http://www.oregongeology.com/Landslide/debrisflow1.htm.

periodically revised. When a storm exceeding the thresholds, discussed in the Trigger Mechanisms section, is forecast, a debris flow advisory is issued. When the storm occurs or additional dangerous conditions exist, a debris flow warning may follow.

Forecasting when debris flows will occur is an extremely difficult task. Weather patterns in Oregon are variable, and the conditions for timing and locating debris flows are more variable still. Despite the limitations, the debris flow warning system is a critical part of the State's effort to protect lives and property. Each new storm event adds to the information database and aids in refining criteria for debris flow forecasting.

Traffic Alerts and Temporary Closures

Roads can be particularly dangerous locations for debris flow impact; several damaging slide events in the 1996/97 storms involved motor vehicles. One of the many useful applications of the debris flow warning system is the temporary closure of areas where debris flows are likely or are already occurring. As mandated by SB 12, the Oregon Department of Transportation (ODOT) has taken steps to provide warnings to motorists during periods of heavy rainfall. Warning signs are posted at known dangerous sections of Interstate Highway 84, and Oregon Highways 6 and 38. Upon notification that a debris flow warning has been issued, the appropriate ODOT dispatch center can activate flashing warning lights on the signs.

Figure 28. Debris fences installed below potential initiation sites in Pacifica, California. (From Montgomery and others, 1991)

Engineered Mitigation

Due to the large size, high-impact forces, and extreme variability encountered in debris flow hazards, active engineering solutions are often prohibitively costly, and nonengineering approaches are typically preferable. Nevertheless, engineered mitigation can be effective in some instances to reduce the potential for debris flow impact or increase the resistance of vulnerable areas. Common engineering measures to address debris flows can be grouped into (a) stabilization of potential source areas, (b) remedial measures in the transport zone, and (c) protection efforts designed to decrease or maintain energy in the deposition zone (VanDine, 1985; Montgomery and others, 1991; United Nations, 1996). The following sections provide brief overviews of common engineering risk-reduction techniques.

Figure 29. Steel-lattice dam constructed in Kirchbachgraben, Austria. (Photo from United Nations, 1996)

Source Area Stabilization

Stabilization strategies employed within potential debris flow source areas include mechanical stabilization of hazardous soil and rock units, planting vegetation, removal of colluvial deposits, and use of retaining structures (Montgomery and others, 1991; Robertson, 1996). Mechanical stabilization of marginally stable rock and soil areas can include such things as rock bolts and dowels to stabilize potential failure blocks and boulders or the use of shotcrete cover. Debris fences (Figure 28) and other channel modifications discussed below can also be implemented in potential source areas to contain landslide materials before they grow into larger debris flows.

Remedial Measures in the Transport Zone

Most active remedial measures focus on reducing the amount of source material that debris flows can carry downslope. Common measures near debris flow initiation sites include stabilizing valley side slopes (to reduce

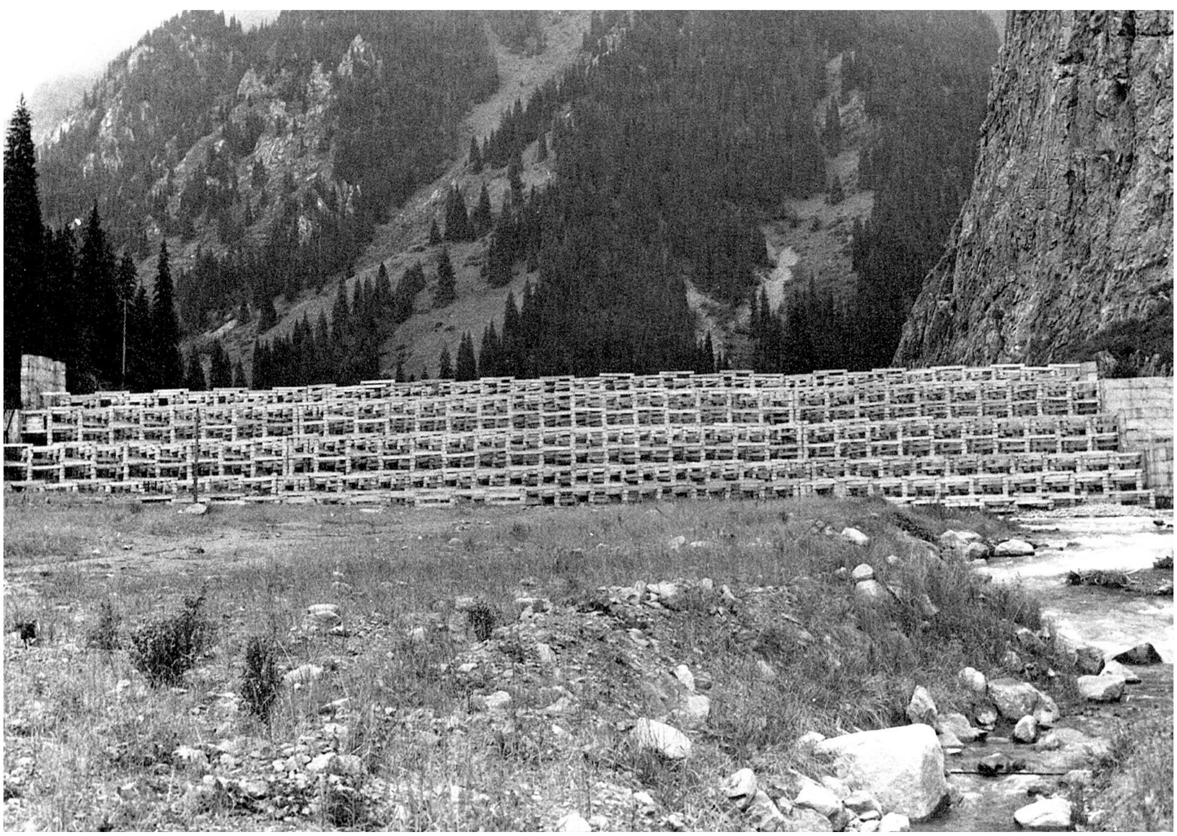
Figure 30. Ground sills constructed in Nagano, Japan. (Photo from United Nations, 1996)

Figure 31. Clear-span bridge constructed in Canton of Bern, Switzerland, along with guidewalls and a concrete-lined channel. (Photo from United Nations, 1996)

side slope failures, which add to the mass of the flows) and installation of debris fences (Figure 28), steel-lattice structures (Figure 29), ground sills (Figure 30), check dams, or other similar structures to reduce the energy and mobility of flows.

In select cases, the objective may be to increase flow capability to guide flows safely through or around vulnerable structures. For example, at public-transportation crossings, debris flows can be routed under critical structures. Examples of such mitigation measures include the construction of clear-span bridges (Figure 31), bridges with removable decks, and/or sacrificeable wooden structures. In conjunction with overpass structures, channel modifications are often designed to help route flows past the infra-

Figure 32. Steel-cell barrage structure set up on the Issyk River, Kazakhstan. (Photo from United Nations, 1996)



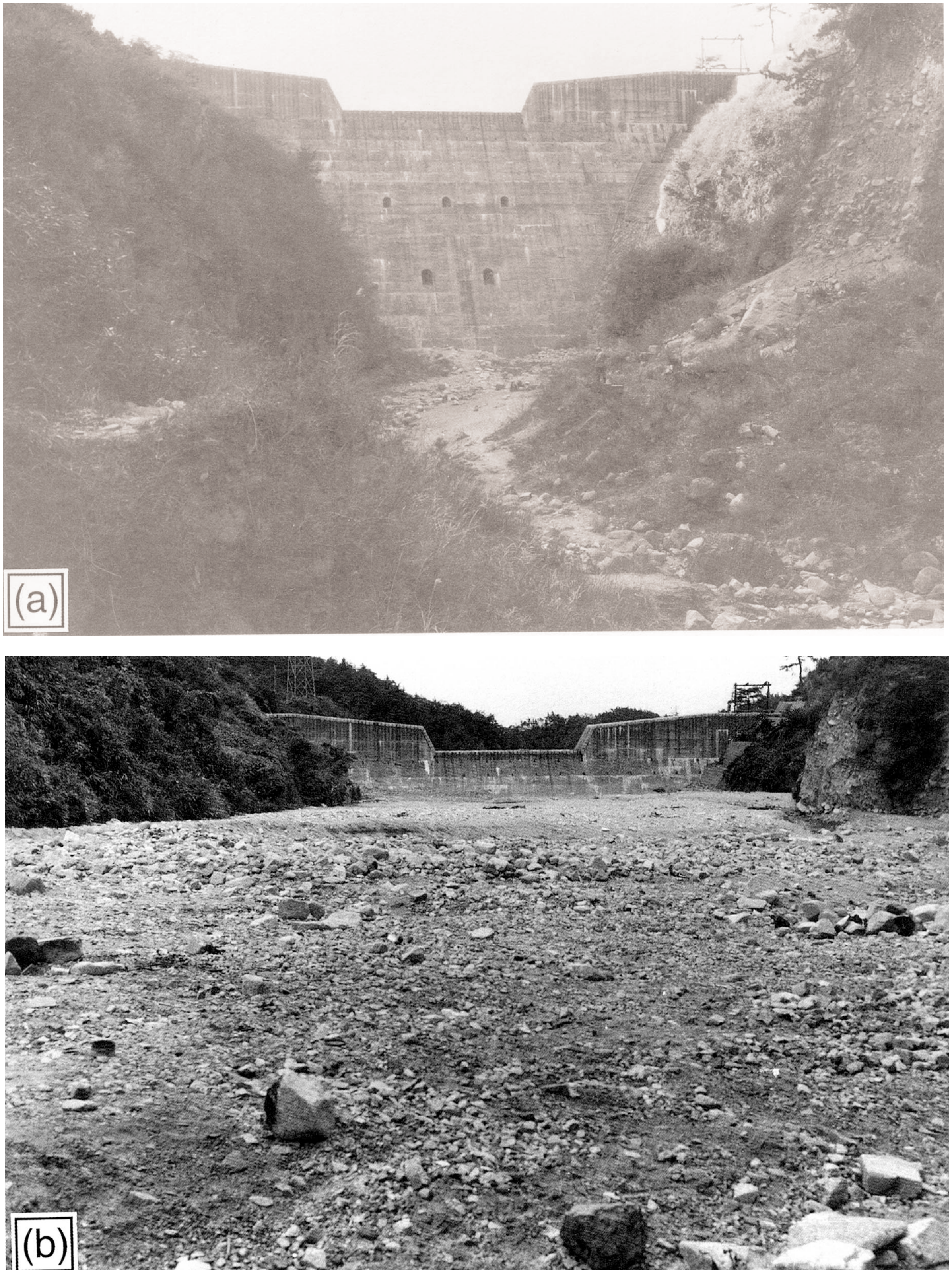
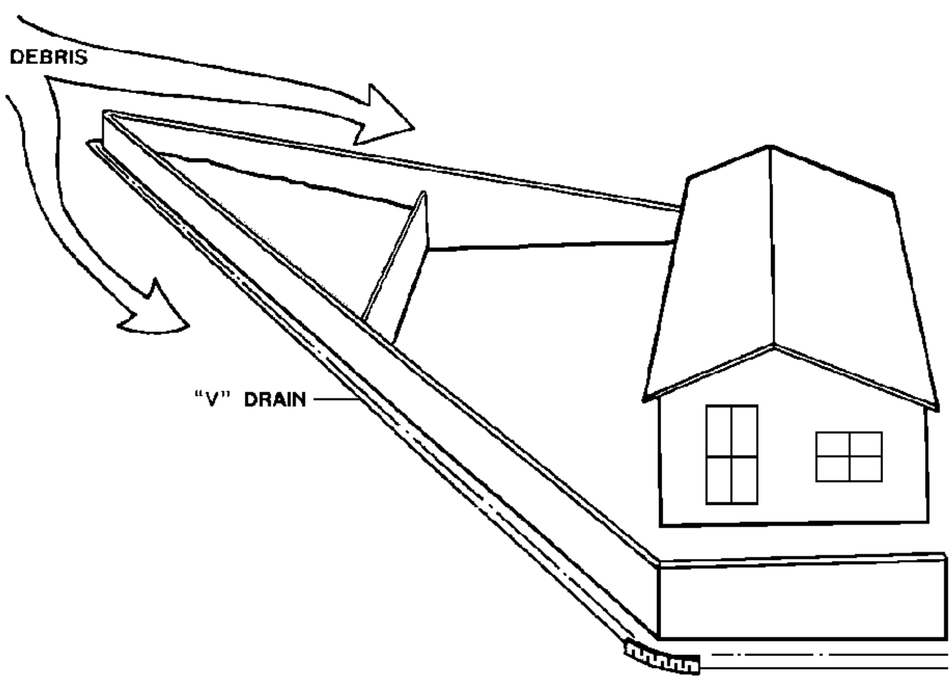


Figure 33. Check dam in Hyogo, Japan (30 m high, 78 m long, storage capacity 300,000 m^3), (a) before and (b) after a debris flow. (Photo from United Nations, 1996)

🡅 **Figure 34. Protection wall constructed on the Bolshaya Almatinka River, Kazakhstan. (Photo from United Nations, 1996)**



🡆 **Figure 35. Schematic of an A-shaped deflection wall serving as a splitting wedge to deflect debris. (Photo from United Nations, 1996)** structure. Removing obstructions, reducing roughness of the channel bed (e.g., by lining with concrete), and increasing channel gradients can all increase the transportability of the debris flow material.

Protection Efforts in the Deposition Zone

Mitigation approaches implemented closer to the deposition end of a debris flow tend to mimic conditions that lead natural flows to settle as deposits. Such measures may include widening the flow path, decreasing the gradient, dewatering the flow material, and increasing the channel roughness. Structures used to achieve these modifications include the construction of debris basins and/or debris flow barriers. Debris basins can take a number of forms, but tend to be designed as structures that mimic the shape of typical debris flow deposits and are lined with rough materials that act to inhibit transport and induce deposition. Debris barriers are often located at downstream locations where debris flows may have bulked up considerably, and therefore such barriers can be quite large and expensive (Figures 32 and 33). In order to block or divert flows, deflection structures such as berms, walls, and groupings of posts and trees have also been used (Hollingsworth and Kovacs, 1981; Van Dine, 1985). An example of a deflection wall is shown in Figure 34, and a schematic for an A-shaped deflection wall to protect a particular structure is shown in Figure 35.

This is just a small sampling of engineered mitigation options. Although these physical measures may be useful and necessary in some situations, there are significant limitations and drawbacks to most engineered structures for debris flows. Limitations (or deterrents) include short- and long-term environmental effects, the requirement for ongoing maintenance, difficulties in developing appropriate design parameters, and the possibility that structures may just relocate the hazard and shift the impact to adjacent properties (Davies, 1997). Much more information is provided in Campbell (1975), Mears (1977), Hollingsworth and Kovacs (1981), Miles and Kellerhals (1981), VanDine (1985), Zhang and others (1985), Montgomery and others (1991), Robertson (1996), United Nations (1996), Davies (1997), and VanDine and others (1997).

MAP UPDATES AND FUTURE WORK

Landslide research and practice is a dynamic field and continues to advance. Although map updates for the present study have not been scheduled or budgeted at this time, specific areas where future work may be particularly beneficial include the following:

- *More detailed mapping at local levels*. The hazard area map is necessarily general. Refinements at local levels (e.g., county or city) may be justified in the future, particularly in regions of highest risk.
- *Tracking locations of, and results from, site-specific studies*. More detailed site-specific studies will provide additional information that will be useful in future hazard assessments. The results of these follow-up studies should be consolidated and preserved.
- *National Flood Insurance Program.* Many of the deposition areas generally conform to the concept of mudslides in the National Flood Insurance Program, but lie outside the current delineation on flood plain maps. Further study could characterize these areas in terms of frequency or probabilities of future events, needed to address the actuarial elements of insurance programs. A pilot project is needed to assess the viability of this application of the map.
- *Additional inventory data collection and consolidation*. Landslide inventories were used extensively in the development of the map and are critical for both short and long-term applications. The value of collected inventory data could be greatly enhanced by adoption of consistent record-keeping procedures and programmatic consolidation of time-sensitive data gathered after major storm events (e.g., Hofmeister, 2000).
- *Expanded inventory data comparisons*. As more data are collected and consolidated, it will be possible to perform valuable, additional testing of the model. This will allow for refinement of parameter selections and further evaluation of regional modifiers to increase capture rates.
- *Incorporation of regional hazard variation by physiographic region*. As part of this project, we looked at modifying input parameters by regional geologic unit in order to narrow the hazard zones in particular terrain conditions (see Final Selection of Parameters and Map Generation section). With improvements in regional geologic map inputs, as well as additional inventory data collection, we could feasibly develop more detailed zonations.
- *Gathering data to evaluate risk assessment and design characteristics*. With further calibration based on local field investigations, the modeling output developed in this project may be correlated with such important factors as debris flow recurrence intervals, design volumes, and storm intensities.
- *Application to eastern Oregon*. The modeling approach is applicable to other regions and would benefit from additional testing and refinements in other terrains. Currently, coverage is comprehensive for western Oregon, but no comparable map has been developed for eastern Oregon.
- *Use of more detailed and/or accurate topographic data when available*. The modeling approach is highly dependent on the quality and resolution of the input elevation data. Several efforts are currently underway to improve these data (for a wide range of applications). The future availability of more detailed terrain data could substantially improve the ability to refine debris flow hazard zones.
- *Addressing other types of landslide hazards on a regional basis*. As mentioned in the intro-

ductory sections, this project focused on rapidly moving landslide hazards. Other landslide types, such as large deep-seated landslides, also cause significant damage and economic loss in Oregon. Further mapping of these other landslide hazards—through aerial photography, GIS modeling, field study, and other investigative techniques—would better define their geographic extent, and allow for more consistent and comprehensive treatment.

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APPENDIX A
GLOSSARY OF TERMS

Aerial photo interpretation—Includes the use of aerial photographs to observe features such as drainage patterns, vegetation and topographic anomalies, and other geomorphologic features to highlight areas of historic and/or potential slope instability.

Capture—Term used specifically herein to refer to the percentage of landslides identified by a particular hazard model selection. Used to evaluate various modeling approaches and used in conjunction with evaluations of the total percentage of map area identified as a potential hazard. Higher capture values indicate that more landslides are identified for a given amount of mapped hazard area, which is considered preferable.

Colluvial materials (or, colluvium)—A general term used to describe poorly sorted and typically loosely consolidated soil and rock that is deposited over time by rainwash, landslide processes, and/or downslope creep.

Confined channels—Channels that are characteristically confined by steep valley walls, constricting potential lateral deposition of debris flows. These channels, particularly when steep, can be quite dangerous in the event of debris flows as material can be funneled through the confined system.

Debris fans—Can develop through debris flow deposition processes. Typically found at the base of steep hillslopes and at the mouths of steep canyons, they can be particularly dangerous locations with repetitive debris flow impacts.

Debris flows—Debris flows are rapidly moving landslides that are characterized by water-charged soil, rock, colluvium, and organic material that travels down steep topography until momentum is eventually lost and the scoured debris is deposited. They are often triggered by small landslides that mobilize and grow to be large flows that can travel great distances (miles in some cases).

Digital Elevation Model (DEM)—A digital representation of topography consisting of a regularly spaced grid of elevation values.

Lahars—Similar to debris flows, but derived from volcanic debris. Lahars can travel extreme distances down the flanks of volcanoes and into flatter, low-lying areas (e.g., historic lahars originating on Mount Hood traveled all the way down the Sandy River to the confluence with the Columbia River). The U.S. Geological Survey (USGS) has mapped lahar and other volcanic hazards for some of the volcanoes in the Cascade Range (www.usgs.gov).

Landslide—A general term referring to the movement of soil, rock, and/or organic materials downslope. Landslides can range from very small to very large and rates of movement can be slow to very rapid. Figure 3 provides a schematic outline of various types of landslides. Debris flows are a specific type of landslide.

Landslide inventory—A database of historic landslide events. Landslide inventories can be particularly useful to test the performance and applicability of various hazard modeling approaches.

Rapidly moving landslides—Landslides that transport material rapidly downslope. Debris flows are a common type of rapidly moving landslide.

Topographic quadrangle—A standardized map produced by the U.S. Geological Survey (USGS). USGS 7 $^1/_2$-minute quadrangles are defined by 7 $^1/_2$ minutes each of latitude and longitude (60 minutes=one degree)—an approximately rectangular area that, in Oregon, measures about 6 mi (10 km) east-west by 9 mi (14 km) north-south.

Trigger mechanisms—Processes and conditions that can trigger slope failures. Includes intense rainfall, earthquake shaking, volcanic eruption, and rapid snow melt. Human alterations can also be significant contributors to increasing the potential for slope instability and/or triggering specific failures.

APPENDIX B
INPUT PARAMETERS FOR THE GIS MODELING

The following are the input parameters used in the modeling. For additional information regarding these parameters and the algorithms, please refer to Miller (2002).

Slope_min = 0.50

Threshold value of the topographic index for slope instability. Pixels with index values greater than Slope_min are considered source areas for landsliding.

Sl = 2

The number of pixels over which slope is calculated (>1 to address pocket terracing).

channel_area_threshold = 7,500 m^2

The contributing-area threshold for channel initiation in high gradient areas (areas with surface gradient ≥*S_max*).

C_min = 1,500 m^2

Used to determine the contributing-area threshold as a function of surface gradient for low-gradient areas (those with surface gradient <*S_max*): $A = C\_min/S^2$, where *A* is threshold contributing area and *S* is surface gradient.

S_max = 0.25

The minimum surface gradient for landslide potential. This value is used to separate low-gradient areas, for which a slope-dependent drainage threshold (*C_min*) is used for channel initiation, from high-gradient areas, for which a drainage area threshold (*channel_area_threshold*) alone is used for channel initiation.

P_min = 1.4

The minimum number of inflowing cells required for channel initiation. This value enforces a topographic convergence threshold, in addition to the drainage area threshold discussed above, for channel initiation.

debris_flow_slope = 0.165

Used in the Benda-Cundy model (Benda and Cundy, 1990) for estimating debris flow runout. This value specifies the channel gradient above which channelized flows do not stop at tributary junctions.

erode_slope_min = 0.15

Used in the Benda-Cundy model for debris flow runout. Specifies the channel gradient above which debris flows erode the channel bed.

thetamin = 0.14

Used for the Benda-Cundy model for debris flow runout. *Thetamin* specifies the channel gradient at and below which debris flows deposit material. Unlike the Benda-Cundy model, the gradient for debris flow deposition is made a function of estimated valley-floor width. This allows a steeper slope to be specified for unchannelized areas, such as where debris flow channels enter steep, unchannelized debris fans.

wmin = 30 m

Used for the Benda-Cundy model for debris flow runout. The valley-floor width at and below which *thetamin* applies. Units correspond to the input DEM (e.g., meters).

erode_slope_max = 0.27

Used in the Benda-Cundy model for debris flow runout. Specifies the unchannelized gradient above which debris flows erode the slope.

thetamax = 0.25

Used for the Benda-Cundy model for debris flow runout. *Thetamax* specifies the channel gradient at and below which debris flows deposit material where valley-floor width is greater than *wmax* (below).

wmax = 100 m

Used for the Benda-Cundy model for debris flow runout. Specifies the valley width at and above which *thetamax* applies. For valley widths between *wmin* and *wmax*, the channel gradient for debris flow deposition is varied linearly between *thetamin* and *thetamax*.

lstop_max = 5,000 m

Specifies the maximum length for unchannelized, low-gradient (<*debris_flow_slope*, above) debris flow runout. If the distance from a source pixel to a channel exceeds *lstop_max*, the source pixel is assumed incapable of producing a debris flow that will travel to a channel.

colluvial_volume = 15 m^3 per meter

Used for estimating debris flow inundation areas. Specifies the average colluvial volume available for debris-flow scour per unit length of low-order channel. Given in DEM units, e.g., m^3 per m traveled.

colluvial_volume_0 = 10 m^3 per meter

Used for estimating debris flow inundation areas. Specifies the average volume available for debris flow scour per unit length of traverse over unchannelized hillslopes.

Xmin = 30 m

Specifies the minimum window length used for channel gradient estimation, in DEM units.

Xmax = 100 m

Specifies the maximum window length used for estimating channel gradient.

Smin = 0.001

Specifies the channel gradient at and below which *Xmax* applies.

Smax = 0.2

Specifies the channel gradient at and above which *Xmin* applies. Window length varies linearly from *Xmin* to *Xmax,* as a function of channel gradi ent, for gradients between *Smax* and *Smin*.

Fit_Order = 2

The (integer) order of the polynomial used for fitting channel profiles.

junction_length = 50 m
: The channel length used to estimate channel flow direction and tributary junction angles, in DEM units.

junction_angle = 11
: Used with the Benda-Cundy model for debris flow runout. Specifies the tributary junction angle, tan (85°), above which debris flows deposit (unless the receiving channel gradient exceeds *debris_flow_slope*).

trigger_angle = 1.0
: Used with the Benda-Cundy model for debris flow runout. Specifies the junction angle, tan (45°), for first-order tributary channels above which debris flows deposit.

Flow direction algorithm = 1
: 1 for Tarboton, 2 for Tarboton + convergence.

a_coef_0 = 0.4
: The coefficient for cross-sectional flow area. Different coefficients may be used for channelized and unchannelized debris flows; *a_coef_0* is used for debris flow tracks traversing hillslope pixels that are not classified as channels.

b_coef_0 = 50.0
: The coefficient for debris flow inundation area; *b_coef_0* is used for debris flows traversing hillslope pixels that are not classified as channels.

a_coef_c = 0.25
: The coefficient for cross-sectional flow area for debris flow tracks traversing pixels classified as channels.

b_coef_c = 75.
: The coefficient for debris flow inundation area for pixels classified as channels.

radius = 25
: Used in creating transects for calculating valley cross-sectional area. First, every hillslope pixel is associated to the nearest channel pixel. Then a circle with a radius of the specified number of pixels is constructed about every channel point. Pixels intersected by the edge of this circle serve as endpoints for the transects. This is done both for a circle of the specified radius and for a circle with radius given by *radius*/5. This procedure produces multiple potential valley-crossing transects for every channel point. The one producing the smallest cross-sectional area is used.

maxbin = 1.0
: The largest ratio of inundation volume to maximum potential debris flow volume to continue estimating inundation hazards.

nbins = 256
: The number of bins to use for tracking the cumulative distribution of debris flow volumes associated with pixels inundated for a debris flow track.

de_min_0 = 0.10

Used for estimating cross sectional area as a function of inundation width over flat areas. Cross sectional area is estimated as

$$A_{cs} = de\_min \cdot W^{rp}$$

where *W* is deposit width, measured from the channel, and *rp* is an adjustable parameter (set to 1.0 in this case, so the cross sectional area corresponds to a deposit with a constant surface slope equal to *de_min*). Separate values for *de_min* may be specified for channelized and nonchannelized debris flows; *de_min_0* applies to hillslope pixels not classified as channels.

de_min_c = 0.06

The value of *de_min* to use for pixels classified as channels.

de_max = 5

Valley transects are terminated if elevation along the transect decreases by an amount greater than *de_max*, in which case it is assumed a drainage divide has been crossed.

rp = 1

The exponent on W in the equation above for estimating cross sectional area through flat areas. A value of 1 corresponds to a deposit with a constant surface slope equal to *de_min.*

smooth_output = *y*

(y/n) Specifies whether the inundation ratio is smoothed prior to output. If smoothing is specified, it is done over a 3x3-pixel weighted average, excluding pixels with zero or no data values. Weighting is based on (1-*B*), where *B* is the inundation ratio of the pixel. This preferentially weights high-hazard pixels.

buffer = 0

The size of buffer added around inundation hazard areas, in pixels. Buffer pixels are added based on the average inundation-ratio value of adjacent pixels with nonzero values.

APPENDIX C
LIST OF DRAFT MAP REVIEWERS

Name	Title	Organization	Area(s) Evaluated
John Beaulieu	State Geologist	Oregon Department of Geology and Mineral Industries, Portland, OR	Portland Metro area, Blue River, Columbia River Gorge, Welches
Tom Ferrero	Engineering Geologist	Ferrero Geologic, Ashland, OR	Ashland
Richard Iverson	Research Hydrologist	Cascades Volcano Observatory, U.S. Geologic Survey, Vancouver, WA	Newton Creek
Ian P. Madin	Geologist, Mapping Section Leader	Oregon Department of Geology and Mineral Industries, Portland, OR	Marshland, Garibaldi, Columbia River Gorge, Portland Metro area
George R. Priest	Geologist, Coastal Section Leader	Oregon Department of Geology and Mineral Industries, Newport, OR	Garibaldi, Blue River, Depoe Bay, McKenzie Bridge
John Seward	Geotechnical Specialist	Oregon Department of Forestry, Roseburg, OR	Tyee Road, Ashland, Talent
Fred Swanson	Research Geologist	USDA Forest Service, PNW Research Station, Corvallis, OR	Cascadia, Echo Mtn., Mapleton, Blue River, McKenzie Bridge, Detroit, Chandler Mtn.
Thomas J. Wiley	Geologist, Southwest Oregon Section Leader	Oregon Department of Geology and Mineral Industries, Grants Pass, OR	Grants Pass, Merlin, Rogue River, Sexton, Grayback Mountain