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

by
R. Jon Hofmeister, Oregon Department of Geology and Mineral Industries;
Daniel J. Miller, Earth Systems Institute;
Keith A. Mills and Jason C. Hinkle, Oregon Department of Forestry; and
Ann E. Beier, Oregon Department of Land Conservation and Development

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.

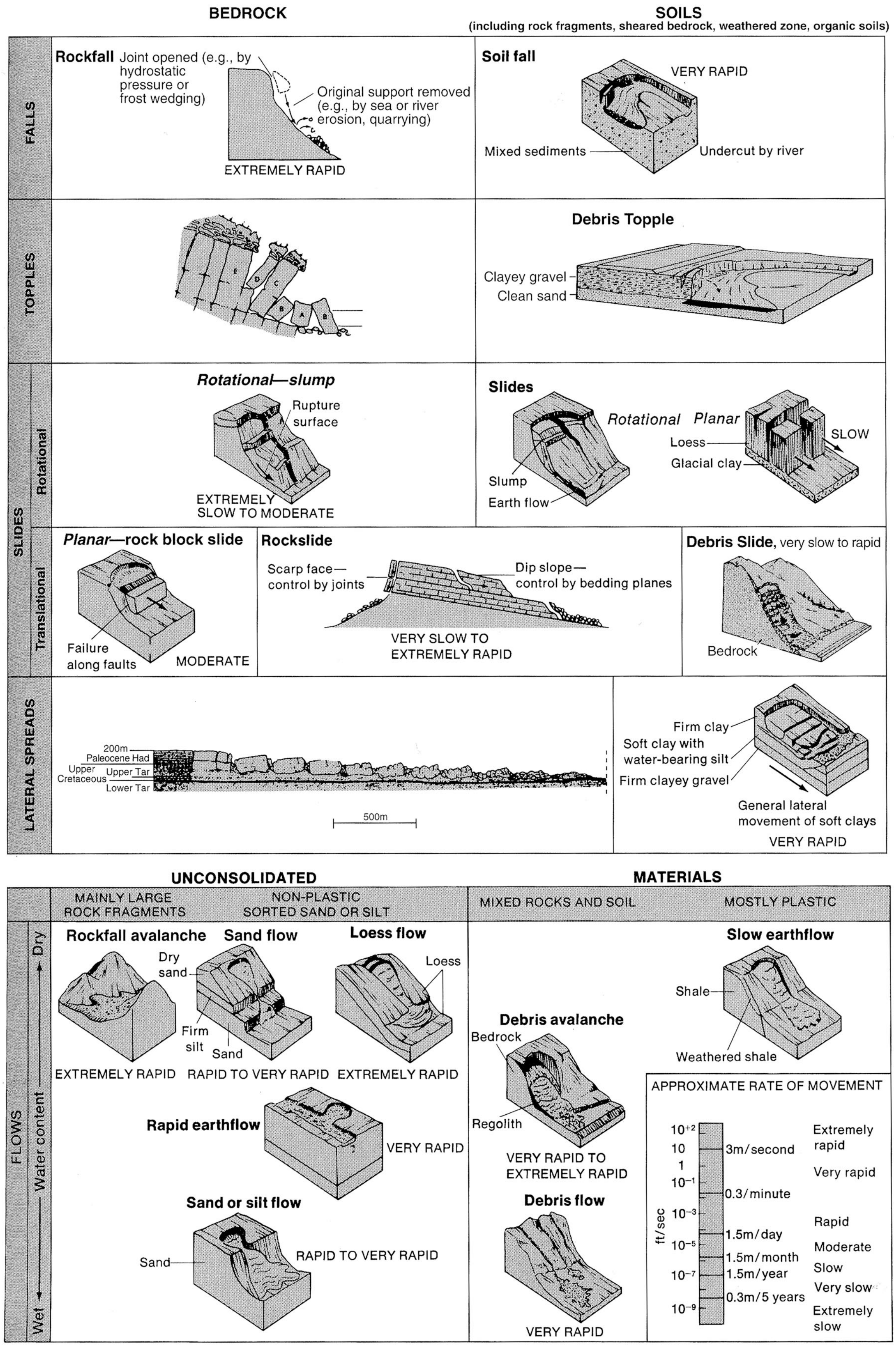

Figure 3. Landslide types. (From Ritter and others, 1995)

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).

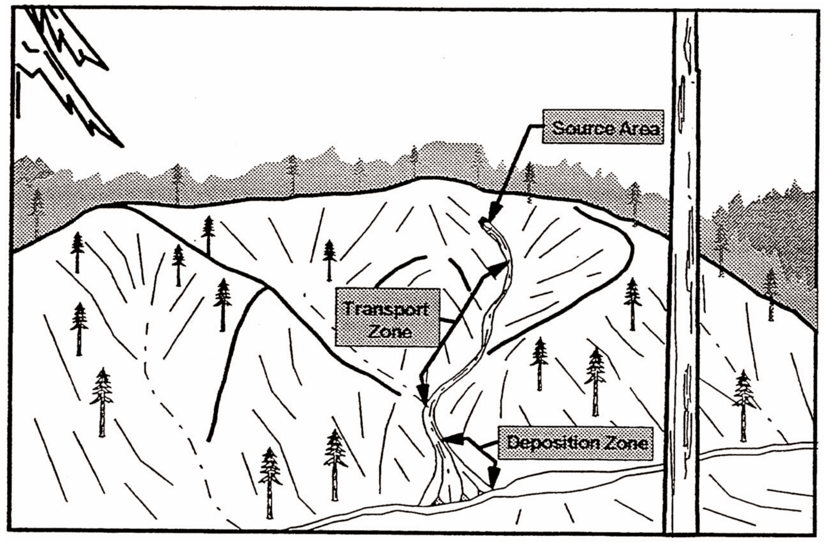

Figure 5. Diagram of a debris flow showing zones of initiation (source areas), transport, and deposition. (From Pyles and others, 1998)

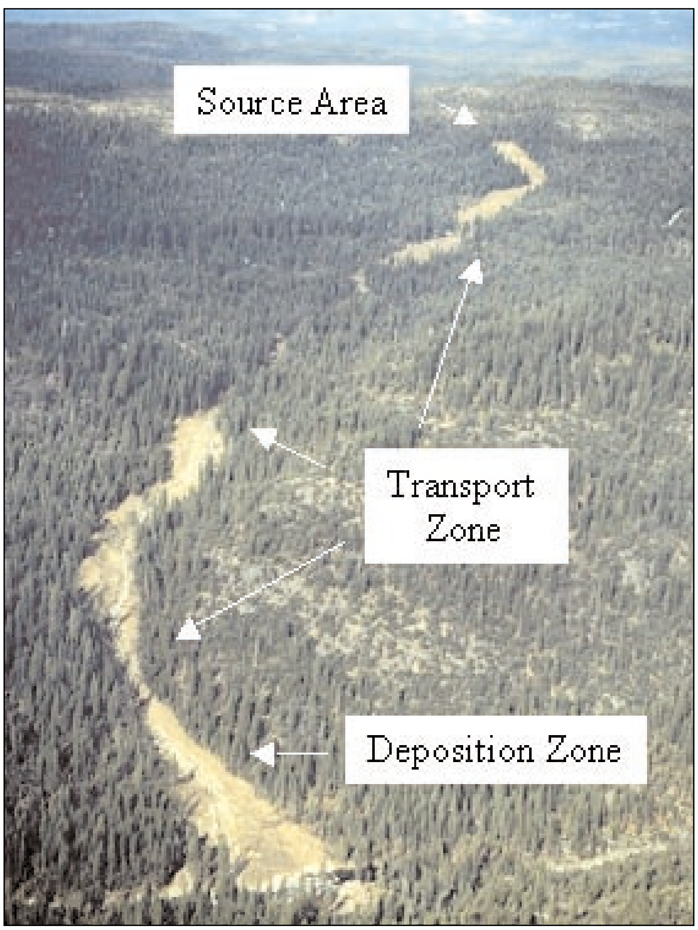

Figure 6. Photo of a debris flow showing zones of initiation, transport, and deposition. (Photo courtesy of U.S. Geological Survey)

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

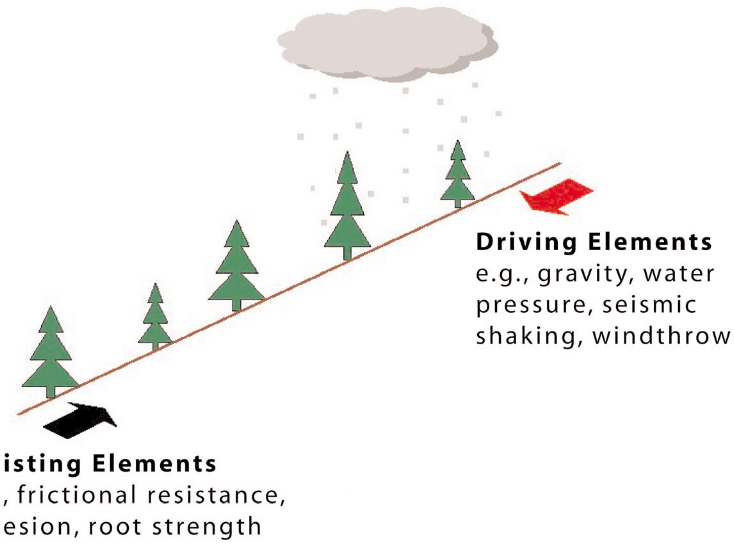

Figure 10. Schematic of a slope, showing driving and resisting elements.

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

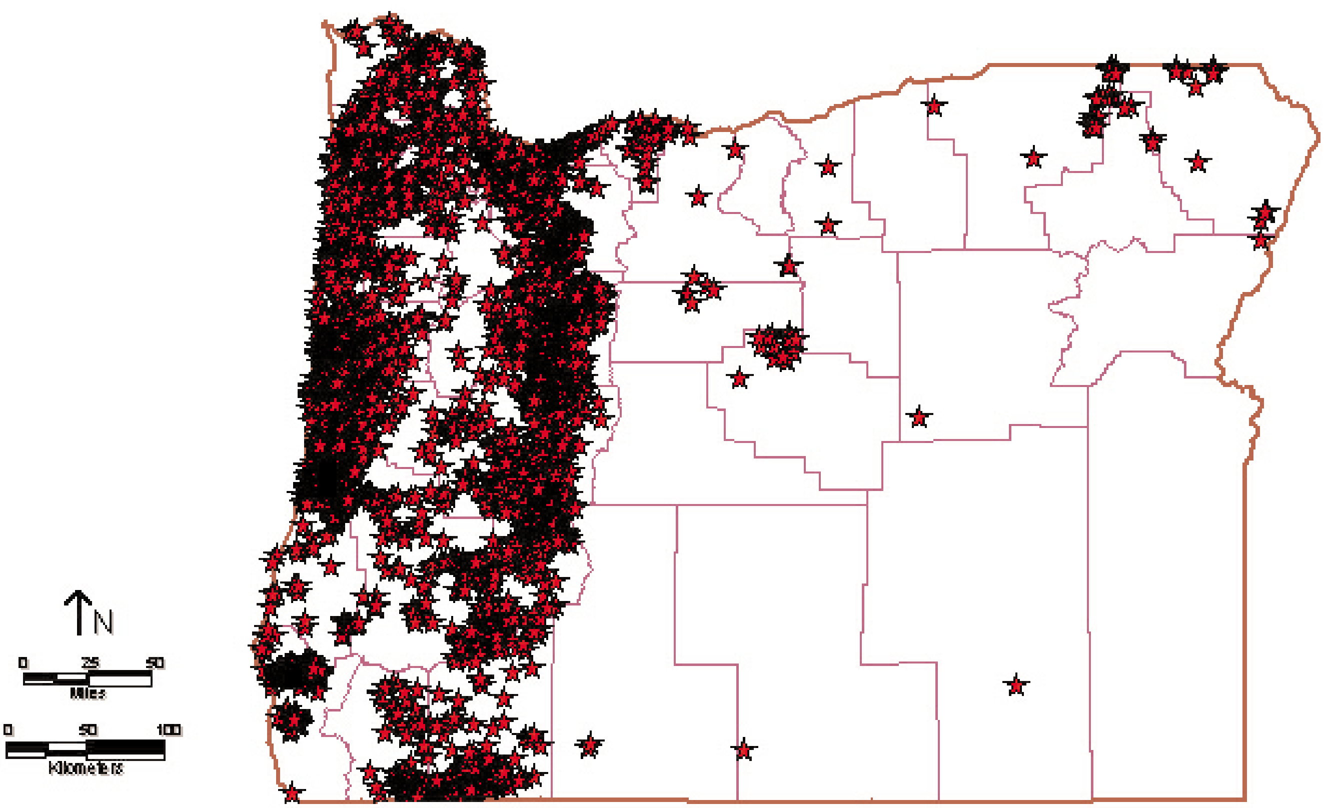

Figure 11. Distribution of the more than 9,500 landslides triggered in Oregon by the storms of 1996-97. (From Hofmeister, 2000)

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

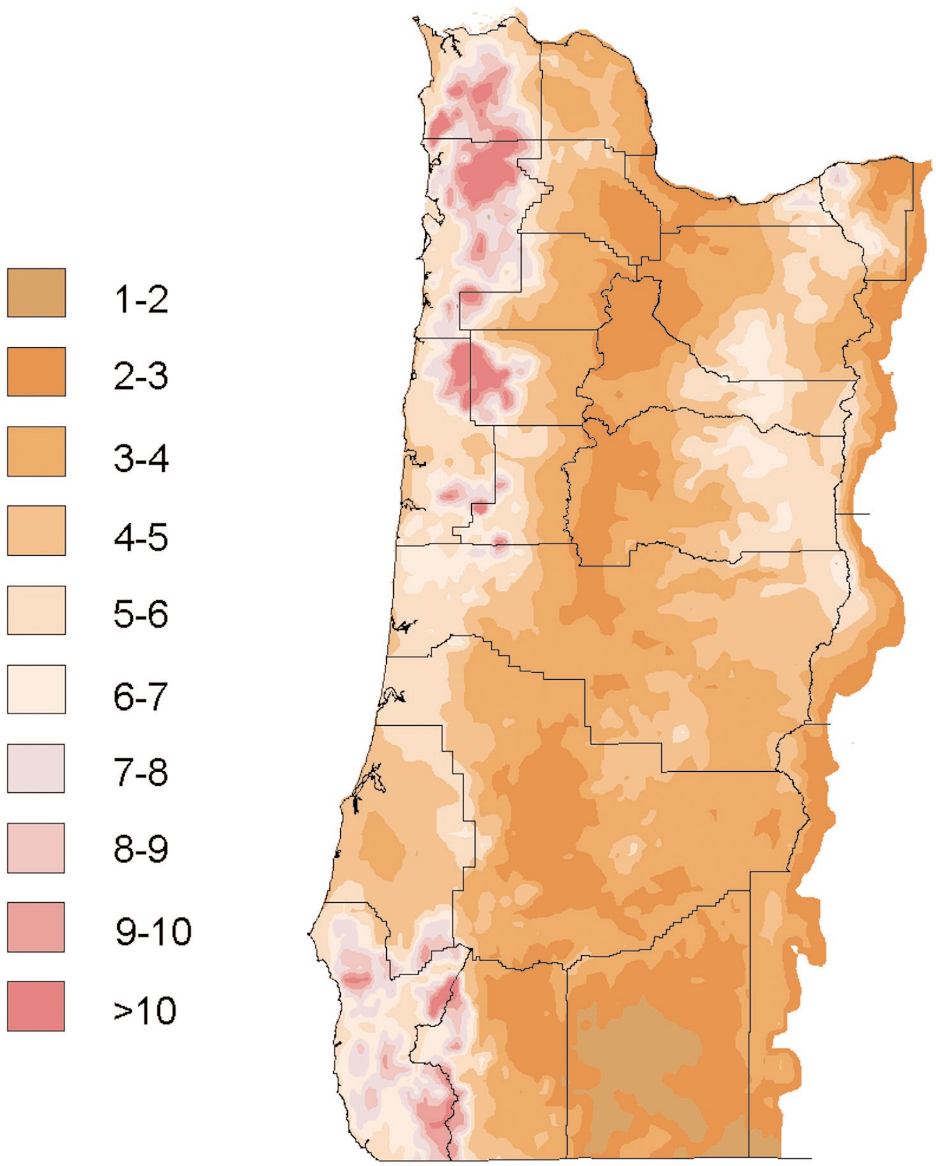

Figure 12. Map of estimated 24-hour rainfall intensity-duration thresholds in western Oregon (measurements in cm). Contours are derived from the Oregon Climate Service data of mean December precipitation. (From Wiley, 2000)

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-

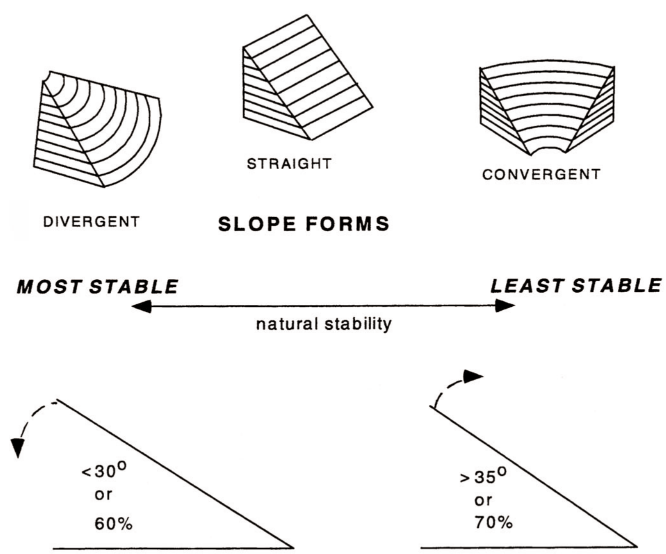

Figure 13. Schematic of divergent, straight, and convergent topography. (From Benda and others, 2000)

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

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.

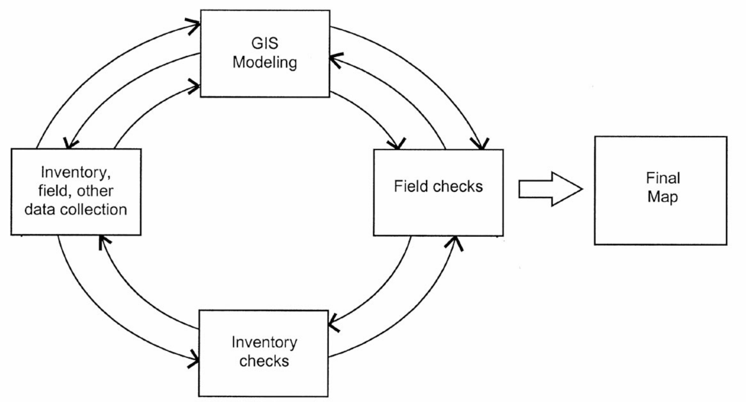

Figure 17. Schematic of the iterative process used to develop the map.

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.

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.

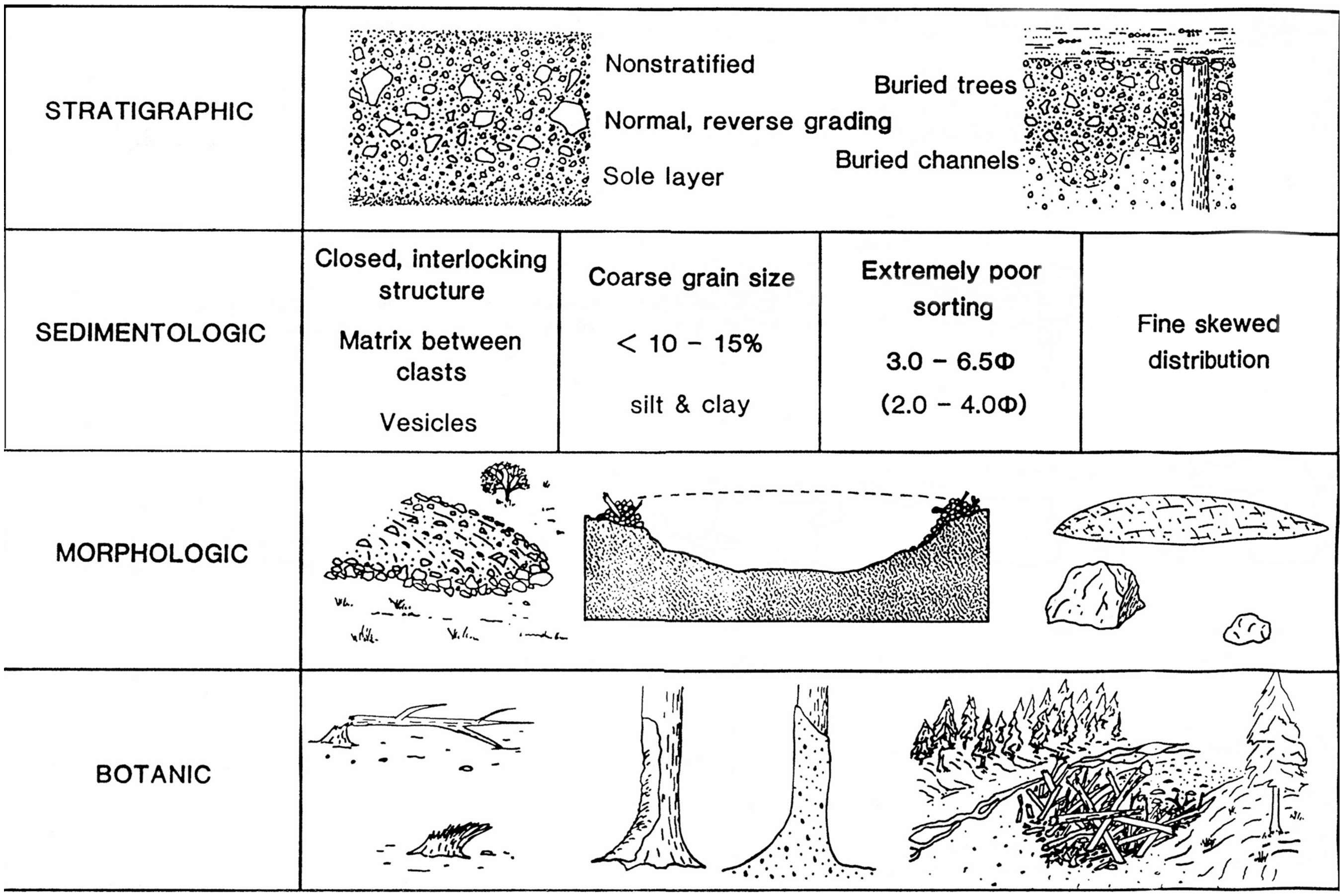

Figure 18. Geomorphic features that can aid in the identification of historic debris flows. (Diagram courtesy of Tom Pierson)

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

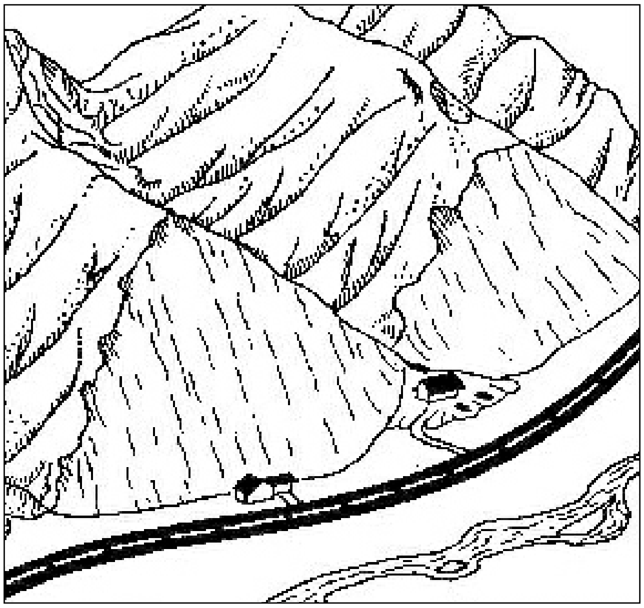

Figure 23. Typical highest hazard home locations: near channel mouths and at the base of very steep slopes. (Illustration courtesy of Oregon Department of Forestry)

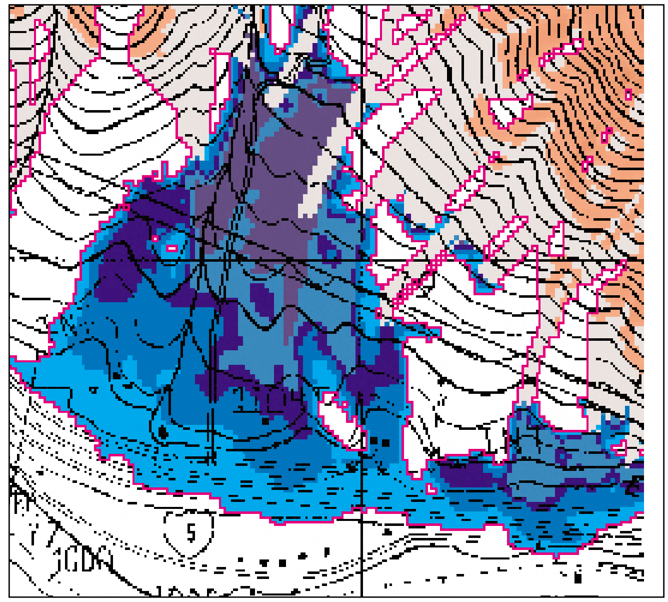

Figure 24. Example of gradation within a hazard zone. Darker shades signify higher relative hazard. Initiation areas are in red; transport areas in gray; and deposition areas in blue.

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).