Oregon Department of Forestry
Storm Impacts and Landslides of 1996: Final Report

Oregon Department of Forestry
Forest Practices Monitoring Program

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Executive Summary

The Storms of 1996

During the months of February and November 1996, two very large storms affected most of Western Oregon and parts of Northeast Oregon. The February storm was a high intensity, long duration rainfall event that affected the northern portion of the state. The November storm was a shorter duration and higher intensity rainfall event than the February storm, and affected an area south of the February storm. Both the storms resulted in large numbers of landslides, debris torrents, and altered stream channels.

Study Design

With oversight from a team of experts in the landslide and natural resource field, the Oregon Department of Forestry implemented a 3-year monitoring project to evaluate the effects of these storms. This project was primarily a ground-based study. However, remote sensing techniques (aerial photographs in particular) have commonly been used both to predict where landslides will occur and to inventory where landslides and channel impacts have occurred. Therefore one goal of the project was to determine the accuracy and precision of remote sensing data in identifying landslides, channel impacts, and landslide-prone areas. A second goal of the project was to determine landslide frequency and channel impacts, particularly as they relate to forest practices. Specific forest practices that were considered include harvest practices that may have caused ground disturbance (i.e. yarding, site preparation), treatment of slash, road construction, and road drainage. Past research and monitoring has related landslide frequency to stand structure (particularly dominant tree species and age). Therefore a related goal of this project was to examine relationships between storm impacts and forest stand structure adjacent to landslide initiation points and along stream channels.

Eight study areas were monitored over a two-year period. Six areas were within the February storm boundaries and two areas were in the November storm boundaries. This ground-based study was designed to: find and measure every landslide that delivered sediment to the stream channel; document and measure the associated debris flows and channel impacts; and gather site information regarding forest practices that may have contributed to the impacts. The most unique aspect of this ground-based survey was comprehensively locating all landslides that delivered sediment to the stream channel. Field data were combined with information gathered in the office or from aerial photographs for analyses.

Five of the study areas were intentionally located in areas estimated to have the highest disturbance in terms of channel impacts, landslides, debris flows, and debris torrents (referred to as red zones). This study focused on areas representing the most severe impacts from the 1996 storms. Therefore, results from red zones do not represent the average forestland responses to these 1996 storms. In addition, by only measuring landslides that resulted from the February and November storms, the study focuses on individual storm events and results can not be extrapolated to predict long-term conditions. Finally this study focused on landslides that delivered sediment to stream channels because these are considered to have the greatest potential to impact public safety and natural resources.

Landslide Detection Using Aerial Photographs

Most landslide inventories rely either in part or completely on air photos for determining the occurrence, location, and characteristics of landslides. Prior to this study, relatively little was known about potential biases in aerial photo inventory methodologies. Although aerial photographs have utility for many purposes, their use for identification of shallow-rapid landslides results in biased and incomplete landslide inventories. This bias significantly underestimates the landslide frequency and erosion volume across all forest stand age classes.

Seventy-two percent of all landslides identified from the ground-based survey were not detected using 1:6000 aerial photographs. The majority (72 to 98 percent) of shallow-rapid landslides were not visible on aerial photographs of any scale. In terms of erosion volume, the landslides that were not identified from aerial photographs (1:6000 scale) accounted for 53 percent and 41 percent of the total landslide related sediment volume delivered to stream channels in two study areas. Landslide identification is most problematic in areas with mature or semi-mature timber. For instance, roughly 50 percent of the landslides were detected in recently harvested areas (0-9 years old) but less than 5 percent of the landslides were detected in mature stands (older than 100 years). Aerial photo analysis will significantly magnify landslide density and erosion volume per unit area for recently harvested areas relative to older forested areas.

Slope and Landform Characteristics Using Digital Elevation Models

Topographic maps, and digital elevation models (DEMs) based on topographic maps are commonly used to identify landslide prone locations. Maps and DEMs can be used in the office, and enable rapid assessments over large areas. DEMs are also used to run landslide hazard models that enable assessment across landscapes.

Digital elevation models (DEMs) at various resolutions were evaluated for their usefulness in identifying areas and sites susceptible to landslides. Slope data collected at the site of each landslide were compared with those derived from a commonly available 30 meter DEM, and also with less commonly available 6 and 1-meter DEMs. On a site-specific basis, slope measurements from 30-meter DEMs were poorly correlated to site-specific slopes at landslide locations measured in the field. DEMs with a higher resolution might better correlate to site-specific slopes, but even their effectiveness in providing accurate values could not be confirmed in this analysis. On an area basis, the 30-meter DEM under-represents the steepness of very steep slopes (over 70%), and over represents moderate slopes (under 50%) over broad areas (hundreds of acres) as compared to the 6 and 1-meter DEMs.

Landslide Occurrence in the Study Areas

There were 506 landslides which entered stream channels in the “core areas” of the eight study areas. “Core areas” are lands where all channels were surveyed for landslides. The total “core area” surveyed was 45.8 square miles. Landslide density is summarized as the number of landslides entering stream channels per each square mile of study area. Landslide density varied from 0.4 to 24.4 landslides per square mile.

The average non-road associated landslide (the initial failure only, and not including the subsequent debris flow) was 24 feet wide, 43 feet long, and 2.5 feet deep (with a maximum depth of 4.3 feet). Landslide erosion is the volume of sediment (soil and rock) that entered stream channels. Total landslide erosion (initial landslide plus debris flow) was 288,376 cubic yards for the eight study areas. For the 45.8 square mile study area, this is an average storm erosion of 6,290 cubic yards of sediment per square mile, or 9.9 cubic yards per acre.

Landslides were common in red zones. The majority of landslides were not associated with roads. There are extreme variations in landslide characteristics between study areas. Caution must be exercised when comparing landslide statistics, especially landslide erosion. Overall, landslide dimensions as identified in this study are similar to those identified in previous studies conducted in the Oregon Coast Range; however, the land area affected by landslides was less than reported in earlier studies.

Landslide Initiation Sites

Landscape differences are very important because geologic factors have a large influence on landslide processes. Stream channels also have major influences on landslides, due both to direct undercutting of slopes by stream erosion and also because of longer-term hillslope processes. The highest hazard for shallow rapid landslides was found on slopes of over 70% or 80% steepness (depending on landform and geology). There was a moderate landslide hazard on slopes of between 50% and 70%.

Landslides that entered stream channels during the storms of 1996 typically occurred in very steep landscapes, or adjacent to stream channels. Even landslides that initiate as relatively small debris slides can mobilize into debris flows that mobilize large volumes of material and move long distances. Landslide characteristics vary greatly according to local landscape and geologic factors. Debris flows that were not initiated by up-slope landslides were uncommon. A debris flow occurs when landslides move downslope, scouring or partially scouring soils from the slope along its path.

Landslides occurred on many different landforms. Concave shaped slopes with larger drainage areas appear to be more susceptible to landslides than other landforms.

However, landslides occurring on concave slopes also tend to be smaller than landslides which occur on other landforms.

At least 78 percent of the up-slope landslides occurred on “high risk sites.” As any landslide hazard designation includes slopes of lesser steepness, it will include more of the overall landscape. Determination of appropriate changes to the high risk site designation will require additional landscape level slope steepness information. These results do suggest that a reduction in the slope used to designate concave landforms as “high risk sites” in one geologic unit may be appropriate. Identification of high risk sites outside of areas where landslides are common may be more difficult than in areas with steep slopes.

Landslides and Forest Stand Age

The effects of forest cover on landslide occurrence has been the subject of much study. Previous studies have speculated that the greatest increase in landslide occurrence occurs after roots have decayed and before new roots have completely taken their place, typically from a few years to a few decades after timber harvesting. Although some root strength theories would suggest the highest incidence of landslides 3 to 15 years after timber harvesting, review of data from this study indicated a higher incidence between 0 and 10 years after timber harvest. Therefore, age classes are grouped as 0 to 9 years (recent clearcut to very young forest); 10 to 30 years (young forest); 31 to 100 years (forest) and older than 100 years (mature forest).

Analysis of variance testing was used to test both landslide density and erosion volume differences between the four age classes on the four multi-age red zone study areas. Partly because of the small number of study areas, there is no significant difference for the four study areas between the four age classes. Nevertheless, in three out of four study areas in very steep terrain both landslides density and erosion volumes were greater in stands which were clearcut in the previous nine years. On the other hand, stands between 10 and 100 years in age typically had lower landslide densities and erosion volumes as compared to forest stands older than 100 years. Landslides in clearcuts are not different in size than landslides in older forests. Because of the increased number of landslides, erosion volume in the 0 to 9-year age class was also increased in three out of four study areas.

There is no observable difference in landslide depth by age class. Therefore, if basal root reinforcement had an influence on slope stability, this influence was not large enough to be observed. This could indicate that other factors associated with removal of vegetation are more important than root reinforcement, that root reinforcement was similar across all age classes, or that root reinforcement is not dependent on soil depth.

There were great differences in landslide characteristics between the study areas. Some of the greatest differences were observed between two study areas that are in the same geologic unit, experienced the same storm event, and are only separated by a distance of 10 to 15 miles. These two sites also had the most contrasting differences in the effects of stand age on landslide occurrence. These differences in landslide characteristics between and within study areas do not appear to help explain the differences in landslide occurrence by stand age.

Compliance with the Forest Practices Requirements for Timber Harvesting on High Risk Sites

Current forest practice rules are designed to limit ground disturbances on high risk sites. These rules are intended to prevent local oversteepening and slope gouging by cable yarding. Rules also require operators to minimize slash accumulations on these sites, and especially in steep channels below high risk sites. The construction of skid trails on high risk sites is prohibited.

Observable physical ground disturbance was not correlated with initiation of the non-road associated landslides. Operators complied with the forest practice rules for timber harvesting on high risk sites in the locations adjacent to the landslides identified in this study. Any effects from forest management should therefore be related to removal of the vegetation. Slash loading at the landslide initiation site was not a factor in debris flow movement. This does not rule out the possibility that wood lower in the debris flow or torrent path might be a factor in travel distance or severity of impacts.

Road Associated Landslides

Past studies have shown that most landslide related impacts on forestlands were related to roads. For this reason, roads are the current focus of the forest practice rules for landslide prevention. The road associated landslides found in this study were typically about four times larger in volume than non road associated landslides. However, these road-associated landslides were smaller than landslides associated with roads as found in prior studies. Landslides associated with old roads (sometimes called abandoned or legacy roads) were typically smaller than the landslides associated with actively used roads. Landslides that were associated with forest roads made up a smaller percentage of the total number of landslides in this study than the road-associated landslides did in most previous studies. However, these road-associated landslides were still several times larger on average than landslides not associated with roads.

Roads on steep slopes have the majority of the landslides. Because landslides were not found on steep slopes where drainage waters were not directed to those slopes, keeping fill off steep slopes appears to reduce landslide hazard. However, at sites where there was drainage water, either intentionally discharged by a culvert or other relief structure, or through drainage system blockage, landslides occurred regardless of fill depth.

Extent of Stream Channel Impacts Due to Landsliding

The type of impacts that occurred during the 1996 storms were delineated. A highly impacted channel was characterized by massive scour and/or fill and overturn of sediments along with considerable damage to the vegetation along the edge of the channel. In order to have this level of impact, a debris flow, debris torrent, or debris flood would have to occur. Overall, 32% of the total of the 145 stream miles surveyed had high impacts due to landslide related effects. For the deliberately chosen high impact “red zone” study areas, this percentage increased to 37%. For the three stratified random areas the percentage was 10%.

Road associated landslides were wholly or partially associated with a large percentage of the highly impacted stream channels at three study areas. The extent of landslide related channel impacts was extremely variable between sites. The percentage of channel length surveyed with highly impacted stream channels was greater than found in past studies.

Differences Between High and Low Impact Storm Reaches

Impact width refers to the width that high water or debris impacted the channel and banks. As would be expected, impact widths were consistently greater for streams impacted by debris torrents as compared to non-impacted stream channels across all stream orders. Stream channels influenced by landslide related impacts were on average more open with less shade and occurred on streams with steeper slopes. However, for several stream size classes the average active channel width was similar for debris torrent impacted reaches as compared to those that had no recent debris torrent impacts.

Slash Loading and Timber Harvesting

The level of slash (i.e., small and large woody debris consisting of generally limbs and branches as well as unmerchantable logs) is believed to affect both travel distances of debris torrents and the amount of damage that they incur. Stream channels in which adjacent stands were recently clearcut harvested had greater slash accumulations as compared to older forests. However, these surveys were in streams un-impacted by debris torrent activity from the 1996 storms and done only in two study areas.

Debris Torrent Travel Distance

Debris torrents are debris flows enter the stream channel and usually contain much large wood. Since they were the cause of a great deal of the stream impacts observed, better understanding of their behavior is critical. Information on the physical characteristics of streams where debris torrents stopped (usually depositing a large “debris jam”) were carefully collected.

An existing model correctly predicted debris torrent travel distances for 258 out of 361, or 71 percent, of the debris torrents identified in this study. Debris torrent travel distance is most dependent on channel junction angles and channel gradient. Factors such as initial landslide size or condition of the riparian stand along the channels were found to be of secondary significance.

Key Conclusions

- Landslide inventories using only aerial photographs without significant on-the-ground surveying do not identify the majority of shallow-rapid type landslides.
- Coarse-scale digital elevation models underestimate slope steepness, especially in areas with irregular, steep slopes.
- Ground-based investigation provides the most reliable information on landslide occurrence and their characteristics in the forests of western Oregon.
- Timber harvesting can affect landslide occurrence on the steepest slopes. In three out of four study areas, higher densities and erosion volumes were found in stands that had been harvested in the previous nine years, as compared to forests that were older than one hundred years.
- Forested areas between the ages of 10 and 100-years typically had lower landslide densities and erosion than found in the mature forest stands.
- Landslides from recently harvested and older forests had similar dimensions, including depth, initial volume and debris flow volume.
- In the locations adjacent to landslides, landowners and loggers complied with the forest practice harvesting rules (as changed in 1983) to minimize ground disturbance and slash accumulations on landslide prone sites.
- Based on the low numbers of road-associated landslides surveyed in this study and on the smaller sizes of these landslides (as compared with previous studies), current road management practices are reducing the size of road associated landslides, as well as the number of landslides.
- Stream channel impacts varied greatly by study area. Impacts were not directly related to the number of landslides. Large, up-slope landslides that enter stream tributaries with small stream junction angles and steep channel gradient slopes resulted in the greatest stream channel impacts.
- When evaluating debris flow or torrent risks to resources based on potential run-out, one should consider the potential for large initiating landslides as well as channel junction angles, stream channel gradients, and the riparian condition along the debris flow/torrent path.

Oregon Department of Forestry
1996 Storm Impacts Monitoring Project
Final Report

E. George Robison, Keith Mills, Jim Paul , Liz Dent and Arne Skaugset

INTRODUCTION

BACKGROUND

During the months of February and November 1996, two very large storm events affected most of Western Oregon and parts of Northeast Oregon. These storms had different precipitation characteristics, different distribution and varying degrees of impacts. Both storms ignited a high level of public concern and media coverage regarding storm impacts on public safety, water quality and aquatic habitat, and how forest-management contributed to those impacts.

The February storm focused public attention on the contribution of forest practices to storm impacts on water quality and aquatic habitat. Following the February storm, the Oregon Department of Forestry (ODF) held a public scoping session to solicit input on the need, direction, and scope for a storm impacts monitoring project. The scoping session precipitated the formation of two committees. First, a coordination team was formed to coordinate efforts between multiple groups researching and monitoring the February storm impacts. Secondly, an expert review team was formed to review the ODF storm monitoring study design, protocol development and study results. Members of the coordination and expert teams are shown in Appendix A. The first phase of this study was implemented during the summer of 1996 on six study areas (four in the northern coastal mountains and two in the cascades).

The November storm re-emphasized concerns over water quality and fish habitat, and tragically an additional concern for public safety was raised when loss of life and property were associated with landslide and debris torrents. The protocol was revised slightly to accommodate different needs and the study was repeated during the summer of 1997 on two more study areas in the southern coastal mountains.

This project was primarily a ground-based study. However, remote sensing techniques (aerial photographs in particular) have commonly been used both to predict where landslides will occur and to inventory where landslides and channel impacts have occurred. Therefore one goal of the project was to determine the accuracy and precision of remote sensing data in identifying landslides, channel impacts, and landslide-prone areas.

A second goal of the project was to determine landslide frequency and channel impacts, particularly as they relate to forest practices. Specific forest practices that were considered include harvest practices that may have caused ground disturbance (i.e. yarding, site preparation), treatment of slash, road construction, and road drainage. Past research and monitoring has related landslide frequency to stand structure (particularly dominant tree species and age). Therefore, a related goal of this project was to examine relationships between storm impacts and forest stand structure adjacent to landslide initiation points and along stream channels.

This report is a culmination of three years of work to study landslide and channel impacts resulting from the February and November 1996 storms. The findings of this report are supported with intensive on-the-ground data associated with forest practices, landslides, debris flows, road construction and maintenance, and channel impacts. These data were analyzed in combination with forest-management data and aerial photograph analyses. The results are intended to provide policy-makers, ODF, and land managers with valuable information regarding the performance of forest practice rules under the relatively extreme conditions that occurred during the February and November 1996 storms.

SPECIFIC OBJECTIVES

In order to meet the goals described above, the specific objectives are:

1. Examine relationships between remote sensing data and ground-based data when interpreting landslide, debris flow, and channel characteristics, as well as landslide frequency as it relates to stand age.
2. Examine the physical ground alterations, landform, vegetative and site characteristics at the location of landslides to determine specific factors that contribute to landslide occurrence.
3. Examine the effects of landslides and debris flows on stream channels to evaluate specific factors that contribute to stream channel impacts.

REPORT ORGANIZATION

The report is organized in the manner by which landslides are typically observed and evaluated (beginning with landslide identification and concluding with effects on stream channels). It begins with background information on landslides, debris flows and stream channel impacts. The report then presents information on landslide identification from the air (using aerial photographs) since this technique has been the dominate method used to conduct landslide inventories in the past. The report then discusses various landslide characteristics and evaluates the effects of forest age, timber harvesting, and road management practices. The final results section discusses the effects of these landslides on stream channels.

The report contains four chapters:

Introduction: The Introduction chapter provides a background on why the study was needed, and identifies the goals and objectives of the study. Descriptions of the storm characteristics and a summary of landslide-related science follow the goals and objectives.

Study Design and Methods: The study design is described and field methods are summarized. Appendix C provides the detailed field data collection protocol.

Results: The results are separated into three sections:

- Finding Landslides and Landslide Prone Locations
- Landslides and Forest Management Effects
- Stream Channel Impacts Related to Landsliding

Conclusions: The Conclusions chapter summarizes and interprets the findings for all three result sections.

LIMITATIONS OF THE STUDY

The combination of variation in storm characteristics (precipitation intensity and duration) and variation across the landscape to susceptibility of landsliding resulted in a range of hillslope and channel responses even within the February and November storm study areas. This variability can limit the ability to separate management-related effects or from natural variability. The focus of this study was on two individual storm events and therefore cannot be extrapolated to predict long term conditions. Doing so could either under-predict or over-predict landslide rates on forestland. In addition, the study focuses on areas determined to have the most severe impacts from the 1996 storms. Therefore, results are expected to be well beyond the average forestland response to these individual storms. The study does not capture the total population of landslides that occurred as a result of these storms. The focus was on landslides that delivered sediment to stream channels because these landslides have the most significant effects on natural resources and public safety.

THE STORMS OF 1996

February Storm

The February storm was a high intensity, long duration rainfall event (Taylor, 1997). Long periods of winter rainfall preceding the February storm resulted in soils with a relatively high water content. In many places in Northwest Oregon, rainfall was 140-180 percent of normal rainfall for the winter season preceding the flood (Taylor, 1997). Cold conditions during the few days immediately preceding the storm most likely resulted in frozen ground in some low elevation locations and a heavy snow pack in the mountains. A subtropical jet stream brought warm heavy rainfall to the region. The storm began on February 5 and lasted through February 9. The subtropical jet stream delivered a long duration storm that melted snow. This contributed to the volume and timing of runoff from wet antecedent soil conditions. Had the storm lasted much longer, results could have been even more catastrophic since reservoirs were at capacity.

The February storm was generally limited to the northern half of the state (a west to east line from just south of Florence on the Oregon Coast to La Grande in Northeast Oregon). However, within the northern half of the state there were variable storm effects in terms of landslides and channel impacts. The long duration storm produced record-setting streamflows on many rivers while on some rivers only normal peak flows were recorded. For instance, the peak flow on the Nehalem River corresponded with a recurrence interval greater than 100 years while the peak flow on the Wilson River (the next major river basin to the south) corresponded with a 25 year recurrence interval flood (Laenen et al., 1997). In the Oregon Cascades, peak flow on the Sandy River near Marmot corresponded with a recurrence interval greater than a 100 year flood while the nearby Hood River experienced a 10-15 year flood (Laenen et al., 1997).

November Storm

The November 1996 storm was a shorter duration and higher intensity rainfall event than the February storm. Since the November 1996 storm occurred early in the season, predominately at lower elevations in Oregon's Willamette Valley and southern Coast Range, it lacked a rain-on-snow component. Since it occurred in the fall it also lacked significant antecedent precipitation. Therefore, soil moisture levels prior to the storm event were relatively low. However, all-time, one-day precipitation records were set at many locations (Table 1).

In addition, the following comments by George Taylor (State Climatologist) characterize the storm:

"Daily and monthly records were set at many sites as well. At Portland Airport, 3.86 inches was recorded between 4 p.m. on the 18th and 4 p.m. on the 19th. This broke the November 24-hour total of 2.82 inches, which was set November 10-11, 1995. Rainfall intensities for some areas in the Willamette Valley and Coast Range were calculated as a 100-year return period. While rainfall amounts were high as were stream flows throughout the Willamette Valley, highest impacts in terms of landslides and debris flows were reported in Douglas and Coos counties."

Table 1. One-day precipitation records for selected stations.

Location	1996 Amount (in.)	Date Records Began	Old Record	Year Old Record Set (in.)
Corvallis	4.45	1889	4.28	1965
North Bend	6.67	1931	5.60	1981
Portland	2.70	1939	2.48	1948
Redmond	2.38	1948	1.81	1969
Roseburg	4.35	1931	3.28	1965

There is tremendous spatial variability in timing and intensity of rainfall events for any given storm. For example, two gages in the Oregon Coast were compared to determine if two gages recorded similar precipitation intensities during the same rainfall events (Surfleet, 1997). The two gages were at a similar elevation, a similar distance from coast and within 10 miles from each other. The two gages recorded markedly different storm intensities during significant rainfall events from 1989-1995. The precipitation timing and intensities were disparate enough to suggest that for the highest storm events at one gage the nearby gage was not experiencing a storm event. For example, 31 of the 33 top storms at one gage were not identifiable as one of the top ten storms at the second gage. The combination of variation in storm characteristics (precipitation and flood levels) and variation across the landscape to susceptibility of landsliding most likely resulted in a range of hillslope and channel responses even within the February and November storm study areas.

SUMMARY OF THE SCIENCE ABOUT LANDSLIDES, CHANNEL IMPACTS AND FOREST PRACTICES

Landslide Studies

Many studies examine the differences in landslide rates between forested and recently harvested sites (Table 2). Table 2 lists studies throughout the Pacific Northwest in which landslide rates (number of slides for a given time period) and/or densities (number of slides per unit area) under different stand treatments were compared directly. In all, there were 35 forest treatment comparisons found from 24 studies. There are several compilations of these studies, such as Ice (1985), Sidle et al., (1985), and Meehan et al. (1991), that have often been used in forest policy decision making. As Table 2 indicates, most studies (28 of the 35 comparisons on Table 2) are based partially or completely on aerial-photo interpretation. In the past, there has been debate on whether it is appropriate to use air photos to compare recently harvested area landslide densities and erosion rates with those areas that contain mature forest stands. For instance, a classic exchange occurred in a discussion on a research paper by Pyles and Froehlich (1987) followed with a reply by Wolfe and Willams (1987). In the discussion Pyles and Froehlich laid out, on theoretical grounds, several reasons why landslides cannot be reliably detected on air photos due to photo angles and the obscuring effect of tall trees. In reply, Wolfe and Williams pointed out that Pyles and Froehlich had no empirical data to verify their findings. In particular they stated :

“Unfortunately Pyles and Froehlich have failed to provide documentation of these statements. It certainly would be of value to know how dramatic the differences are between these two types [ground vs. air based] of inventories.”

Some of the studies in Table 2 have particular relevance to this study either because they were in close proximity to ODF study areas or similar methods were used. The 1977 study by Swanson et al. utilized an aerial photo inventory to determine landslide frequency in clearcut areas, and a ground survey of 1300 acres to find landslides in older forests. The study was conducted in the Mapleton ranger district of the Siuslaw National Forest and overlapped one of the study sites used for the ODF study. Swanson found that erosion rates were higher in clearcuts than unmanaged stands. The clearcut erosion rates ranged from 1.2 to 1.3 times higher than unmanaged stands for most landtypes. For the most landslide prone landtype, clearcut erosion rates were 4.0 times higher than in unmanaged stands. Since not all landslides can be detected on aerial photos even in clearcuts, and the study compares an air-based clearcut sample to a ground-based in forest sample, these erosion rate ratios may be artificially low.

A 1978 study by Ketcheson and Froehlich field-investigated small watersheds (100 acres or less) in the Mapleton area that were unaffected by forest roads. The watersheds were generally inspected by walking on one side of the drainage and carefully inspecting each headwall. They found 104 landslides in a 1,076 acre study area. Landslide data were collected on failures as old as 15 years with unspecified dating techniques. This study found that the erosion rate in clearcuts was approximately 3.7 times higher than that of undisturbed forests.

There are also landslide studies that have attempted to understand the behavior of landsliding rather than simply compare rates between different age forests. A study site located northeast of Coos Bay, Oregon, has been the location of several of these studies (Montgomery et al., 1997). Detailed field measurements of a specific landslide prone site have been made here for about the last ten years. The study site is covered with an array of instruments to determine: soil pore water pressure, interactions between rock and soil water, long-term weathering rates, and many other physical processes. Information from this site was used to help develop a topographic model for assessment of landslide hazard (Montgomery and Dietrich, 1994). The role of vegetation in the stability of this site is also being examined. A debris slide/flow occurred at this site in the November 1996 storm. This failure is providing a unique opportunity for study of the specific factors associated with landslide initiation.

The Oregon State University headwall leave area study (Martin, 1997) also was conducted in the Mapleton area. The headwall leave area technique has been used to attempt to reduce landslides associated with timber harvesting. Headwalls, or very steep concave slopes which contain no channels, are first identified. Once identified, the trees on these headwalls are protected from harvest activities. The OSU study identified landslides in forested headwalls, clearcut headwalls, and headwalls protected with leave areas. They found no statistical difference in landslide occurrence between mature forests, leave areas, and clearcuts. However, the period of time such sites were subject to landslide producing storms was longer for the forested headwalls, a factor which may have overestimated the comparative failure rate of the forested headwalls.

Another study based on the February 1996 storm is being conducted in the H.J. Andrews Experimental Forest east of Eugene. This study is evaluating the factors associated with landslides that travel to large streams. It is also examining the effects of roads on the movement of debris flows and other landslides. Hydrologic changes associated with the road drainage network have also been studied. In addition, several of the National Forests have conducted aerial surveys of landslides due to the 1996 floods near or overlapping study sites for the ODF study including Bush et al. (1997) and Smith (1997).

Table 2. Studies of comparative landslide ("L.S.") densities and erosion rates in recently harvested forests versus unharvested mature forests.

Reference	Site	Measure-ment Type*	Recently Harvested		Road Right of Way	
			Ratio L.S. Density	Ratio L.S. Erosion	Ratio L.S. Density	Ratio L.S. Erosion
Amaranthus, et al., 1985	Siskiyou Mtn., Oregon	Air	19.0	6.8	138.0	111.0
Bishop and Stevens, 1964	S.E. Alaska, Maybeso Cr.	Air	19.5	NA	NA	NA
Bush et al., 1997	Oregon Coast Range	Air/Size	2.6	NA	31.6	NA
Chesney, 1982	Oregon Cascades, 1949	Air/Field Visit	0.0	NA	11.1	NA
	Oregon Cascades, 1959	Air/Field Visit	3.7	NA	33.3	NA
	Oregon Cascades, 1967	Air/Field Visit	12.9	NA	208.0	NA
	Oregon Cascades, 1972	Air/Field Visit	21.8	NA	705.0	NA
	Oregon Cascades, 1979	Air/Field Visit	4.7	NA	254.0	NA
Dyrness, 1967	Oregon Cascades, H.J. Andrews	Air/Size	9.8	5.0	309.0	60.1
Fiksdal, 1974	Olympic Pen. Washington, Sequaleho Cr.	Air/Field Visit	0.0	0.0	1600.0	224.0
Gresswell et al. 1979	Oregon Coast Range, Mapleton Area	Air/Field Visit	23.5	NA	72.2	NA
Hicks, 1982	Oregon Cascades, Middle Santiam	Air/Field Visit	3.6	3.4	73.7	95.3
Hughes and Edwards, 1978	Oregon Cascades, Umpqua basin	Ground	8.0	10.0	NA	NA
Johnson, 1991	Washington Cascades; S Fk. Canyon Cr.	Mixed	5.3	NA	97.0	NA
Ketcheson and Froehlich, 1978	Oregon Coast Range, Mapleton Area	Ground	2.2	3.4	NA	NA
Lyons, 1982	Oregon Cascades, 1959-67	Air/Field Visit	22.8	29.5	NA	NA
	Oregon Cascades, 1967-72	Air/Field Visit	6.8	10.0	NA	NA
Marion, 1981	Oregon Cascades, Blue River	Air/Field Visit	10.0	9.0	106.0	44.0
McHugh, 1987	S.W. Oregon	Air/Field Visit	7.0	NA	48.0	NA
Morrison, 1975	Oregon Cascades, Alder Creek	Air/Size	13.5	2.6	415.0	343.0

NA = Not available

Table 2 (Continued). Studies of comparative landslide densities and erosion rates in recently harvested forests versus unharvested mature forests.

Reference	Site	Measure-ment Type*	Recently Harvested		Road Right of Way	
			Ratio L.S. Density	Ratio L.S. Erosion	Ratio L.S. Density	Ratio L.S. Erosion
Robison et al., 1999 (This	Oregon Cascades, near Vida	Ground	1.4	3.2	2.7	40.9
	Oregon Coast Range, Elk Creek	Ground	0.8	0.3	1.0	0.8
	Oregon Coast Range, Mapleton	Ground	1.9	1.5	5.0	13.6
	Oregon Coast Range, Scottsburg	Ground	5.2	2.6	NA	NA
Rood, 1984	British Columbia; Graham and Moresby Island	Air	30.0	31.2	76.7	89.7
Schroeder and Brown, 1984	Oregon Coast Range, Palouse Cr.	Air	9.6	NA	NA	NA
	Oregon Coast Range; Larson Cr.	Air	6.1	NA	NA	NA
Schwab, 1983	British Columbia, Queen Charlotte Islands	Mixed	17.0	5.0	41.0	46.0
Smith, 1996	Oregon Cascades; Weak Rock, Steep Slopes	Air	10.7	NA	NA	NA
Swanson and Dyrness, 1975	Oregon Cascades, H.J. Andrews Unstable	Mixed	3.2	2.8	33.0	30.0
Swanson and Grant, 1982	Oregon Cascades, WNF Mod. Stable	Mixed	3.0	2.5	47.0	37.0
	Oregon Cascades, WNF Unstable	Mixed	7.0	5.0	336.0	250.0
Swanson et al., 1977	Oregon Coast Range, Cedar Cr.	Mixed	1.2	NA	15.0	NA
	Oregon Coast Range, Soil Type 47	Mixed	1.3	4.0	15.5	30.8
Swanston and Swanson, 1976	S.W. British Columbia Coast Range	Air/Size	5.0	2.2	20.0	25.2

**Measurement types: 1. "Air"A study based on air photos with our without ground verification regarding the size of landslides and whether the feature was a landslide. 2. "Air/Size" – A study based on air-photos with a minimum landslide size used to decrease the chance of bias between old and young stands. 3. "Mixed" – Studies that combine more than one method of detection. For instance, one study used air-photos to detect landslides in clearcuts and a ground-based sample in older forests. 4. "Air/Field Visit" – An air based sample with non-systematic field visits used to get some incluinations that most landslides are being found. 5. "Ground" – studies that detect landslides based on a systematic sampling of landslides using the channel network and/or the slope contours as a search path.*

Landslides on Forest Lands

Landslides are the dominant erosional process on steep forested slopes in western Oregon and throughout the Pacific Northwest (Swanson et al. 1987). A landslide is the movement of a mass of soil, rock or debris down slope and they occur most frequently after intense winter rains. The most common landslides on steep forestlands are often referred to as debris slides. This is especially true in the Oregon Coast Range. A debris slide is relatively small and shallow, with typical dimensions of 3 feet in depth, 30 feet in width, and 40 feet in length with a relatively planar failure surface (same shape as the ground surface).

Forest practices may alter both physical and biological (vegetative) properties related to slope stability. Physical alterations can include slope steepening, slope-water effects, and changes in soil strength. Most of the physical alterations are caused by roads (and skid roads). Roads have, by far, the greatest effect on stability of slopes on forestlands, at least on a unit area basis (Sidle et al., 1985). Vegetation may also have both hydrological and mechanical effects on the stability of slopes (Greenway, 1987).

Hydrological effects of vegetation on the hillslope include:

- Water removal: by interception (storage of water on leaves and branches), evaporation or evapotranspiration (removal of water from the soil or vegetation by plant growth or climate); and
- Influencing water routing: by temporary storage via interception and by creating and routing water to macropores (natural pipe-like structures common in forest soils) via stem flow or by creating areas of concentrated flow.

Mechanical effects of vegetation include:

- root reinforcement (where roots have penetrated into a potential landslide failure surface and added strength);
- buttressing and arching (where trees at the base of a potential landslide act like piles);
- surcharge loading by trees, logs and/or debris (where the weight of these materials may add to the gravity force on the slope);
- wedging and loosening of soil (lowering strength) by roots;
- windthrow (as trees blow down, soils are displaced and oversteepened, and also subject to vibration).

Tree removal can have the following effects on slopes:

- a reduction in interception or evapotranspiration;
- alteration of macropores or water pathways thus changing water routing;
- a reduction in the soil infiltration rate;
- alteration of snowmelt patterns (Coffin and Harr 1992);
- reduction in root reinforcement;
- loss of buttressing and arching.

Most of the research on the effects of vegetation on forest slope stability in northwest forests has concentrated on “root strength.” The root strength concept is somewhat analogous to the effect of steel in reinforcing concrete. Root strength models assume that roots penetrate the failure surface; roots are anchored and do not move downslope with the landslide; and that the tensile strength of roots is developed (Greenway, 1987).

Landslides, Roads and Washouts

Roads create a contiguous linear physical alteration to hillslopes, as shown in Figure 1. To create the running surface, or tread, it is necessary to excavate into the natural hillslope. On less steep slopes this excavated material can be used as fill to make a portion of the running surface. Both cut and fillslopes are steeper than the natural slopes, and, at least for some period of time after construction, are not vegetated. Thus, cut and fill slopes have a higher landslide potential than the native hillslopes. Roads also alter the flow of water. Road cuts may intercept groundwater, and the road surface normally collects surface water. This water is routed along the road to a location where it is discharged downslope of the road. Roads must also periodically cross streams. Most forest stream crossing structures are culverts. During high flows, stream flows can exceed culvert capacity. When drainage system capacity is exceeded or when it becomes blocked by debris, fill washouts or landslides on or below the fill may occur.

In areas with steep slopes, landslides are typically the dominant erosional mechanism. Landslide frequency can be greatly accelerated by road management practices (Sidle and others, 1985). For example, Megahan and Kidd (1972) found that 70% of accelerated sediment production in an Idaho batholith study site was associated with road related landslides. Piehl et al. (1988) found only two landslides at culvert outlets yet they comprised 72% of the total outlet erosion associated with 515 cross-drainage culverts.

Road construction on steep slopes requires significant excavation into and further steepening of these slopes (Figure 1). With other factors being equal, the steeper the slope, the lower the relative stability. Therefore, some increase in landslides is to be expected.

The location of landslide initiation in relation to the road prism has a tremendous influence on potential sediment delivery to streams. Landslides affecting the cutslope portion of the road are typically deposited in the road. While cutslope landslides may be eroded by road surface waters, they may also divert surface waters away from designed drainage structures or divert water onto fillslopes. Fillslope failures are more likely to become debris flows, increasing in size and then entering intermittent and perennial channels.

Almost all major (delivering sediment to streams) road-related landslides investigated by ODF prior to the 1996 storms have been related to road fills or road sidecast (Mills, 1991). Sidecast is a term used to describe uncompacted excavated fill material pushed onto the downhill side of the road.

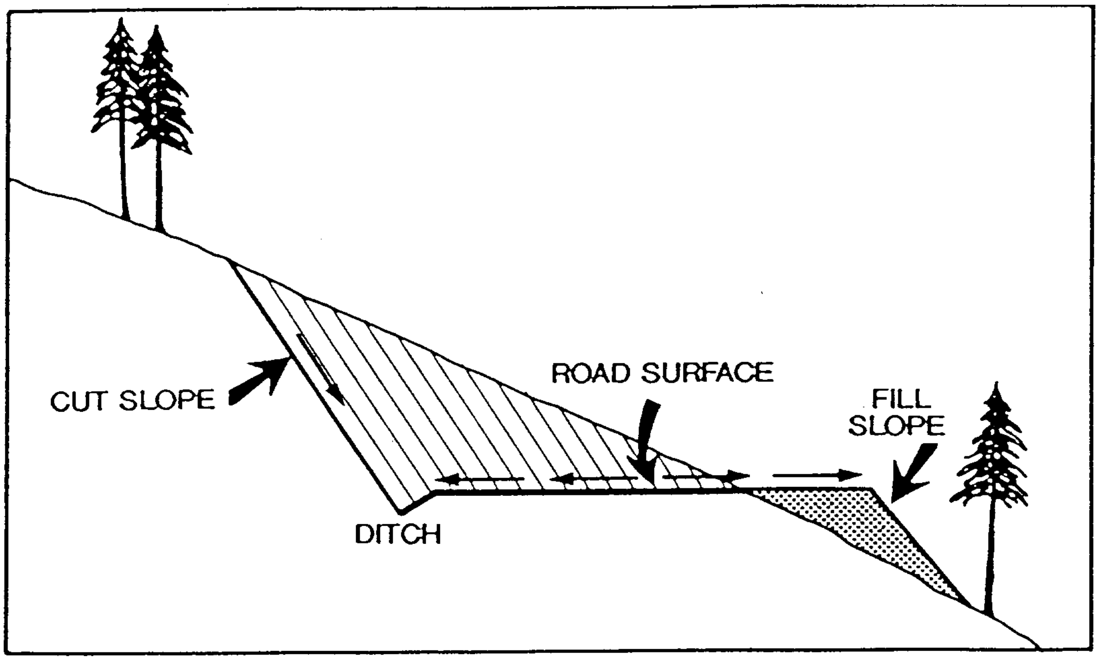


Figure 1. Road/hillslope cross-section schematic

Current forest practice regulations prohibit sidecasting to the extent that landslides and channel damage are likely. A technique known as end-hauling is used to transport excess excavated materials to more stable waste area locations. Using steeper grades to keep roads on ridgetops is a far less expensive road system design alternative than end hauling, and is also effective at landslide prevention. However, where these practices are not possible, end hauling may be an effective, albeit expensive, technique for reducing landslides (Sessions et al., 1987). Forest practice regulations for end-hauling have been in place since 1983. However, most existing forest roads in western Oregon were constructed prior to 1983, when sidecasting was the common construction practice.

A road damage inventory conducted in Washington found that roads constructed in the last 15 years survived a landslide inducing storm with minimal damage, while roads constructed earlier had very high damage rates (Toth, 1991). Department of Forestry landslide monitoring has made similar findings (Mills, 1991). Although most surface erosion tends to occur in the first few years after construction or during periods of heavy traffic use, landslides can occur many decades after original construction.

ODF monitoring has also found that road drainage is associated with about one-third of the investigated road-related landslides (Mills, 1991). Culverts were associated with 29 percent of the damage sites in the Deschutes River (Washington State) study (Toth, 1991). Concentration of road drainage can also be associated with interactions between road systems and channels in steep terrain, sometimes resulting in landslides (Montgomery, 1994).

Stream crossings with culverts, and to a lesser extent under-designed bridges, are subject to plugging and/or the capacity being exceeded by high flows. If water backs up and flows over the surface, a washout type failure similar to a dam breaching may occur. When a road grade climbs through the stream crossing, there may be a high potential for channel diversion down the road (Weaver and Hagans, 1994). Such diversions can cause large gullies running long distances down the road, and can cause additional landslide and washouts.

Landslides and Stream-Channel Modifications

The principal landslide related effects with the storms of 1996 were both off-site and in-channel. Based on aerial reconnaissance, ODF determined that scour and deposition from landslides, debris flows and torrents modified many stream channels. Another potential concern with landslides was their effect on forest productivity. However, past studies in the Pacific Northwest have shown that even in areas with high landslide densities, generally less than two percent of the land was directly impacted by these landslides (Ketcheson and Froehlich, 1978 and Ice, 1985).

In steep terrain, small shallow landslides can quickly transform into debris flows. A debris flow occurs if the landslide moves down slope as a semi-fluid, viscous mass scouring or partially scouring soils from the slope along its path. A debris flow is any movement below the initial landslide and outside of a channel (on hillslopes and hillslope depressions steeper than about 40 percent gradient). Upon entering and continuing down a channel, debris flows are considered debris torrents (Van Dine, 1985). In Western Oregon, landslides initiate most debris flows and torrents (Swanson and Lienkaemper, 1978). Debris torrents in the Pacific Northwest typically contain a significant amount of large wood not common to debris flows in non-forested regions. Debris flows and debris torrents travel varying distances and result in variable degrees of impact depending on channel slope, confinement, layout of the channel network, and other characteristics (Fannin and Rollerson, 1993).

The impacts of landslides on small streams (1st to 3rd order) can be severe as well as extensive. It is postulated that while landslide features may constitute less than 1% of the total land surface in mountainous terrain in the Pacific Northwest they can scour and impact over 10% of the channel network (Swanson et al., 1987). Small streams are suppliers of wood, sediment, and relatively cool water to larger fish bearing streams. In addition, small streams often provide habitat for critical life stages of fish and other aquatic organisms (Beschta and Platts, 1986). Landslides and debris flows provide most of the sediment input into these small streams in steep mountainous forested watersheds (Benda and Dunne, 1987). Previous studies have documented channel changes for small and large streams resulting from high water and landslide activity including channel scour and fill, channel widening, changes in channel longitudinal profile, and decreases in ecological stability (Lyons and Beschta, 1983; Kaufmann, 1987; Lamberti et al., 1991; Reeves, et al., 1995). Reeves et al. (1995) have suggested that the input of gravel, large wood, and floodplain sediment from naturally occurring landslides is an important factor for maintaining productive fish habitat. According to Reeves and others, short term disturbances from landslide events is necessary to improve long-term conditions.

Debris flows and torrents commonly transport many times more sediment than the initiating landslide through scour of hillslopes and channels. In some cases, an initiating landslide of 10 cubic yards or less may become a debris torrent moving thousands of yards of material into and through channels. Debris flows and torrents tend to deposit sediment where channel gradient declines (Benda and Cundy 1990). They often stop (deposit as a debris jam) at tributary junctions where the junction angle is high (Benda and Cundy, 1990). An empirical model for predicting deposition of debris flows in channels was developed using these relationships for channels in coastal Oregon (Benda and Cundy, 1990). This model was applied to debris torrents in this study.

Forest Practices Requirements for Harvest Operations

The Oregon Board of Forestry adopted most of the current landslide prevention rules on June 8, 1983. Rules for harvesting on high risk sites were adopted in 1985. The forest practice rules for both road construction and timber management are intended to minimize both surface and mass (landslide) erosion. However, the following discussion focuses only on regulations for timber harvesting. It does not include requirements for forest roads.

Harvest practices are subject to added regulation if they affect high risk sites. "High risk sites" are specific locations determined by the department based on risk of landslide-related damage to waters of the state. Administrative guidance defines high risk sites as:

1. Actively moving landslides;
2. Slopes steeper than 80%, excluding stable rock;
3. Headwalls or draws steeper than 70%;
4. Abrupt slope breaks, where the lower slope is steeper and exceeds 70%, except where the steeper slope is stable rock;
5. Inner gorges with slopes steeper than 60%; or
6. Sites determined to be of marginal stability by ODF personnel.

Practices which have become standard for the protection of high risk sites during forest harvesting and stand management activities on private lands in Oregon include:

1. Felling timber to minimize ground disturbance and slash accumulations on high risk sites;
2. Not building skid trails on high risk sites;
3. When yarding across high risk sites, providing at least one end suspension and ensuring that logs do not gouge soils;
4. Not building landings on high risk sites, and avoiding placement of landing debris or landing drainage on high risk sites; and
5. Replanting as soon as possible after logging.

The following additional practices have been used to protect high risk sites, but are not considered standard practices or requirements in most cases:

1. Leaving non-merchantable trees and understory vegetation relatively undisturbed;
2. Avoiding prescribed burning;
3. Avoiding use of herbicides;

4. Leaving a buffer area around headwalls (headwall leave areas);
5. Thinning the stand instead of clearcut harvesting to retain some root strength; and
6. Not harvesting the area.

STUDY DESIGN

SITE SELECTION

A total of eight study areas were monitored over a two-year period. Six areas were impacted by the February storm and two areas were impacted by the November storm (Figure 2).

Six February Storm Study Areas

Immediately following the February storm, ODF implemented an aerial reconnaissance of the storm-impacted areas. Based on this reconnaissance, storm boundaries and areas with particularly high landslide and debris-torrent disturbances were delineated and referred to as "red zone" areas. Three study areas (Mapleton, Tillamook, and Vida) were delineated using 2x5 mile grids laid out within the red zone areas. The criteria for selecting red zone study-areas were:

1. These areas had to have extreme disturbance relative to other areas when viewed from the air in terms of debris torrents and landslide scars.
2. A variety of stand age classes were present and in close proximity to each other. (Note: for the area near Tillamook an exception was made because the whole area is fairly uniform regeneration from the Tillamook burn.)
3. Relatively similar slope and geologic conditions occur within the study area (i.e. no major shifts in characteristics).
4. The area also needed to have a large portion of the land in private or state ownership.

Criteria number two was necessary because impacts as viewed from the air were highly variable over short distances and over areas with similar slopes and geology. Many of these differences appeared to be related to the variability of the storm itself. As stated earlier, gaged peak flows were extremely variable in terms of magnitude even in neighboring basins. Precipitation was most likely variable as well. Precipitation at gages within 10 miles of each other have been shown to experience tremendous variation in timing and intensity for given storms (Surfleet, 1997).

In addition to the red zone study areas, three study areas (Dallas, Estacada, and Vernonia) were located using a stratified random sample (Figure 2). The criteria for the random study area selection was:

1. The area had to be within the February flood event zone in western Oregon, which is North of a line that runs approximately from Florence to Bend.

2. Fifty percent or more of the land in the 2x5 mile grid had to be in State or private forest land.
3. The area had to be 10 or more air miles from the nearest “red zone” study area.
4. Ninety percent or more of the resulting grid had to be on forest land.
5. The entire study area grid must be in Oregon.

Random numbers were generated within a range of latitude and longitude that was within the storm area and within Western Oregon. The longitude and latitude selected formed the southern middle section of a horizontal 2x5 mile grid which formed the study area.

The purpose of this study selection design was two-fold. First, by selecting red zone study areas forest practice effectiveness could be documented in areas known to be most-heavily impacted by the storm. The randomly selected study areas provide a broader perspective of storm effects. The stratified random selected study areas were predominately on private ownerships.

These February Storm study areas were surveyed during the summer of 1996. Due to time limitations, the study areas were modified to sample smaller portions of the 10 mi^2 grids. These smaller areas have been termed “core areas.” Core areas are those areas within the 10 mi^2 study grids where all channels were field surveyed for evidence of landslide entry. The Tillamook and Vida study areas were expanded to include areas outside of the 10 mi^2 study areas. These watershed surveys were conducted to identify landslides outside of the core area that were contributing to cumulative channel impacts in the core areas. A total of 32 mi^2 were surveyed in the February study core areas and an additional 6 mi^2 were surveyed in the extended watershed areas.

Two November Study Areas

Following the November 1996 storm, two additional red zone sites were selected in areas affected by the storm (Figure 2). The study areas were selected in Douglas and Coos County. These were regions that were observed to have the highest rates of landslides and debris torrents from the November 1996 storm. These two red zone areas are described as Elk Creek and Scottsburg. The Elk Creek study area includes the entire Elk Creek basin and the Scottsburg study area is a combination of a number of smaller basins. A total of 13.7 mi^2 were surveyed in these two areas.

Study Area Summary

A total of 51.7 mi^2 (including 6 mi^2 outside of the core study areas) and over 145 stream channel miles were surveyed. In the total area surveyed, 42% was on Private industrial land, 36% was on State owned forest land, 20% was on federally-owned land, and 2% was on private non-industrial land.

STUDY AREA DESCRIPTIONS

Six of the eight study areas are located in the Coastal Mountains, the other two are located in the western slopes of the Cascade mountains. The Oregon Forest Practices Act administrative rules use the term "geographic region" to describe large areas with similar combinations of climate, geomorphology and potential natural vegetation. There are three geographic regions represented by these study sites. The "Coast Range" includes the wetter and typically steeper portions of coastal mountains. The "Western Cascades" consist of all volcanic rock units in higher rainfall areas, and are generally mountainous. The "Interior" region is drier and typically consists of foothills on both sides of the Willamette Valley. The Mapleton, Tillamook, Vernonia, Scottsburg, Elk Creek, and Dallas study areas are in the Coast Range Georegion. Part of the Estacada study area is in the Interior and part is in the Western Cascade Georegion. Vida is in the Western Cascades georegion.

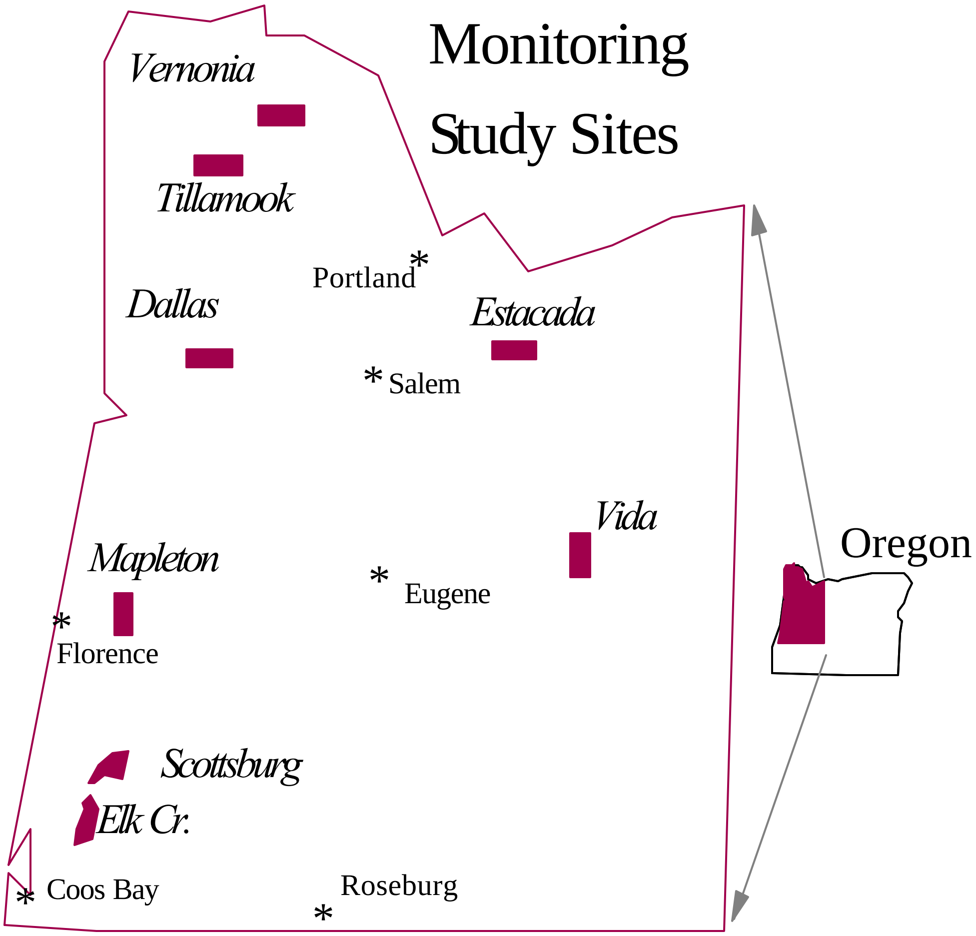


Figure 2. General locations of the eight 1996 storm study sites (not to scale).

Detailed physiographic summaries for each study area are shown in Table 3. Geology is based on available geologic mapping. Lithology, landform, soil and channel network information is based on current and past field interpretations for this study and other geotechnical projects. Maps with detailed study area locations are given in Appendix B.

FIELD METHODS

This was a ground-based study, meaning that crews collected all landslide, debris flow and stream channel data on-site. Field data were combined with information gathered in the office regarding forest management and stand structure. Aerial photographs were analyzed in the office. The objectives of the field-data collection were to: find and measure every landslide that delivered sediment to the stream channel; document and measure the associated debris flows and channel impacts; and gather site information regarding forest practices that may have contributed to the impacts. For example, forest practices that result in ground disturbance or poor road construction may contribute to channel impacts, whereas a well designed road and stream crossing may have reduced the risk of road-related impacts.

The detailed field measurements protocol used for the 1997 field season on the Elk Creek and Scottsburg study areas is given in Appendix C. Refinements were made to the 1997 protocols based on lessons learned in 1996. Differences between the 1996 and 1997 data collection methods are described in each results section. What follows are some of the key elements of the field protocol essential for interpreting the results of this study.

Search for Landslides and Documentation of Channel Effects

Crews used the stream-channel network to search for landslides that delivered to the stream channel. Using this method, landslides ranging in size from small streambank failures to debris flows that moved thousands of feet were easily identified.

The stream crews walked (and sometimes climbed) every channel to its headwaters searching for landslides. Many tributary channels were sufficiently small that they were not represented on USGS 7.5 minute quadrangle maps. Crews systematically took channel measurements to document degree of channel impact as they searched for landslides. The crews walked up every channel in the study area regardless of impact, until the channel gradient consistently reached 40% or greater. If the crews reached a sustained 40% or greater stream channel gradient and there was no evidence of either a landslide or moderate to high channel impacts, the channel was documented as unimpacted from a landslide. The crew then began the search for landslides on the next channel. Measurements were taken on every landslide, debris flow, and debris jam as they were encountered. There was no difference in this approach between years.

Table 3. Physiography of ODF study areas.

	Study Sites							
Physiography	Scottsburg	Elk Creek	Mapleton	Vida	Tillamook	Dallas	Vernonia	Estacada
Georegion/ Storm event	Coast Range November 96	Coast Range November 96	Coast Range February '96	Western Cascades February '96	Coast Range February '96	Coast Range February '96	Interior February '96	Interior/ West. Cascade February '96
Geologic Map Units	Tt – Tyee Formation	Tt – Tyee Formation	Tt – Tyee Formation Tim – Mafic Intrusion	Tu - Undifferentiated volcanogenic rocks (ground investigated; Thi - Hypabyssal intrusives	Tbl – Subaerial flow basalt, tuff & breccia; Tbr – Submarine flow basalt, tuff and breccia; Tbpl – Subaerial flow basalt; Qls – Landslide deposit	Ti – Intrusive; Tsv - Siletz typically submarine volcanics; Ty - Yamhill siltstone	Tss - Marine siltstones; Tco - Cowlitz sandstone	QTba - high cascade basalt flows; Tbaa and Tfc – basalt flows with some interbedded pyroclastics
Lithologies	Thick sequence of 5-80 foot sandstone beds w/0.1 to 5 ft. thick siltstone interbeds. Gently dipping (usually under 10 degrees). Joints are typically widely spaced	Thick sequence of 5-80 foot sandstone beds w/0.1 to 5 ft. thick siltstone interbeds. Gently dipping (usually under 10 degrees). Joints are typically widely spaced	Thick sequence of 5-80 foot sandstone beds w/0.1 to 5 ft. thick siltstone interbeds. Gently dipping (usually under 10 degrees). Joints are typically widely spaced	Mixed basalt flow rocks, flow breccia, & volcaniclastic deposits. Often hydrothermally altered & moderately sheared. Very variable	Commonly 10 to 30 ft. flows; highly sheared; often deeply weathered	Intrusion is massive, relatively unweathered; volcanics highly sheared & unaltered; Yamhill deeply weathered	Rocks generally very deeply weathered to near soil consistency	Relatively unweathered, moderately jointed

Table 3 (continued). Physiography of ODF study areas.

	Study Sites							
Physiography	Scottsburg	Elk Creek	Mapleton	Vida	Tillamook	Dallas	Vernonia	Estacada
Landform	Slopes are highly to extremely highly dissected, especially near ridgetops	Slopes are highly to extremely highly dissected, especially near ridgetops	Slopes are highly to extremely highly dissected, especially near ridgetops	Long hillslopes, uniform to moderately dissected	Long slopes, slightly to moderately dissected, often irregular	Gentle mountain plateau with incised channels. Dissection increases away from Laurel Mtn.	Rolling hills, occasional incised slopes near larger channels	Gently sloped except steep canyon walls adjacent to larger channels
Slope Steepness	Except near larger streams, most hillslopes exceed 75%, & some slopes are over 100%	Except near larger streams, most hillslopes exceed 55%, & some slopes are over 100%	Except near larger streams, most hillslopes exceed 65%, & some slopes are over 100%	Typically 50 to 90%	Generally 60 to 100%	Level to 35% on the plateau to over 90% on canyon sidewalls	20 to 60%	10 to 40% on upper slopes, to 70%, with cliffs adjacent to channels
Soils	Shallow, sandy gravels with low plasticity in colluvial depressions, valley stage features, & in alluvial deposits around larger streams	Shallow, sandy gravels with low plasticity in colluvial depressions, valley stage features, & in alluvial deposits around larger streams	Shallow, sandy gravels with low plasticity in colluvial depressions, valley stage features, & in alluvial deposits around larger streams	Variable, low to moderate plasticity	Less than 1 to 5 ft. in thickness, low plasticity, deeper in valley stage & landslide deposits	Variable	Deep sandy silts, generally low plasticity	3 to 10 feet thick on upper slopes, 0 to 3 feet adjacent to channels
Channel Network	Dense dendritic	Dense dendritic	Dense dendritic	Dendritic, steep	low density dendritic, very steep	Irregular	Moderate density dendritic	Widely spaced dendritic

Documenting Road Associated Landslides

In addition to all landslides that delivered to the channel, all road-related landslides that did not deliver to the channel were documented for the February storm study areas (Mapleton, Vida, Tillamook, Dallas, Vernonia, and Estacada). A road crew surveyed every active road, identifying and measuring landslide and road wash-out parameters. In addition, information on road location, construction, and drainage practices was recorded. For the November storm study areas (Elk Creek and Scottsburg), only road-related landslides that delivered to the stream channel were measured. These were found during the stream network search. Road-related landslides in the November study areas that did not deliver to the stream channel were not documented.

The 1996 comprehensive road survey consisted of a complete road inventory in conjunction with a road-landslide inventory. Within each 10 square mile study area, all active roads were either driven or walked. For the purposes of this study, active roads are those roads that have been used to access timber since 1972. Roads that have not been used since 1972 and roads that were overgrown and not driveable prior to the 1996 flood were not surveyed. The year 1972 was chosen because the Forest Practices Rules became effective that year. State highways and county roads were not inventoried during these surveys.

Each road was divided into distinct segments, and each segment was defined by endpoints. End points included locations of surface road drainage discharge, live stream crossings, or significant grade breaks. For each road segment, attributes describing that segment were measured and recorded. These attributes included segment length, road grade, road prism construction type, surface conditions, drainage features, slope location, and general topographic features. Length of each segment was measured to the nearest foot with a Distance Measuring Instrument (DMI) installed in the field vehicle, or by hip chain when on foot. Road grade and side slopes were measured using a clinometer. Fill depth at the shoulder of the road and cutslope height was estimated. Road segments that drained surface runoff directly to live streams were noted.

Road related landslides and fill washouts were located and identified in relation to the road and segment on which they occurred. The type of erosion, mode of failure, and magnitude relative to the road was recorded. The length, width, and depth of the original failure mass was estimated and recorded. Conditions of the road including percent of road width comprised of bench and fill, width before and after failure, fill depth at the shoulder of the road, cutslope height, and drainage feature was recorded. Topographic conditions of the landform and the hillslope above and below the failure were estimated and recorded. A description of the dominant vegetation, significant wood in the road fill, presence of large amounts of slash, soil type, and delivery to stream were also recorded.

Field Information Gathered on Landslides That Delivered To Channels

The landslide protocol provided a method to identify and measure all landslides that entered stream channels and associated debris flows. This landslide measurement protocol was developed using the information learned from over five years of landslides monitoring by the Department of Forestry. Development of this protocol was also influenced through review of other landslide investigation protocols and from input by the team of experts. The field portion of this protocol was designed for use by persons with science and/or resource management training under the direction of geotechnical specialists.

Since most debris flows can be traced to source landslides, landslides were found by walking up-slope from the point of sediment delivery to the channel. Efforts were made to only include landslides that occurred during the February and November storms. Observed landslides that were significantly re-vegetated, had consolidated deposits, or which were known through air photos or other means to have occurred in earlier years were not included in this database. Detailed data descriptions and methods of the measurements taken can be found in the storm study protocols (Appendix C). Field measurements included: landslide location, condition and type; debris flow and landslide dimensions, aspect and slope steepness; landform and soil characteristics; slash depth, slope alterations or ground disturbance from forest practices at the source area of the landslide; and overstory and understory vegetation characteristics.

Field Information Gathered on Channel Impacts

The objective of the channel impacts protocol was to document storm and landslide effects on stream channels. As described earlier, field crews used the channel network as a means of searching for landslides. As they walked up the channels they gathered channel and debris jam data. The channel impacts protocol was implemented on all impacted streams and a subset of unimpacted streams within the eight study areas. The measurement stations were established systematically, every 100 to 200 feet, depending on the degree of impact and year studied. In the 1996 survey, stations were 100 feet apart on impacted channels and 200 feet apart on unimpacted channels. In the 1997 survey, stations were 150 feet apart on all channels.

Field measurements at each measurement station included: station locations measured as distance from landmark (culvert, tributary, road); associated landslide(s) affecting the stream reach; type and degree of storm impact; scour and deposition volumes; channel type, width and depth, gradient, and azimuth; and shade**.** Field measurements for large wood included a continuous tally of wood based on diameter, length and location.

Field Data Gathered on Debris Jams

The objective of the debris jam protocol was to map the occurrence and volumes of debris jams and very large depositional features in the field so as to understand (in a gross sense) the sediment budget of landslides, torrents and channel impacts. The protocol was used whenever a debris jam of any size or a large sediment deposit (> 10,000 ft^3) was encountered. Field measurements include: length of jam, width, height, location, shape, junction angles, surface composition, and associated landslides.

Aerial Photographs and Other Remote Sensing Data

Aerial photographs of the six February study sites were taken during the spring and summer of 1996. These photographs are at an approximate scale of 1:6,000 and, in most cases, include sufficient overlap for stereo-pair coverage. In addition to this coverage, the Siuslaw National Forest obtained photographs after the February storm at 1:24,000 scale of a very large area that included the Mapleton study area. Finally, 1:12,000 scale photos of the Tillamook State Forest (which includes the Tillamook study area) were taken during the summer of 1996 after the storm. All of these photo sources were used to identify landslides and debris flow visible on the photographs, and to help the field crews locate landmarks on the ground as well as verify forest and stand characteristics information.

Slope steepness of the overall study area landscapes were evaluated using ten-meter and 30-meter digital elevation models (DEMs) developed from USGS maps. For the Elk Creek and most of the Scottsburg study area, orthophoto-based 20 foot contours were also available that were developed for the Elliot State Forest. Using this contour map, a six-meter DEM was developed using Geographic Information System (GIS) software. For a portion of the Scottsburg study area, a one-meter DEM was developed from airborne laser altimetry that was able to more precisely determine slope steepness. All this information was integrated with other field information on a GIS to evaluate the spatial distribution of slopes and other characteristics for the study areas.

Forest Management Data

A list of all landowners for all study areas was compiled using ODF and county tax assessor data. All landowners in the study areas were then contacted and asked to provide specific data on management on their lands. Landowners were very cooperative, and provided information on:

- the location of all forest stands,
- the age class of forest stands,
- the date of most recent timber harvest for those stands, and
- the date forest roads were constructed on those study sites.

Data Reliability

A small portion of data collected were not used in the following analyses either because of reliability issues that were raised from quality control tests of the methods or because the method of collection did not facilitate reliable analyses. These data include: presence or absence of roots at the headscarp of landslides, volumes of sediment stored or scoured from channels, and the distribution of large wood in the channels (exclusive of debris jams) for the February study areas.

RESULTS SECTION ONE: FINDING LANDSLIDES AND LANDSLIDE PRONE LOCATIONS

Most landslide inventories rely either in part or completely on air photos for determining the occurrence, location, and characteristics of landslides (Table 2). Prior to this study, relatively little was known about potential biases in air photo inventory methodologies. The degree to which the forest canopy obscures landslides has been subject to much speculation, but was largely unknown (Pyles and Froehlich, 1987). A higher percentage of landslides in a recently harvested area may be visible as compared to what is visible in a mature forest. This bias could significantly influence comparisons of landslide density and erosion volume between mature forests and recently clearcut stands.

Prior to this study, a systematic ground based sample of landslide occurrence was conducted in only two other forest landslide studies (Table 2). The geographic extent of these two other studies was relatively small. Hughes and Edwards (1978) was about 0.3 square miles and Ketcheson and Froehlich (1978) covered about 2.8 square miles (this study covered 52 mi^2). These studies made no attempt to correlate landslide detection using aerial photos with their ground-based methods. Since most of the existing landslide inventories are based on aerial photographs, land managers have used these to develop forest management policies. This section provides the most exhaustive comparison of aerial and ground based landslide inventories conducted to date.

Topographic maps, and digital elevation models (DEMs) based on topographic maps are commonly used to idetnify landslide prone locations. Maps and DEMs can be used in the office, and enable rapid assessments over large areas. DEMs are also used to run landslide hazard models that enable assessment across landscapes (Montgomery and Dietrich, 1994).

The data collected during this study was used to evaluate the effectiveness of both aerial photographs and DEMs for finding landslides and landslide prone locations. These results are intended to provide land managers with information on the reliability of aerial photo inventories and DEMs. This reliability information is important when considering the results and conclusions of aerial photo based landslide inventories. It is also of critical importance when considering different options for identifying areas and sites prone to landslides.

Specifically, the following questions are addressed in this section:

- How well does air photo analysis detect landslides?
- Is there a threshold of landslide size when air photo detection is assured?
- How well do digital elevation models identify slope steepness and landforms?

AIR PHOTO LANDSLIDE DETECTION COMPARED TO GROUND BASED SAMPLING

Air photo inventories can include the initial landslide, the pre-channelized debris flow, and sometimes the channelized debris torrent in volume or area calculations. Unless otherwise noted ‘landslide’ characteristics discussed in this section will include both the initial landslide combined with the associated pre-channelized debris flow.

Air photos were obtained at 1:6,000 scale for the six February storm study areas (Mapleton, Tillamook, Vida, Dallas, Estacada, and Vernonia). Of these study areas, the Mapleton and Vida study areas had numerous landslides in stands with variable age classes that allowed for an evaluation of how well air photo analysis detected landslides under various stand ages and tree heights surrounding the landslides. It was not possible to make stand-age comparisons for the Tillamook study area, as it consisted almost entirely of forest stands between the age of 31 and 100 years.

The Mapleton study area had an independent air photo analysis conducted at 1:24,000 scale (Bush et al., 1997). The Tillamook study area had additional air photos available at 1:12,000 scale taken during the summer of 1996. These different photo coverages allowed a comparison of how effective air photo inventories are at detecting landslides at various scales and across different forest stand ages.

Table 4. Non-road associated landslides and erosion volumes for ground-based samples versus air-photo analysis under various scales.

	Landslides Observed (#)				*Landslide Erosion Volume (cubic yards)*			
Type of Survey Method	Age Class				Age Class			
	0-9	10-30	31-100	100+	0-9	10-30	31-100	100+
Mapleton								
Ground-based	29	2	7	38	3788	20	2373	5232
Air-Photo 6k	17	0	2	2	3083	0	2296	1308
Air-Photo 24k	7	0	2	1	2819	0	2296	1090
Vida								
Ground-based	16	5	5	25	4943	3936	941	4548
Air-photo 6k	8	4	0	0	3595	3092	0	0
Tillamook								
Ground-based	ND	4	49	ND	ND	ND	39,045	ND
Air-photo 6k	ND	ND	12	ND	ND	ND	28,661	ND
Air-photo 12k	ND	ND	1	ND	ND	ND	15,471	ND

Note: The erosion volumes for all survey methods were determined from on-the-ground measurements and include both the initial landslide and pre-channelized debris flow volume. “ND” refers to no data, since these age classes were not represented in the Tillamook study area, except for 54 acres of 25 year-old forest where 4 landslides occurred. These were combined with the ‘31-100’age class for the analyses herein.

Air-photo surveys detected a greater percentage of landslides in recently clearcut stands versus uncut or mature stands as compared to the ground survey results for the same age class (Table 4). For example, at Mapleton, 59% (17 of 29) of landslides observed on the ground were visible in air photos at 1:6,000 scale for forest stands clearcut within the last nine years. However, for landslides found in stands over 100 years old, only 5% (2 of 38) of landslides observed on the ground are visible in the 1:6,000 scale photos. The results for erosion volume are similar. For stands clearcut harvested within the last nine years the percent erosion volume from landslides visible in 1:6,000 photos was 81% (3083 of 3788 yd^3) of the erosion volume measured on the ground at Mapleton. In mature stands older than 100 years the percent erosion volume from landslides visible in 1:6,000 photos dropped to 25% (1038 out of 5232 yd^3) of the erosion volume measured on the ground. The results for the Vida study area showed an even greater discrepancy between the air-based and ground-based methods. In Vida, only 50% (8 of 16) of the landslides observed on the ground in the youngest age class were detected and none of the 25 landslides in the oldest age class were detected using 1:6000 scale air photos. In terms of erosion, 72% (3595 of 4943 yd^3) of the volume observed on the ground in the youngest age class was detected and none of the volume (0 of 4548 yd^3) was detected using 1:6000 scale air photos.

In most cases 1:6,000 air photo analysis detects more landslides than analyses using 1:12,000 or 1:24,000 scale air photos (Table 4). For example, at Mapleton the 1:6,000 scale analysis detected 59% of the landslides in areas recently clearcut, but the 1:24,000 scale analysis only detected 24%. At Tillamook only one landslide could be detected with air photo analysis at 1:12,000 scale, while 13 were detected at 1:6,000 scale. For erosion volume, 73% of the ground-measured volume was detected with 1:6,000 scale photos at Tillamook for stands aged from 31-100 years old, while only 40% was detected with 1:12,000 scale air photos.

This bias towards detecting a greater percentage of the landslides and erosion volume in younger versus older forests when using air photos will significantly affect landslide density (number per unit area) and erosion (volume per unit area) calculations. Table 5 presents the different landslide density and erosion calculations that will result using different inventory methods and various aerial photograph scales for the Mapleton, Vida, and Tillamook study areas. It is evident that results can vary significantly depending on which method is chosen. For example, using 1:24,000 air photos in Mapleton to calculate the landslide density in 100+ year-old forests will result in 0.3 landslides per square mile. Using the ground-based methods results in 11.2 landslides per square mile – a 37-fold differences in density. The 1:6,000 scale increases the density calculation for this age class to 0.6 landslides per square mile, but this is still almost a 19-fold difference as compared to the ground-based results. Differences in erosion volume (volume per square mile) are less but still significant (Table 5). For example, for the 100+ year age class in Mapleton the 1:24,000 and 1:6,000 scale air photos will detect an erosion rate of 0.5 and 0.6 yd^3, respectively. The ground-based method calculates an erosion volume of 2.4 yd^3 – a five-and four-fold difference in erosion from the 1:24,000 and 1:6,000 scale air photos, respectively.

Table 5. Non-road associated landslide densities and erosion volumes per acre for ground-based samples versus air-photo analysis under various scales.

Type of Survey Method	*Landslide Density (#/square mile)* Age Class 0-9	10-30	31-100	100+	*Landslide Erosion (cubic yards/acre)* Age Class 0-9	10-30	31-100	100+
Mapleton								
Ground-based	21.1	1.9	2.8	11.2	4.3	0.03	1.50	2.4
Air-Photo 6k	12.4	0.0	0.8	0.6	3.5	0.00	1.45	0.6
Air-Photo 24k	5.1	0.0	0.8	0.3	3.2	0.00	1.45	0.5
Vida								
Ground-based	13.7	3.3	3.4	8.4	6.6	4.0	1.0	2.4
Air-photo 6k	6.8	2.6	0.0	0.0	4.8	3.1	0.0	0.0
Tillamook								
Ground-based	ND	ND	11.8	ND	ND	ND	13.6	ND
Air-photo 6k	ND	ND	2.7	ND	ND	ND	10.0	ND
Air-photo 12k	ND	ND	0.2	ND	ND	ND	5.4	ND

Note :The erosion volumes for all survey methods were determined from on-the-ground measurements of landslide volume. "ND" refers to no data. These age classes were not represented in the Tillamook study area, except for 54 acres of 25 year-old forest where 4 landslides occurred. These were combined with the '31-100' age class for the analyses herein.

The difference in level of detection between the 1:6,000 and 1:24,000 air photos may be explained in part by the time of year in which the photos were taken. The 1:6,000 photos were taken in the middle of the summer when the sun angle is relatively high and the shadows are minimal. The 1:24,000 photos, on the other hand, were taken soon after the February storm in the spring when the sun angle was still relatively low. Longer shadows could have been a factor in obscuring some landslides that may have been visible had the 1:24,000 photos been taken at a different time of the year. In the summer, however, deciduous trees had a chance to green up and possible re-vegetation of landslide impacted areas became a factor as well. The potential loss in landslide detection due to these factors may counteract any potential gains in detection achieved by reducing the influence of shadows.

This bias towards detecting more landslides within younger forest stands using air photos significantly affects the ratio of landslide densities and erosion volume per acre for recently clearcut stands compared to mature stands. For instance, at the Mapleton study area, if one were comparing landslide density using 1:6,000 air photo analysis the ratio of landslides in the clearcut stands versus those in mature forest stands is about 21:1 (Table 6). For the ground-based sample, that ratio is about 2:1. For 1:24,000 scale air photo analysis, the clearcut to mature forests ratio of landslide density is 17:1. Bush et al. (1997) recalculated the relative landslide density including only those landslides detected that were greater than 0.5 acres. This resulted in a ratio of 2.6:1 (landslides per acre in forests < 20 years compared to forests > 20 years), which is much closer to the ratio reported using the ground-based survey. However, including only those landslides greater than 0.5 acres excludes 98% of the landslides that occurred in the Mapleton study area.

Table 6. Ratios of non-road associated landslide density and erosion volume of younger stand age classes as compared to those from stands that are 100 years and older for the Mapleton and Vida study areas.

Ratios compared to 100+ age class								
Type of Survey Method	Landslide Density				Landslide Erosion Volume			
	Age Class				Age Class			
	0-9	10-30	31-100	100+	0-9	10-30	31-100	100+
Mapleton								
Ground-based	1.9	0.2	0.3	1.0	1.8	0.01	0.6	1.0
Air-Photo 6k	20.7	0.0	1.3	1.0	5.8	0.00	2.4	1.0
Air-Photo 24k	17.0	0.0	2.7	1.0	6.4	0.00	2.9	1.0
Vida								
Ground-based	1.6	0.4	0.4	1.0	2.8	1.7	0.4	1.0
Air-photo 6k	Infinity	Infinity	Infinity	1.0	Infinity	Infinity	Infinity	1.0

Note: "Infinity" refers to the fact that the Vida site had no landslides detected using air photos in stands over 100 years old. The division by zero results in infinity for the ratio.

Table 2 (in the introduction) indicates that air photo inventories generally result in greater apparent increases in landslide density and erosion volume associated with stands recently clearcut than do ground–based inventories. Table 7 shows the average and range of landslide densities for the various studies given in Table 2. The average ratio between clearcut and mature landslide densities for air photo inventories is about five-times the average for the ground-based inventories (a 15-fold increase versus a 3-fold increase).

Table 7. Increase in landslide occurrence after clearcutting as reported by studies (from Table 2) using different methods for landslide identification. The "ratio" is defined as the landslide frequency or density (depending on the study) calculated for clearcut areas divided that for areas in mature forests.

Method	Number of Studies	Average Ratio	Maximum Ratio	Minimum Ratio
Air	6	15.8	30	0
Ground	6	3.3	8.0	0.8
Mixed	7	5.4	17.0	1.2
Air/Field Visits	12	9.7	23.5	0
Air/Size	4	7.7	13.5	2.6
All Studies	35	8.6	30	0

While these studies are from a wide range of geographic areas and reflective of various storm types which preclude a direct comparison to this study, the large differences between ground-based and aerial photo based results are similar to the differences in Table 6. When comparing the air photo to the ground-based results in Table 6, an order of magnitude difference is observed in the ratios for the '0-9' age class. The 1:6,000 and 1:24,000 methods result in about a 21 and 17-times increase in landslide occurrence in clearcut verses mature forest respectively, while the ground-based method results in about a 2-times increase. For past landslide studies that depended completely or in part on information acquired from air photos, it is likely that measurement bias had a significant influence on comparisons between landslide density and/or erosion volume per acre between clearcut and mature stands.

The Utility of Minimum Landslide Size Criteria in Reducing Air Photo Detection Bias

A method commonly used to eliminate the bias in detecting landslides under various cover types is a minimum landslide size criterion. The four "Air/Size" studies and a few of the "Mixed Method" approaches attempted to use a minimum size criteria. Figure 3 is a scatter plot of every non-road-related landslide identified on the ground in Mapleton, Vida, and Tillamook and within the area covered by the air photo surveys for forests older than 30 years old. Those landslides that could be seen in the air photos were plotted with an "O" and those that could not be seen were plotted with a "X". Landslides with a total area of less than 210 square feet were not detected with 1:6,000-scale air photos. Landslides were only detected with a high degree of certainty when the total area was 0.27 acres or greater (Figure 3). However, using the minimum size criterion of 0.27 acres would preclude evaluating 137 of the 143 landslides observed on the ground that occurred in forests older than 30 years.

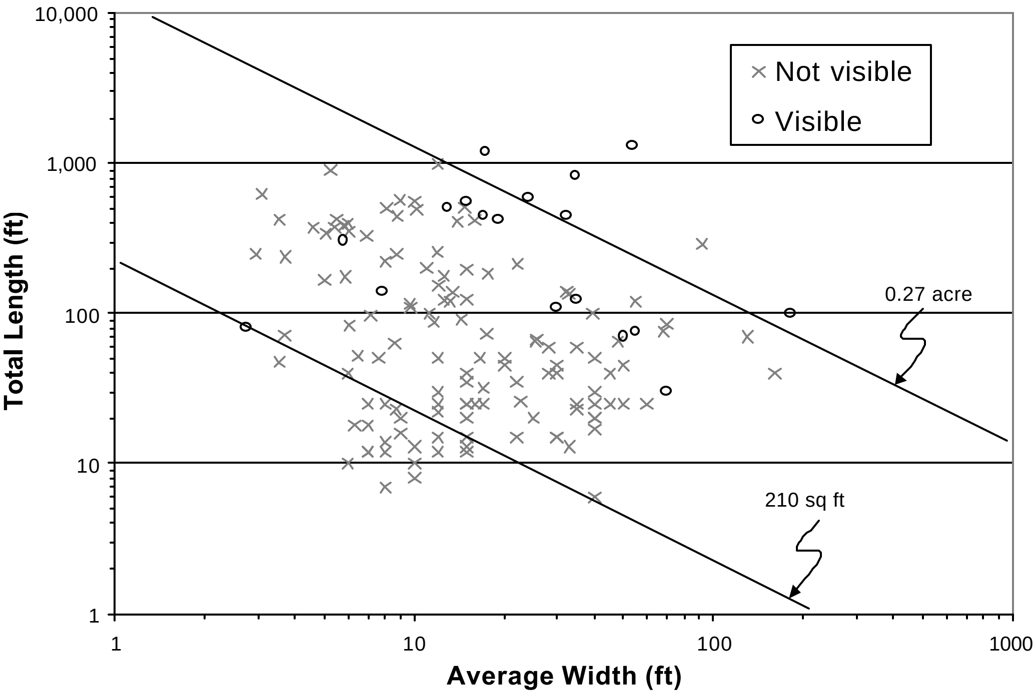


Figure 3. Visibility of non-road-associated landslides (n=143) in 1:6,000 air-photos plotted by total length and width (both initial failure area and debris flow). All non-road-related landslides in Mapleton, Vida, and Tillamook within the area covered by the air photo surveys in 30+ year-old forests are included here.

Figure 4 is a plot of all landslides in Mapleton. For 1:24,000-scale air photo analysis no landslides are detected less than 560 square feet in area, and to achieve a high degree of certainty for detection the landslides must be greater than 0.43 acres. Using this minimum size criterion precludes evaluating 94 of the 96 landslides observed on the ground. If air photos are to be relied on completely for a landslide inventory one is faced with the choice of severely underestimating landslide density verses having a biased sample for comparative purposes because of the inability to see most landslides under forest cover.

For road-associated landslides at the Mapleton and Vida study areas at 1:6,000 scale, it appears that the use of air photos with a minimum size criterion is a more robust tool (Figure 5). All landslides greater than 0.07 acres are visible in photos. Using this minimum size criterion would eliminate just over half of the landslides observed on the ground (21 of 38 total landslides).

It should be re-emphasized that the minimum size criteria presented herein are from ground-based measurements. Landslide length and width dimensions as measured on air photos may be different and in many cases included the area of at least part of the debris torrent (in-channel). Landslide areas determined from air photo analysis at 1:24,000 scale (based on Bush et al., 1997) and ground-based measurements (this study) were compared for the Mapleton study area and the values differed considerably (Figure 6). The following two equations from Figure 6 describe the degree of over-prediction for the area of individual of road and non-road associated landslides that occurred using air photos:

Road related landslides plus debris flow
Air-based area = 4.03 * Ground-based area ($r^2 = 0.92$)
Non-road associated landslides plus debris flow
Air-based area = 1.82 * Ground-based area ($r^2 = 0.90$)

Based on the high r^2 for each equation, and the relatively small amount of scatter, the regression equations could be used to adjust the air-based values determined by Bush et al. (1997). Also, this bias to over-predict should be compensated for when choosing a minimum size criterion such as that laid out in Figures 3-5. For instance, using 1:24,000 air photo analysis, the acreage in which all non-road associated landslides would be detected is 0.43 acres (from ground-based area measurements, Figure 4). Using the above equation, the minimum size criteria would be adjusted to 0.78 acres as measured in the air photos.

These results appear to contradict findings by Pyles and Froehlich (1987) that argue for a tendency to underestimate actual landslide area using air photos. Pyles and Froehlich estimate minimum landslide size from the geometry of the air photos and the topography by computing the forest canopy displacement as a function of ground slope and radial distance from the principle point of the photograph. Using this method they calculate the theoretical canopy displacement for a 0.25-acre (104 ft x 104 ft) landslide in a 160-foot tall stand on 1:24,000 average scale photographs. They conclude that a landslide with an area as large as 3.0 acres on an 80% slope can appear in the air photo as 0.25 acres, depending on where the photo is taken from. It should be noted that the linear relationships presented by Pyles and Froehlich were for square landslides with hillslope contours located normal to a radial line on the air photo. This is why these relationships are relatively simple and only intended to indicate potential bias.

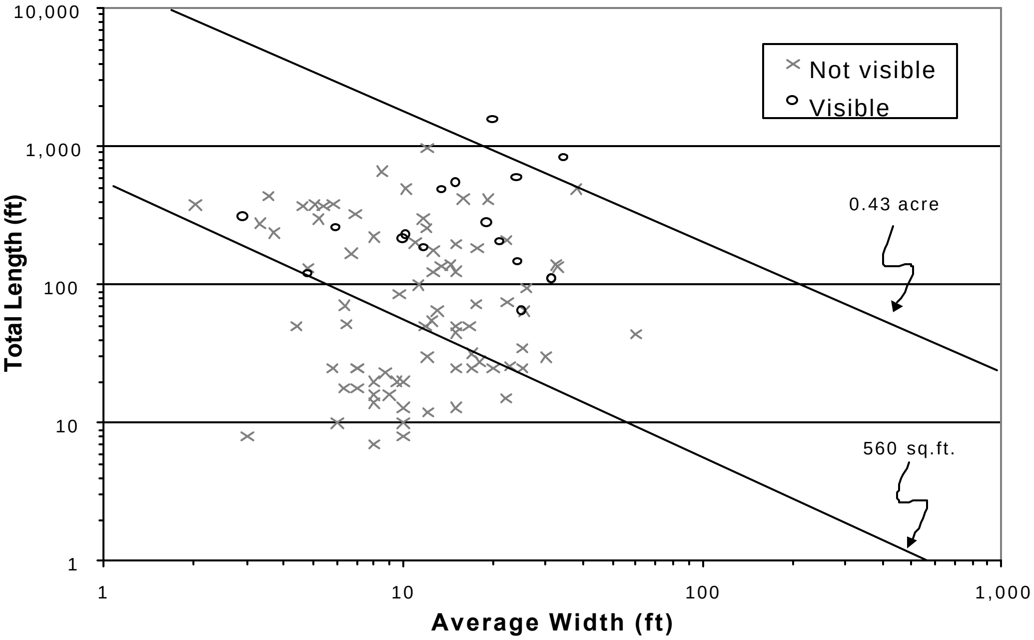


Figure 4. Visibility of non-road-associated landslides (n=96) in 1:24,000 air-photos plotted by total length and width (both initial failure area and pre-channelized debris flow). All non-road-related landslides in Mapleton are included here.

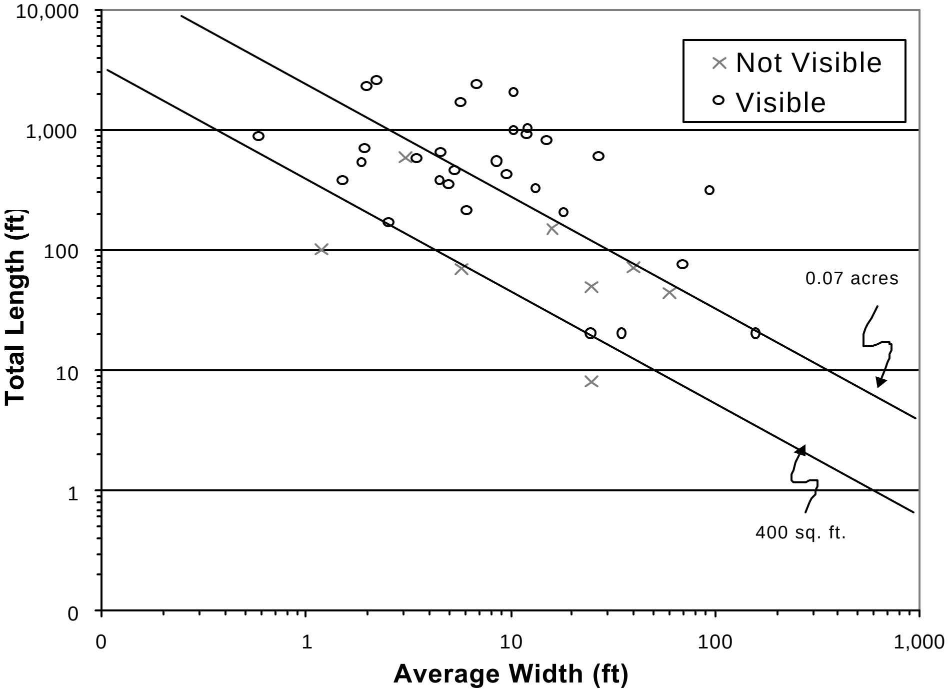


Figure 5. Visibility of road-related landslides (n=38) in 1:6,000 air-photos plotted by total length and width (both initial failure area and pre-channelized debris flow). All road-related landslides in Mapleton, Vida, and Tillamook within the area covered by the air photo surveys are included here.

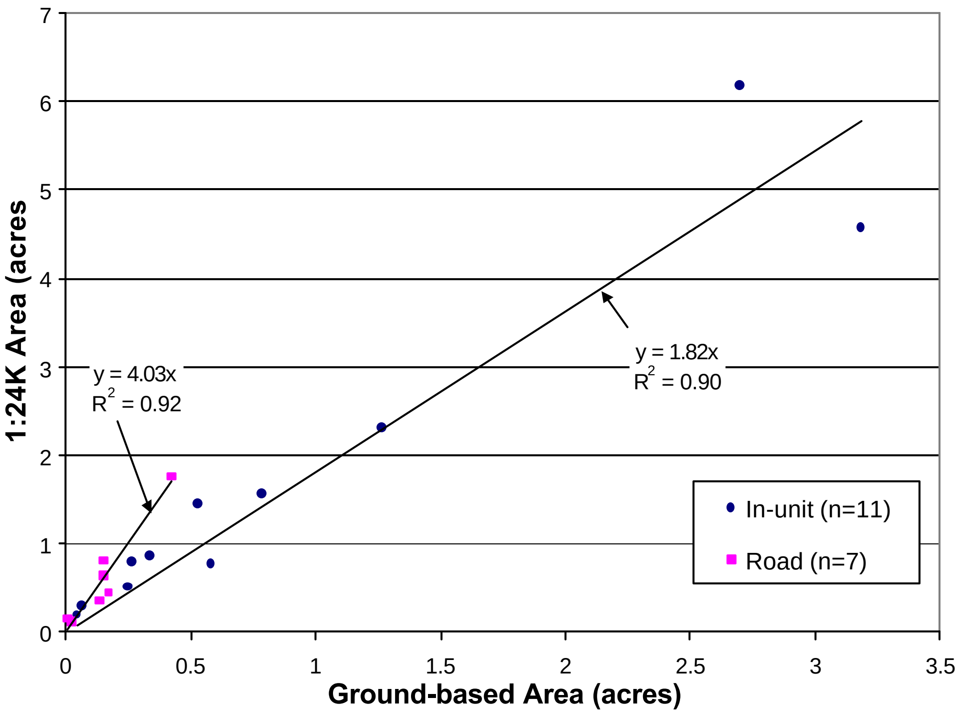


Figure 6. Comparison of landslide areas determined from ground-based measurements versus air photo measurements at 1:24,000 scale. All non-road-related landslides in Mapleton, Vida, and Tillamook within the area covered by the air photo surveys are included here.

The landslide area in the analysis presented in Figure 6 includes the area of the debris flow, and in some cases the channelized debris flow. Debris flows tend to be relatively long features with an impact width that can be difficult to define in an air photo. When measuring the width of a debris flow on the ground it is evident that the width of ground that is exposed (and thus potentially visible in air photos) is greater than the width that is actually impacted by the debris flow. The method used to map the landslides in the 1:24,000 inventory appears to have systematically over predicted the width of these features and mistaken visible ground that was not impacted as an impacted area. Since the debris flow can easily comprise 90% of the total landslide impact area, it would make sense that overestimating this portion of the landslide impacts might cause a significant overestimation of the total impact area.

In the case of Bush et al. (1997), there appears to be a consistent tendency to over-estimate landslide area with the air photo measurement method that was used. Different air-photo analyses methods can have different measurement biases, so unique ground-based to air-based relationships would need to be developed for air photo-based studies on an individual basis. The relationships expressed in Figure 6 should not be used for other air photo analyses that utilize different measurement methods and examine areas outside of the Mapleton study area.

The Influence of Tree Height in Air Photo Landslide Detection

The height of the surrounding trees is a critical factor in understanding potential measurement bias for air photo-based landslide inventories (Pyles and Froehlich 1987).

Pyles and Froehlich express the influence of tree height on landslide detection in air photos as a linear function. The taller the trees, the less of the landslide will be visible in the air photo. For this study, the dominant height of trees surrounding the landslide initiation area was estimated in the field. As tree height increases, there is more difficulty in detecting landslides, especially those landslides encompassing small areas (Figure 7). However, unlike the linear functions given in Pyles and Froehlich (1987), the empirical data indicates a threshold of about 80 feet in height beyond which only one landslide out of a total of 46 could be detected (see Figures 7 and 8). Figure 8 shows that even for the lowest tree heights more than half of the landslides that delivered to channels could not be detected. However, the majority of the landslide-affected area (i.e. the landslide initiation area plus pre-channel debris flow) could be detected in those areas with tree heights up to approximately 60 feet. For tree heights in excess of 100 feet, less than 10% of the landslide-affected area was visible in 1:6000 air photos (Figure 8).

Summary

Although aerial photographs have utility for many purposes, their use for identification of shallow-rapid landslides results in biased and incomplete landslide inventories. This bias significantly underestimates the landslide frequency and erosion volume across all forest stand age classes. For example, in the Mapleton and Vida study areas, 72 percent of all landslides identified from the ground-based survey were not detected using 1:6000 aerial photographs. The majority (72 to 98 percent) of shallow-rapid landslides were not visible on aerial photographs of any scale. In terms of erosion volume, the landslides that were not identified from aerial photographs accounted for 53 percent and 41 percent of the total landslide related sediment volume delivered to stream channels in the Vida and Mapleton study areas (1:6000 scale). Landslide identification is most problematic in areas with mature or semi-mature timber. For instance, roughly 50 percent of the landslides can be detected in recently harvested areas (0-9 years old) but less than 5 percent of the landslides can be detected in mature stands (older than 100 years). Air photo analysis will significantly magnify landslide density and erosion volume per unit area for recently harvested areas relative to older forested areas.

DIGITAL ELEVATION MODELS (DEMS) AND GROUND-SLOPE COMPARISONS

Topographic maps are considered a useful tool to help identify areas on the landscape that may be prone to landslides (Figure 9). Slope steepness, a critical landslide susceptibility parameter, can be easily derived from these maps. Using a geographic information system (GIS), contour maps can be made into a digital elevation model (DEM). DEMs can be developed at various resolutions, depending on the resolution of the original contour information. The resolution most commonly available for DEMs is 30 meters. This means that the smallest unit-area represented by the DEM is 30 by 30 meters, or a little less than one-quarter of an acre. Each unit area, or pixel, is associated with a single elevation value. Using a simple algorithm, slope steepness can be derived for each pixel. These data can then be used to analyze slopes and other landscape characteristics using a GIS.

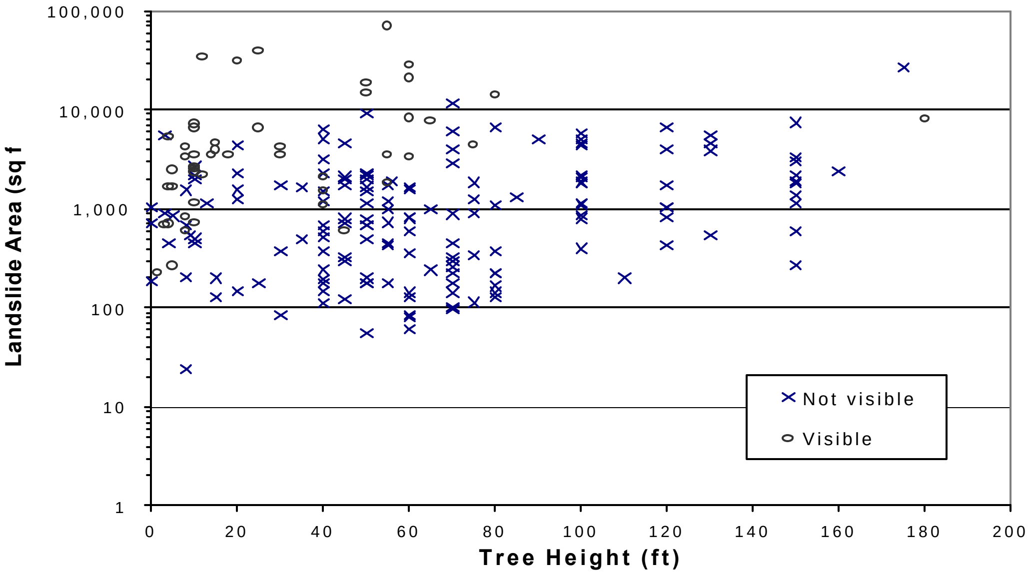


Figure 7. Visibility of non-road-associated landslides in 1:6,000 air-photos plotted by landslide area versus dominant tree height for trees surrounding the landslides. All non-road-related landslides in Mapleton, Vida, and Tillamook within the area covered by the air photo surveys are included here.

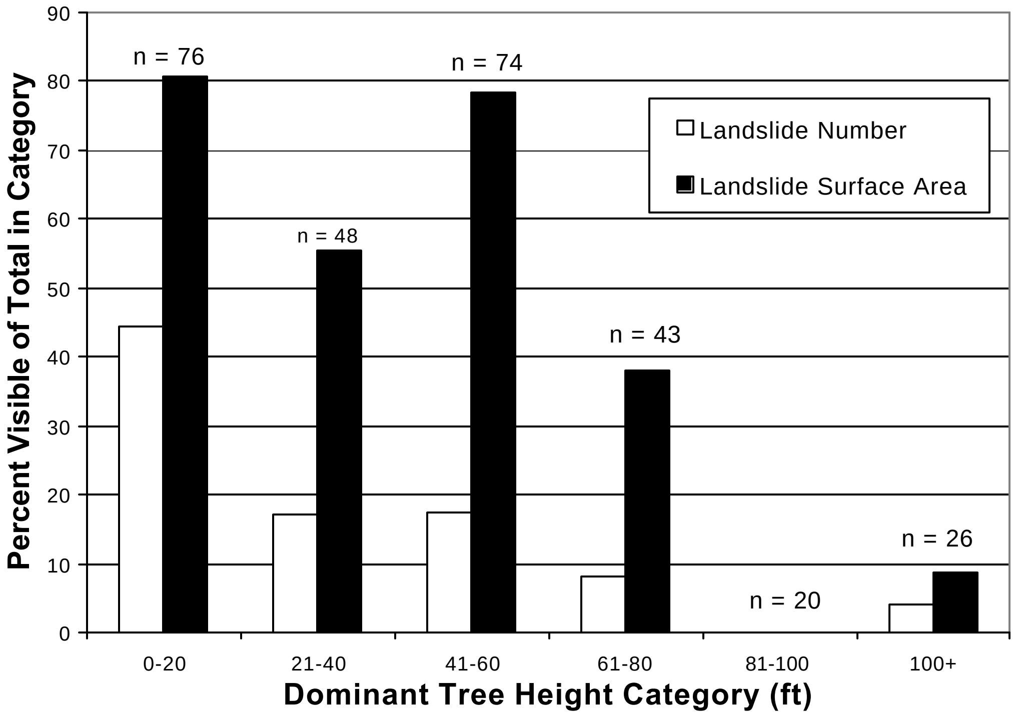


Figure 8. Percent of total landslides and total landslide surface area visible in 1:6,000 air photos relative to ground-based measurements.

The 30-meter DEM coverage is available free of charge from several sources and was originally developed by the United States Geological Survey (USGS). There is currently an effort to create 10-meter DEMs for the entire state of Oregon that should be completed in the near future (they are currently available for only part of the state). For this study, 30-meter DEMs were acquired for all study areas. In addition to this 30-meter data, 10-meter DEMs were acquired for all the February study areas, 6-meter DEMs were acquired for the Elk Creek and a majority of the Scottsburg study areas, and a 1-meter DEM was acquired for a 1.5 square mile area within the Scottsburg study area.

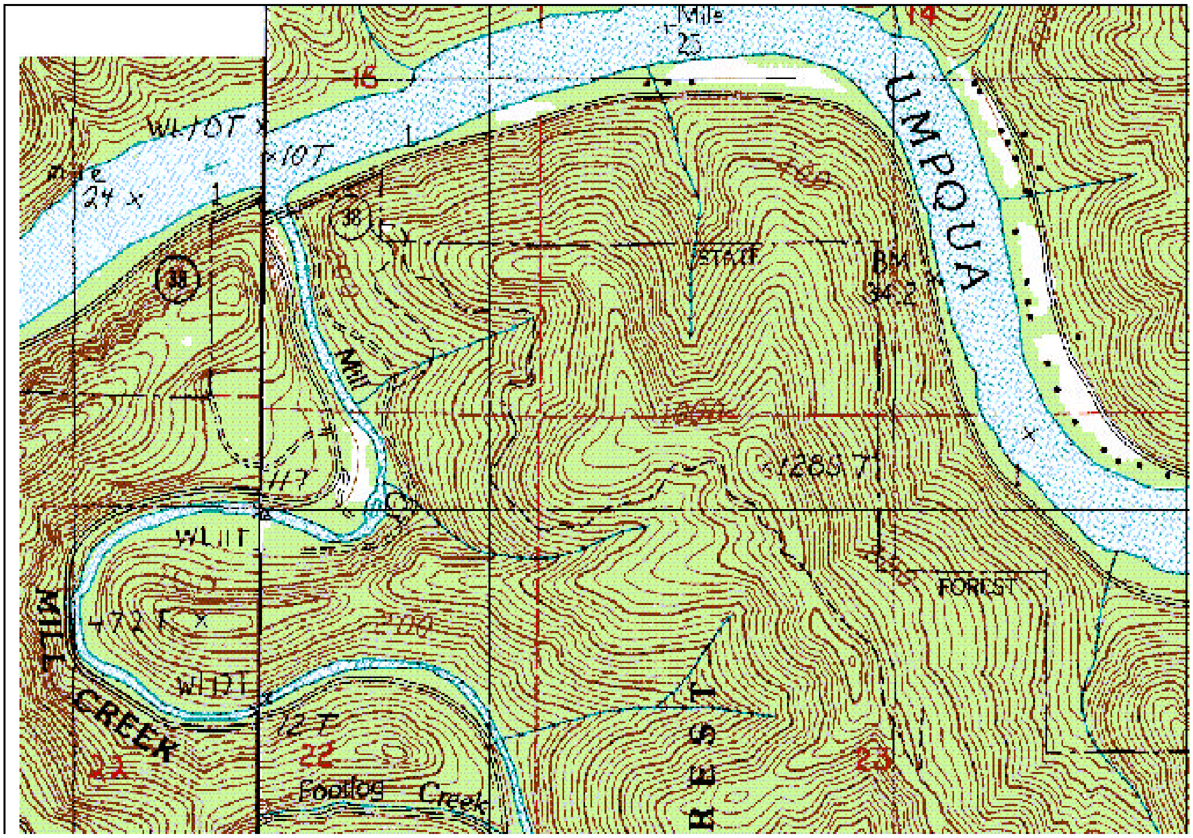


Figure 9. USGS 7.5 minute quadrangle of part of the Scottsburg study area

There are currently several GIS-based models that use DEMs to predict areas prone to failure (for an example see Montgomery and Dietrich, 1994). The Montgomery and Dietrich model assumes steady state precipitation and requires land elevations across the landscape to generate slope steepness and drainage areas above potential landslide sites. Landslide hazard is then determined based on water input (precipitation) needed to initiate a landslide. ODF is currently preparing a debris flow hazard map coverage of western Oregon that is based in part on slope steepness. While other factors besides slope steepness are used in both the ODF hazard mapping and in predictive models, slope steepness for both methods is often based all or in part on information from DEMs. The ODF maps are intended as a screening tool, not as a means to identify specific landslide prone locations.

Any slope information derived from a DEM is going to represent a generalization of the actual slope on the ground. A 10-meter DEM, for example, represents a 1076 square-foot area (10m^2) with only a single value. The actual slope for an area of this size may vary greatly depending on where the measurement is taken and the variable of the local terrain. A single slope value as represented by a single pixel of a DEM is an average of a potentially wide range of values that occur on the actual piece of ground represented by that pixel. The accuracy of this average value must be assessed if land managers are going to rely on GIS models to predict landslide-prone areas. Using the hundreds of ground-based measurements of slope steepness at landslide sites and the various resolutions of DEMs, this study examines how well DEMs represent slope steepness at both the site and area level.

At the site level, slope measurements were made in the field using a clinometer. Slope was measured above and below each landslide as well as systematically along the stream channel. For results reported here, only the measurement below the landslide was used and it was compared with the slope attained from the 30-meter DEM for the same location. For the November study areas, a hand-held global positioning system (GPS) device was used to map the landslides in the field. About half of the total landslides inventoried were mapped with an accuracy of plus-or-minus five meters. Problems with satellites not being within range prevented the other half of the population from being mapped with the GPS. For these georeferenced landslides, the results of this analysis indicate that the ground-slope measurements do not correlate to determinations of slope steepness from the 30-meter DEM (Figure 10). The same analysis was done using the 6-meter and 1-meter DEM and they showed very poor correlation to the ground-measured slope as well (not shown here).

The poor correlation between the 30-meter DEMs and ground-slope measurements is most likely due to the high degree of variability at a site-specific scale. A 30m^2 area represents just under a quarter-acre. Ground-slope measurements can often vary widely over a quarter-acre, especially in steeper forested terrain that is characteristic of the red zone study areas.

The poor correlation between the 6-meter DEMs and ground-slope measurements is likely due to at least two separate factors. One is the high degree of variability at a site-specific scale discussed above in the 30m comparison. Ground-slope measurements over an area of 1,076 square feet (10m^2) can also vary widely depending on the terrain. The second factor has to do with the method and accuracy in the derivation of the 6-meter DEM itself. The contour map used to derive this DEM was created from a mapping technique that acquired elevation data exclusively from valley bottoms and ridge tops. Contour lines were then drawn by ‘connecting the dots’ between these two locations. As a result, the contours across a given hillslope represent an average value based on the elevation points on the valley and ridge. This method is somewhat different than the typical USGS method that attempts to distribute the elevation points evenly across the landscape. The detail that might be provided by a 10m DEM using the more typical method may have been lost due to this ridge top and valley bottom ‘averaging’ method.

The factors responsible for the poor correlation between the 1-meter DEMs and ground-slope measurements are uncertain, but there are at least two explanations. The first has to do with the possible errors caused by the method used to create the DEM. A relatively new and somewhat experimental technique called laser altimetry was used that can detect changes in elevation as fine as one meter. This method, however, has a range of variability that can be as great as 10 or more meters. On average the DEM resolution using this technique can be as much as four meters (William E. Dietrich, pers. comm.). If a four-meter DEM had been built using the laser altimetry data instead of a 1-meter DEM, there might have been better correlation with the ground-based measurements. The second possible explanation has to do with the ground-slope measurements being of a lower resolution than the DEM. The 'slope below' measurement for each landslide was taken over a distance equal to the length of the landslide. The majority of time this distance was significantly greater than one meter, and sometimes tens of meters long. Slope values derived from a DEM that detects changes in elevation down to a 1-meter resolution may be detecting a slope at a specific point in the landslide that is different than the average slope over the length of the landslide.

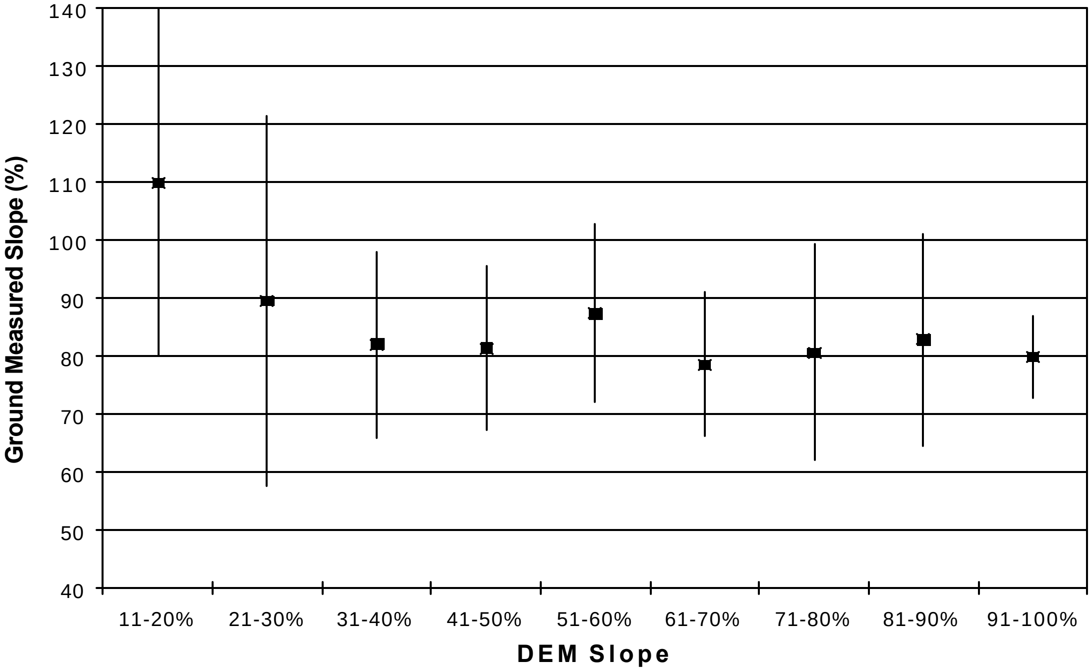


Figure 10. Slope measurements at landslide locations mapped with a GPS compared to slope measurements from the 30-meter digital elevation model (DEM). The box represents the average of the ground-slope measurements for all landslides corresponding to the DEM slope range. The bars represent plus or minus one standard deviation.

Despite the potential problems that can result in trying to use the 6 and 1-meter DEMs to predict site-specific slopes, contour maps at these finer resolutions should be able to detect significant micro-site variations that go undetected using 30-meter DEMs. A comparison of the 30-meter DEM generated contour maps (Figure 11) to those generated with 6-meter and 1-meter DEMs (Figures 12 and 13), indicates that micro-site variations in slope steepness are not accurately represented by a 30-meter DEM. For example, Figure 13, and to lesser extent Figure 12, are detailed enough to detect road and headwall topographic features. Figure 11 cannot detect either of these and portrays mostly a uniform slope. These micro-site variations are extremely important in terms of landslide-hazard assessments.

DEMs can also be used to determine the general distribution of slopes across broad areas (100s of acres). This type of information is useful to land managers who may want to conduct landslide-risk assessments for broad areas of land based on some combination of attributes that include ground slope. It would be useful, therefore, to compare the various resolutions of DEMs to determine if any significant differences exist in terms of the percent area of land represented by different slope classes. The 30-meter DEM was compared with the 6-meter and 1-meter DEM (Figure 14). Assuming that the 1-meter DEM is the most accurate portrayal of slope steepness on an area basis, Figure 14 indicates that 30-meter DEMs have a tendency to under-represent slope steepness across the landscape. The 30-meter DEM shows 50% of the area with slopes less than 50%, while the 1-meter DEM shows only 28% of the area in this slope class. Only 18% of the area has slopes greater than 70% using the 30-meter DEM, while the 1-meter DEM shows about 56% of the area in this slope class. The distribution of slope class for the 6-meter DEM is similar to that of the 1-meter DEM.

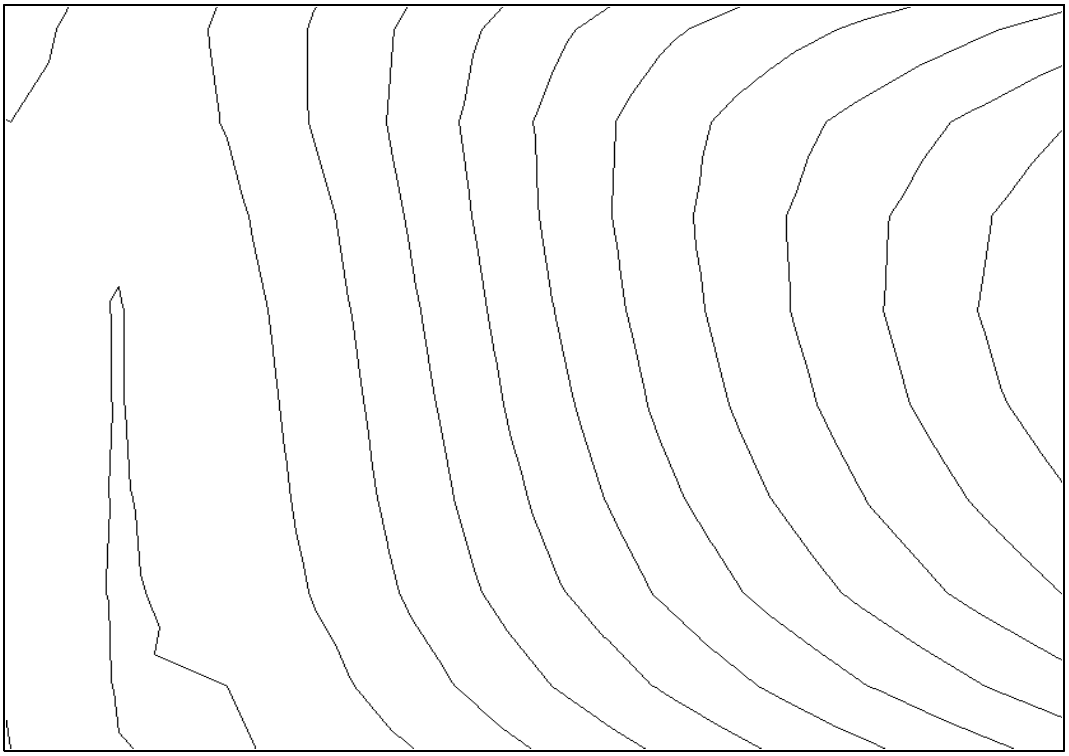


Figure 11. A portion of a USGS 7.5-minute quadrangle map of the Scottsburg study area. Contour intervals are 40 feet. This area is identical to that in Figure 12 & 13 (1 inch = 190 feet).

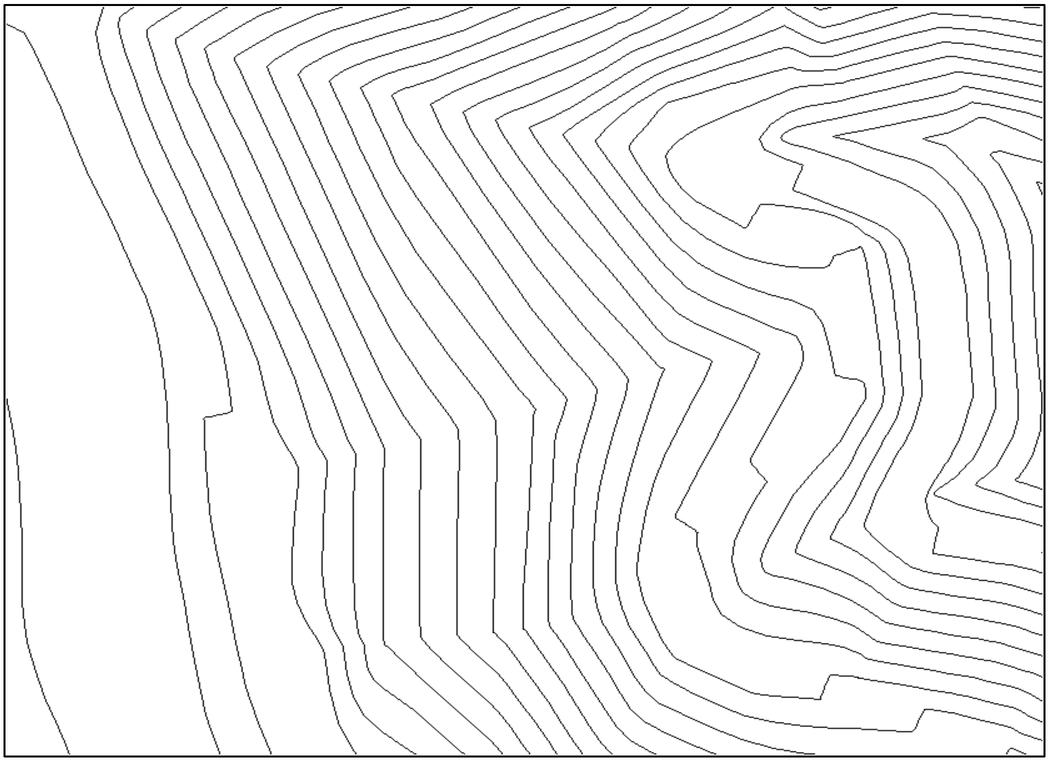


Figure 12. A portion of a 20-foot contour interval map of the Scottsburg study area developed from a 6-meter digital elevation model (DEM). This area is identical to that in Figure 11 & 13 (1 inch = 190 feet).

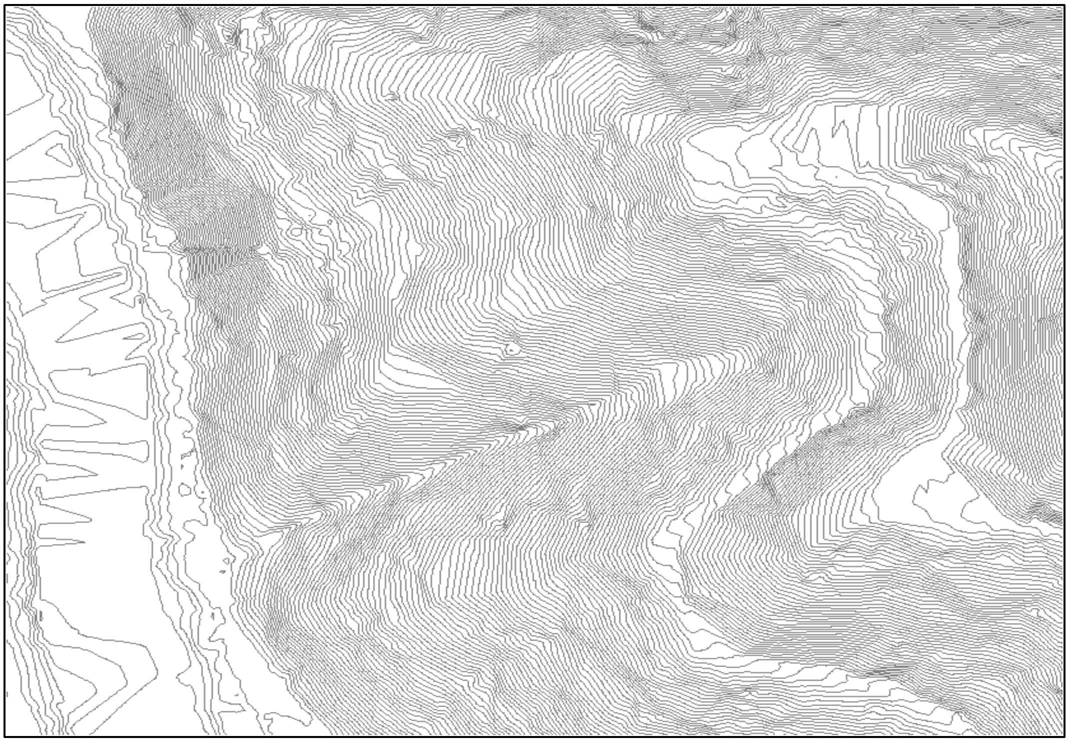


Figure 13. A portion of a one-meter contour interval map of the Scottsburg study area developed from a one-meter digital elevation model (DEM). This area is identical to that in Figure 11 & 12 (1 inch = 190 feet).

Based on the results given above, a 30-meter DEM based on USGS quadrangles will seriously underestimate slope steepness across the landscape. The 30-meter scale does not indicate the micro-site variability in slope steepness that can influence landslide susceptibility. DEMs with a higher resolution should provide more reliable slope steepness information, but even their effectiveness in providing accurate site-specific values is uncertain based on this analysis.

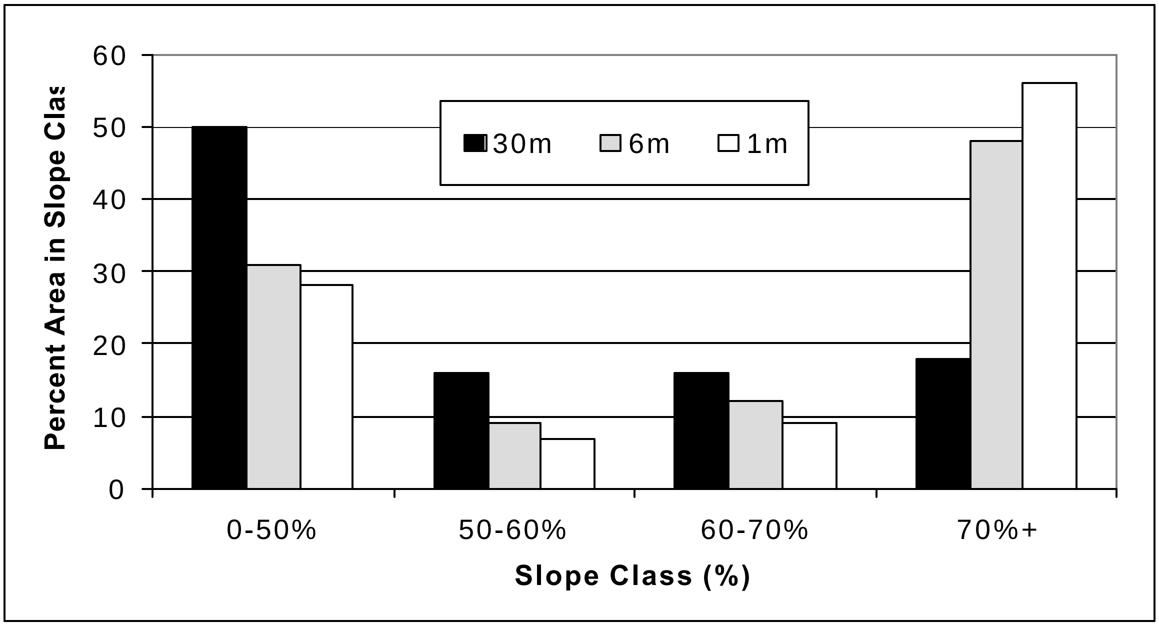


Figure 14. Percent of area in various slope classes for 1, 6, and 30-meter DEMs for a 1000-acre area within the Scottsburg study area.

Summary

Digital elevation models (DEMs) at various resolutions were evaluated for their usefulness in identifying areas and sites susceptible to landslides. DEMs developed from topographic maps and other sources are commonly used to derive slope steepness measurements instead of using on-the-ground measurements. Slope data collected at the site of each landslide were compared with those derived from a commonly available 30 meter DEM, and also with less commonly available 6 and 1-meter DEMs. On a site-specific basis, slope measurements from 30-meter DEMs were poorly correlated to site-specific slopes at landslide locations measured in the field. DEMs with a higher resolution might better correlate to site-specific slopes, but even their effectiveness in providing accurate values could not be confirmed in this analysis. On an area basis, the 30-meter DEM under-represents the steepness of very steep slopes (>70%), and over represents moderate slopes (< 50%) over broad areas (hundreds of acres) as compared to the 6 and 1-meter DEMs.

RESULTS SECTION TWO: LANDSLIDES AND FOREST MANAGEMENT EFFECTS

This section of the report provides information on a number of important questions about landslides in western Oregon forests. It also provides information about the association between these landslides and forest management practices (both logging and the growth of forests). Specifically, the following questions are addressed in this section:

- How extensively did landslides occur in the forests of western Oregon in 1996?
- How many of these landslides were associated with forest roads?
- How big were these landslides?
- What locations were most prone to landslides?
- How many landslides occurred on high risk sites?
- How is landslide occurrence affected by timber harvesting and forest re-growth?
- Are landslides in recent clearcuts larger or smaller than landslides in older forests?
- Are most landslides associated with physical disturbance of the ground?
- Did landowners and loggers comply with the forest practice rules designed for landslide prevention in the locations adjacent to landslides?
- How does the landslide occurrence from the storms of 1996 compare to other landscape level disturbances?

This section provides information about both the initiating landslides and, where present, subsequent debris flows. Field survey after the landslide requires some reconstruction of conditions prior to the landslide, including some estimations of parameters impacted by landslide movement. Estimations of the accuracy of reported measurements and calculations are therefore presented as applicable throughout these discussions.

LANDSLIDE OCCURRENCE IN THE STUDY AREAS

Where landslides occur is important for many reasons. Land managers need to know where the most hazardous locations are so that appropriate land management practices may be applied. They also need to know if landslides are occurring in areas where they are not expected, and if there are other areas that they do not need to be greatly concerned with. This information is also of great importance to the general public, especially those who might be in landslide prone locations during the next major storm. In the same light, governmental agencies need to know these locations so that public safety and natural resource protection issues can better be addressed. Therefore, an overview of the landslides found during this study is presented in this section.

There were 506 landslides which entered stream channels in the “core areas” of the eight study areas (Table 8). “Core areas” are lands where all channels were surveyed for landslides. The total “core area” surveyed was 45.8 square miles. The Elk Creek study area had the greatest number of these landslides (159) while only two landslides were found in the core area of the Estacada study area.

Table 8. General summary of landslides for core area portions of the eight study areas (core study area refers to that subset of each study area surveyed in which all stream channels were systematically checked for delivering landslides).

	Red zone Study Areas					**Random Study Areas**			
	Elk	Scottsburg	Mapleton	Tillamook	Vida	Vernonia	Dallas	Estacada	All
Core-study area (sq/mile)	6.5	7.2	8.3	4.5	7.1	3.4	3.1	5.5	45.8
Landslides									
Active Road	2	5	13	7	6	2	2	0	37
Old Road	5	6	1	5	0	1	2	0	20
Non-road	152	78	92	50	53	16	6	2	449
Total	159	89	106	62	59	19	10	2	506
Landslide Erosion									
Active Road (yd^3)	1261	11544	4243	31603	14892	1240	167	0	64951
Old Road (yd^3)	2434	7654	191	8877	0	25	35501	0	54683
Non-road (yd^3)	49898	43628	17442	34014	14357	868	8516	20	168743
Total (yd^3)	53593	62826	21876	74495	29249	2133	44184	20	288376
Landslide Densities									
Total Slides (per sq. mi.)	24.4	12.3	12.8	13.8	8.3	5.5	3.2	0.4	11.1
#Non-road slides (per sq.mi.)	23.3	10.8	11.1	11.1	7.4	4.7	1.9	0.4	9.8
Landslide Erosion Rate									
Non-road slides (yd^3/ac)	12.0	9.5	3.3	11.8	3.1	0.4	4.2	0.01	5.8
All slides (yd^3/ac)	12.8	13.6	4.1	25.9	6.4	1.0	22.0	0.01	9.9

Table 9. Landslides identified outside of the core study areas. Streams were not systematically surveyed for landslides in these areas. This table shows only those landslides that directly influenced channels in the core areas.

Landslide Category	**Redzone Study Areas**					**Random Study Areas**			**Total**
	Elk	Scottsburg	Mapleton	Tillamook	Vida	Vernonia	Dallas	Estacada	All Sites
	Channel Delivering Landslides								
Active Road	NA	NA	0	3	18	0	0	NA	21
Old Road	NA	NA	0	2	1	1	0	NA	4
Non-road	NA	NA	3	5	14	0	5	NA	27
Total	NA	NA	3	10	33	1	5	NA	52

Of these 506 landslides, 37 were associated with active roads, 20 were associated with old roads, and 449 were not associated with roads. "Active" roads are being maintained in a driveable condition (as per the forest practice rules). "Old" roads are abandoned or not maintained, and are often unrecognizable as roads without on-site inspection. The road-associated landslides section of this report discusses landslides from forest roads in much more detail. This survey, as is the case with all landslide surveys, did not determine specific "causes" of any landslides. Without detailed geotechnical monitoring of these sites prior to and after the landslides, it is not possible to determine a true cause and effect relationship. However, through statistical analysis it may be possible to infer such relationships. It is likely that some of the landslides that were associated with roads (by proximity) were not actually caused by those roads.

Landslide density is summarized as the number of landslides entering stream channels per each square mile of study area. Landslide density reflects only those landslides which occurred in a single, very large storm event. Therefore, density cannot reasonably be correlated with landslide frequency (or the number of landslides per unit area occurring over a given time period).

In this study, the Elk Creek study area had the greatest total landslide density (24.4 landslides per square mile and Estacada had the lowest density (0.4 landslides per square mile) (Table 8). The five red zone study areas had non-road associated landslide densities between 7.4 and 23.3 landslides per square mile. These red zones include the Tillamook, Vida, Mapleton, and Scottsburg and Elk Creek study areas. The other three study areas (selected using a stratified random sample) had non-road associated landslide densities of 0.4 to 4.7 landslides per square mile. The five red zone study areas had greater overall landslide densities than did the three non red zone study areas. This was expected, as the red zone study areas were selected because a high number of landslides and debris flows had been observed in these areas. However, a comparison of the Elk Creek and Scottsburg study areas show a great difference in landslide density, despite the fact that they were both affected by the November storm, are in the same geologic unit, and are separated by a distance of just 10 to 15 miles.

The stratified random selected study areas experienced few landslides, even though they were are all within the area affected by the February 1996 storm. (The Dallas study area includes the weather station that reported the highest rainfall in Oregon during this storm.) These non red zone study areas are more representative of how the majority of western forestlands responded to the February storm event. On the other hand, the red zone study areas reflect the most extreme effects from the storms of 1996.

Landslide Erosion

Since protection of water quality is a major function of the forest practice rules, this study focused on landslides which entered stream channels. For the purposes of this study, landslide erosion is the volume of sediment (soil and rock) that entered stream channels. Potential water quality and fish habitat impacts of landslides include: sedimentation, turbidity problems and physical stream scour related to debris flows and torrents. In general, the greater the volume of sediment delivered to stream channels, the greater the potential for detrimental sediment impacts.

Total landslide erosion (initial landslide plus non-channelized debris flow) was 288,376 cubic yards for the eight study areas, as shown in Table 8. For the 45.8 square mile study area, this is an average storm erosion of 6,290 cubic yards of sediment per square mile, or 9.9 cubic yards per acre. Note that this is an average for these study areas only, and is not an average for western Oregon. Fifty-eight percent of the sediment volume delivered to stream channels was from non-road associated landslides, nineteen percent came from landslides associated with old roads, and twenty-three percent from landslides associated with active roads.

The Elk Creek and Tillamook study areas had the highest non-road associated landslide erosion volumes (including non-channelized debris flows), 12.0 and 11.8 cubic yards per acre, respectively (Table 8). Although the two erosion volumes are approximately equal, the Elk Creek study area had a much higher landslide density (23.3 versus 11.1 landslides per square mile). Interestingly, the Dallas study area (non-red zone) had a higher non-road erosion volume (4.2 cubic yards per acre) than did the Mapleton (3.3 cubic yards per acre) or Vida (3.1 cubic yards per acre) red zone study areas. In terms of total landslide erosion volumes (non-road, active road and old road combined), the Tillamook study area (25.9 cubic yards per acre) was greatest followed by Dallas at 22.0 cubic yards per acre.

The high landslide erosion in Dallas is due to a few very large landslides, one of which moved 32,000 cubic yards (more than ten percent of the total study landslide volume). Very large landslides, though relatively rare, can completely skew comparisons of landslide erosion volume. The other stratified random study areas had much lower erosion volumes (0.01 cubic yards per acre for Estacada, and 1.0 cubic yards per acre for Vernonia). Landslide erosion volume (calculated using the entire landslide and non-channelized debris flow) for the non-road related landslides was 5.8 cubic yards per acre (over all eight study areas). This erosion volume is for a very large storm event and thus cannot be used to determine a yearly erosion rate.

During the first year of this study, it became apparent that surveys within the rectangular 10 square mile survey areas would not always include the landslides and debris flows responsible for the observed channel effects. This was particularly true for the South Fork of Gate Creek in the Vida study area, and to a lesser extent for Rogers Creek in the Tillamook study area. There are also a few off site landslides that affected stream channels in the Mapleton, Vernonia and Dallas study areas. For this reason, surveys outside the original core areas were conducted using sub-basin or watershed boundaries, and a brief summary of the results is shown in Table 9. Fifty-two landslides were identified in the six square miles surveyed outside of core areas. Of particular note are the large number of road-associated landslides in the watershed just outside the Vida study area (18 active and one old road slide). There were only six road-associated landslides observed in the original core survey area. Due to the non-systematic sampling design used outside of core areas, these landslides are not included in the analysis of the road and non-road associated landslides. Specific watershed level effects from these "outside of core area" landslides are discussed in the channel effects chapter.

Non-Road Associated Landslide Characteristics

This section is intended to give the reader information about the typical landslides identified in this study. Landslides are highly variable in size, velocity of movement, and appearance. Landslide depth measurements are accurate to about 0.5 feet. Landslide width and length are accurate to about five feet. No attempt was made to estimate landslide velocity.

The terminology used to describe landslides can be confusing, even to technical specialists that work with landslides. Terminology has been simplified in this section. In addition, some of the landslides surveyed in this study (especially those adjacent to stream channels) were only portions of much larger landslides that extended well up-slope. Nevertheless, the volume reported for these landslides reasonably reflects only those portions of these landslides that entered stream channels. The volume of sediment entering stream channels for all investigated landslides is believed to be accurate to plus or minus 25 percent of the initial landslide volume and plus or minus 50 percent for the debris flow volume.

Non-road associated landslide characteristics are shown in Table 10. The average non-road associated landslide (the initial failure only, and not including subsequent debris flow) was 24 feet wide, 43 feet long, and 2.5 feet deep (with a maximum depth of 4.3 feet). Depth is the vertical distance from the original ground surface to the current ground surface. Most of the landslides were translational, meaning they had a roughly planar, as opposed to rotational shaped failure surface. There tended to be a depression in the center top portion of the slide (near the scarp), thus a maximum depth value was also determined. The area covered by the initial landslide (not including debris flows) was on average 0.023 acres (or 1,000 square feet). Despite their small initial size, some of these landslides resulted in debris flows that traveled rapidly over long distances, affecting slopes well below these landslides and also affecting a significant portion of the channel network.

Initial non-road associated landslide dimensions were highly variable. Landslide widths varied between 2 and 182 feet. Landslide lengths varied from 5 to 184 feet. Volumes of the initial landslides varied from 0.3 to 4,500 cubic yards and total volumes (including debris flows) for these landslides varied from 0.7 to 15,000 cubic yards. The average initial volume of non-road associated landslides was 109 cubic yards, while the average total volume of these landslides (including non-channelized debris flow volume) was 376 cubic yards. Other Oregon studies have found similar sized landslides (although most past studies have not included measurements of debris flow volume). Ketcheson and Froehlich (1978) found an average volume of 41 cubic yards for landslides within forested areas and 47 cubic yards for landslides in clearcuts. Swanson and others (1977) found an average volume of 80 cubic yards for forested landslides and 145 cubic yards for landslides in clearcuts. Both of the studies took place in the Mapleton area. Note that the Swanson study did not include landslides smaller than ten cubic yards. The ODF study had no minimum landslide volume (all landslides were counted, although small areas of stream adjacent scour were not considered landslides).

Between the eight study areas, average initial landslide volumes varied from 5 to 340 cubic yards (Table 10). (For perspective, the average gravel dump truck holds about 10 cubic yards of material.) The extreme cases were both in non red zone study areas (Dallas the largest and Estacada the smallest). Average total landslide volume (including debris flow volume) varied from 10 to 1,419 cubic yards (again with Dallas the largest and Estacada the smallest).

Using landslide and debris flow dimensions, the land area directly impacted by slope movement was calculated. For the eight study areas, initial landslide scars accounted for 0.04 percent of the landscape, while 0.15 percent of the landscape was directly impacted by combined landslides plus debris flows. The study area with greatest impact was Elk Creek, where initial landslide scars covered 0.07 percent of the landscape, and debris flow scars covered 0.32 percent of the landscape. These values do not include landslides that did not enter stream channels. In part, this may explain why they are much lower than the 1 to 2% typically reported for land area affected by landslides from other studies (Ice, 1985). The lower impact area identified by this study may also be related to the fact that these other studies have often attempted to identify and measure landslides over a given time period (Swanson and others, 1977, Ketcheson and Froehlich, 1978). Note also that the percent of channel impacted was far greater than the percent hillslope area impacted (see Results Section 3).

Summary

Landslides were common in “red zones,” areas with steep slopes and apparently affected by higher rainfall. The majority of landslides were not associated with roads. The typical landslide was relatively small. Most of the erosion that entered stream channels was related to debris flows. There are extreme variations in landslide characteristics between study areas. Just a few large landslides in Dallas resulted in a total erosion volume greater than all but one red zone study area. Therefore, caution must be exercised when comparing landslide statistics, especially landslide erosion. Overall, landslide dimensions as identified in this study are similar to those identified in previous studies conducted in the Oregon Coast Range; however, the land area affected by landslides was less than reported in earlier studies.

Table 10. Characteristics of landslides within the core study areas.

	Red zone Study Areas					**Random Study Areas**			**Total**
Landslide Density	Elk	Scottsburg	Mapleton	Tillamook	Vida	Vernonia	Dallas	Estacada	All Sites
# Non-road related Slides	152	78	92	50	53	16	6	2	449
Area surveyed (sq. mi)	6.52	7.21	8.29	4.49	7.14	3.44	3.14	5.49	45.7
#Non-road slides (per sq.mi.)	23.3	10.8	11.1	11.1	7.4	4.7	1.9	0.4	9.8*
Landslide Characteristics									Average
Average Width (ft)	22.3	29.7	15.1	36.4	18.1	23.0	62.0	13.0	24.0
Average Length (ft)	34.6	44.6	24.5	30.6	32.2	24.9	44.2	21.5	43.1
Average Area (acres)	0.020	0.035	0.010	0.046	0.015	0.015	0.076	0.006	0.023
Average Depth (ft)	1.9	3.3	2.1	2.4	2.7	2.1	2.9	0.6	2.5
Maximum Depth (ft)	3.5	5.5	3.6	4.5	4.6	3.9	5.0	2.3	4.3
Landslide Average Volume (yd^3)	58	216	26	274	74	49	340	5	109
Average Total Volume (including debris flow) (yd^3)	328	559	190	680	271	54	1419	10	376
Erosion (yd^3/acre.)	12.0	9.5	3.3	11.8	3.1	0.4	4.2	0.01	5.8

*Average

LANDSLIDE INITIATION SITES

This section provides information on the occurrence of the investigated landslides in relation to hillslope position and other factors. Landscape differences are very important because geologic factors have a large influence on landslide processes. Stream channels also have major influences on landslides, due both to direct undercutting of slopes by stream erosion and also because of longer-term hillslope processes. Channel adjacent landslides may therefore be less influenced by timber harvesting. This section concludes with a discussion about identification of high risk sites, those locations that are provided special practices for landslide mitigation under the Oregon's forest practice rules.

Landscape Characteristics

As measured in this study, slope steepness reflects the original ground slope (plus or minus 2 percent) that existed prior to landslide movement. It was measured by carefully identifying the original ground surface (based on landslide depth measurements, and then recording the average slope over the length of the landslide). This is typically a less steep value than would be made by measuring from above the head scarp to the base of the landslide.

Table 11 segregates landslides by general occurrence into two categories, 1) where they occurred in relation to a channel, and 2) where they occurred by red zone geology. There are three categories for position relative to the stream channel, "up-slope," "channel adjacent" and "gully." "Up-slope" landslides occurred on a hillslope (including a non-channelized hollow) location and had a distinct initiating landslide. "Channel adjacent" landslides occurred next to or very close to a channel (a stream with defined bed and banks, typically with a gradient of under 40 percent) and had little or no debris flow path. Features labeled as "gully" originated in a steep channel or ephemeral drainage on a hillslope, and had no initiating landslide (the debris flow was initiated as a fluvial process). Channel adjacent and gully failures are often related to streamflow erosion and undercutting. Up-slope landslides have been the focus of most previous studies of landslides from forestlands, and were usually classified as debris slides (shallow, translational landslides) with a few slumps and complex landslides.

Three of the study areas (Mapleton, Elk Creek, and Scottsburg) are located in the "Tyee" geologic unit (see Table 3 for more detail on study area geology). Igneous (volcanic) rocks underlie the Tillamook and Vida study areas. The Tyee formation is of sedimentary origin, typically with gently dipping, massive sandstone beds separated by thin beds of mudstone. The Tillamook study area is underlain by thin lava flows, while the Vida study area contains a mixture of tuffaceous and basalt lava flow rock typical of the Western Cascades. The non-red zone study areas contain both igneous and sedimentary rock units.

In the Tyee red zone study areas, 75 percent of the landslides originated as up-slope failures, while in the igneous red zones 50 percent were up-slope and 50 percent were in-channel. In the stratified random study areas, only 25 percent of the landslides originated as up-slope landslides, while 75 percent were channel adjacent. Only three landslides were classified as "gully" origin in the entire study, while 295 were of "up-slope" origin and 151 were channel adjacent (Table 11).

Table 11. Landslide occurrence by origin of occurrence and by study area geology.

Origin	Slides (No.)	Avg. Slope Blw. L.S. (%)	Landslide Characteristics				
			Depth Avg. (ft)	Initial L.S. Avg. Vol. (cu. yd.)	Initial L.S. Med. Vol. (cu. yd.)	Total L.S.* Avg. Vol. (cu. yd.)	Total L.S.* Med. Vol. (cu. yd.)
Red zone Tyee Sandstone Geology Study Areas (Elk Cr., Mapleton Scottsburg)							
Up-slope	239	82	2.5	104	36	446	174
Channel Adj.	82	91	1.9	41	46	55	17
Gully	1	55	0	0	0	4	4
Red zone Igneous Geology Study Areas (Tillamook, Vida)							
Up-slope	50	86	2.9	116	25	702	171
Channel Adj.	51	92	3.2	231	53	253	53
Gully	2	56	0	0	0	163	163
Stratified randomly Selected Study Sites (Dallas, Estacada, Vernonia)							
Up-slope	6	78	2.9	341	82	1434	142
Channel Adj.	18	93	2	44	17	44	17
Gully	0	NA	NA	NA	NA	NA	NA
All Study Sites							
Up-slope	295	83	2.5	111	36	509	171
Channel Adj.	151	92	2.3	105	24	120	25
Gully	3	56	0	0	0	110	61

The channel adjacent landslides occurred on steeper slopes than did the up-slope landslides (92% versus 83% steepness). Steepness is measured as rise (vertical distance) over run (horizontal distance) from the top of the landslide scarp downslope over the "reconstructed" (prior to the landslide) ground surface. Field crews were careful to try to measure slope on the initial landslide surface, based on the landslide depth measurements. Failure to do this can lead to overestimation of the pre-landslide slope steepness (which is a critical parameter for determination of landslide hazard). Note that slope percent and slope degrees are very different. A slope of 100% is equal to 45 degrees. The up-slope landslides originated on average slopes of 82% in the Tyee red zone study areas, 86% on the igneous red zone study areas, and 78% on the non red zone study areas; however, there were only six up-slope landslides in the stratified random study areas. Average slope steepness for the channel adjacent landslides was similar across all study zone types (91% to 93%).

Initial median landslide volumes for the Tyee and igneous study areas are similar (up-slope volume of 36 yards in the Tyee and 25 yards in the igneous, with channel adjacent volume of 46 and 53 cubic yards respectively). However, mean initial volumes are very different. In the Tyee study areas, up-slope landslides averaged 104 cubic yards while channel adjacent landslides averaged 41 cubic yards. In the red zone igneous study areas, the channel adjacent landslides were larger than the up-slope landslides (231 cubic yards compared to 116 cubic yards). However, after including debris flow volumes, up-slope landslides provided a great deal more sediment to stream channels. For the Tyee study areas, average total volume for up-slope landslides was 446 cubic yards. It was 702 cubic yards for the red zone igneous study areas and 1,434 cubic yards for the stratified random study areas (only 6 landslides in this sample, however).

For the entire database, there were 295 up-slope landslides that moved an average of 509 cubic yards of sediment into channels. The 151 channel adjacent landslides moved an average of 120 cubic yards of sediment into channels, while the three gully initiated debris flows, each moved an average of 110 cubic yards into channels. Up-slope landslides/debris flows contributed 89 percent of the total sediment volume, channel adjacent landslides contributed 11 percent, and gully initiated debris flows contributed less than one percent of the total non-road associated sediment delivered to channels.

Most of the landslides identified during this study occurred on very steep slopes. Figure 15 shows the number of non-road associated landslides by slope class (by 10% increments). Up-slope landslides are shown by the dark shading, while channel adjacent landslides are given light shading. Of note, no up-slope landslides occurred on slopes under 40% (22 degrees), while 84 percent occurred on slopes over 70% (35 degrees) and 92 percent occurred on slopes over 60% (31 degrees). For channel adjacent landslides, 86 percent occurred on slopes over 70% and 97 percent occurred on slopes steeper than 60%.

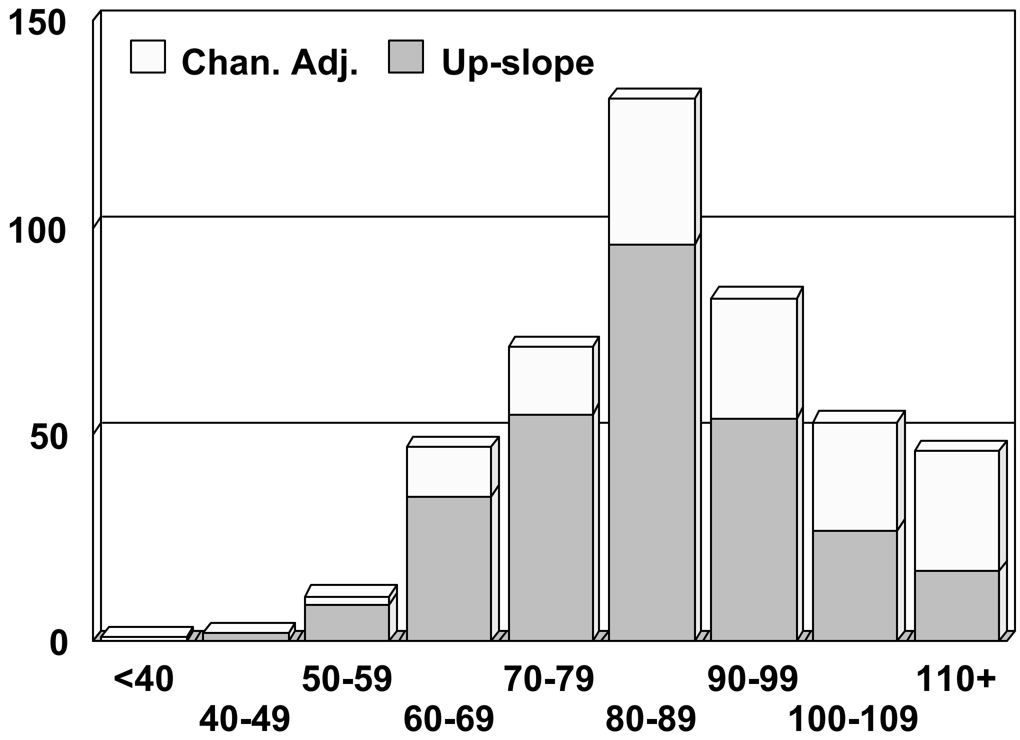


Figure 15. Frequency distribution of reconstructed slope steepness at the initial landslide both for channel adjacent and up-slope landslides (non-road associated).

Landform Characteristics

At the present time, identification of landslide prone locations is typically based in part on slope steepness and in part on landform (the shape of the ground surface) characteristics. The shape of the ground surface can be an important indicator of the potential for landslides, especially at up-slope sites. This shape was categorized by evaluating the curvature across the slope (i.e., along the slope contour) at the scarp of landslides, and also whether there was a change in slope steepness perpendicular to the slope contour (called a "slope-break") at that scarp. Across-slope categories were concave (water accumulates towards these landforms), uniform (a more or less straight slope), convex (ridge type) and other (irregular or multiple shapes at the scarp) (Chorley and others, 1984). The field crews used the ground shape at or above the scarp of each landslide to make this determination. During the field surveys, the crews encountered cases where a hollow (a sharply concave slope) was noted along the bedrock-soil contact in the landslide scarp, but this hollow was not apparent on the un-failed terrain above the landslides. These landforms are often called "filled hollows." Landslides at these locations were classified as occurring on a uniform slope because it would have been seen as a uniform slope prior to the landslide.

Slope steepness was also measured directly above the landslide scarp. Slope breaks of greater than 10% were identified using this information. Slope breaks often result from the interaction of two very different erosional processes. Where a retreating (because of active stream downcutting) slope meets an old valley terrace of weaker (weathered alluvial or residual) materials, landslides are not uncommon (Chorley and others, 1984), and may be larger than other typical "up-slope" landslides.

Table 12 shows landforms observed for the up-slope landslides only. A concave landform was observed at 126 (53 percent) of the landslides in the Tyee geology, and in 21 (42 percent) of the landslides in the igneous red zones. Uniform landforms were found at 72 (30 percent) of the landslides in the Tyee geology, and at 19 (38 percent) of the landslides at igneous study areas. Of interest, nine of the landslides (18 percent) in the igneous red zones occurred on convex landforms (where landsliding is thought to be rare, at least where soils are shallow). For all the non-road associated up-slope landslides in the database, 50 percent occurred in concave hollows, 32 percent on uniform slopes, 10 percent on convex slopes and 8 percent on irregular landforms. Slope breaks were found at 56 landslides (23 percent) of the Tyee landslides, 19 (38 percent) of the igneous landslides and, of interest, four of the six up-slope landslides occurred in the non red zone study areas.

Table 12 also shows the average slope steepness by the landform where the landslides occur. In the Tyee geology, landslides in concave landforms occurred on the least steep slopes (80% steepness, on average), landslides on uniform landforms occurred on slightly steeper slopes (average 84%) and convex on the steepest slopes (89%). In the igneous red zones, landslides on concave and uniform landforms occurred on similar slopes (84% and 83%, respectively) while landslides on convex landforms occurred on an average 93% slope. In terms of landslide depth, the greatest average depth (2.9 feet) was found at landslides on uniform slopes. Overall soil depths averaged 2.6 feet. The average depth of landslides on slope breaks (2.8 feet) was also slightly than the average depth for all landslides.

Table 12. Landform above the scarp (upslope landslides only).

Origin	Slides	Avg.	Landslide Characteristics					
	(No.)	Slope Blw. L.S. (%)	Depth Avg. (ft)	Initial L.S. Avg. Vol. (cu. yd.)	Initial L.S. Med. Vol. (cu. yd.)	Total L.S.* Avg. Vol. (cu. yd.)	Total L.S.* Med. Vol. (cu. yd.)
Red zone Tyee Sandstone Geology Study Areas (Elk Cr., Mapleton, Scottsburg)							
Concave	126	80	2.4	72	39	431	203
Convex	18	89	2	49	25	212	149
Uniform	72	84	2.7	184	35	565	164
Other	23	85	2.2	67	39	331	121
Average	239*	82	2.5	104	36	446	174
Slp. Brk>10%	56	92	2.8	109	44	565	166
Red zone Igneous Geology Study Areas (Tillamook, Vida)							
Concave	21	85	2.7	60	22	284	142
Convex	9	93	2.9	158	25	2027	255
Uniform	19	83	3.3	164	38	572	248
Other	1	120	1	3.6	3.6	25	25
Average	50*	86	2.9	116	25	702	171
Slp. Brk>10%	19	94	2.8	95	25	1057	142
Stratified randomly Selected Study Sites (Dallas, Estacada, Vernonia)							
Concave	2	78	1.8	24	24	86	86
Convex	2	89	2	77	77	116	116
Uniform	2	66	5	922	922	4100	4100
Other	0	NA	NA	NA	NA	NA	NA
Average	6*	78	2.9	341	82	1434	142
Slp. Brk>10%	4	78	3.5	499	358	2108	1644
All Study Sites							
Concave	149	81	2.4	69	36	405	190
Convex	29	90	2.3	85	27	769	142
Uniform	93	83	2.9	197	38	643	174
Other	24	86	2.2	67	39	333	120
Average	295*	83	2.5	111	36	509	171
Slp. Brk>10%	79	92	2.8	183	40	762	154

**This value is the total number of landslides. All other values in this row are averages.*

Average landslide volume (both of the initial slide, and of the combined slide/debris flow) is also shown in Table 12 (for all landslides in core areas). For the Tyee landforms, median initial landslide size is similar for the concave (39 cubic yards) and uniform (35 cubic yards) slopes. However, average volumes provide a different perspective because a few large landslides skewed the mean to a greater value. Average initial landslide volumes for the Tyee geology study areas are 72 cubic yards and 184 cubic yards for concave and uniform landforms respectively. The average total landslide volumes, including debris flow volume, are also higher for those landslides initiating on uniform slopes.

In the Tyee geology study areas, landslides that originated on convex and other slopes were generally smaller than those from uniform or concave slopes. In the red zone igneous study areas, the landslides that originated from concave slopes were generally smaller than the landslides that originated on uniform and convex slopes. These relationships hold both for the initial landslide and the total landslide (including debris flow) volumes. And, although there were only six upslope landslides in the stratified random study areas, the same relationship holds here as well. In the igneous red zone study areas, 17 percent of total landslide sediment delivered to channels was attributed to concave slope landslides, while in the stratified random study areas only two percent of the total volume could be attributed to concave slopes.

Figure 16 is a box and whiskers diagram (which illustrates population distribution) showing the distribution of landform shape by slope steepness for all the non-road associated up-slope landslides. Tests for significant differences in these distributions were conducted. There is a significant difference between the slope steepness of the concave and convex slopes, with an Analysis of Variance (AOV) p-value equal to 0.008. This indicates that landslides from concave landforms occurred on significantly less steep slopes than did landslides from convex landforms. There is also an overall p-value of 0.006, based on Bonferroni compensation testing for differences between the four landform types (meaning that landform characteristics influence the slope steepness where landslides occur). Figures 17 and 18 are box and whiskers diagrams for the upslope landslides from the Tyee and igneous red zones, respectively. AOV tests were conducted on both of these sets of distributions. In both of these cases, there was no significant difference in slope steepness between any of the individual landforms.

An important consideration regarding these statistical tests is that this testing could not consider the percent of the landscape in each of these landforms. Convex and concave slopes are believed to be generally less common than uniform slopes, at least when considering sharply concave or convex slopes. Despite this, the majority of these up-slope landslides occurred on concave slopes. In addition, landslides on concave landforms occurred on slightly less steep slopes than did landslides occurring on the other landforms. Therefore, concave slopes appear to be more susceptible to failure at given slopes, at least in the Tyee geology. However, both the initial landslides and subsequent debris flows are smaller for concave slopes as compared with uniform hillslopes.

Drainage area above the landslide initiation site was another landform characteristic measured in the field. The drainage area for each landslide was calculated by multiplying the distance from the landslide scarp to the drainage divide (typically a ridge) by the field-determined average width of the drainage path. Using this method, field crews were able to locate drainage boundaries that could not be seen on the contour maps. Nonetheless, because of poor visibility due to brush cover and slope changes, these estimates of drainage area may be over- or under-estimated 50 percent of the true value. Figure 19 shows a scatter plot of the drainage area versus slope steepness. There is tremendous variability in these values.

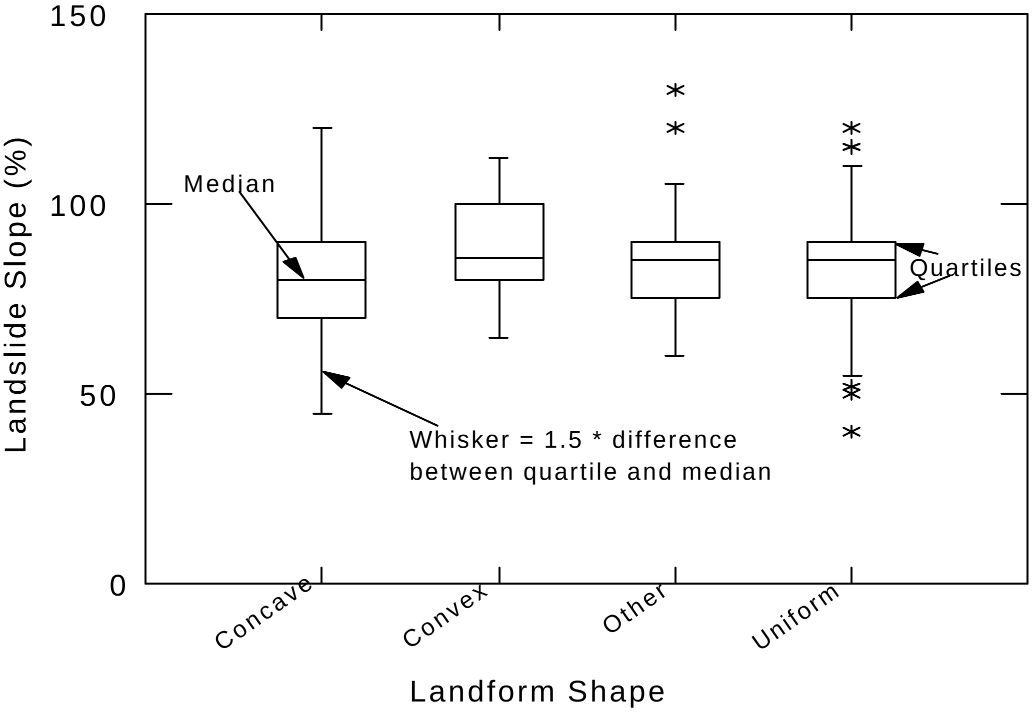


Figure 16. Graphical comparison of slope steepness distributions by landform type for up-slope landslides for all study areas. (A quartile includes 25 percent of the data.) There is a significant difference between the slope steepness of the concave and convex slopes, with an Analysis of Variance (AOV) p value equal to 0.008.

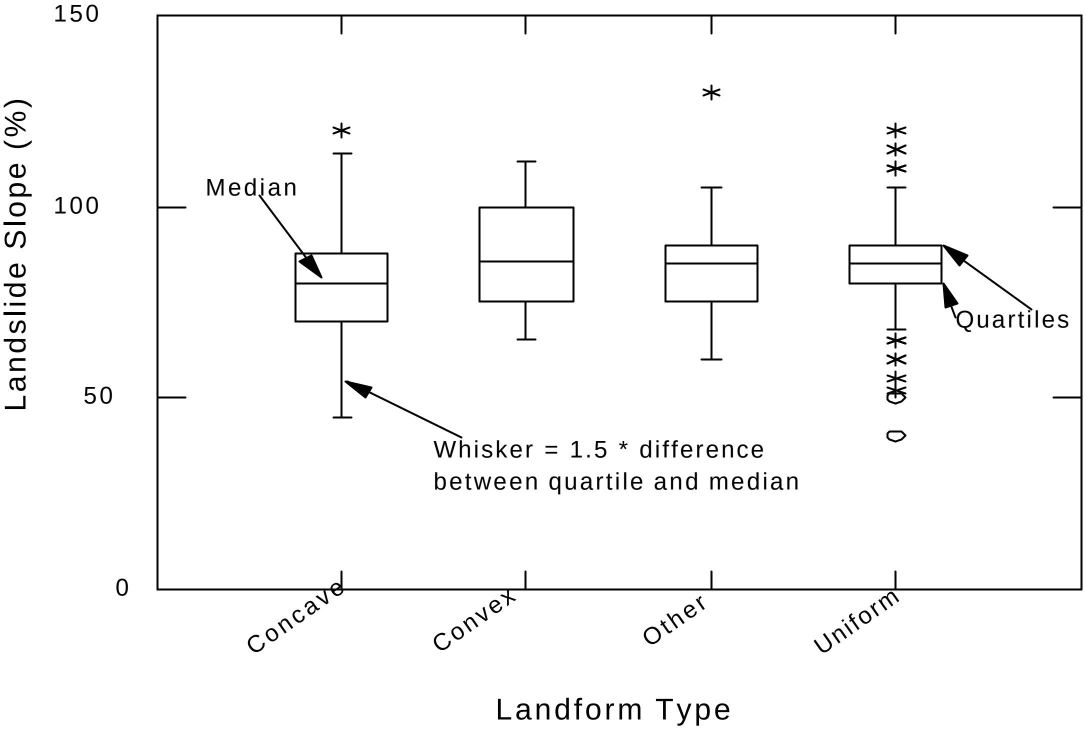


Figure 17. Graphic comparison of slope steepness distributions by landform for landslides in the three Tyee red zone study areas. AOV tests were conducted on both of these sets of distributions. In both of these cases, there was no significant difference in slope steepness between any of the individual landforms.

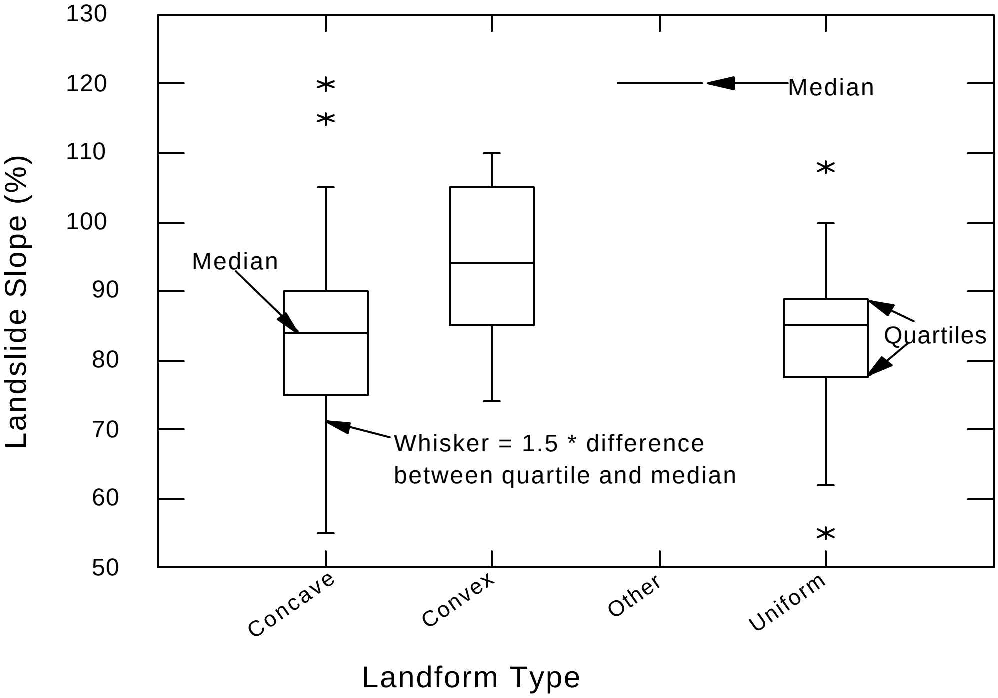


Figure 18. Graphical comparison of slope steepness distributions by landform for landslides in the igneous red zone study areas. AOV tests were conducted on both of these sets of distributions. In both of these cases, there was no significant difference in slope steepness between any of the individual landforms.

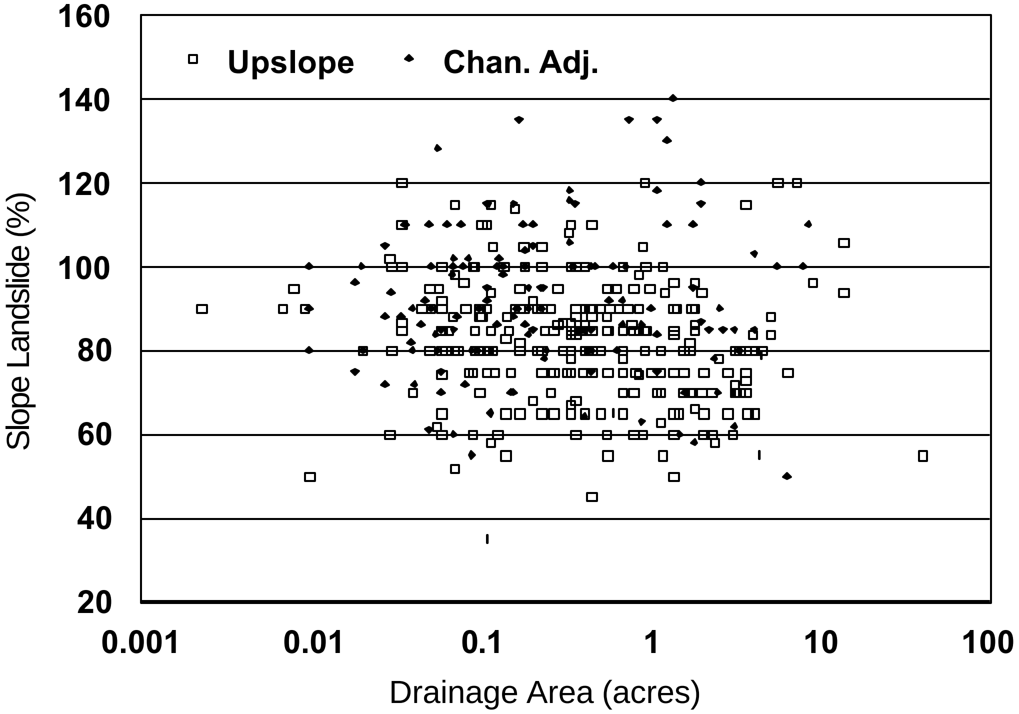


Figure 19. Scatter plot of basin area contributing to the landslide initiation site vs. slope steepness for both upslope and channel adjacent landslides.

Figure 20 is a box and whiskers diagram of the data after it was sorted into small, medium, and large drainage area size classifications. A small drainage area is less than 0.5 acres, a large drainage area is over three acres, and medium drainage areas include all values in between. When sorted in this manner, median slope steepness at the landslide initiation site for the small watersheds is 85%, 80% for the medium watersheds, and 75% for the large watersheds. Analysis of variance testing indicates there are significant differences (p = 0.002) between the populations, especially between the medium and small basins. This indicates that as drainage area increases, the slope steepness where landslides initiate decreases moderately (with a ten percent decrease between the large and the small drainage areas). Therefore, even though the field measurements for drainage area were not precise, it remains a factor affecting slope stability. Drainage area is a critical factor in some slope stability models (Montgomery and Dietrich, 1994). To some extent, slope concavity is a good indicator of drainage area. Given similar slopes and other factors, concave slopes with larger drainage areas appear to fail at a lesser slope steepness. In practice, identification of “headwalls,” or those concave slopes most prone to landslide, includes a qualitative evaluation of drainage area. These data suggest drainage areas are important in assessment of landslide hazard on concave slopes.

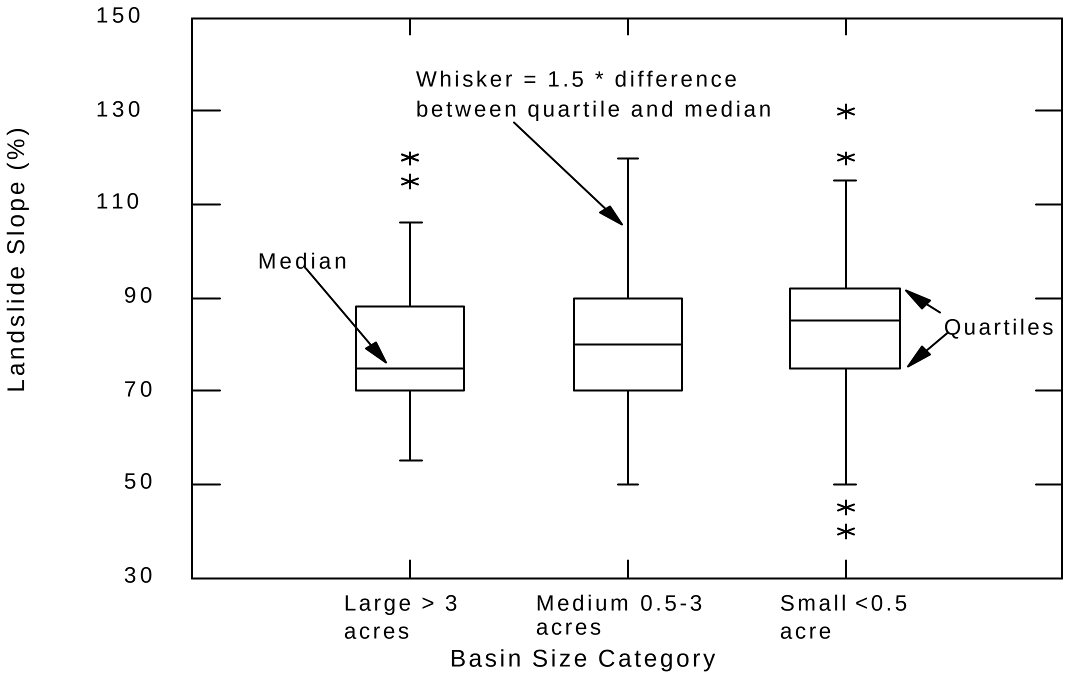


Figure 20. Graphical comparison of slope steepness distribution by size of drainage area for landslides in all study areas. Analysis of variance testing indicates there are significant differences (p = 0.002) between the populations, especially between the medium and small basins.

Identification of High Risk Sites

High risk sites are designations used by ODF for locations that are vulnerable to landslides capable of causing damage to natural resources (specifically water quality and fish habitat). Evaluating the accuracy of these high risk site determinations is critical, since there are specific rules and administrative procedures which apply only after high risk sites are identified. High risk sites have been designated as having the following landform characteristics:

1. Actively moving landslides;
2. Any slope steeper than 80%;
3. Concave slopes steeper than 70%;
4. Slope breaks where the lower slope exceeds 70%;
5. Inner gorges with slopes steeper than 60%; and
6. Other sites determined to be of marginal stability by ODF personnel.

It was possible to evaluate the identification of three of the six high risk site landform characteristics listed above with the data collected in this survey. This survey information can be used to determine slopes over 80% steepness (category 2); concave slopes over 70% steepness (category 3); and slope breaks where the lower slopes exceed 70% (category 4). During these surveys it was obviously not possible to determine if landslides were actively moving during the forest operation (category 1 high risk sites). Inner gorges (category 5) are a landform typically common only to the Siskiyou Mountains of southwest Oregon (outside of these study areas), so were not included in this analysis. Nor was any attempt made to identify the specific high risk site determinations by ODF personnel (category 6). Category 6 determinations which would not be already identified by high risk site categories 1 through 5 are considered rare.

Figures 21 and 22 are cumulative frequency curves for the slope below the landslides, sorted by landforms. Plots for the four plan view landforms (concave, uniform, convex and other) for the three Tyee study areas are in Figure 21. The most important differences in these distributions (between concave and uniform slopes) occur between slopes of 65% and 75%, where landslides on concave slopes are more common. Figure 22 compares the concave and all other landforms for the igneous study areas. The sample is too small to separate convex, uniform, and irregular landforms. In the igneous study areas, the difference between the concave and other landforms is most pronounced on slopes between 75% and 85%.

Landslides that occurred at slope breaks were typically found on steeper slopes than the non-slope break landslides. This is contrary to current high risk site guidance. However, landslides on slope breaks tend to be larger than landslides from other landforms (this was especially true in Scottsburg) so that comparison of landslide numbers and/or slopes alone may be inappropriate. This is because landslides occurring at slope breaks can pose a greater risk to resources.

The cumulative frequency information was used to determine the percentage of up-slope landslides that occurred on high risk sites. At least 78 percent of the up-slope landslides occurred on "high risk sites." Landslides in the igneous red zone study areas were best

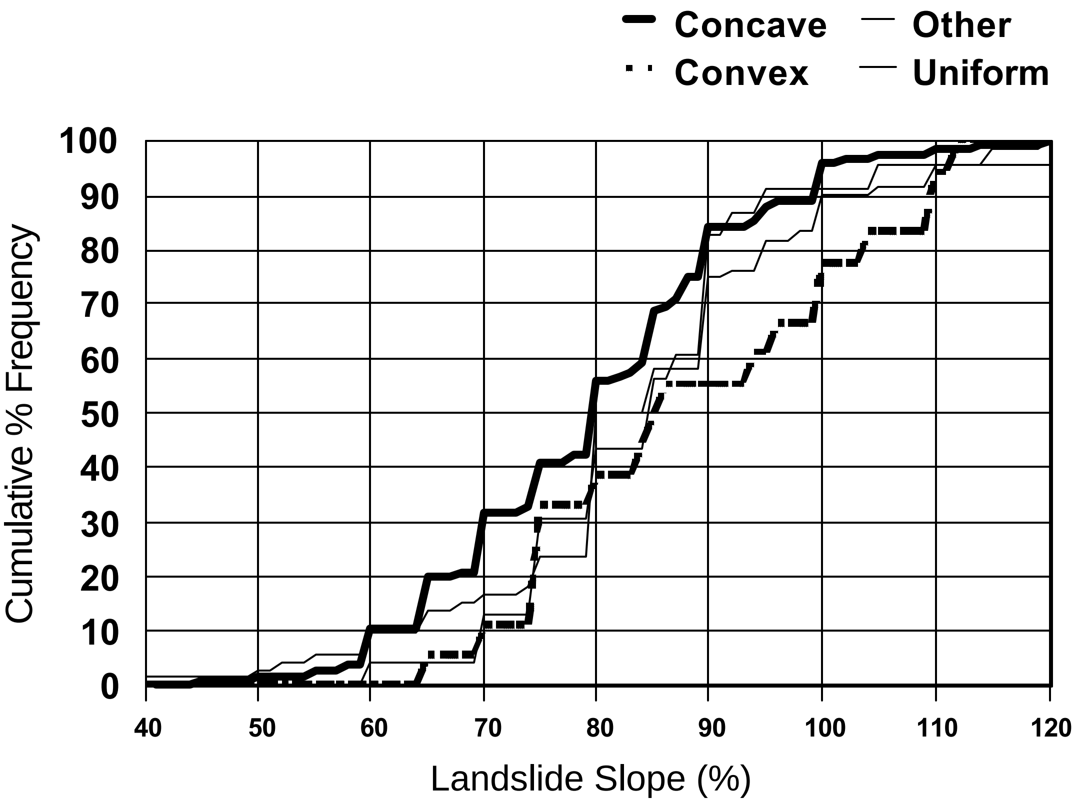


Figure 21. Cumulative percent frequency distributions of slope steepness by landform type for landslides in the Tyee red zone study areas.

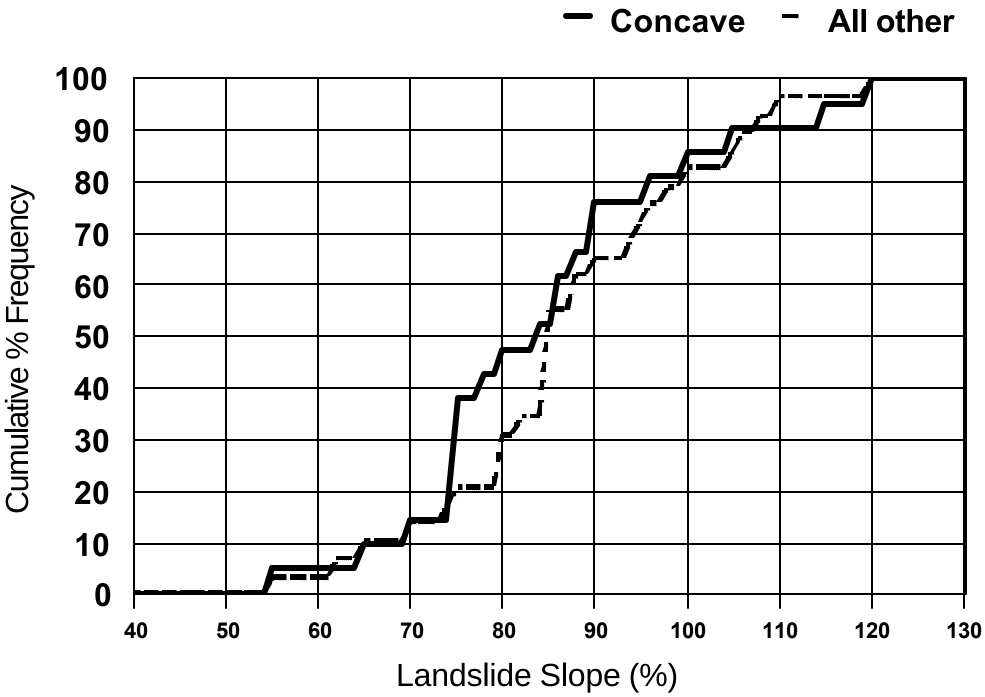


Figure 22. Cumulative percent frequency distributions of slope steepness by landform type for landslides in the igneous red zone study areas.

identified as high risk sites (at least 86 percent), while only 67 percent of the non red zone landslides occurred on landforms meeting the high risk site criteria in the randomly selected study areas. Landslides not identified as high risk sites occurred most commonly on uniform landforms. Since only three high risk site categories were evaluated as part of this analysis, it is possible that the high risk sites would have been captured by the other three high risk site categories. Therefore, these values presented here are minimum values. Reliable information on the distribution of these landforms across the landscape was not available; thus, it was not possible to determine what percentage of the study areas met the high risk site criteria. While very steep slopes are not considered typical of Oregon's forests, neither are they considered rare.

Summary

Landslides that entered stream channels during the storms of 1996 typically occurred in very steep landscapes, or adjacent to these stream channels. Even landslides that initiate as relatively small debris slides can mobilize into debris flows that mobilize large volumes of material and move long distances. Landslide characteristics vary greatly according to local landscape and geologic factors. Debris flows that were not initiated by up-slope landslides were uncommon in these study areas.

Landslides occurred on many different landforms. Concave shaped slopes with larger drainage areas appear to be more susceptible to landslides than other landforms. However, landslides occurring on concave slopes also tend to be smaller than landslides which occur on other landforms.

At least 78 percent of the up-slope landslides occurred on "high risk sites." As any landslide hazard designation includes slopes of lesser steepness, it will include more of the overall landscape. Determination of appropriate changes to the high risk site designation will require additional landscape level slope steepness information. These results do already suggest, however, that a reduction in the slope used to designate concave landforms in the Tyee geologic unit may be appropriate (probably from 70 to 65 percent). These results also suggest that elimination of the slope break category should be considered. Finally, identification of high risk sites outside of areas where landslides are common may be more difficult than in those very steeply sloped areas.

LANDSLIDES AND FOREST STAND AGE

The effects of forest cover on landslide occurrence has been the subject of much study. Previous studies have speculated that the greatest increase in landslide occurrence occurs after roots have decayed and before new roots have completely taken their place (Burroughs and Thomas, 1977), typically from a few years to a few decades after timber harvesting. Previous landslide inventories analyses have typically contrasted recently clearcut areas with mature forests (Ice, 1985). The following sections describing the study areas in terms of forest stand age provide the first detailed analysis of landslide occurrence as related to forest stands of many different ages.

The red zone study areas were selected for a combination of the highest observed densities of landslides, debris flows and debris torrents (as observed only in recent clearcuts) and also for representation of multiple forest stand ages. Tillamook was the only exception, since the stands there are all around 40 years old. The three stratified random study areas were selected with no prior knowledge of age class distribution. Table 13 shows the acreage distribution by age class for the eight study areas. Study areas were grouped into four age classes based on theories concerning the effect of vegetation on root strength and hydrology (Greenway, 1987, Washington Forest Practices Board, 1995). Although some root strength theories (Sidle et. al., 1985) would suggest the highest incidence of landslides 3 to 15 years after timber harvesting, review of data from this study indicated a higher incidence between 0 and 10 years after timber harvest. Therefore, age classes are grouped as 0 to 9 years (recent clearcut to very young forest); 10 to 30 years (young forest); 31 to 100 years (forest) and older than 100 years (mature forest). Mature forests had not been subject to clearcut harvesting, though in some limited cases they had been subject to salvage of selected dead or wind-thrown trees. Mature forests may also have been affected by wildfires over 100 years ago. In addition, there was significant partial cut harvest in the Elk Creek study area (between the 1960's and the early 1970's). These partial cut acres were determined and separately categorized in Table 13.

For the Elk Creek, Scottsburg, Mapleton and Vida red zone study areas, there was a good distribution of age classes. The smallest sample is the 0 to 9-year age class in the Elk Creek study area at 462 acres. The oldest age class (100-year plus) is well represented with over 1,000 acres for all four study areas. The middle age stands are also well represented with no less than 660 acres for any study area. It should be noted that within the "31-100" year age category that 50-80 year old stands were virtually absent. For the stratified random study areas, the distribution of age classes tended to be under-represented in one or more age classes. The "other" category in Table 13 includes situations with missing data and land uses other than forestry (agricultural land, highways and building sites).

Table 13. Survey acreages by stand age class. The first four age classes represent the time period between stand replacement (by clearcut logging or fire) and the 1996 Storm event. The 100+P.C. represents those stands in the Elk Creek Study Area where partial cutting occurred in prior decades.

Site	Acres in each Stand Age Class*						Total
	0-9	*10-30*	*31-100*	100+	100+P.C.	Other	Acres
Elk	462	1127	623	1153	814	0	4179
Mapleton	881	660	1582	2180	0	0	5283
Scottsburg	989	1701	618	1235	0	0	4543
Tillamook	0	0	2878	0	0	0	2878
Vida	749	984	941	1895	0	0	4569
Dallas	101	845	790	157	0	114	2007
Estacada	1067	1027	851	89	0	475	3509
Vernonia	582	201	1406	0	0	3	2189

** Stand ages were determined to the nearest year in actual dataset. They were grouped in for this table because these age classes correspond to theories regarding root strength and hydrologic maturity.*

Figures 23 through 26 show the steepness of slope by age class for the four study areas with multiple stand age classes based on a 6 and 10-meter digital elevation models (DEM). Coarse DEMs tend to “smooth” out actual slopes and under represent the steeper slopes. Nevertheless, the 6 and 10-meter DEM provide the best slope information available at all study areas, and therefore are the most reliable tool for data stratification for all the study areas, since geology and proximity are already similar based on how the red zones were selected.

For the Vida study area, the 100-year plus stands were on steeper slopes than other age classes, with the 31 to 100 year age class having the gentlest slopes. In Mapleton, the 10 year to 30-year age class had the steepest slopes, while the 0 to 9-year class was slightly less steep than the slopes in the 100-year and older stands. In Scottsburg, the steepest slopes were in the 31 to 100-year class, the 10 to 30 were least steep, and the 0 to 9 and 100 plus stands had slopes of similar steepness. For Elk Creek, the 100-year plus stands where partial cutting occurred a few decades ago were on less steep slopes than the other age classes.

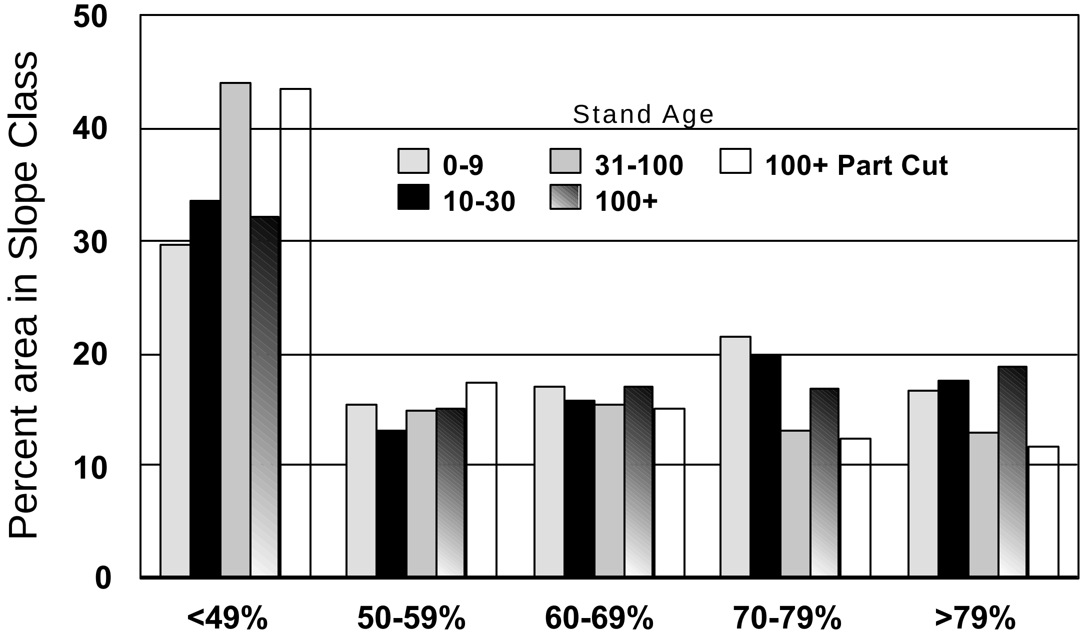


Figure 23. Slope steepness distribution by age class in the Elk Creek study area based on 6 meter DEM GIS coverage.

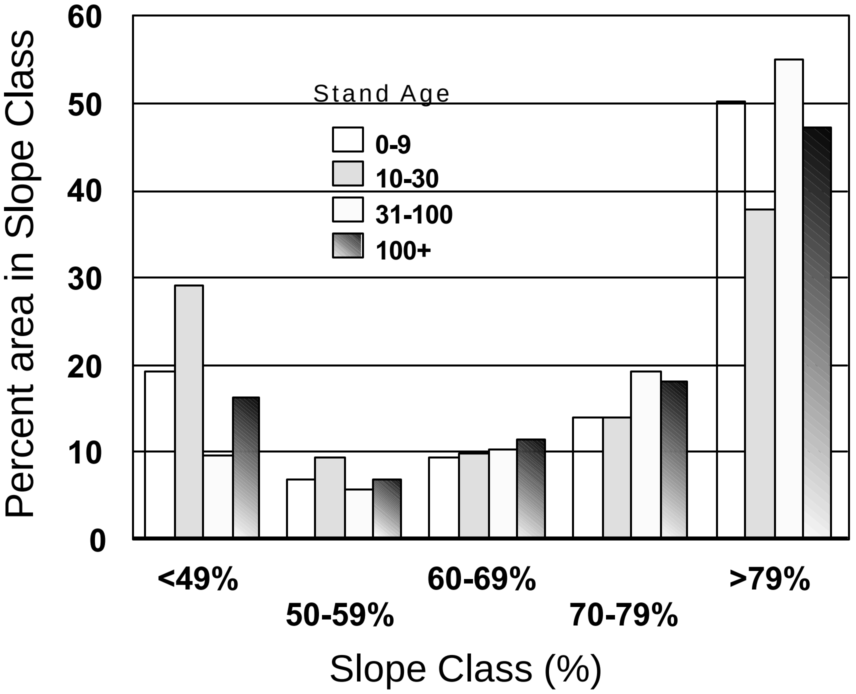


Figure 24. Slope steepness distribution in the Scottsburg study area based on stand age class from 6 meter DEM GIS coverage.

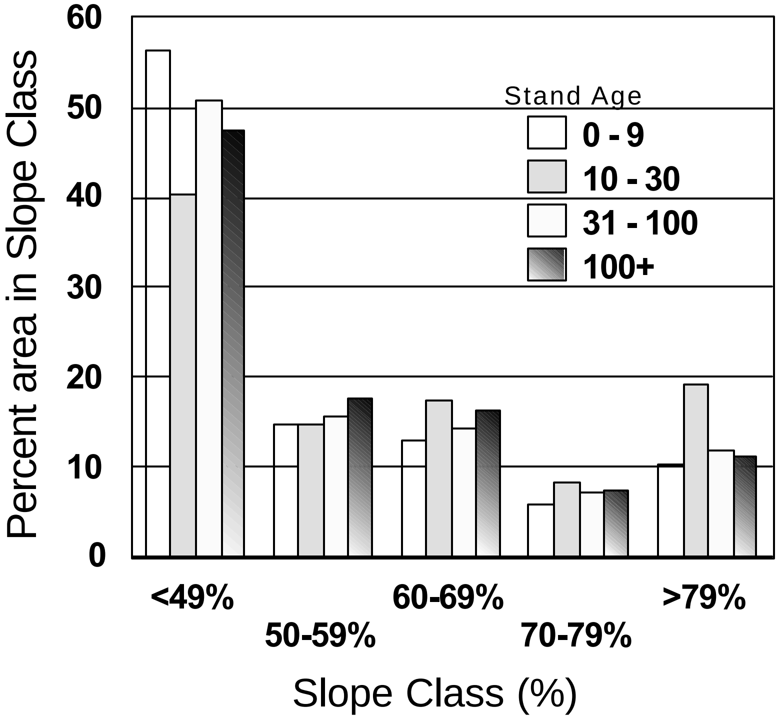


Figure 25. Slope steepness distribution by stand age class in the Mapleton study area based on 10 meter DEM GIS coverage.

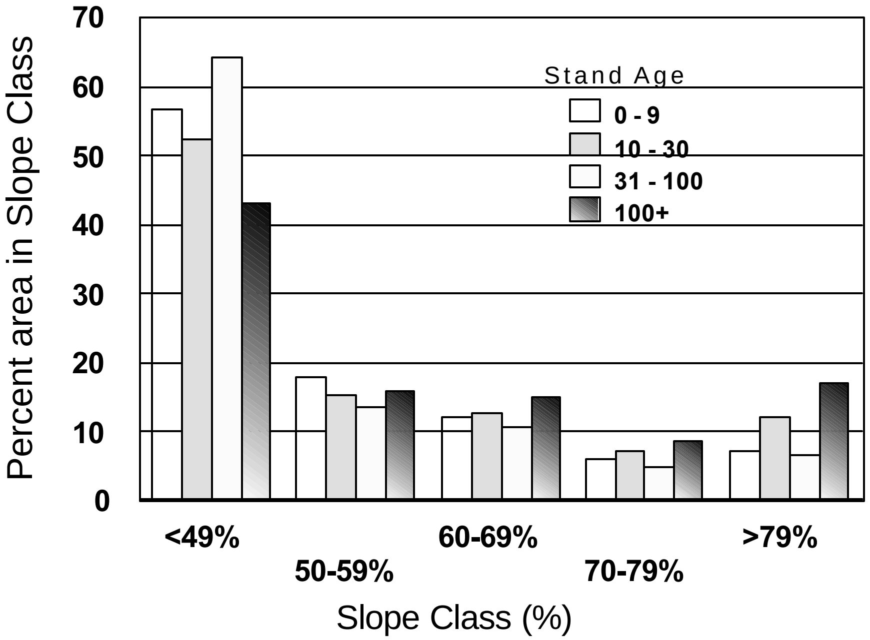


Figure 26. Slope steepness distribution by stand age class in the Vida study area based on 10 meter DEM GIS coverage.

Landslide Density and Erosion

Landslide differences are evaluated by looking at both landslide density and landslide erosion in the four different age classes. Density is the number of landslides per unit area. Erosion volume includes the total sediment moved by landslides and debris flows, also reported on a per unit area basis. In this way, differences between the stand age classes can be directly compared.

Landslide density and erosion were calculated for each stand age class (Table 14). Landslide density is reported by the number of non-road associated landslides per square mile. Erosion includes the initial landslide volume plus the non-channelized debris flows, and is reported in terms of cubic yards per acre. Densities and erosion volumes are sorted by channel adjacent landslides, up-slope landslides, and total. The classification "NA" (not applicable) is used where there were no stands with these age classes or characteristics. Information for the stratified random selected study areas (Dallas, Estacada, and Vernonia) is also provided. Table 12 presents data unadjusted for the effect of slope. Stratification results in minor to moderate changes in this information (see Table 15).

The greatest total landslide density (30.7 landslides per square mile) was found in the 100-year plus stands in the Elk Creek study area, which were partially cut by selective timber harvest 20 to 30 years ago. In part, this high landslide density is due to a very high number of channel adjacent landslides (10.2 per square mile). Note that the erosion volume for these channel adjacent landslides in the Elk Creek study area was very low (0.37 cubic yards per acre). The high landslide erosion volume for the 100-year plus age class in Dallas (33 cubic yards per acre) is due to one very large landslide that occurred in a fairly small area (157 acres). Other widely different values by age class in the stratified random selected study areas are also related to a few landslides in small sample areas.

Analysis of variance testing was used to test both landslide density and erosion volume differences between the four age classes on the four multi-age red zone study areas (Elk Creek, Scottsburg, Mapleton, and Vida). There is no significant difference for the four study areas between the four age classes (p-value is 0.654). In fact the F statistic is less than one (F = 0.556) which means the variation in erosion volumes between the study areas is greater than the variation in erosion volumes between the age classes. None of the individual comparisons are significantly different. Figure 27 provides a graphical display of this information using a bar chart with error bars. The high standard deviation of the error bars indicates the variation in erosion volume between study areas is extremely high. Note that this is from an extremely small sample (4 study areas vs. 4 age classes). The high variability between study areas in erosion volume precludes seeing any relationships within the age classes using commonly accepted statistical techniques. Tests for differences in landslide density by age class yielded similar findings (no significant difference between the four age classes).

Table 14. Landslide density and erosion volume grouped by age class.

	Stand Age Class					Stand Age Class				
	0-9	*10-30*	*31-<100*	100+	100-PC	*0-9*	*10-30*	*31-100*	100+	100-PC
Site	Landslide Density (number per square mile)					Landslide Erosion (cubic yard per acre)				
	Channel Adjacent Landslides					*Channel Adjacent Landslides*				
Elk	4.15	6.82	5.14	3.89	10.22	0.20	0.80	0.23	0.31	0.37
Mapleton	5.09	0.97	3.24	4.99	NA	0.65	0.01	0.07	0.09	NA
Scottsburg	1.29	0.75	1.04	2.07	NA	0.15	0.14	0.25	1.02	NA
Tillamook	NA	NA	7.12	NA	NA	NA	NA	4.16	NA	NA
Vida	5.13	1.30	1.36	2.70	NA	0.21	0.09	0.11	0.21	NA
Dallas	0.00	0.76	0.81	0.00	NA	0.00	0.01	0.05	0.00	NA
Estacada	0.00	0.00	0.00	7.19	NA	0.00	0.00	0.00	0.15	NA
Vernonia	5.49	0.00	4.10	NA	NA	0.09	0.00	0.49	NA	NA
	Upslope Landslides					*Upslope Landslides*				
Elk	18.00	13.63	10.27	22.21	20.44	5.90	10.94	2.66	17.66	13.68
Mapleton	15.98	0.97	2.83	8.51	NA	3.66	0.03	5.06	2.44	NA
Scottsburg	18.77	9.78	6.22	3.63	NA	16.45	8.24	6.04	6.31	NA
Tillamook	NA	NA	3.11	NA	NA	NA	NA	7.49	NA	NA
Vida	8.55	1.95	1.36	6.08	NA	6.42	3.93	0.79	2.04	NA
Dallas	0.00	1.51	0.00	8.16	NA	0.00	3.89	0.00	33.15	NA
Estacada	0.00	0.00	0.00	7.19	NA	0.00	0.00	0.00	0.07	NA
Vernonia	0.00	0.00	0.46	NA	NA	0.00	0.00	0.08	NA	NA
	All Non-Road Landslides					All Non-Road Landslides				
Elk	22.15	20.45	15.41	26.09	30.67	6.10	11.74	2.89	17.98	14.05
Mapleton	21.07	1.94	6.07	13.50	NA	4.31	0.03	5.13	2.53	NA
Scottsburg	20.06	10.53	7.25	5.70	NA	16.60	8.38	6.30	7.33	NA
Tillamook	NA	NA	10.23	NA	NA	NA	NA	11.65	NA	NA
Vida	13.67	3.25	2.72	8.78	NA	6.63	4.02	0.90	2.25	NA
Dallas	0.00	2.27	0.81	8.16	NA	0.00	3.90	0.05	33.15	NA
Estacada	0.00	0.00	0.00	14.38	NA	0.00	0.00	0.00	0.22	NA
Vernonia	5.49	0.00	4.55	NA	NA	0.09	0.00	0.57	NA	NA

NA – Refers to “no area” in these stand age classes.
PC – Refers to “partial-cuts” that occurred from 20-30 years ago. Partial cutting only occurred in Elk Creek study area.

However, on a case study basis, the Scottsburg study area clearly has a much greater landslide density in the younger age classes. In addition, in three out of four study areas there is a greater landslide density and landslide erosion volume in the recently clearcut stands (0 to 9-year age class) as compared to the mature forest stands (Figures 28 and 29). Therefore, for the most landslide prone landscapes, these results indicate there is a 75 percent chance that recently clearcut areas will have greater landslide erosion or density as compared to mature forest stands after a very large storm. For the 10 to 30 year old forests, three out of four study areas had lower landslide densities than found in mature forest, and two of four had reduced erosion volume. For the 31 to 100 year old forests, three out of four study areas had both lower landslides and erosion volume as compared to mature forests. Therefore, for the most erosion prone landscapes, these results also indicate that 10 to 30 year old forests have a 75 percent chance of having a lower landslide density than mature forests. In a similar light, 31 to 100 year old forests have a 75 percent chance of having both lower landslide density and erosion (sediment delivery to channels) as compared with mature forests.

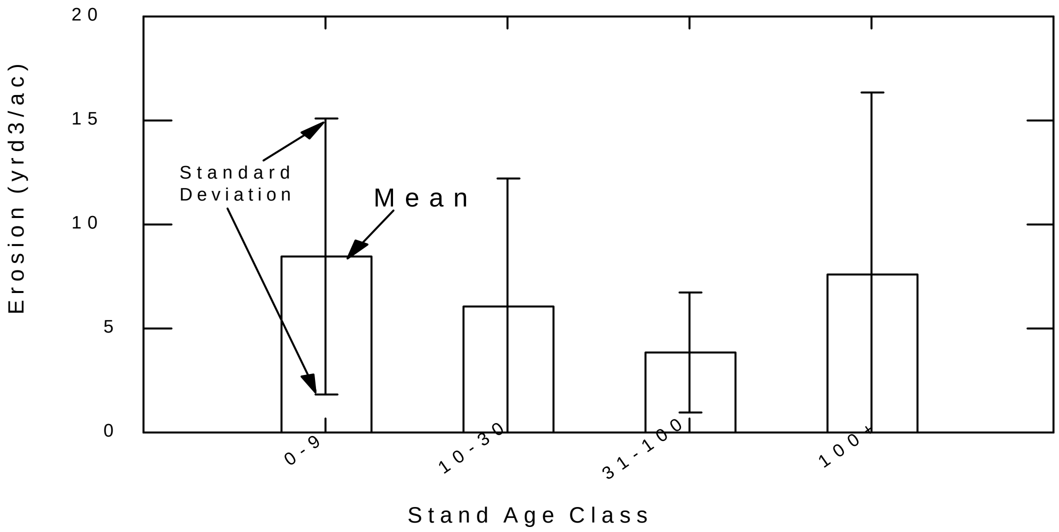


Figure 27. Bar graph showing distribution in erosion of the four multi-stand-age red zone study areas by age class.

Figure 28 illustrates fairly consistent landslide densities for the 0 to 9-year age class (between 14 and 22 landslides per square mile). There is a great deal more scatter in landslide densities in all the other age classes, with typically reduced landslide densities in the 10 to 30 and 31 to 100-year age classes. Landslide density in the 10 to 30-year class varies between 2 and 20 landslides per square mile, and between 3 and 16 landslides per square mile in the 31 to 100-year class. For the 100-year and older unmanaged stands, landslide density varies from 6 to 26 landslides per square mile. Figure 28 also illustrates that channel adjacent landslides are, in most cases, a fairly small subset of the total population (with relatively higher numbers in the Elk Creek and Mapleton study areas).

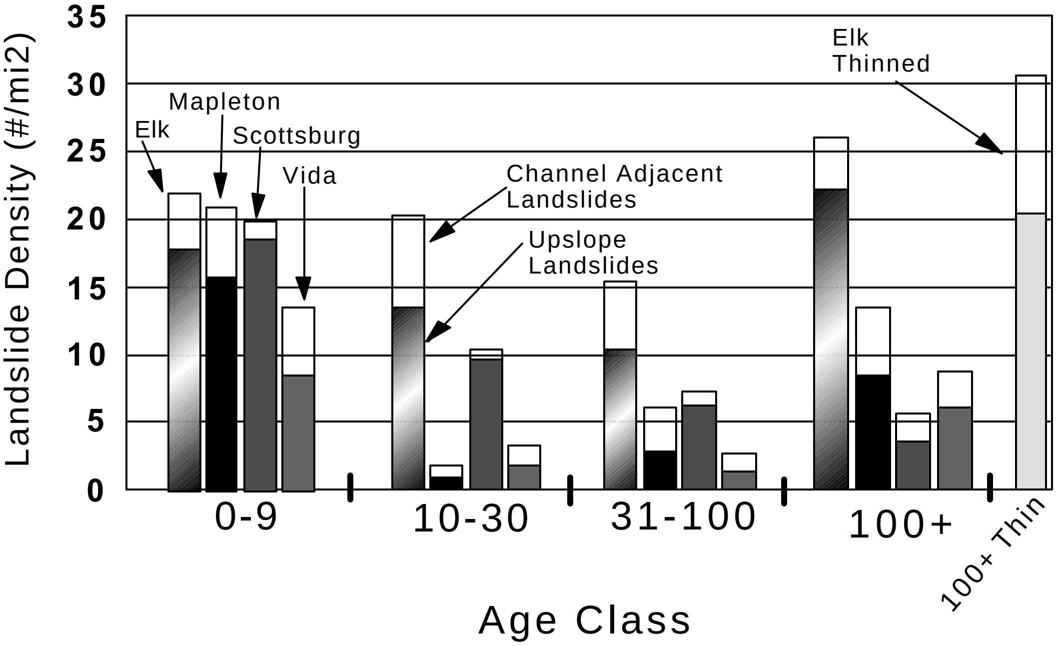


Figure 28. Stacked bar graph of landslide density for upslope and channel adjacent landslides by stand age class for the four red zone study areas.

Landslide erosion volumes are illustrated in Figure 29. In general, this figure indicates there is greater variability in erosion volumes than in landslide densities. Again, the erosion volume is the total volume, including the initial landslide plus the non-channelized debris flow volume. Therefore, the channel adjacent slides (smaller with little or no debris flows) make up only a very small portion of the total landslide erosion.

Landslide erosion volume for the 0 to 9-year class was much more variable than the landslide density, varying between 4 and 17 cubic yards per acre. For the 10 to 30-year age class, it varied between 0.03 and 11 cubic yards per acre, while in the 31 to 100-year class the low value was 0.9 cubic yards per acre and the high value was 6 cubic yards per acre. For the 100-year plus age class, the values ranged between 2 and 18 cubic yards per acre. The aforementioned volumes are for the four red zone sites with good age class distribution (Elk Creek, Scottsburg, Mapleton and Vida). Erosion volumes for the four other sites (Dallas, Vernonia, Estacada and Tillamook) are also compared in Table 14.

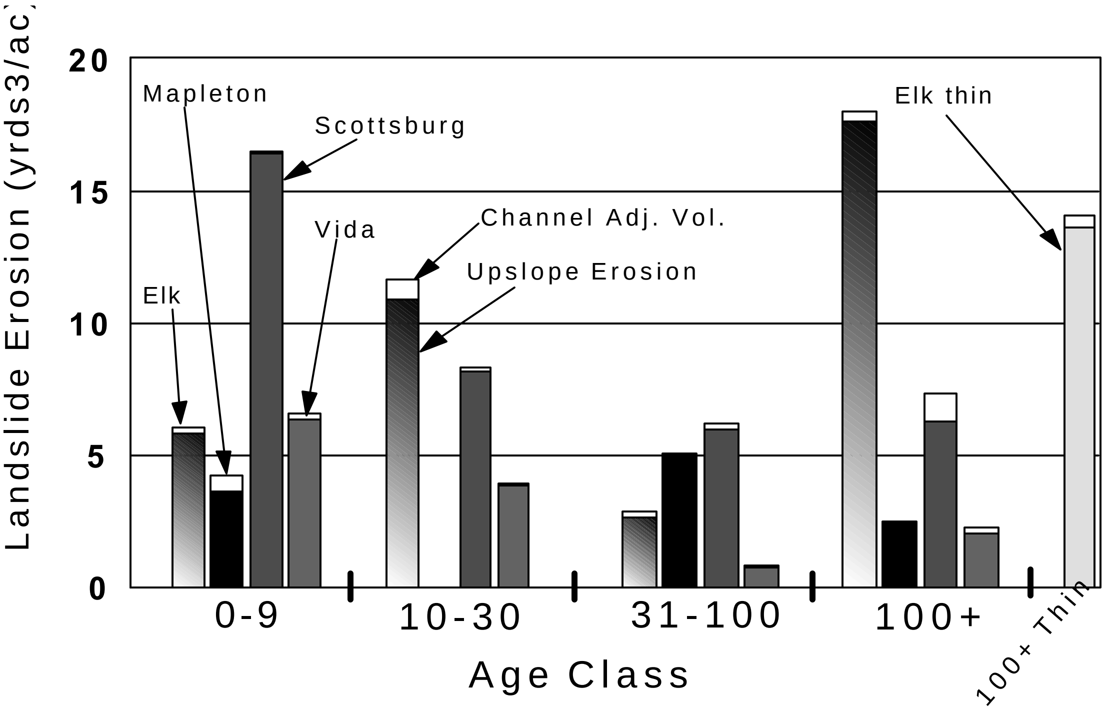


Figure 29. Stacked bar graph of landslide erosion rate for channel adjacent and upslope landslides by stand age class for the red zone study areas.

Landslide density and erosion volume results were adjusted using the ratio of the steeply sloped land in the 100-year plus stands to the amount of steeply-sloped land in the other age classes. This simple ratio was A=B/C (where A is the adjustment factor, B is the percent of land with slopes over 60% in each of the younger age classes, and C is the percent of land with slopes over 60% in the 100-year plus age class). DEM slope steepness classes are shown in Figures 23 through 26. When the DEM indicates a slope of 60%, field experience is that actual on-the-ground slopes are commonly over 70%, which is the slope where shallow-translational landslides became much more common. Therefore, lands with slopes over 60% (as determined from a DEM) were considered most susceptible to landslides.

The adjusted erosion volumes, presented as the ratio of the younger or partial cut classes to the 100-year plus classes, is shown in Table 15 (next to the unadjusted data). This table represents what we believe to be the most accurate comparison between the different stand ages, as it removes as much inter-study area slope variability as possible with the available data. Again, AOV testing using stratified data finds no significant difference for the four study areas and between the four age classes.

Table 15 shows that, for three out of four study areas, there is both a higher landslide density and landslide erosion volume in the 0 to 9-year class as compared to the 100-year plus age class. The stratified difference varies between 0.78 and 5.38 times for landslide density, and between 0.32 and 5.05 times for landslide erosion volume. For the 10 to 30-year age class, three out of four study areas have a lower landslide density, and half the study areas have a lower landslide erosion volume (as compared with the 100-year plus stands). Three out of four of the 31 to 100-year stands have both lower landslide densities and erosion volumes than the 100-year plus stands.

Table 15. Ratio between different stand ages against stand ages 100 years and older. Ratios are: (1) for entire landbase; and (2) adjusted for slopes over 60%.

	Comparative Ratio of Upslope Landslides With unmanaged 100+ year old stands					
	Ratio for total landbase		Ratio adjusted for land-area over 60% slope			
Stand Age (years)	Density	Erosion	Density	Erosion	Total Area (acres)	Area W Slopes Over 60% (acres)
Elk Creek Study Area						
0-9	0.81	0.33	0.78	0.32	462	254
10-30	0.61	0.62	0.61	0.62	1124	598
31-100	0.46	0.15	0.59	0.19	509	209
100+ thin	0.92	0.77	1.24	1.04	920	362
Mapleton Study Area						
0-9	1.88	1.50	2.26	1.81	882	256
10-30	0.11	0.01	0.09	0.01	646	289
31-100	0.33	2.08	0.35	2.16	1499	503
Scottsburg Study Area						
0-9	5.17	2.61	5.38	2.71	506	373
10-30	2.70	1.31	3.35	1.63	1537	948
31-100	1.71	0.96	1.55	0.87	421	356
Vida Study Area						
0-9	1.41	3.15	2.26	5.05	852	217
10-30	0.32	1.92	0.41	2.44	984	318
31-100	0.22	0.39	0.42	0.72	946	207

Vegetative Characteristics Around Landslides

One study objective was to understand how forest practices may have either contributed to or minimized storm impacts. The most obvious means by which forest practices affect the landscape is by removing the older trees and replacing them with seedlings. In most of western Oregon, these trees grow until thinned, and then until final harvest (typically by clearcut). Vegetation characteristics can be considered on three different scales: landscape (square miles), stand (acres), and site (square feet). Landslide density and erosion rates as related to forest age have been reported using age determined at a stand scale.

Vegetative characteristics at the landscape scale reflect ecosystem diversity over broad land areas. Size, shape and connectivity can be used to characterize this diversity.

Examples of disturbances of the landscape scale include large wildfires and volcanic eruptions.

The stand scale partitions the landscape into areas characterized by dominant overstory vegetation. The reported stand age typically dates to the last date of major disturbance. Examples of disturbance at the stand scale include clearcuts and small wildfires. It is critical for the reader to understand that although stand age is used to describe a large area, these stands are not homogenous and consist of a mix of trees of different age, species and density. For example, an unmanaged forest (what this study categorizes as 100-year plus) often has a complex stand structure. It may be composed of a 200-year old Douglas-fir overstory, a mix of 75-year old big leaf maple and red alder understory, a lower layer of shade-tolerant hemlock saplings and seedlings, and a brush layer of salmonberry and sword fern with scattered openings in the canopy.

The site scale applies to features including riparian areas, geomorphic landforms such as hollows, and other areas from less than an acre to a few acres in size. Vegetation in steep hollows and riparian areas typically develop under a higher-frequency disturbance regime than the upland areas. For example, these areas have higher volumes of soil disturbance from landslides and floods than the less steep uniform hillslopes. Therefore, riparian and headwall areas are typically characterized by a mix of species that are adapted to disturbances.

While most vegetation-landslide relationships that follow are reported at the stand scale, a brief analysis was performed at the site scale. Past and current research have investigated the role of root strength in relation to slope stability (Burroughs and Thomas, 1977; Gray and Leiser, 1982; Skaugset, 1997). Debate persists on how and to what extent roots might influence the stability of slopes, and also on the strength differences afforded by coniferous versus hardwood vegetation and shrubs. The information presented here does not provide a mechanistic explanation, but rather a qualitative index of the overstory vegetative characteristics adjacent to the landslide initiation sites. Overstory vegetation was described as either conifer, hardwood, mixed, or none.

Vegetation has been widely reported to be an important factor affecting the stability of slopes (Greenway, 1987). An important issue related to the differences, or lack of differences, in landslide density and erosion volume by age class is the specific vegetative characteristics around the landslides. More specifically, do landslides in older forests occur in areas with little or no vegetation, or with hardwood vegetation? To help answer this question, field data were collected on the types and heights of the trees around and within 10-30 feet of the scarp of each landslide.

Height of the vegetation around each landslide is plotted in Figure 30 (for all five red zones study areas). There is a clearly evident trend toward increasing height with stand age. However, there is a great deal of variability in the height of vegetation, especially around age 0-years and again beyond age 100-years. This may reflect a multiple age canopy with openings in the older stands, and residual or sprouting hardwoods/brush in the recently harvested stands.

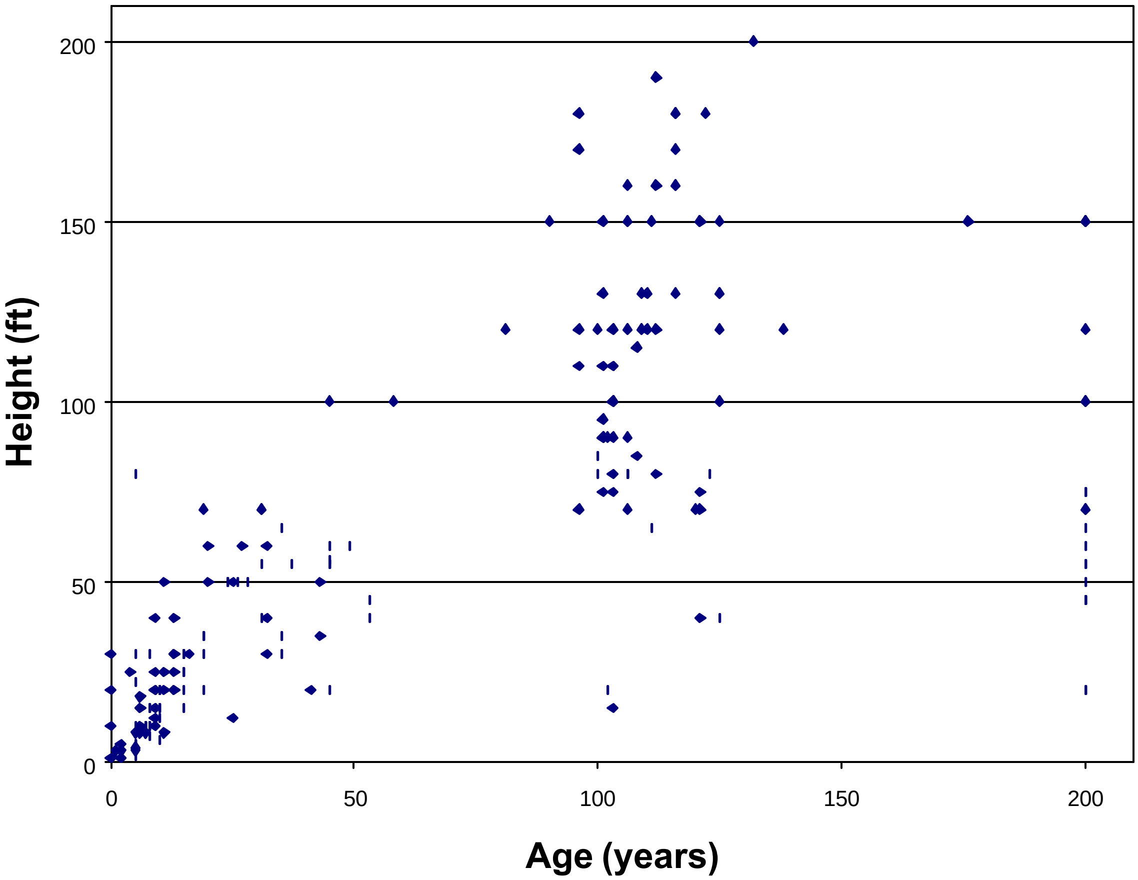


Figure 30. Dominant height of vegetation adjacent to landslides for all five red zone study areas. (Note: not all landslides sampled had these measurements taken.)

The vegetation components by height class is shown in Figure 31. For most height classes, conifers are the dominant vegetation adjacent to landslides. However, where trees are between 38 and 88 feet tall, hardwoods make up about half of the vegetation next to these landslides. Figure 32 shows the dominant tree height in the 100-year plus stands. Over 90 percent of the trees around landslides in the 100-year plus stands are over 40 feet tall. Therefore, landslides occurring in these 100-year old stands are not occurring in unusual openings in the forest (locations with no vegetation).

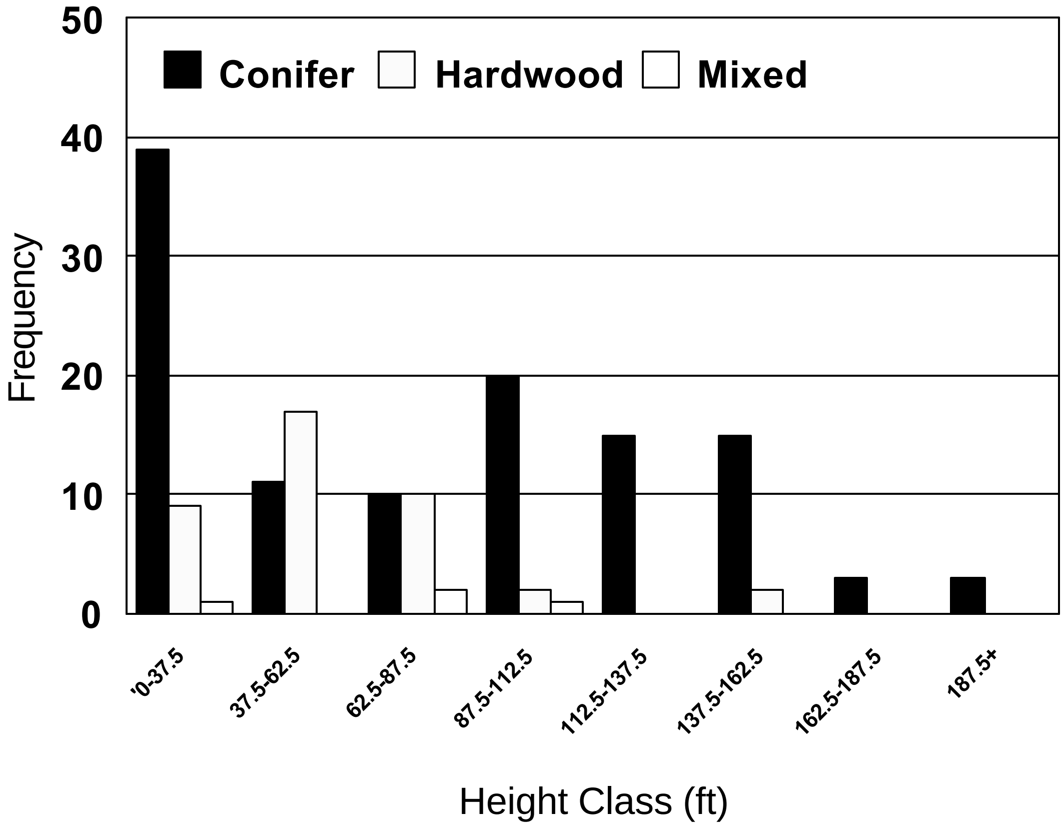


Figure 31. Vegetation type (conifer, deciduous, or mixed) around landslides that had dominant vegetation of various heights.

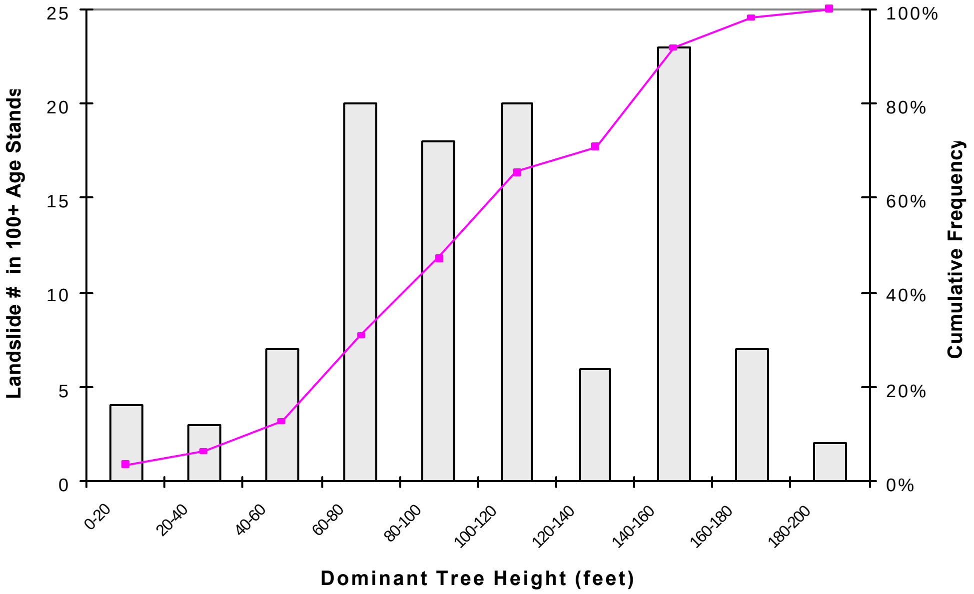


Figure 32. Frequency histograph of dominant vegetative height classes for red zone in mature (100 year-plus stand ages) forests.

Landslide Characteristic Differences by Age Class

Landslide data were examined to see if there were significant differences in selected parameters between the different age classes and study areas. These factors included landslide slope, average landslide depth, landslide initial volume, and landslide total volume. The results of this analysis are shown in Table 16. Only up-slope landslides are shown in this table.

Table 16. Dimensions (slope, depth, and volume) of landslides for different stand age classes for those red zone study areas containing a range of stand ages.

		Averages for Landslides			
Stand Age	Number of Landslides	Slope (%)	Depth (ft)	Volume (yd^3)	Total (including debris flow) Volume
Elk Creek Study Area					
0-9	13	82	1.7	35.7	210
10-30	24	77	2.3	103	514
31-100	9	86	2.8	91	172
100+	40	84	1.7	49	509
100+ Thin	26	81	1.9	52	428
Mapleton Study Area					
0-9	22	84	2.1	40	147
10-30	1	95	1.0	18.1	18.1
31-100	7	79	2.8	44.5	1144
100+	29	87	2.3	28	183
Scottsburg Study Area					
0-9	29	81	3.5	272	561
10-30	26	83	3.1	169	539
31-100	6	79	3.3	127	622
100+	7	75	4.1	372	1113
Vida Study Area					
0-9	10	86	3.4	110	481
10-30	3	72	5.3	476	1288
31-100	2	89	3.8	131	370
100+	18	81	2.3	23	214

The 0 to 9 and the 100-year plus age classes are best represented in this data set (with only one study area having fewer than ten landslides, in these age classes). However, the 10 to 30-year age class contain only one and three landslides, in the Mapleton and Vida study areas respectively. In the 31 to 100-year age class, no study area has more than ten landslides (ranging from two in Vida to nine at the Elk study area). Therefore, the most meaningful comparisons can be made between the 0 to 9 and the 100-year plus age classes.

A difference in average slope steepness at the landslide between different age classes might suggest that certain practices make less steep slopes more vulnerable to landslides. Average slope steepness at the sites of the landslides varies from 81% to 86% in the 0 to 9-year class, and from 75% to 87% in the 100-year plus class. In two study areas, the 0 to 9-year class has the greater average slopes, while in the other two study areas the 100-year plus has the greater average slopes. The range in average landslide slope in the other two age classes was more variable. Average slope in the 10 to 30 class ranged from 72% to 95%, while in the 31 to 100 class it ranged from 79% to 89%. The data show there is no difference in slope steepness between the landslides in the 0 to 9 and the 100-year plus age classes.

Variations in the depth of the landslides may be an indicator of root strength differences by age class. Where root strength is a significant slope stability factor one would expect fewer landslides in shallow soils where roots penetrate the failure surface. Slopes with deeper soils would be less affected by the roots and therefore might be expected to experience proportionally more landslides in the older stand age classes, especially when most trees in western Oregon have a shallow rooting system. Following this reasoning, the youngest age class would be expected to have proportionally fewer deep landslides than the older age classes, or more shallow landslides than found in older forests. Looking at the average depths in Table 16, there is no clear relationship between the stand age of landslide occurrence and landslide depth in those stand ages. For the 0 to 9-age class average depth varies from 1.7 feet to 3.5 feet. For the 100-plus age class depth varies from 1.7 feet to 4.1 feet. In two of the study areas, the average depth is less in the 0 to 9-year age class. It is greater in one case, and the same in the other case.

Landslide volumes were also considered in this analysis. The 0 to 9-year age class had a greater average initial landslide volume in two cases and a lesser volume in two cases as compared with the 100-year plus. Considering total volume, the 0 to 9-year age class had the smallest average volume in three out of four cases. Variability in volumes is much greater in the other age classes than in the oldest and youngest age classes. Overall, however, there appear to be no differences in landslide size by age class.

Major differences in landslide characteristics exist between the Scottsburg and Elk Creek study areas, even though they are both in the same geologic unit (Tyee sandstone), both experienced the same November storm, and are separated by a distance of 10 to 15 miles. Table 15 illustrates some of these differences. In the Elk Creek study area and only at this study area both landslide density and landslide erosion volume are lower in the 0 to 9-year age class as compared to the 100-year plus age class. On the other hand, the Scottsburg study area has the greatest relative increase in landslide density in the 0 to 9-year age class. Scottsburg is also the only study area to have greater landslide densities in both the 10 to 30 and 31 to 100-year age classes, as compared to the 100-year plus age class.

Table 16 indicates that the Scottsburg landslides have about twice the average depth of the Elk landslides and are much larger (both initial and total volumes). Figure 33 shows this very different distribution in landslide depths. The average slope at the landslides in the Elk study area are 82% for the 0 to 9 age class, and 84% for the 100-year plus (no partial cutting) class. At Scottsburg, average slope in the 0 to 9-year age class is 81%. In the 100-year plus class it is 75%.

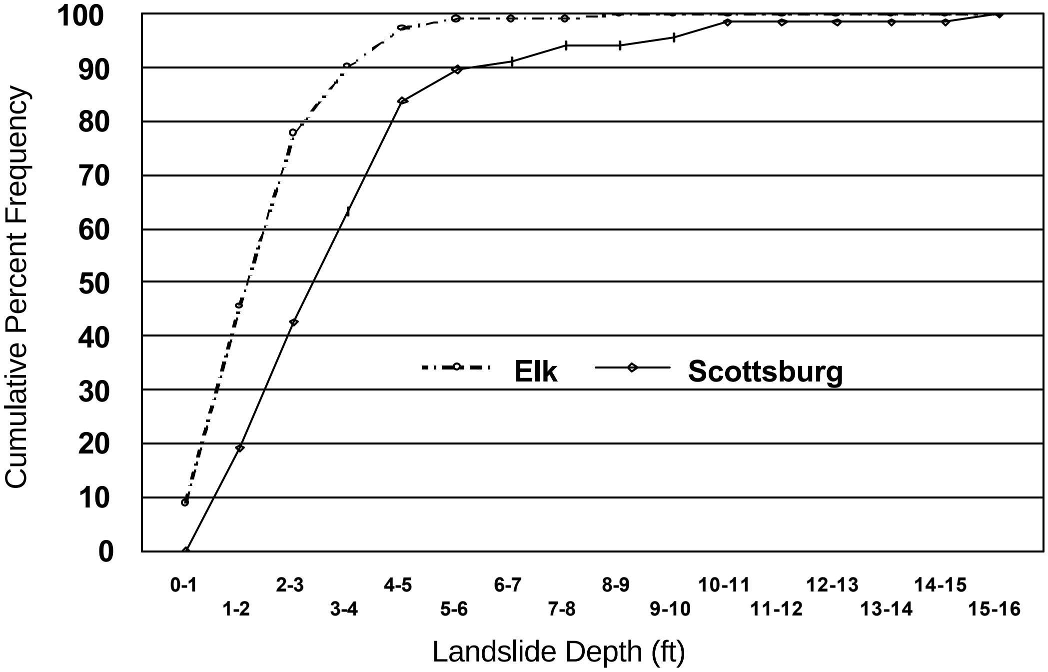


Figure 33. Landslide depth comparisons (via percent cumulative frequency distributions) between the Elk Creek and Scottsburg study areas.

Landslide depth and size is very different between these two study areas. In addition, there were fewer slides on very steep slopes with shallow soils in the 100-year plus age class in the Scottsburg study area. This is not for the lack of steep slopes in Scottsburg (Figures 23 and 24). In Scottsburg, the DEM model shows that about 60 percent of the slopes exceed 70% steepness, while in Elk Creek only about 30 percent of the slopes exceed a DEM slope of 70%.

In only the Scottsburg site, the lower landslide density in the 100-year plus class might be partially related to a lack of shallow landslides on steep slopes. The average depth of the landslides in the 0 to 9-year age class is 0.6 feet less than the average depth for the 100-year plus age class (3.5 versus 4.1 feet). Considering the overall steepness of the Scottsburg study area, the lack of shallow landslides on very steep slopes (in all age classes) is surprising. Even though the overall landscape is significantly less steep than Scottsburg, the landslides in the Elk Creek study area typically occurred on steeper slopes than the Scottsburg landslides.

Summary

Partly because of the small number of study areas, it was not possible to detect significant differences in landslide occurrence by stand age. Nevertheless, in three out of four study areas in very steep terrain both landslides density and erosion volumes were greater in stands which were clearcut in the previous nine years. On the other hand, stands between 10 and 100 years in age typically had lower landslide densities and erosion volumes as compared to forest stands older than 100 years. Landslides in clearcuts are not different in size than landslides in older forests. Because of the increased number of landslides, erosion volume in the 0 to 9-year age class was also increased in three out of four study areas.

There is no observable difference in landslide depth by age class. Therefore, if basal root reinforcement had an influence on slope stability, this influence was not large enough to be observed. This could indicate that other factors associated with removal of vegetation are more important than root reinforcement, that root reinforcement was similar across all age classes, or that root reinforcement is not dependent on soil depth.

There were great differences in landslide characteristics between the study areas. Some of the greatest differences were observed between the Elk Creek and Scottsburg areas. This occurred despite the fact that they are in the same geologic unit, experienced the same storm event, and are only separated by a distance of 10 to 15 miles. These two sites also had the most contrasting differences in the effects of stand age on landslide occurrence. These differences in landslide characteristics between and within study areas do not appear to help explain the differences in landslide occurrence by stand age.

COMPLIANCE WITH FOREST PRACTICES REQUIREMENTS FOR TIMBER HARVESTING ON HIGH RISK SITES

Current forest practice rules are designed to limit ground disturbances on high risk sites. These rules are intended to prevent local oversteepening and slope gouging by cable yarding. Rules also require operators to minimize slash accumulations on these sites, and especially in steep channels below high risk sites. The construction of skid trails on high risk sites is prohibited.

Physical disturbances related to logging practices include linear gouging (where logs are dragged during cable yarding and create a linear trench in the soil); construction of skid trails; and creation of slash (non-merchantable parts of trees). The survey crews identified any observable signs of these physical disturbances adjacent to the investigated landslides. Due to vegetative re-growth, it may not have been possible to identify all locations where physical disturbances (slope alteration) had occurred, especially in stands logged more a few years prior to these investigations.

Yarding gouging was not observed around any of the landslides investigated in this study. Skid trails were not found around any of the landslides in the younger stands (under ten years). However, a small portion of the old road category as listed in Table 8 might include skid roads rather than trucking roads.

Presence of slash was determined for the area immediately adjacent to the landslide scarp. This is the closest location to landslides and debris flows which was not altered by slope movement. Whether it is representative of the slash loading on the landslide, or especially in the debris flow path on steep hillslopes, is uncertain. Still, it remains the best data available about wood presence prior to failure. For these purposes, slash includes any wood of fine to moderate size on the ground above the landslide (logging slash or natural branches, limbs and chunks). It does not include individual large trees.

Figure 34 shows the distance debris flows traveled with and without measurable slash at the landslide initiation sites. This shows no difference in movement distances between those landslides with and without slash loading at the failure site. This figure does not say that slash/wood is unimportant in debris flow movement. The lack of a relationship between the presence of slash around the landslide and debris flow movement distance suggests that slash at the landslide initiation site is not a factor in movement distance. Wood in the channel may have a significant influence on debris flow/movement, but without measurements of wood prior to the debris flows, its significance cannot be evaluated.

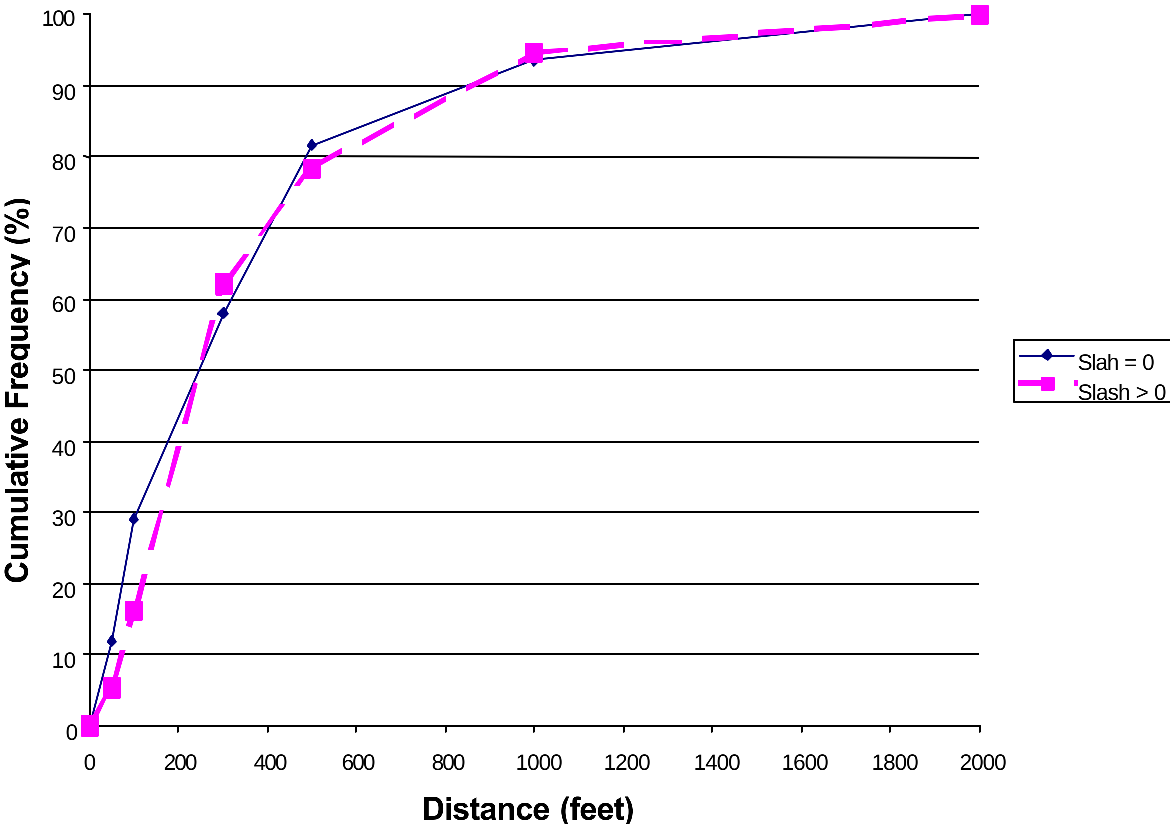


Figure 34. Percent cumulative frequency histogram for slash depth around initiating landslides versus distance traveled by debris flow for the November 1996 landslides.

Slash loading in the vast majority of cases in the November study areas was described as non-contiguous or sparse, meaning that woody debris is distributed so debris on the ground is not commonly covered by other pieces of debris. At only three of the landslides was slash loading greater than two feet in depth.

Summary

Based on this information, observable physical ground disturbance cannot be correlated with initiation of the non-road associated landslides. Any effects from forest management should therefore be related to removal of the vegetation. Also, although slash loading at the landslide initiation site was not a factor in debris flow movement, this does not rule out the possibility that wood lower in the debris flow or torrent path might be a factor in travel distance or severity of impacts. This information also means that operators complied with the forest practice rules for timber harvesting on high risk sites in the locations adjacent to the landslides identified in this study.

LANDSCAPE LEVEL DISTURBANCES IN THE CONTEXT OF THE KILCHIS WATERSHED

Logging is one means by which vegetation can be removed from hillslopes. On the larger (landscape) scale, major forest fires, windstorms, and volcanic eruptions can disrupt forests over large areas. These landscape level disturbances may also affect the recovery of forest vegetation over long periods since nearby seed sources are often eliminated.

The “Tillamook Burn” was used to place the landslide densities observed in this study into a major landscape disturbance context. The Tillamook Burn is actually an area that in some locations, had four wildfires burn through it over a period of about 20-years. The Tillamook study area is completely within the burned area. The Kilchis basin has been the focus of a recent watershed analysis, and is adjacent to the Wilson River basin (between 5 and 20 miles from the Tillamook study area). Figure 35 locates the Kilchis watershed in relation to the Tillamook study area. It consists of similar geology and slopes to the Tillamook study area.

Fires played a major role in the erosional processes and management of the upper two-thirds of the Kilchis watershed. The 1918 Cedar Butte Fire and the 1933, 1939 and 1945 Tillamook fires all burned in portions of the upper two-thirds of the basin. Salvage logging of burned timber in the Kilchis watershed began in the 1950’s and continued through the 1970’s.

As part of the Kilchis River Watershed Analysis, an aerial photo assessment of landslides was conducted (Tillamook Bay National Estuary Project, 1998). Aerial photographs of the Kilchis River watershed at 1:12,000 scale date to 1954. A landslide inventory was conducted using the 1954 aerial photos and three subsequent series of photos (including photos taken after February 1996).

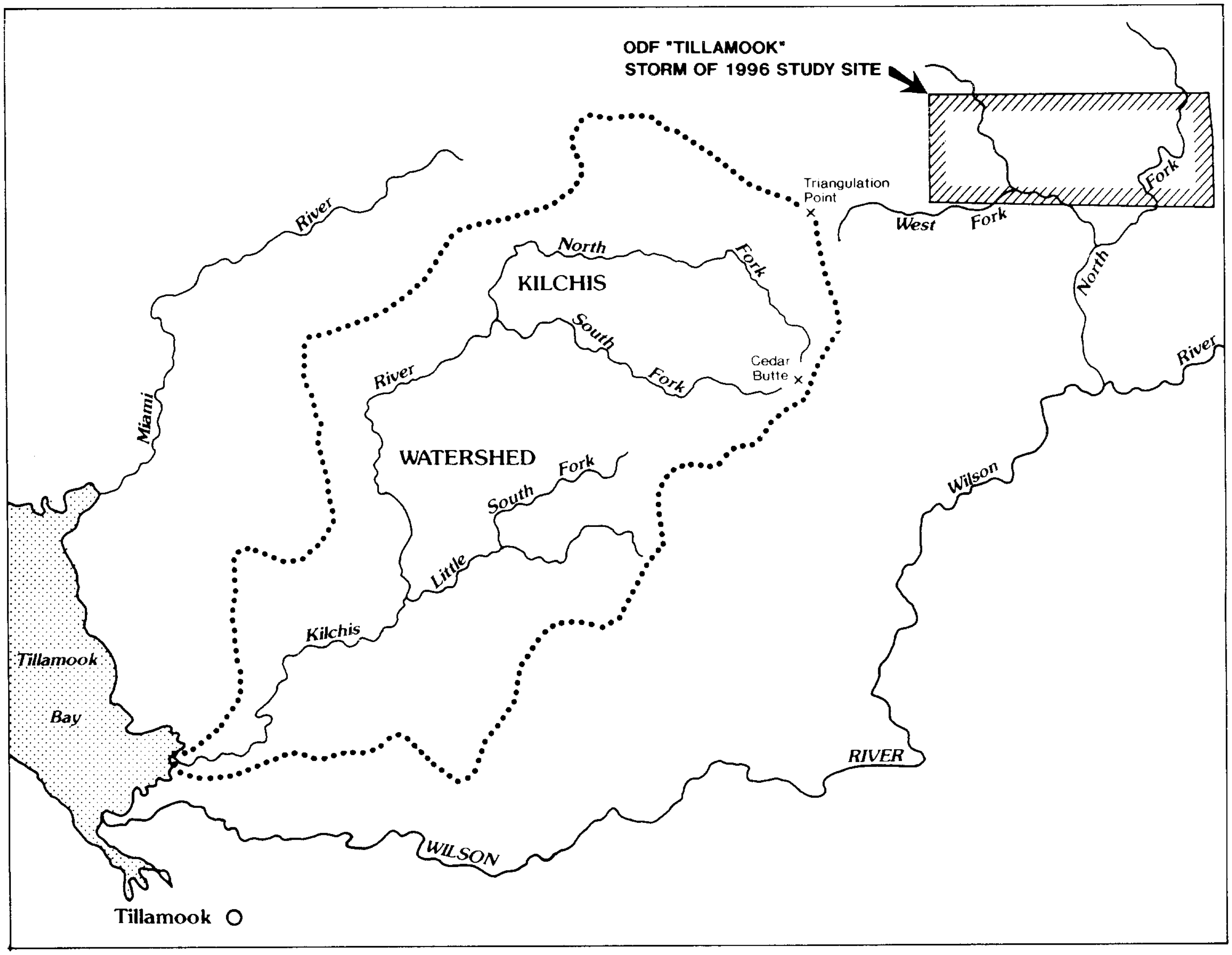


Figure 35. Kilchis watershed and location of Tillamook study area for this study.

A total of 1,403 different landslides were observed on the four series of aerial photographs. The earliest observed landslides probably date back to the first "Tillamook Burn" in 1933. A total of 505 landslides were observed on the 1954 photographs. These landslides occurred over a period of about 20 years (from the winter of 1934 to the winter of 1954). Although in subsequent photo series most identified landslides were associated with salvage logging and roads, the vast majority of the landslides (359 out of the 505) observed on the 1954 photos were in burn areas that had not been salvaged logged or covered by roads. Note that the methods used to identify landslides (interpretation of aerial photographs) almost certainly had a significant influence on the number of observed landslides. Vegetative regrowth and erosional processes would have obscured many of the landslides that actually occurred. Based on the information in the aerial photo chapter of this report, it is estimated that at best only one-third of the actual landslides were observed on the aerial photographs. This means there were potentially 1,150 landslides in the non-salvaged (at that time) 26,000-acre burned area of the Kilchis watershed.

A graph of annual peak flows from the Wilson River (Figure 36) indicates that there was only one potential large landslide producing storm between the early 1930s and 1954 as this was an uncharacteristically dry period. The largest flood over this time period occurred during December 1933 and had peak flows considerably smaller than the 1996 storm. Even though this period was relatively dry, the estimated landslide density from the recently burned landscape was nearly three times greater than identified in the Tillamook study area from the 1996 storm (28 landslides per square mile versus 10 landslides per square mile in the Tillamook study area). In the ODF study, only the Elk Creek study area had a landslide density similar to that identified in the Kilchis watershed. These densities are not directly comparable. The Kilchis density reflects a 20-year period with perhaps no unusually large storm events, while this study evaluated only landslides from a single extreme storm. The Kilchis watershed landslide density illustrates that disturbances such as fire (which can be a natural part of the ecosystem) may also greatly affect landslide occurrence on an order of magnitude similar to what was observed in this study.

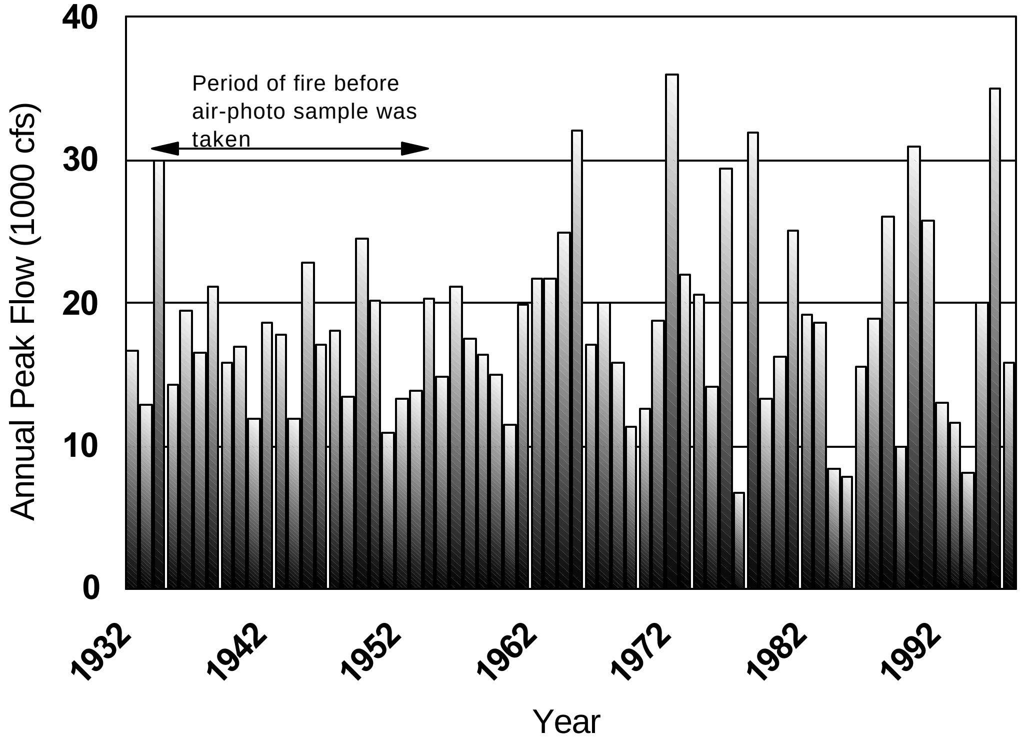


Figure 36. Annual peak flows for the Wilson River near it mouth for the history of the stream-flow gage.

The high number of landslides observed in the burn area was expected. Up to four wildfires killed much of the original forest, and then killed regenerating vegetation. The landslide density listed above (mostly debris flows) does not reflect roads and salvage logging. Many more landslides occurred between 1954 and 1962, a period of unregulated road construction and salvage logging when roads and skid trails were constructed over very steep slopes, excavated and waste materials were left on these steep slopes, and drainage systems were not installed.

Summary

Both logging associated and natural disturbances can increase landslide densities. However, the nature of these disturbances can still be different. It is likely that the time required for conifer forests to occupy large areas where seed sources are scarce (large forest fires, for example) will be much greater than in a stand where timber harvesting is immediately followed by intensive reforestation efforts. Another major difference is the fate of the large trees. Forest management disturbances remove most of the trees, while dead trees remain on the landscape in the natural setting. Large wood provides important structure and complexity to aquatic ecosystems.

ROAD ASSOCIATED LANDSLIDES

This section of the report describes those landslides that were associated with forest roads (including currently used and abandoned features that are currently used or had been used in the past for log haul by truck or railroad). Past studies have shown that most landslide related impacts on forestlands were related to roads (Megahan and Ketcheson, 1996; Ice, 1985). For this reason, roads are the current focus of the forest practice rules for landslide prevention. Forest roads are also the focus of an ongoing "road hazard and risk reduction project" currently being implemented by most major forestland owners in Oregon.

The following questions are addressed in this section:

- Were the road associated landslides different from the other landslides identified in this survey?
- Were the road associated landslides different from road associated landslides found in other studies?
- Are there many landslides associated with abandoned roads?
- Do certain practices appear to be causing these road-associated landslides?
- What are the implications for forest road managers?

Two Survey Protocols

Landslides associated with roads were surveyed using two different methods. The road crew drove, bicycled, or walked all active roads. For the purpose of this study, active roads were maintained in a driveable condition prior to the storms of 1996. The road crews surveyed all the active roads within the original 10 square mile areas of the original six February study areas only. The road crew classified the entire road length by drainage segments, slope, and construction practices. The stream crews surveyed debris flows that resulted from active road landslides and also surveyed both initial landslides and subsequent debris flows that entered channels and initiated in the road prism of "old" roads (abandoned and unmaintained) in all eight study areas. The stream crew surveyed landslides in the "core areas" (less than the original ten square mile areas) that delivered sediment to channels, while the road crew identified all landslides (exclusive of small bank sloughs) regardless of delivery to a stream channel.

Awareness of the different survey methods is critical when comparing numbers of road-associated landslides. Each table is clearly marked with the data sources. Landslide data vary between the road and stream survey crews. Stream crew data include only those landslides that delivered to channels. Road crew data include only the volumes of the initial landslides (no debris flows). The only accurate measurement of road mileage (for active roads only) is in the road crew data. The road crew data also contain the only information on road design, construction and maintenance practices. All stream effects information and all "old" road associated landslide data are found in the stream crew database.

Active Road Characteristics

Table 17 summarizes the road crew survey data. Active road length in the 60 square mile survey area is 170 miles. The Vernonia study area has the greatest mileage (46) while Tillamook has the least (17.8 miles). Average active road density is 2.8 miles per square mile (2.1 miles per square mile in the red zones and 3.6 miles per square mile in the stratified random study areas). Average natural side slope just below the road is 40% overall, greatest at Mapleton (74%) and gentlest at Estacada (18%). Roads (including the surface, cut and fill slopes) cover 1.6 percent of the landscape in the red zones, and 2 percent of the landscape in the stratified random study areas (1.8 percent overall). It is important to note, however, that there are large areas in the Vida and Mapleton red zone study areas that do not contain roads. The road density in the managed portions of these study areas may have been significantly greater than the averages reported here, at least for the Mapleton and Vida study areas.

Eighty-five road-associated landslides were found during the road survey. Twenty-nine of these landslides occurred in the Mapleton study area and none in the Estacada study area. These totals include all active road-associated landslides, not just those delivering sediment to stream channels. Fourteen of these road-associated landslides were smaller than 10 cubic yards (nine of these small landslides were in Mapleton). Fifty-nine washouts were also identified during this survey. A washout is the loss of road prism due to fluvial processes. In most cases, washouts are related to stream flow diverted down or across the road at stream crossing locations, and are often related to problems with the way the drainage system on the road was designed (or not designed). Washouts also include fill erosion by streams below the road. The Tillamook study area has more than half of the total washouts (36) while Estacada has no washouts.

For the six ten square mile study areas, there was an average of 0.5 landslides per mile of road and an average 0.35 washouts per mile of road. The Mapleton study area had the greatest road-associated landslide density (1.57 landslides per mile of road) followed by Vida at 0.85 landslides per mile of road and Tillamook at 0.56 landslides per mile. For the stratified random study areas, Vernonia had a landslide density (0.43 landslides per mile) near Tillamook, while Dallas was much lower at 0.14 landslides per mile.

Table 17. Characteristics of road associated landslides in the six 10-square mile February storm study areas.

	Red zone Study Areas			Random Study Areas			Total
Road Length Characteristics	Mapleton	Tillamook	Vida	Vernonia	Dallas	Estacada	
Road Length (mi)	18.4	17.8	25.9	46.0	28.3	33.4	170.0
Road Density (mi/mi^2)	1.8	1.8	2.6	4.6	2.8	3.3	2.8
Segments	192	160	284	380	198	284	1498
Average Side Slope (%)	74	54	51	27	46	18	40
Landslides and Washouts							
Landslides	29	10	22	20	4	0	85
Slides/road mile (#/mi)	1.57	0.56	0.85	0.43	0.14	0	0.50
Initial Landslide Volume	84	62	96	182	53	0	99
Washouts (#)	3	36	10	4	4	0	59
Washouts/ Road mile (#/mi)	0.16	2.02	0.39	0.09	0.14	0	0.35
Number of Failures							
Total Failures	29	46	32	24	8	0	144
Failures per road mile	1.73	2.58	1.24	0.52	0.28	0	0.85
Landslide Types							
Fill slope	18	7	15	16	3	0	59
Cut Slope	8	3	7	4	1	0	23
Below Fill	3	0	0	0	0	0	3
Road Drainage Related	11	3	8	7	2	0	31

Table 17 also shows the average volume of the road related landslides. This is the initial volume only and <u>does not</u> include debris flow volume. Average initial landslide volume varied from 53 cubic yards in Dallas to 182 cubic yards in Vernonia (there were no landslides in Estacada). These are the stratified random study areas. There was less variability in the red zone study areas. The average road associated landslide volume was between 62 and 96 cubic yards.

The Tillamook study area had 36 washouts compared to only 10 landslides. There were 10 washouts in Vida; all other study areas had four or fewer washouts. Due to the washout rate in Tillamook, it had the highest combined landslide/washout failure rate (2.6 failures per mile of road). The next highest failure rate was Mapleton at 1.7 failures per mile of road.

Almost all past studies have found road-associated landslides to be much larger than non-road associated landslides. Although it is not clearly reported in these studies, they generally only measured initial landslide volume and included only landslides over a certain volume (often ten cubic yards) regardless of their entry into streams. For Cascade Range study areas, Swanson and Dyrness (1975) found an average road-associated landslide volume of 1,767 cubic yards in the H.J. Andrews Experimental Forest east of Eugene. Morrison (1975) determined an average road-associated landslide volume of 1,868 cubic yards for a sample of roads in the western Cascade Mountains (Table 18). For the Vida area in this study, average road-associated landslide volume (for core area delivering landslides) was 96 cubic yards.

Table 18. Oregon studies of road associated landslides.

Locations/Studies	Practices	Average Landslide Volume (yd3)	Erosion Rate (yd3/acre/yr)
Coast Range Mountains			
Swanson et al. 1977	old	505	8.4
Sessions et al. 1987	old	285	NA
	new	111	NA
Cascade Mountains			
Swanson and Dyrness, 1975	old	1767	9.95
Morrison, 1975	old	1868	82.3

For the Mapleton area, Swanson and others (1977) found an average road-associated landslide volume of 505 cubic yards. For the steepest landforms in their study area near Mapleton, Sessions and others (1987) found an average landslide volume of 285 cubic yards on roads constructed using older construction practices, and an average volume of 111 cubic yards for roads constructed using newer design and construction practices. Initial road-associated landslide volume for the Mapleton study area in this study was 84 cubic yards.

Based on previous studies and the results from this study, active road-associated landslides appear to be smaller than similar landslides occurring two decades ago. However, this finding is tempered by the fact that other studies may have measured landslides differently. Total landslide volume (see following section) for landslides delivering to stream channels is much larger than the initial landslide volume of these road associated landslides. Unfortunately, it is generally not clear from the earlier studies how or if they considered debris flow volume.

These data suggest that as slopes become steeper, fewer roads are constructed. However, the roads that are constructed on steep slopes tend to disturb more area on a per mile basis (because of the necessity for larger cuts and fills). Therefore, the net ground area disturbed by road systems constructed in steep areas may in some cases be similar or greater to that area disturbed by roads on less steep slopes. The greatest road-associated landslide and washout densities were found in areas with steep slopes. However, even on these steep slope areas, landslide occurrence was highly variable.

Core Area Landslides

The previous discussion applies to all landslides observed on open roads in the February study areas. The following discussion relates to those road-associated landslides which delivered sediment to channels in all eight study areas. This discussion also includes landslides from old (abandoned or vacated) roads. In most cases, there is no reliable information on the total length of old roads in the study areas. Elk Creek is the one exception, where road mileage reflects the total of active and old roads.

A total of 37 active road and 20 old road-associated landslides (with sediment delivery to streams) occurred within the core study areas (45.8 square miles) as shown in Table 19. While this is far fewer than the 449 non-road associated landslides, note again that roads make up less than about two percent of the total land base. On a per mile basis, there were 0.28 delivering landslides per mile of active road in the core areas. This is just over half of the 0.5 landslides/mile determined from the road survey, indicating that about half the road-associated landslides deliver sediment to stream channels. Mapleton and Tillamook had similar delivering landslide densities (0.76 and 0.72 landslides/mile, respectively), even though Mapleton had a much higher density of total active road associated landslides (see Table 17). Therefore, the road-associated landslides that occurred in Tillamook were much more likely to enter stream channels than were road-associated landslides in Mapleton.

The two November study areas had fewer active road-associated landslides than did the February red zone study areas. This is especially true for the Elk Creek study area, where there were only two active road landslides in the entire 6.5 square mile study area. The Elk Creek study area had 0.19 landslides per mile of road compared to the non-red zone study areas of Dallas (0.19 landslides per mile) and Vernonia (0.12 landslides per mile) despite the fact that it has many roads (36.3 miles) and had the greatest density of non-road associated landslides (152).

Table 19. Road-associated landslide core areas that delivered to stream channels.

	Red zone Study Areas					Random Study Areas			
Summary Information	Elk	Scottsburg	Mapleton	Tillamook	Vida	Vernonia	Dallas	Estacada	All sites
Active Roads									
Number of landslides	2	5	13	7	6	2	2	0	37
Landslides per square mile	0.31	0.69	1.57	1.56	0.85	0.59	0.65	0	0.81
Average Volume (yd^3)	630	2309	330	4515	2482	620	84	-	1755
Erosion (yd^3/acre)	0.30	2.51	0.80	10.97	3.28	0.57	0.08	0	2.22
Road length (miles)	36.3*	NA**	17.0	9.8	22.3	17.0	10.6	16.9	129.9
Landslides per road mile	0.19	NA**	0.76	0.72	0.27	0.12	0.19	0	0.28
Road right of way erosion (yd^3/acre)	14.0	NA**	34.3	444.8	92.0	10.0	2.2	0	59.1
Old Roads									
Number of landslides	5	6	1	5	0	1	2	0	20
Landslides per square mile	0.77	0.83	0.12	1.11	0	0.29	0.65	0	0.44
Average Volume	487	1276	191	1763	-	25	17751***	-	2734
Erosion (yd^3/acre)	0.59	1.66	0.04	3.06	0	0.01	27.74***	0	1.87

*Road length in Elk includes active and inactive road total.

**Road length not available in Scottsburg

***Very large landslide; probably not caused by road.

Average total volume (including the debris flow) for the active road-associated landslides varied from 84 cubic yards in Dallas to 4515 cubic yards in Tillamook. Much of the road-associated landslide volume was related to a few very large landslides. The largest active road landslides were 11,400 cubic yards in Scottsburg and 11,200 cubic yards in Tillamook. The largest landslide found in this study was 32,000 cubic yards and associated with an old road in the Dallas study area. For at least the Dallas case, this landslide covered an area much larger than the road prism and, based on professional judgment, movement was not significantly related to that road. However, most of the other road-associated landslides that entered stream channels were more clearly related to failure of fill/sidecast material. These road-associated landslides, although relatively few in number, were much larger than the non-road associated landslides. In terms of mean values of the initial landslides, the active road landslides were 4.3 times the size of the non-road slides.

Excluding Dallas (because it includes a very large landslide that was most likely only coincident in space to the road), average total landslide volume for the old road-associated landslides varied from 25 in Vernonia to 1763 cubic yards in Tillamook. In all cases (except Dallas) the old road-associated landslides were smaller than active road-associated landslides.

Even though the road associated landslides identified in this study appear to be much smaller than road-associated landslides found in past studies, active road landslides are still about four to five times the size of the non road-associated landslides. Old road-associated landslides are typically smaller than the active road landslides. Based on the low numbers of road-associated landslides surveyed in this study and on the smaller sizes of these landslides (as compared with previous studies), it appears that current road management practices are reducing both the size and number of road-associated landslides. Since there are not many post 1983 roads in this survey, these reduced numbers may be related to better maintenance and road reconstruction practices. As the most unstable portions of road systems have failed, they apparently have been reconstructed using current practices.

Factors Associated with the Road Landslides

The road crew collected information on road construction and drainage practices around the landslides in particular, and for all roads in the survey area in general. Few roads were constructed since 1983 (when the latest landslide prevention rules became effective), so it was not possible to analyze these data by construction period. However, there is a reasonably good sample of different excavation and drainage practices, so this analysis deals with drainage water discharge locations and cut and fill practices in proximity to the surveyed landslides.

For the 85 landslides surveyed by the road crew, 23 were failures in the cutslope, 56 in the road fill, three included all or most of the road prism, and three occurred below the fill (Figure 37). The cutslope failures generally did not enter streams and were smaller in volume. The 56 fill failures were typically shallow translational debris slides and the three deep seated landslides were slumps or earthflows.

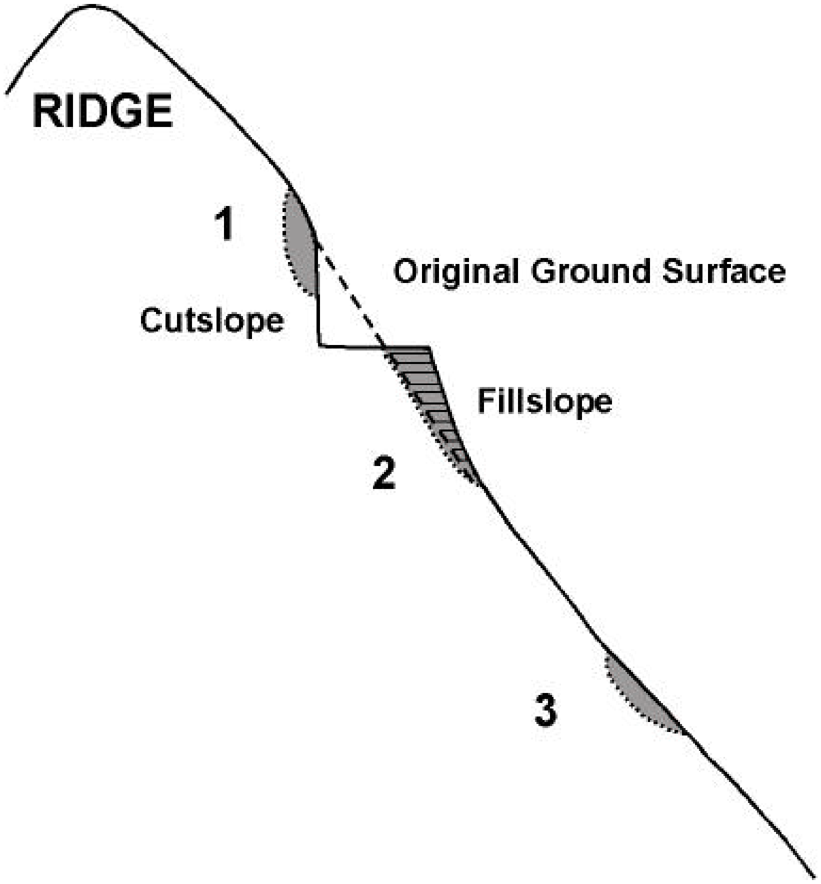


Figure 37. Typical locations of road associated landslides surveyed in this study.

1) *In the cutslope.*
2) *In the fillslope.*
3) *Associated with drainage discharge and below the fill.*

Of the 59 shallow translational landslides (including the three landslides well below the fill) 28 were not associated in any way with road surface water drainage. Precipitation and groundwater flowing through the soil and/or rock were the principal water sources for these 28 landslides. The other 31 shallow landslides were associated in some way with road surface water drainage. Fourteen landslides occurred at or near culvert locations, five at other types of road drainage features (waterbars, dips, etc.), eight at locations where cutslope slides filled the ditch and may have diverted water across the road, and four at locations where uncontrolled surface water left the road. Twelve of the 31 drainage-associated landslides occurred where water had been diverted from its design flow path. Seven of the 12 drainage/diversion associated landslides were associated with culverts that had been filled or otherwise blocked.

In addition to road drainage, the other factors most commonly associated with these landslides were slope steepness, cutslope height, and fill depth. Figure 38 shows the failure rate by road segment for different categories of slope steepness. A segment is a section of road where the water all drains to the same location. This figure shows the greatest failure rate on the steepest slopes (over 89%) with a similar failure rate for slopes between 70% and 89% (both with 12 to 14 percent of the segments having a landslide). Slopes between 30% to 49% had a much lower failure rate (3.5) percent while only one percent of the

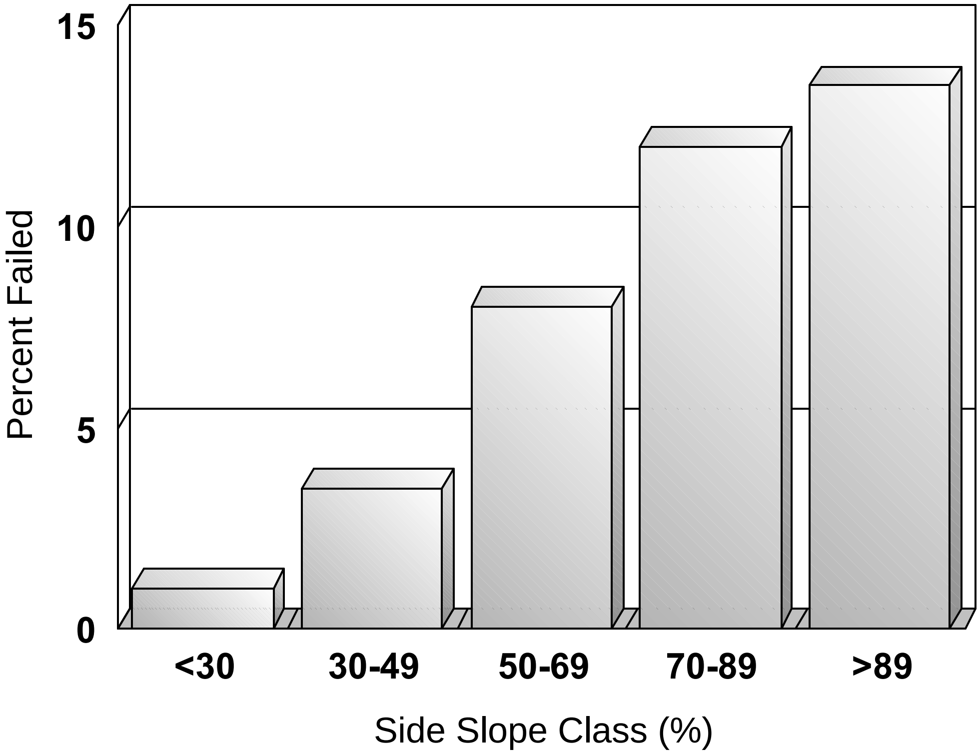


Figure 38. Failure rate by slope steepness for all road-associated landslides in the 6, 10 square mile February study areas.

segments with slopes under 30% had landslides. Note that these values include both deep seated failures and cutslope-associated landslides. Looking only at fill related landslides, the highest incidence of failure occurred on slopes between 70% and 79%.

Figures 39 and 40 show the fill depth for the drainage-associated and non drainage associated landslides on fill slopes steeper than 50%, respectively. Fill depth does not appear to be a major factor in the drainage-associated landslides since 13 percent of the road segments with landslides occurred where the fill depth was one foot. This is a higher failure rate than experienced by road segments with deeper fills. However, for the landslides not associated with surface water drainage, there does appear to be a relationship between fill depth and landslide occurrence. The failure rate gradually increases as fill depth increases, reaching a 6.5% failure rate of fill depths of over 5 feet.

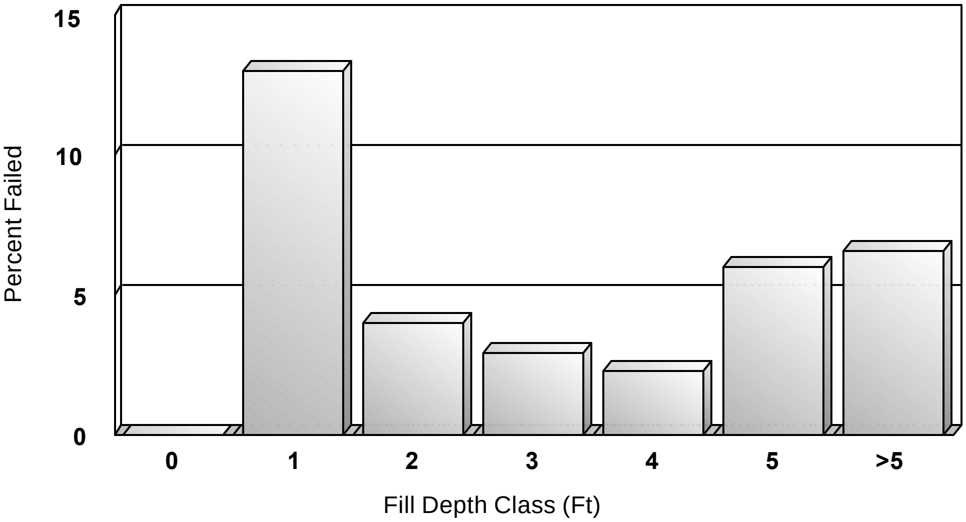


Figure 39. Fill failure rate by fill depth class for roads on steep slopes (over 50%) at locations of drainage discharge.

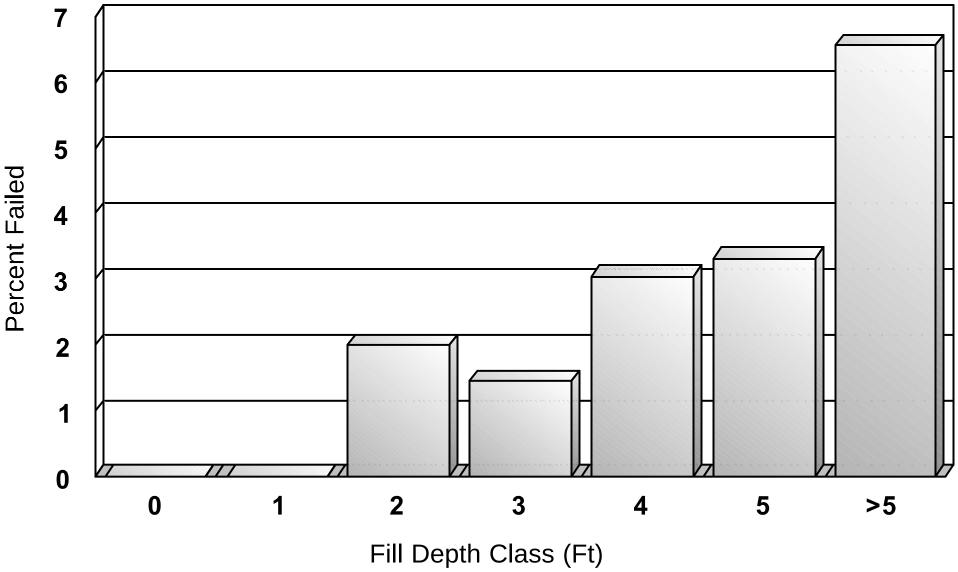


Figure 40. Fill failure rate by fill depth class for roads on steep slopes (over 50%) at locations <u>without</u> drainage discharge.

Figures 41 and 42 show the height of the cutslope for the surface drainage associated and non drainage associated landslides, respectively. Cutslope height appears to be a major factor in the surface water drainage associated landslides, with almost 22% of the failures occurring where cutslope height exceeds 17 feet with all other height categories having a failure rate of under 6%. For the non drainage associated landslides, the greatest failure rate (4.25 percent) was in the 6 to 11 foot height class and there were no failures in the over 17 foot class. This indicates that cutslope height and surface water drainage combine to become a very important factor contributing to landslide hazard.

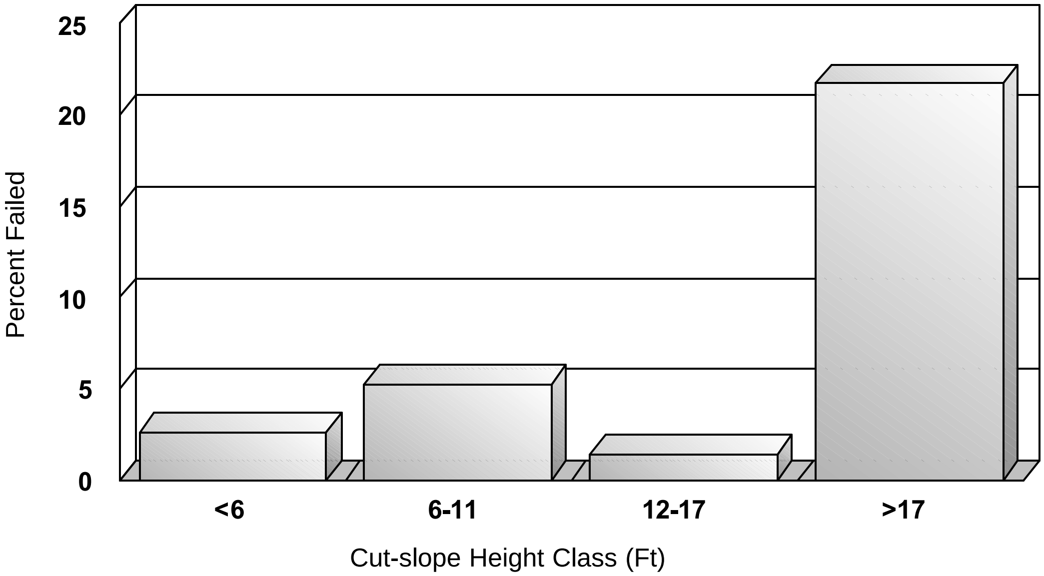


Figure 41. Fill failure rate by cutslope height for roads on steep slopes (over 50%) at locations of drainage discharge.

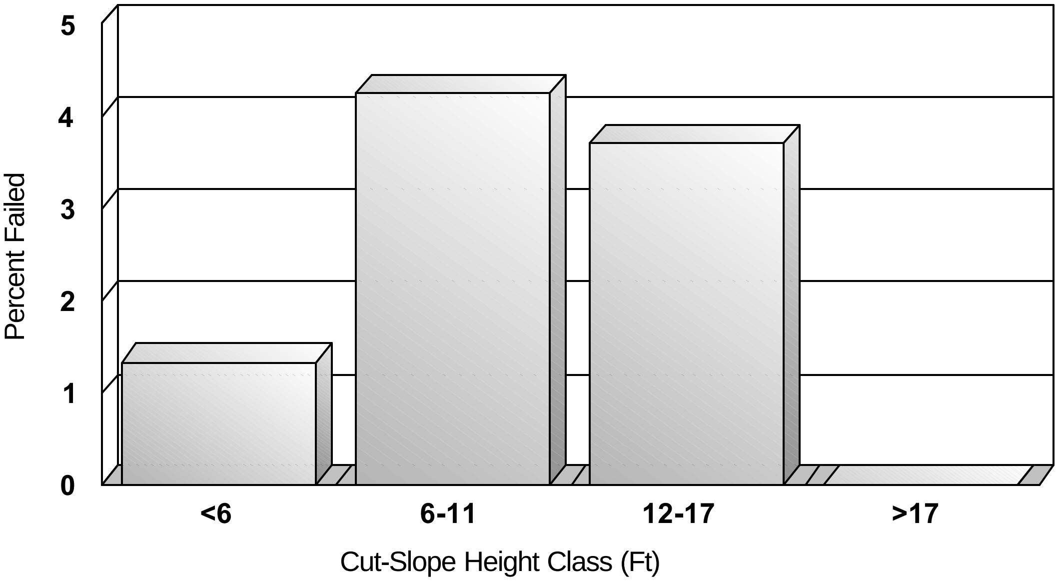


Figure 42. Fill failure rate by cutslope height for roads on steep slopes (over 50%) at locations <u>without</u> drainage discharge.

Data on slope position (valley, ridge or midslope) did not indicate a correlation between landslide occurrence and road position on the landscape. This result may be related to data collection methods, because the field crews classified almost all roads as midslope. These data reinforce prior studies that found that slope steepness below the road, fill depth, and drainage practices are the major factors that can contribute to road associated landslides. To our knowledge, cutslope height has not been previously identified as a factor associated with landslides <u>below</u> the road. Other factors (geology, land type, and road width (Megahan and others, 1979)) may have also influenced the occurrence of these road-associated landslides, however the data set is too small to make such determinations.

Summary and Implications for Road Management

Road associated landslides were typically about four times larger than non road associated landslides. However, these road-associated landslides were smaller than landslides associated with roads as found in prior studies. Landslides associated with old roads (sometimes called abandoned or legacy roads) were typically smaller than the landslides associated with actively used roads.

Although this sample of road associated landslides is small, it does suggest some relationships important to road managers. Most obvious, roads on steep slopes have the majority of the landslides. When drainage waters are not directed to a site, keeping fill off steep slopes appears to reduce landslide hazard. However, at sites where there was drainage water, either intentionally discharged by a culvert or other relief structure, or through drainage system blockage, landslides occurred regardless of fill depth.

The following considerations are based on a general review of all the road data, including notes from the road and stream crews:

- Good drainage can reduce the landslide hazard, however, drainage systems must be functional during storms to prevent road-associated landslides. While it is not clear that any specific drainage spacing criteria are appropriate for hazard reduction, results indicate that it is critical to keep all drainage waters off of the steepest slopes.

- High cutslopes are more likely to experience failures that block ditches, sometimes directing drainage waters to landslide prone locations.

- It is not clear how many drainage blockages were due to a lack of routine maintenance or how many occurred during storm events. Timely correction of drainage (which may be neither safe nor possible in a major storm) might have prevented as many as 12 (or 14 percent) of these landslides.

- Slope, landform, and fill depth should be evaluated prior to locating or relocating cross drainage structures. Even a small length of road draining to a marginally stable slope appears to greatly increase the likelihood of landslide occurrence.

- Areas with old roads on slopes steeper than 70% should receive a priority for upgrading (by removing unstable fillslopes and through improved surface water drainage), especially when opening up old roads on these slopes.

- Damaging landslides are unlikely for roads constructed on slopes of less than 50% sideslope if these roads have frequent and properly sized drainage structures and also use minimum and balanced excavation practices.

- Fill placed on steep slopes creates an increased landslide hazard even where no surface drainage water is directed to those fills.

RESULTS SECTION THREE: STREAM CHANNEL IMPACTS RELATED TO LANDSLIDING

As stated earlier, landslides can have significant effects on channel morphology and aquatic habitat. The fact that crews used the channel to survey for landslides provided an opportunity for stream channel measurements to document the extent and some of the characteristics of landslide related stream channel effects. The overall objective was to evaluate the extent of stream channel impacts due to these storms as well as the specific landslide and topographic factors that contributed to stream channel impacts. More specifically, the following questions are addressed:

- How extensive were the channel impacts for the study areas evaluated and how does this compare with past studies?
- Were the channel impacts fairly consistent within and between the study areas? If there was variation, what might some of the factors be that led to the variation?
- What were some of the observed differences between stream reaches impacted by landslides from those that were not?
- How did these channel impacts vary between sites that had mature adjacent riparian stands versus those that were recently harvested?
- What effects did debris torrents have on near-stream riparian conditions such as shading? Did these effects differ when tree stands adjacent to the stream were recently harvested as compared to those with more mature stands?
- What effects did recent timber harvesting have on slash loading?
- How far did landslide-related debris torrents travel and what factors predict travel distance?

Overall there were 145 miles of stream channel surveyed. The channels measured varied in stream order from one to six, in channel width from less than 1 to 99 feet, and in channel slope from 0-110% (Table 20). Most of the surveyed channels occurred in the deliberately chosen "red zone" study areas (118 miles out of 145 miles measured).

EXTENT OF STREAM CHANNEL IMPACTS DUE TO LANDSLIDING

The type of impact that occurred during the 1996 storms were delineated for each measurement point along the stream channel. In all there were 11 subtypes classified into three broad disturbance levels; low, medium and high (Appendix C). A highly impacted channel was characterized by massive scour and/or fill and overturn of sediments along with considerable damage to the vegetation along the edge of the channel. In order to have this level of impact, a debris flow, debris torrent, or debris flood (Benda, 1985) would have to occur. Overall, 32% of the total of the 145 stream miles surveyed had high impacts due to landslide related effects (Table 20). For the deliberately chosen high impact "red zone" study areas, this percentage increased to 37% (Figure 43). For the three stratified random areas the percentage was 10% (Figure 43). Among the five high impact study areas, there was large variation between the percentage of stream miles highly impacted (Figure 44). Mapleton and Elk Creek had relatively low percentages of stream channels highly impacted (22% and 29%, respectively). In contrast Tillamook, Vida, and Scottsburg had 66, 40, and 73% of the channel network in high impact types, respectively (Figure 44). The two November 1996 study areas differ greatly in terms of channel impact (29 Elk Creek vs. 73% Scottsburg) even though they are geographically near, geologically similar, and influenced by the same storm.

There are large percentages of highly impacted stream lengths between individual study areas (Figure 44). The large differences in percentage of stream miles impacted may be due to the patchy nature of the February storm and because of the differences between the February and November storms. In the Tillamook area, there were more road washouts than all the other study areas combined. This may indicate that a relatively larger rainfall event occurred in Tillamook as compared to Vida and Mapleton. This difference in washouts could also be due to differing road practices or differences in geology. The Tillamook study area is underlain by basalts while Mapleton is underlain by sandstone. In Vida, there was one very large road associated slide (that initiated outside the core study area) that influenced several miles of the main channel.

Table 20. Length of channel measured, length of channel in high and low storm related impacts, ranges of channel measurements taken for all eight study areas.

				Ranges		
Study Area	Length Measured (miles)	Length High Impact (miles)	Length Low Impact (miles)	Stream Channel Orders	Channel Widths (ft)	Channel Slope (%)
February Storm "Red Zone" Areas						
Mapleton	38.3	8.4	29.4	1-4	<1-45	0-68
Tillamook	11.9	7.9	4.0	1-6	<1-80	0-85
Vida	20.0	8.0	12.0	1-4	<1-55	0-50
Total	70.2	24.3	45.4	1-6	<1-80	0-85
February Storm Random Study Areas						
Dallas	7.3	2.3	5.0	1-2	<1-30	0-50
Estacada	9.9	0.1	9.8	1-3	<1-44	0-45
Vernonia	10.5	0.4	10.1	1-3	<1-55	0-50
Total	27.7	2.8	24.9	1-3	<1-55	0-50
November Storm Study Areas						
Elk Creek	35.6	10.5	23.0	1-4	<1-99	1-99
Scottsburg	11.8	8.6	1.0	1-3	<1-50	1-110
Total	47.5	19.1	24.0	1-4	<1-99	1-110
Grand Total	145.4	46.2	94.3	1-6	<1-99	0-110

Road associated landslides were wholly or partially associated with a large percentage of the highly impacted stream channels at the Tillamook, Vida, and Scottsburg study areas (Figure 45). At the same time, roads were associated with a very low percentage of stream channel impacts at the Mapleton and Elk Creek Study areas (Figure 45). For

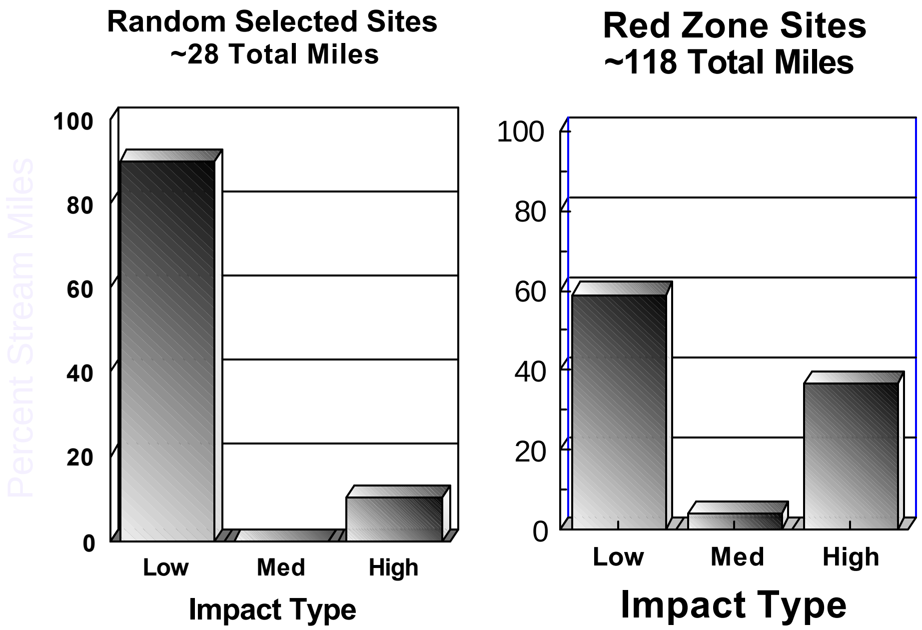


Figure 43. Percent of streams in high, medium, or low impacts for five deliberately chosen “red zone” study areas (Elk Creek, Mapleton, Scottsburg, Tillamook, and Vida) along with stratified randomly selected study areas (Dallas, Estacada, Vernonia).

Tillamook, Vida and Scottsburg it appears that road associated slides account for farm more impacted channel length than their numbers would indicate. One reason for this increase in effect could be that road associated landslides are four to eight times as large as non-road associated landslides in volume.

Another reason is a few road associated landslides were located in positions in the watershed that had favorable junction angels (see Debris Torrent Travel Section) such that they could travel long distances before terminating. As an example, one slide at the Vida study area initiated upstream of our study area and carried through to beyond the downstream end of the study area totaling several miles. Another example is a road associated landslide initiated in the upper watershed at Scottsburg and carried all the way to the bottom of the watershed.

Summary

The extent of landslide related channel impacts was extremely variable between sites. The percentage of channel length surveyed (32%) with highly impacted stream channels was greater than found in past studies (i.e., Ketechson and Froelich, 1978 and Swanson et. al. 1987). The percentage of landslide impacted channels related to road associated landslide activity was quite variable but remarkably high especially at the Vida, Scottsburg and Tillamook study areas because roads made up only a small percentage of the total population of landslides.

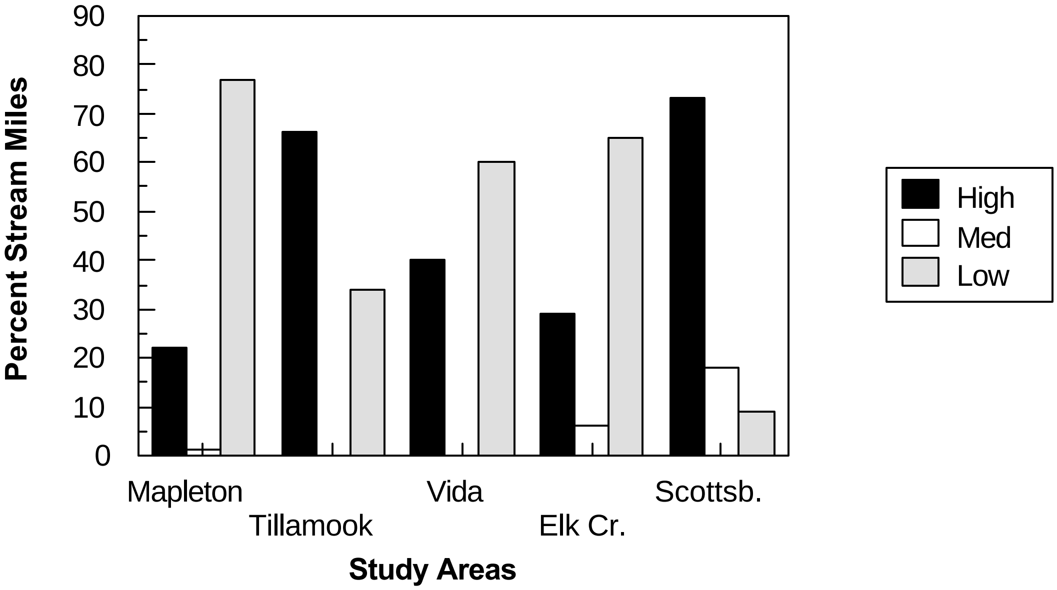


Figure 44. Percentage of different channel impact types for each of the five deliberately chosen "red zone" study areas.

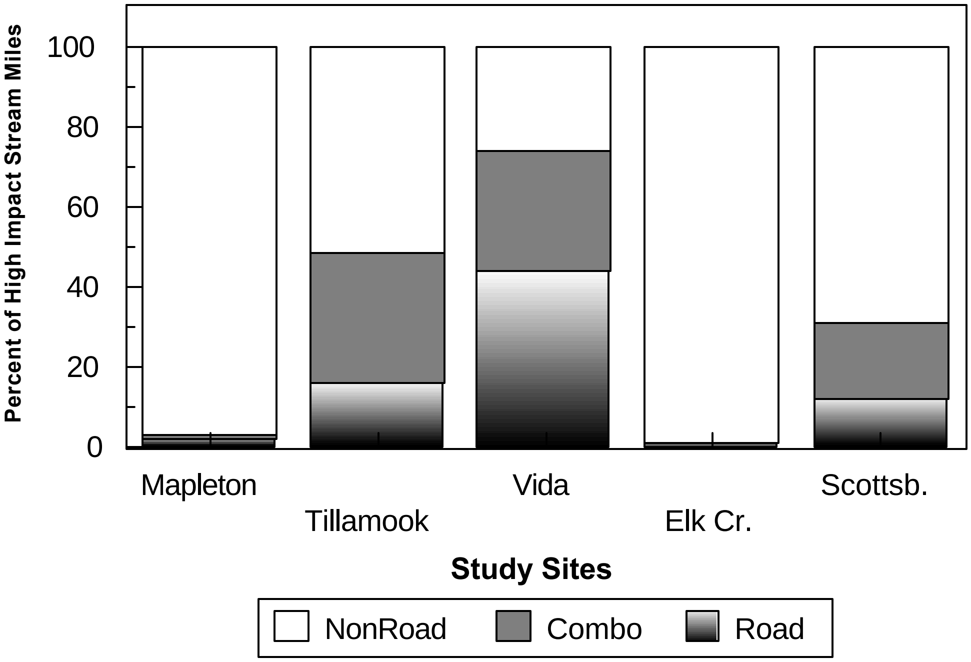


Figure 45. Extent of highly impacted stream length that had impacts either wholly or partially caused by road associated landslides and resulting debris flows and torrents.

DIFFERENCES BETWEEN HIGH AND LOW IMPACT STREAM REACHES

Field crews measured several features related to stream channel morphology as they used the channel network to search for landslides. Key measurements include the width of impact, active channel width, stream slope, and stream shading. These parameters are known to change as watershed size increases, thus stream channel order was determined for all measurement points to allow for stratification by watershed area. Stream channel order, based on the Strahler ordering system (Dunne and Leopold, 1978) was determined based on field measures of stream channels. Therefore, the reported stream orders in this study will necessarily become larger than those compiled from 1:24,000 scale maps because the drainage density is greater when measured on the ground. It should also be noted that the drainage densities obtained in this study are not absolute because crews stopped measuring channels when they reached a sustained slope at 40% and had low impacts.

Impact width refers to the width that high water or debris impacted the channel and banks. As would be expected, impact widths were consistently greater for streams impacted by debris torrents as compared to non-impacted stream channels across all stream orders (Figure 46). In order to test for significance, the impact widths were log transformed to obtain more normal distributions (Engelman, 1997) to meet assumptions for using an un-equal variance t-test. In every case, a highly significant ($p < 0.01$) difference was found between debris torrent impacted reaches as compared reaches having minor impacts for the log transformed impact width (Table 21).

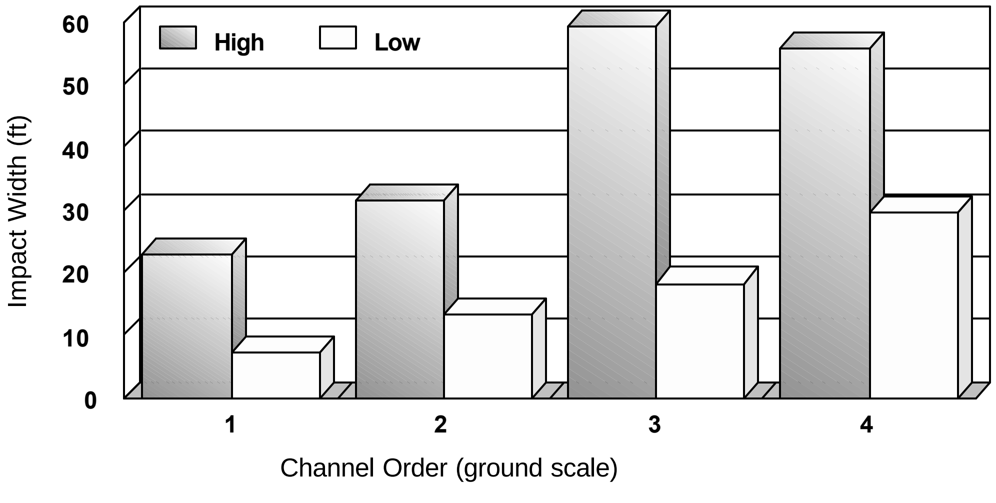


Figure 46. Average impact width for streams that were highly impacted by debris torrents and dam-break floods associated with the storms of 1996 compared with streams that had little or no storms of 1996 related impacts.

Table 21. Significance results in testing the differences in widths, slopes and shading between streams that were highly impacted by debris torrents and dam-break floods associated with the storms of 1996 compared with streams that had little or no impact.

	T-Test Results for Log Transformed Values			**KS Test Results**
Channel Size	Impact Width	Active Width	Channel Slope	Shade
	(ft)	(ft)	(%)	(%)
First Order	HS	HS	HS	HS
Second Order	HS	S*	HS	HS
Third Order	HS	HS	HS	HS
Fourth Order	HS	HS*	HS	HS

*Note: HS- Refers to highly significant $p < 0.01$ and S refers to significant $p < 0.05$. All highly debris torrent impacted streams were greater in impact and active channel width and slope than low impact streams except where * is noted. All highly debris torrent impacted streams had lower average shade values but the distributions tended to be bi-modal so the cumulative frequency distributions were tested against each other using the Kolmogorov-Smirnov two sample test. Widths and slope were tested using log-transformed values using un-equal variance t-tests.*

Active channel width is defined by bed and banks that exhibit scour and fill activity from flowing water, and the width usually represents the high water marks from annual flooding. Unlike impact width, active channel widths were not consistently greater for highly impacted stream reaches over all stream orders (Figure 47). Active channel width values were log transformed for the same reasons as given above. For first order channels there was a highly significant difference between log-transformed values of active channel width (Table 21). For second order streams the difference between high and low impact stream channels is only significant ($p < 0.05$). For third order channels the difference is highly significant and for fourth order the low impact channels are actually highly significantly wider (Table 21). Even though the values are at least significantly greater for three out of four cases the actual differences in mean active widths are small (Figure 47) and the detection of differences is due to large sample size with fairly low variability.

The close correspondence in active channel widths is somewhat surprising considering that streams that have high sediment loads are thought to widen (Schumm, 1977). However, within the impact width, the active channel reforms itself and develops an active channel with similar to that of nearby streams un-impacted from recent debris torrents. The impacted channel adjusts its width and depth dimensions to the slope, channel forming streamflow, and sediment supply available. The result is a channel within the width of impact that is similar in width to stream channels not recently disturbed because channel forming influences like sediment input and hydrologic regime are similar across the impact types. First order streams may be an exception because they tend to be colluvial (Montgomery and Buffington, 1993) and are not able to reform channels within impact widths as readily as larger streams. This similarity in active channel widths was also found in landslide and channel impact work conducted in coastal British Columbia (Tripp and Poulin, 1992) (Figure 48). In some follow-up visits to stream reaches in the Vida, Mapleton and Elk Creek study areas it was observed that disturbance-related tree species like red alder (Alnus rubra) invade the disturbed impact area outside of the channel leading to a predominance of alder near the streams that are chronically impacted by debris flows. In many streams impacted by landslide related debris torrents in 1964, crews observed narrow alder corridors that had similar widths to impact widths related to the 1996 storms.

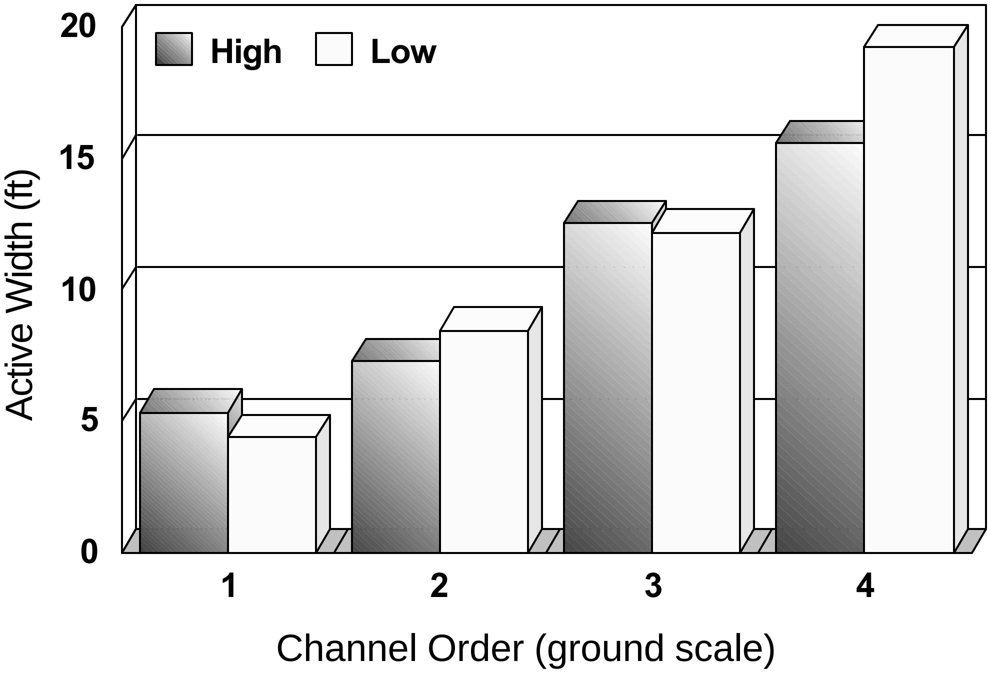


Figure 47. Mean active channel width (similar to bankfull channel width) for streams that were highly impacted by debris torrents and dam-break floods associated with the storms of 1996 compared with streams that had little impact.

Stream channel slope was consistently greater in highly impacted reaches relative to nearby low impact reaches (Figure 49 and Table 21). It has been established that debris torrents tend to deposit and terminate when channel slope decreases (Benda and Cundy, 1990). Some of the non-landslide impacted channels had channel gradients such that debris torrents and other landslide related debris features would terminate upstream from some of the reaches measured.

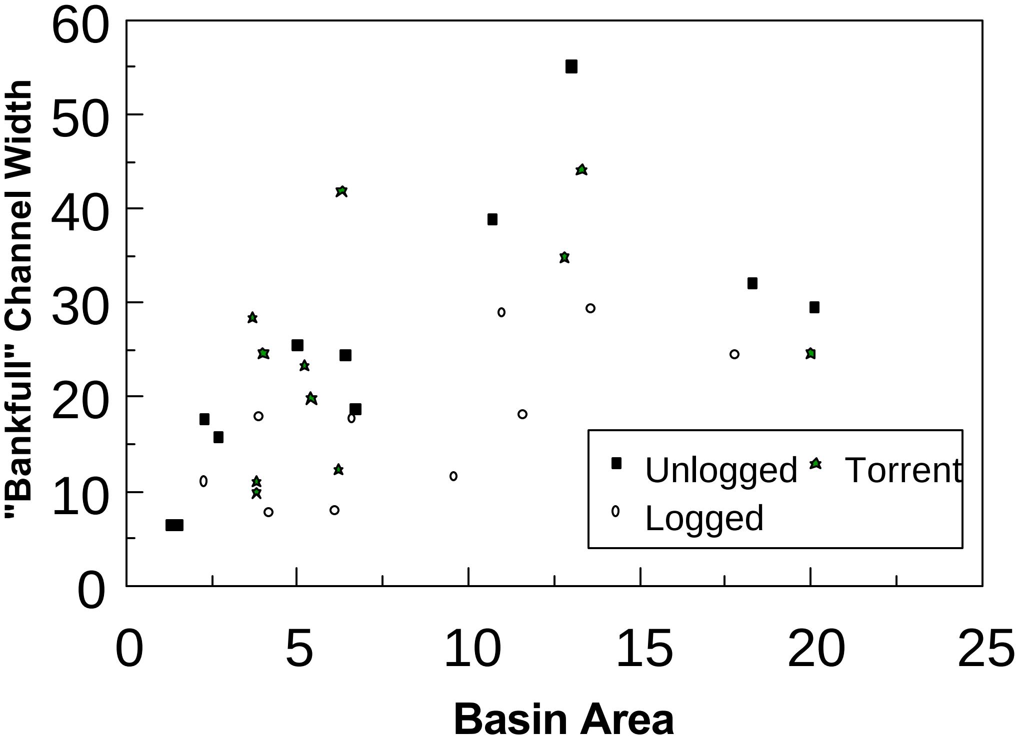


Figure 48. Bankfull channel width for several unlogged, logged and debris torrent impacted reaches in British Columbia (from Tripp and Poulin, 1992).

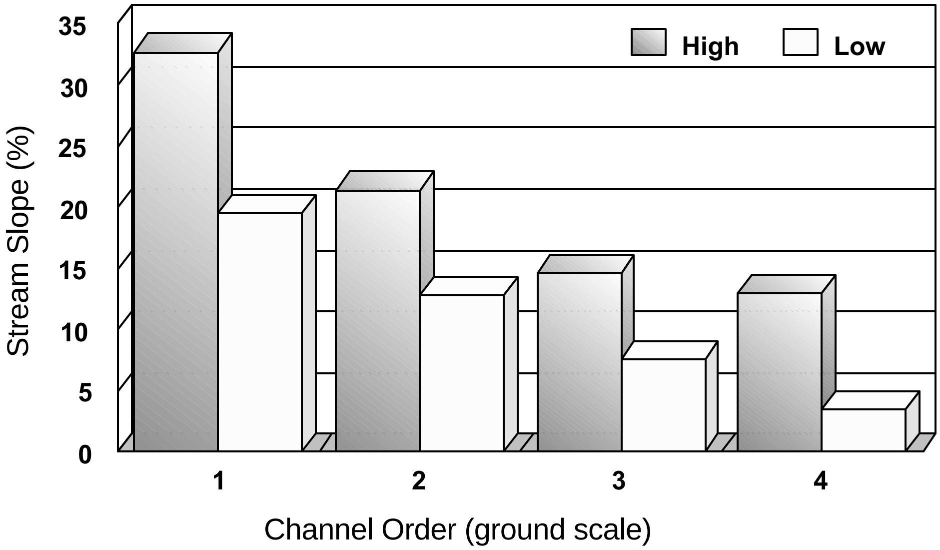


Figure 49. Stream slope for streams that were highly impacted by debris torrents and dam-break floods associated with the storms of 1996 compared with streams that had little impact.

Shading was measured in the middle of the stream using a convex canopy densiometer (see Appendix C). Debris torrent impacted channels were generally lower in shading as compared to reaches not recently impacted (Figure 50). However, the level of shading in highly impacted stream reaches had large variation, with a range from no shading to nearly 90% stream shading for different stream reaches. In some cases, shade values for certain stream sizes tended to clump at both low and high shade levels (i.e. creating a bi-modal distribution). To test for differences, the cumulative frequency distributions for high and low impacted streams were compared (Figures 51 and 52 and Table 21). In every case, there was a highly significant difference between the distributions. In examining Figures 51 and 52, it should be noted that the first and second order channels contained little or no water when surveyed during the summer. However, both the third and fourth order channels typically had water in the summer and some were even fish bearing. Figure 51 indicates that for third order channels, 80% of low impacted reaches have 80% or better shade over the stream. For torrent impacted reaches, 80% shading only occurs in 30% of the reaches. This loss of shading does not occur on all highly impacted reaches and is sensitive to harvesting activity adjacent to the stream (Figure 53). For instance, for the Elk Creek and Scottsburg study area first order streams, average shading is only 15% for streams with adjacent clearcut harvest within the last nine years but is nearly 90% for streams with no adjacent clearcutting activity or were cut over 30 years ago (Figure 53). For second order streams, this difference is not as pronounced, possibly due to the use of streamside vegetative buffers. For third and fourth order streams, the small sample size precluded such a comparison.

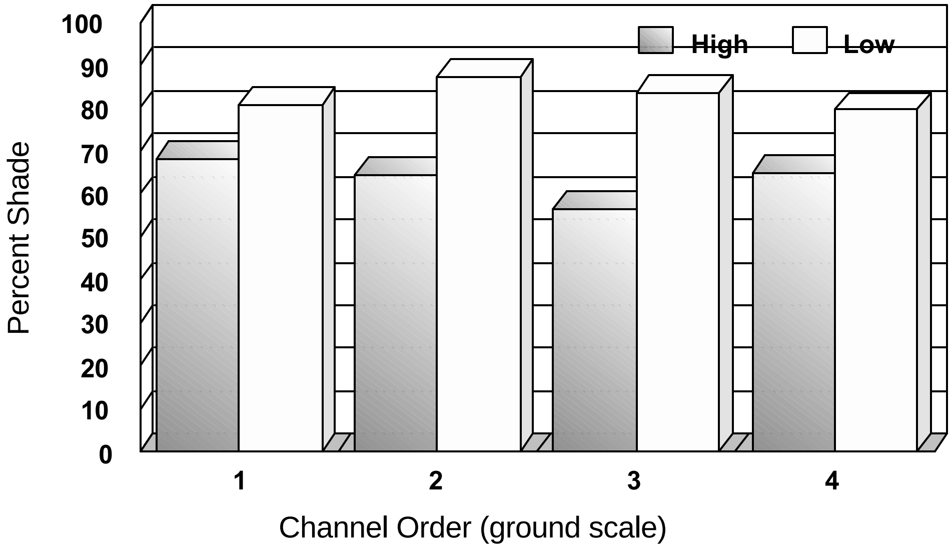


Figure 50. Average stream shading for streams that were highly impacted by debris torrents and dam-break floods associated with the storms of 1996 compared with streams that had little or no impact.

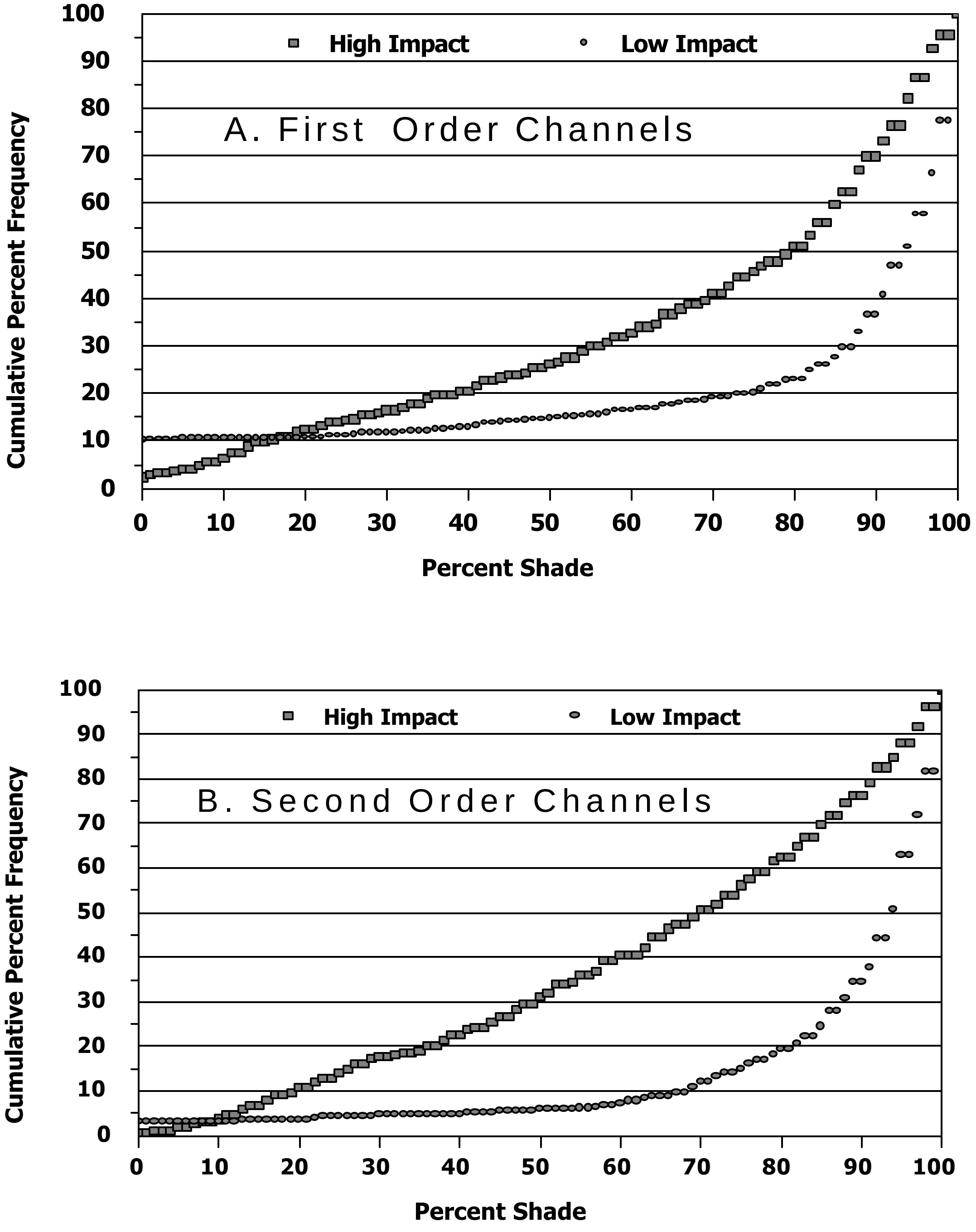


Figure 51. Cumulative frequency distribution for percent shade for first and second order streams that were highly impacted by debris torrents and dam-break floods associated with the storms of 1996 compared with streams that had little or no impacts.

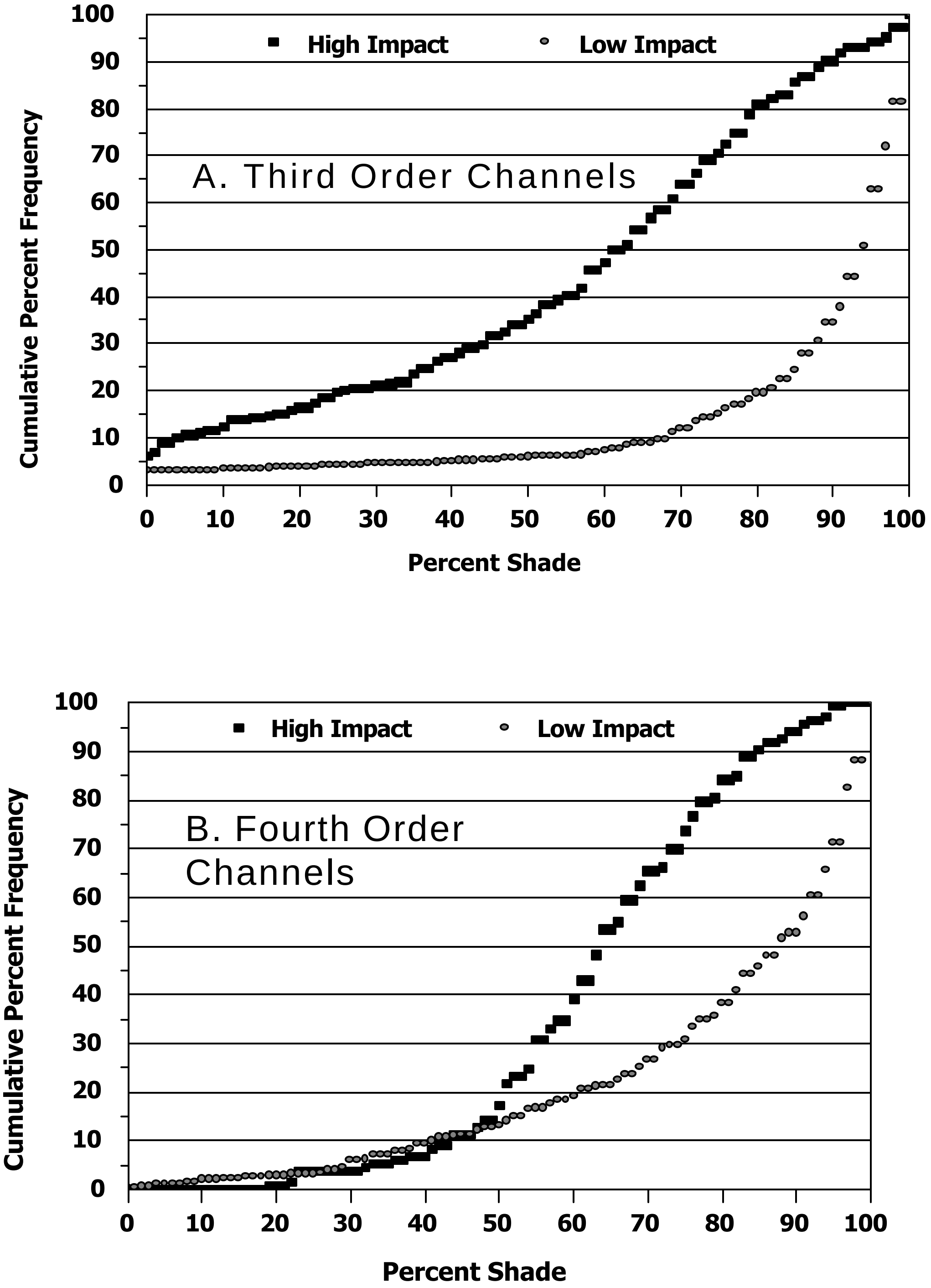


Figure 52. Cumulative frequency distribution for percent shade for third and fourth order streams that were highly impacted by debris torrents and dam-break floods associated with the storms of 1996 compared with streams that had little or no impacts.

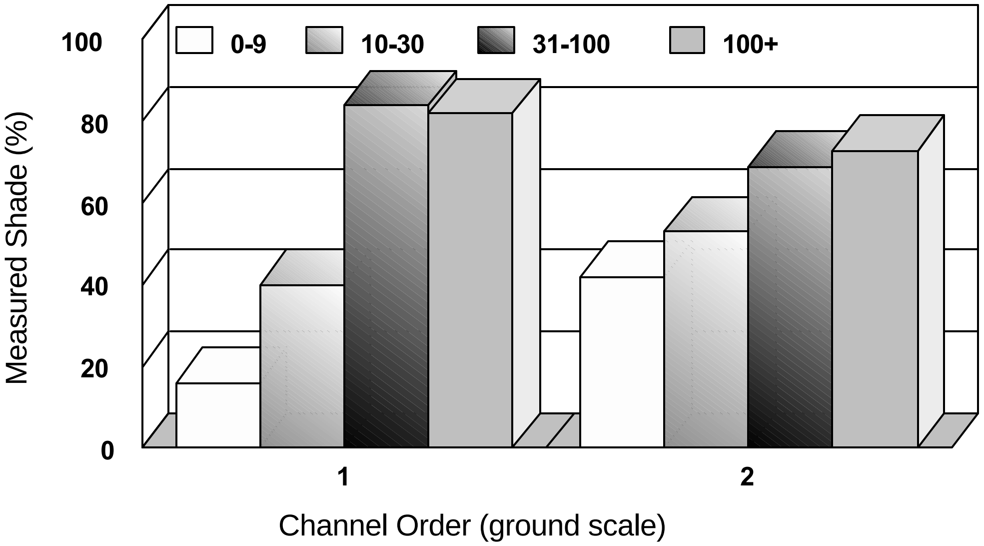


Figure 53. Stream shading for stream reaches highly impacted by landslide and debris torrents by channel adjacent stand age for Elk Creek and Scottsburg study sites only.

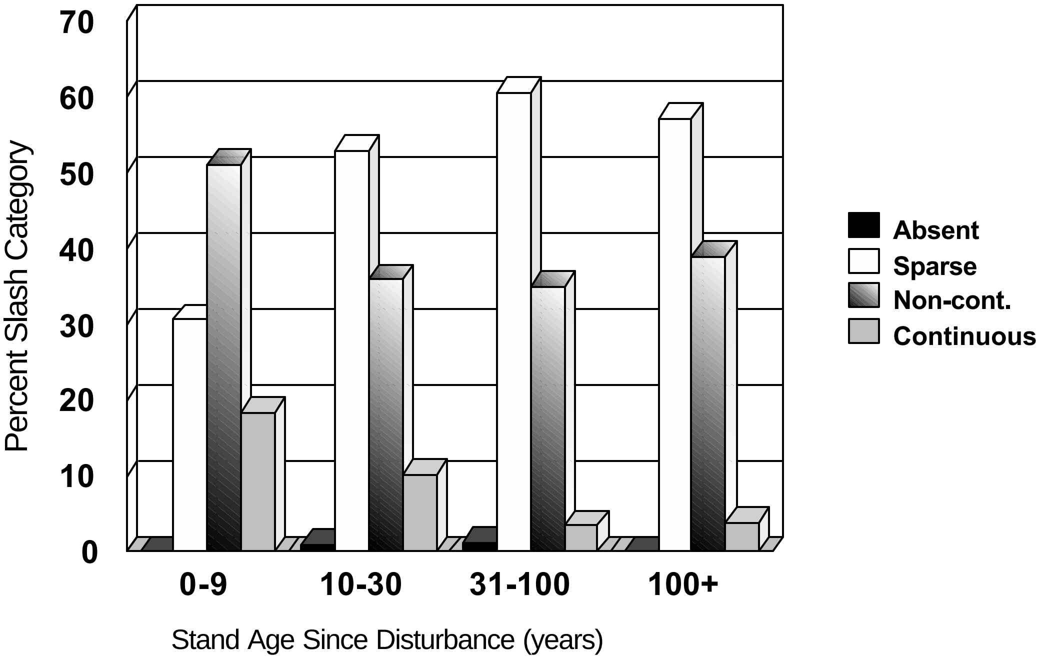


Figure 54. Percentage of channel length for various categories of slash loading for stream reaches that were not impacted by debris flows or torrents from the storms of 1996 for the Elk Creek and Scottsburg study sites only.

Summary

Stream channels influenced by landslide related impacts were on average more open with less shade and occurred on streams with steeper slopes. However, for several stream size classes the average active channel width was similar for debris torrent impacted reaches as compared to those that had no recent debris torrent impacts.

SLASH LOADING AND TIMBER HARVESTING

The level of slash (i.e., small and large woody debris consisting of generally limbs and branches as well as unmerchantable logs) is believed to effect both travel distances of debris torrents and the amount of damage that they incur. For this reason, ODF has established rules to minimize slash accumulation in streams. For the Elk Creek and Scottsburg study areas, levels of slash loading (both logging related and natural) was estimated for all stream measurement points (see Appendix C for details on how this measurement was taken). The measurements were taken to compare the level of slash in recently harvested areas to those that were harvested years before or never harvested. Since debris torrents remove nearly all of the slash as they move, only areas that did not experience recent debris torrent or flood activity were compared. Figures 54 and 55 indicate that for streams with recent clearcutting (i.e. within last nine years) occurring adjacent to them, slash loading was greater. Sixty nine percent of low-impacted channels adjacent to recent clearcuts were characterized as having continuous or nearly continuous slash. This compares with continuous or nearly continuous slash in 40-47% for stream reaches that have older stands adjacent (Figure 54). Similarly, the percentage of channel measurement points with slash depth equal or greater than 1.5 feet is only two to five percent in older stands and is 12.5% for streams with adjacent recent clearcutting activity.

Summary

Stream channels in which adjacent stands were recently clearcut harvested had greater slash accumulations as compared to older forests. Note, however, that these surveys were in streams un-impacted by debris torrent activity from the 1996 storms and done only in the Elk Creek and Scottsburg study areas.

DEBRIS TORRENT TRAVEL DISTANCES

Since crews continually measured the start and duration of all channel impacts including those of debris torrents, the travel distances of debris flows, torrents, floods, and dam break floods could be determined from the collected data. There are several studies that attempt to describe debris torrents and their travel lengths (i.e., Fannin and Rollerson, 1992). There are also studies that attempt to apply simple models to predict how far given landslide generated debris torrents will travel (i.e., Benda and Cundy, 1990). For this study there were hundreds of landslides that formed into debris torrents with ground-based measurements that described their extent of travel. What follows is an attempt to correlate of landslide travel distance with landslide and channel characteristics and an evaluation of a debris torrent travel distance model (i.e. Benda and Cundy, 1990).

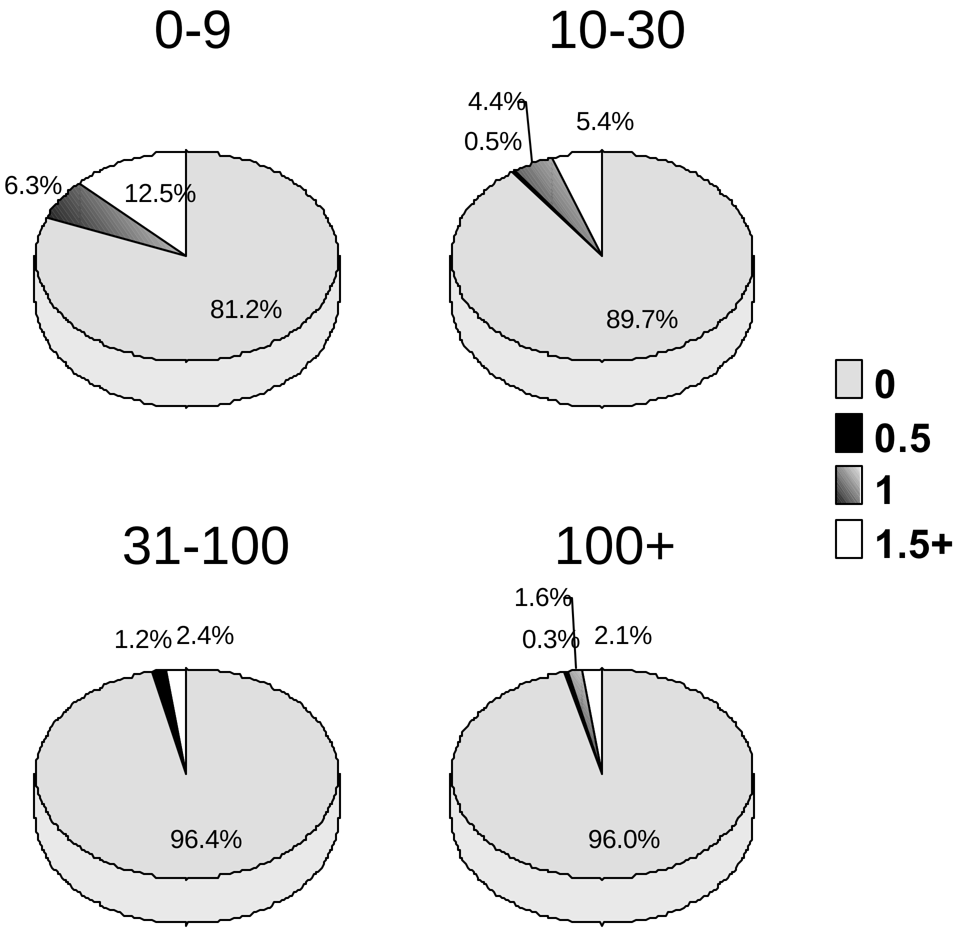


Figure 55. Extent of stream reaches with various slash depths for streams not impacted by landslides or debris torrents from the storms of 1996 for the Elk Creek and Scottsburg study areas.

The distance traveled by debris torrents has been correlated with the total landslide volume of those debris flows (Iverson and others, 1998). For large landslides the total volume of the debris torrent is proportional to the initial landslide volume. Unfortunately, the initial landslides in Oregon's forests generally make up only a small percentage of total debris torrent volume, so this relationship has little utility in the prediction of debris flow travel distance in these cases.

Larger landslides are often expected to travel further downslope than smaller landslides since there is greater mass to produce greater momentum to carry the material further downslope. However, ODF data suggests that landslide size is at best a secondary factor in determining debris torrent travel distance (Figure 56). Furthermore, even when factoring in initial landslide slope steepness and multiplying it by initial landslide volume to get an index of momentum, no relationship with debris torrent travel distance is found. For this reason, other factors such as the junction angles downslope and the slopes of the downstream channels as postulated by Benda and Cundy (1990) may be a more determining factor of debris torrent travel distance. Figure 57 indicates that the Benda Cundy model predicts the stop point for the majority (258 out of 361) of the debris torrents evaluated. This means that for at least 92% of the debris torrents, that junction angles and stream gradient alone can predict a maximum run-out distance. In most cases, the model predicted correctly the end of debris torrents at sharp junction angles (i.e. >70^{o} horizontal angle for slopes or stream gradients that are less than 20^{o}). A smaller number end where stream gradient lessens to 3.5^{o}. However, there are 73 debris torrents that stopped short of the predicted distance and 30 that went further than the model predicted (Table 22).

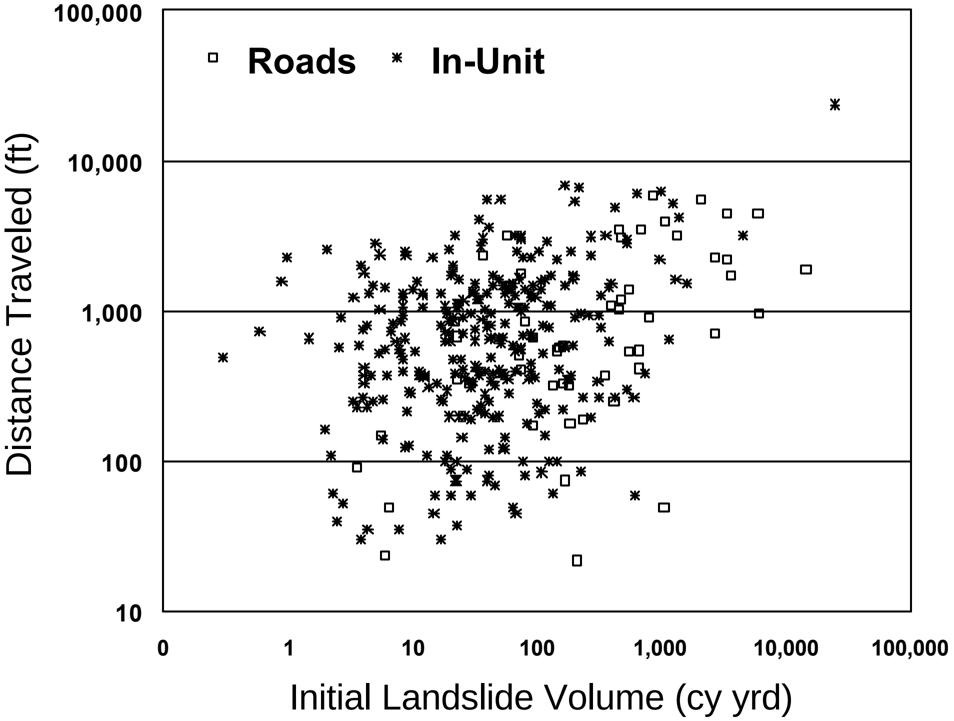


Figure 56. Scatter-plot of torrent travel distances versus a landslide momentum index that consists of % slope at the initial landslide times initial landslide volume.

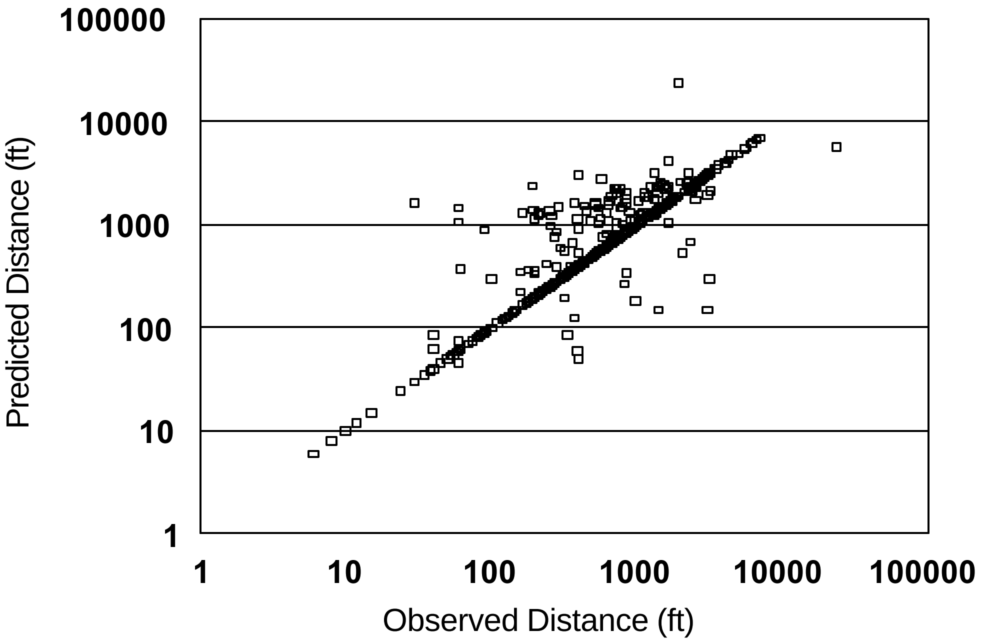


Figure 57. Observed versus predicted debris flow and torrent run-out distance using the Benda and Cundy (1990) model.

Table 22. Tabulation of the differences between the observed and Benda and Cundy (1990) model predicted run-out distances for debris flows and torrents.

Difference	Number	
<-2000	4	Over predicted they stopped short
1000-2000	17	= 73
500-1000	28	
200-500	11	
100-200	11	
1-100	2	
0-(-1)	0	
0	258	Correctly Predicted
1-100	2	Under Predicted they went further
100-200	6	=30
200-500	8	
500-1000	6	
1000-2000	5	Total All Slides = 361
>2000	3	

In comparing the 73 debris torrents that had shorter travel distances (over-predicted) to the 31 debris torrents that had greater travel distances (under-predicted) there are two interesting differences. First, the average initial landslide volume of the debris torrents that traveled greater distances than predicted was 1281 cubic yards compared to 137 cubic yards for those that traveled less distance than predicted by the model. This result indicates that initial landslide volume can affect debris torrent run-out distance but is of lessor significance than junction angles and channel gradient. Secondly, debris torrents that stopped short of predicted disturbances have larger and more mature riparian vegetation in and around their end points. During subsequent data analysis the riparian vegetation condition along all debris flows were characterized on a scale of between one and four with one being low growing trees and brush to four representing mature conifer stands in the riparian area (for more information, see Appendix C). Under-predicted debris torrents had an average index of 2.8 while the over-predicted average index was 2.1. This result indicates that more mature riparian vegetation may tend to cause debris torrents to terminate sooner than expected based on junction angles and channel gradients alone.

Summary

Debris torrent travel distance is most dependent on channel junction angles and channel gradient. For this data set, factors such as initial landslide size or condition of the riparian stand along the channels are of secondary significance.

CONCLUSIONS

IDENTIFICATION OF LANDSLIDES AND LANDSLIDE HAZARDS

1. Landslide inventories using only aerial photographs without significant on-the-ground surveying do not identify the majority of shallow-rapid type landslides. In this study, over 72 percent of the landslides could not be observed on aerial photographs. Landslides that were detected only accounted for about 50% of the total landslide erosion.
2. Forest canopy further obscures any ability to identify or accurately measure landslide areas. The average ratio between clearcut and mature landslide densities for air photo inventories is about five-times the average for the ground-based inventories. Therefore, landslide inventories based solely on aerial photographs have limited use for identifying those landslides most common in steep forested terrain, especially in areas with dense forest cover.
3. Coarse-scale digital elevation models underestimate slope steepness, especially in areas with irregular, steep slopes.
4. Ground-based investigation provides the most reliable information on landslide occurrence and their characteristics in the forests of western Oregon.
5. Slope steepness, landform shape, and drainage area above the landslide are important factors for determination of those sites most susceptible to landslides.
6. The factors currently used in the determination of high risk sites could be modified to improve accuracy in identifying those sites prone to debris slides and flows, and may need to include differences by geologic unit.
7. The highest hazard for shallow rapid landslides in western Oregon occurs on slopes of over 70% to 80% steepness (depending on landform and geology). There is a moderate risk of these landslides on slopes of between 50% and 70%.
8. Subsequent scour by debris flows and torrents, and not the initial landslide volume, represent most (about 90%) of the landslide related sediment that is carried into and through stream channels.
9. In any given storm, most landslide prone locations (high risk sites) do not fail and move into stream channels.

LANDSLIDES AND FOREST STAND CONDITION

1. Timber harvesting can affect landslide occurrence on the steepest slopes. Higher densities and erosion volumes were found in stands that had been harvested in the previous nine years, as compared to forests that were older than one hundred years in three out of four study areas.
2. Forested areas between the ages of 10 and 100-years typically had lower landslide densities and erosion than found in the mature forest stands.
3. There is significant background (mature forest) landslide risk on very steep slopes, especially in certain geologic formations, where major storms and landsliding processes are the dominant means by which the landscape is shaped.
4. Landslides from recently harvested and older forests had similar dimensions, including depth, initial volume, and debris flow volume.

5. Variability in both storm and site characteristics precluded the determination of significant differences by age class.
6. Landslides in mature forests generally did not occur on sites with young or sparse vegetative cover.

LANDSLIDES AND TIMBER HARVESTING PRACTICES

1. In the locations adjacent to landslides, landowners and loggers complied with the forest practice harvesting rules (as changed in 1983) to minimize ground disturbance and slash accumulations on landslide prone sites.
2. Removal of vegetation on steep, landslide prone locations may result in increased landslide occurrence. Both the length of time these locations are in a condition with reduced forest cover and the extent of lands with reduced vegetative cover affect landslide density and erosion rate.
3. Landscape level disturbances (such as the “Tillamook Burn”) can result in large, contiguous areas in a vegetative condition susceptible to landslides.
4. Alternative management strategies for high risk sites should be carefully monitored. This will take considerable time, since landslides are a geologic process (variable in both time and space). Effectiveness of any specific practices, therefore, will be difficult to evaluate until the landscape has experienced major storms and/or sufficient exposure to geologic processes. This one study of single extreme storm effects could not address these longer-term process questions.

LANDSLIDES AND FOREST ROADS

1. Landslides that were associated with forest roads made up a smaller percentage of the total landslides in this study than the road-associated landslides did in most previous studies.
2. The road-associated landslides identified during this study were smaller, on average, than road-associated landslides in past studies. However, these road-associated landslides were still several times larger on average than landslides not associated with roads.
3. Landslides that delivered sediment to stream channels rarely occurred on roads across slopes of under 50% steepness, especially when roads had well spaced drainage systems and fills of minimal depth.
4. Road fill placed on steep slopes creates an increased landslide hazard even where no drainage water is directed to those fills.
5. Road drainage waters directed onto very steep slopes create an increased landslide hazard even when there is no road fill placed on those very steep slopes.
6. Washouts were a significant problem in Tillamook, and to a lesser extent in Vida. Washouts were often related to undersized culverts (installed prior to current rule requirements).
7. Based on the low numbers of road-associated landslides surveyed in this study and on the smaller sizes of these landslides (as compared with previous studies), current road management practices are almost certainly reducing the size of road associated landslides, as well as the number of landslides.

STREAM CHANNEL IMPACTS

1. Stream channel impacts varied greatly by study area. Impacts were not directly related to the number of landslides. Large, up-slope landslides that enter stream tributaries with small horizontal stream junction angles and steep channel gradient slopes resulted in the greatest stream channel impacts.
2. Debris torrents reduce stream shading, especially when they travel through younger stands.
3. Debris torrents have only a minor effect on active channel width.
4. The Benda-Cundy model provides a reliable tool for determining maximum potential travel distances of "typical" debris flows and torrents from forested slopes. Less than 10% of the total landslides traveled further than predicted by the Benda-Cundy model. This means channel junction angles and channel gradient are the dominant factors in determining landslide run-out distance.
5. The debris torrents that traveled further than predicted were on average larger and had younger riparian vegetation near their terminus, indicating that landslide volume and composition of the riparian area along debris torrent prone channels may be important secondary factors in determining landslide run-out distances.
6. More slash was found in channels that flowed through recent harvest units as compared to channels that flowed through mature forests. However, whether these differences in slash resulted in increased travel distances by debris torrents could not be determined.
7. Based on these conclusions, when evaluating debris flow or torrent risks to resources based on potential run-out, one should consider the potential for large initiating landslides as well as channel junction angles, stream, and the riparian condition along the debris flow/torrent path channel gradients.

LITERATURE CITED

Amaranthus, M.P., R.M. Rice, N.R. Barr, and R.R. Ziemer. 1985. Logging and Forest Roads Related to Increased Debris Slides in Southwestern Oregon. Journal of Forestry 83:229-233.

Benda, L. and T. Cundy. 1990. Predicting deposition of debris flows in mountain channels. Canadian Geotechnical Journal. Volume 27, Number 4. pp 409-417.

Benda, L. and T. Dunne. 1987. Sediment routing by debris flow. p. 213-222 IN: Erosion and sedimentation in the Pacific Rim (Proceedings of the Corvallis Symposium, August, 1987). IAHS Publication No. 165.

Benda, L.E. 1985. Delineation of channels susceptible to debris flows and debris floods. p. 195-201. In International Symposium on Erosion, Debris flow and disaster prevention. September 3-5, 1985, Tsukuba, Japan.

Beschta, R.L. and W.S. Platts. 1986. Morphological features of small streams: significance and function. Water Resour. Bull. 22(3): 204-210.

Bishop, D.M. and M.E. Stevens.1964. Landslides on Logged areas in Southeast Alaska.U.S.F.S. Northern Forest Experiment Sta. Research Paper. NOR-1.Juneau, Alaska.18 p.

Burroughs, E.R. and B.R. Thomas. 1977. Declining root strength in Douglas-fir after felling as a factor in slope stability, USDA Forest Service Research Paper INT-190, 27 pp.

Bush, G., C. McConnell, C. Cloyd, K. Musser, B. Metzger, and H. Plumley. 1997. Assessment of the effects of the 1996 Flood on the Siuslaw National Forest. USDA, Siuslaw National Forest, Corvallis, Oregon. 47 p.

Chesney, C.J. 1982. Mass erosion occurrence and debris torrent impacts on some streams in the Willamette National Forest. M.S. Thesis, Oregon State University, Corvallis Oregon. 116 p.

Chorley, R.J., S.A. Schumn and D.E. Sugden. 1984. Geomorphology. Methuen and Co., London.

Coffin, B. A. and R.D. Harr. 1992. Effects Of Forest Cover On Volume Of Water Delivery To Soil During Rain-On-Snow. Washington DNR-CMER Report TFW-SH1-92-001. 118p.

Dietrich, W.E. 1996. Personal Communication. Professor, University California at Berkely.

Dunne, T. and L. Leopold.1978. Water in environmental planning. W.H. Freeman and Company. San Francisco, CA. USA. 818 p.

Dyrness, C.T. 1967. Mass Soil Movements in the H.J. Andrews Experimental Forest. USDA Forest Service, Res. Pap. PNW-42, 12 pp.

Engelman, L. 1997. T-tests. Chapter 5 In – Systat 7.0. Statistics. SPSS Inc. Chicago, IL, USA. 751 p.

Fannin, R.J., and T.P. Rollerson. 1993. Debris flows: some physical characteristics and behavior. Can. Geotech. J. Vol. 30: 71-81.

Fiksdal. A.J.1974. A landslide survey of the Stequaleho Creek Watershed.Final Report #1 - FR1-UW-7404. 8 p.

Follensbee, B. and A. Stark. 1998. Kilches Watershed Analysis. Tillamook Bay National Estuary Project. U.S. EPA. Girabaldi Oregon, 206 p.

Gray, D.H. and A.T. Leiser. 1982. Biotechnical Slope Protection and Erosion Control. Van Nostrand Reinhold Co. New York.

Greenway, D. 1987. Vegetation and Slope Stability, In: Anderson, M.G. and K.S. Richards, ed. Slope Stability, Geotechnical Engineering and Geomorphology. Wiley and Sons. Chinchester.

Gresswell, S., D. Heller, D.N. Swanston.1979. Mass movement response to forest management in the Central Oregon Coast Ranges.U.S.F.S. Pacific Northwest Experiment Station. Resource Bulletin PNW-84. 26 p.

Hicks, B.A.1982. Geology, geomorphology, and dynamics of mass movement in parts of the Middle Santiam River drainage, Western Cascades, Oregon.Masters Thesis, Oregon State University, Corvallis Oregon.169 p.

Hughes, D.R. and R.V. Edwards. Granite Creek landslip survey. Unpublished Document, USFS Umpqua National Forest, Roseburg, Oregon. 22 p.

Ice, G. 1985. Catalog of landslide inventories for the northwest. Technical bulletin 456. National Council of the Paper Industry for Air and Stream improvement. New York.

Iverson, R.M., S.P. Schilling and J.W. Vallance. 1998. Objective delineation of lahar-inundation hazard zones. GSA Bulletin; v. 110, no.8.

Johnson, A.C.1991.Effects of landslide-dambreak floods on channel morphology.Department of Natural Resources, State of Washington, Timber, Fish and Wildlife. Report No:TFW-SH17-91-001. 90 p.

Kaufmann, P. 1987. Channel morphology and hydraulic characteristics of torrent-impacted forest streams in the Oregon Coast Range, U.S.A. Ph.D. Dissertation, Oregon State University, Corvallis, Oregon, 235 p.

Ketcheson, G. and H.A. Froehlich. 1978. Hydrologic Factors and Environmental Impacts of Mass Soil Movements In The Oregon Coast Range. Water Resources Research Institute Bulletin 56, Oregon State University, Corvallis, Oregon.

Laenen, A., L.E. Hubbard, and T.J. Zembrzuski. 1997. Flooding in Oregon and Washington from the storm of February 6-11, 1996 – Flood Magnitudes and Frequencies. p. 15-24. In: The Pacific Northwest Floods of February 6-11, 1996: Proceedings of the Pacific Northwest Water Issues Conference, Portland, Oregon, October 7-8, 1997. American Institute of Hydrology.

Lamberti, G.A., S.V. Gregory, L.R. Ashkenas, R.C. Wildman, and K.M.S. Moore. 1991. Stream ecosystem recovery following a catastrophic debris flow. Can. J. Fish. Aq. Sci. 48: 196-208.

Lyons, J.K. 1982. Influence of landslides, floods, landuse on channel changes of the Upper Middle Fork Willamette River, Oregon 1936-1980. M.S. Thesis, Oregon State University.

Lyons, J.K. and R.L. Beschta. 1983. Land use, floods, and channel changes: Upper Middle Fork Willamette River, Oregon (1936-1980). Water Resources Research 19(2):463-471.

Marion, D.A. 1981. Landslide occurrence in the Blue River drainage, Oregon. M.S. Thesis, Oregon State University, Corvallis.

Martin, K. 1997. Forest Management on Landslide prone Sites: The Effectiveness of Headwall Leave Areas and Evaluation of Two Headwall Risk Rating Methods. M.S. Engineering Report. Oregon State University, Corvallis.

McHugh, M.H. 1987. Landslide occurrence in the Elk and Sixes River basins, Southwest Oregon. M.S. Thesis, Oregon State University, Corvallis. 106 p.

Meehan, W.R.1991. Influences of forest and rangeland management on salmonid fishes and their habitats.American Fisheries Society, Special Publication 19. 751 p.

Megahan, W.F. and J.W. Kidd. 1972. Effect of logging roads on sediment production rates in the Idaho batholith. USDA Forest Service Research Paper. INT-123, Intermountain Forest and Range Experiment Station, Ogden, Utah. 14 p.

Megahan, W.F., N.F. Day and T.M. Bliss. 1979. Landslide occurrence in the western and central northern Rocky Mountain physiograph provinces in Idaho. In Forest Soils and Land Use, Proc. Fifth North Amer. For. Soils Conf., Aug 6-9, 1978, Ft. Collins, Colo. p 226-239, Colorado State Univ. Ft. Collins, Colo.

Mills, K. 1991. Winter 1989-90 Landslide Investigations. Unpublished Report. Oregon Department of Forestry, Salem, Oregon. 26 pp.

Montgomery, D. R. and W.E. Dietrich. 1994. A Physically Based Model For The Topographic Control On Shallow Landsliding. Water Resources Research, Volume 30, No. 4, pp 1153-1171.

Montgomery, D.R. and J.M. Buffington. 1993. Channel classification, predicition of channel response, and assessment of channel condition. State of Washington, Timber Fish and Wildlife Paper, TFW-SH10-93-002. 84 p. + fig.

Montgomery, D.R., W.E. Dietrich, R. Torres, S.P. Anderson, and J.T. Keffner, and K. Loague. 1997. Hydrologic response of a steep unchanneled valley to natural and applied rainfall. Water Resour. Res. 33(1) 91-109.

Morrison, P.H.1975. Ecological and geomorphological conseqences of mass movements in the Alder Creek watershed and implications for forest land management. Unpublished Bachelors Thesis, University of Oregon. 102 p.

Piehl, B.T., R.L. Beschta, and M.R. Pyles. 1988. Ditch relief culverts and low-volume forest roads in the Oregon Coast Range. Northwest Science: 62(3) 91-98.

Pyles, M.R. and H. A. Froehlich. 1987. Discussion of “Rates of landsliding as Impacted by timber management Activities in Northwestern California” by M. Wolfe and J. Williams. Bulletin of the Association of Engineering Geologists. Vol XXIV, No. 3, pp 425-431.

Reeves, G.H., L.E. Benda, K.M. Burnett, P.A. Bisson, and J.R. Sedell. 1995. A disturbance based ecosystem approach to maintaining and restoring freshwater habitats of evolutionary significant units of anadromous salmonids in the Pacific Northwest. Amer. Fish. Soc. Suppl. 17: 334-349.

Rood, K.M.1984.An aerial photograph inventory of the frequency and yield of mass wasting on the Queen Charlotte Islands, British Columbia.Land Management Report #34. Information Services Branch, Ministry of Forests, Victoria B.C. Canada. 55 p.

Schroeder, W.L. and G.W. Brown. 1984. Debris torrents, precipation and roads in two coastal Oregon watersheds.p. 117-122. In: Sympsium on effects of Forest Land Use on Erosion and Slope Stability.

Schumm, S.A. 1977. The fluvial system. John Wiley and Sons. 338 p.

Schwab, J.W. 1983. Mass wasting: October-November 1978, Rennell Sound, Queen Charlotte Islands, British Columbia.Province of British Columbia, Ministry of Forests, Research Note No. 91. 1983 23 p.

Sessions J., J.C. Balcom, and K. Boston. 1987. Road Location and Construction Practices: Effects on Landslide Frequency and Size in the Oregon Coast Range. Western Journal of Applied Forestry 2(4):119-124.

Sidle, R.C., A.J. Pearce and C.L. O'Loughlin. 1985. Hillslope Stability And Land Use. American Geophysical Union Water Resources Monograph 11.

Skaugset, A.R. 1997. Modeling Root Reinforcement in Shallow Forest Soils. Ph.D. Dissertation. Oregon State University.

Smith, D.A.1996. Landslide frequency in the Fish creek and Roaring river watersheds, Clackamas River subasin: A validation of watershed analysis?p. 95-106. In: Proceedings of the Pacific Northwest Floods of Febuary 1996 Water Issues Conf. Oct. 7-8. 1996. American Insitute of Hydrology.

Surfleet, C.G. 1997. Precipitation characteristics for landslide hazard assessment for the central Oregon Coast Range. M.S. Thesis, Oregon State University, Corvallis, 168p.

Swanson, F. J., M. M. Swanson and C. Woods. 1977. Inventory Of Mass Erosion in The Mapleton Ranger District, Siuslaw National Forest.

Swanson, F.J. and C.T. Dyrness. 1975. Impact of Clearcutting and Road Construction on Soil Erosion by Landslides in the Western Cascade Range, Oregon. Geology 3(7):393-396.

Swanson, F.J. and G. Grant. 1982. Rates of erosion by surface and mass erosion processes in the Willamette National Forest. U.S.D.A. Forest Service Pacific Northwest Range and Forest Experiment Station, Unpublished Document, November 22, 1982.

Swanson, F.J. and G.W. Lienkaemper. 1978. Physical consequences of large organic debris in Pacific Northwest streams. USDA Forest Service. Gen. Tech. Report. PNW-69. 12 p.

Swanson, F.J., L.E. Benda, S.H. Duncan, G.E. Grant, W.F. Megahan, L.M. Reid, and R.R. Ziemer. 1987. Mass failures and other processes of sediment production in Pacific Northwest forest landscapes. p. 9-38. IN: Streamside management: forestry and fishery interactions. University of Washington, Institute of Forest Resources, Contribution No. 57. 471 p.

Swanson, F.J., S.L. Johnson, S.V. Gregory, and S.A. Acker. 1998. Flood disturbance in a forested mountain landscape: interactions of land use and floods. BioScience: 48(9) 681-689.

Swanston D.N. and F.J. Swanson. 1976. Timber harvesting, mass erosion, and steepland forest geomorphology in the Pacific Northwest. p. 199-219 in Geomorphology and engineering, D.R. Coates (ed.). Dowden, Hutchinson and Ross, Stroudsburg, PA. USA.

Taylor, G. 1997. Causes of the flood and a comparison to other climate events. p. 3-7 In: The Pacific Northwest Floods of February 6-11, 1996: Proceedings of the Pacific Northwest Water Issues Conference, Portland, Oregon, October 7-8, 1997. American Institute of Hydrology.

Tillamook Bay National Estuary Project. 1998. Kilchis Watershed Analysis.

Toth, S. 1991. A road damage inventory for the upper Deschutes River Basin. Timber Fish and Wildlife Report. TFW-SH14-91-007.

Tripp D.B. and V.A. Poulin. 1992. The effects of logging and mass wasting on juvenile salmonid populations in streams on the Queen Charlotte Islands. Land Management Report No. 80. British Columbia Ministry of Forests, Victoria, British Columbia, Canada. 38 p.

VanDine, D.F., 1985. Debris Flow And Debris Torrents In The Southern Canadian Cordillera. Canadian Geotechnical Journal. Volume 22, Number 1. pp 44-68.

Washington Department of Natural Resources. 1995. Board manual: Standard methodology for conducting watershed analysis: Under Chapter 222-22 WAC. Version 3.0. Washington DNR, Olympia, Washington.

Weaver, W.E. and D.K. Hagens. 1994. Handbook for forest and ranch roads. Mendocino County Resource Conservation District in Cooperation with the California Department of Forestry and the U.S. NRCS.

Wolfe, M.D. and J.W. Williams. 1987. Rates of Landsliding as impacted by timber management activities in Northwestern California: Discussion.Bull. of Ass. Eng. Geol. 24(3):429-431.

Appendix A

Flood Monitoring Coordination Team

July 1996

NAME	**ORGANIZATION**
Willy Bronson	Willamette Industries Company
Blake Rowe	Oregon Forest Industries Council
Bruce McCammon	US Forest Service Region 6
Dan Newton	Oregon Small Woodlands Association
Dr. Fred Swanson	US Forest Service Pacific Northwest Research Station
Dr. George Ice	National Council for Air and Stream Improvement
Dr. George Robison	Oregon Department of Forestry
Jim Stark	Weyerhaeuser Company
Keith Mills	Oregon Department of Forestry
Kelly Moore	Oregon Department of Fish and Wildlife
Liz Dent	Oregon Department of Forestry
Rick Hafele	Oregon Department of Environmental Quality
Dr. Steve Tesch	Oregon State University College of Forestry
Charlie Dewberry	Pacific Rivers Council

Expert Team Members:

Dr. Robert L. Beschta: Forest Hydrologist, Oregon State University

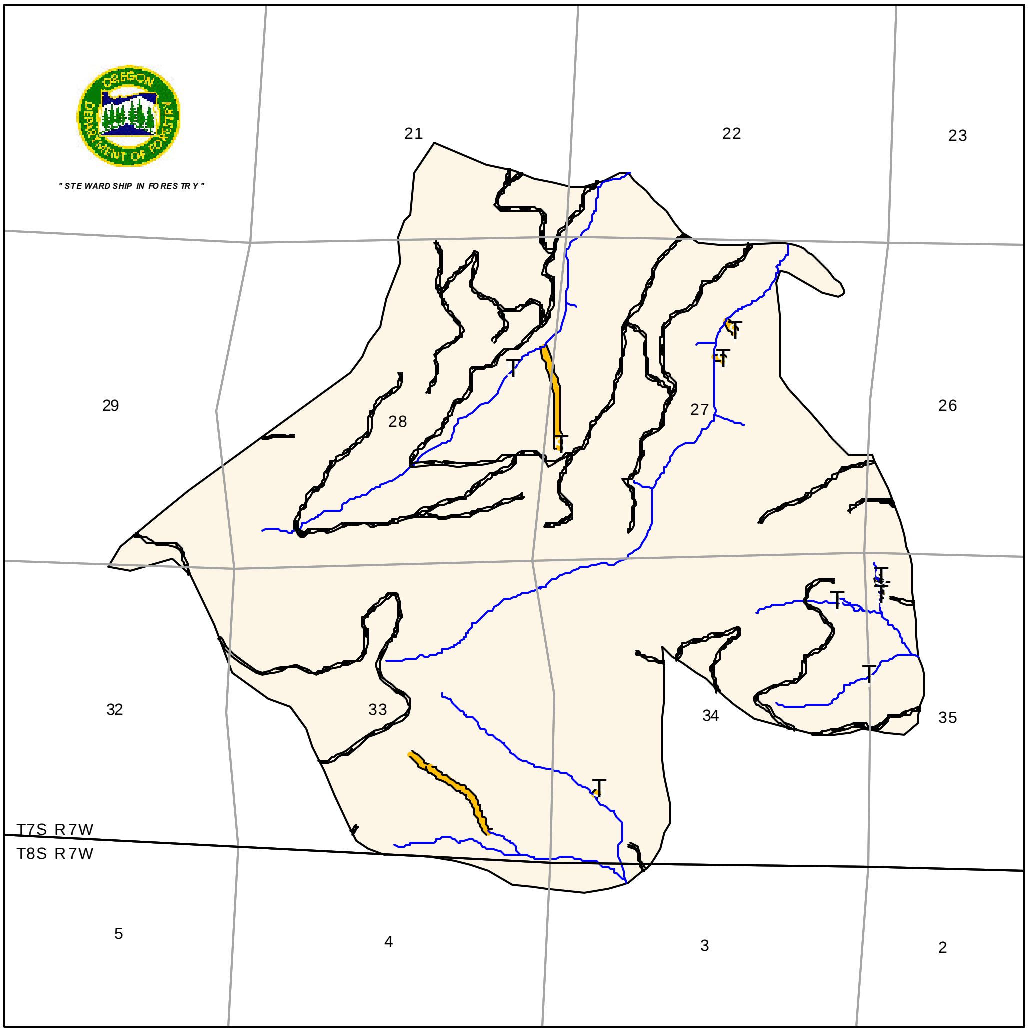
Dr. Marvin Pyles: Geotechnical Engineer, Oregon State University

Dr. Stan Gregory: Aquatic Biologist, Oregon State University

Dr. Bill Dietrich: Geomorphologist, University of California at Berkeley

Appendix B

Maps of the Eight Study Areas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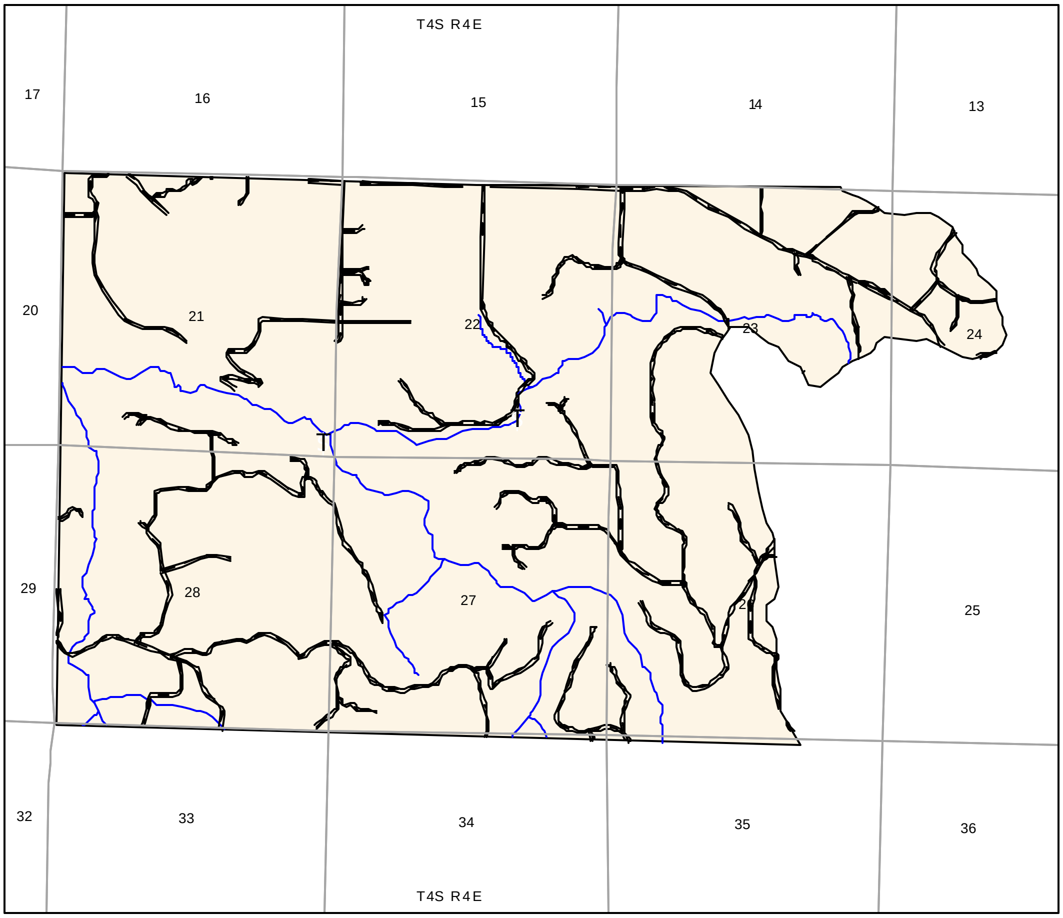
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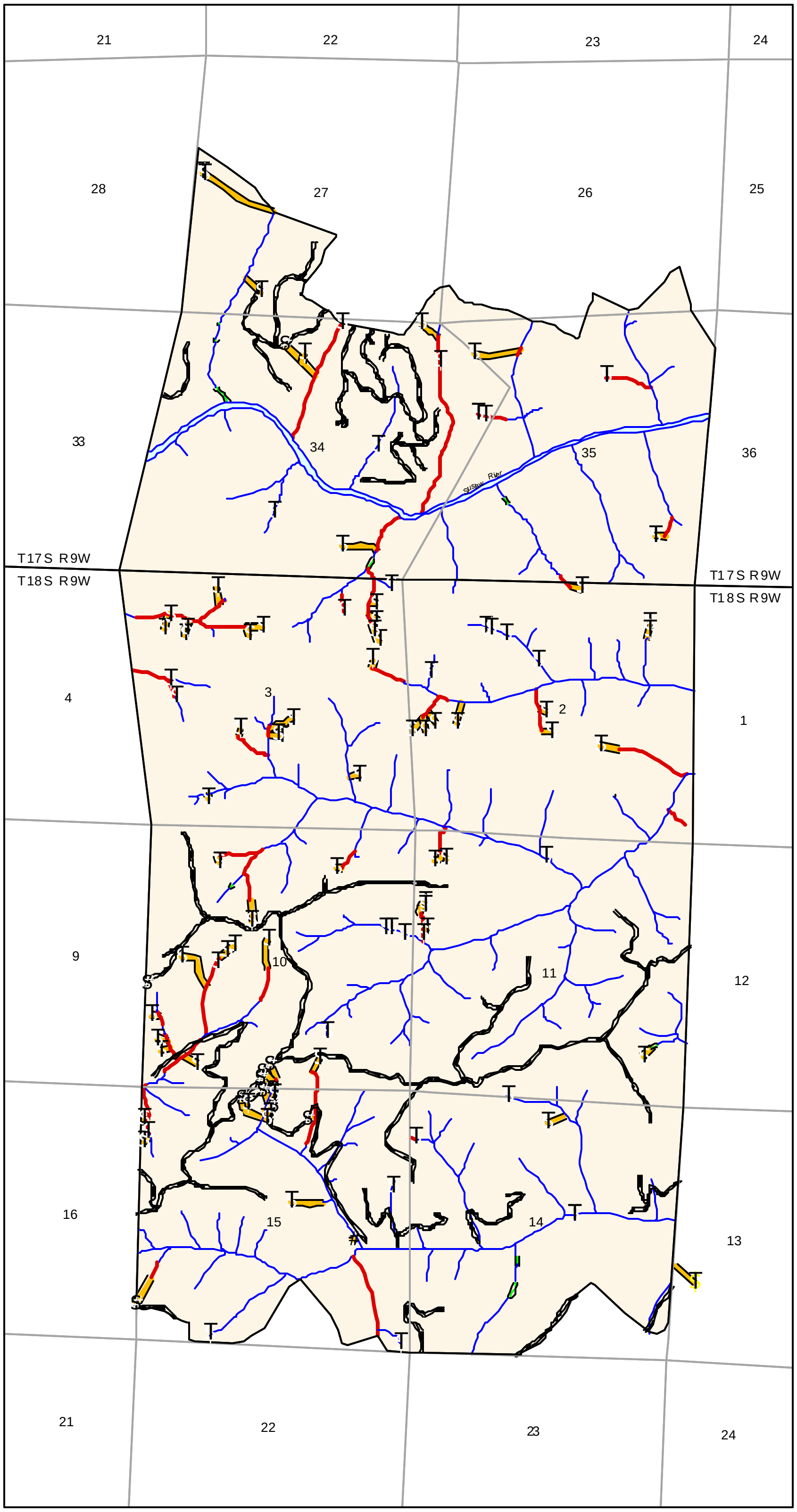
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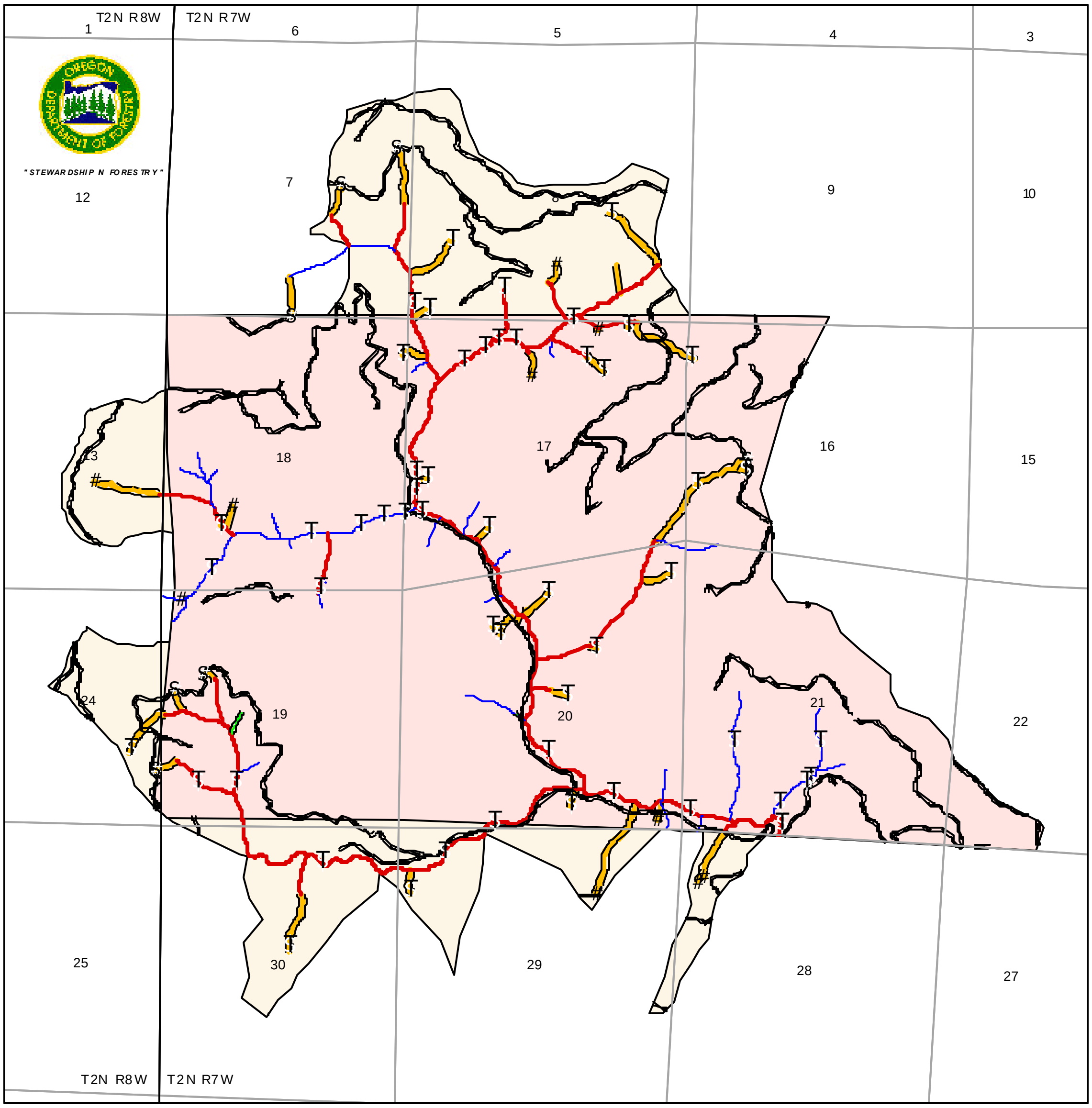
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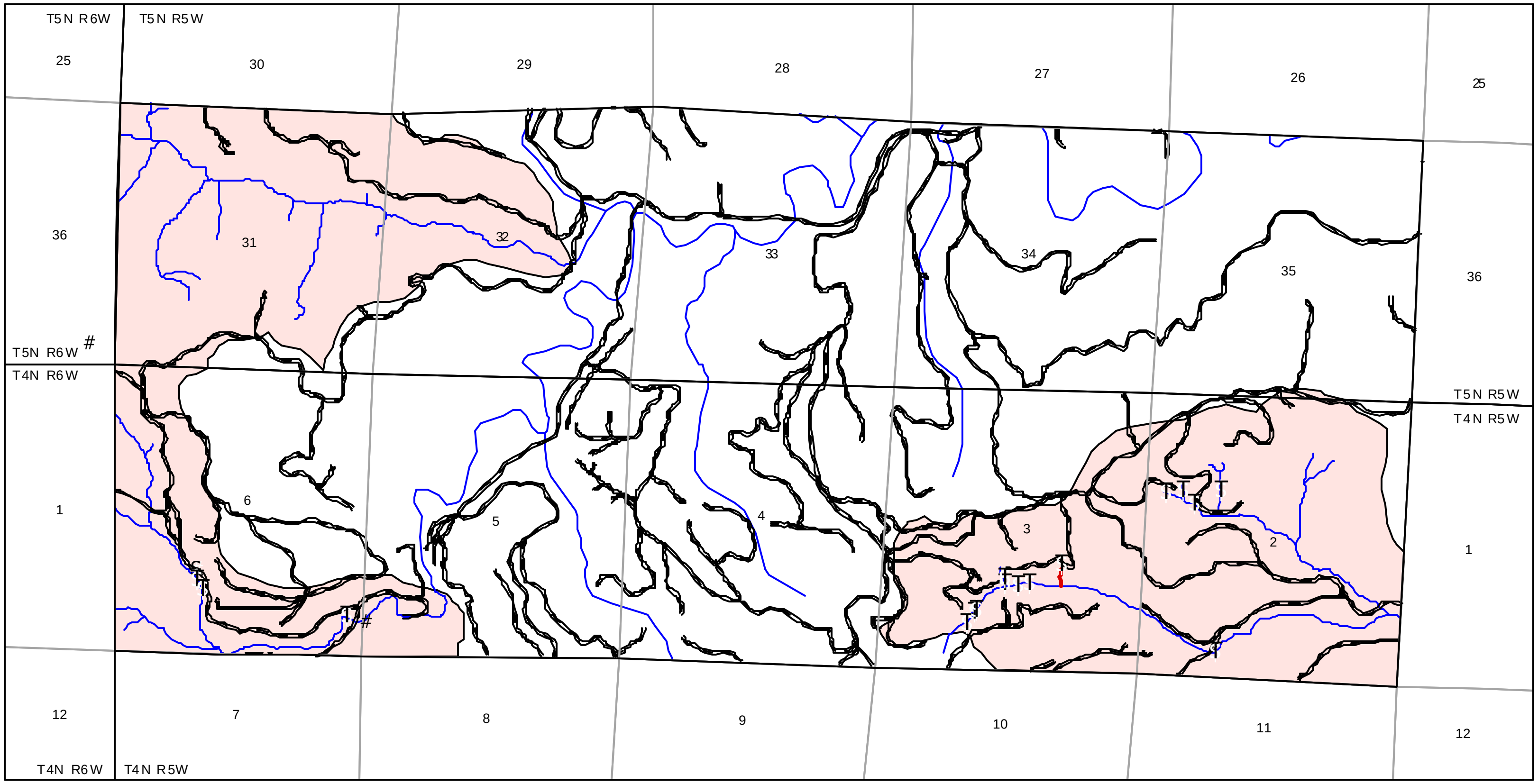
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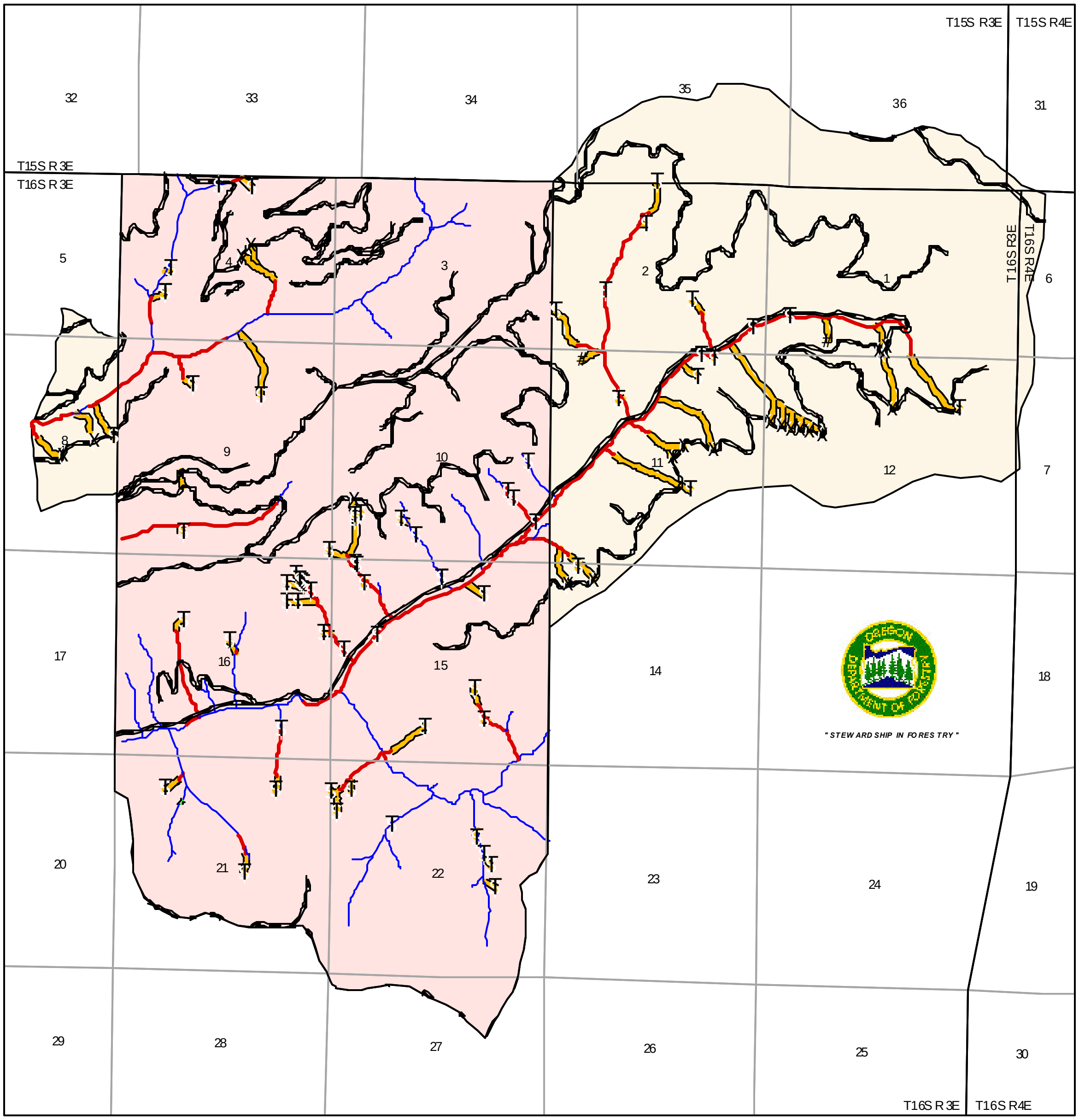
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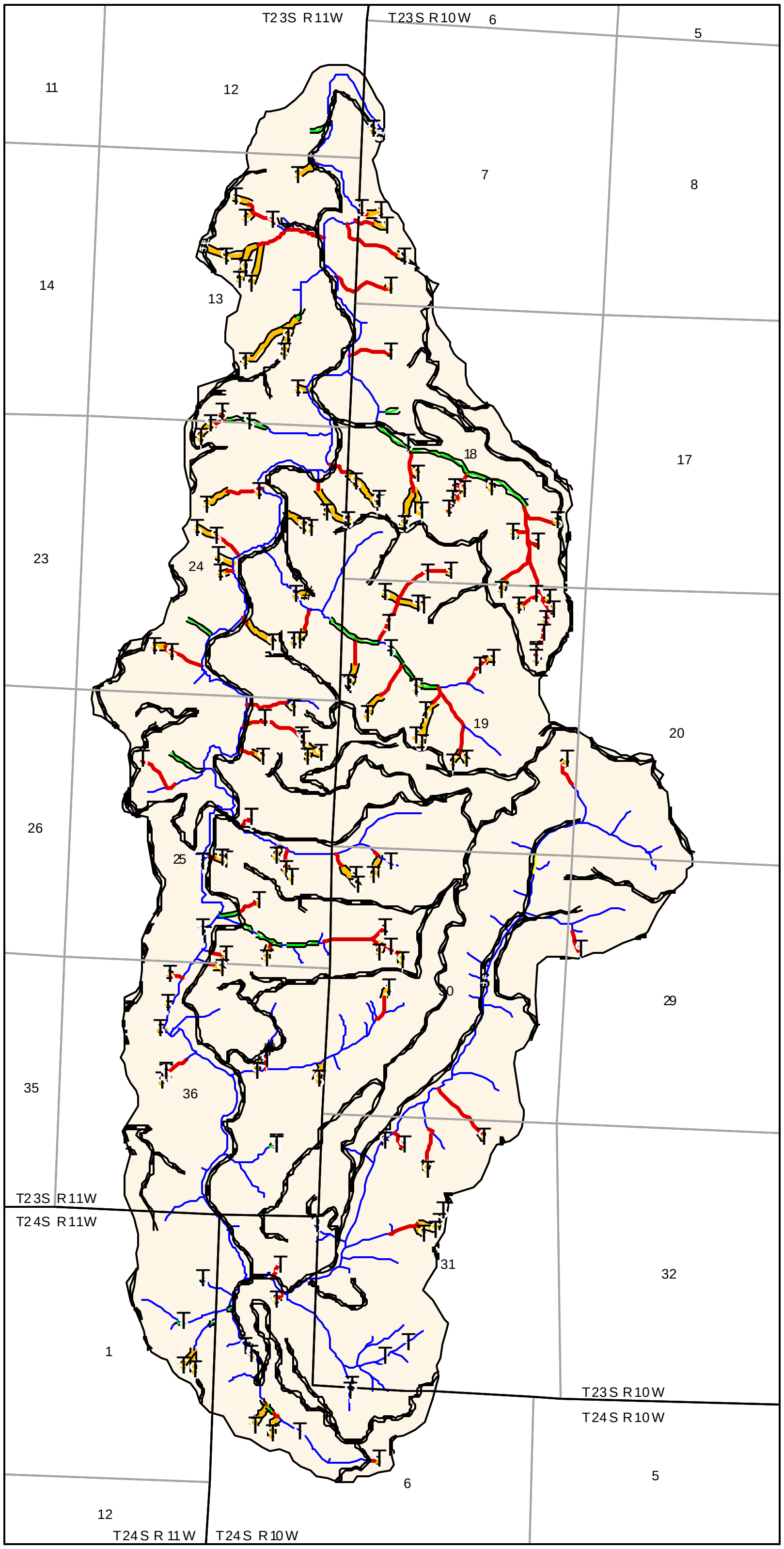
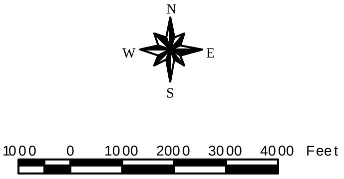
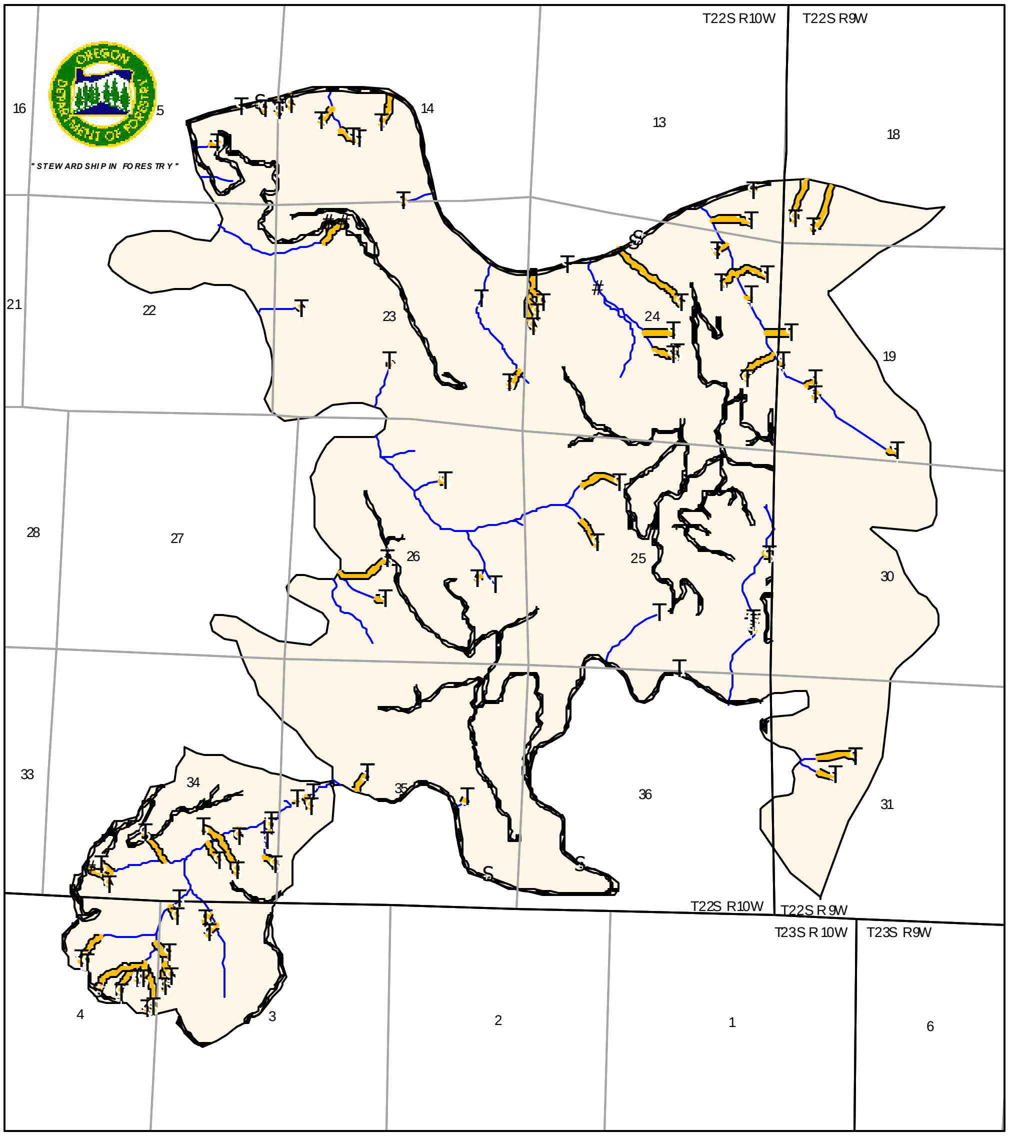
" STEWARDSHIP IN FORESTRY "

Elk Creek Study Area in Coos County





ODF Graphic Services
May 18, 1999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Appendix C

Oregon Department of Forestry

FOREST PRACTICES MONITORING PROGRAM

NOVEMBER 1996 STORM IMPACTS MONITORING PROJECT

Prepared by:
Liz Dent, Monitoring Coordinator
Keith Mills, Geotechnical Specialist
George Robison, Forest Hydrologist
Jenny Walsh, Monitoring Assistant
Jim Paul, Monitoring Assistant

November 1997

Introduction

This November 1996 Storm Impacts Monitoring Project is an extension of the February1996 Storm Impacts Monitoring Project implemented by the Oregon Department of Forestry (ODF) in the summer of 1996. Preliminary results from this project are inconclusive in terms of determining a link between specific forest management practices and landslide frequency. The November 1996 storm in southwestern Oregon has provided an opportunity to repeat the basic study design from the previous year and attempt to verify and clarify preliminary findings from the 1996 Storm Impacts Monitoring Project.

PRELIMINARY RESULTS FROM THE FEBRUARY 1996 PROJECT

Landslide frequencies (#/acre) were calculated for the Mapleton and Vida (red zone) sites, using the following age class categories: 0-5, 5-10, 10-30, 30-100, and 100+ years. The “background rate” is assumed to be the landslide frequency associated with unmanaged, mature forests. In terms of the ODF study, the background rate is that of the 100+ year-old age class category (exclusive of road influences). For the Mapleton site, the 5-10 year stands had a landslide frequency that was approximately double the background rate, while the 0-5 year stands were somewhat less than background. In the Vida study area just the opposite occurs. The 0-5-year stands had approximately double the background rate, while the 5-10 year stands were somewhat less than background. Both sites consistently showed landslide frequencies below background levels for those stands between 10 and 100 years in age. In general the pattern supports the following preliminary hypothesis for landslide frequency over time following harvest: There is an increase in landslide frequency at some time during the first 10 years after harvest. This increase is followed by a drop below background levels between 10 and 100 years and a return to background levels sometime after 100 years following harvest.

Specific Objectives

The November 1996 Storm Impacts Monitoring Project will attempt to verify the general long-term pattern that was observed in the February 1996 storm consistent with two red zone sites. This monitoring project will also attempt to clarify contradictory findings in landslide frequencies during the first ten years after a clearcut harvest.

Specific objectives include the following:

1) Determine factors influencing the distance traveled by landslide runout such as debris paths and torrents. Determine high-risk criteria for determining the length of channel impacts by landslide runout.
2) Collect sound information on the specific forest practices applied at the sites of landslides, flood-altered streams, and riparian areas.

3) Link hillslope processes and forest management practices to channel responses or lack of responses.
4) Identify specific forest management practices applied in the sample areas and determine if practices were appropriate for the times of the operations.
5) Develop a comprehensive relational database for detailed ODF monitoring analysis and for subsequent cause and effect type research.

Coordination

Similar to the previous storm-monitoring project, this project will be coordinated in part with the involvement of a Coordination Team and a team of four experts representing different disciplines (the Expert Team). The coordination team is composed of corporate and small private landowners, the USDA Forest Service (USFS), researchers, the Bureau of Land Management (BLM), and the Oregon Department of Forestry State Lands Program. The Expert Team is composed of a hydrologist/riparian specialist, geomechanical engineer, aquatic biologist, and a geomorphologist (see Appendix A for members).

Study Design and Methods

The study design and methods will be very similar to that of the previous storm-monitoring project, with only a few minor changes. Each crew made up of two people is assigned one sub-basin at a time to complete within one of the two study areas. The sub-basins are partitioned into stream segments. Using the stream network to search for only those landslides that deliver to the stream channel and associated debris torrents, the crew walks every stream segment and implements the Channel Impacts Protocol (CHIP) until the gradient is greater than or equal to 40 percent. If at a 40 percent channel gradient no torrent impacts are encountered the crew stops collecting channel impacts and large woody debris (LWD) data and moves on to the next stream segment. When torrent impacts and landslide evidence is encountered up to and beyond a 40 percent channel gradient, the crew continues walking upstream in search of the source using the channel impacts and LWD protocol. When the crew reaches the source landslide(s) they document the landslide characteristics and record the location using a global positioning system (GPS) device and manually on a map. The crew also records the location of and collects data on torrent jams and large deposits that were generated during the November storm. The following sections are detailed descriptions of the Landslide, Channel Impacts, LWD, and Torrent Jam Protocols.

Landslide Investigation Protocol

Introduction

This protocol was developed using the information learned over six years of landslide monitoring by the Oregon Department of Forestry. The development of this protocol was also influenced through the review of other landslide investigation protocols, the February 1996 Flood Monitoring protocol, and in consultation with the Expert Team.

The field portion of this protocol is designed for use by persons with science and/or resource management training under the direction of geotechnical and riparian specialists. Additional data on land management history will be collected directly from landowners in the study areas.

All landslides (both road and non-road related) that deliver material to channels will be field investigated by the ODF monitoring crews using the channel network to locate the landslides. The crews will collect similar information on landslide characteristics, landform at origin, and soils. Information collected on slope and vegetative alterations from roads and harvesting will be consistent with forest practices requirements.

Methods

<u>Landslide Identification</u>**:** The study area will be inspected for landslides delivering to channels. Landslides include any slope movements where shear failure occurs along a specific surface or combination of surfaces. Some landslides may be less than one cubic yard in total volume, and move less than one-foot down-slope. Other landslides may consist of thousands of cubic yards, moving long distances as subsequent torrents down channels.

All channels within the sample areas will be walked (at least to a 40 percent slope) to identify all points of landslide sediment delivery. Observed landslides will be mapped using a GPS device and manually on a topographic map. Landslides will be found by walking up-slope from the point of sediment delivery and/or debris torrent impacts. Three distinct and separate terms will be used to describe landslide-related impacts in this study. The *landslide* refers to the initial scarp of material on the hillslope or hollow. *Debris path* refers to the subsequent material mobilized by the landslide that is downslope of the initial scarp but upslope of the channel network. *Debris torrent* refers specifically to channel impacts caused by material from the landslide and debris path moving through and being deposited in the channel network.

The principal concerns with the November storm of 1996 impacts are off-site and in-channel effects. Therefore, landslides that enter channels or result in debris paths that enter channels are of principal concern for their effects on water resources. Often a relatively small landslide can have a large effect on the channel down-slope. One of the objectives of this study is to determine what types of slides have the greatest impacts on the channel network and result in adverse effects such as threatening human lives and property and potentially negative impacts on fisheries production.

Efforts will be made to survey only those landslides that occurred during the November storm of 1996. Landslides that are significantly re-vegetated, have consolidated deposits, or which are known through air photos or other means to have moved only in earlier years, will not be included as part of the database for this monitoring project. This past November's landslide scars already have vegetative re-growth on exposed soils, but have less re-growth than older landslides, and can usually be distinguished from older landslides by the presence of unconsolidated landslide or debris torrent deposition. Also, precipitation events occurring in and around the study areas after the November storm were orders of magnitude smaller in intensity, making it unlikely that a significant number of subsequent landslides occurred there.

Terminology**:** Landslides and debris paths will be investigated using the landslide protocol, while debris torrents, torrent jams, and LWD will be investigated with the channel impacts and torrent jam protocol. Debris torrents can usually be traced to the landslide origin. Occasionally, however, there is the appearance of a debris torrent in channels without a landslide origin. Where this occurs the “channel modified” classification will be used (see the Channel Impacts protocol).

A *landslide* is any slope movement where shear failure occurs along a specific surface or combination of surfaces. For this study, landslides are separated from debris paths. Landslides may have a rotational, planar, or irregular failure surface. At the time of landslide initiation, a landslide has a discrete failure surface or surfaces.

A *debris path* occurs if the landslide moves down-slope as a semi-fluid mass scouring, or partially scouring, soil from the slope before reaching a channel. For the purpose of this study, a debris path is the mass soil movement below the initial landslide scarp and up-slope of a channel. Using this definition, debris paths occur only on landforms classified as hillslopes or hollows (i.e. non-channel types of landforms). Upon entering and continuing down a channel the landslide is considered a *debris torrent*. Debris paths will be sampled within the landslide protocol, while debris torrents will be sampled using the channel impacts protocol. It should be noted that not all landslides will have a debris path, but every debris path will have an associated landslide.

Field Data Collection

A GPS device will be used to record the locations of landslides when possible. This, in conjunction with mapping the landslides manually, will allow for the data to be entered into a geographic information system (GIS) and subsequent spatial analysis of the entire data set. Each crew will carry a 35mm camera to record every landslide with a photograph. Each photograph will be recorded on the Photo Record data sheet with a brief description.

Landslide (*LS*): Each landslide will be given a unique number as they are found. One crew will start with 501 and the other with 701.

Stream Segment Number (*Seg*): The segment to which the landslide delivers. (See channel measures protocol.)

Distance (*Dist*): This is the distance along the segment where the landslide or associated debris path enters the channel.

Debris Path Beginning Distance (Bdist): The distance in feet indicated by the hip-chain at the start of the debris path. If the path is in a hollow at the end of a channel segment this distance will be the same as the distance recorded at the last channel cross-section measured. If the path is on a hillslope this distance will be zero (the hip-chain is reset).

Debris Path Average Width (*AveW*): This is the average width of the debris path in feet.

Debris Path Average Depth (*AveD*): This is the average depth of the debris path in feet.

Debris Path Slope (*Slope*): This is the percent slope of the debris path.

Form: There are two general landslide forms evaluated in this protocol, and they are as follows.

1) A *slide (E)* is reasonably close to its point of initiation (materials remain on site).

2) A *slid (D)* has moved completely from the site and may have a debris path and resulted in a debris torrent. It may also be mixed as a torrent jam, eventually residing as channel deposits. A slid that deposits to the channel directly (channel-bank related) will not have an associated debris path.

Type: Landslide type will be evaluated by the following three choices:

1) *Shallow translational (ST)*: Often called debris slides, are slope failures where the failure surface is roughly parallel to the natural ground slope (translational) and the maximum depth to failure surface is usually less than 10 feet. These slides generally move off site (slides).

2) *Rotational (RO)*: Often called slumps, are landslides with a generally rotational failure surface, usually in cohesive material. They have a spoon shape appearance, usually with a pronounced accurate scarp. They generally remain on site (slides).

3) *Other (OT)*: This includes structural translational (block failures), complex slope failure exhibiting several modes of movement, and anything not described above. The geotechnical specialist will investigate these failures. When using this category, detailed notes should be taken to describe the landslide.

Delivery Type (*Torr?*): Record if the landslide resulted in a debris path only (*HO*), a debris path and debris torrent (*HC*), or no debris path or debris torrent (*NO*).

Landslide dimensions: Landslide dimensions will be evaluated by the average landslide width, maximum depth, average depth, and length of the initial landslide, as follows (to the nearest foot):

1) *Begdist* is the distance up the channel segment recorded at the base of the landslide scarp. If the landslide has a debris path this will be the end-distance of the debris path indicated by the hip-chain.

2) *Length* is measured up and down the slope. For length, only the original slide, and not the debris path or other movement is included in this measurement. When length is unknown, as is the case for most slides, the length is estimated based on a change in width or depth of soil.

3) Average *width* is measured across the slope, usually on a contour.

4) *Depth* is a vertical measurement, recorded as maximum (at the center) and the average.

Slope steepness: Measured from the top of the landslide scarp. The "above" measurement is made using a clinometer and sighting to a point at eye height about 100 feet up-slope, while the "below" measurement is made sighting down slope, projected over the hillslope as it existed before the landslide occurred. These are recorded to the nearest 5 percent.

Aspect: Measured in degrees (1-360) using a compass. Stand on the landslide scarp facing down slope.

Drainage Area: Categorize the *plan view (Pview)* shape of the drainage area above the landslide scarp. If there is any hesitation in calling the plan view something other than uniform, it should be called a uniform shape. Only shapes that are obviously concave, convex, or irregular should be classified as such.

1) *Concave (CV)* slopes include *headwall hollows.* This is a concave area in the headwall and most often has an aspect coincident with that of the channel down-slope. This landform is clearly curved inward in plan view and has a valley type appearance. However, there is no defined channel at these locations, as they are often observed close to the ridge-top.

2) *Uniform (UN)* slopes include *hillslopes* adjacent to channels. This is an area high above the channel where the aspect is often perpendicular to the aspect of the channel down-slope. This landform has a relatively uniform slope with no outstanding landform characteristics.

3) *Convex (VX)* slopes are clearly curved outward in plan view. These are often related to old landslide deposits and ridge tops.

4) *Irregular (IR)* slopes are also often related to old landslide deposits, and are evidenced by hummocky, broken terrain with many slope changes.

5) *Other (OT)* includes conditions such as lineaments, contacts, and unusual landforms. When using this classification include specific details in the notes.

Drainage area is determined using a map while at the landslide. Estimate the distance to the drainage divide (*Ridge Dist*) and the average width (*AvgW*) of the area draining to the slide.

<u>Soil Characteristics</u>: Whether or not *bedrock (Y/N)* is exposed is recorded to determine where soil depth and landslide depth is in fact different. The dominant s*oil type* will be identified:

1) *Non-cohesive (N)*: Non cohesive soils include gravel, sand, and fine-grained soils that do not stick together when dry (dry cubes are easily crushed between the fingers).

2) *Cohesive (C):* Cohesive soils are "sticky" and when dry their strength increases greatly (cannot be crushed between the fingers when dry).

<u>Debris Load/Depth</u>: Estimate the amount of organic debris (all sizes) around the perimeter of the landslide scarp using the following categories:
Absent (*AB*)- No visible debris, other than one or two pieces over the entire visible area.
Sparse (*SP*)- A few pieces of debris over the visible area, but no significant clusters.
Non-contiguous (*NC*)- A significant number of pieces, but a majority of the pieces are not touching each other.
Contiguous (*CN*)- Many pieces that are mostly touching each other.

Estimate the depth of debris to the nearest foot in the *Debris depth* column only when using the *contiguous* category.

<u>Slope alterations at source area of landslide</u>: *Slope alterations* are also recorded. These include alterations due to management as well as natural alterations such as *windthrow (W)* or *fire (F)*. If there is a linear *gouge (G)* on the slope adjacent to the landslide which when projected intersects the landslide this is also recorded, as is the presence of a *skidroad (S)* located at the landslide or adjacent to the landslide scar. *Road-related* alterations include landslides originating from, or being influenced by, old (*D*) or active (*A*) roads. This includes landslides in close proximity to a road where road drainage or construction is associated with the failure location. *Other (O)* will be recorded for any other type of alteration not discussed above and details will be recorded in the notes. Where no alterations have occurred *none (N)* will be recorded. There can be multiple entries for this item.

<u>Vegetation</u>: The *height* of the *dominant* commercial vegetation immediately about the scarp is recorded, along with an estimate of the *percent cover* that existed at the location of the landslide scarp prior to the occurrence of the landslide.

<u>Picture Number (*Pic#*)</u>: The roll and picture number, along with the crew letter (A or B), is recorded.

<u>Notes</u>: Other information is recorded as necessary to describe the landslide and any unusual observations.

Non-field landslide and forest practices information

The following additional information will be collected for each landslide, after the field investigation:

1) Elevation at the slide origin (GPS; GIS)

2) Drainage area (GIS)
3) Most recent timber harvest (year)
4) Geologic map unit
5) Ownership (State, Federal, Industrial Private, Non-industrial private)

CHANNEL IMPACT FIELD PROTOCOL

Introduction

The objective of the channel impacts portion of the storm monitoring will be to document storm effects on stream channels. Primarily the monitoring will examine possible alterations to channel geometry (channel widening, aggradation/degradation), woody debris loading, scour/depositional patterns, and shade. The channel measurements will be taken in three distinct phases:

Channel impact protocol (CHIP): This includes cursory measurements for stream channels. These include channel type, impact type, slope, impact width, length of torrent, shade, woody debris size and distribution, and classification of scour, depositional, and transitional reaches. CHIP will be implemented on all stream channels.

Field measurements for the channel impacts protocol

As described in the overall methods section, the crews will use the channel network as a means of searching for landslides. They will walk up all channels and stop every 150 feet to sample channel characteristics using the following protocol. All measurements will be at a point, or two-dimensional cross-section, at 150-foot intervals. For low impact channels, the crews will stop when coming to a gradient of 40 percent or greater. When the channel gradient becomes 40 percent or greater before reaching the next 150-foot cross-section, the crew will sample an additional cross-section at the end of that segment. At torrent junctions a revised CHIP will be used to sample that cross-section, where only the junction angle measurements and distance will be recorded.

The crews are encouraged to photograph any channel or debris torrent features that are unusual or unique in terms of severity of impacts. Care will be taken to include an adequate description on the Photo Record data sheet.

Stream Segment Number (*Seg*): Segment numbers are assigned as the field crews survey the streams. One crew begins numbering segments with 101 and the other with 301 and labels new segment numbers on the map as the channels are surveyed. New segment numbers are assigned at channel junctions and for all first-order streams.

Distance: The distance (*Dist*) from landmark in feet measured using a hip chain. This is also the *Dist* for the current interval of LWD data collection.

Landmark: The landmark is the start of a new segment at a stream junction. Record the segment and distance up that segment that is the landmark for the beginning of the segment currently being sampled.

Direction (*Updn*): The crew can move from the landmark in an upstream or downstream direction, and the direction of travel will be noted *(U/D)*.

Landform: This is a description of the average valley landform in the immediate vicinity of the cross-section. It is based primarily on the configuration of the valley floor. Descriptions are divided into the following categories:

1) Narrow Valley Floor has a valley floor width < 2.5 times the active channel width. A narrow valley floor is further categorized as one of the following:

a) Steep V-Shaped (*SV*)- valley or bedrock gorge with at least one of the side slopes >60%.

b) Moderate V-Shaped (*MV*)- valley with at least one of the side slopes between 30% and 60%.

c) Open V-Shaped (*OV*)- valley with side slopes <30%.

d) Filled V-Shaped (*FV*)- valley with considerable fill so that the valley width vs. active channel is greater than 2.5 and yet it still has steep side slopes (>60%).

2) Broad Valley Floor has a valley floor width > 2.5 times the active channel width. A broad valley floor is categorized as having one of the following:

a) Constraining Terraces (*CT*). Terraces typically high and close to the active channel. Terrace surface is unlikely to receive flood flows.

b) Multiple Terraces (*MT*). Surfaces with varying height and distance from the channel. High terraces may be present but they are a sufficient distance from the channel that they have little impact.

c) Wide-Active Flood plain (*WF*). Significant portion of valley floor influenced by annual floods. Any terraces present do not impinge on the lateral movement and expansion of the channel.

4) Fan (*FN*)- This is commonly seen when a steep canyon enters into a broader canyon at tributary junctions.

5) Hillslope (*HS*)- Used only for high impact types, this will indicate the end of the channel impacts and the start of a debris path and/or landslide. The debris flow path occurs on a hollow or hillslope with no defined channel bed and bank.

6) Hollow (*HO*)- Used only for high impact types, this will indicate the end of the channel impacts and the start of a debris path and/or landslide. This can be a transition area between a “steep-valley” channel-type landform and a hillslope. The debris flow path occurs in a hollow or hillslope with no defined channel bed and bank landform.

Impact Type: Each cross-section and the reach immediately about the cross-section will be classified by impact type. Evidence of high water is usually indicated by minor alterations to the riparian area and minimal channel changes. Torrent scour is when the stream is typically scoured to bedrock and there is evidence of a torrent moving through such as severe alterations to the riparian area or wood stored high out of the channel. Torrent deposition reaches typically are widened and aggraded. Torrent jam reaches are distinctive, as they are jammed with wood and sediment. (Be careful to check for jam removal around road crossings). Dambreak flood reaches are identified by a possible breached roadfill or evidence of a breached debris deposit followed by high-water damage much greater than what is normally seen in other nearby stream reaches. See categories below.

1) Low Impact Group (no torrent impacts)

a) No (*NO*) perceivable impact from high water, flood or torrent. Winter flows appear to be contained within the active channel.

b) High Water (*HW*) impacts only. Indications of high flow, such as bird nests (i.e., twigs gathered in brush above stream) in streamside vegetation and cleaning of litter from low terraces and flood plains.

c) Scour and deposition patches (*SD*). Localized channel, bank, and floodplain scour or deposition of fines, gravel, or cobble. Scale: patch size generally less than a few channel widths long.

2) Moderate Impact Group (no torrent impacts)

a) Channel modified (*CM*). Larger scale (multiple channel widths long) channel relocation, deposition of new gravel bars, or scour of new side channels. These areas may appear to be torrent-impacted reaches. Look for the impact width extending up to, but not beyond, the channel bank-full height. A torrented reach will have impacts relatively high above the channel bank, where as *channel modified* impacts do not extend very far beyond the bank-full width/height, if at all.

3) High Impact Group (torrent impacts)

a) Torrent scour impacted (*TS*). Greater then 75 percent of the reach is scoured. Massive lengths of channel are scoured deeply and often to bedrock. Often times a depositional reach is downstream where gradient moderates or the valley widens.

b) Torrent transitional (*TT*) Greater than 25 percent of the reach consists of scour and deposition. There are definitive torrent impacts but scour and deposition roughly balance out.

c) Torrent deposition reach (*TD*). Greater then 75 percent of the reach is deposition. Consists of massive lengths of channel with deposits of generally poorly sorted material. Generally the deposition is wider than you would expect the channel to be.

d) Torrent jam (*TJ*). This is a plug in the channel that backs up wood and other debris, ranging in depth from three to 30 feet. The active channel is unable to form a new path around this feature and appears to disappear at some point and re-emerge downstream. When encountering this feature, measurements will be recorded on the Torrent Jam data sheet. Care is taken not to mistake large deposits as torrent jams, where the active channel is still present off to one side or down the center of the feature.

e) Dambreak torrent scour (*DS*). This is a dambreak scour combination caused by a dambreak flood. Dambreak flood effects are evident by unusually high water and evidence of a roadfill or torrent deposition breaching upstream. Dambreak floods are much less frequent than debris torrents and can be very difficult to identify. When encountering this feature it is important to record it with photograph.

f) Dambreak torrent deposition (*DD*). A dambreak and deposition combination.

g) Dambreak torrent jam (*DJ*). A dambreak-jam combination.

Channel Type: Channel types are categorized using a variation on ODF&W's small stream protocol. The channel type is categorized as one of the following:

1) Meadow Trench (*MT*). Low gradient, low energy system with meandering channel flowing through meadow soils and peat. Typical of low gradient headwater meadow and wetland reaches. Poorly defined pool-riffle sequences may be present, but the scour pools are not much deeper than the riffles or glides.

2) Braided (*BR*). Multiple channels with poorly defined riffles and few pools.

3) Pool-Riffle (*PR*). Low to moderate gradient. Sequence of full channel width pools

4) Pool-Step-Pool (*PS*). Moderate to high gradient. Full-channel-width pools separated by steps, riffles, rapids, or cascades. Easily identified pools with a mix of habitat types in between.

5) Cascade (*CA*). High gradient. Rapids, boulder strewn chutes falls, and very small pools.

6) Colluvial Debris (*CD*). Channel filled with unsorted material from the adjacent hillslopes (boulders, smaller sediments, and/or large wood).

7) Bedrock (*BD*). The channel bottom is more that 50 percent bedrock, typical of "sluiced out" sections of headwater tributaries. It is important to continue the survey far enough to identify the source of the channel failure (road, landslide, or other source).

Aspect: Measured in degrees (1-360) using a compass. This is measured facing down stream. If the channel is meandering try to visualize the straight-line general direction of the channel 150 feet down stream.

Slope: Measured facing upstream with a clinometer in percent. Sight to a point at eye height about 100 feet up slope, or as far as you can see, which ever is shorter.

Thalweg: Maximum wetted depth of the channel cross-section in feet. A dry channel has a zero depth. If flow present but immeasurable (trace amounts) use 0.01 feet.

Active Width: Width of the active channel, and not the over-bank areas where excess water may have run.

Sediment Type: Channel bed substrates will be sampled using three general categories:
Boulders to Bedrock (B): > 250mm (basketball size and greater)
Coarse Gravel and Cobbles (C): 16mm – 250mm (marble to basketball size)
Fines, Sand, and Fine Gravel (F): < 16mm (silt to pea size)
At each cross-section along the channel segment observe the substrates on the stream bottom. For the area bound by the active width and a one-foot unit length, estimate the percent that falls in the three categories defined above. Estimate to the nearest five or ten percent for each and record these values on the channel impacts data sheet. To avoid a bias towards larger particles that are easier to see, be sure to look carefully for the smaller gravel, sand, and fines.

Impact Width: Impact width in feet. This is the area impacted by debris torrents and flood flows during the November 1996 storm. May extend over floodplains, terraces and side slopes. The impact can be seen in the form of scour and depositional features on the side slopes. For those cross sections classified as a high impact type, this measurement will be an estimate of the width of impacts related to the debris torrent.

Impact Height: Impact height above channel. This is measured vertically from the low point of channel cross section in feet to the height of the top marks of flood/torrent related impacts. Use the surveyor rod to get the height. For those cross-sections classified as a high impact type, this measurement will be an estimate of the depth of impacts related to the debris torrent.

Debris Load/Depth (reach): Estimate the amount of organic debris (all sizes) using the following categories:

Absent (*AB*)- No visible debris, other than one or two pieces over the entire visible area.
Sparse (*SP*)- A few pieces of debris over the visible area, but no significant clusters.
Non-contiguous (*NC*)- A significant number of pieces, but a majority of the pieces are not touching each other.
Contiguous (*CN*)- Many pieces that are mostly touching each other.

The visible area is 75 feet up and down stream of the cross-section, or as far as you can see, which ever is shorter. When surveying a high impact channel, look just beyond the impact width to assess the debris load. For a low impact channel, look in and around the active channel itself. When using *contiguous*, estimate the depth of debris to the nearest foot in the *Debris depth* column.

Shade: Shade is measured with a convex densiometer. Take measurement facing upstream, downstream, left direction and right direction from the center of the channel at each station. Record the count of intersections covered by vegetation (maximum is 17). For details on how to use the densiometer see Kaufmann and Robison, 1994.

Channel Junctions: Along those channels with torrent impacts, all of the channel junction angles that the torrent moved through will be recorded. The angle is determined by finding the acute angle between the incoming tributary and the main channel. This is determined by taking two aspect measurements. One aspect is taken facing downstream of the channel that is being traversed. The other aspect is taken looking upstream at the entering tributary with torrent impacts. (At a later time the difference between these two aspects will be subtracted from 180 degrees to determine the acute angle.) An additional observation will be recorded that answers the following question: Is there evidence of a torrent riding high up over the channel bank opposite the incoming torrented channel? In other words, does it appear that the torrent from the tributary channel moved through the junction? (*Opim, Y/N*)

Notes: It is very important to note any comments about a measurement point. Especially important are any comments about possible dambreak areas or debris torrent particulars.

Method for large woody debris

The measurement protocol is simplified from the one used in ODF&W habitat surveys (Moore et. al, 1995 p. 23-24). Two matrices of wood diameter versus wood length are used (Appendix B). One matrix is for wood stored partially or wholly within the active channel. The other is for wood stored outside the active channel but within the impact zone or potential impact zone. The impact zone is the area that is encompassed by the impact width measurement. For low impact reaches this is the estimated width that would be impacted had a torrent occurred. For each channel segment, a continuous tally is kept of LWD based on diameter, length and location (150-foot intervals). LWD tally intervals correspond with channel sampling intervals to allow for an analysis of the spatial distribution of LWD.

There are nine different size classes for LWD that are a combination of diameter and length categories. The small, medium, and large diameter categories are 10-18, 18-36 and greater than 36 inches, respectively. The small, medium, and large lengths categories are 6-15, 15-35, and greater than 35 feet, respectively. The following diagram is a matrix of the nine size classes:

Length → Diameter ↓	**S** (6-15 ft)	**M** (15-35ft)	**L** (> 35 ft)
S (10-18 in)	**SS**	**SM**	**SL**
M (18-36 in)	**MS**	**MM**	**ML**
L (>36 in)	**LS**	**LM**	**LL**

Torrent jam/deposit measures

The Torrent Jam protocol (Appendix B) is used to map the occurrence and volumes of torrent jams and very large depositional features in the field to understand in a gross sense the sediment budget of the landslides, torrents and channel impacts. This form should be used whenever a torrent jam is encountered, or if a large sediment deposit greater than 10,000 cubic feet is encountered. This is equivalent to a deposit that is 10 feet deep, 10 feet wide, and 100 feet long. A torrent jam is defined as a large deposit that plugs the entire channel width and causes a distinct drop off. This is often, but not always, the end-point of a debris torrent.

Crew, date, major basin name, and segment number are described under the channel measures protocol. The following categories are unique to the torrent jam form:

TJ: This is the number assigned to the jam (or deposit) by the crew. One crew will start with 901 and the other with 951.

Type: This is the feature type. It will be either a torrent jam (*J*) or a large deposit (*D*).

Beginning Distance: The distance to the down stream end of the depositional feature from the landmark in feet.

Beg Width: Width of feature measured at the point furthest down stream.

Beg Height: Height of feature measured at the point furthest down stream.

Slope Down: Take a slope measurement, facing downstream, standing just below the feature.

Frontal Textures: The percentage of material that is visible at the front (downstream end) of the feature. This includes any pieces that appear to have played a role in stopping the torrent and causing the jam. Wood refers to large wood over 10" in diameter and six feet in length (LWD). Anything smaller should be placed in the organic category (*O*). Everything else should go in the inorganic category (*IO*). The three columns should add up to 100%. The predominant diameter *size* of the LWD will also be recorded (*S = 10”-18”; M=18”-36”; L=36”+*).

Ending Distance: The distance to the up stream end of the depositional feature from the landmark in feet.

End Width: Width of feature measured at the point furthest up stream.

Slope Up: Take a slope measurement, facing upstream, at the upstream end of the feature.

Surface textures: The same measurements taken for frontal textures but applied to the surface of the feature instead. This includes any pieces that do not appear to have played a role in stopping the torrent and causing the jam.

Channel Junction *(Y/N)*: Is feature within 100 feet downstream of the junction of an incoming landslide?

Aspect Down: *If at a channel junction* the junction angle must be determined. This is done by finding the acute angle between the incoming landslide and the main channel, and is described in the channel impact measures protocol. Measure the aspect facing downstream while standing at the channel junction.

Aspect Up: *If at a channel junction*, measure the aspect facing up the torrented tributary while standing at the channel junction.

Notes: Record any additional notes here.

LSFR_Pre_text_Master_Document.doc/Jaz B