STORM-INDUCED MASS WASTING IN FORESTED AREAS: CONDITIONS AND CHARACTERISTICS FOR THREE WESTERN OREGON STUDY SITES

by

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ABSTRACT

Much of the rich forestlands of Oregon are subject to frequent mass wasting events, resulting in severe environmental and economic damages. Extensive research has shown that this landslide hazard is often exacerbated by many management activities. Following a severe storm event which triggered thousands of landslides, the Oregon Department of Forestry implemented a project designed to study these slides. By analyzing the study site stability conditions, landscape setting characteristics at failure initiation point, and landslide parameters for three of the ODF study sites, the erosional characteristics of these areas can be better understood. For each of these western Oregon sites this paper identifies hazard areas, landslide behaviors, impact types, and the implications of these findings for forest management and high-risk site assessment.

KEY WORDS: Storm-Induced Mass Wasting, Landslides, Slope Stability Factors, Erosonal Hazards, High-Risk Site Assessment, Forest Management

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OBJECTIVES

This project is designed to address management and prevention aspects of Oregon's landslide hazard through achievement of the following three objectives:

1. Identification of impacts, processes, and triggering factors involved in storm-induced mass wasting events in western Oregon,

2. Examination of differences in slope stability conditions, landscape setting characteristics at initiation points, and morphometric landslide parameters for three western Oregon study sites,

3. Discussion of specific erosional hazards for these western Oregon sites they relate to forest practices and high-risk site classification.

BACKGROUND

Forests in Oregon

Forest Distribution

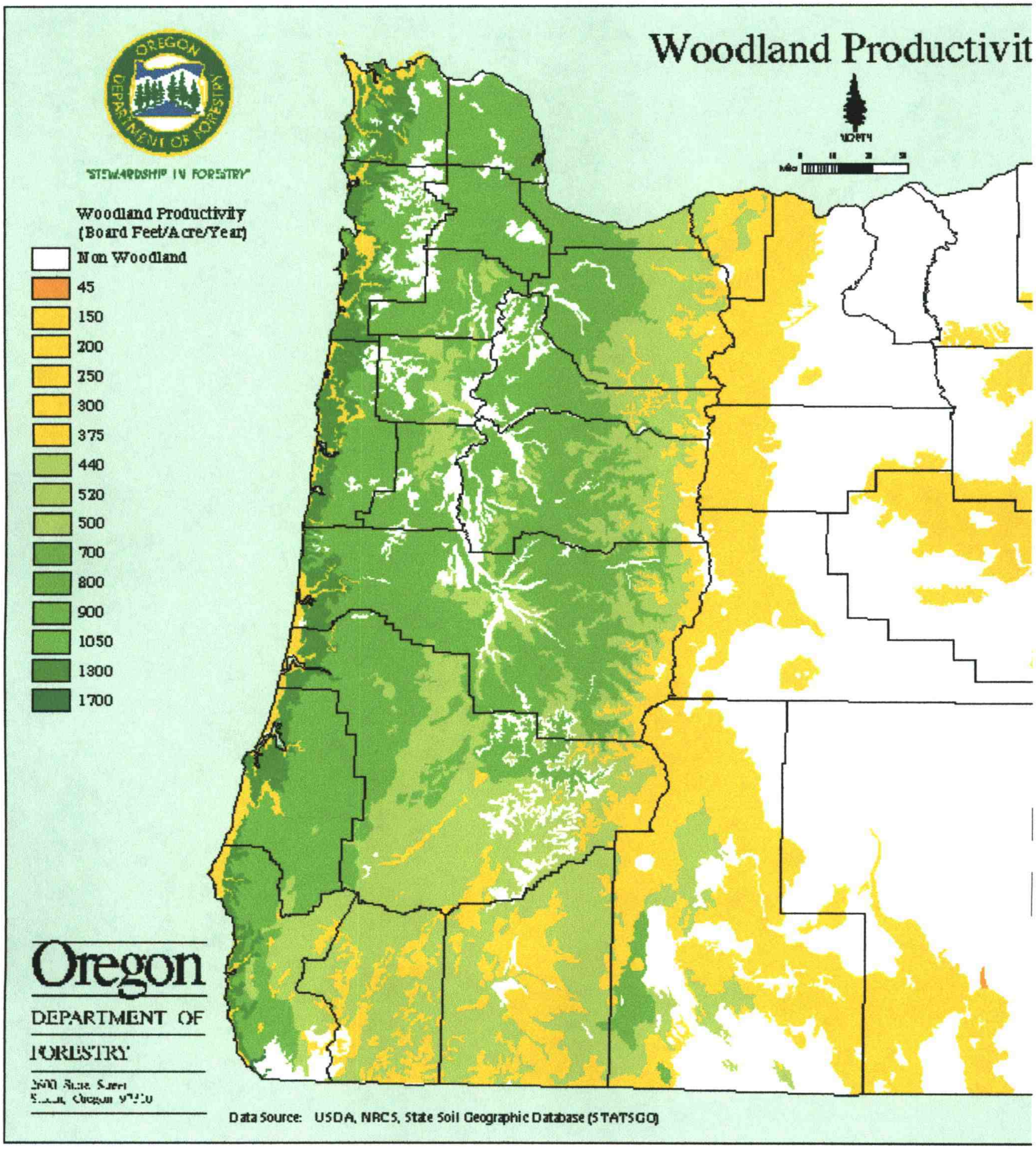
The State of Oregon contains 28 million acres of forestland, giving it the largest forest resource base in the conterminous United States (ODF 1995). Within these 28 million acres are some of the most timber-productive soils in the world, with potential growth rates exceeding 1000 board feet/acre/year at some western sites. The majority of Oregon's forestlands lie in or near the Cascade, Coast, and Klamath/Siskiyou Mountain regions in the western portion of the state (Map 1), but significant forests also exist in the Ochoco, Blue, and Wallowa Mountain areas of central and northeast Oregon.

Forest Functions and Uses

Oregon's forests provide diverse types and structures of wildlife habitat, as well as indispensable watershed settings for fish and other aquatic populations. On a global scale, these forests are a vital element in the hydrologic cycle and for carbon storage. Humans also receive many benefits from this forest resource, including recreational opportunities, municipal water supplies, and timber production.

Timber Harvesting

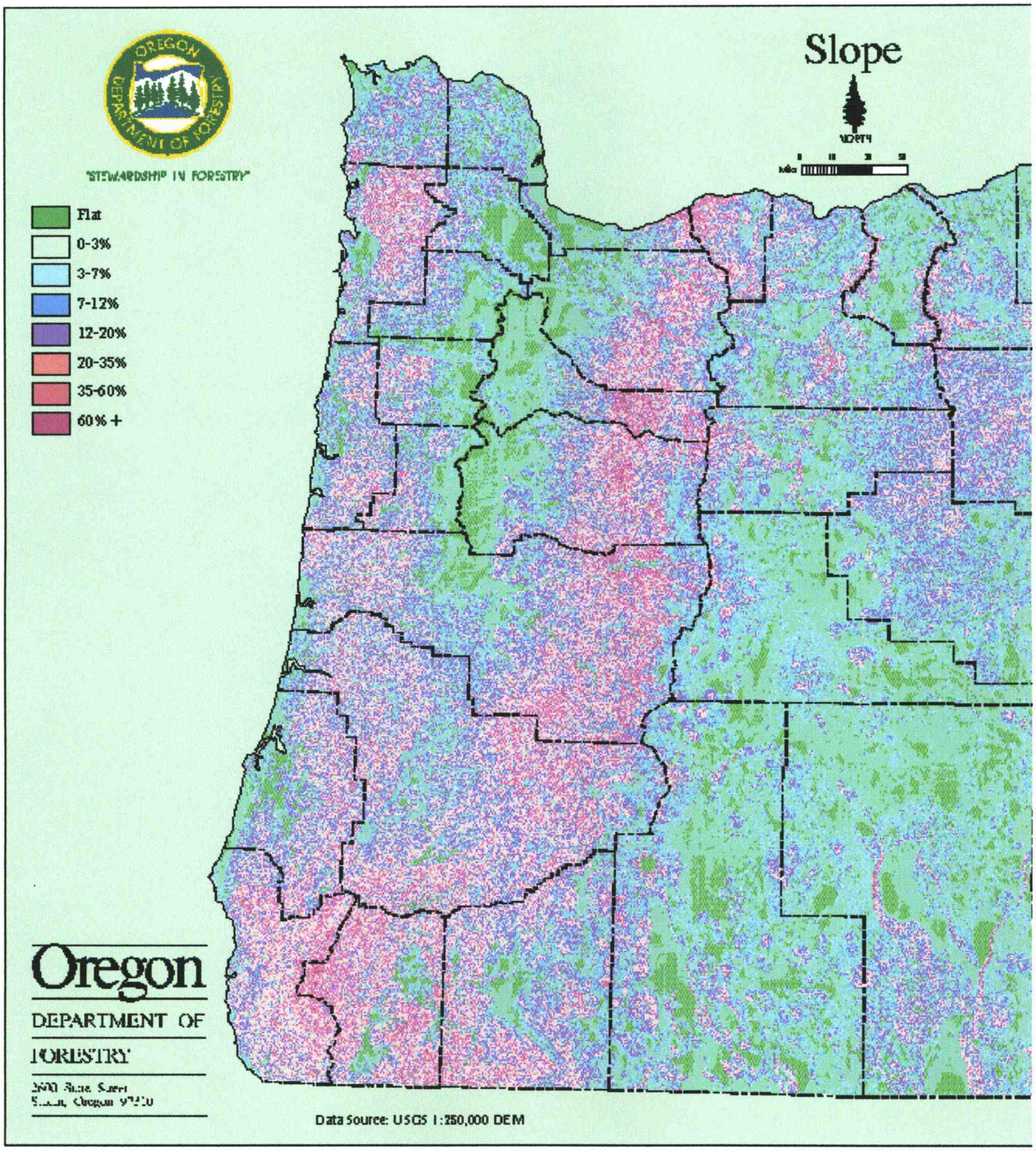
Harvesting of these forests has long been an integral aspect of both the social and economic identities of Oregon. These resources have supplied a forest products industry which has traditionally been the giant of Oregon's economy. Although recent years have seen many changes, the forest products industry continues to lead the state at $5.5 billion per year (Seideman 1996). Currently, 65,000 people are employed in Oregon's forest products industry (ODF 1995).



Map 1

Western Oregon timber production potential

From *ODF 1998a*



Map 2

Western Oregon hillslope steepness

From *ODF 1998b*

Landslide Hazard in Oregon

Landslide Hazard Distribution

These high-relief, forested portions of the state also tend to have the greatest landslide hazard. Burroughs (1983) found that 10-12 percent of the state's land could be classified as "unstable", largely coinciding with those western Oregon regions of greatest timber production potential (roughly represented by slope steepness, map 2). The various existing geologic, geomorphic, hydrologic, and soil characteristics all help to make soil mass movement the dominant erosional process of Western Oregon's steep, mountainous areas (Burroughs 1983, Gresswell et al. 1979, Sidle et al. 1985).

Landslide Damages

Although soil mass movement events can be a beneficial part of long-term ecological processes, from a resource management point-of-view they are a major erosional hazard. Structural and ecological damage caused by landslides and resulting debris flows and torrents is a central issue facing forest managers today. As failed soil, rock, and vegetation masses move down hillslopes or become debris torrents in stream channels they cause damage in four general ways:

1) *Decreased site productivity*

The most site-specific landslide impact is the removal of the vegetation-producing medium, which limits both the economic and ecological productivity of a site. Brown (1985) noted that, relative to normal rates, Douglas fir seedlings in six- to 28-year-old landslide tracks were reduced 38 percent in height growth, 25 percent in tree stocking density, and 40 percent in average volume. Thirty percent of the area of these tracks remained unstockable, even six to 28 years later.

2) *Degraded water quality*

As landslide and debris flow material moves downhill, soil can be immediately delivered to a stream or later flushed into channels by surface runoff. The increased turbidity from heavy sediment loads lowers water quality for human, wildlife, aquatic insect, and fish uses. The loss of shade from streamside vegetation removed as debris torrents scour channel banks can also lead to lowered water quality for fish in the form of elevated stream temperatures.

3) *Loss of anadromous fish habitat*

Perhaps the most focused-on landslide issue in forest management today are their impacts on the state's economically, socially, and ecologically valuable fish populations. Fish habitat can be damaged by debris torrents that scour stream channels to bedrock and by material deposits which bury or dam streams, or subsequent sediment delivery which clogs gills and spawning gravel.

4) *Damage to structures and human fatalities*

Fatalities and damages caused to man-made structures are the most readily observable impacts of soil mass movement events and have the greatest immediate effects on human activities. Landslides frequently destroy roads, bridges, homes, utilities networks, and occasionally take lives. Like water quality and fish habitat degradation, structural damage from landslides can occur far downslope or downstream from the initial site of the failure. Damages of this type are the most readily quantifiable in terms of economic losses and have traditionally received the greatest attention.

(Brown 1985, Amaranthus et al. 1985, Swanston 1974a, Swanston and James 1975)

LANDSLIDE RESEARCH

Slope Stability Factors

Natural hillslopes are held into place by a combination of slope strength properties that, together, outweigh the various stresses which would cause the slope to fail. Landslides result when an increase in stresses or a decrease in strengths brings the strength-stress ratio below 1. The hillslope stability factors which contribute to this ratio can be grouped into five major process areas: geologic/geomorphic characteristics, soil properties, hydrologic factors, vegetative conditions, and seismic activity (Sidle et al. 1985). Some of the natural characteristics of Oregon's forested areas such as weak rock structures, steep slopes, unconsolidated soils, and intense precipitation regimes, can give a region a predisposition to mass movement events. Other factors of a hillslope's strength-stress ratio can altered by human activities such as tree harvesting and road building. (Burroughs 1983, Brooks 1987)

Geologic/Geomorphic Site Characteristics

Landform and geologic traits such as drainage density, relief, slope steepness and shape, bedrock composition and structure, and weathering play significant roles in landslide hazard evaluation. Because these factors are highly influential to a hillslope's susceptibility to landslides and often dictate the types of failures that will occur, understanding of a region's geologic characteristics is an important part of successful slope stability analysis (Chowdhury 1978). Many studies have been conducted in Oregon and the Western United States in an attempt to better understand at what angle hillslopes approach instability. These studies show that landslides generally occur on slopes between 56 and 81 percent, averaging 66 percent (Table 1).

Maximum Slope of Natural Hillslope Stability

Source	Location	Max. Stable Slope
Gresswell et al. 1979	Central Oregon Coast Range	70%
Swanson 1974b	Southeast Alaska	67%
Sidle et al. 1985	Western United States	56%
Bishop and Stevens 1964	Southeast Alaska	70%
O'Loughlin 1972	Southwest British Columbia	67%
Swanston 1972	Southeast Alaska	76%
Swanston 1969	Southeast Alaska	67%
Ketcheson & Froelich 1978	Central Oregon Coast Range	81%
Dyrness 1967a	Western Oregon Cascades	78%
Amaranthus et al. 1985	Southwest Oregon	50%
Neely and Rice 1990	Northwest California	65%
Dyrness 1967b	Western Oregon Cascades	50%
Average Slope of Instability		**66%**

Table 1

Slopes at which hillslope stresses begin to exceed hillslope strengths,
as reported in landslide studies in western North America

Soil Properties

Soil structure and composition properties can have significant impacts on slope stability conditions. Innate soil strength and soil water concentration based on soil water movement rates and soil water capacity both affect a hillslope's predisposition to failure. Some of the important soil properties involved are soil depth, soil cohesion and plasticity, water retention capacity, chemical properties, grain size, pore size distribution, and internal angle of friction.

Vegetative Conditions

Plant roots generally have a very large contribution to the strength factors of hillslopes in three general ways. First, large tree roots can provide vertical anchoring of soil into the underlying bedrock. This is most common in rather thin soils underlain with weathered bedrock. Second, lateral root extension across soil planes of weakness can serve to lock slide-susceptible soil masses into more stable, adjacent masses. Third, the dense network of smaller roots in the upper portion of the soil mantle help to hold soils together on a smaller scale. (Sidle et al. 1985, Swanson and Swanston 1977) The vegetative characteristics of a site can also help increase slope stability by increasing groundwater infiltration rates and subsurface flow, retarding soil eroding surface runoff, and by removing water from soils through increased evapotranspiration (Brooks 1997).

Hydrologic Factors

Concentration of soil water is the most common triggering mechanism of mass soil erosion events because it greatly increases the weight of a soil mass and reduces its cohesion. Sidle et al. (1985) reported that the maximum angle of natural hillslope stability drops from 97 percent for unsaturated soils to 45 percent when saturated. As well as landform, soil, and vegetation conditions, local hydrology factors such as rainfall intensity and total amount, snowmelt regime, and water table levels have great influence on soil water concentration . Shallow, rapid landslides are most commonly triggered by intense rainfall or snowmelt events which quickly overload the stability of steep, shallow soils. Deep-seated mass soil movements are more dependent on longer-duration events and an accumulation of water within the soil throughout a rainy season to the point where the sheer weight of the soil mass exceeds the hillslope strength properties.

Seismisity

Seismic activity is another landslide-triggering mechanism, especially at sites where other factors have greatly weakened soil strengths. The influences of seismic activity are often not included in slope stability analysis because they cannot be easily predicted or managed for. As well, significant seismic events are infrequent in Oregon.

Forest Management and Landslides

Management-Stability Research

The influences of timber harvesting and forest management practices on slope stability in western Oregon were first recognized in the 1950s (Gresswell et al. 1979). Since then, many of the ways in which practices such as clearcut logging and road building alter stability have become well understood, and numerous studies have identified mass movement as one of the major hazards associated with forest harvesting in unstable terrain. Quantification of these relationships have been attempted by researchers in universities, public agencies, and private groups and industries throughout North America, with great focus on the mountainous regions of Western Oregon.

As well as being an important focus of researchers, the link between forestry operations and landslides has been a common topic of debate in the public, political, and resource management arenas. The statement of Swanson and Dyrness in their 1975 article that "environmental impacts of forest management practices, especially clearcut logging, have been the subject of heated, unresolved controversy in technical and popular literature and before legislative committees" certainly holds true today.

Stability Influences of Forest Management

There are many ways in which both forest harvesting and road construction practices are generally accepted to contribute to slope instability. Landform alterations due to road construction can create a hazard from slopes that exceed the angle of natural hillslope stability, the removal of cut-slope support, and the addition of hillslope weight (Sidle et al. 1985). Road ditches can also act as artificial drainage networks while also intercepting subsurface flow at cut faces, and re-routing and concentrating surface water.

As well, the resulting increased peak streamflows can also cause greater bank erosion and higher incidence of streamside slides. Vegetation removal and soil compaction associated with timber harvesting both alter evaportranspiration and groundwater infiltration. The results are more rapid concentrations of greater amounts of soil water and subsequently more frequent landslides. (Brooks 1997)

Vegetation removal is one of the greatest slope stability impacts of forest operations because root deterioration after harvest greatly reduces the ability of soil masses to remain intact. Much research has been conducted on net soil root strength based on tree root diameter decay tests, tree root strength decay tests, landslide frequencies following harvest, and regeneration root strength. Research findings are summarized in Figure 1 and Table 2. This research suggests that the small roots responsible for soil cohesion decay within the first 10 years, while the tensile strength of the larger "anchoring" roots declines rapidly over this period as well. The resulting period of weakest net soil root strength is generally about 3 to 10 years after harvest, before the roots of forest regeneration have begun to take hold.

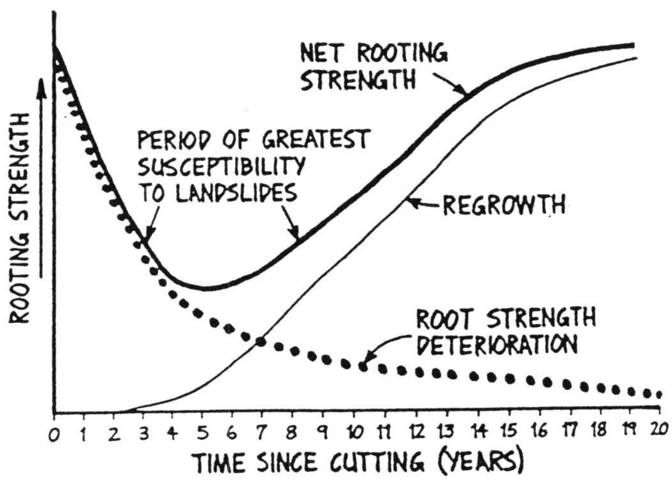


Figure 1

Hypothetical model of net soil root strength following harvest
From *Sidle et al. 1985*

Loss of Soil Strength Due to Root Decay

Source	Location	Years after Harvest
Bishop & Stevens 1964	Southeast Alaska	3 – 5
Gresswell et al. 1979	Central Oregon Coast Range	0 – 10
Katamura & Namba 1966	Japan	15
O'Loughlin 1972	Southwest British Columbia	3
O'Loughlin 1974	Coastal British Columbia	3 – 5
Sidle et al. 1985	Western United States	3 – 8
Swanston & Dyrness 1975	Western Oregon Cascades	3 – 12
Craft & Adams 1950	Utah	4 – 10
Schwab 1983	Queen Charlotte Islands	4 – 6
Nakano 1971	Japan	6 – 12
Ziemer & Swanston 1977	Southeast Alaska	2

Table 2

Period of least net soil root strength following harvest based on root decay tests, root strength tests, and landslide frequencies

Research Findings on Erosion Rates

While the types of effects which forest management activities have on slope stability factors are reasonably well recognized and understood, their magnitudes are not. Much research has been carried out in recent decades in attempts to quantify the impacts of harvesting and road construction on landslide volumes and frequencies. While this research has extended around the globe, western Oregon has been on of the world's leading focal points for landslide studies.

Summarized in Table 3 are the results of 16 studies which examined the erosion rates of recently harvested areas (generally clearcuts) and naturally forested areas. The table lists landslide volume, landslide frequency (slides/acre/year), and overall erosion rate (cubic yards/acre/year) for harvested areas relative to the background levels of naturally forested areas found for each study.

Sixty-seven percent of the studies reported an in-unit average landslide volume greater than background levels, with a nearly two-fold average volume increase across the studies (1.9 times). The landslide frequency was an average of 6.3 times greater in harvest units than background levels, with 100 percent of the studies reporting and increased frequency. Each study also reported an increased overall erosion rate for harvested areas, with the erosion rate averaging 11.9 times that of naturally forested areas.

Harvest Unit Landslide Rates Relative to Background Levels

Source	Study Location	Volume	Frequency	Erosion Rate
Swanston et al. 1977	Oregon Coast Range	2.0	1.9	3.9
Ketcheson 1978	Oregon Coast Range	1.3	3.4	11.5
Swanston & Dyrness 1975	Central Oregon Cascades	0.9	2.9	3.7
Morrison 1975	Cascades	0.2	11.4	2.6
Amaranthus et al. 1985	Klamath Mountains	0.3	19.0	6.9
O'Loughlin 1972	British Columbia	0.4	5.7	2.2
Gresswell et al. 1979	Oregon Coast Range	2.3	2.3	5.4
Bishop & Stevens 1964	Alaska	5.0	4.5	22.5
Schwab 1983	Queen Charlotte Islands	2.9	14.0	41.0
Swanston & Dyrness 1975	Western Oregon Cascades	3.1	2.8	11.4
Ketcheson & Froehlich 1978	Oregon Coast Range	3.5	1.0	3.7
Marion 1981	Western Oregon Cascades	-	-	8.7
Gray & Megahan 1981	Idaho	-	-	20.0
O'Loughlin & Pearce 1976	New Zealand	-	-	40.4
Dyrness 1967a	Western Oregon Cascades	-	-	1.0
Fredrikson 1970	Western Oregon Cascades	1.0	-	-
Average		**1.9**	**6.3**	**11.9**

Table 3

Harvest-unit landslide frequencies, volumes, and overall erosion rates relative to rates in naturally forested areas, as reported in the studies cited

Summarized in Table 4 are the results of those studies that examined road-related landslides. This table lists the landslide volume, frequency, and overall erosion rate relative to the background levels reported by each study. Sixty-seven percent of the studies reported an average road-related landslide volume greater than that of naturally forested areas, with an average volume increase of 11.5 times for all of the studies cited. As with harvest-units, all of the studies reported elevated road-related landslide frequencies and erosion rates. The landslide frequency and overall erosion rates were 268.5 and 186.0 times those of background levels, respectively, averaged across the studies.

Road-Relate Landslide Rates Relative to Background Levels

Source	Study Location	Volume	Frequency	Erosion Rate
Swanston et al. 1977	Oregon Coast Range	7.8	15.0	123.5
Fiksdal 1974	Olympic Mountains	0.1	1326.7	164.3
Swanston & Dyrness 1975	Central Oregon Cascades	1.0	41.5	49.3
Morrison 1975	Cascades	0.9	359.3	343.9
Amaranthus et al. 1985	Klamath Mountains	0.7	137.8	111.6
O'Loughlin 1972	British Columbia	1.2	230.4	24.8
Gresswell et al. 1979	Oregon Coast Range	6.9	7.2	50.0
Swanston & Dyrness 1975	Western Oregon Cascades	31.5	30.0	946.0
Marion 1981	Western Oregon Cascades	-	-	44
Gray & Megahan 1981	Idaho	-	-	188
O'Loughlin & Pearce 1976	New Zealand	-	-	267
Dyrness 1967a	Western Oregon Cascades	-	-	60
Schwab 1983	Queen Charlotte Island	-	-	46
Fredrikson 1970	Western Oregon Cascades	53.5	-	-
Average		**11.5**	**268.5**	**186.0**

Table 4

Road-related landslide frequencies, volumes, and overall erosion rates relative to landslides in naturally forested areas, as reported in the studies cited

METHODS

February 1996 Storm

Following an extended heavy winter precipitation period, a high-intensity storm hit western Oregon February 5 – 9. This storm delivered heavy rainfall amounts in the north and central western Cascades, the Willamette Valley, and the entire coastal region. The greatest precipitation intensity was in the north Coast Range area but intensities in many areas were calculated to be at the 100-year return interval, exceeding 30 inches of rainfall for the four day period in some areas (NOAA 1996, ODF 1997).

Because these warm rains commonly fell on snow-covered, frozen, or saturated soil conditions, surface runoff amounts and peak flows were magnified. On top of devastating flooding impacts, this storm was estimated to have triggered tens of thousands of landslides throughout western Oregon, with the highest landslide and debris flow impacts in Douglas and Coos Counties. (Rosenfeld 1997, ODF 1997)

ODF Study Objectives and Design

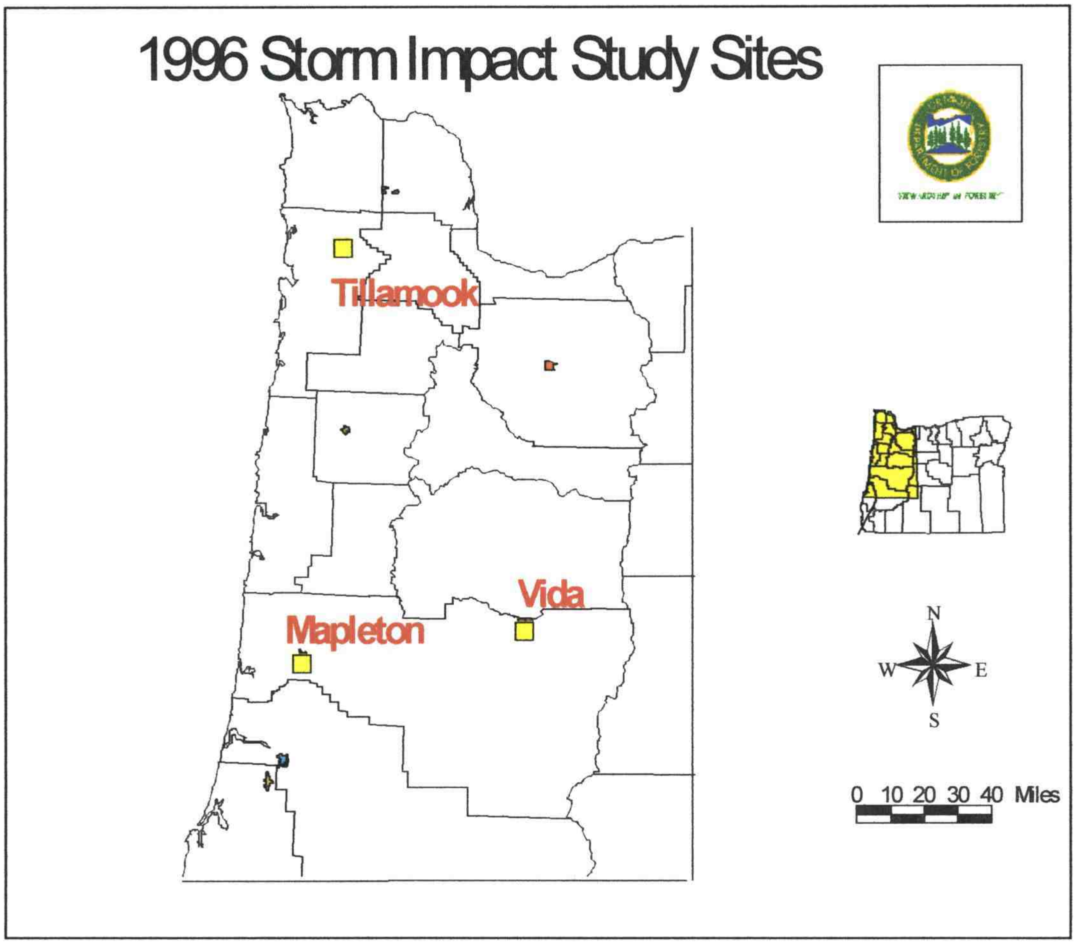
In order to take advantage of the incredible research opportunities created by this storm, the Oregon Department of Forestry designed a monitoring project to study these landslides and their relationships to forest practices. The design of this study was channel-oriented, with data-collection and analysis focusing on stream delivery and impacts. This study is the largest known ground-based landslide inventory, covering 38 square miles in the six western Oregon study sites selected after the February storm. The study was expanded following a second high-intensity storm event in November, adding two more sites to the study and bringing the total to 52 square miles. Data was collected on 136 miles of stream channel and 558 landslides over two field seasons. This data was combined with ownership information, forest management and road construction history, and airphoto interpretation for analysis by ODF. (ODF 1997)

Study Sites

The three study sites used for analysis in this paper were are termed "red zone" sites and were delineated by subjectively chosen 5-by-2-mile grids. Their locations were based on aerial photography identifying those parts of the state with the greatest number of landslides as well as site geographic distribution, ownership boundaries, and management histories. Selection of these sites was designed to address those areas with the greatest storm impacts across a variety of natural conditions, ownership types, stand ages, and management practices. Site boundaries were later adjusted due to time limitations and to match watershed divides. (ODF 1997)

The three "red zone" sites were named after the nearby towns of "Tillamook", "Mapleton", and "Vida" and are shown in Map 3. The Mapleton site (Map 4) is located in the central Coast Range of western Lane County and covers 5331 acres; the Tillamook site (Map 5) is located in the northern Coast Range of northeastern Tillamook County and covers 2874 acres; and the Vida site is in the central western Cascades of northeastern Lane County and covers 4570 acres (Map 6). This paper will focus on these three sites because of the high number of slides within these sites, their stability condition differences, and data availability considerations. A more detailed, process-oriented description of the sites analyzed in this paper is given in the *Analysis* section.

Three other February storm sites were selected using a stratified random sampling method of 5-by-2-mile grids. These sites were designed to provide a broader picture of the storm's impacts across Western Oregon. Following the November 1996 storm event,



Map 3

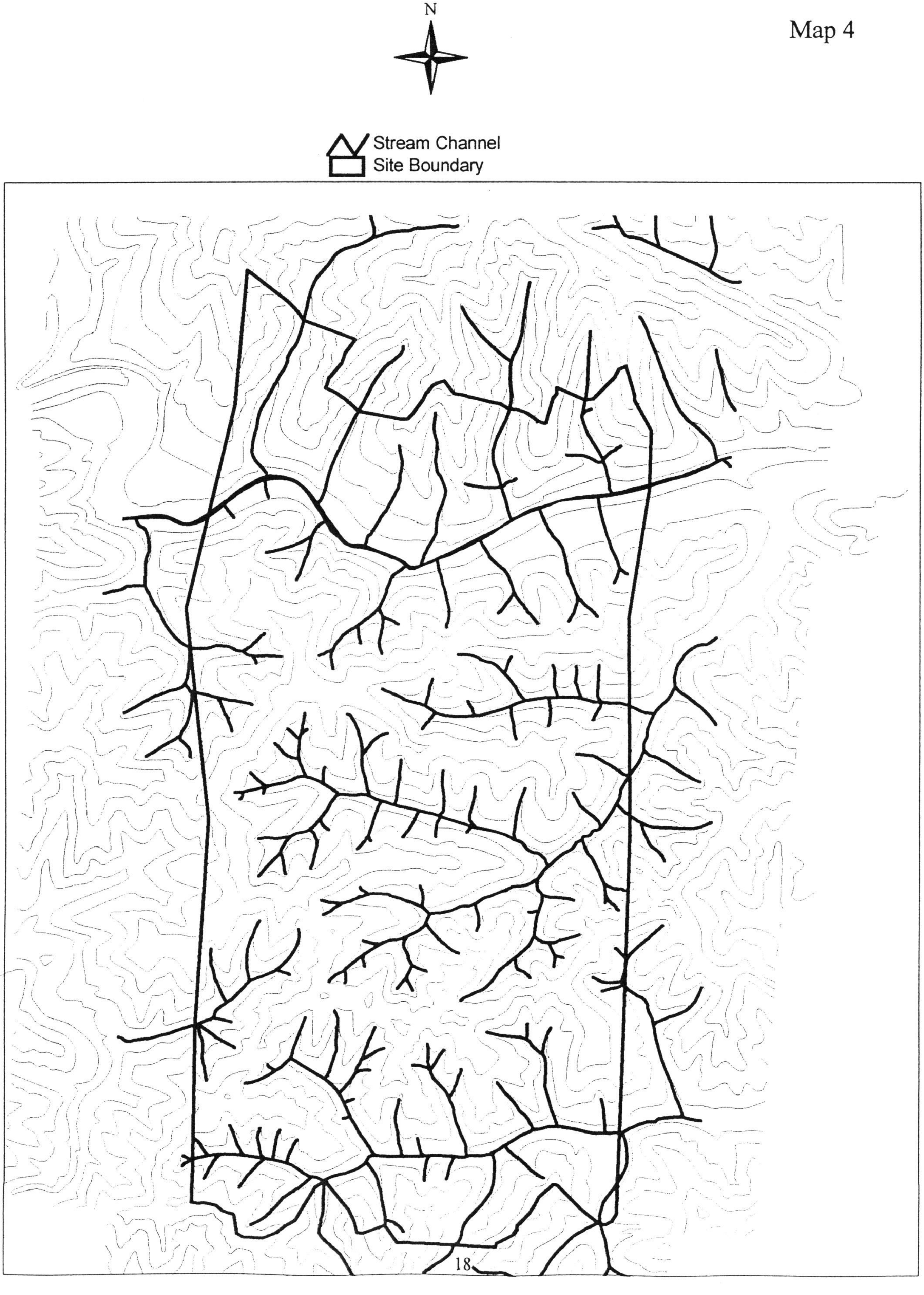
Locations of study sites

From *ODF 1997*

Mapleton Study Site

1:40000

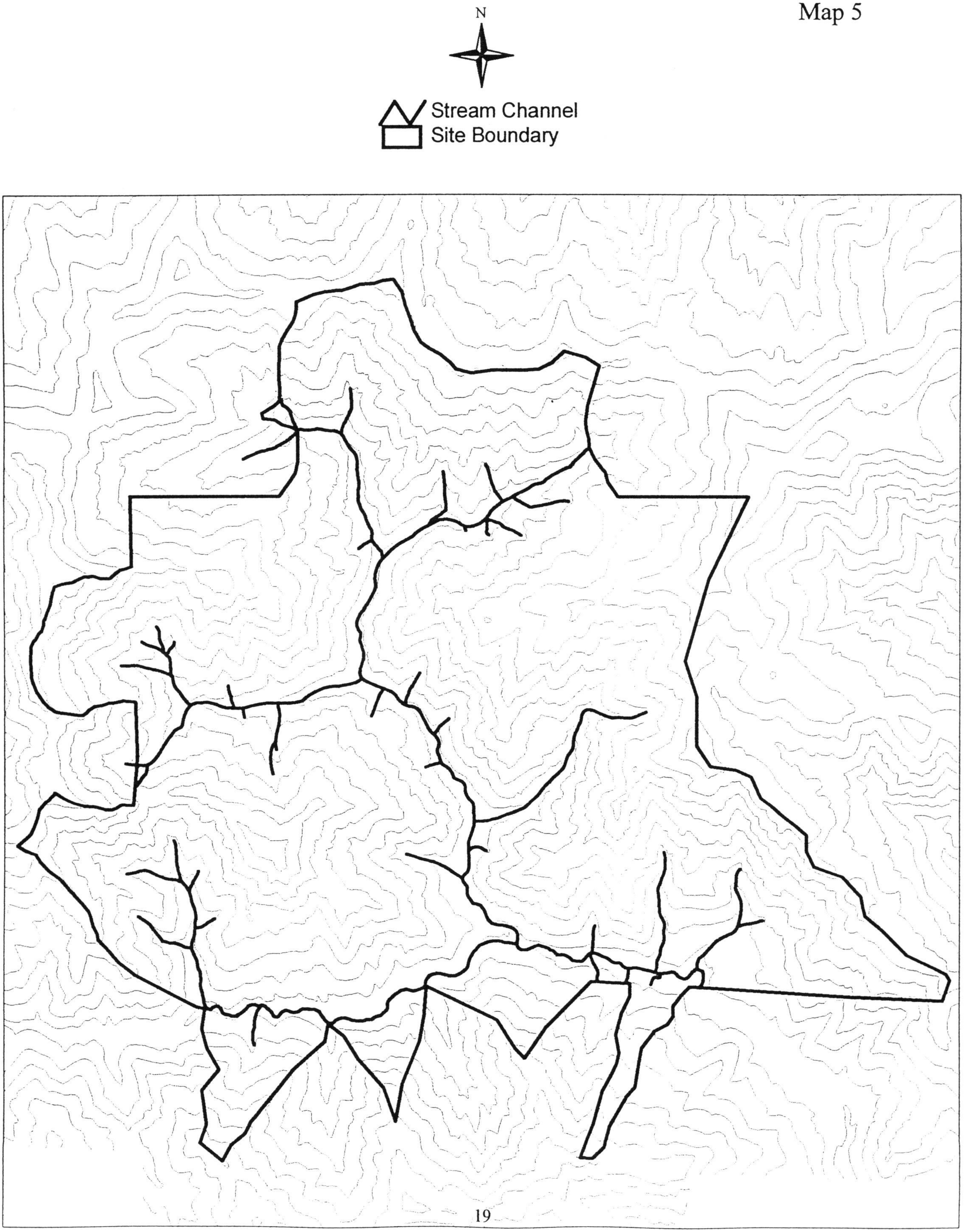
Map 4



Tillamook Study Site

1:31000

Map 5



Vida Study Site

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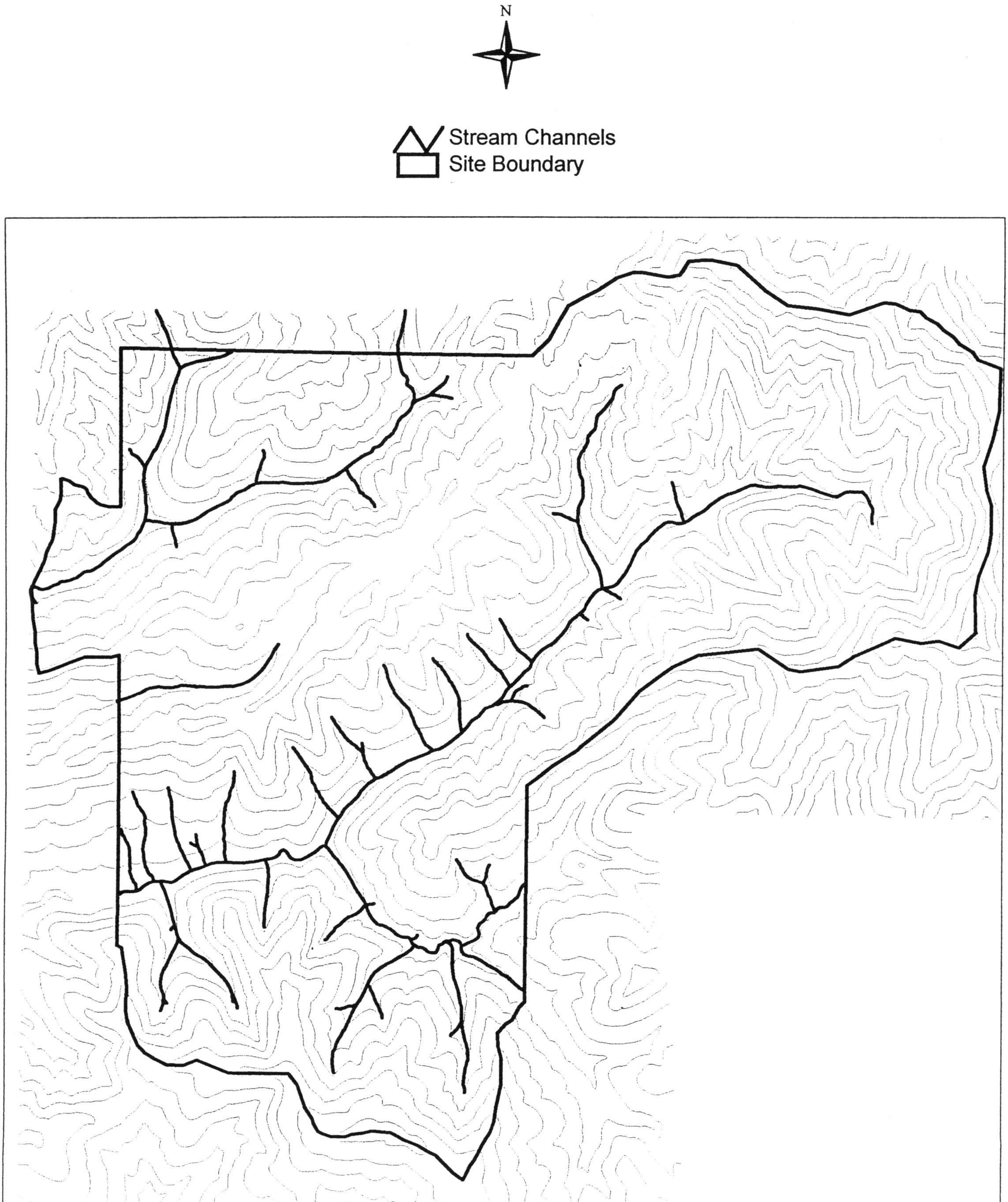
Map 6



two additional study sites were selected and surveyed the following summer. These were also subjectively selected "red zone" sites in the heavily impacted southern portion of the Coast Range. Site boundaries were delineated to fit watershed boundaries so that slide impacts could be contained within the sites. (ODF 1997)

Of the total area of all eight sites, 42 percent was private industrial forestland, 36 percent was state-owned forestland, 20 percent was federally-owned forestland, and 2 percent was non-industrial private forestland (ODF 1997).

Data Collection

Data collection for the six February-storm-induced landslide sites was conducted during the 1996 summer field season. Data for the two November-storm-induced study sites was collected in the 1997 summer field season, of which this author was a part. Crews walked all channels within each site in order to systematically document stream characteristics and channel impacts. Unimpacted channels were walked to a slope of 40 percent while crews continued up impacted channels or those which showed signs of landslide delivery until the failure was found or the channel was no longer impacted. Landslide and debris flow parameters were measured and recorded as they were found. Also recorded at each landslide was information on geomorphic, drainage, soil, and vegetative site conditions. As well as the channel-related landslide inventory, all road-related slides were documented also well. Oregon State University field crews traveled all active and abandoned roads in the February-storm sites and recorded parameters of all landslides that were found (ODF 1997).

A more detailed description of the study, field protocol, and data collection can be found in the ODF web site (www.odf.state.or.us/FP/Fld_proj.htm).

Analysis Methods

The purpose of slope stability analysis is to allow for the utilization and development of resources while protecting against economic and environmental losses due to erosional hazards. Analysis of landslide parameters and site information can tell us a great deal about contributing factors and hazard distribution, as well as the influences of human activities. While considerable research has demonstrated the relationships of some slide parameters with management activities, this paper focuses on their relationships of slide parameters with site characteristics and stability conditions. The morphometric landslide characteristics and the landscape setting characteristics specific to each site will be analyzed and compared, towards the ultimate goal of identifying the type, magnitude, and distribution of the landslide hazard in these three western Oregon sites.

The analysis consists of three parts. The first focuses on the overall slope stability conditions of each site using a process-group approach. This is designed to identify those site stability conditions, and subsequent landslide behaviors, associated with different site characteristics. These stability and erosional conditions can then be extrapolated to larger geographic regions. The second section is an examination of the landscape setting characteristics at the landslide initiation points within each site. Appropriate transformations and t-tests have been conducted to measure the strengths of statistical differences in landscape setting characteristics between sites. The third section is a summary of some of the landslide parameter means for each site and a statistical measure of the differences between sites. These will be discussed as they relate to landscape setting characteristics and overall site stability conditions.

ANALYSIS

Site Stability Conditions

Process-Group Site Stability Conditions

The stability conditions and resulting erosional characteristic of each of the three study sites vary greatly. Table 5 emphasizes this contrast between sites, especially in overall erosion rates. Slides at the Mapleton site were most frequent but quite small, giving it a relatively low erosion rate. The other two sites had very high erosion rates, due largely to their extremely high average landslide volumes.

A description of the process-group conditions and the resulting erosional characteristics of the Mapleton, Tillamook, and Vida sites are given in Tables 6, 7, and 8, respectively. These tables summarize the basic geologic/geomorphic, soils, vegetative, hydrologic/climatic, and seismic traits of each site as well as the impacts which these traits have on slope stability.

Study Site Erosion Rates

	Non-Road-Related Slides			Road-Related Slides		
	Mapleton	Tillamook	Vida	Mapleton	Tillamook	Vida
Total Number of Slides	96	69	85	20	9	18
Frequency (Slides/1000 Acres)	17.8*	15.0*	11.6*	358.7	166.9	229.3
Erosion Rate (Cubic Yards/1000 Acres)	474.0	4442.0	4727.0	20446	24878	51900

Table 5

General erosional characteristics of each study site

*From *ODF 1997*

Mapleton Site Stability Conditions

Process Group	Site Description	Stability Influences
Geologic and Geomorphic	Geology is Tyee Formation – rhythmically bedded 5-80' marine and estuarine sandstone with thin siltstone layers. These These beds are gently dipping (<10%) with widely spaced joints. Landforms are highly disected with very steep slopes and many headwall areas. Site hypsometric integral is 0.53.	Smooth bedded sandstones create a barrier to tree root and water percolation. Geology and steep slopes provide a failure plane for frequent sliding.
Soils	Site has thin sandy and gravelly soils, generally less than three feet deep. soils are non-cohesive with very low placticity and poor water-holding capacity.	Stability is low due to very low cohesion, poor attachment to bedrock and shallowness. Soil conditions contribute to small translational debris slides.
Vegetative	Vegetation is generally very dense and fast growing. Average stands are of medium age due to ownership patterns and management histories.	Small, shallow roots are a critical stability component due to soil and bedrock conditions. Stability-related hydrologic influences of vegetation are small.
Hydrologic	Channel network is dense drendritic with poor soil-bedrock interaction and rapid soil water movement and discharge. Precipitation total is 90-100" per year with very little rain-on-snow . 25-year, 24-hour precipitation total is 6-8" (Appendix A, p. 1).	Rapid subsurface water concentration in thin soils of highly disected steep slopes causes frequent shallow slides. Relatively small storms and early part of storms can trigger landslides.
Seismic	Peak ground acceleration for a 50-year event is 25-30% of gravity (Appendix A, p. 2).	Seismic hazard is relatively moderate to high. Seismic events can trigger slides in unstable areas.

Table 6

Description of stability conditions by process groups and their influences on hillslope stability for Mapleton study area

Compiled from *ODF 1997, Sidle et al. 1985, Sessions et al. 1987, Swanson and James 1975, Fredriksen 1970*

Tillamook Site Stability Conditions

Process Group	Site Description	Stability Conditions
Geologic and Geomorphic	Geology is sub-aerial and submarine flow basalt, tuff, and breccia. These 10-30' flows are highly sheared and deeply weathered. Hillslopes are long, irregular and slightly to moderately disected. Site hypsometric integral is 0.43.	Deep weathering of bedrock enhances stability by allowing for interactions with soil, water, and vegetation as well as providing a poor failure plane. Stability is decreased by steepness.
Soils	Soils are generally 1-5' deep. Soils are fairly non-cohesive with low placticity and poor water holding capacity.	Greater soil-bedrock attachment leads to higher stability than Mapleton site. Slides tend to be larger and deeper earthflows.
Vegetation	Vegetation is generally very dense and fast growing. Average stands are generally young due to ownership patterns and history of intensive management .	Vertical anchoring of tree roots into bedrock very important factor of site soil stability due to weathering of bedrock. Vegetation serves a moderate role in soil water interception and movement.
Hydrologic	Lower density dendritic channel network with good soil-bedrock interaction and moderate to rapid soil water movement and discharge. Precipitation is 90 " per year with very little rain-on-snow. 25-year, 24-hour precipitation total is 8-14" (Appendix A, p. 1).	Lower hillslope disection and greater storm intensities mean greater amounts of soil water are concentrated in fewer areas, resulting in less frequent but larger slides.
Seismic	Peak ground acceleration for a 50-year event is 20-25% of gravity (Appendix A, p. 2).	Seismic hazard is relatively moderate. Seismic events can trigger slides in unstable areas.

Table 7

Description of stability conditions by process groups and their influences on hillslope stability for Tillamook study area

Compiled from *ODF 1997, Sidle et al. 1985, Sessions et al. 1987, Swanson and James 1975, Fredriksen 1970*

Vida Site Stability Conditions

Process Group	Site Description	Stability Conditions
Geologic and Geomorphic	Undifferentiated volcanic and hypabyssal intrusive geology consists of mixed basalt flow, breccia flow, glacial till, and volcanoclastic and fluvial deposits. Hillslopes are long, steep, and uniform to moderately disected. Site hypsometric integral is 0.35.	Bedrock conditions enhance stability by allowing for interactions with soil, water, and vegetation. Stability decreased by steepness.
Soils	Soils are clay rich, cohesive, and very deep. Plasticity is low to moderate and water retaining capacity is moderate to high.	Stability is relatively high due to cohesion and depth. Conditions are more conducive of large, deep earthflows, slumps, and rotational failures.
Vegetation	Vegetation growth is less rapid and dense than at other two sites. Stand ages are generally older due to landownership patterns and a less-intensive management history.	Vegetation roots play important role in groundwater infiltration . Roots provide cohesion of soil masses but provide less bedrock anchoring due to soil depth. Vegetation has small role in stability of deep-seated slides.
Hydrologic	Channel network is dendritic with slow soil water buildup, movement, and discharge. Precipitation total is 90" per year with much rain-on-snow. 25-year, 24-hour precipitation total is 5-7" (Appendix A, p. 1).	Rapid surface runoff from rain-on-snow events can result in shallow and streamside slides. More common are less frequent but deeper failures which are more a result of longer-term soil water buildup than individual ppt. events.
Seismic	Peak ground acceleration for a 50-year event is 10-15% of gravity (Appendix A, p. 2).	Seismic hazard is relatively low. Seismic events can trigger slides in unstable areas.

Table 8

Description of stability conditions by process groups and their influences on hillslope stability for Vida study area

Compiled from *ODF 1997, Sidle et al. 1985, Sessions et al. 1987, Swanson and James 1975, Fredriksen 1970*

Area-Altitude Analysis

Area-altitude analysis relates a drainage basin's (or an otherwise-delineated region's) horizontal cross-sectional area to relative basin elevation. A hypsometric curve is created by plotting elevation as a percent of total basin height (y-axis) against the percent of total basin horizontal area above that elevation (x-axis). This creates a dimensionless parameter that allows for site comparisons regardless of elevation or basin size. The area below this curve (as a fraction of 1.0) is known as the hysometric integral and can be used as an indicator of a region's morphometric maturity and level or erosional equilibrium. Graphs with a large area beneath their curve tend to represent younger landforms with high erosion potential relative to curves with less area beneath them. (Strahler 1952)

The hysopmetric curves for each of the study sites are plotted in Appendix B. The hysometric integrals for the Mapleton, Tillamook, and Vida sites are 0.53, 0.43, and 0.35, respectively. Based on these numbers, area-altitude analysis would suggest that the Mapleton site is the youngest and least erosionally mature landscape of the three while the Vida site is the oldest and presumably most stable landscape, with the Tillamook site falling in between the other two.

Indeed, this stability relationship is cofirmed when these numbers are compared with landslide frequency rates. The hypsometric integrals relative to each other have a relationship nearly identical to that of the landslide frequency rates for each study site. An integral directly proportional with slide frequency suggests that area-altitude analysis is an effective tool for the evaluation and estimation of the general slope stability of a site.

Landscape Setting Characteristics

What are the mean landscape setting values for each study site landslide population?

The average values for several landscape setting characteristics at the point of landslide initiation for non-road related and road-related slides for each study site population are summarized in Table 9. These mean landscape setting characteristics are: hillslope above initiation point (percent), pre-failure hillslope of slide surface (percent), distance from ridgetop of initiation point (feet), area draining to initiation point (acres), soil depth at initiation point (feet), and age of tree stand at initiation point (years). For calculations involving tree stand ages at initiation points, previously unharvested stands were assigned a value of 400 years old.

As well as these mean values, some breakdowns of the populations are shown in order to provide an impression of the distribution of these values. These are also included in Table 9 and are: landform type at initiation point (percent of population total in concave/CV, convex/CX, uniform or irregular/UN, and other/OT landforms), slides within 100 feet of ridgetops (percent of population total), slides with less than 0.1 acres draining to them (percent of population total), and slides initiating in tree stands less than ten years old (percent of population total).

Study Site Landscape Setting Characteristics

	Non-Road-Related Slides			Road-Related Slides		
	Mapleton	Tillamook	Vida	Mapleton	Tillamook	Vida
Total Number of Slides	96	69	85	20	9	18
Average Hillslope Above (Percent)	86.3	68.5	78.6	60.1	53.3	57.5
Average Slide Slope (Percent)	88.8	89.9	84.1	78.5	56.1	60.0
Landform Type (CV, CX, UN, OT) (Percent of Pop. Total)	CV = 28 VX = 18 UN = 49 OT = 5	CV = 22 VX = 23 UN = 51 OT = 4	CV = 25 VX = 11 UN = 62 OT = 1	n/a	n/a	n/a
Avg. Distance from Ridge (Feet)	298	891	476	293	n/a	n/a
Slides W/in 100' of Ridgetop (Percent of Pop. Total)	16	16	15	45	n/a	n/a
Avg. Drainage Area (Acres)	0.68	1.87	1.97	n/a	n/a	n/a
Slides W/ <.1 Acre Drainage (Percent of Pop. Total)	38	30	25	n/a	n/a	n/a
Average Soil Depth (Feet)	3.5	6.0	5.3	n/a	n/a	n/a
Average Stand Age (Years)	118	28	195	n/a	n/a	n/a
Slides in <10 Yr. Old Stands (Percent of Pop. Total)	30	26	20	n/a	n/a	n/a

Table 9

Average landscape setting characteristic at landslide initiation point for each study site population

How do landscape setting characteristics differ between sites?

The statistical strengths of the differences in non-road-related landscape setting characteristics between study site populations are given in Table 10. The population differences tested here are hillslope above initiation point (percent), pre-failure slope of slide surface (percent), initiation distance from ridgetop (feet), area draining to initiation point (acres), and soil depth at initiation point (feet). These p-values were obtained from two-sample t-tests of population data sets using pooled standard deviations. A log transformation was applied to some data sets in order to achieve normality. A lack of normality in landform type, stand age, and all road-related-landslide data sets prevented valid statistical analysis of those populations. Distributions, moments, and confidence intervals for the means of the transformed data for each study site are in Appendix C.

Strength of Study Site Setting Differences

	P-value for Difference Between Sites		
	Mapleton-Tillamook	Mapleton-Vida	Tillamook-Vida
	d.f. = 163	*d.f.* = 179	*d.f.* = 152
Average Slope Above	0.001	0.001	0.02
Average Slide Slope	> .50	0.03	0.05
Avg. Ridge Distance	0.001	0.01	0.005
Average Drainage Area	> .50	0.01	0.04
Average Soil Depth	0.001	0.001	0.30

Table 10

T-test p-values for differences between mean slide settings characteristics for each study site population

Summarized in Table 11 are the actual differences between some study site population landscape settings and their confidence intervals. The differences for the slope above and slide slope parameters are additive values for their means. Because the ridge distance, drainage area, and soil depth data sets were log-transformed, the values for these differences are multiplicative. The values listed for these sets are the estimated multipliers that explains the differences between population medians. The values in parenthesis are the 95-percent confidence intervals for each additive value or multiplier.

Study Site Settings Differences

	Estimated Difference with 95% Confidence Intervals		
	Mapleton-Tillamook	Mapleton-Vida	Tillamook-Vida
	d.f. = 163	*d.f.* = 179	*d.f.* = 152
Mean Slope Above	Mapl. 17.8 > Till. (10.6 to 24.9)	Mapl. 7.6 > Vida (3.2 to 12.1)	Till. 10.1 > Vida (2.3 to 18.0)
Mean Slide Slope	Till. 1.1 > Mapl. (-4.3 to 6.5)	Mapl. 4.7 > Vida (.4 to 9.0)	Till. 5.8 > Vida (.2 to 11.4)
Median Dist. from Ridge	Till. 6.97x Mapl. (3.49 to 13.93)	Vida 2.19x Mapl. (1.25 to 3.86)	Till. 3.18x Vida (1.45 to 6.93)
Median Drainage Area	Mapl. 1.43x Till. (.27 to 7.73)	Vida 4.80x Mapl. (1.54 to 14.89)	Vida 7.13x Till. (1.12 to 45.2)
Median Soil Depth	Till. 3.07x Mapl. (1.87 to 5.13)	Vida 2.79x Mapl. 1.75 to 4.45)	Till. 1.30x Vida (.80 to 2.10)

Table 11

Estimated additive and multiplicative differences between means and medians, respectively, of landscape setting characteristics at initiation points for each study site population, with 95% confidence intervals of values in parenthesis

From Tables 10 and 11 it can be seen that, with 95 percent confidence, several differences exist between the landscape setting characteristics at landslide initiation points for each study site population. The average hillslope above slides in the Mapleton site is steeper than that of both of the other two sites, with the Tillamook site having a value that is also steeper than the Vida site. This pattern remains the same for the average pre-failure slopes of the slide surfaces with the exception of the Tillamook-Mapleton site relationship, which is reversed. The median distance of slides from the ridge is greatest for the Tillamook site, with the Vida site also significantly greater than the Mapleton site. The Vida population has a median drainage area to slide initiation points greater than that of each of the other two sites and both the Vida and Tillamook sites have median soil depths at initiation greater than that of the Mapleton site population.

Landslide Parameters

What are the mean landslide parameter values for each study site population?

The average values and breakdown of several landslide parameters for each study site are displayed in Table 12, grouped as non-road-related and road-related slides. The five parameters looked at are landslide frequency (slides/1000 acres), maximum landslide depth (feet), landslide volume (cubic yards), total landslide length and runout distance (feet), and Crozier's (1973) classification index (maximum depth/total length ratio).

Study Site Landslide Parameters

	Non-Road-Related Slides			Road-Related Slides		
	Mapleton	Tillamook	Vida	Mapleton	Tillamook	Vida
Total Number of Slides	96	69	85	20	9	18
Average Volume (Cubic Yards)	26.6	296.1	407.5	57.0	149.1	226.3
Slides 100+ Yd3 (Percent of Pop. Total)	4	36	33	10	56	61
Avg. Maximum Depth (Feet)	3.9	7.0	6.4	3.0	4.8	5.3
Slides 10+ Feet Deep (Percent of Pop. Total)	2	25	15	0	100	17
Avg. Total Length + Runout (Feet)	153	271	293	n/a	n/a	n/a
Average D/L Ratio (100*Depth/Length)	7.8	12.8	7.1	n/a	n/a	n/a

Table 12

Average landslide parameter values for each study site population

How do landslide parameters differ between study sites?

The statistical strengths of the differences in non-road-related landslide parameter values between study site populations are given in Table 13. The population differences tested here are the maximum depth, volume, total length and runout distance, and depth/length ratio parameters. These p-values were obtained from two-sample t-tests of population data sets using pooled standard deviations. A log transformation was applied to the data sets in order to achieve normality. Distributions, moments, and confidence intervals for the means of the transformed data for each study site and parameter can be found in Appendix D. A lack of normality in road-related-landslide data sets prevented valid statistical analysis of the road-related populations.

Strength of Study Site Landslide Parameter Differences

	P-value for Difference Between Sites		
	Mapleton-Tillamook	Mapleton-Vida	Tillamook-Vida
	d.f. = 163	*d.f.* = 179	*d.f.* = 152
Average Volume	0.001	0.001	> 0.50
Avg. Maximum Depth	0.001	0.001	0.30
Avg. Total Length + Runout	0.03	0.001	0.005
Average D/L Ratio	0.13	> 0.50	0.05

Table 13

T-tests p-values for differences between mean landslide parameter values of each study site population

Summarized in Table 14 are the study site population differences in volume, maximum depth, total length and runout distance, and depth/length ratio parameters and the confidence intervals for those values. Because the values are back-transformed from calculations on log-transformed data sets, the differences are multiplicative. The values listed are the estimated multiplier which explains the differences between population medians. The value ranges are the 95-percent confidence intervals for each multiplier.

Study Site Landslide Parameter Differences

	Estimated Difference of Medians with 95% Confidence Intervals		
	Mapleton-Tillamook	Mapleton-Vida	Tillamook-Vida
	d.f. = 163	*d.f.* = 179	*d.f.* = 152
Median Volume	Till. 29.2x Mapl. (9.78 to 87.1)	Vida 42.3x Mapl. (14.3 to 125)	Vida 1.45x Till. (.391 to 5.36)
Med. Maximum Depth	Till. 3.44x Mapl. (2.14 to 5.53)	Vida 2.65x Mapl. (1.70 - 4.13)	Till. 1.30x Vida (.791 to 2.14)
Med. Total Length + Runout	Till. 1.62x Mapl. (1.01 to 2.56)	Vida 3.54x Mapl. (2.27 to 5.51)	Vida 2.18x Till. (1.33 to 3.59)
Median D/L Ratio	Till. 2.12x Mapl. (.813 to 5.55)	Mapl. 1.33x Vida (.945 to 3.14)	Till. 2.87x Vida (1.03x 7.83)

Table 14

Estimated multiplicative differences between landslide parameter medians for each study site population, with 95% confidence intervals of multipliers in parenthesis

From Tables 13 and 14 several study site landslide parameters differences can be found with 95 percent confidence. Both the Tillamook and Vida populations have median landslide volumes, maximum depths, and total length and runout values larger than those of the Mapleton population. The median total length and runout for the Vida site is greater than that of the Tillamook site as well. The only significant difference in the median depth/length ratio is a Tillamook median larger than the Vida median.

DISCUSSION

Hazard Areas and Impacts

By looking at the site stability conditions and landscape setting characteristics at the initiation points, it is possible to identify those areas for each study site which are most susceptible to storm-induced mass wasting. Because the various stability conditions existing in each of these three sites are not limited to the boundaries of this study, these sites and their stability conditions can viewed as regional representatives. If done properly, the site-specific hazard areas identified here can be applied to those more extensive geographic regions that possess similar geologic, geomorphic, soil, vegetation, hydrologic, climatic, and seismic characteristics as those described in Tables 6, 7, and 8. In the same manner, the landslide parameters, behaviors, and impacts of each study site could possible be extrapolated to larger regions.

Mapleton Site

Slide-prone areas of the Mapleton site and the larger region of similar stability condition regularly lie in very steep slopes, with the average pre-failure slope of the slide surfaces within the study area of approximately 90 percent. This is fairly consistent, as 90% of all slides occur on slopes of 70% or greater. Failures generally occur near ridgetops (site average < 300 feet) and have small drainage areas (site average < 1 acre and 38 percent < 0.1 acres) due to the intense landform dissection of the area. Uniform or irregular hillslope forms are the source of half of all failures, with concave hillslopes accounting for the bulk of the remaining failures. An erosional hazard exists even during the early part of storms because of the thin soils on smooth bedrock and the great precipitation intensity common with storms in this area.

The cumulative stability conditions of this region result in landslides which are both frequent and occur at high densities. They are generally small, shallow translational slides of unconsolidated soil (only 4 percent of the landslide population had a volume over 100 cubic yards and only 2 percent had a depth of over ten feet). The rate of delivery of slide material to channels is very high due to the dense dendritic drainage network and steep slopes, but stream impacts are largely abated by the small size of most slides. Timber productivity is greatly reduced at slide sites because these areas are often exposed, de-soil bedrock.

Tillamook Site

The landslide hazard for the Tillamook study site and similar areas lies in the steeper areas as well, with an average pre-failure hillslope of the slide surfaces within the site of 90 percent. This is more inconsistent than the Mapleton site, as a hillslope of 65 percent or greater is needed to account for 90 percent of all Tillamook slides. On average, failures occur quite far from ridgetops (nearly 900 feet), but just as many occur within 100 feet of ridgetops as in the other two sites (16 percent), suggesting tremendous variation in slope position. Uniform or irregular drainage forms provide half of the failures, with the remaining slides split evenly between convex and concave drainage forms. Slide initiation points in this region tend to have large areas draining to them (site average nearly 2 acres), but are still common with small drainages (30 percent < 0.1 acres).

The existing stability conditions of the Tillamook study site region result in larger slides of moderate frequency. Slides of the study site population average nearly 300 cubic yards, with 36 percent of the total population over 100 cubic yards. These failures would be classified as deep translational and consist of relatively unconsolicated soil. They are generally quite deep, with an average depth of seven feet and with 25 percent of slides having a depth of ten feet or more. The rate of delivery of material to the channel network is high and the impacts are elevated by their large volumes.

Vida Site

The landslide hazard areas for the Vida site and similar areas once again are focused on the steeper slopes. The average pre-failure slide slope within the study site was 84 percent, with 90 percent of all slides occurring on slopes of 65 percent or more. Uniform or irregular hillslope forms produce the majority of slides (62 percent of site slides) with a significant amount on concave slopes (25 percent). The average distance from ridgetops is moderate, but variability is again very high. Like the Tillamook site, the average drainage area to initiation points is nearly 2 acres, but a full quarter of the slides had less than 0.1 acres draining to them. The landslide hazard in this region increases greatly with longer-duration storms or high antecedent soil moisture.

Landslides in the Vida site occur at lower frequencies relative to the other two sites (two-thirds that of the Mapleton site, three-fourths that of the Tillamook site). These events are characterized by generally deep, massive earthflows, averaging over 400 cubic yards in volume, with a depth of over six feet. The delivery rate to channels is less than that of other sites, but for those slides that do deliver to channels their large sizes cause great impacts. Slides rarely fail to bedrock in these deep soils, so limitations on growth potential are much less significant than in other regions.

Implications for Forest Management

Tree harvesting and road construction amplify the stability hazard of hillslopes, especially where stability is already weakened by natural conditons. Because these activities are the factor of slope stability over which we have the most direct control, the application of forest management prescriptions must be based on their interactions with existing cumulative hillslope stability conditions. This means both an understanding of the basic processes influencing slope stability as well as the additional impacts of forestry operations are necessary to best predict and prevent management-related mass wasting events.

A description of the landslide hazard areas and types specific to the regions represented by each study site is given in the *Analysis* section . Because assessment of hazard is also based on damage, delineation of hazard areas should not only address high-risk slopes but impact factors such as landslide volume, depth, and runout distance.

Landslides and Slope Steepness

	Non-Road-Related Slides			Road-Related Slides		
	Mapleton	Tillamook	Vida	Mapleton	Tillamook	Vida
Total Number of Slides	96	69	85	20	9	18
Slope ≥ 90% of Slides (Percent)	70	65	65	70	0	20
Slides on Slopes < 80% (Percent of Pop. Total)	19	33	34	20	78	83

Table 15

Breakdown of hillslope percent at or above which 90% of each landslide population occurred and percent of each total slide population which occurred on hillslopes of 80% or greater

The State of Oregon's high-risk assessment system for harvest and road construction areas is based on the high-risk site rules listed in Appendix E. Although they are applied on a site-by-site basis, these rules outline a set of high-risk evaluation criteria for the entire state and do not address the great variation in regional stability conditions. These can be discussed using the landscape setting characteristics at initiation points as descriptors of the actual high-risk conditions for each study site. Table 15 breaks down the slide populations of each study site based on hillslope steepness at slide initiation points. While high-risk classification is site specific and can include slopes below 80 percent, this number is used for reference purposes here.

Within the Mapleton study area, 19 percent of all non-road-related landslides occurred on hillslopes of less than 80 percent slope, with a slope of 70 percent or greater needed to account for 90 percent of all slides. Within both the Tillamook and Vida study sites a full one-third of all non-road-related landslides occurred on hillslopes of less than 80 percent slope, with a slope of 65 percent or greater needed to account for 90 percent of all slides.

The slopes for these two categories of the Mapleton site road-related failures are the same as those for the non-road-related slides. Within the Tillamook study site 78 percent of the road-related landslides occurred on hillslopes of less than 80 percent and it would be necessary to go down to a zero percent slope in order to account for 90 percent of the slides. Of the Vida site road-related landslide population, 83 percent of all failures initiated on hillslopes of less than 80 percent, with a slope of down to 20 percent needed to encompass 90 percent of the slides.

Limitations of Design, Data, and Applications

Design and Data

Specific to this study, the focus of data collection on channel-delivering landslides provides for detailed resource impact information but limits population completeness and evaluation of each site's overall mass-wasting characteristics. Subjective selection of study sites removes the possibility of extrapolation of results to a larger population or geographic region. The populations of road-related landslides recorded were not large enough for statistical analysis due to data variability.

As well, there are several limitations inherent to observational natural resource studies, which are not excepted here. Sampling methods must often be adjusted to meet access and ownership considerations. Data collection must occur within the bounds of time, monetary, political, training, and human element constraints. Study replication is not possible and the extreme variability common to data sets precludes the use of many statistical tool. Statistically valid conclusions about larger population are often difficult to draw. Contributing and confounding variables are difficult to remove, quantify, or even identify. Particularly confounding to the analysis within this paper is the fact that the various historical and ongoing forest management patterns across western Oregon have very real influences on stability conditions and landslide behavior.

Applications

The application of any results from this or related studies to forest management activities or regulations is also limited by numerous factors. The actual landslide hazard in real-world hillslope conditions is not always identifiable and quantifiable, regardless of how much it is studied. The resources of state foresters are private companies are limited and the accuracy of most maps to convey slope steepness on a site-specific scale is poor. As with all natural resource issues, economic, social, political, and environmental considerations also have great influences on forest management above and beyond a simple stability assessment approach.

In order to improve assessment of high-risk areas, however, there is a need for the delineation of landslide hazard georegions based on process-group stability conditions. Unfortunately, the measuring and mapping of these various stability factors and the assessment of their cumulative impacts would be an extremely large and difficult task.

CONCLUSIONS

Soil mass-movement is the dominant erosional process in the timber-rich regions of western Oregon and is a significant hazard for site productivity, water quality, fish habitat, man-made structures, and human occupance. Landslide research has consistently identified elevated erosion rates for harvested and roaded areas. For the studies cited, the average erosion rate increases for harvest unit and roaded areas are 11.9 times and 186 times background levels, respectively.

The hypsometric integrals from area-altitude analysis of each of the three sites studied in this paper are shown to be excellent representations of the relative landslide frequencies for each site. Some significant differences in landscape setting characteristics and landslide parameters were also found to exist between study site populations. Within the Mapleton site, 90% of all slides occurred on slopes of 70% or greater, compared to slopes of 65% or greater for the Tillamook and Vida sites slide populations. Only 19% of all Mapleton site slides occurred on slopes of less than 80%, while one-third of the Tillamook and Vida site slides initiated on slopes of less than 80%. While less frequent, the average slide volume in the Tillamook and Vida sites was more than ten times greater than the average slide volume for the Mapleton site population.

Natural resource studies, with limited numbers of observed events, are constrained in the applications of analytical tools and the statistical confidence levels which can be drawn. In order to map regional distributions of landslide characteristics and the contributing factors suggested by this paper, further research should address a process-group-based delineation of stability conditions throughout western Oregon.

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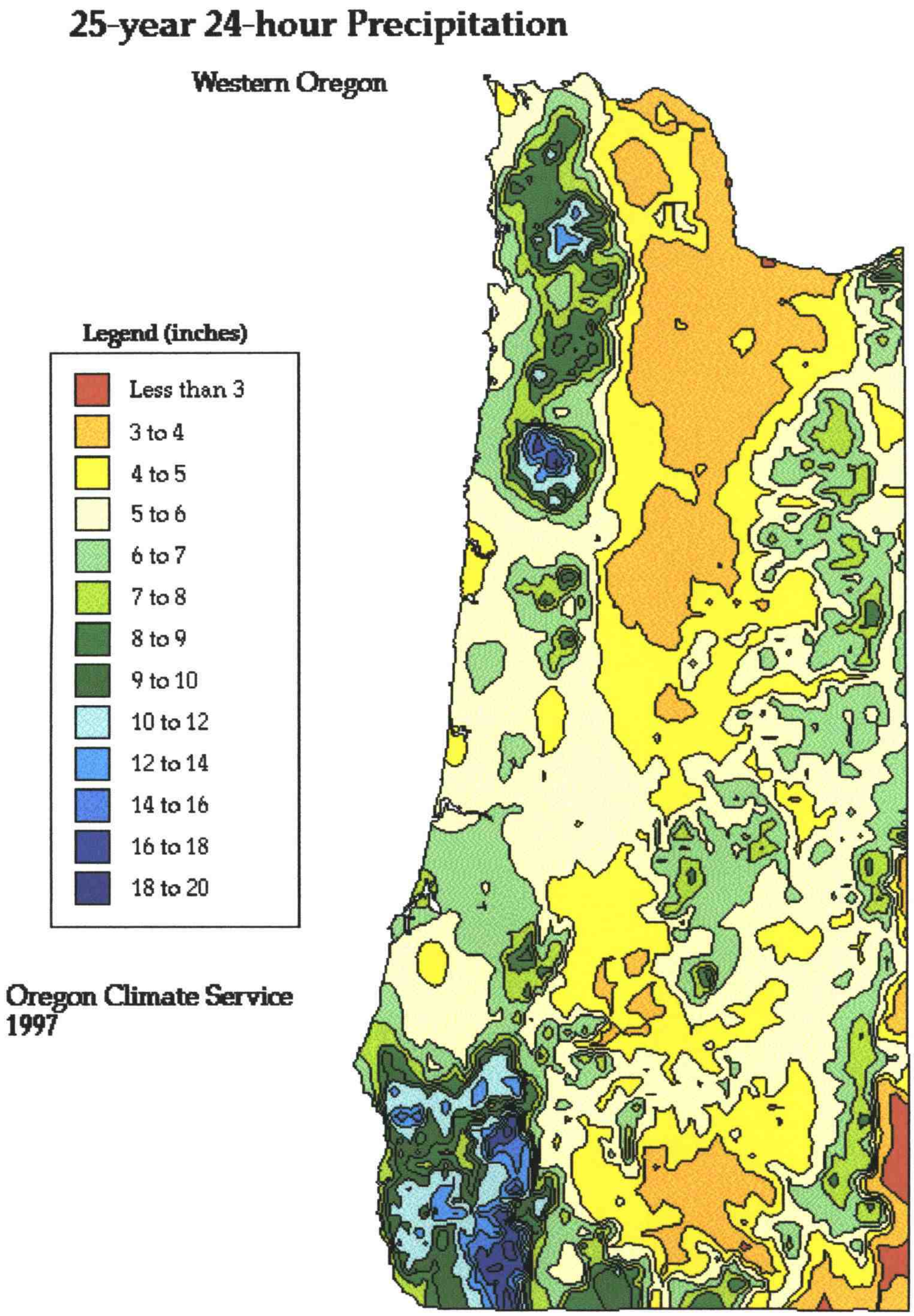
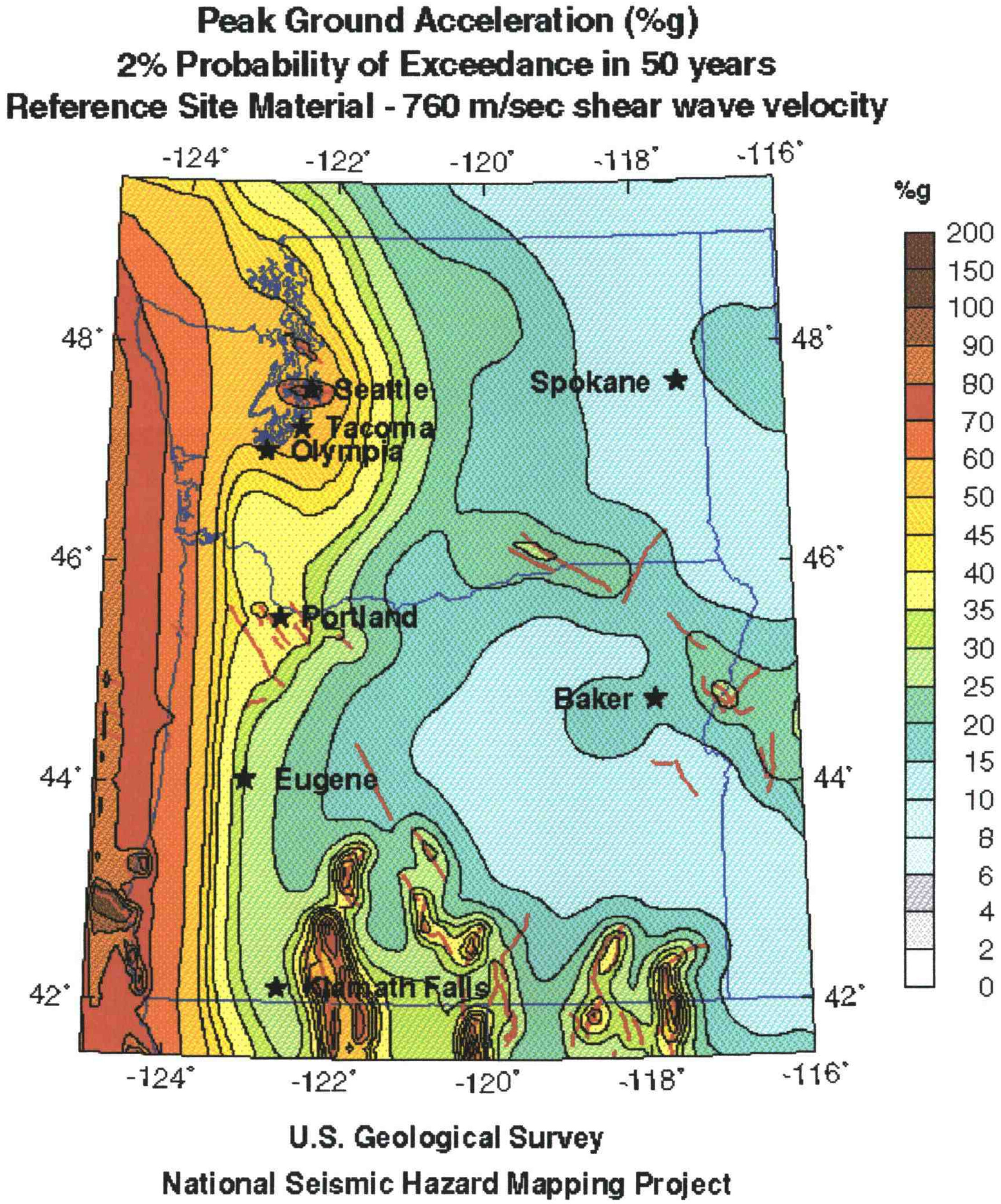
APPENDIX A



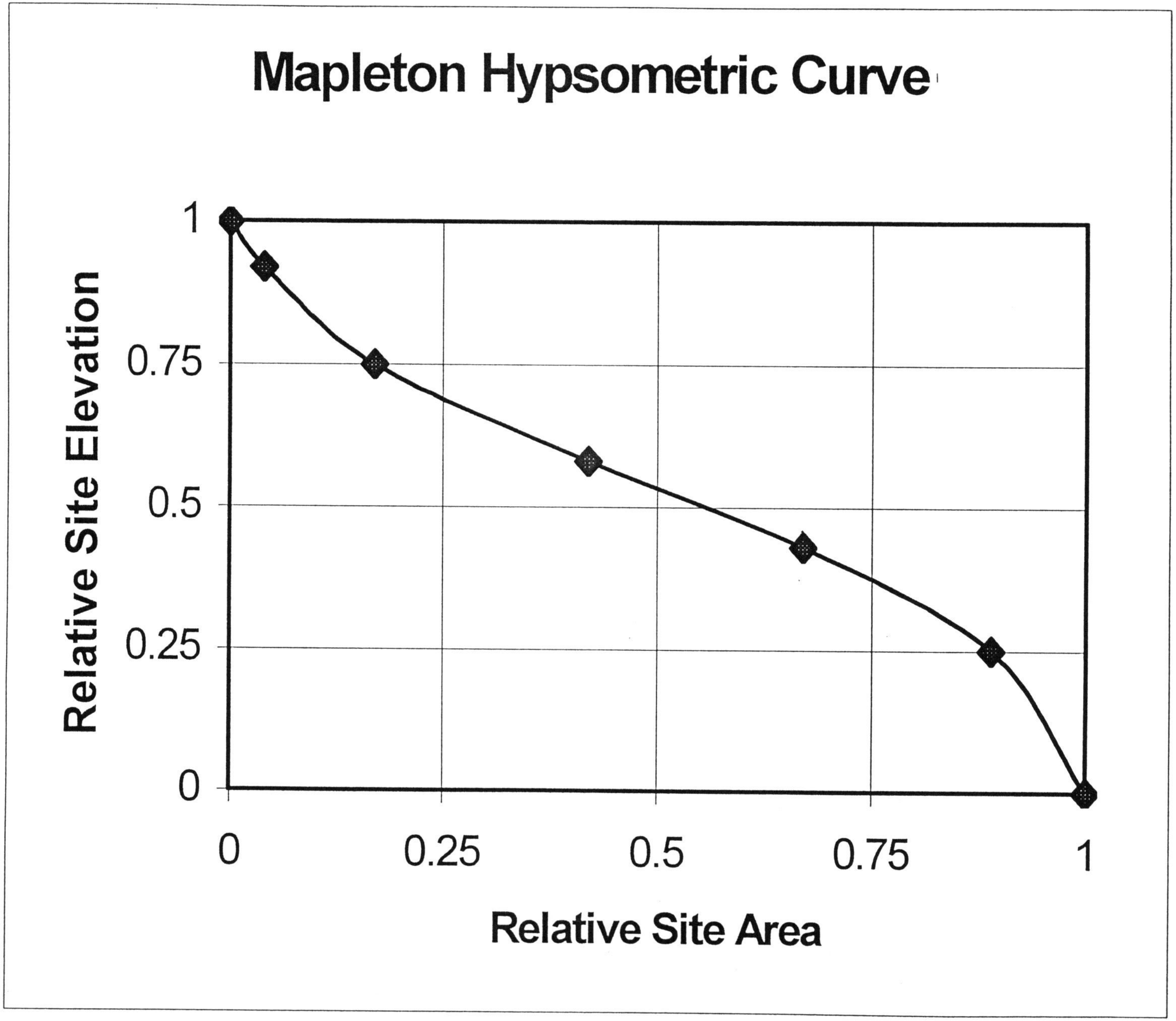
Western Oregon 25-Year 24-Hour Precipitation Total

From *Oregon Climate Services 1997*

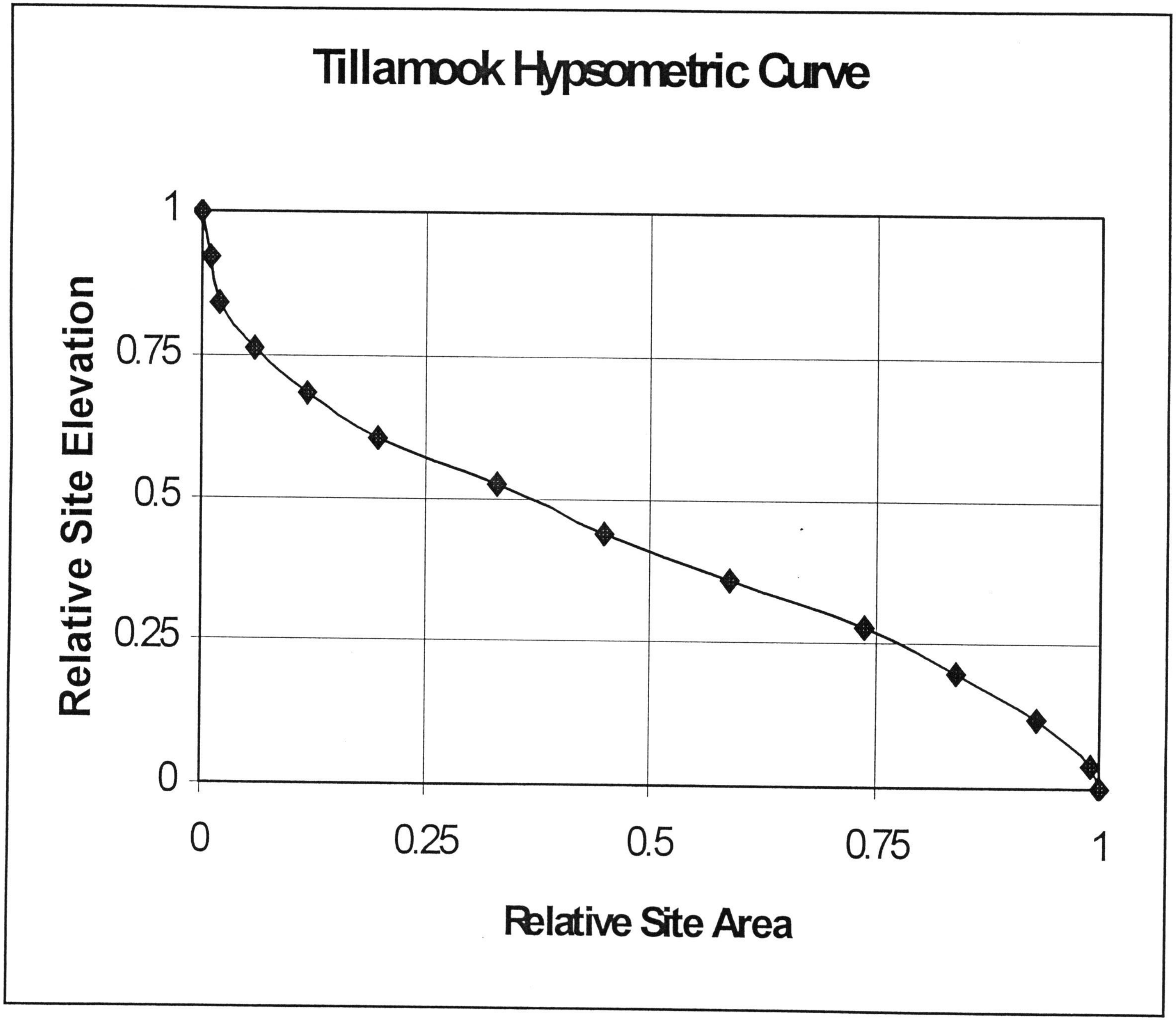

Peak Ground Acceleration (%g)
2% Probability of Exceedance in 50 years
Reference Site Material - 760 m/sec shear wave velocity
-124°
-122°
-120°
-118°
-116°
48°
46°
44°
42°
Seattle
Tacoma
Olympia
Spokane
Portland
Baker
Eugene
Klamath Falls
%g
200
150
100
90
80
70
60
50
45
40
35
30
25
20
15
10
8
6
4
2
0
U.S. Geological Survey
National Seismic Hazard Mapping Project

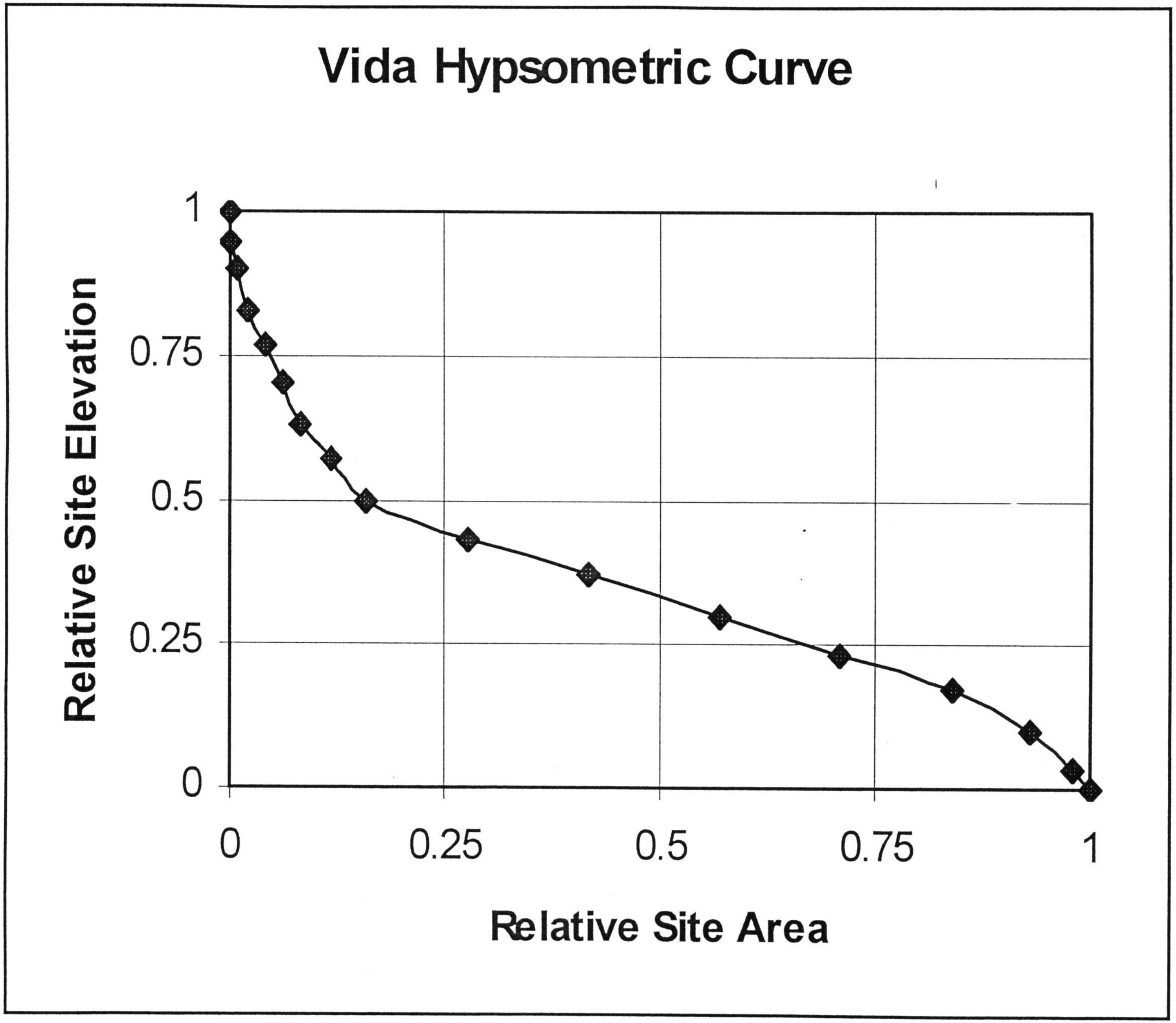
APPENDIX B

Study Site Hypsometric Curves



Mapleton Hypsometric Curve
Relative Site Elevation
1
0.75
0.5
0.25
0
0
0.25
0.5
0.75
1
Relative Site Area


Tillamook Hypsometric Curve
Relative Site Elevation
1
0.75
0.5
0.25
0
0
0.25
0.5
0.75
1
Relative Site Area



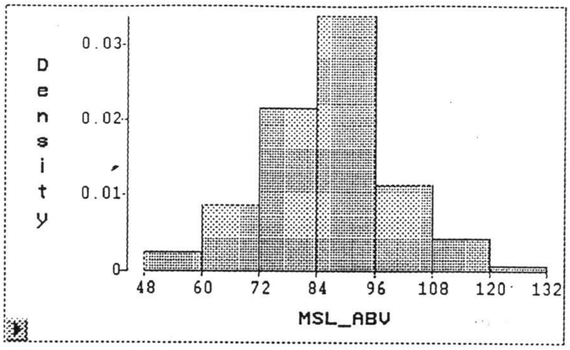
Vida Hypsometric Curve
Relative Site Elevation
1
0.75
0.5
0.25
0
0
0.25
0.5
0.75
1
Relative Site Area

APPENDIX C

Distributions, Moments, and Confidence intervals of Transformed Landscape Setting Characteristics

SLOPE OF HILLSLOPE ABOVE INITIATION POINT

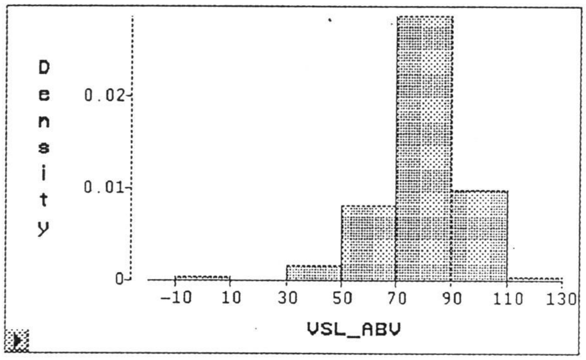
MAPLETON



Moments			
N	96.0000	Sum Wgts	96.0000
Mean	86.2708	Sum	8282.0000
Std Dev	13.5743	Variance	184.2627
Skewness	0.0784	Kurtosis	0.9262
USS	732000.000	CSS	17504.9583
CV	15.7346	Std Mean	1.3854

Confidence Interval for Mean			
Mean	Level (%)	Lower Limit	Upper Limit
86.2708	95.0000	83.5204	89.0213

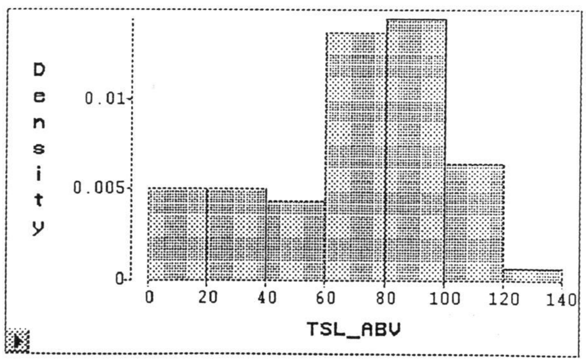
TILLAMOOK



Moments			
N	85.0000	Sum Wgts	85.0000
Mean	78.6235	Sum	6683.0010
Std Dev	16.5694	Variance	274.5452
Skewness	-1.3162	Kurtosis	5.4799
USS	548503.000	CSS	23061.7957
CV	21.0744	Std Mean	1.7972

Confidence Interval for Mean			
Mean	Level (%)	Lower Limit	Upper Limit
78.6235	95.0000	75.0496	82.1975

VIDA

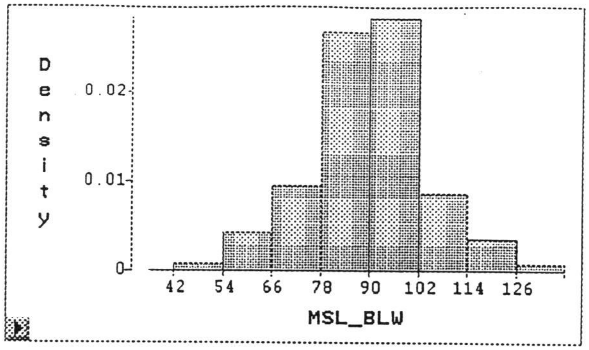


Moments			
N	69.0000	Sum Wgts	69.0000
Mean	68.4928	Sum	4726.0002
Std Dev	31.2803	Variance	978.4591
Skewness	-0.6129	Kurtosis	-0.3661
USS	390232.000	CSS	66535.2190
CV	45.6695	Std Mean	3.7657

Confidence Interval for Mean			
Mean	Level (%)	Lower Limit	Upper Limit
68.4928	95.0000	60.9784	76.0071

SLOPE OF PRE-FAILURE HILLSLOPE AT INITIATION POINT

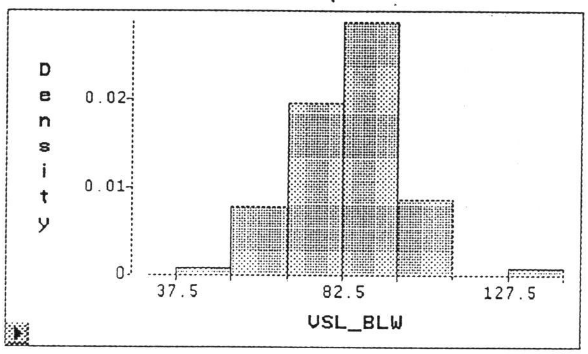
MAPLETON



Moments			
N	96.0000	Sum Wgts	96.0000
Mean	88.7708	Sum	8522.0000
Std Dev	14.5019	Variance	210.3048
Skewness	0.0836	Kurtosis	0.5553
USS	776484.000	CSS	19978.9583
CV	16.3363	Std Mean	1.4801

Confidence Interval for Mean			
Mean	Level (%)	Lower Limit	Upper Limit
88.7708	95.0000	85.8325	91.7092

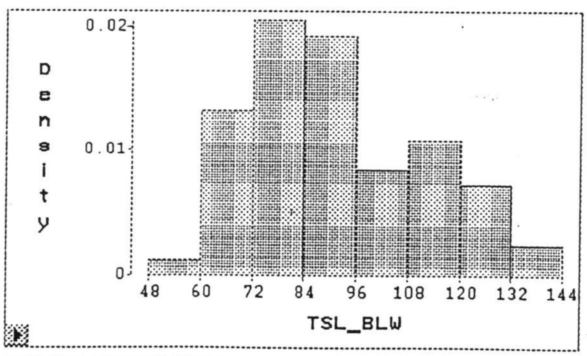
TILLAMOOK



Moments			
N	85.0000	Sum Wgts	85.0000
Mean	84.0824	Sum	7147.0000
Std Dev	14.6906	Variance	215.8146
Skewness	0.2007	Kurtosis	1.8812
USS	619065.000	CSS	18128.4235
CV	17.4717	Std Mean	1.5934

Confidence Interval for Mean			
Mean	Level (%)	Lower Limit	Upper Limit
84.0824	95.0000	80.9137	87.2510

VIDA

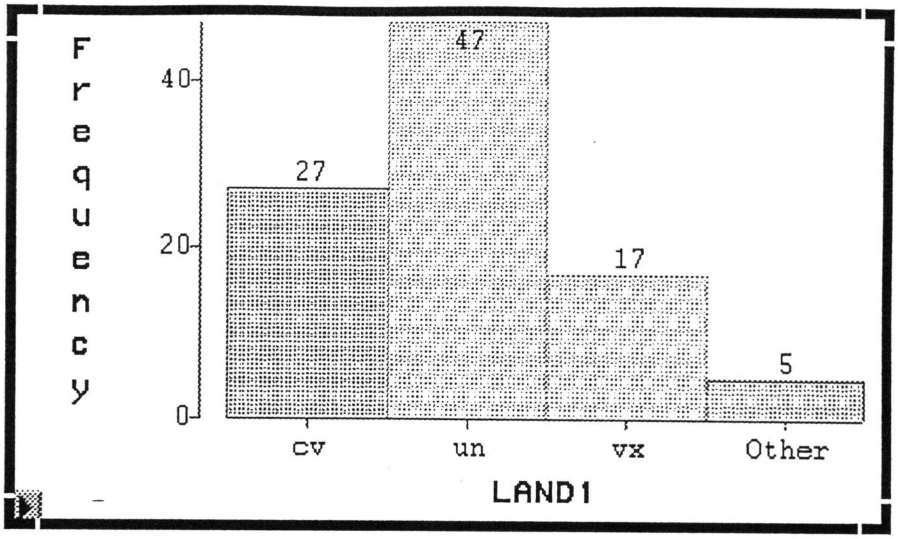


Moments			
N	69.0000	Sum Wgts	69.0000
Mean	89.8696	Sum	6201.0000
Std Dev	20.4097	Variance	416.5563
Skewness	0.4830	Kurtosis	-0.6159
USS	585607.000	CSS	28325.8261
CV	22.7104	Std Mean	2.4570

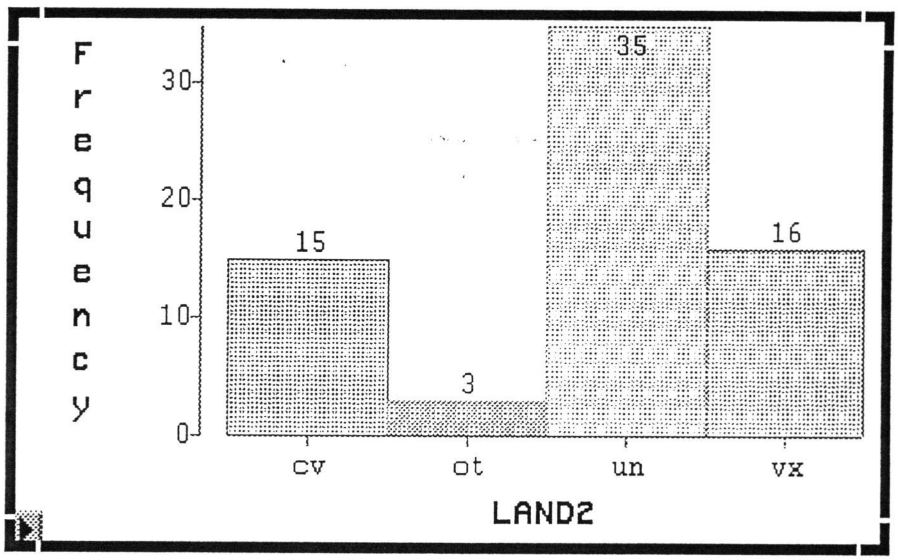
Confidence Interval for Mean			
Mean	Level (%)	Lower Limit	Upper Limit
89.8696	95.0000	84.9666	94.7725

LANDFORM TYPE AT INITIATION POINT

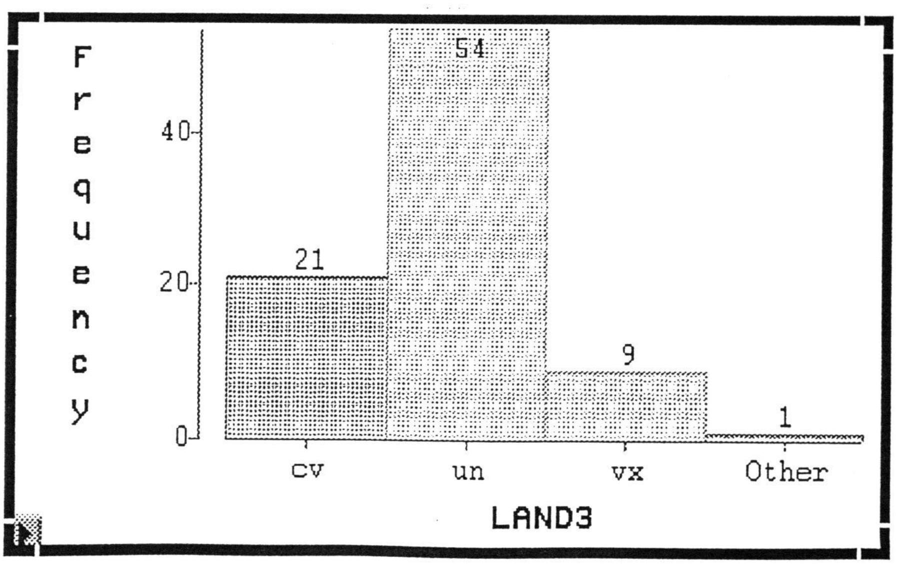
MAPLETON



TILLAMOOK

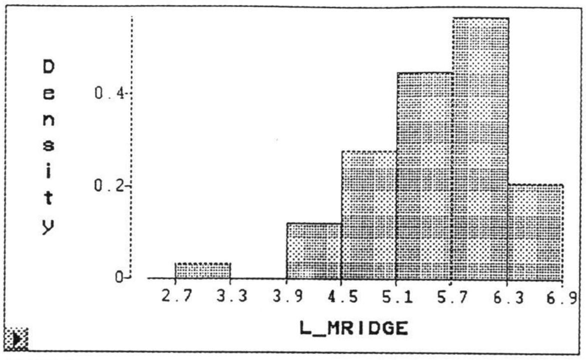


VIDA



DISTANCE TO RIDGE FROM INITIATION POINT

MAPLETON

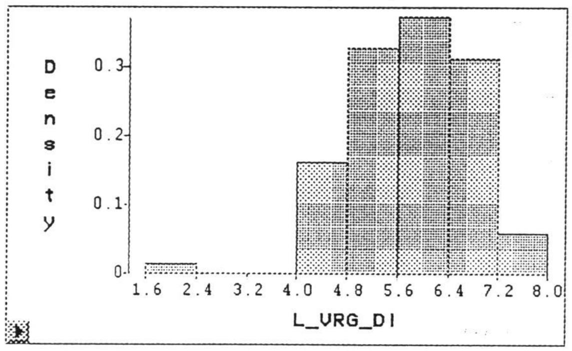


Moments			
N	96.0000	Sum Wgts	96.0000
Mean	5.4720	Sum	525.3136
Std Dev	0.7389	Variance	0.5460
Skewness	-0.8138	Kurtosis	0.9154
USS	2926.3916	CSS	51.8665
CV	13.5031	Std Mean	0.0754

Confidence Interval for Mean

Mean	Level (%)	Lower Limit	Upper Limit
5.4720	95.0000	5.3223	5.6217

TILLAMOOK

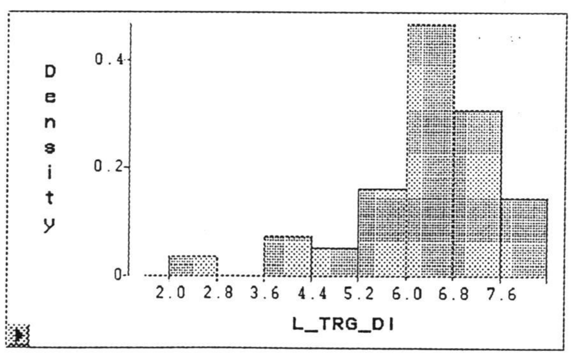


Moments			
N	84.0000	Sum Wgts	84.0000
Mean	5.8134	Sum	488.3286
Std Dev	0.9171	Variance	0.8411
Skewness	-0.5360	Kurtosis	1.2487
USS	2908.6767	CSS	69.8097
CV	15.7756	Std Mean	0.1001

Confidence Interval for Mean

Mean	Level (%)	Lower Limit	Upper Limit
5.8134	95.0000	5.6144	6.0125

VIDA



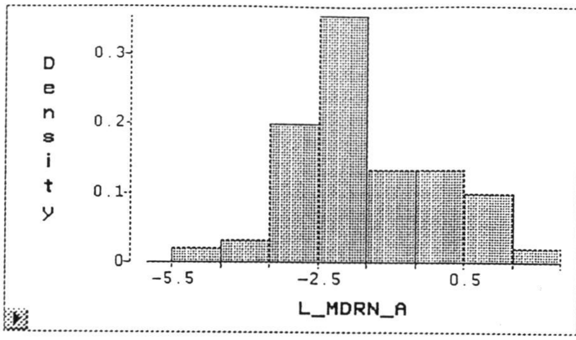
Moments			
N	69.0000	Sum Wgts	69.0000
Mean	6.3152	Sum	435.7493
Std Dev	1.1953	Variance	1.4288
Skewness	-1.3514	Kurtosis	2.5160
USS	2849.0084	CSS	97.1612
CV	18.9280	Std Mean	0.1439

Confidence Interval for Mean

Mean	Level (%)	Lower Limit	Upper Limit
6.3152	95.0000	6.0281	6.6024

LOG OF AREA DRAINING TO INITIATION POINT

MAPLETON

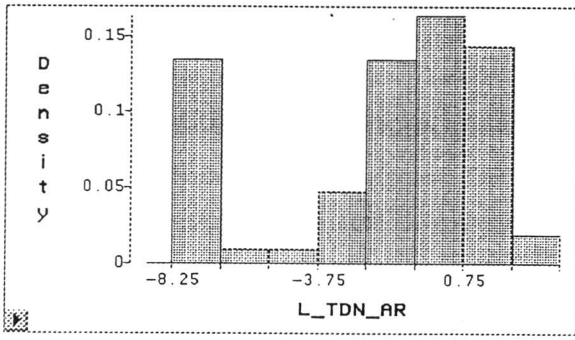


Moments			
N	90.0000	Sum Wgts	90.0000
Mean	-1.5038	Sum	-135.3401
Std Dev	1.5173	Variance	2.3021
Skewness	0.4180	Kurtosis	-0.3625
USS	408.4070	CSS	204.8855
CV	-100.8966	Std Mean	0.1599

Confidence Interval for Mean

Mean	Level (%)	Lower Limit	Upper Limit
-1.5038	95.0000	-1.8216	-1.1860

TILLAMOOK

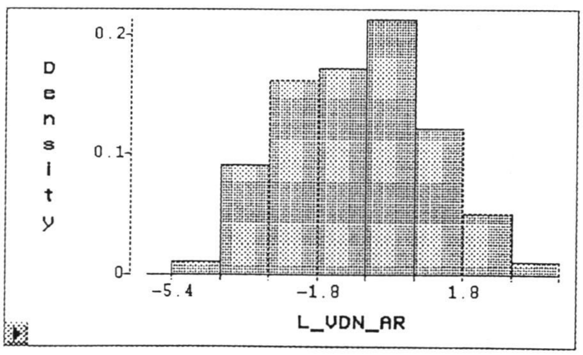


Moments			
N	69.0000	Sum Wgts	69.0000
Mean	-1.6606	Sum	-114.5835
Std Dev	3.1217	Variance	9.7451
Skewness	-0.6917	Kurtosis	-0.8339
USS	852.9455	CSS	662.6645
CV	-187.9833	Std Mean	0.3758

Confidence Interval for Mean

Mean	Level (%)	Lower Limit	Upper Limit
-1.6606	95.0000	-2.4105	-0.9107

VIDA



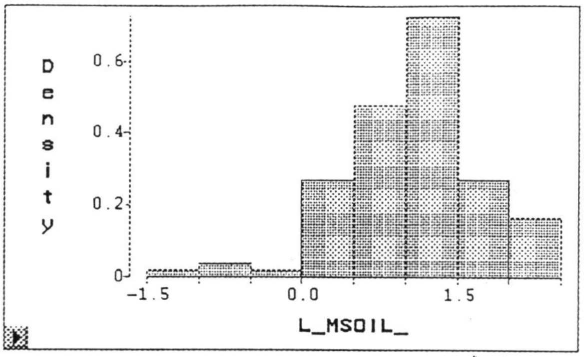
Moments			
N	82.0000	Sum Wgts	82.0000
Mean	-0.8230	Sum	-67.4841
Std Dev	1.8077	Variance	3.2678
Skewness	0.1084	Kurtosis	-0.4559
USS	320.2278	CSS	264.6900
CV	-219.6537	Std Mean	0.1996

Confidence Interval for Mean

Mean	Level (%)	Lower Limit	Upper Limit
-0.8230	95.0000	-1.2202	-0.4258

LOG OF SOIL DEPTH AT INITIATION POINT

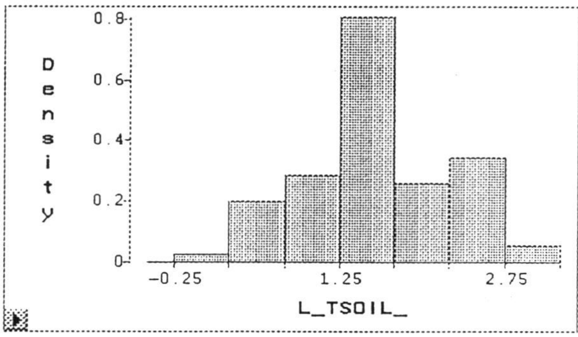
MAPLETON



Moments			
N	96.0000	Sum Wgts	96.0000
Mean	1.0150	Sum	97.4426
Std Dev	0.7132	Variance	0.5087
Skewness	-0.5125	Kurtosis	0.3087
USS	147.2347	CSS	48.3278
CV	70.2682	Std Mean	0.0728

Confidence Interval for Mean			
Mean	Level (%)	Lower Limit	Upper Limit
1.0150	95.0000	0.8705	1.1595

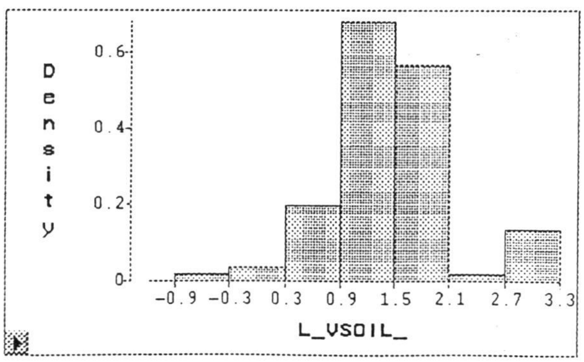
TILLAMOOK



Moments			
N	69.0000	Sum Wgts	69.0000
Mean	1.5748	Sum	108.6596
Std Dev	0.6425	Variance	0.4128
Skewness	0.2757	Kurtosis	0.0570
USS	199.1843	CSS	28.0696
CV	40.7985	Std Mean	0.0773

Confidence Interval for Mean			
Mean	Level (%)	Lower Limit	Upper Limit
1.5748	95.0000	1.4204	1.7291

VIDA

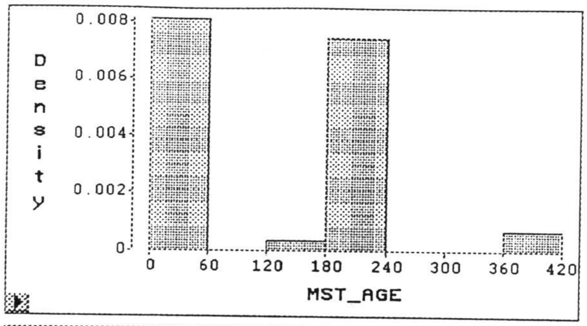


Moments			
N	85.0000	Sum Wgts	85.0000
Mean	1.4609	Sum	124.1795
Std Dev	0.6435	Variance	0.4141
Skewness	-0.0997	Kurtosis	1.4195
USS	216.2009	CSS	34.7827
CV	44.0464	Std Mean	0.0698

Confidence Interval for Mean			
Mean	Level (%)	Lower Limit	Upper Limit
1.4609	95.0000	1.3221	1.5997

STAND AGE AT LANDSLIDE INITIATION POINT

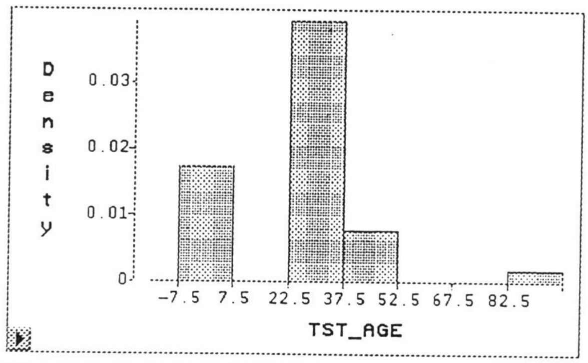
MAPLETON



Moments			
N	96.0000	Sum Wgts	96.0000
Mean	118.2500	Sum	11352.0000
Std Dev	106.6646	Variance	11377.3474
Skewness	0.5573	Kurtosis	-0.2823
USS	2423222.00	CSS	1080848.00
CV	90.2027	Std Mean	10.8864

Confidence Interval for Mean			
Mean	Level (%)	Lower Limit	Upper Limit
118.2500	95.0000	96.6377	139.8623

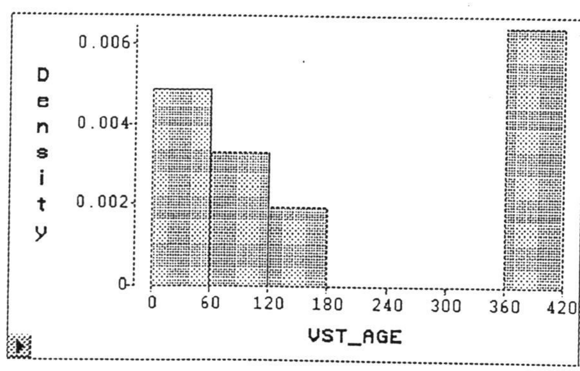
TILLAMOOK



Moments			
N	69.0000	Sum Wgts	69.0000
Mean	27.9275	Sum	1927.0000
Std Dev	19.9450	Variance	397.8035
Skewness	0.5405	Kurtosis	2.3958
USS	80867.0000	CSS	27050.6377
CV	71.4170	Std Mean	2.4011

Confidence Interval for Mean			
Mean	Level (%)	Lower Limit	Upper Limit
27.9275	95.0000	23.1362	32.7189

VIDA



Moments			
N	85.0000	Sum Wgts	85.0000
Mean	194.6247	Sum	16543.1000
Std Dev	169.6851	Variance	28793.0255
Skewness	0.2836	Kurtosis	-1.7326
USS	5638310.11	CSS	2418614.14
CV	87.1858	Std Mean	18.4049

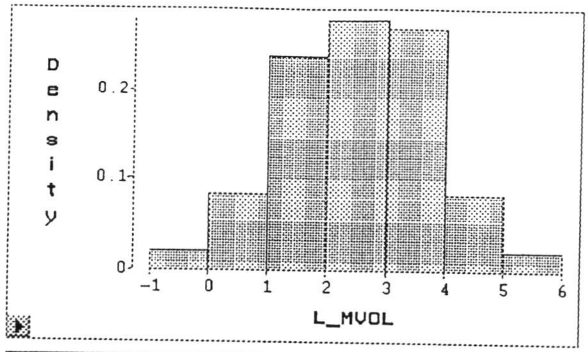
Confidence Interval for Mean			
Mean	Level (%)	Lower Limit	Upper Limit
194.6247	95.0000	158.0245	231.2249

APPENDIX D

Distributions, Moments, and Confidence intervals of Transformed Landslide Parameters

LOG OF LANDSLIDE VOLUME

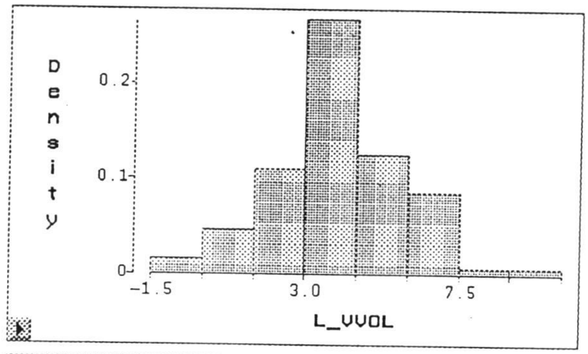
MAPLETON



Moments			
N	96.0000	Sum Wgts	96.0000
Mean	2.5568	Sum	245.4542
Std Dev	1.2849	Variance	1.6510
Skewness	-0.2393	Kurtosis	-0.2318
USS	784.4216	CSS	156.8406
CV	50.2537	Std Mean	0.1311

Confidence Interval for Mean			
Mean	Level (%)	Lower Limit	Upper Limit
2.5568	95.0000	2.2965	2.8172

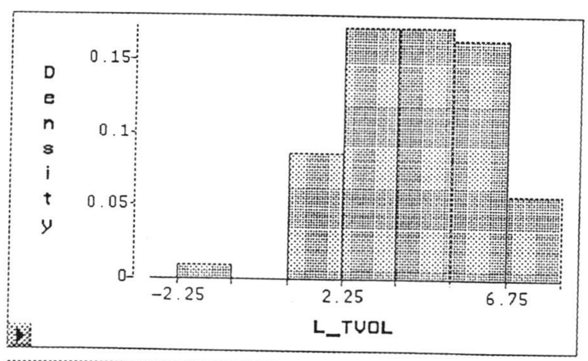
TILLAMOOK



Moments			
N	85.0000	Sum Wgts	85.0000
Mean	4.0221	Sum	341.8821
Std Dev	1.8304	Variance	3.3503
Skewness	0.1713	Kurtosis	0.5220
USS	1656.5198	CSS	281.4214
CV	45.5073	Std Mean	0.1985

Confidence Interval for Mean			
Mean	Level (%)	Lower Limit	Upper Limit
4.0221	95.0000	3.6273	4.4169

VIDA

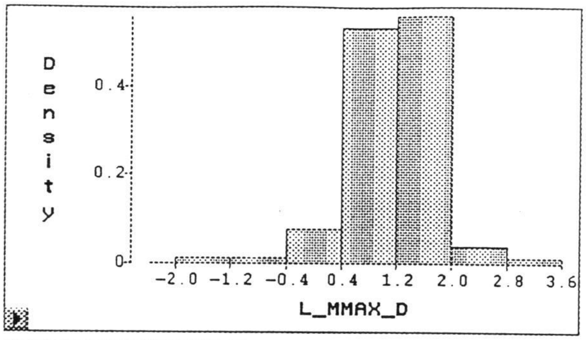


Moments			
N	69.0000	Sum Wgts	69.0000
Mean	4.1831	Sum	288.6317
Std Dev	1.8701	Variance	3.4973
Skewness	-0.0874	Kurtosis	0.1400
USS	1445.1809	CSS	237.8149
CV	44.7065	Std Mean	0.2251

Confidence Interval for Mean			
Mean	Level (%)	Lower Limit	Upper Limit
4.1831	95.0000	3.7338	4.6323

LOG OF LANDSLIDE MAXIMUM DEPTH

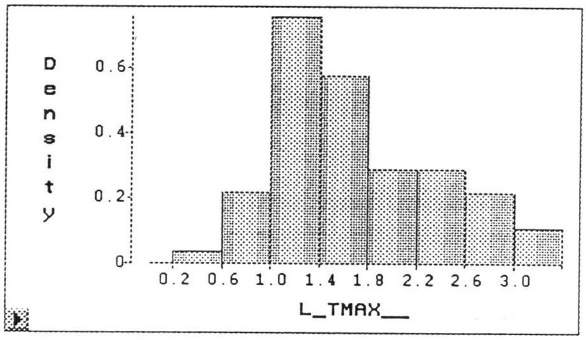
MAPLETON



Moments			
N	96.0000	Sum Wgts	96.0000
Mean	1.1716	Sum	112.4730
Std Dev	0.6368	Variance	0.4056
Skewness	-1.0128	Kurtosis	4.2651
USS	170.3016	CSS	38.5290
CV	54.3570	Std Mean	0.0650

Confidence Interval for Mean			
Mean	Level (%)	Lower Limit	Upper Limit
1.1716	95.0000	1.0426	1.3006

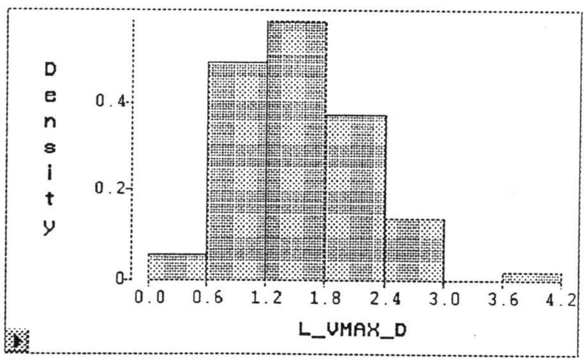
TILLAMOOK



Moments			
N	69.0000	Sum Wgts	69.0000
Mean	1.7087	Sum	117.8969
Std Dev	0.6741	Variance	0.4544
Skewness	0.3877	Kurtosis	-0.4084
USS	232.3416	CSS	30.8970
CV	39.4503	Std Mean	0.0811

Confidence Interval for Mean			
Mean	Level (%)	Lower Limit	Upper Limit
1.7087	95.0000	1.5467	1.8706

VIDA

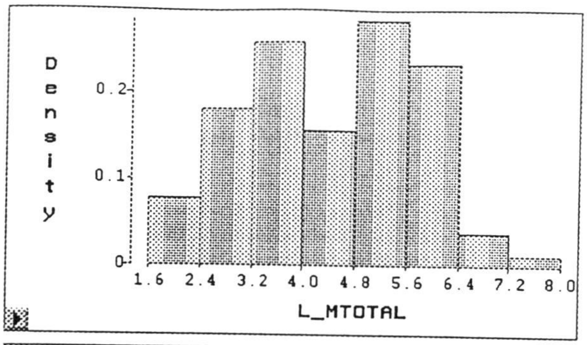


Moments			
N	85.0000	Sum Wgts	85.0000
Mean	1.5948	Sum	135.5569
Std Dev	0.6618	Variance	0.4380
Skewness	0.5476	Kurtosis	1.7274
USS	252.9755	CSS	36.7911
CV	41.4982	Std Mean	0.0718

Confidence Interval for Mean			
Mean	Level (%)	Lower Limit	Upper Limit
1.5948	95.0000	1.4520	1.7375

LOG OF TOTAL LANDSLIDE LENGTH AND RUNOUT DISTANCE

MAPLETON



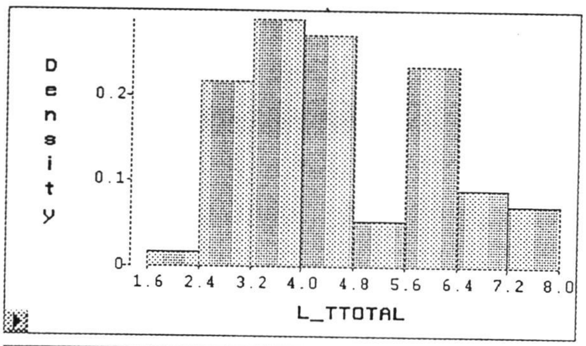
Moments

N	96.0000	Sum Wgts	96.0000
Mean	4.4133	Sum	423.6753
Std Dev	1.3259	Variance	1.7580
Skewness	-0.0129	Kurtosis	-1.0753
USS	2036.8058	CSS	167.0064
CV	30.0430	Std Mean	0.1353

Confidence Interval for Mean

Mean	Level (%)	Lower Limit	Upper Limit
4.4133	95.0000	4.1446	4.6819

TILLAMOOK



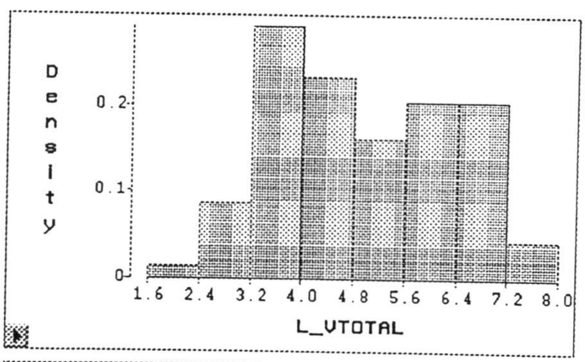
Moments

N	69.0000	Sum Wgts	69.0000
Mean	4.6232	Sum	318.9991
Std Dev	1.5170	Variance	2.3014
Skewness	0.4106	Kurtosis	-0.9337
USS	1631.2862	CSS	156.4978
CV	32.8140	Std Mean	0.1826

Confidence Interval for Mean

Mean	Level (%)	Lower Limit	Upper Limit
4.6232	95.0000	4.2587	4.9876

VIDA



Moments

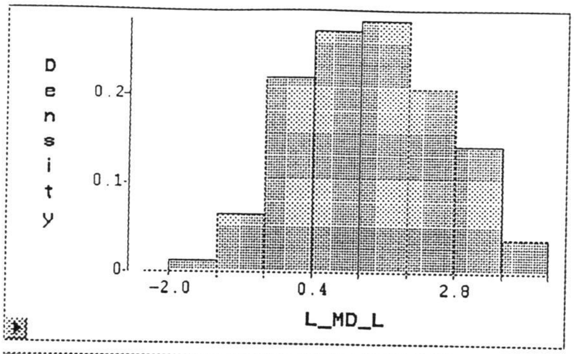
N	85.0000	Sum Wgts	85.0000
Mean	4.9622	Sum	421.7865
Std Dev	1.4104	Variance	1.9892
Skewness	0.0163	Kurtosis	-1.0952
USS	2260.0763	CSS	167.0901
CV	28.4225	Std Mean	0.1530

Confidence Interval for Mean

Mean	Level (%)	Lower Limit	Upper Limit
4.9622	95.0000	4.6580	5.2664

LOG OF SLIDE DEPTH/LENGTH RATIO

MAPLETON

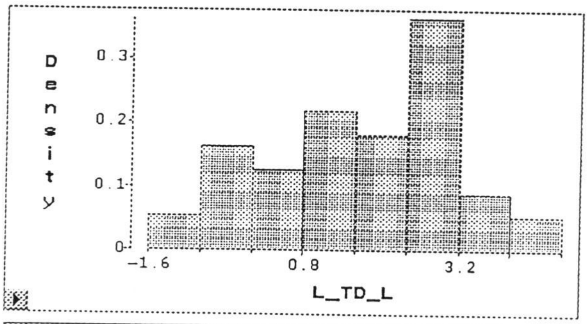


Moments			
N	96.0000	Sum Wgts	96.0000
Mean	1.3635	Sum	130.8940
Std Dev	1.2244	Variance	1.4993
Skewness	0.0207	Kurtosis	-0.6212
USS	320.9012	CSS	142.4299
CV	89.8029	Std Mean	0.1250

Confidence Interval for Mean

Mean	Level (%)	Lower Limit	Upper Limit
1.3635	95.0000	1.1154	1.6116

TILLAMOOK

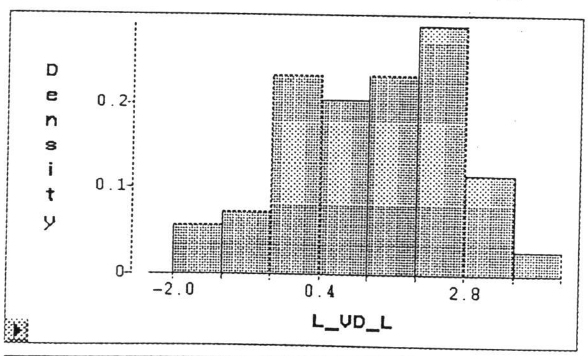


Moments			
N	69.0000	Sum Wgts	69.0000
Mean	1.6906	Sum	116.6546
Std Dev	1.4564	Variance	2.1211
Skewness	-0.2568	Kurtosis	-0.7497
USS	341.4561	CSS	144.2345
CV	86.1445	Std Mean	0.1753

Confidence Interval for Mean

Mean	Level (%)	Lower Limit	Upper Limit
1.6906	95.0000	1.3408	2.0405

VIDA



Moments			
N	85.0000	Sum Wgts	85.0000
Mean	1.2378	Sum	105.2099
Std Dev	1.2864	Variance	1.6548
Skewness	-0.1079	Kurtosis	-0.7319
USS	269.2314	CSS	139.0065
CV	103.9298	Std Mean	0.1395

Confidence Interval for Mean

Mean	Level (%)	Lower Limit	Upper Limit
1.2378	95.0000	0.9603	1.5152

APPENDIX E

Forest Practices Requirements

From *ODF 1997*

The State Forester has determined that a high-risk site includes the following landforms:

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 with other characteristics determined to be of marginal stability by ODF personnel.

Practices which have become standard practices 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 at times 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; and
3. Avoiding use of herbicides.