AN ABSTRACT OF THE THESIS OF

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Arne E. Skaugset III

Debris flows in the Pacific Northwest play a major role in routing wood and sediment stored on hillslopes and in first- through third-order channels to higher order channels and valley floors. Forest practices on steep, unstable slopes and removal of riparian trees along low-order streams can affect the frequency, magnitude, and composition of debris flows. The quantity and quality of debris flow deposits provides sediment and wood fundamental to the development of the receiving channel. Field surveys document characteristics of the initiation site, runout zone, and deposit of 53 debris flows in the Siuslaw Basin of the central Oregon Coast Range, during the winter of 1996. Landslides that initiated debris flows in clearcuts had a higher frequency, larger average volume, and runout zones that affected a greater length of stream channel than landslides from forested slopes. This difference resulted in an increase in the total volume of sediment mobilized by the debris flow, and a greater proportion of this sediment came from hillslope sources. Debris flows initiated at roads had an order of magnitude greater volume of sediment compared to non-road-related failures. Debris flows of equivalent size that traveled through a forested channel delivered only a slightly greater volume of large wood, than those through clearcuts. Size-class distributions of wood in the deposit and trees on the hillslope were not well correlated. The average diameter of wood in the deposit was greater than the diameter of trees currently present on the surrounding hillslopes. This difference reflects the legacy of large woody debris stored in low-order channels and valley floors. Large trees along the edge of the runout

zone is also an important component in the recovery of these low-order channels, which were transformed into a bedrock state. Large trees along the edges of forested slopes are already supplying wood to these channels, and were the only mechanism observed for trapping large volumes of sediment. This mechanism for retaining sediment in high gradient, low-roughness channels is not available in clearcuts, which now contain the greatest proportion of bedrock channels. Forest practices, by altering the frequency, magnitude, and composition of the debris flow, may alter the long-term potential for developing complex channel morphology and high-quality aquatic habitat.

Debris Flow Characteristics Associated with Forest Practices in the Central Oregon Coast Range

by

Christine L. May

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APPROVED:

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Head of Department of Forest Engineering

Dean of Graduate School

I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

Christine L. May, Author

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INTRODUCTION

General

Naturally occurring debris flows in the Pacific Northwest play a major role in routing wood and sediment down steep hillslopes and through 1^{st} – 3^{rd} order streams to higher-order streams and valley floors (Benda, 1994; Swanson et al. 1982; Keller and Swanson, 1979). The size and composition of debris flow deposits provide sediment, boulders, and wood that structure the morphology of the receiving channel and affects the long-term potential to develop high-quality aquatic habitat. Forest practices on steep slopes and the harvest of riparian trees along low-order streams may affect natural disturbance regimes by altering the frequency, magnitude, and composition of debris flows.

After the February 1996 flood, many questions were raised regarding the interaction between forest management and regional floods, and how potential interactions might affect aquatic ecosystems. Of particular interest was how the source and flow path of debris flows, through managed and unmanaged forests, affects the composition of material deposited in larger, anadromous fish bearing streams. While characteristics of the surrounding landscape affect the initiating landslide of a debris flow and the runout path, the absence of large riparian trees along stream channels susceptible to debris flows has unknown consequences on the behavior of debris flows and the composition of debris flow deposits. An alteration in the volume and size class distribution of large wood in a deposit may affect the capability of the receiving stream channel to store sediment and its ability to form complex aquatic habitat. Sediment storage can be an important factor affecting the morphology of many Coast Range streams that might otherwise be bedrock-dominated. Similarly, a transition to smaller pieces and lower volumes of wood from harvested areas could reduce the stability of debris jams because large, individual logs, which have a major influence on debris jam stability, are absent (Montgomery et al.1996). The composition of debris flow deposits can also influence the evolution of the receiving channel by contributing structural elements to the channel and shaping the surrounding landforms. Formation of valley floor surfaces, such as debris flow fans, constrain the receiving stream channel, alter the flow path, increase sinuosity, and are a future source of wood and sediment to mid-order streams.

Forest road construction and timber harvesting have replaced wildfire as major disturbances of forests in much of the Pacific Northwest (Reeves et al. 1995). Assessment of management impacts requires knowledge of the frequency and consequences of both management and pre-management disturbances (Swanson et al. 1982). Modifications in the type of disturbance or in the frequency and magnitude of natural disturbances can alter the species composition, habitat features, and resilience of an ecosystem (White and Pickett, 1985). A disturbance-based habitat recovery plan (e.g. Reeves et al. 1995) indicates that changes in the legacy of disturbance, or the conditions that exist immediately following a disturbance, may be another important component of altered disturbance regimes. Also, any legacy of debris flows has both upstream and downstream consequences. The 'downstream legacy' of debris flows is largely dependent on the size and composition of the deposit. The 'upstream legacy' of the debris flow is a low-order channel scoured to bedrock that will refill overtime with wood and colluvium.

Large trees along the perimeter of a debris flow scoured channel represent as an important component of channel recovery. As trees fall into the channel or are delivered by streamside landslides, the local slope is reduced (Montgomery et. al, 1996), channel roughness is increased (Beschta and Platts, 1986), and the sediment transport ability of the stream channel decreases. A lack of physical obstructions to sediment movement in steep channels, because of forest harvesting, has an unknown and potentially adverse effect on the recovery of low-order channels. If sediment is not being stored, then the low-order channels may become a chronic source of sediment to higher-order streams.

Objectives

The overall goal of this research is to determine if forest management, in the form of road construction and clearcut silviculture have altered the frequency, magnitude, or composition of debris flows in the central Oregon Coast Range. Specific questions to be addressed include the following:

Initiation Site:

Is there a difference in the frequency, magnitude, or location of landslides that initiate debris flows in forested compared to clearcut basins?

Runout Zone:

Does the debris flow behave differently if it travels through a forested vs. clearcut riparian area? For example, is the runout zone larger or longer?

Deposit:

Is there a difference in the volume of sediment and wood, a change in the size class distribution of wood, or the type of deposit formed based on upslope or upvalley management practices?

LITERATURE REVIEW

The Role of Disturbance in Shaping River Ecosystems

While erosion and sedimentation are often viewed negatively from a biological point of view, they are essential to the ecological functioning of aquatic and terrestrial communities because they provide the sources and surfaces necessary for habitat (Naiman et al. 1992). Naiman et. al. (1992) hypothosized that the delivery and routing of water, sediment, and woody debris to stream channels are key processes that determine the ecological health of watersheds in the Pacific Northwest coastal ecoregion. Other factors that influence the ecological health of watersheds include nutrient and energy dynamics. 'Ecologically healthy' refers to functions that affect biodiversity, productivity, biogeochemical cycles, and evolutionary processes that are adapted to the climatic and geologic conditions of the region (Karr et al. 1986, Karr 1991).

In addition to more frequent and chronic processes, episodic disturbances (e.g. large-scale and infrequent) in steep mountainous terrain, play a major role in creating and maintaining aquatic habitat over time. 'Living Systems Theory' (Warren et al. 1979) indicates that developing systems change in state and organization through time, expressing new performances (observable behaviors) in new environments. Disturbance events, such as floods and debris flows, set the stage for the expression of new performances in river ecosystems by changing the environmental setting. The direction and nature of the disturbance, and subsequent responsive change, comprises the course of development or developmental trajectory of a system (Warren et al. 1979). For example, system responses to debris flow disturbances will depend on the frequency, size, and composition of events. We may be fundamentally changing the direction and nature of channel responses by altering these aspects of natural disturbance regimes through land-use practices.

Life history adaptations of anadromous salmonids have allowed populations to persist in dynamic environments; these environments are naturally subjected to periodic catastrophic disturbances and a series of recovery states (Reeves et.al. 1995). Catastrophic disturbance can be considered an event that overturns the order in a system. Botkin (1990) indicated that an ecosystem approach to the conservation and restoration of endangered organisms must recognize that ecosystems are dynamic in space and time because of natural disturbances. Over time, changes in environmental conditions may suppress or enable the expression of specific performances, resulting in a dynamic pattern in which habitats emerge, are extinguished, and reemerge over time (Warren and Liss 1980; Reeves et al. 1995; Ebersole et al. 1997). Thus, not all possible channel conditions or habitats may be expressed at any one time; rather, the existing array of such features at any point in time will reflect the landscape's developmental history and environmental capacity.

Benda and Dunne (1997) modeled the stochastic nature of sediment supply to alluvial channels (mid- and higher-order channels) by debris flows. These sediment supplies promoted cycling between channel aggradation, which resulted in a gravel-bed morphology, and channel degradation, which resulted in a mixed bedrock- boulder-bed morphology. Agradation can increase the likelihood of overbank flows by increasing connectivity with floodplains. provides a deformable bed in which a diverse array of habitat types can form, and provides a diversity of substrates. Cycles of sediment supplyy also produce temporal variability in both fish habitat and juvenile salmonid assemblages (Reeves et al. 1995).

Geomorphic Setting

Zero-order basins in steep mountainous terrain, also termed bedrock hollows or headwalls, are defined by concave depressions in bedrock with axes that extend downslope and commonly merge with the headward tip of first-order channels. Hack and Goodlett (1960) used the terminology "nose" for convex contours, "side slopes" for straight contours, and "hollow" for concave contours. Typically all 3 topographic features comprise the basin upslope of the head of the channel (Dietrich et al. 1986). The concave surfaces function to concentrate sediment, wood, and water from the surrounding hillslopes. Benda (1988) found that the majority of debris flows in the central Oregon Coast Range are initiated by landslides that occur in the distal portion colluvium-filled bedrock hollows. Similarly, Reneau and Dietrich (1987) found that 62% of the 61 landslides surveyed in Marin County, California occurred in bedrock hollows. These shallow rapid landslides are normally triggered during single rainstorms of either high intensity or long duration. Other initiation sources for debris flows include landslides from relatively planar side slopes, which normally enter a stream network perpendicular to the axis of the hollow or first-order tributary. Large deep-seated earthflows that enter streamside, or failures within first-order streambeds (i.e. no hillslope source), also occasionally initiate debris flows.

After episodic removal of colluvium from bedrock hollows, colluvium slowly refills the hollow and thickens over a period of hundreds to thousands of years (Dietrich et al. 1986; Benda and Dunne, 1987). As colluvium depth increases over time, the stability of the site changes due to the changing balance of gravitational forces, and the ability of roots to bind the soil to the underlying bedrock diminishes as depth of soil increases (Reneau and Dietrich, 1987). Benda and Cundy (1990) reported that hollow failures which joined a channel head at angles less than 45° consistently transformed landslides into debris flows that scoured wood and sediment from first- and second-order channels. Hollow failures that joined a channel at approximately right angles, caused the landslides to deposit at the mouth of the hollow; these landslides typically did not evolve into debris flows. While the landslide deposits become stored in low-order channels, they are subject to scour by subsequent debris flows (Montgomery and Dietrich, 1994). Thus, the legacy of previous landslides contributes wood and sediment to the composition of current debris flows.

First- and second-order channel segments (referred to hereafter as low-order channels) can represent more than 70% of the cumulative channel length in mountain watersheds (Benda et al. 1992). For example, the Siuslaw National Forest classified 5,000 miles (61%) of the 8,200 miles of stream channel on the Forest as intermittent streams (Siuslaw National Forest, 1990). Therefore, low-order channels are viewed as important conduits for water, sediment, and wood routed from hillslopes to higher-order rivers (Naiman et al. 1992). Low-order channels in mountainous terrain are naturally prone to episodic erosion due to steep slopes adjacent to high gradient channels that are dominated by landslides and debris flows (Naiman et al. 1992), and relatively little sediment and wood is transported by fluvial processes (Swanson et al. 1982). Hogan et al. (1995) reported that with an increased degree of constraint (measured in terms of valley width index) the connectivity between the hillslope and the stream channel becomes progressively stronger. Low-order streams in the Coast Range are generally steep, have a narrow valley width, and are highly responsive to hillslope processes. Research in the Oregon Cascades reports that total sediment yield is controlled largely by hillslope processes, however, the timing of sediment exported fluvially from a stream may be regulated by large woody debris in the channel that obstructs the transfer of material downstream (Swanson et al. 1982). Sediment budgets show that fluvial processes account for only 10 to 20% of the total sediment yield in low-order channels (Swanson et al. 1982). This suggests that the relative importance of chronic, fluvial transport is low relative to episodic transport by debris flow processes. Sediment stored in first- and second-order channels is re-mobilized episodically when debris flows scour out these low-order channels. As valley floors accumulate sediment over time, the hypothesis can be made that large wood is stored, and at times, buried in these valley floor accumulations. This legacy of wood stored in the channels and valley floors may be an important source of wood to present-day debris flows.

Debris flows that enter third- through fifth-order channels (referred to hereafter as mid-order streams) in the Coast Range commonly create debris flow fans at the mouths of the first- and second-order basins and the streams are often 'forced' toward the opposite hillslope by the debris flow fans. Benda (1990) found that 65 percent of the stream meanders in a fifth-order basin in the Oregon Coast Range were maintained by debris flow fans. In narrow valley floors, Hogan et al. (1995) and Perkins (1989) document the importance of large woody debris dams, originating from debris flows, which completely block the valley floor and result in the accumulation of a large wedge of sediment upstream of the obstruction. Perkins (1989) in a study of four streams in Washington with deposits of seven years old or less, observed that once debris dams were breached the deposit eroded rapidly and 20 to 80% of the initial debris flow deposit volume was removed in less than seven years. The study also showed that sediment from landslides in Salmon Creek, a fourth-order stream with partial bedrock control, had a short residence time due to high bedload transport rates and the breakdown of gravel to suspendable size. Benda (1990) surveyed debris flow deposits in the Oregon Coast Range and estimated the percent of the deposit remaining, and concluded that the erosion rate of the deposit was directly related to drainage area of the receiving channel.

To assess the response of stream channels to debris flows in British Columbia, Hogan et al. (1995) grouped sub-basins using a multivariate procedure that calculates a dissimilarity matrix among sub-basins, based on 14 morphologic and morphometric parameters. This study indicated that the connectivity between hillslopes and stream channels became progressively weaker with increasing valley width. In stream reaches that were hillslope constrained, also termed 'coupled streams' due to the direct connection of hillslopes and the stream channel in the absence of a floodplain, large woody debris jams were formed primarily at the terminus of debris flows that entered the stream channel. In what was termed 'uncoupled stream' reaches, debris flows that originated on steep hillslopes did not reach the stream because of the presence of wide valley floors, and large woody debris jams originated primarily from floated debris. Hogan concluded that in large watersheds with predominately uncoupled stream channels, mass wasting events rarely impact the channels. Thus, large rivers, with extensive alluvial terraces and floodplains isolate the river from direct contact with hillslopes and low-order tributary basins, and limit the direct influence of mass wasting on the main channel (Naiman et al., 1992, and Hogan et al. 1995). However, debris flow deposits stored on valley floor surfaces may act as future sources of wood and sediment to the stream channel during high flows or as a result of channel migration and bank erosion. In such instances, the debris flow deposits function as wood and sediment sources that release material directly to the stream channel at relatively slower rates. The difference in the rate of delivery of wood and sediment to the stream channel may play an important role in the dynamics of the stream channel over time.

Landslide and Debris Flow Processes

Shallow landslides, or debris avalanches, are defined as the rapid downward sliding of unsaturated, unconsolidated soils and forest debris. The distinction between a debris avalanche and a debris flow is whether the mass movement occurs on a hillslope or in a stream channel. Debris flows are defined as the rapid movement of water-saturated soil and debris transported by true-flow processes. Debris flows erode not only the hillslope where the landslides initiate, but also erode the long-accumulated sediment and wood from the valley floors of first- and second- order channels (Benda 1990). Factors that control sediment storage in these channels are the rate of soil production, storage capacity of the channel (strongly correlated to large woody debris), the time since disturbance, and the legacy of past disturbances in the basin.

Forests of the Oregon Coast Range and other areas of the Pacific Northwest have been historically influenced by infrequent, high-severity fire regimes (Agee, 1990). The average recurrence interval of large stand-resetting wildfires in the Oregon Coast Range was found by Agee (1990) to be approximately 200 years. Reeves et al. (1995) noted several aspects of timber harvest related disturbance that differ from stand-resetting wildfires. The primary difference is the legacy of disturbance, where high severity wildfires, unlike timber harvest, were observed to leave large amounts of standing and downed wood (Benda and Dunne, 1997). Other differences include the time between disturbance events, and the difference in landscape pattern of wildfire vs. timber harvest, which changes from a pattern of concentrated disturbance to one of dispersed disturbance (Reeves et al. 1995).

Fire or timber harvest, and the resulting mortality of the forest, lead to an apparent reduction in soil strength due to the decay of root systems (Ziemer, 1981). Ziemer observed that root systems of living forests increase the stability of shallow soils by binding the soil mantle to the underlying fractured bedrock and across potential failure surfaces, in addition to providing interlocking long fiberous binders within weak soil. The vertical decrease in the density of roots may control the depth of the failure plane and strength from lateral roots may determine the size of the failure (Reneau and Dietrich, 1987). However, little is known about the partitioning between vertical anchoring by roots that penetrate fractured bedrock and lateral reinforcement (Benda and Dunne, 1997). The loss of root strength is believed to result in reduced soil strength during the time when the previous root systems decay and the roots of new vegetation become fully established (Ziemer, 1981). If the forest slope is only marginally stable or unstable, landslide frequency often increases after trees are removed.

High intensity spikes of precipitation are hypothesized to trigger shallow landslides when they occur in conjunction with high antecedent moisture conditions (Surfleet, 1997). While forest canopies may theoretically influence the timing and spatial distribution of rainfall arriving at the soil surface, and the subsequent development of positive pore pressure in the soils of landslide-prone sites, this topic has received essentially no research effort. Rainfall that interacts with the overstory and understory canopy may arrive at the soil surface as larger, less frequent drops distributed over a greater length of time. Absence of a vegetative canopy allows all rainfall to fall directly on the soil surface without being attenuated by the vegetation. Although forest canopies may have some potential to dampen high-intensity rainfall spikes, research is required to determine its significance, if any.

The majority of studies on slope stability focus on hillslope characteristics at the initiation site, and research on the downstream consequences of landslides is limited. Research results from landslide inventories for forests, clearcuts, and roads in Oregon, Washington, British Columbia, and New Zealand was summarized by Skaugset (1997). Increased erosion rates (yd^3/acre/year) from clearcuts relative to unharvested forests ranged from 2 to 7 in the Pacific Northwest, and 22 in New Zealand. Erosion rates for roads were from 12 to 343 times greater than adjacent forests in the Pacific Northwest. However, few of these studies were 'ground-based' and thus their results were biased because of the unequal probability of detecting landslides associated with clearcuts and forested hillslopes during aerial photo interpretation. Detection of relatively small landslides under a forest canopy is reduced due to visual obstruction by the canopy. Pyles and Froehlich (1987) indicate that in most cases an air photo inventory of landslides on forest land will underestimate the number of landslides on forest land to a greater degree than for landslides associated with harvesting. This bias would then serve to confirm the hypothesis that management increases landslides, even if there is no difference in the actual landslide occurrence.

Road-related landslides often result in landslide initiation sites relatively high in a basin, or on hillslopes that may not have failed naturally. Benda (1988) observed that road associated landslides often resulted in failure of almost the entire body of colluvium in the hollow and adjacent hillslopes beginning at or near the ridge.

Benda (1988) also found that non-road related landslide volumes showed a high degree of variability, which he attributed in part to the variation in the proportion of the sediment in a hollow that experienced failure. This variation reflects the location of the failure within the hollow, which is directly associated with the depth of colluvium. For example, 14 landslide scars studied by Benda (1988) were located in the lower portion of hollows and contained an estimated 1.5 meters of average colluvium depth.

The lower portion of the hollow is frequently identified as the most landslide-prone portion of the hollow in the present climate (e.g. Benda, 1988). Reneau and Dietrich (1991) studied the upper portion of hollows along road cuts and found that hollows contained an estimated average of 2.7 meters of colluvium. Dunne, (1991) developed a simulation model which predicted that landslides occur less frequently in the upper portion of a hollow and therefore have a greater depth of stored colluvium. Drainage area may also play a role in the portion of the hollow that fails due to its topographic control on the amount of water accumulated in the hollow. It was suggested by Reneau and Dietreick (1991) that an unusually large storm may be necessary to trigger landslides in the upper portion of hollows. The portion of a hollow that fails, and the associated soil depth, may explain some of the observed variability in landslide volumes, and is in need of further study.

Less is known about the likelihood of a landslide propagating into a debris flow in forested basins compared to those with clearcuts and roads. Montgomery and Buffington (1993) noted that debris flows originating at the heads of long, straight channels tend to scour long channel segments, and deliver sediment to downslope alluvial channel confluences. Debris flows that originate in obliquely-oriented tributaries tend to form deposits at channel confluences and increase sediment loading in downslope channels (Benda and Dunne, 1987). Morrison (1975) reported that rates of soil mass movement in clearcuts in the Oregon Cascades were between 2.5 and 5.6 times greater than rates in forested areas of comparable stability. The increased rates of mass wasting in clearcuts was greater for debris flows than for debris avalanches, with the frequency of debris flows increasing as much as 8.8 times. The author speculated that large standing trees and downed wood may play a major role in explaining these differences. Ketcheson and Froehlich (1978) reported that debris flows from clearcuts traveled 1.7 times farther than in unmanaged watersheds. Deposits from debris flows that ran through clearcuts contained 3.2 times more inorganic material and 2.5 times more organic debris than deposits from debris flows that occurred in forested basins.

Run-out distance and the terminal location of debris flows is determined by the properties of the moving mass and the geometry and roughness of the surface the debris flow travels over (Benda, 1988). Parameters that characterize the moving mass include the volume of the debris flow, particle size distribution, water content, and volume of logs at the flow front. Debris flows lose velocity where a channel widens, gradient decreases, direction changes abruptly, or roughness increases (Benda and Cundy, 1990). This is particularly evident where high gradient, hillslope confined, low-order channels enter higher-order channels (for example, a second-order stream entering a fifth-order stream). Higher-order channels in the central Oregon Coast Range typically have wide valley floors, which are low-gradient, often have numerous debris flow fans, and extensive alluvial terraces. Debris flows that enter the active channel of a large river at high flows can become super saturated and travel great distances as a 'debris flood' (Benda, 1985). Benda used the term debris flood to describe a hyperconcentrated flow, that is heavily laden with sediment and large woody debris, which is formed when a debris flow enters a large channel at floodstage. Debris floods may be less common in third- and forth-order streams, which lack the large volume of water required to sustain transport of this material. Debris floods scour less of the bed and concentrate disturbance along the banks and the surrounding riparian area.

Temporal Characteristics of Debris Flows

The history of the basin, including the time since the last mass wasting event, fire, stream-cleaning practices, splash-damming, or other effects of previous land-use practices and geologic events, influences the potential a site has for experiencing a debris flow and the potential magnitude of failure. Both the time since the latest debris flow and the rate of channel recovery are important factors affecting the morphology of channels subject to debris flow processes (Montgomery and Buffington 1993). Hollows and low-order stream channels go through long periods of filling by chronic processes interspersed by infrequent catastrophic failures.

The response of the receiving channel and the resulting habitat development will also change with time. The process of developing high quality habitat and the redistribution of sediment and wood may take decades of centuries to evolve (Reeves 1995). The time elapsed between the presence of favorable habitat conditions will affect the life history adaptations and realized capacities of aquatic communities (Warren and Liss, 1980).

STUDY AREA

Field research was located in the Siuslaw Basin of the central Oregon Coast Range. The Siuslaw Basin extends from the Pacific Ocean to the Coast Range mountains, and is bordered on the east by the Willamette basin. Salmonid species in the Siuslaw basin include chinook (*Oncorhynchus tshawytscha*) and coho (*Oncorhynchus kisutch*) salmon, steelhead trout (*Oncorhynchus mykiss*), sea-run cutthroat (*Oncorhynchus clarki*), and resident cutthroat (*Oncorhynchus clarki*).

The western slope of the Oregon Coast Range has a maritime climate characterized by warm, wet winters, and dry summers. The average annual precipitation is approximately 2100 mm, which occurs primarily as winter rain. Snow is infrequent and seldom persists more than a few days. Strong orographic effects and patchy storm cells produce rainfall intensities and durations that are locally highly variable.

The climatic conditions that often result in winter flooding in the Pacific Northwest are produced by warm, wet weather systems referred to locally as the "Pineapple Express." These systems draw tropical heat and moisture via unusually strong jet stream winds from the central Pacific Ocean northward to the Pacific Northwest, and result in low-pressure systems that produce sustained precipitation, often with high intensities, over several days. These large storms, combined with above-average precipitation can produce widespread wet-mantle conditions with a highly variable distribution of high-intensity rainfall cells (George Taylor, State Climatologist, Oregon State University, personnel communication).

The Oregon Coast Range extends in elevation from sea level to 1220 m (4000 ft). The study basins are underlain primarily by Tertiary marine sedimentary rocks of the Tyee formation (Baldwin, 1964), with localized marine basaltic intrusions. The Tyee marine sedimentary formation is composed of massive, rhythmically bedded sandstones with interbeds of siltstones and mudstones. The sandstone and siltstone layers generally dip to the west and form a pattern of gentle west-facing slopes and short, steep east-facing slopes. The majority of large, deep-seated earthflows have been observed on south and west facing slopes (J. J. Roering, J.J., Department of Geology and Geophysics, University of California at Berkeley, CA, personnel communication; F.J. Swanson, U.S. Forest Service, Corvallis, OR, personal communication) and it appears to be correlated with the direction of the bedding planes. Shallow, rapid failures are hypothesized to occur more frequently on the steeper, more dissected north and east facing slopes that cut across the bedding planes.

The central Oregon Coast Range is comprised of highly dissected low mountains shaped by debris flow processes on slopes of 40 to 120% (Siuslaw National Forest, 1997). The topography is characterized by a dense, dendritic drainage pattern in first- and second-order mountain streams, which drain short, steep hillslopes (Figure 1). These low-order channels drain into large, low-gradient higher-order channels and valley floors. Benda (1988) documented that steep, debris flow prone first- and second-order channels make up 95% of all channels of all orders in this landscape. Therefore, the erosion and sediment storage characteristics of these low-order drainage basins are important to the sediment mass balance of large rivers in the Oregon Coast Range (Benda, 1994).

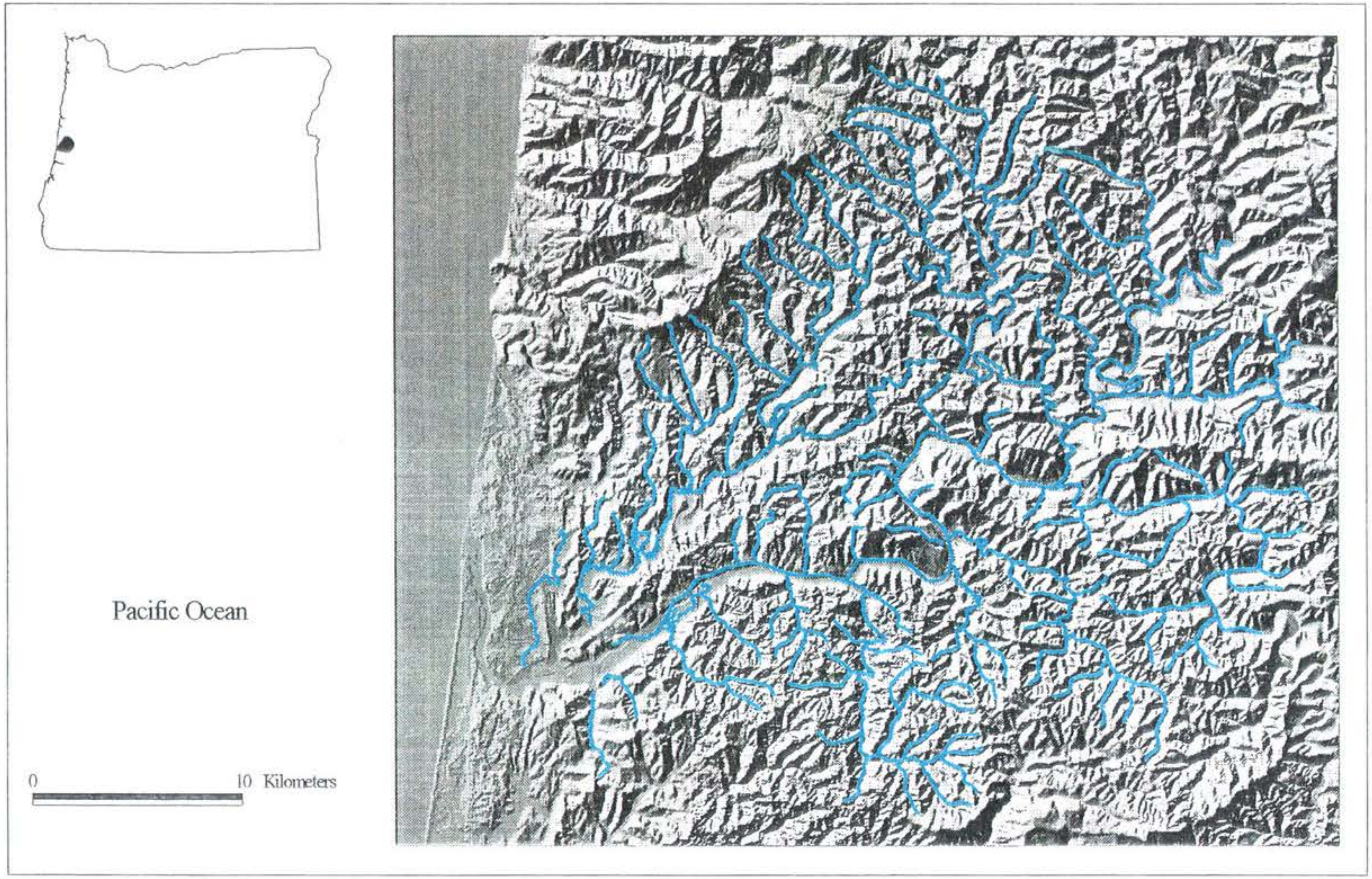


Figure 1. Digital elevation model (DEM) of the Siuslaw River basin.

The soils in the region are well-drained and range from loams to clay loams with generally high nutrient levels (Siuslaw National Forest, 1990). Soils on steep slopes are prone to mass movement, especially during high intensity rainstorms. Rocks produced from the Tyee sandstone are mechanically weak particles that break apart rapidly during transport.

Dense Douglas-fir *(Pseudotsuga menziesii)* forests dominate the central Oregon Coast Range. The climax tree species is western hemlock *(Tsuga heterophylla)*, however, because of major fires in the 1800s and extensive logging in the 1900s, very little climax forest exists today (Siuslaw National Forest, 1990). Most Coast Range forests currently are in a state of relatively young (20-120 years old) Douglas-fir. Red alder *(Alnus rubra)*, typically found along stream systems or areas of recent disturbance, are the most common deciduous species. A heavy ground cover of shrubs consisting mostly of salmonberry *(Rubus spectabilis)*, thimbleberry *(Rubus parviflorus)*, vine maple *(Acer circinatum)*, swordfern *(Polystichum munitum)*, salal *(Gaultheria shallon)*, and huckleberry *(Vaccinium parvifolium)* are present in many areas.

Very little commercial timber harvesting took place in this area prior to World War II, however, after the war, timber harvesting became widespread (Siuslaw National Forest, 1990). Numerous road systems were constructed on steep slopes to access timber stands in the Coast Range and clearcutting was the most common method of timber harvest. The amount of timber harvested annually on the Siuslaw National Forest has decreased dramatically since 1991, however, the amount of timber harvested on adjacent private land remains high. Air photo analysis from the Siuslaw National Forest (1997) Assessment of the Effects of the 1996 Flood classified 29% of this region as conifer stands less than 20 years old, and of these stands, 70% were on private land. All other conifer and broadleaf stands occurred on 65% of the land and the remaining 6% was classified as other (bare ground, water, etc.).

METHODS

Study Site Selection

Study sites were initially selected using a stratified random sample of debris flows detected during 1:24,000 aerial photo interpretation by the Siuslaw National Forest (1997). Sites within the Tyee sandstone portion of the basin were selected in this manner, however, the fact that forested debris flows detected by air photo interpretation were not representative of the overall population became evident when field work began. Dense canopy cover, trees leaning over the landslide and debris flow scars, shadows on steep north facing slopes, and small scale photography result in unequal probability of detection of landslides and debris flows on forested sites compared to clearcut sites. The Oregon Department of Forestry also conducted a ground-based landslide survey in the Mapleton area during this time. They observed that landslides that were less than 2000 m^2 (0.5 acres) in size and under a dense canopy were not reliably detected from air photos, however, identification of landslides larger than 2000 m^2 (0.5 ac) were 'more commonly' detected (Oregon Department of Forestry, unpublished data).

The unequal probability of detection of landslides and debris flows on forested sites had a high risk of biasing the sample by including fewer and larger forested sites in the sample. Therefore, random sampling was not used for the final site selection. In addition, no information is available on the differing inclusion probabilities, so a sampling method that takes into account the unequal inclusion probabilities in order to derive reasonable estimates of population quantities was not available. Instead, the study sites were selected during a ground-based investigation of selected basins.

The ground-based selection procedure identified 36 third- to fifth-order streams with previous stream habitat inventory data (collected by the U.S. Forest Service and Oregon Department of Fish and Wildlife) within the Siuslaw Basin. Third- to fifth-order streams were chosen for this study because first- and second-order streams were believed to be the primary conduit for debris flows, and streams larger than fifth-order were believed to have a greater capability to transport debris flow deposits, thus increasing the uncertainty of the measurements. Streams with previous stream inventory data were selected to give some baseline for previous conditions, however, the rational for selecting streams for the initial stream inventory was not specified.

Stream habitat data was collected during this study using Oregon Department of Fish and Wildlife (ODFW) protocols (Moore et al. 1996) and although the results will not be presented in this document, the data will hopefully allow for future evaluations of broad-scale debris flow induced habitat changes. Streams that met the selection criteria were field-inspected during the early summer of 1996 and any stream with a debris flow that interacted with the stream channel or valley floor was included in the sample. Because of time constraints, not all streams on the list could be investigated, however, researchers at the Mapleton Ranger District had been out on many of these streams recently and were able to provide information on the presence or absence of debris flows. This information was useful for prioritizing streams for the field-investigation. A priority for investigating streams was assigned to basins with mature forests as this category was the most limited.

The selection process ultimately resulted in twelve, third- to fifth-order streams in the Siuslaw Basin that had previous stream survey data available (Figure 2). Only eleven of these streams were used in the analysis because a large storm occurred in November 1996, before the last stream could be surveyed. Including data from this last stream could have biased the results.

Preliminary analysis of the Soil Resource Inventory (Siuslaw National Forest, 1974) showed no apparent bias in landform type by basins in different vegetation classes. The primary difference in vegetation class appears to be associated with land ownership boundaries. The majority of clearcut sites were on private land, the Siuslaw National Forest land is primarily second-growth forest, and Bureau of Land Management land had the largest land base of mature forest.

The site selection procedure resulted in a case study of eleven basins. Previous research on this topic and literature that is extensively used for management decisions are almost entirely based on case studies. While case studies are a valuable tool for gaining insight into processes within selected basins, caution should be taken when extrapolating these results to other areas. Similar results would not be expected in basins with a different climate, underlying geology, drainage network structure, or disturbance history.

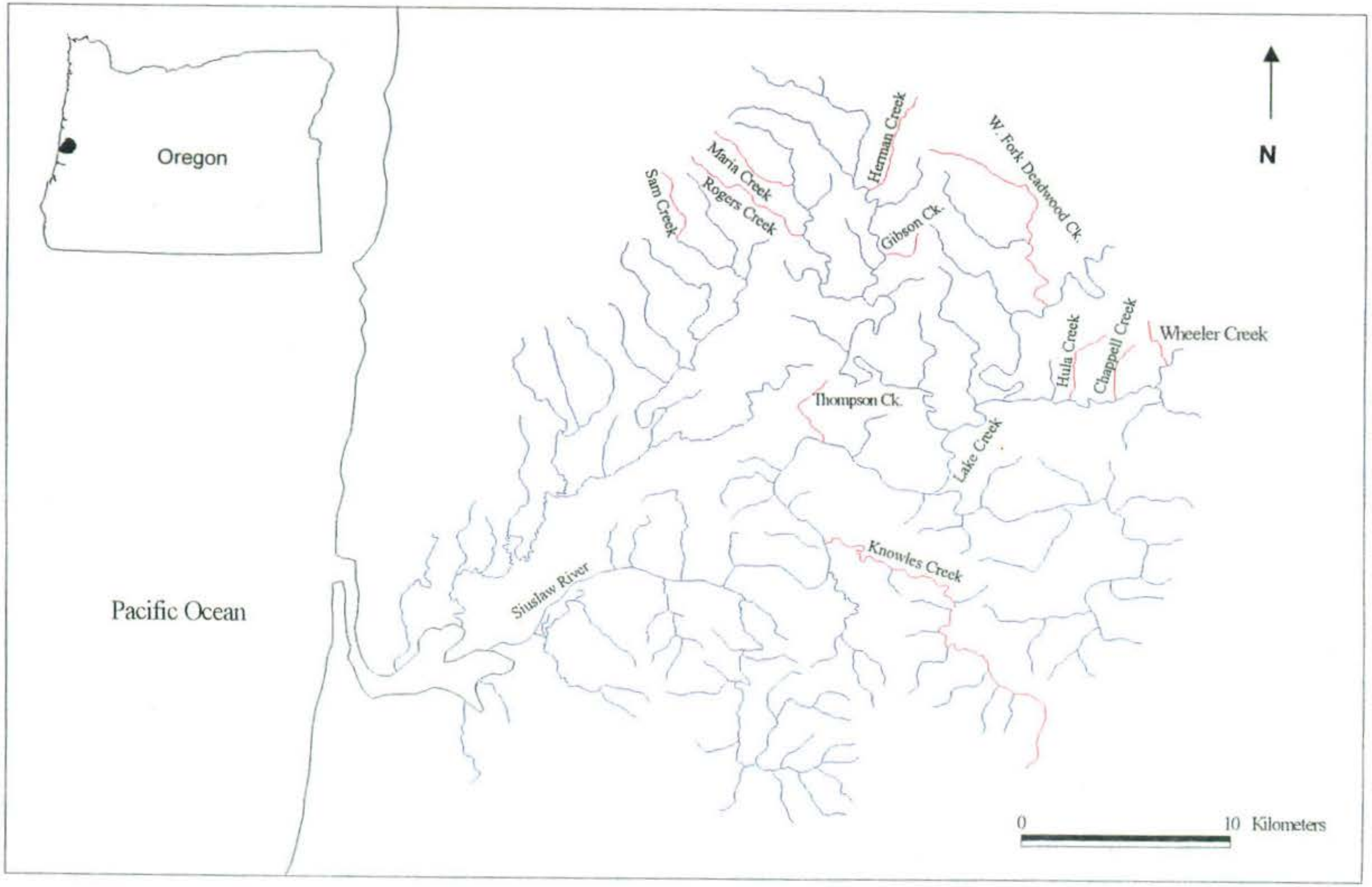


Figure 2. Study site locations for debris flow survey in the Siuslaw River basin.

Data Collection

Debris flows were located during the summer (June – September) of 1996 by walking the selected mid-order streams. All debris flows that were observed from the mid-order channel or valley floor were mapped. Only debris flows from channels that apparently had not experienced large failures prior to the winter of 1996 were included in the sample. Field evidence for previous failures included valley floor deposits with young, even-age vegetation (typically a dense stand of alder less than 10 cm in diameter), deposits in the active channel that were noted on previous stream surveys, and presence of moss on the bedrock of low-order channels suspected of failure. Deposits from previously failed channels were expected to introduce more variability into the sample and further reduce sample sizes by including more categories for comparison. Channels that experienced recent failures were expected to have a reduced volume of stored wood and sediment. Sites that had previously failed were documented on field maps for future research.

During the summer of 1996, ODFW stream inventory protocols (Moore et al. 1996) were used to document the present stream habitat conditions above and below debris flow deposits in the selected mid-order streams. Habitat unit types, morphological reach types, substrate characteristics, large woody debris volumes, and longitudinal profiles were documented. Longitudinal profiles of the stream channels consisted of slope measurements taken with a clinometer at every habitat unit break. In the fall of 1996, all debris flows identified during the initial survey were re-visited to collect data on the debris flows.

Debris flow surveys began at the debris flow deposit and traversed up the runout zone until the initiating landslide scar was encountered. All visible large woody debris greater than 20 cm average diameter and longer than 2 m was recorded. The average diameter and length of the piece were visually estimated and the location of the piece relative to the channel was noted. Due to the amount of wood present in large deposits, poor visibility in large debris jams, and the burial of wood under sediment, the estimated volume of large woody debris is likely an underestimate of actual volumes. Additional uncertainty in estimating the volume of wood in the deposits arose from removal of wood by road crews and the cutting of wood deposited on valley floors, presumably for firewood and construction of habitat structures. For large debris dams, measurements of length, width, and height were also taken for the feature as a whole. The volume of stored sediment in discrete deposits was also estimated. This method was only feasible when large debris dams formed wedges of sediment upstream of the obstruction or when the debris flow deposited on the valley floor. Small debris flow deposits that enter the flow of the main channel, especially deposits which lack large volumes of wood, tended not to leave a discrete deposit that can be measured accurately, and they often experienced a high rate of subsequent fluvial erosion. Uncertainty in these estimates was further confounded by the removal or re-working of this material by road crews.

The dimensions of debris flow deposits were measured using a hip chain; slopes along the debris flow runout path were estimated using a clinometer. Tributary junction angles between the low-order channels and the receiving mid-order channels were taken using compass bearings. The type of debris flow deposit was recorded along with the degree of 'interaction' with the channel. Debris flow deposit types that interacted with the active channel were categorized as debris dams (valley spanning jams associated with an agraded area above the dam), scattered debris jams (characterized by small, scattered debris jams and few discrete accumulations of sediment), or no residual deposit remaining. Debris flow deposits that interacted primarily with the valley floor were classified as existing debris flow fans (deposits that built up existing fans), or new debris flow fans (deposits that created debris flow fans where there was no evidence of one existing prior to this event).

After the primary deposit was measured, the runout zone was ascended and longitudinal segments were delineated at every major morphological change. When long, homogenous runout zones were encountered, segments did not exceed 150 m in length. Each segment was classified as erosional, depositional, or transitional. When multiple landslides coalesced into a single runout zone and debris flow deposit, the longest channel, or the farthest landslide upstream of the receiving channel, was called the 'primary channel'. The additional, contributing failures were called secondary channels and their lengths were included in the 'cumulative runout length'. Runout lengths were measured using a hip-chain along the axis of the runout zone. Because extremely hazardous terrain was often encountered, it was not always possible to travel the axis of the runout zone or the head scarp of the landslide. In these cases, lengths were measured parallel to the failure path or estimated visually.

Three width measurements were obtained at a representative location for each segment (Figure 3). Segments consisted of morphologically similar lengths of channel,

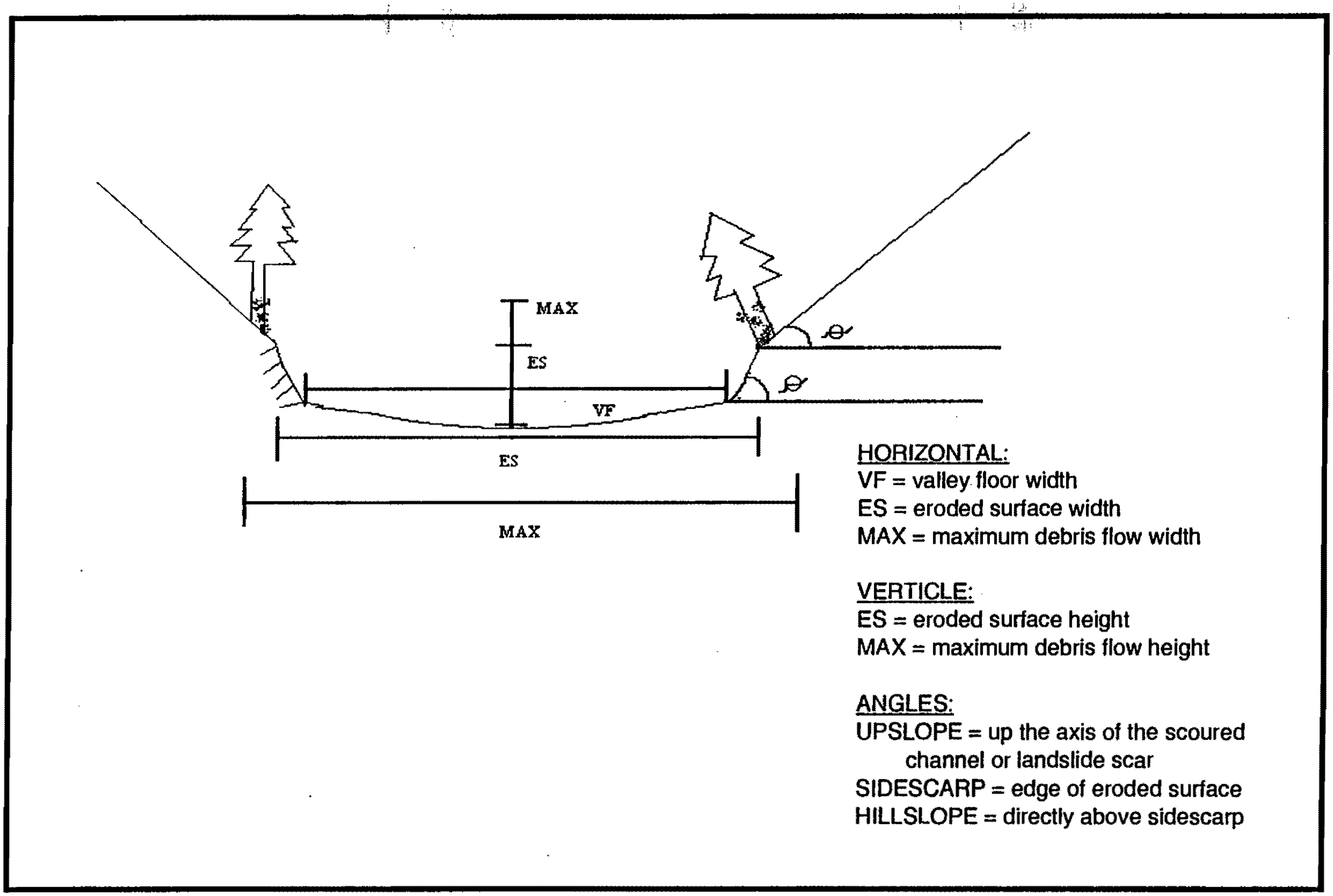


Figure 3. Cross-section measurements taken in the field during surveys of the erosional zones of debris flows.

and the measurement site was considered average for that unit. No measurements were taken on corners or constrictions where the debris flow would be expected to hyper-elevate. The 'valley floor width,' the 'erosional or depositional surface width,' and the 'maximum debris flow width' were measured when possible or estimated when necessary. Height measurements were obtained at the 'height of the erosional or depositional surface' and 'maximum debris flow height'. The heights were measured using a two-meter rod or by visual estimation. Maximum debris flow height and width included the erosion or deposition surface plus any splash zone that was evident beyond the more severely impacted runout zone. Evidence for the maximum width and height was typically found by observing mud lines and tree scars along the perimeter of the runout zone.

Slope measurements were obtained along the axis of the runout zone using a clinometer. Sideslope measurements for both side scarps of the runout path were measured from the edge of the valley floor to the top of the eroded surface. The hillslope angle was measured from the edge of the eroded surface up to the first two meters of the hillslope along the perimeter of the runout zone. The two-meter rod was used as a level with the clinometer set on top of it and the angle measured from the side dial of the instrument. This method was used when it was possible to climb the sides of the runout zone and it was also used to calibrate the observer's eye. Visual estimation was frequently used because of the difficult terrain. Compass bearings were determined at the beginning of each segment along the major trajectory of the axis.

The average diameter at breast height (dbh) of trees along the perimeter of the runout zone was estimated at two locations. The first location was comprised of trees directly adjacent to the perimeter of the landslide and runout zone, the second location was the surrounding forest beyond the direct influence of in-channel processes. The reason for these two measurements was the frequent presence of smaller size trees directly along the perimeter of the landslide and runout zone, which often included a higher proportion of hardwoods. These two measurements were also useful when characterizing situations where streamside buffer zones were encountered in clearcuts. The forest was classified by percent hardwoods and conifers and the percent in 0-20 cm, 30-40 cm, 40-60 cm, 60-80 cm, and greater than 80 cm dbh size classes. Sites classified as clearcuts were those sites where the average dbh was less than or equal to 10 cm when seedlings were present. Sites classified as second-growth forests were those sites that had greater than 75% of the trees along the perimeter of the runout zone between 20 - 50 cm dbh. Sites classified as mature forest were sites with greater than 75% of the trees along the perimeter of the runout zone were greater than 60 cm dbh. All other sites were considered to be mixed forest stands.

Segments classified as depositional were characterized by a net gain in sediment, however, they were commonly both erosional and depositional. The original surface was typically scoured as the debris flow passed and new material was deposited on the scoured surface. Depositional sites were also characterized by the burial of an existing surface under a large load of new material. Depositional segments were further classified as 'agraded' or 'gradually depositing'. Agraded segments were typically found upstream of large quantities of wood or other obstructions which forced storage of a large, discrete wedge of sediment. Gradually depositing segments were all other sections where deposition occurred in the runout zone. These segments were typically low-gradient and near the confluence with the receiving channel. In transitional zones, where the channel appeared to have gained approximately as much sediment as it lost, the segment was not used in sediment volume equations. Erosional segments that experienced a net loss of material, were classified as bedrock or incised. Bedrock segments were scoured to greater than 75% exposed bedrock within the eroded surface width. Incised segments were scoured to a lesser extent and the percent of exposed bedrock was recorded.

Characterization of the landslide initiating the debris flow included the type of failure, dimensions of the failure surface, slope, and aspect. Initiation types included landslides in bedrock hollows, landslides on relatively planar side slopes, large deep-seated earthflows, in-channel failures, and road initiated landslides. Road initiated landslides came directly off of a forest road or road drainage feature, or occurred within 20 m of the road surface. Dimensions of the failure surface included the average length, width, and height of the surface and the percent bedrock exposed.

Calculations for Sediment Volumes

There is a high degree of uncertainty involved when the actual debris flow deposit volume is measured, due to subsequent fluvial transport, therefore, the deposit volume could not be used to back-calculate the volume of sediment eroded from the stream channel as the debris flow passed. Further uncertainty results from the fact that the actual depth of previously stored sediment in stream channels and valley floors that were scoured by debris flows is not known. In light of this uncertainty, a method of approximation was developed to estimate the volume of sediment in the debris flow. The estimated volume from this approximation method should be considered a relative number calculated for comparisons from a consistent method, as there is no way to know the actual value. The estimated level of precision of this method is on the order of tens of cubic meters due to variable conditions in the field, measurement techniques, and the assumptions that underlie the volume calculations.

For estimation of the initiating landslide volumes, the length and average width of the landslide scar was estimated, or measured when possible, and the average sediment depth was estimated from the depth of soil on the surrounding hillslopes and the geometry of the failure. For distinct hollows the method described below for estimating sediment volumes using triangular geometry was applied.

Erosional segments in the stream channels were complicated to measure. For extremely narrow, hillslope constrained, first-order stream channels where extensive valley floor surfaces were assumed absent, triangular geometry was used (Figure 4). The area of the surrounding rectangle was calculated and the volume of the three triangles were subtracted, leaving the area of material in the void, which was then multiplied by the length of the transect to obtain the volume. The area of the oblique triangle (labeled triangle 1 in Figure 4) was calculated by extending the hillslope angles down for the two opposing sides, the base was equal to the width of the eroded surface. With two angles and one side, it was possible to calculate the remaining dimensions using the law of sines. The two right triangles (labeled triangles 2 & 3 in Figure 4) which approximated the sediment stored from the adjacent hillslopes were calculated from the sideslope and hillslope angles recorded in the field. The base of the triangles was calculated by

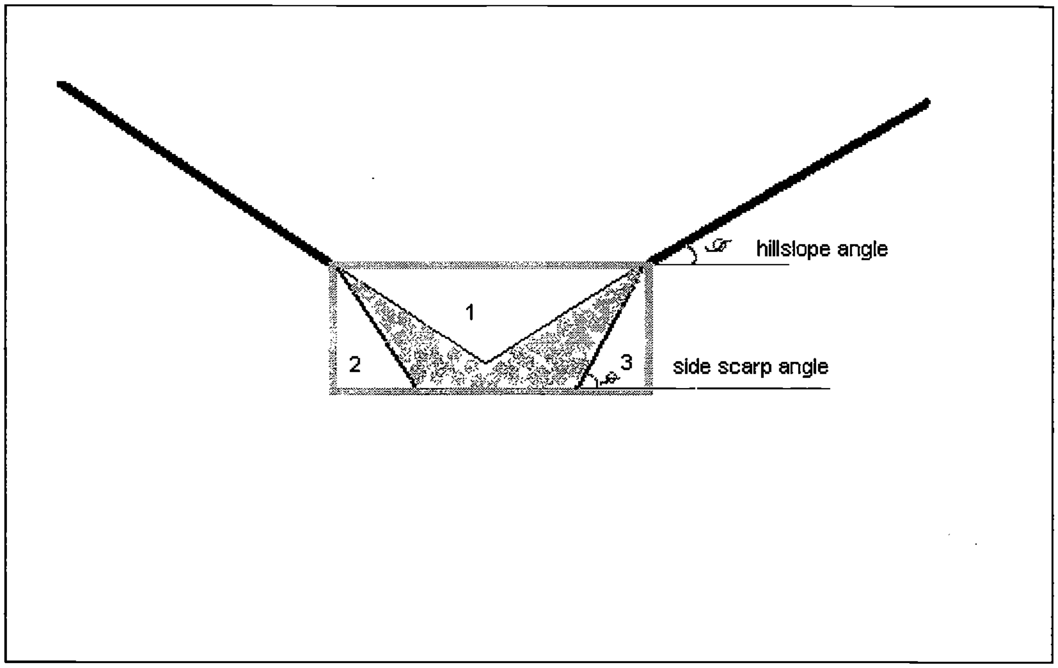


Figure 4. Triangular geometry utilized to estimate the eroded sediment volume from small headwater channels. Shaded area represents the estimated eroded sediment volume.

subtracting the valley width from the eroded surface width and dividing it by two. The height of the triangles was equal to the height of the eroded surface. This method underestimates the sediment storage, by assuming that the volume of sediment in the channel was equivalent to the volume of material that would be present if the hillslope angles were extended down, with out accounting for additional filling of the valley floor. The depth of sediment stored in the void was calculated by subtracting the height of the oblique triangle from the height of the rectangle.

When the estimated depth of stored sediment was less than 0.5 m, a second method for calculation in larger channels was used (see below). A thickness of 0.5 m was used because it was consistent with the minimum depth observed by Benda (1988). The method described above was used for a small proportion of the runout lengths, and was typically used just for short sections of at the head of the basin.

For larger first-order stream channels with wider valley floors, and all second- and third-order channels, the volume of stored sediment was calculated using an approximating ellipse. This change in method is consistent with a change in processes for larger channels where relatively wide valley floors and depositional surfaces are assumed present. Benda (1988) in a study of debris flow runout zones observed that the shape of scoured channels is very close to semi-circular. Field observations during this study are consistent with observations reported by Benda (1988), however, half an ellipse was used for the analysis because it was determined that the semicircle method overestimated the sediment storage in the channel and valley floor.

$$\text{Area} = (2ab\pi)/2$$

$$a = \text{eroded surface width} / 2$$

$$b = \text{eroded surface height}$$

This was especially true for very large debris flows that had eroded surface heights that were extremely high (Figure 5). For these cases the assumption was made that the height represented both hillslope sediment and channel / valley floor sediment. A maximum sediment depth was imposed at a height of two meters, and the width of the ellipse was adjusted to the two-meter height. A correction factor was used for all cross-sections to remove 20% of the estimated elliptical volume for the channel area. An additional weighted correction factor was used for channels that were not scoured to bedrock; this factor was proportional to the percentage of the valley floor not scoured to bedrock.

A method used by Benda (1988) to estimate the sediment volume stored in stream channels was based on field measurements of the maximum thickness of deposits in the centerline of six first-order channels and six second-order channels. The values for first-order channels generally ranged from 0.4 to 2.0 m, however, in one instance a thickness of 3.5 m was measured in a landslide deposit at the base of a hollow. The values for second-order channels ranged from 1.1 to 4.5 m, averaged 2.3 m, and again included measurements of deposits below landslides and debris flows. These larger, discrete accumulations, directly associated with landslide or debris flow deposits are an important component in the sediment storage of low-order channels, however, their spatial distribution is small, and therefore the average values observed over the greater channel

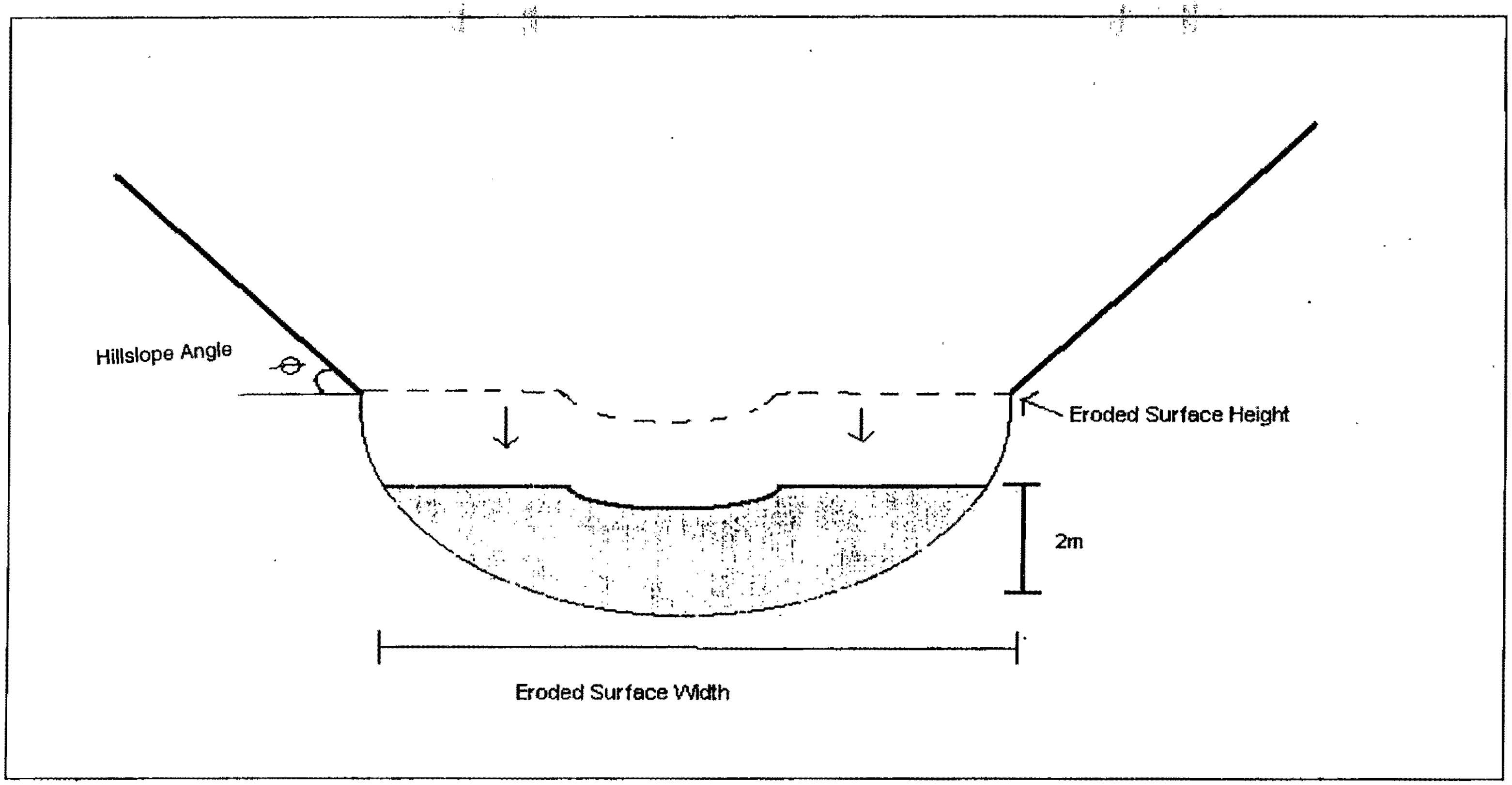


Figure 5. Eliptical geometry utilized for channelized valleys. Diagram shows the maximum height limit imposed at 2m.

length was used in this study. Swanson, et al. (1982) assumed a sediment depth of 1.5 m when estimating transport from a small watershed by debris flow processes.

These assumptions may underestimate the volume of sediment stored in first- and second-order streams because field observations indicated that the eroded surface height was often higher than the previous valley floor surface. Evidence for this was observed in second-order channels where debris flows entered from tributaries and the volume of sediment stored in the channel and valley floor upstream of the debris flow could be observed. The scour line downstream of the debris flow was often higher than the surface that was present upstream of the failure. Using the eroded surface height as a measure of sediment accumulation could greatly overestimate the volume of sediment stored in a channel, thus the height of two meters was selected. If the height of the eroded surface was greater than two meters, the additional sediment depth was assumed to be a relatively thin layer of hillslope sediment and not a thicker valley floor accumulation.

For agraded sections of the runout zone, the volume of a triangular sediment wedge was calculated (Figure 6). The 'base' of the triangle was equal to the height of the debris dam and the 'height' of the triangle was equal to the up-valley length of the sediment wedge measured in the field. This area was multiplied by the average valley width to calculate the sediment volume. For debris flow deposits that did not form a wedge, the average length, width, and depth of sediment spread over a surface was multiplied to obtain a rectangular volume (Figure 7). This latter method was also used for debris flow fans and depositional zones within the failed tributary (Figure 8). For debris flow fans this method will overestimate the sediment volume because the sloping surface of the fan was not accounted for.

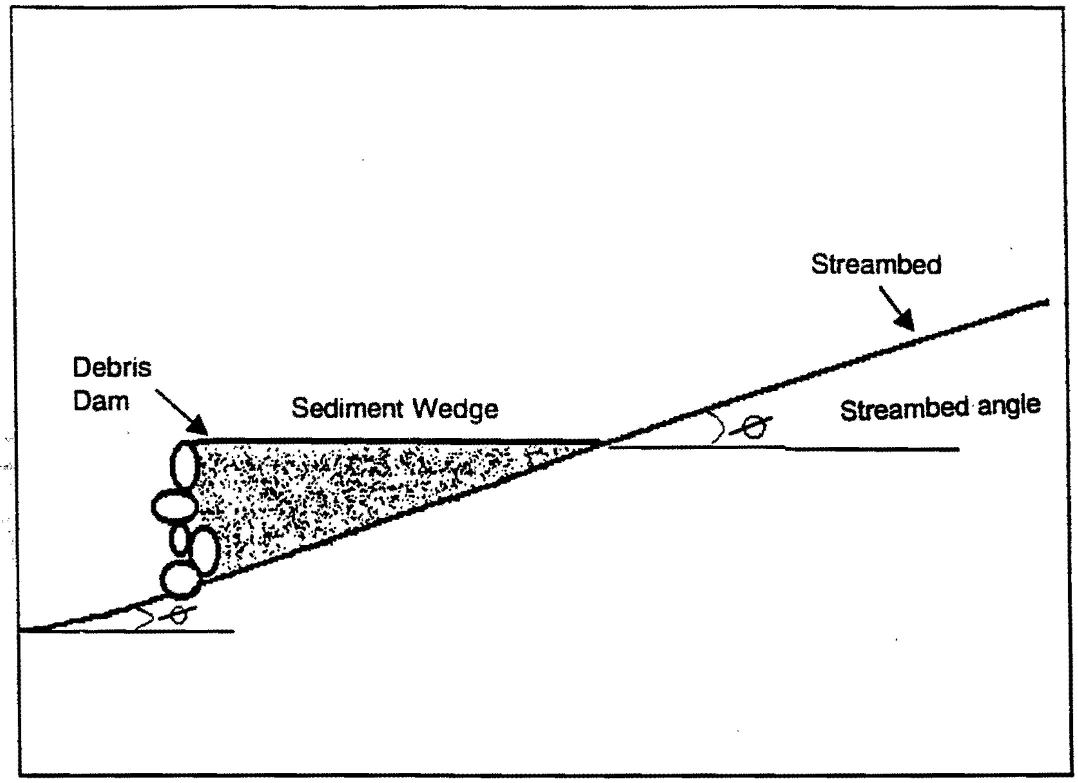


Figure 6. Longitudinal profile of agraded stream reach, volume of sediment wedge calculated using triangular geometry.

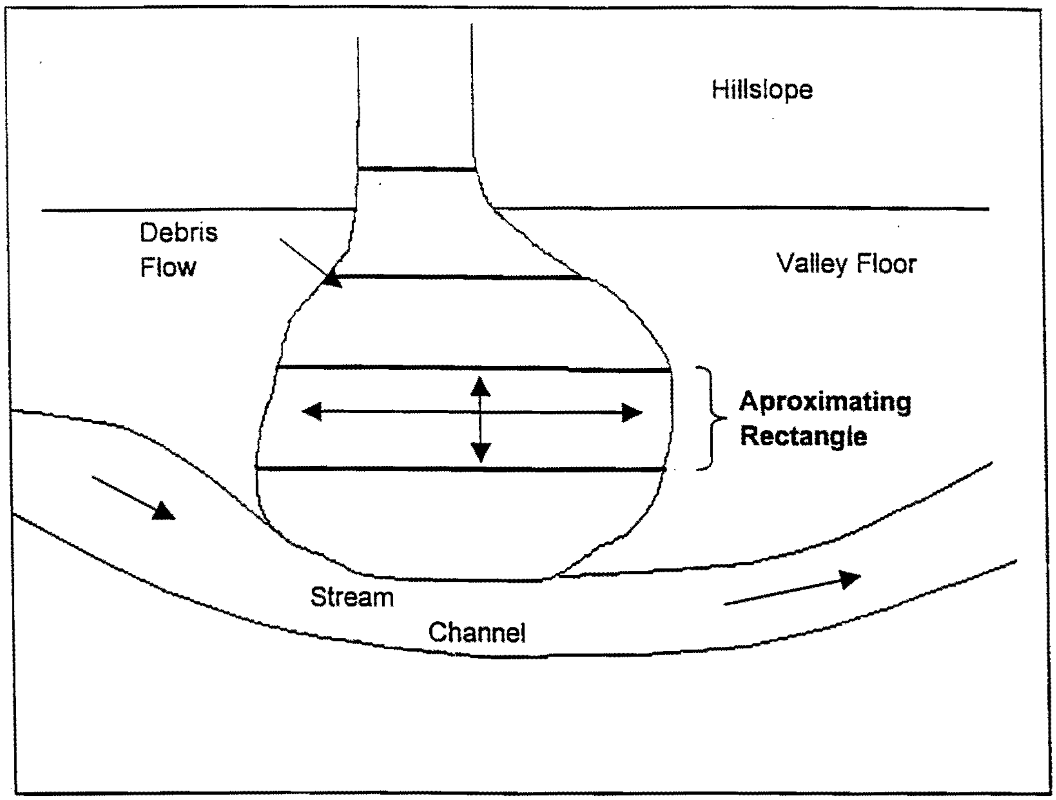


Figure 7. Plan view show approximating rectangle measured in the field to estimate the volume of sediment stored in debris flow fans.

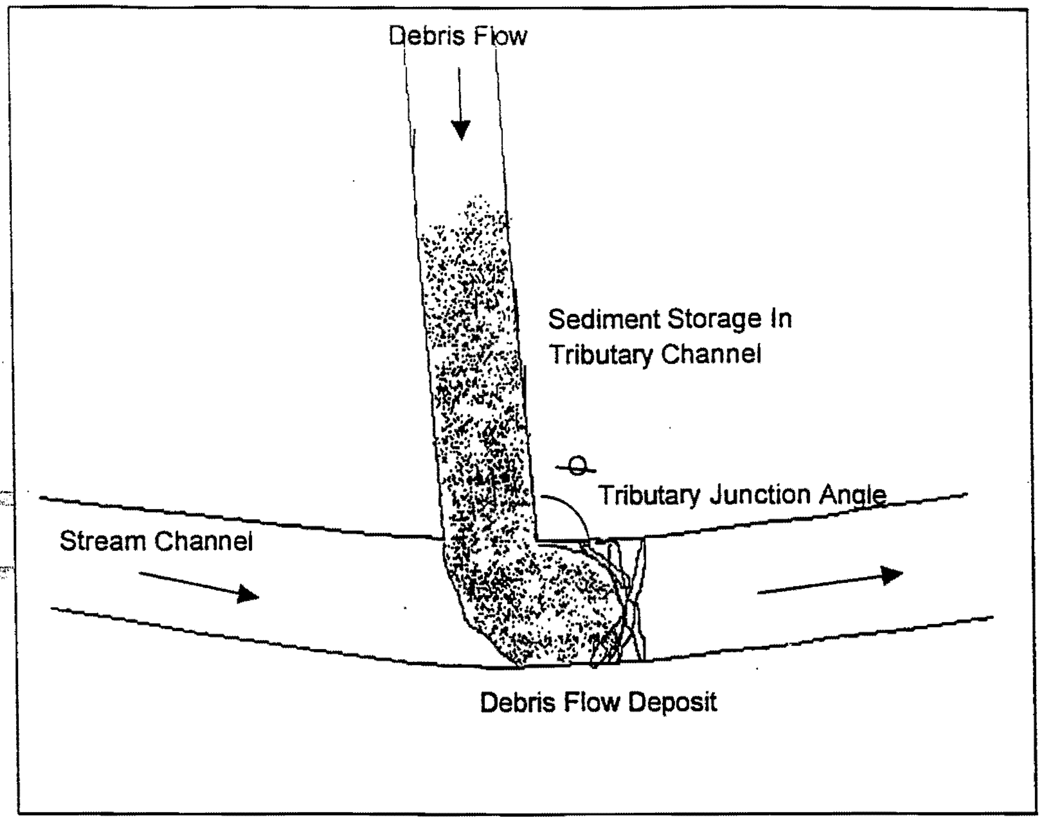


Figure 8. Sediment stored in low-order tributary and not accessible to subsequent fluvial erosion by higher flows in the receiving, mid-order stream. Sediment is backed-up in the tributary as a function of high tributary junction angle, limiting downstream movement of the deposit.

Landslide Density

The number of landslides that contributed to debris flows in the selected study basins were compared to the area of the basin in each vegetation class. The vegetation data was provided by the Coastal Landscape Analysis and Modeling (CLAMS) project at the Pacific Northwest Forest and Range Experiment Station, USFS. This database consists of GIS data created from 1:100,000 scale air photos, with 25 m^2 pixel resolution. The designated vegetation classes in the CLAMS database are currently 10 years old. It was therefore necessary to age the trees in the less than 25 cm diameter trees and 'open' (i.e. clearcut) categories. The area for the less than 25 cm diameter class was included into the larger 25-50 cm category. The area for the 'open' vegetation class was then put into the less than 25 cm category. These changes were made because they were consistent with the size classes of vegetation documented in the field. A hardwood category is also designated in the CLAMS database, however, this was not specifically designated as a vegetation category for this study. The area designated as hardwood vegetation was therefore lumped into the 25-50 cm category. Data on less than 10 year-old clearcuts and roads was not available in the CLAMS database. These features were located on 1996, 1:24,000 scale air photos and the area of clearcuts and additional length of roads was determined. These areas were subtracted from the appropriate vegetation classes to account for the removal of the previous forest stand. Road lengths and densities (length / basin area) were calculated from the GIS database, however, little data was present for roads on the private lands so these values were obtained from the 1:24,000 air photos.

Statistical Analysis

Multiple linear regression was used to analyze the data. Transformations on the natural log scale were common due to the presence of extreme values, which produced skewed distributions. Forward and backward selection methods were used to reduce the number of parameters in the model. Interactions were tested when applicable. Parameters tested in the models are listed in Table 1.

A correlation matrix analysis was performed to test for intercorrelations among all predictor variables, using a pair-wise comparison. Correlations were reported as 'serious' if they had an absolute value greater than 0.5, but did not including the constant term. Multicolinearity causes inflated variance of estimated coefficients and predicted values, increases the likelyhood of having influential points, and the effects of measurement error in any of the explanatory variables is more severe (Ramsey, F. and D. Schafer, 1996). Correlations among variables tends to increase the variance and the addition of numerous explanatory variables increases the R^2 estimate. The number of explanatory variables in the regression analysis was reduced by performing sequential variable selection techniques. Serious multicolinearity was defined as correlations among the predictor variables with absolute values of greater than 0.5 (not including constant term).

Influential points were identified by studentized residuals, leverage values, and the DFITS statistic. Because multiple linear regression is not resistant to statistical outliers, one or two observations can have a strong influence on model results. The studentized residual is a residual divided by its estimated standard deviation (Ramsey, F. and D.

Table 1. List of model parameters for statistical analysis.

Abbreviation	Parameter
CumL	Cumulative Runout Length (m)
Darea	Drainage Area (km^2)*
ErodedCV	Eroded Sediment from the Runout Zone (m^3)
LSC	Longest Single Channel Runout Length (m)
Ninitial	Number of Landslides per Debris Flow
PcCC	Percent of Perimeter of Runout Zone in Clear Cuts
PcLt	Percent of Perimeter of Runout Zone in Mature Forest
PcSg	Percent of Perimeter of Runout Zone in Second Growth
PcYt	Percent of Perimeter of Runout Zone in Young Second Growth
Road	Road Initiated Failures **
TinitV	Volume of all Landslides that Contributed to the Debris Flows (m^3)
TJ Angle	Tributary Junction Angle (degrees)
TwdV	All Large Woody Debris Recorded in the Depositional Zone (m^3)
UpslopeD	Slope of Depositional Zone (degrees)
UpslopeE	Slope of Erosional Zone (degrees)
UpslopeI	Slope of Initiation Zone (degrees)
VWI	Valley Width Index (width of receiving valley / width of failed tributary)

* Drainage area contributing to debris flow above point of deposition.

** Binomial variable, all others are continuous.

Schafer, 1996). Leverage is a measure of the distance between the explanatory variable values and the average of the explanatory variable values in the entire data set (Ramsey, F. and D. Schafer, 1996). It measures the potential a data point has for dictating the location of the estimated regression, because there are no other points in the region. The DFITS statistic estimates the influence of an individual observation on the fitted line of the regression analysis by measuring how much the estimated coefficient would change if an observation was removed from the data set. An observation has significant influence if it has an absolute value of DFITS that is greater than 2 times the square root of the number of coefficients divided by the number of observations, and these values were reported as 'unusually large'.

Kolmogorov-Smirnov two-sample, two-sided test was used to test for differences in the cumulative distribution for LWD length and diameter. Kolmogorov-Smirnov test statistic (D) measures agreement as the absolute value of the largest vertical difference between the cumulative frequency distributions of two samples.

Due to the highly variable topography in the Oregon Coast Range, and the dynamic nature of stream channels and debris flow processes, it is extremely difficult to determine statistical differences between sites. The relatively high variability in statistical results reflects the high degree of variability observed on the landscape.

RESULTS AND DISCUSSION

Population of Debris Flows

A total of 53 recent debris flows from first- through third-order stream channels were surveyed following the winter floods of 1996. These 53 debris flows delivered sediment and wood to 11 third- through fifth-order stream channels. Eleven debris flows initiated and ran through clearcuts, and an additional three debris flows initiated at roads and traveled through clearcuts before depositing in a larger channel. Ten debris flows initiated and ran through second-growth forests (20 – 50 cm dbh), and four additional debris flows initiated at roads and traveling through second-growth forests. Five debris flows initiated and ran through mature forest (>50 cm dbh), and two additional debris flows initiated at roads and traveled through mature forests. Fourteen debris flows ran through a mixture of forested and clearcut patches, and four additional debris flows initiated at roads. Landslides initiated at roads triggered a total of 13 debris flows.

The mixed forest category was difficult to interpret and remains ambiguous. A grand average of 50% of the perimeters were clearcut, 37% had young second growth (20-30 cm dbh), 8% had older second growth (40-50 cm dbh), 4% had mature forest (60-70 cm dbh), and less than 2% had old growth forest (> 80 cm dbh).

Initiation Sites

Landslide Density

The number of landslides that contributed to debris flows in clearcuts had a higher frequency than landslides in mature forests (Table 2). An average of 2.6 landslides per debris flow was observed in clearcuts, compared with 1.6 in mature forests. Debris flows from forested basins never had more than 3 landslides contributing to a debris flow, but debris flows through clearcuts had as many as 9. This higher landslide frequency resulted in a pattern of multiple failures that was not observed in the forest. Road-related landslides also had a large number of landslides per debris flow, with an average of 2.4 landslides per debris flow.

The landslide density was derived by dividing the number of landslides by the area of the basins in each vegetation class (Table 3). A ten-fold increase in the density of landslides from clearcuts was observed relative to the mature forest rate. Landslides in clearcuts also accounted for a disproportionately high number of failures relative to the total basin area. Approximately 24% of the total basin area was in a recently clearcut state, but landslides in clearcuts accounted for 46% of the landslides. Second-growth stands accounted for most of the basin area (47%) and contributed 32% of landslides. Mature forest accounted for 29% of the basin area, but contributed only 6% of landslides. The remaining 16% of landslides were initiated at roads.

Table 2. Landslide density for failures contributing to debris flows in selected tributaries of the Siuslaw River.

Forest Type	Sample Size	Number of Landslides per Debris Flow	
		Average	Range
Clearcut	11	2.6	(1 - 9)
Second Growth	10	1.2	(1 - 3)
Mature Forest	5	1.6	(1 - 3)
Mixed Forest	14	2.1	(1 - 5)
Road Related	13	2.4	(1 - 6)
Total:	53		

Table 3. Landslides per unit area in each forest type for failures contributing to debris flows in selected tributaries of the Siuslaw River.

Forest Type	Tree Diameter (cm)	Area (km^2)	slides / ha	% of Total Area	% of Observed Landslides
Clearcut	< 20	11	4.3	24	46
Second Growth	25 - 50	22	1.6	47	32
Mature Forest	> 50	14	0.4	29	6
Total:		47		100	84*

*Remaining 16% of landslides were road-related failures.

Comparison of landslide densities between forest types requires better topographic context to avoid spurious correlations and warrants further investigation. Without further considering the vegetation classes by slope categories and degrees of convergence it is difficult to confirm that each vegetation class had an 'a priori' equal area of potentially unstable sites. Results of an analysis at this level could be a signature of the vegetation itself or perhaps a signal of how vegetation has been managed over time. The percentage of the area in the study basins that was in an un-managed state (i.e. mature forest) was approximately 25% of the area; this percentage is likely to be high relative to the surrounding basins due to the preferential selection of basins with mature forest patches.

Landslide frequency was higher for roads on public land than private land, however, road densities were substantially higher on the private land (Table 4). Approximately one landslide occurred per every 2 km road length on public lands, and an average or one landslide occurred per 7 km road length on private lands. A comparison of landslide frequency between roads on public and private land is likely to be an unfair comparison without consideration of the position of the road on the hillslope and some critical slope class. A large proportion of roads on private lands were valley bottom roads that have no potential to propagate into a debris flow.

Failure Type

Five types of initiation sites for debris flows were observed during this study (Table 5). Landslides occurred most commonly in distinct bedrock hollows and from relatively planar side slopes (approximately 40% each), however, initiation sites also

Table 4. Road density and landslides per road length in selected tributaries of the Siuslaw River.

	Road Density (km/km^2)	landslides / km road length
Public Land	1.4	0.52
Private Land	3.8	0.14
Average	2.3	0.28

Table 5. Types of landslides that triggered debris flows in selected tributaries of the Siuslaw River.

Landslide Type	Sample Size	%
Landslides in bedrock hollows	38	39
Planar failures on side slopes	39	40
Large, deep-seated earthflows entering streamside	3	3
In-channel failure (no hillslope failure)	3	3
Road initiated failures	15	15
Totals:	98	100

occurred as large deep-seated earthflows that entered stream-side (3%), as in-channel failures with no discrete hillslope source (3%), and road related failures (15%). Much of the literature on landslides in the Pacific Northwest focuses on the role of bedrock hollows as the major producer of sediment. In Benda's 1990 study of the Knowles Creek basin, 78% of the 36 initiation sites were from landslides that occurred in colluvium-filled bedrock hollows and the remaining 22% of failures occurred along relatively planar hillslopes. In this study, landslides from relatively planar slopes had a greater contribution to debris flows.

Reneau and Dietrich (1987) documented the presence of many failures on side slopes which indicate that conditions of sufficiently thick soils and elevated pore pressure can be met in areas of little or no topographic convergence. However, slides from planar slopes may be overestimated in this study due to the difficulty in identifying and defining subtle hollows. Measurements on the angle of topographic convergence are needed to clarify results of this study. The distribution of landslides from planar slopes across the landscape is not known at this time. Further study is warranted to determine the frequency and role of these landslides in local sediment delivery processes and their potential for propagating into debris flows.

The proportion of landslides that originated in hollows or on planar slopes was consistent across vegetation classes. Roughly half the landslides were from hollows and half from planar slopes, with slightly more (57 %) landslides on planar slopes in second-growth stands. Planar failures had a slightly lower estimated sediment volume relative to failures in hollows when comparison is made on the original scale, however, the geometric mean is more appropriate due to skewness in the data (Table 6). Both values

Table 6. Average landslide volume by type of failure in tributaries of the Siuslaw River.

	Landslides in Hollows:				Landslides on Relatively Planar Slopes:			
Forest Type	Sample Size	Average Volume (m^3)	Geometric Mean (m^3)	Standard Deviation (%)	Sample Size	Average Volume (m^3)	Geometric Mean (m^3)	Standard Deviation (%)
Clearcut	19	750	130	35	20	540	210	35
Second Growth	12	760	260	30	16	540	190	30
Mature Forest	4	270	90	40	2	190	90	20
Totals:	35				38			

	Road-Initiated Landslides:				Earthflows:			
Forest Type	Sample Size	Average Volume (m^3)	Geometric Mean (m^3)	Standard Deviation (%)	Sample Size	Average Volume (m^3)	Geometric Mean (m^3)	Standard Deviation (%)
Clearcut	6	1240	720	45	2	775	-	-
Second Growth	7	2800	2040	10	1	7500	-	-
Mature Forest	2	1150	1150	-	0	-	-	-
Totals:	15				3			

are reported in order to make comparisons with other studies. Landslides in the distal portion of hollows and on planar slopes were smallest when they originated in mature forest stands. The unbalanced sample size between mature forests and managed stands makes for a difficult comparison. The increased sample size of landslides compared to debris flows is attributed to the pattern of multiple landslides per debris flow in clearcut basins and due to the increased resolution of landslides from debris flows previously grouped into the mixed forest stand category. Landslides from debris flows that ran through a mixture of forest stand types (i.e. a mixture of forest and clearcut patches) had a total of 41 landslides, 51% were in clearcuts, 32% in second-growth forests, 5% in mature forests, and 11% initiated at roads.

Large, deep-seated earth-flows that entered stream-side to the low-order channel were less common, but delivered large quantities of sediment. These earthflows were excluded from further analysis because of a high potential to bias the results due to the extremely high volumes of sediment. In-channel failures also occurred on a few occasions, and these sites had no hillslope input of sediment and no identifiable mechanism for triggering the debris flow. Road-related landslides had the largest initial volume (excluding the largest earthflow) and occurred most commonly in fill failures on upper- and mid-slope positions.

Magnitude

Landslides that initiated at roads were an order of magnitude larger in size than non-road related failures (Table 7). When the data is analyzed on the original scale,

Table 7. Average landslide volume by forest type for failures contributing to debris flows in tributaries of the Siuslaw River.

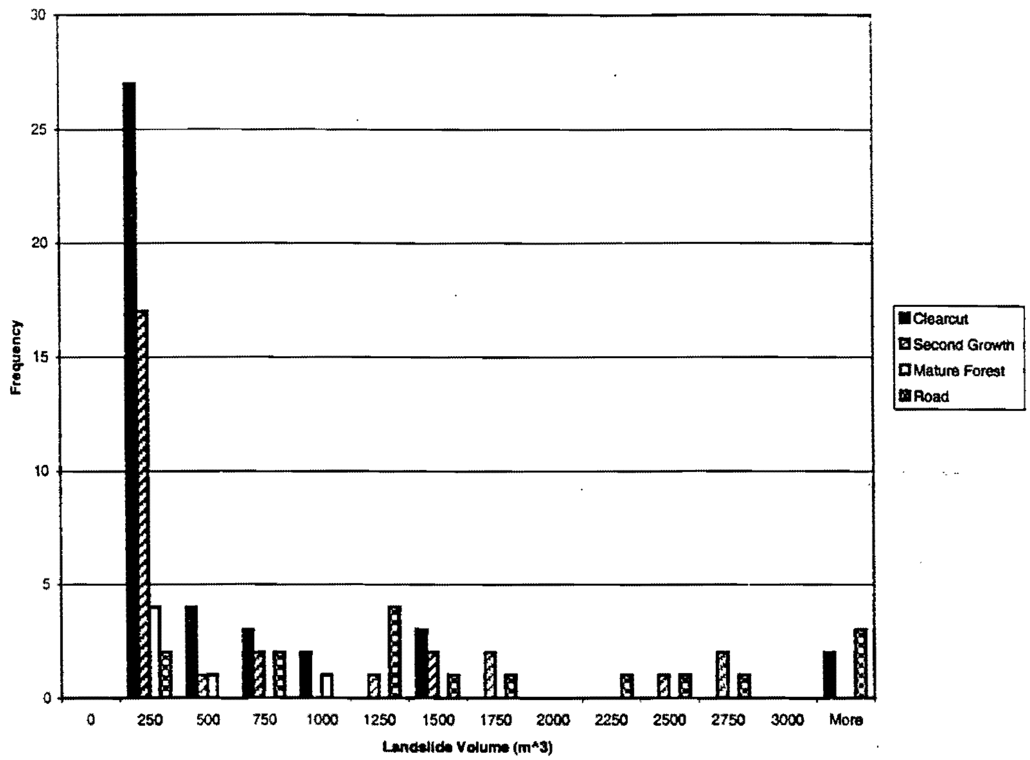
Forest Type	Sample Size	Average Volume (m^3)	Standard Deviation (%)	Geometric Mean (m^3)	Standard Deviation (%)	% of Total Observed Landslides
Clearcut	41	650	260	180	30	46
Second Growth	28	650	130	210	30	31
Mature Forest	6	240	140	90	40	7
Road	15	1970	100	1150	20	17
Totals:	90					100

shallow landslides from both clearcuts and second-growth forests had an average volume of 650 m^3, which was 2.7 times more than the average volume (240 m^3) in mature forests. This study supports the hypothesis proposed by Reneau and Dietrich (1987) which states that the size of the colluvium deposit, and therefore landslide scar size, associated with shallow landslide failures is related to local vegetation. Other results that support this hypothesis were found in Marin County by Lehre (1982) and in New Zealand by Shelby (1976). However, this difference was less distinct when the geometric mean is used to account for skewness in the data (Figure 9 and Figure 10). Using the geometric mean the second growth sites had the highest average sediment volume for the non-road initiated failures. Second growth sites had 2.3 times more sediment than mature forest sites, and clearcut sites had 2.0 times more sediment than mature forest sites. Road related failures were two orders of magnitude larger.

Slope and Soil Depth at Failure

To determine if clearcuts had a higher landslide frequency because of site characteristics, soil depths and slopes at the failure plane were compared. No difference was found in the average or range of slopes at the failure plane when comparing landslides in clearcuts, second-growth, and mature forests. The average slope for shallow landslides was 80% (40°), with a standard deviation of +/- 22%. There was also no difference in the average or range of soil depths at the failure plane when comparing shallow landslides in the different vegetation categories. The average depth was 1.1 m,

(A)



(B)

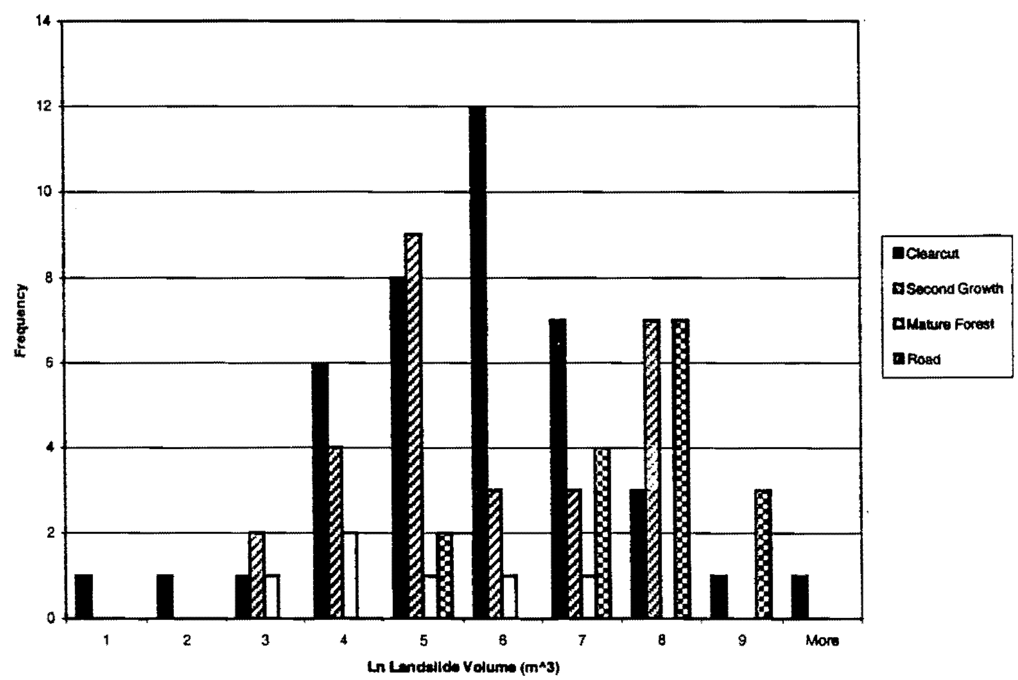


Figure 9. Frequency distributions of landslide volume on the original scale (A) and natural log scale (B).

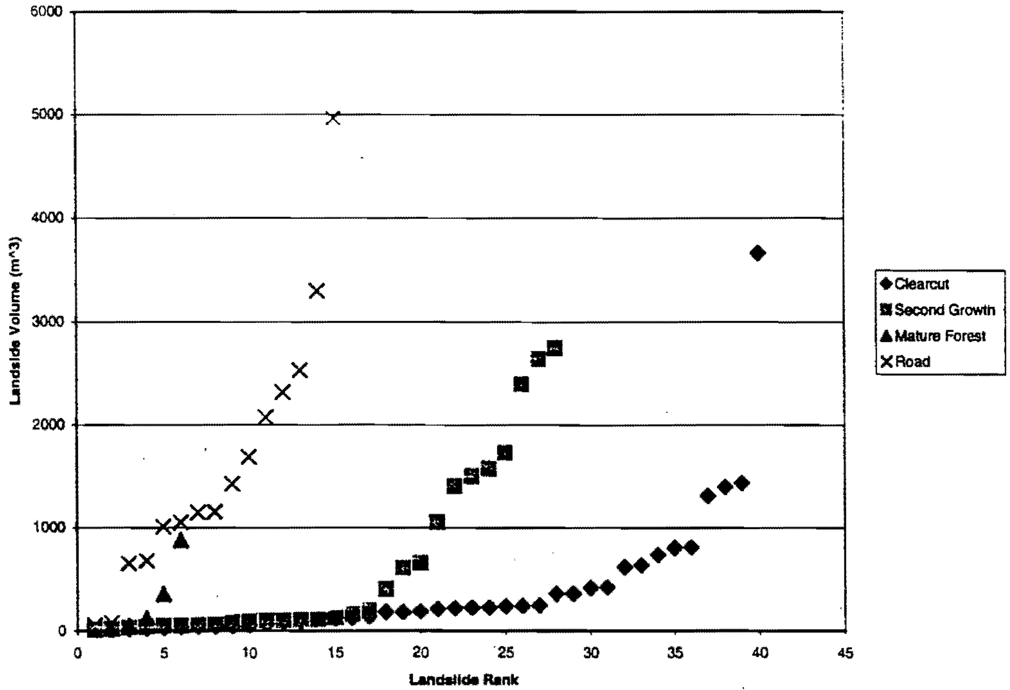


Figure 10. Plot of landslide volume by forest type showing skewness in the data and the presence of extreme values. Landslides are ranked by volume in ascending order.

with a standard deviation of +/- 0.7 m. The relatively large standard deviations reflect the high degree of variability observed in the field.

Another important site characteristic is the drainage area contributing water to the potential failure site. This information could not be derived from field notes because landslides could not be located with enough precision on topographic maps in the field without the aid of GPS equipment. Furthermore, the 1:100,000 scale GIS database would provide little resolution for these zero-order basins.

Aspect

Analysis of the aspect of non-road related, shallow landslides showed that 30% of landslides in clearcuts occurred on north facing slopes (Table 8). Clearcut sites were the only vegetation category that had a distribution roughly equal across the four aspects. The aspect of landslides in second-growth stands was 57% for north facing slopes, and 22% on east facing slopes. This results in almost 80% of landslides occurring on north and east facing slopes that typically cut across the bedding planes. The aspect of landslides in mature forest stands was 50% for north facing slopes, with the remaining half evenly distributed between the other aspects.

Several alternative hypothesis's can be proposed from the pattern of increased failure frequency on north facing slopes. J.J. Roering (Department of Geology and Geophysics, University of California at Berkeley, personnel communication) and F.J. Swanson (U.S. Forest Service, Corvallis, OR, personal communication) both observed that south and west aspects were dominated by deep-seated earthflows, which correlates

Table 8. Aspect of landslides contributing to debris flows in selected tributaries of the Siuslaw River.

Forest Type	North	East	South	West
Clearcut	30%	28%	13%	28%
Second Growth	57%	22%	10%	13%
Mature Forest	50%	17%	17%	17%
All Types:	46%	22%	13%	19%

with the bedding plane dip direction. Therefore it can be hypothesized that shallow-rapid failures would be more common in the strike direction of north and east facing slopes that cut across the bedding plane and may be forming steeper, more dissected slopes. However, the pattern of failures occurring more frequently on north facing slopes is not as prevalent in clearcuts (only 32%), which suggests the vegetative community is important in affecting the spatial distribution of landslides. Therefore, an alternative hypothesis may be that the slightly cooler and wetter conditions on north facing slopes has resulted in a different plant community composition at these sites, such as an increased density of shrubs and hardwoods compared to conifers. Ziemer (1981) showed that soil strength increased linearly as root biomass increased, however, shrubs and hardwood species have smaller but stronger roots than conifers, and this difference in strength may compensate for the lower biomass. The lateral extent of shrub and hardwood root networks is not known, and could be considerably less than large conifers. It is unlikely that evapotranspiration is playing a significant role during these major storm events due to their long duration, high ambient humidity and high intensity. Other alternative explanations, could include wind direction during storms. Wind direction may produce a differential windthrow rate based on aspect, which may interact with landslide initiation processes.

Runout Zones

Longest Single Channel Runout Length By Stream Order

Debris flows that initiated along first-order stream channels and ultimately connected directly to the larger, receiving channels were termed "first-order debris flows", consistent with the terminology used by Benda (1988). First-order debris flows that initiated and ran through clearcuts had six occurrences (43% of all debris flows through clearcuts), second-growth stands had seven occurrences (64% of all debris flows through second-growth) with two additional road initiated failures, mature forest had three occurrences (43% of all debris flows through mature forests), and mixed forest stands had 5 occurrences (33% of all debris flows through mixed forest stands). The runout length, of first-order debris flows range from 30 and 500 m. In the 38 first-order debris flows observed by Benda (1988) the range was from 144 and 480 m.

Debris flows that initiated within a second-order basin, typically initiated at the head of a first-order channel and continued through a second-order channel, and were termed "second-order debris-flows". Second-order debris flows that initiated and continued through clearcuts had two occurrences (21% of all debris flows through clearcuts), plus one road-initiated failure. Second-growth stands had three failure occurrences (36% of all debris flows through second-growth), in addition to two road-initiated failures. Mature forests had two occurrences (57% of all debris flows through mature forest), plus two road-initiated failures. Debris flows that ran through a mixture of forest stands had seven occurrences (50% of all debris flows through mixed forest stands), with two additional road-initiated failures. Runout length, based on the longest single channel length, of second-order channels ranged between 280 and 1270 m. The runout length of second-order debris flows documented by Benda (1988) ranged from 72 to 720 m. Second-order debris flows from clearcuts and mixed forest stands frequently had multiple failures that resulted in greater cumulative runout lengths and the formation of larger debris flow deposits relative to mature forest sites.

Debris flows that initiated along first-order channels and continued through a second- and third-order channel, or initiated in a first-order channel that connected directly to a third-order channel, were termed "third-order debris flows". Third-order debris flows that initiated and ran through clearcuts had three occurrences (36% of all debris flows through clearcuts), plus two road-related landslides. Third-order debris flows that ran through a mixture of forest stands occurred twice (17% of all debris flows through second-growth), plus 2 additional road-related landslides. No third-order debris flows were observed in completely forested basins. The runout length, based on the longest single channel length, of third-order debris flows ranged from 520 to 1710 m. Third-order debris flows documented by Benda (1988) ranged from 240 to 720 m. Third-order debris flows have a high potential to accumulate sediment and wood because of the increased travel distance and the higher probability of large volumes of sediment and wood stored from previous first- and second-order debris flows that did not propagate downstream.

Debris flows observed by Benda (1988) never exceeded 720 m in runout length. Debris flows that ran through forested basins in this study never exceeded 790 m, however, four debris flows that initiated and ran through clearcuts exceeded this value slightly (ranging from 810 to 1030 m). Also, debris flows that initiated and traveled through mixed forest stands had five occurrences, ranging from 960 to 1710 m in runout length. The above mentioned debris flows, nine in total, all exceeded the range in runout length observed in completely forested basins.

Longest Single Channel Runout Length

The runout length discussed in this section accounts only for the longest single channel runout length of the debris flows and does not include the total length of stream channel affected by multiple landslides within the basin (Figure 11). Thus, the average runout length was calculated by transforming the data to the natural log. The data was skewed by numerous small failures and infreqeunt large failures. After transformation the data had a relatively normal distribution; the values reported here and in Table 9 have been backtransformed for ease of interpretation and are referred to as the geometric mean.

The runout distances documented in this study are the expression of the potential a basin has for propagating a debris flow in a low-order channel until it reaches a depositional environment in a higher-order channel. Debris flows in first- and second-order stream channels in this portion of the Coast Range rarely travel more than 50 m beyond the tributary junction with a third- or forth-order channel. The valley floors of third- and higher-order streams are typically wide, low-gradient, and promote deposition quickly. The measurement of runout length included this limited travel distance in the mainstem when discrete deposits were present. Where only minor deposits formed or

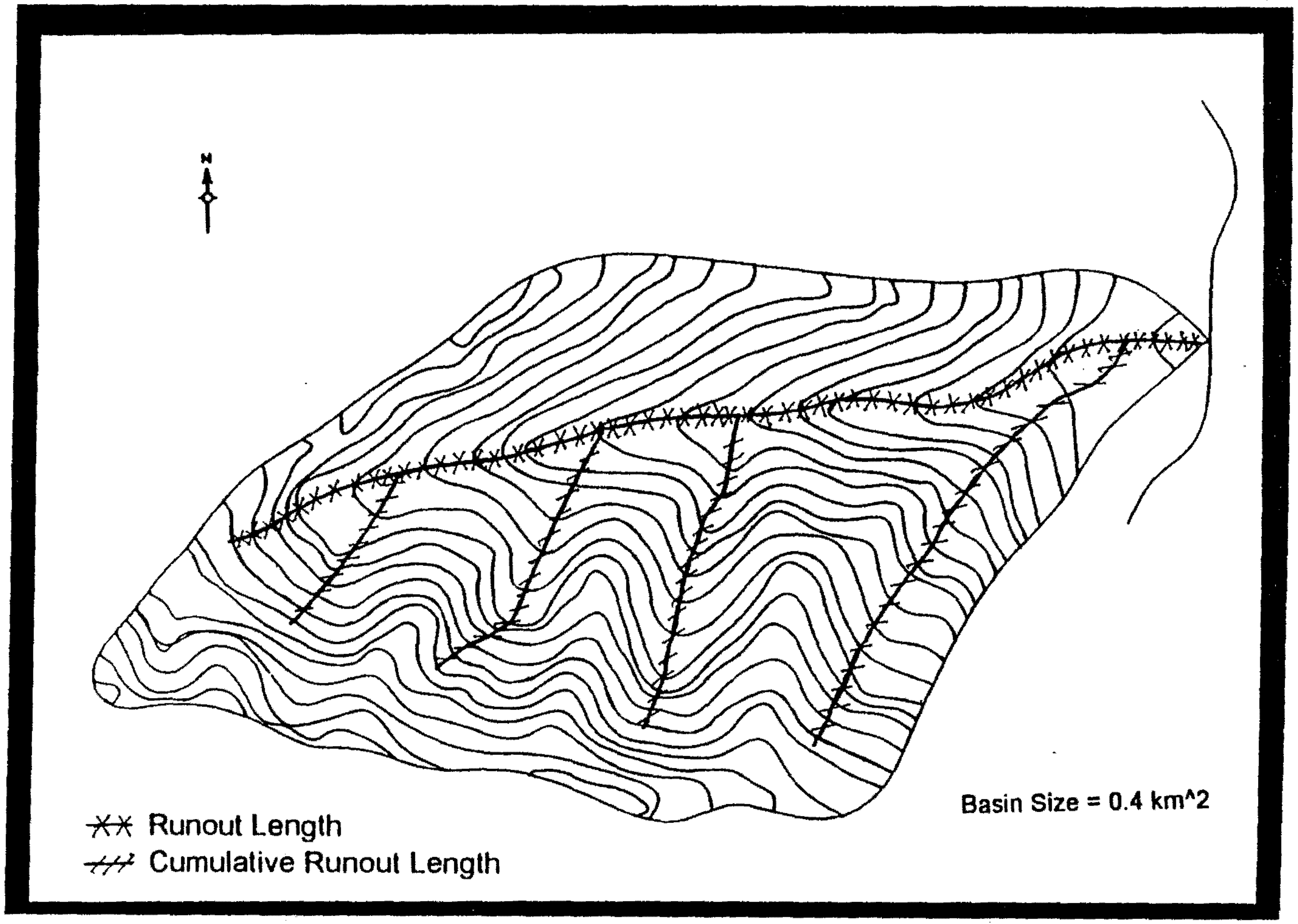


Figure 11. Topographic map of low-order basin that experienced multiple failures. The longest single channel runout length is represented by cross-hatched lines and the cumulative runout length is distinguished by slanted lines (this distance includes the slanted lines and the cross-hatched lines). The asymmetrical shape of the basin is common in this region.

scattered debris jams accumulated downstream, the runout length ended at the tributary junction due to likelihood of fluvial transport of these small deposits that entered a larger stream at floodstage. The runout distance of debris flows in this study is based primarily on the distance of the initiating landslide to a mid- or higher-order stream/valley floor, this distance is therefore controlled by the structure of the drainage network. Debris flows that deposited within the low-order channels were not detected by this study.

The average runout length, considered here to be the longest single channel, or primary channel of the debris flow, if multiple failures were present, was longest for debris flows through mixed forest stands. The mixed forest category, which consists of debris flows that initiated and traveled through a mixture of forest and clearcut patches, is difficult to interpret because a debris flow that travels farther has a higher probability of running into different forest or clearcut patches. Runout length was plotted against the percent of the perimeter that was forested and no relationship was evident. For debris flows that initiated and ran through a consistent forest type, the runout length was longest for debris flows in clearcuts and second-growth forests, and decreased in mature forests (Table 9). Debris flows that initiated at roads were the longest runout paths observed and traveled an average of 3.0 times farther than debris flows through mature forests.

Table 9. Longest single channel runout length for debris flows in tributaries of the Siuslaw River.

Forest Type	Sample Size	Geometric Mean of Runout Distance (m)	Range (m)	Standard Deviation as Per Cent of Mean Value
Clearcut	11	280	30 - 1030	20
Second Growth	10	290	110 - 800	11
Mature Forest	5	190	40 - 700	20
Mixed Forest	14	460	110 - 1700	13
Road Initiated	13	580	160 - 1430	8
All Sites	53	370		15

A multiple linear regression analysis was performed with the full model (Model #1) including the following variables (see Table 1 for list of abbreviations):

Model #1 Ln(Runout Length) = 6.483 - 0.009*Road + 0.505*Ln(Darea) – 0.039*Ln(TwdV) - 0.013 * PcLT + 0.003*PcSG + 0.000*PcYT + 0.005*Tj – 0.005*UpslopeD - 0.002*UpslopeE - 0.001*UpslopeI - 0.001*VWI

The significant associations in this model (at the 0.05 level) are:

constant (non-rd, PcCC)	p-value 0.00	+ coefficient
Ln(Darea)	p-value 0.00	+ coefficient
PcLt	p-value 0.00	- coefficient
Ln (Total Wood Volume)	p-value 0.00	+ coefficient
TJ angle	p-value 0.02	+ coefficient

Model #1 accounted for 83% of the observed variability (adjusted R^2), and had a standard error of 0.34. A correlation matrix was calculated and no correlations with an absolute value > 0.5 were detected between the predictor variables, however, it is logical to assume that the wood volume in the deposit is largely controlled by the debris flow's potential to accumulate wood as it travels. Therefore, the runout length and total wood volume should be highly correlated variables and may affect the results of this model. Outliers were identified by studentized residuals with an absolute value greater than 2.0, leverage values greater than 3 times the average data point, and with unusually large

DFITS values relative to the number of coefficients and the number of observations. Three data points were identified as potential outliers using this criteria. The analysis was run without these points without causing significant changes to the model results, so the potential outliers were left in the dataset. A debris flow initiated by a massive earthflow was removed from the dataset for the regression analysis because it involved a different process and had a large degree of influence on model results.

A forward and backward selection process for variable selection was run to produce a model with fewer variables (Model #2). Both processes selected the same model with all variables significant at the 0.05 level:

Model #2 Ln(Runout Length) = 6.324 + 0.508*Ln(Darea) + 0.164*Ln(TwdV) – 0.013*PcLT + 0.005*TJ - 0.008*UpslopeD

Standard Error: 0.33

Model #2 of the multiple linear regression analysis determined that 83% (adjusted R^2) of the variability in runout length was accounted for by drainage area of the low-order basin, total wood volume, and the tributary junction angle. These parameters were associated with an increase in the runout length. An increase in runout length was apparently associated with an increase in the tributary junction angle due to the structure of the drainage network. Tributaries with low junction angles tended to be shorter than tributaries with high junction angles, and does not suggest that debris flows are traveling farther beyond the junction. The percent of the perimeter of the debris flow runout path that was in mature forest was associated with a decrease in the runout length. The slope of the depositional zone became significant in Model #2 when fewer parameters were included than in Model #1. An increase in slope of the depositional zone was associated with a decrease in runout length. This reflects the gradual deposition in tributaries before entering a low-gradient valley floor of a larger channel.

Cumulative Runout Length

The term cumulative runout length will be used to describe situations where multiple landslides coalesced into a larger debris flow, which formed a single deposit. This distance consists of all contributing landslides and debris flow affected channels that occurred in a low-order basin (Figure 11). For example four first-order channels may contribute to a single second-order debris flow. The cumulative runout length is important for determining the sediment and wood contributed to the debris flow deposit by this additional channel length, and for quantifying the portion of the drainage network affected by debris flows. The runout length documented in the previous section only considered the longest single channel.

A decreasing trend in the average cumulative runout length is evident when comparing debris flows that initiated and ran through forested to non-forested channels (Table 10). The maximum cumulative length of debris flows that initiated and ran through clearcuts is an order of magnitude larger than the maximum cumulative length for debris flows that initiated and ran through forested channels. The cumulative runout length in clearcuts is also twice the distance of the longest single channel runout length for the same basins. The additional runout length contributed by numerous initiating

Table 10. Cumulative runout length of debris flows in tributaries of the Siuslaw River.

Forest Type	Geometric Mean of the Cumulative Runout Distance (m)	Maximum (m)	Standard Deviation as Per Cent of Mean Value
Clearcut	450	2190	16
Second Growth	300	960	11
Mature Forest	200	860	18
Mixed Forest	590	1700	13
Road Initiated	690	2130	10
All Sites:	490		14

landslides and scoured first-order channels can therefore double the length of channel affected.

The pattern of multiple failures associated with clearcuts produced the largest deposit volumes because of the increase in the channel length affected, and therefore an increase in the potential for the debris flow to accumulate sediment and wood as it traveled. A deviation in cumulative runout length from the longest single channel runout length is evident in Figure 12. The two measures of runout length are well correlated for debris flows that initiated and ran through forested channels, but debris flows through clearcuts and a mixture of forest and clearcut patches show an obvious deviation from this pattern.

No debris flows through forested basins exceeded 960 m in cumulative runout length. Debris flows through clearcuts had 32% of all observed debris flows exceeded 1000 m in cumulative runout length, ranging from 1020 to 2190 m. The cumulative runout length for debris flows through mixed forest stands had 22% of all observed debris flows exceed 1,000 m, ranging from 1710 to 2130 m. For road initiated debris flows, 30% had a cumulative runout length that exceeded 1000 m, ranging from 1200 to 2100 m. Debris flows of this magnitude may be outside the range of natural variability when compared to debris flows in mature forests. But the forests of the Coast Range are dynamic and historically have undergone large, stand resetting fires. These fires may have played a role in triggering high magnitude debris flows if a large storm occurred when the forests were in a more sensitive state. A pattern of multiple failures was observed in air photos of the Tillamook basin, which experienced a large stand

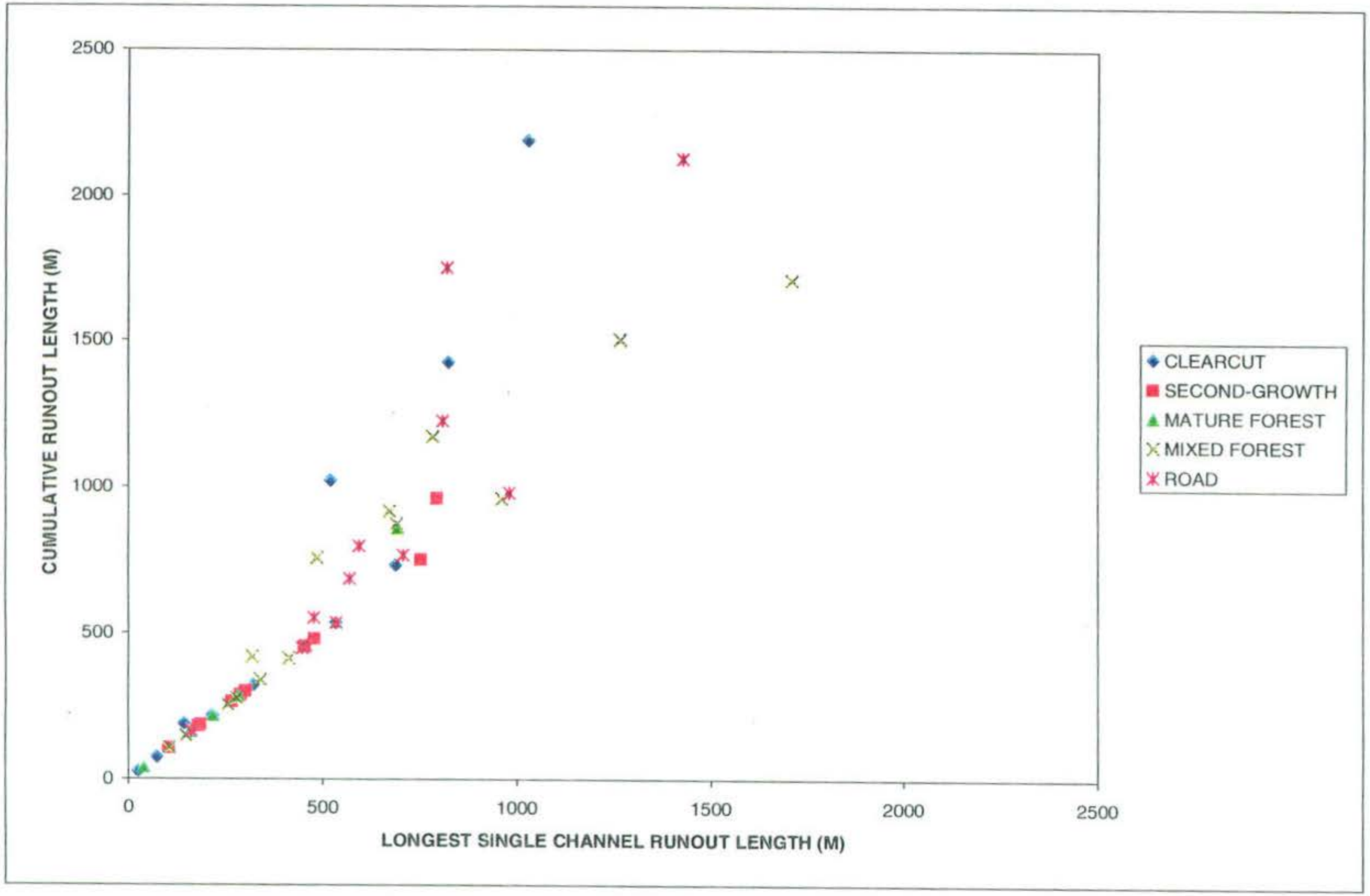


Figure 12. Longest single channel runout length plotted against the cumulative runout length for debris flows in tributaries of the Siuslaw River.

replacement fire followed by a large storm. Large volumes of standing dead and down wood were present on the slopes, but canopy cover was absent after the fire. Based on air photo interpretation, Benda and Dunne (1997) indicated rates of 30 or more failures per 100 hollows following the Tillamook burns.

Another confounding variable in this study is an unequal drainage area in the study basins (Table 11). Clearcut basins had a larger average drainage area than mature forest basins. Two explanations can be suggested. First, mature forest basins are small and discontinuous on the current landscape, however, upon examination of the air photos this does not appear to be the case. Second, clearcuts may be associated with debris flows that travel farther and therefore incorporated larger drainage areas. This larger drainage area for clearcut basins has the potential for a greater water content in the debris flows and a greater number of potential sites to fail. Examination of the range of drainage areas shows that the minimum drainage areas are similar among forest types, but road-related landslides were occurring in slightly larger basins. The maximum drainage areas for clearcuts, mixed forest stands, and road related debris flows is approximately double the maximum drainage area for mature forests.

A multiple linear regression analysis was performed with the full model (Model #3) including the following variables (see Table 1 for list of abbreviations):

Model #3 Ln(CumL) = 6.616 - 0.012*PcLt -0.000*PcSg + 0.000*pcYt + 0.125*Ninitial + 0.480*LnDarea - 0.054*Ln(TinitV) + 0.205*Ln(TwdV) - 0.054*Ln(TinitV) + 0.001*UpslopeE + 0.006*UpslopeD - 0.000*UpslopeI + 0.043*Road

Table 11. Drainage area of basins that experienced debris flows in the Siuslaw River.

Forest Type	Average Drainage Area (km^2)	Minimum (km^2)	Maximum (km^2)	Standard Deviation (km^2)
Clearcut	0.13	0.01	0.47	0.16
Second Growth	0.10	0.01	0.33	0.12
Mature Forest	0.07	0.01	0.23	0.09
Mixed Forest	0.18	0.02	0.44	0.14
Road Initiated	0.24	0.06	0.61	0.18
All Sites	0.16			0.16

The significant associations in this model (at the 0.05 level) are:

Constant (non-road, PcCC)	p-value 0.00	+ coefficient
Ln (Darea)	p-value 0.00	+ coefficient
PcLT	p-value 0.00	- coefficient
Ln(TwdV)	p-value 0.00	+ coefficient
Ninitial	p-value 0.01	+ coefficient

This model accounted for 87% of the observed variability (adjusted R^2 value) and had a standard error of 0.34. A correlation matrix was calculated and no correlations with an absolute value > 0.5 between the predictor variables was observed. However, it is logical to assume that the total wood volume in the deposit is largely controlled by the debris flow's potential to accumulate wood as it travels. Therefore, the runout length and total wood volume should be highly correlated variables and may affect the results of this model. Outliers were identified by studentized residuals with an absolute value greater than 2.0, leverage values greater than 3 times the average data point, and with unusually large DFITS values (absolute value < 0.6). Four data points were identified as potential outliers using this criteria. One debris flow that was initiated by a massive earthflow was removed from the model because it involved a different process, and had a large degree of influence on model results. The analysis was run without the other potential outliers without significant changes to the model results. Therefore, three of the potential outliers were left in the data as no reason could be established for their removal.

Forward and backward variable selection methods were run to reduce the large number of explanatory variables in the model. Both methods selected the following model:

Model #4 $\quad Ln(CumL) = 6.141 - 0.012*PcLt + 0.088*Ninitial + 0.458*Ln(Darea) + 0.218*Ln(TwdV)$

Standard Error: 0.34

All variables in Model #4 were significant at the 0.02 level of probability and the model accounted for 87% of the observed variability in cumulative runout length (adjusted R^2). The significant parameters in Model #4 were the drainage area of the low-order basin, total wood volume, and the number of landslides contributing to the debris flow. These parameters were associated with an increase in the cumulative runout length. The percent of the perimeter of the runout path that was in mature forest was associated with a decrease in the cumulative runout length.

Slope

To address the question of whether debris flows are more erosive or less erosive if they travel through a forested vs. clearcut riparian area, the slopes of the erosional and depositional zones were compared. A consistent pattern of erosional zones accounting for 75% of the runout length, and depositional zones accounting for 25%, was consistently observed. This pattern was consistent across and within vegetation categories. The average slope of the erosional zone was 50% regardless of forest type and may be controlled by the structure of the drainage network. The average slope of the depositional zones was slightly higher for debris flows through clearcuts (20%) compared to debris flows through second-growth (15%) and mature forests (13%). Depositional zones in mixed forest stands had an average slope of 17%.

Debris flows from first- and second-order channels tended to scour short, steep tributaries that deposited abruptly on the receiving valley floor. Debris flows from larger second- and third-order channels tended to deposit more gradually due to a less abrupt change in slope when the receiving valley floor was encountered. This may account for the change in depositional slopes between the different forest categories.

Eroded Channel Sediment

Because of the high variability in the runout length, which is highly correlated to sediment and wood delivery, estimates were normalized to volume per meter. The average volume of sediment eroded from the channel was divided by the length of runout in erosional zones of the debris flow (not including initiation site). This value was used to determine the volume of eroded sediment per meter length of travel and therefore account for the variability in runout length. The average volume of sediment mobilized from eroded stream channels was greatest for debris flows through mature forests and debris flows initiated at roads (Table 12). Road-related landslides had a large average volume and the highest maximum volume of eroded sediment. Road-related landslides often originated in high slope positions, and debris flows produced a wider cross-

Table 12. Average volume of sediment eroded from low-order stream channels scoured by debris flows in selected tributaries of the Siuslaw River. Volume estimates scaled to length of the erosional zone of the runout path.

Forest Type	Sediment Volume per Channel Length (m^3/m)	Minimum (m^3/m)	Maximum (m^3/m)	Standard Deviation (m^3/m)
Clearcut	5.7	1.0	11.9	3.6
Second Growth	5.2	0.7	12.1	4.3
Mature Forest	8.3	7.0	10.3	1.4
Mixed Forest	5.1	1.3	12.1	3.0
Road Initiated	8.2	1.0	24.4	6.7
All Sites	6.3			4.6

sectional area that scoured the stream channel and surrounding toe-slopes. Sediment accumulations and soil depth were often thickest in channels that were scoured by road initiated debris flows, suggesting these channels were less likely to fail without the presence of the road.

The average estimated volume of sediment eroded from stream channels scoured by debris flows was highest for mature forests. The narrowest range of eroded channel sediment also occurred in debris flows through mature forests. Sediment accumulation in low-order channels and valley floors is governed by the time-since-failure, the storage capacity of the channel, and the rate of sediment production. Therefore, sediment volume is directly tied to the frequency of debris flows. Results from this study suggest that debris flows may be occurring more frequently under the current management scenario. Since the volume of sediment stored in the low-order channel is largely a function of time, this result suggests that a window of time exists where low-order channels are susceptible to failure. For example, channels with little stored sediment (i.e. channels that have failed relatively recently) did not experience a debris flow in 1996. However, low-order channels in clearcuts and second-growth forests had a wider range of sediment volumes in the eroded stream channels, commonly with lower values, suggesting that more frequent failures are occurring.

Benda (1988) estimated an average sediment thickness of 1.8 m in eroded stream channels using semi-circle geometry. Benda's measurements yield an average of 5.1 m^3 of sediment per meter length of runout in first-order channels, and an average of 9.8 m^3/m in second-order channels. The average eroded sediment volume per meter length of runout in the erosional zone for this study was 5.7 m^3/m for non-road initiated debris flows.

DEPOSITS

Total Sediment Volume

The total sediment volume includes the landslide volume and the volume of eroded stream channel sediment. Debris flows that initiated and ran through clearcuts had a larger total volume of sediment (Table 13). These debris flows had larger, more frequent landslides, and a pattern of multiple failures that increased the cumulative runout length and therefore increased the quantity of sediment and wood accumulated from the low-order channels. Deposits from debris flows through clearcuts had an average of 1.7 times more sediment than debris flows through mature forests. Road initiated debris flows had the highest total sediment volume, which averaged more than 4.8 times more sediment than debris flows through mature forest. The large sediment volume for road-related debris flows is attributed to the order of magnitude increase in the initiating landslide volume, long runout lengths, and the high number of landslides contributing to the debris flows. Debris flows through clearcuts, that initiated at roads, had the greatest range in sediment volumes, with the high end of the range being an order of magnitude greater than the maximum sediment volumes observed in debris flows through mature forests. This suggests that a few, extremely large debris flows occurred under these land

Table 13. Total volume of sediment from debris flows in selected tributaries of the Siuslaw River (includes landslide volume and sediment scoured from the eroded stream channel).

Forest Type	Geometric Mean of the Total Sediment Volume (m^3)	Minimum (m^3)	Maximum (m^3)	Standard Deviation as Per Cent
Clearcut	1700	40	24,500	28
Second Growth	1200	60	7,500	23
Mature Forest	1000	50	4,000	25
Mixed Forest	2800	500	9,500	11
Road Initiated	4800	1600	22,000	9
All Sites	2200			19

use conditions that are outside the range of events that occurred in the forest. Factors that kept sediment volumes relatively low for debris flows through mature forests were the smaller landslide volumes, fewer landslides per debris flow, and shorter cumulative runout lengths.

As a check on the accuracy of estimated sediment volumes, actual deposit volumes were measured in the field. A comparison was made when discrete deposits formed and appeared to have undergone little fluvial transport after deposition. A large debris dam on Chappel Creek effectively blocked a large sediment wedge upstream of the obstruction. The estimated sediment volume from the landslides and eroded stream channel was 11% less than the volume measured at the deposition site. A large debris dam on Thompson Creek also effectively blocked a large sediment wedge and the estimated sediment volume underestimated the measured deposit volume by 22%. However, these debris dams could have accumulated additional sediment from fluvial transport from upstream sources if the dams were not filled to capacity when formed. On the lower portion of Knowles Creek, two debris flow fans built upon existing fans and the estimated volume of sediment was 28 and 38% less than the volume measured at the deposits. The estimation procedure consistently underestimated the measured deposit volumes except in 4 cases (8% of all debris flows surveyed). Measured volumes were not used for analysis because a high degree of subsequent fluvial erosion was suspected in the majority of cases.

Ratio of Initial to Eroded Stream Channel Sediment Volume

A ratio of the landslide volume, to the volume of sediment eroded from the channel as the debris flow passed, was calculated in order to understand the major sources of sediment contributing to debris flow deposits (Table 14). The initiating landslide volumes accounted for a higher proportion of the total sediment volume in debris flows that initiated and ran through clearcuts (0.91) compared to debris flows that initiated and ran through mature forest (0.14).

A high value for this ratio could be a function of an increased landslide volume and / or a decrease in the eroded channel sediment. A low value for this ratio could be a function of a lower landslide volume and / or a higher eroded channel sediment volume or runout length. Debris flows that initiated and ran through clearcuts had a higher initiating landslide volume and multiple failures per debris flow, but they also had a longer cumulative runout length and a lower volume of eroded stream channel sediment when compared to debris flows through mature forests. Debris flows through mature forest had fewer hillslope sources of sediment and larger sediment accumulations in eroded channels, and a shorter cumulative runout length.

The percent of the total sediment volume that was accounted for by the landslide volume was also calculated. This data indicates that a greater proportion of the sediment in debris flows through clearcuts is originating from landslides on hillslopes (48%), where the majority of sediment in debris flows through forested basins is from the eroded stream channel (only 12% of the total volume was accounted for by the landslide volume).

Table 14. Ratio of initial landslide volume to the eroded stream channel volume, averaged over all sites for debris flows in selected tributaries of the Siuslaw River. The data is also expressed in percent of the total deposit volume accounted for by the initial landslide volume.

Forest Type	Ratio (m^3/m^3)	% Initial to Final
Clearcut	0.91	48
Second Growth	0.25	19
Mature Forest	0.14	12
Mixed Forest	0.31	24
Road Initiated	0.73	42

Total Wood Volume

Since the volume of wood in debris flow deposits was correlated with runout distance, wood volumes were scaled to runout length for this analysis. Debris flows through mature forests consistently had the highest volume of wood in deposits, and both minimum and maximum values were the highest. Debris flows through clearcuts and second-growth forests had only 1/3 less wood, on average (Table 15). This volume difference reflects the legacy of large wood stored in channels and valley floors over time, and wood that may have been left behind by previous logging practices. Many of the pieces from managed basins appeared old, had a high frequency of burnt pieces, and some pieces had cut ends. Cedar was common in these deposits and it has been suggested that cedar was less merchantable during the early logging history of this area and may have been left behind after harvesting. Cedar also has a long residence time due to its slow decay rate. Bark was common only on wood in deposits from debris flows through second-growth and mature forests.

At the present time, debris flows through clearcuts had a relatively large volume of woody debris. This condition is a legacy from previous forests, but as this large wood that was previously stored in the channel network is transported down the network it is unlikely to be replaced. The majority of debris flows observed during this study are the first generation of failures after logging began in the Coast Range. The next generation of debris flows may be characterized by a lack of large trees in the basin and the subsequent lack of large wood in low-order channels.

Table 15. Average large woody debris volume in debris flow deposits from selected tributaries of the Siuslaw River.

Forest Type	Volume of Large Woody Debris Per Unit Length of Runout (m^3/m)	Minimum (m^3/m)	Maximum (m^3/m)	Standard Deviation (m^3/m)
Clearcut	0.20	0.00	0.63	0.19
Second Growth	0.20	0.09	0.36	0.09
Mature Forest	0.31	0.12	0.70	0.24
Mixed Forest	0.22	0.07	0.49	0.14
Road Initiated	0.26	0.07	0.58	0.15
All Sites	0.23			0.16

The total volume of large wood delivered from debris flows in the study basins ranged from zero in a small debris flow through a recent clearcut to 930 m^3 for the largest debris flow observed (Chappel Creek). Of the total volume, approximately 370 m^3 of wood, or 40% of the total deposit volume, were in direct contact with the active channel of the mainstem and accounted for 60% of the total large woody debris volume within the surrounding 1750 m of the mainstem channel surveyed. McGarry (1994), in a study on Cummins Creek found that approximately 45% of the large woody debris currently present in the channel was from debris flows.

A multiple linear regression analysis was performed with the full model (Model #5) including the following variables (see Table 1 for list of abbreviations):

Model #5 Ln(TwdV) = -5.819 + 1.286*Ln(CumL) - 0.292*Ln(Darea) – 0.010*Ln(ErodedCV) + 0.234*LnTinitV + 0.018*PcLT + 0.000*PcSG + 0.007*PcYT- 0.155*Road - 0.014*Ninitial

The significant associations in this model (at the 0.05 level) are:

constant (non-road, PcCC)	p-value 0.015	- coefficient
Ln(CumL)	p-value 0.001	+ coefficient
Ln (Total Initial Volume)	p-value 0.004	+ coefficient
PcLT	p-value 0.014	+ coefficient

Model 5 accounted for 71% of the observed variability (adjusted R^2) and had a standard error of 0.74. A correlation matrix was calculated and detected one correlation with an absolute value > 0.5 between the predictor variables. Outliers were identified by Studentized residuals with an absolute value greater than 2.0, Leverage values greater than 3 times the average data point, and with unusually large DFITS values (absolute value > 0.4). Three data points were identified as potential outliers using this criteria. The analysis was run without these points without significant changes to the model results. Therefore, the potential outliers were left in the data as no reason could be established for their removal.

The forward and backward selection processes selected the following model (Model #6), and all variables were significant at the 0.05 level (including constant term):

Model #6 $$\text{Ln(TwdV)} = -2.83 + 0.979*\text{Ln(CumL)} + 0.186*\text{Ln(TinitV)} + 0.012*\text{PcLT}$$

Standard Error: 0.73

Model #6 from the multiple linear regression analysis indicated that the cumulative runout length, the sediment volume of the initiating landslide (reflecting the size of the initiation site) and the percent of the perimeter of the runout zone that was in mature forest explained 71% (adjusted R^2) of the observed variability in the total wood volume. Increases in these parameters were associated with an increase in the volume of wood in the deposit.

Wood Size

The diameter distribution of wood in deposits was similar regardless of the age of the present day forest (Figure 13). However, the diameter of the wood in debris flow deposits was typically much larger than the forest currently present on the surrounding hillslopes (Figure 14). This reflects the legacy of LWD stored in the channels and valley floors over time. No significant differences in the diameter of LWD in deposits was detected using pair-wise comparisons of each forest type, p-value > 0.1 (Kolmogorov-Smirnov two-sided, two-sample test).

The length class distribution of wood in the debris flow deposits shifted when comparing deposits from debris flows through clearcuts and mature forests (Figure 15). While the majority of pieces were in short length classes, debris flows through mature forests had a greater proportion of the wood in their debris flow deposits in the longer length classes compared to deposits from debris flows through clearcuts. Cumulative frequency distributions of clearcut and mature forest sites were significantly different at a p-value < 0.01 (Kolmogorov-Smirnov two-sided, two-sample test).

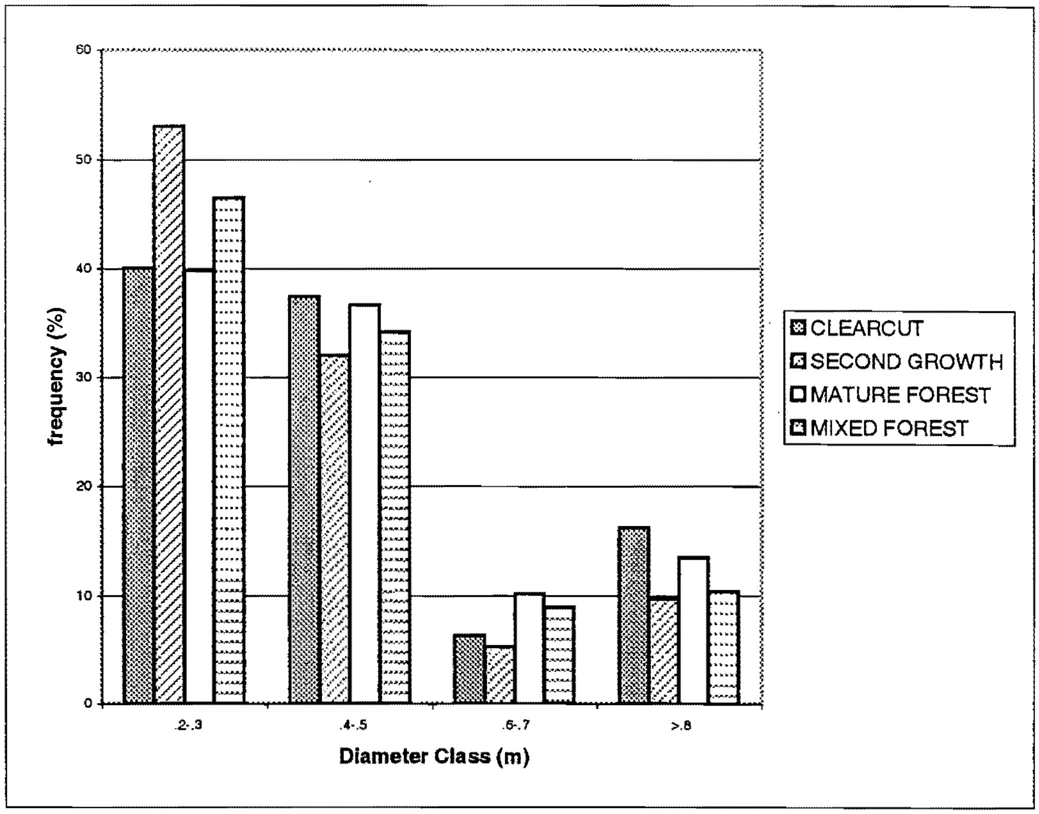


Figure 11. Diameter distribution of large woody debris in deposits from debris flows in tributaries of the Siuslaw River.

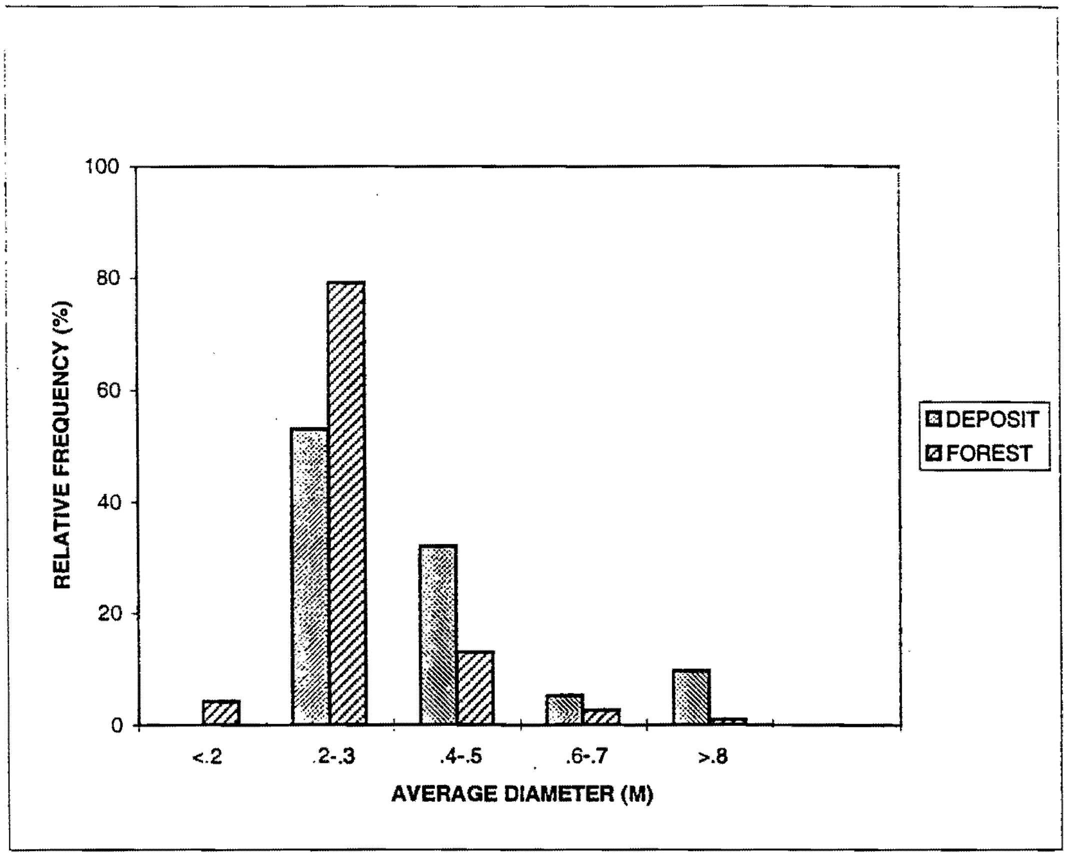


Figure 14. Comparison of the diameter distribution of large woody debris in debris flow deposits and diameter of trees along the perimeter of the debris flows through second growth forests. (Data on woody debris less than 0.2m in diameter was not collected.)

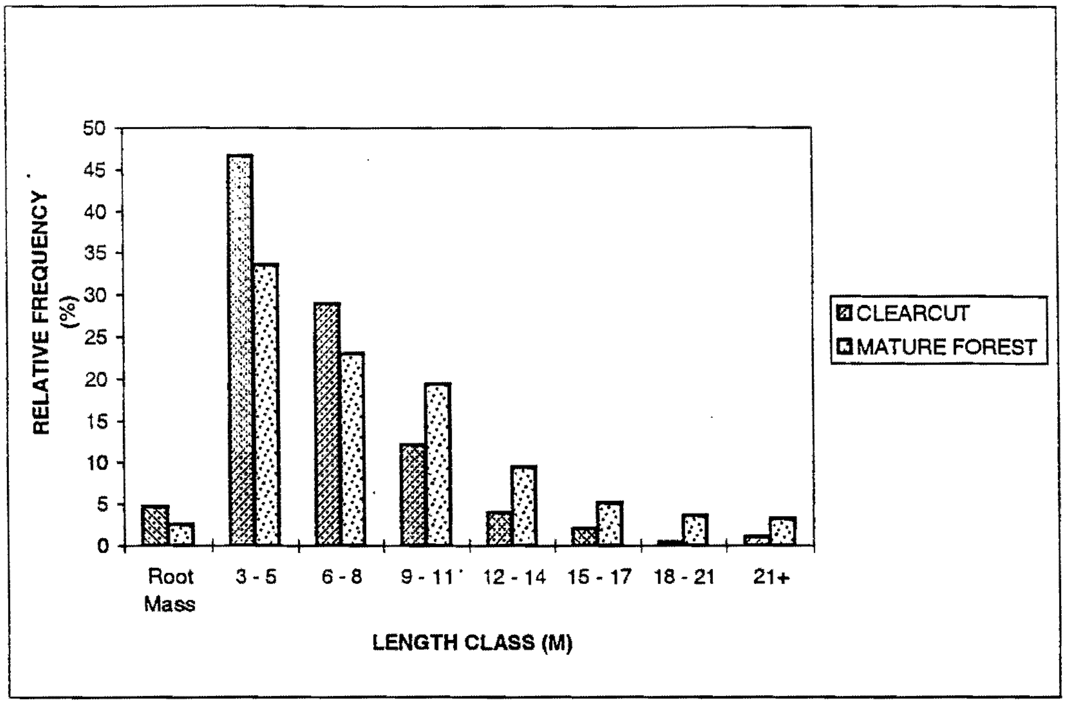


Figure 15. Length class distribution of large woody debris in deposits from debris flows through clearcut and mature forests in tributaries of the Siuslaw River.

Role of Roads

Road initiated failures had an order of magnitude larger initiation volume, had the longest runout lengths for debris flows, and deposits had the highest sediment volumes. All road related landslides were initiated from roads in the upper mid-slope position on the hillslope, and commonly contributed a large volume of fill material to the landslide volume. Swall (1996, Department of Forest Engineering, Oregon State University, unpublished data) found that most road related landslides occurred as fill failures from midslope roads, however, ridge-top roads also initiated a large proportion of the failures in the Oregon Coast Range. Valley-bottom roads acted as both sources and sinks for sediment depending on the erosional or depositional nature of the debris flow when it contacted the lower road system. Stream crossings on valley-bottom roads contributed large volumes of fill when the road was encountered in the erosional zone of the debris flow. Valley-bottom roads that were encountered in the depositional zone of the debris flow stored large volumes of sediment, and such deposits were subsequently removed by road maintenance crews. Debris flow deposits commonly spread over the road, increasing their width and decreasing their depth. When roads were on a steep grade, sediment from the debris flow traveled down the road and entered the stream channel downstream of the actual deposit.

Road failures typically occurred high on the hillslope and therefore may be associated with a greater proportion of the channel affected by debris flows and/or may be associated with failures that may not have occurred naturally. Not all low-order streams may be prone to debris flows and roads may be triggering failures in otherwise stable channels. Several road initiated failures triggered debris flows in channels that did not scour to bedrock. These channels had extremely large sediment accumulations, of the magnitude not observed in non-road related failures, which in all cases scoured the channel to bedrock.

Deposit Type

The types of debris flow deposits formed are listed in the order of severity that they impacted the receiving channel (Table 16). One 'debris flood' was observed, in this case the debris flow continued to travel down the receiving channel in a super-saturated slurry of mud and wood, but traveled by processes that do not function as a typical of debris flow. The single debris flood observed during this study traveled for many hundreds of meters downstream in the only fifth-order stream reach surveyed. Benda (1985) determined that a sufficiently large drainage area is necessary to produce the flood discharge required to initiate a debris flood in Knowles Creek. For Benda's data from debris flows in the 1980s it was calculated that a drainage area of approximately 28 km^2 was needed to produce a debris flood. For the 1996 flood, a drainage area of only 15 km^2 was needed to produce a debris flood. The debris flood was highly destructive to the receiving channels and valley floor. Riparian trees were sheared off at a height of approximately 0.5 meters and indicators of a very high flood were observed in the surrounding riparian area. All woody debris previously in the channel was removed and transported downstream along with the broken riparian trees. This process appeared to excert more force on the stream banks and less on the streambed.

Table 16. Type of deposit formed from debris flows in selected tributaries of the Siuslaw River. Deposit type listed by degree of impact with the receiving channel.

Type of Deposit	Sample Size	Percent of Total
Debris Flood	1	2%
No Deposit Remaining	5	9%
Debris Dam	12	23%
Scattered Debris Jams	8	15%
Debris Flow Fan	19	36%
Debris Dam in Tributary	8	15%
Totals:	53	100%

Two of the debris flow deposits that were no longer present at the time of surveying were located downstream of the above mentioned debris flood. The other three debris flow deposits that were no longer present at the time of the survey, were small in relation to the receiving channel and were carried away by the receiving flood waters. This occurred where small first-order debris flows directly entered the active channel of a larger, typically fourth-order channel.

Debris dams consisted of 23% of all the debris flow deposits, and these deposits formed in relatively narrow, hillslope constrained valley floors. Debris dams were characterized as large, valley-spanning wood jams that completely block the channel and valley floor and accumulate a large wedge of sediment upstream. Narrow valley floors permitted direct access to the active channel of the receiving stream and provided little room for storage on the valley floor. Headwater channels were unique in that no major transition to a larger channel, in the form of increased width, decreased gradient, or abrupt angle, was experienced. Thus all of the material transported by the debris flow was incorporated into the receiving channel, without losses to the valley floor.

Debris dams completely blocked the channel and valley floor and forced the accumulation of a large wedge of sediment upstream (Figure 6), which altered the local profile of the channel (Figure 16). These deposits appear to function as 'active sediment storage' components within the channel (Figure 17). The primary control on the sediment from these deposits acting as a supply to downstream reaches is the decay rate of the debris dam (Perkins, 1989). The volume of sediment stored upstream of debris dams was dependant upon the height of the debris dam and the slope and width of the valley floor. Sediment volumes ranged from 600 to 7800 m^3 of sediment. Large wood in the dams

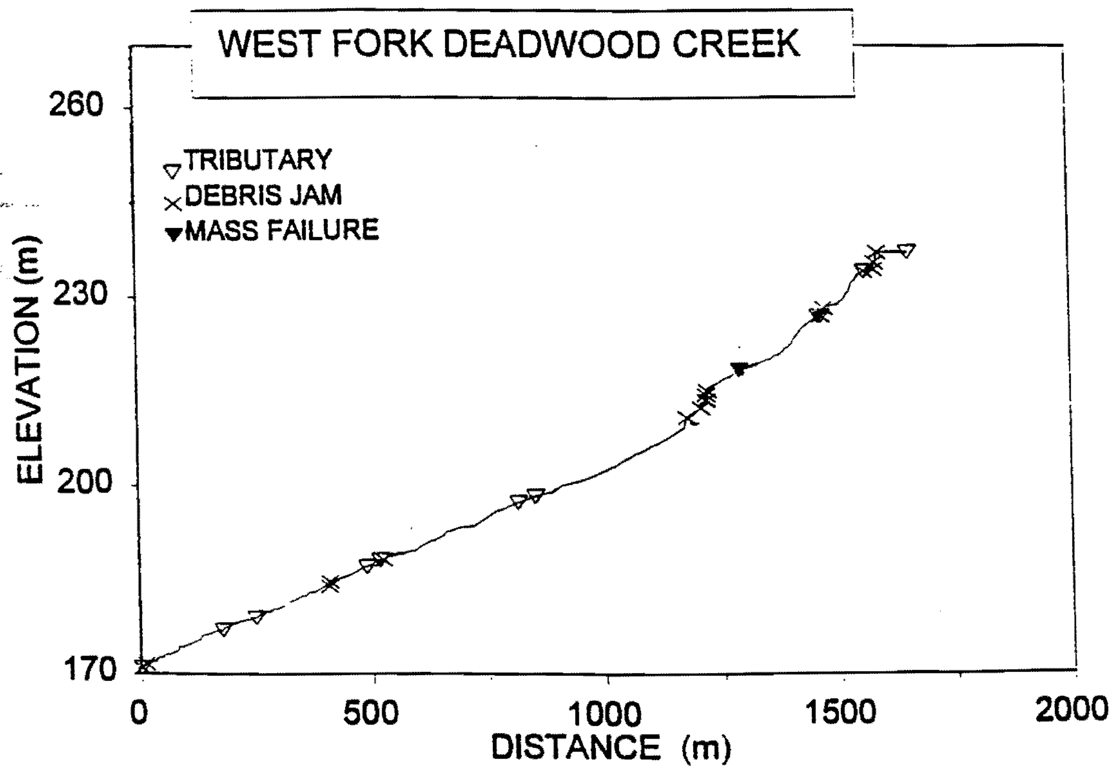


Figure 16. Longitudinal profile of the West Fork of Deadwood Creek, showing affects of debris dam and sediment wedge on the stream profile.

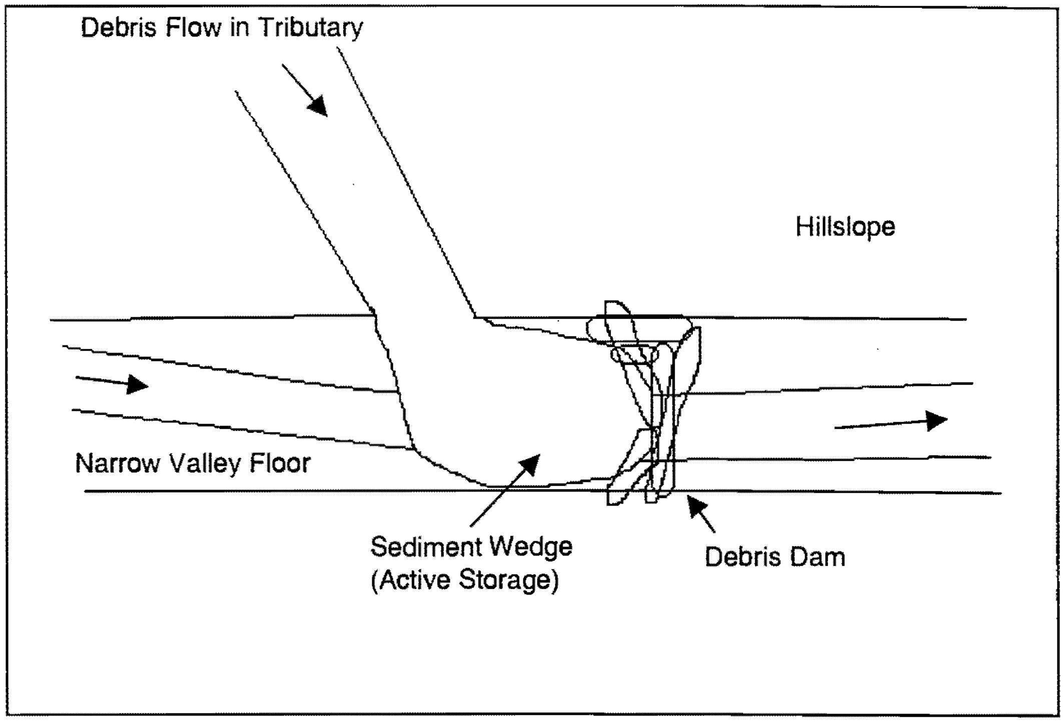


Figure 17. Debris flows entering narrow valley floors consistently had direct contact with the active channel and functions as a large, instantaneous pulse of sediment and wood to the channel.

ranged from 50 to 400 m^3 of large woody debris. The volume of wood generally increased the volume of the sediment wedge stored upstream, however, the results were highly variable (Figure 18).

Previous research noted the presence of major pools or ponds behind debris dams which sustained a large proportion of juvenile salmonids until they filled in with sediment in the following years (C. Dewberry, Pacific Rivers Council, personnel communication). Few large pools were found during this study, and almost all debris dams were completely filled with sediment at the time of survey. It is speculated that the high potential for alluvial deposits from upstream sources, which were transported as bedload during the flood, could have filled the debris dams which were not yet to capacity when formed. A high percentage of rounded rock was observed in the surface layers of these deposits. Most of the debris flows that deposited on valley floors were dominated by angular rock.

Scattered debris jams where less discrete, did not trap substantial volumes of sediment, and did not block the receiving channel. This type of deposit was formed when the debris flow directly contacted the channel, and the receiving channel was large in relation to the volume of material delivered by the debris flow. These deposits occurred at 8 sites and made up 15% of the deposits observed in this study. These deposits have already functioned to supply sediment and wood to downstream reaches.

Debris flow fans were the most common deposit type and were observed at 36% of all deposit sites. Debris flow fans deposited in moderately wide to wide valley floors and built on existing debris flow fans or built new fans atop existing terraces. In moderately wide valley floors the mainstem channel was pushed into the opposite

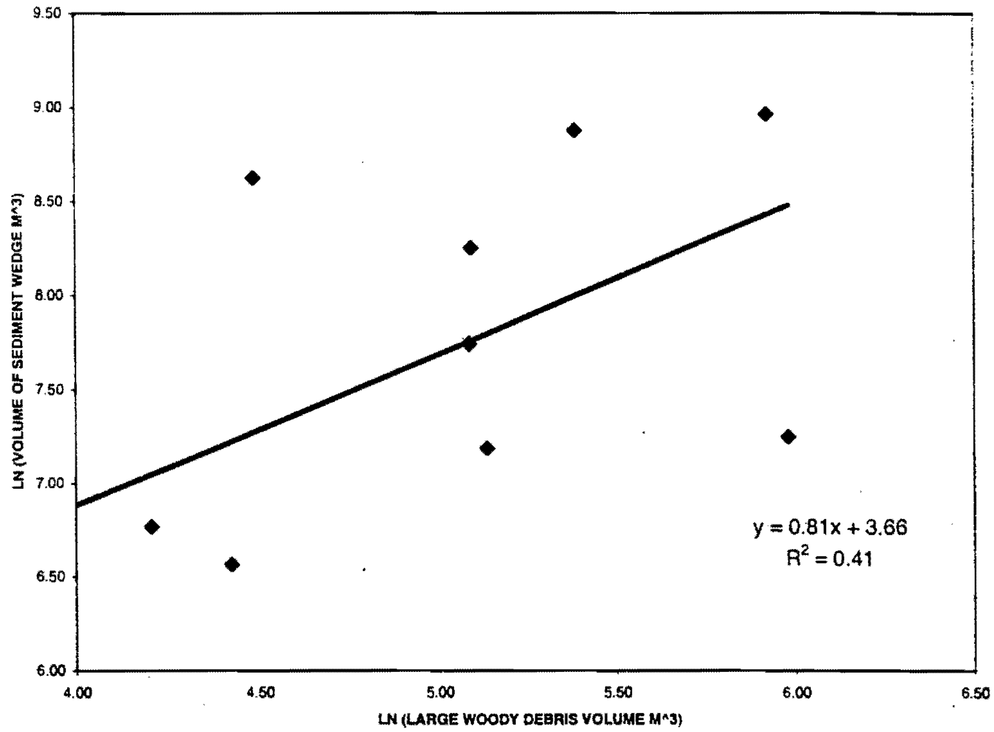


Figure 18. Large woody debris volume in debris dams plotted against volume of stored sediment for debris flow deposits in tributaries of the Siuslaw River basin. Data is plotted on the natural log scale.

hillslope and these deposits functioned to increase the sinuosity of the channel (Figure 19). This situation often resulted in erosion of the toe of the opposite hillslope, which acted as a source for large woody debris when trees were present. In some cases the channel was able to cut back through the deposit to form a complex channel with a series of side channels and islands.

Wood and sediment in debris flow fans is positioned alongside the active channel and is typically accessed during bank erosion, channel migration, and high flow events. Large wood travels at the flow front and therefore is in closest contact with active channel, this protects or armors the sediment from rapid fluvial erosion. Such deposits therefore function, on a temporal scale of sediment supply to the active channel, as an 'intermediate sediment storage'. On one occasion the channel was completely blocked by a debris flow fan and a large pond formed upstream.

In wide valley floors debris flow fans rarely had a direct impact on the active channel (Figure 20). These deposits provide 'long-term sediment storage' on the valley floor. Extreme channel migration or large floods are necessary to access these storage components. The wider the valley floor, the lower the probability the deposit would contact the channel. If the channel was encountered, it cut through the existing terrace, opposite the deposit, and created a new channel alongside the deposit. In a few cases extremely large conifers, up to 1.7m in diameter, were exposed in the lower portion of the terrace, and a high percentage of these pieces were burnt. Where existing debris flow fans were built up by additional deposits, the recent deposits were smaller and did not completely bury the existing fan. These existing surfaces often had large conifers, up to

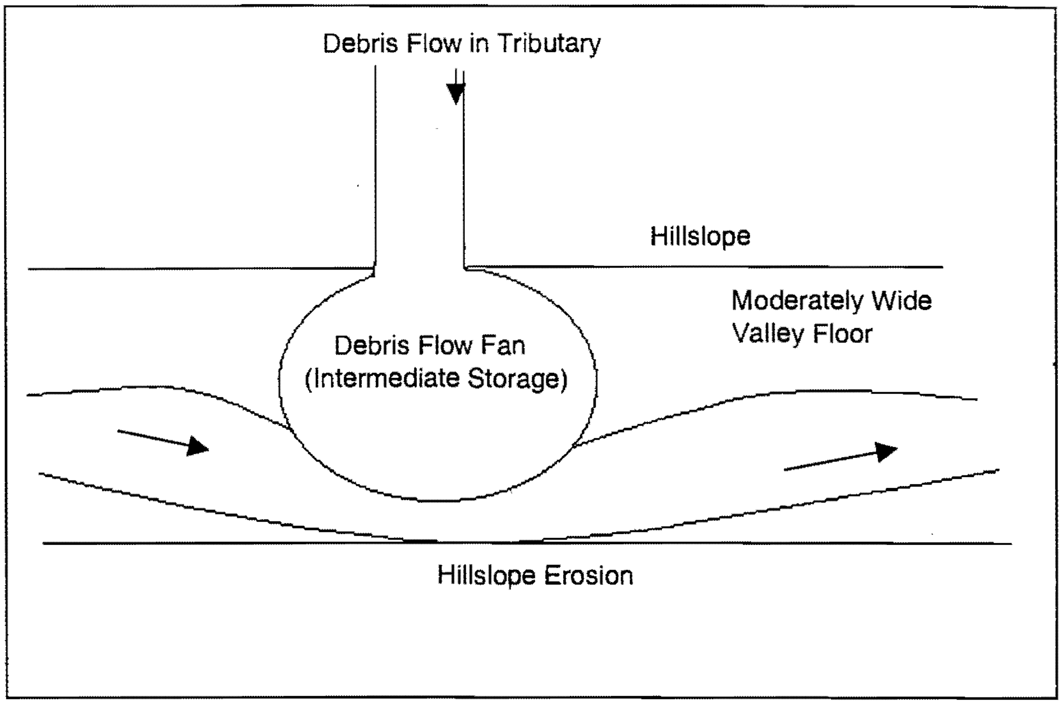


Figure 19. Debris flow deposits in moderately wide valley floors pushed the channel into the opposite hillslope and the deposit will function as an intermediate storage site for sediment and wood.

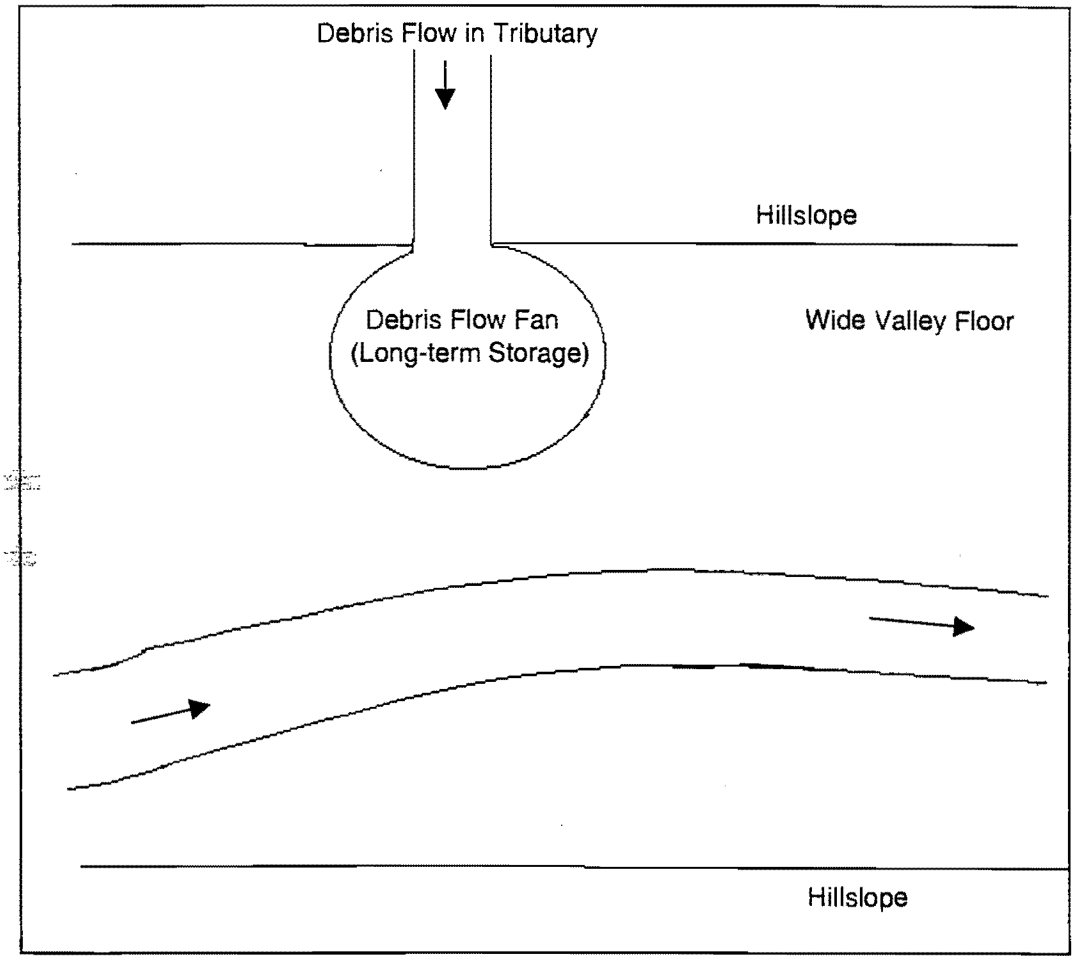


Figure 20. Debris flow deposits on wide valley floors had little contact with the active channel and functions as a long-term storage of sediment and wood.

1.2 m dbh, or large diameter stumps, which could give an indication of time since the last failure.

Debris dams that set up in tributaries, before entering the receiving channel, had the smallest direct impact to the receiving channel. Secondary deposits were observed in the receiving channel and therefore included in the sample, however, the majority of the material was found just above the tributary junction. This type of deposit occurred at 15% of all the debris flow deposits observed. These deposits stored the majority of the sediment and wood in the tributary and it is therefore not easily accessible for transport by higher flows in the mainstem. Debris flows that entered at high tributary junction angles also tended to deposit immediately at the tributary junction and caused a high proportion of the sediment to be backed up into the tributary (Figure 7).

Legacy on Hillslopes

Debris flows leave a legacy of low-order channels and valley floors that are scoured to bedrock. These low-order channels are often directly impacted by land-use activities and many previous policies and management activities have not recognized the value of low-order channels and their associated riparian habitats (Beschta and Platts, 1986). Beschta and Platts (1986) also noted that channels that are steep, straight, with hydraulically "smooth" banks and beds, uniform in cross section, and a large hydraulic radius also have high unit stream power. This morphological pattern accurately describes the condition of recently scoured to bedrock channels in the Coast Range, and these channels have a high potential for bedload transport. The transport ability of these channels is therefore affected by sediment supply, which may be high immediately following a debris flow because of the oversteepened side scarps and exposed soil. The lack of roughness in these channels results in high velocities, but the drainage area of these basins is low, so relatively large storms may still be required to transport bedload. High bedload transport rates are contrary to previous studies of low-order channels that have shown fluvial processes to account for only 10-20% of the total sediment yield (Swanson et al. 1982). Swanson's results suggest that low-order streams are transport limited a majority of the time, however, that study occurred on a stream with high roughness and storage potential. Due to the large number of initiating landslides, producing multiple failures and high cumulative runout lengths in clearcuts, a greater proportion of the channel network is currently being converted to bedrock dominated systems.

Beschta and Platts (1986) reported that trees in the riparian zone that are relatively large, in relation to the stream, function to retard the downstream routing of sediment. This situation increases the overall residence time of coarser sediments while encouraging the sorting of fines during high flows. Removing or preventing the replacement of woody debris would therefore set the stage for more rapid downstream transport of bedload sediment into lower gradient channel systems. The absence of large woody debris will influence the structure and function of the low-order channel as well as the sediment supply of the receiving channel. Clearcuts in steep terrain, in addition to lacking a source for large wood, have sometimes been shown to have an increased rate of erosion.

Therefore more sediment is likely to be routed through low-order channels and less sediment is retained by the system.

Montgomery et al. (1996) investigated the distribution of bedrock and alluvial channels in forested mountain drainages and found that slopes of bedrock reaches exceed those of alluvial reaches with comparable drainage areas. Longitudinal profiles from their study indicate that physical obstructions to sediment movement and backwater effects associated with valley-spanning log jams force deposition of alluvium in otherwise bedrock reaches. Montgomery's study gives strong evidence that the removal of large wood from high gradient streams will convert forced alluvial reaches into bedrock reaches, or prevent bedrock reaches from developing into alluvial reaches. Therefore, the presence of large trees along the perimeter of the debris flow-scoured channels are a vital source for large wood that can function to trap sediment in these otherwise storage limited systems. Landslides on the surrounding hillslopes also deliver sediment and wood to these highly coupled channels.

Field observations during the summer following the 1996 flood indicated that the only bedrock reaches that had re-accumulated substantial volumes of sediment were those associated with large woody debris. Trees along the perimeter of debris flows through forested basins were often undercut and leaning over the eroded channel. Such trees were already falling into the channel and were actively trapping sediment and smaller wood.

Downstream Legacy

Because streams are dynamic, establishing fixed habitat standards for parameters such as temperature, fine sediment concentration, woody debris abundance, or pool frequency is unlikely to be a successful strategy for protecting the overall capacity of watersheds to produce fish or to recover from natural or anthropegenic disturbances (Reeves et al. 1995). Holling (1973) noted that attempts to view and manage systems and resources in a static context may increase the rate of extinction of some organisms. Rather, a mosaic of conditions occurs within an ecosystem at any time as a consequence of disturbances (White and Pickett 1985). How much time elapses between the existence of favorable habitats at particular locations and the distance between such habitats can also affect the life history patterns of aquatic organisms (Warren and Liss, 1980). Ebersole et al. (1997) state that the analysis of watershed condition and development of prescriptions should include a consideration of the eventuality of large, infrequent natural disturbances to ensure that when these events do occur, important transfers of organic and inorganic materials from terrestrial to aquatic ecosystems are not significantly altered and riparian processes are not impeded.

Restoration challenges expressed by Ebersole et al. (1997) were twofold: (1) where possible, ensure that human activities do not increase the frequency or severity of disturbance events so greatly that the capacity of aquatic ecosystems to recover from either natural or anthropogenic disturbances is significantly impaired, and (2) ensure that, when anthropogenic disturbances do occur, the essential linkages (e.g., coarse sediment and woody debris inputs, nutrient and fine organic matter transfers, floodplain connections) that promote habitat recovery are not disrupted. The natural disturbance regime in the central Oregon Coast Range is believed to include an interaction of infrequent stand-resetting wildfires (Agee, 1990) and frequent intense winter rainstorms, which trigger debris flows. Reeves et al. (1995) stated that the perspective gained from natural cycles of disturbance and recovery of the aquatic environment must be incorporated into recovery plans for freshwater habitats.

Disturbance events, such as floods and debris flows, have potential to set the stage for the expression of new performances in river ecosystems by changing the environmental setting. The direction and nature of this responsive change comprises the course of development or developmental trajectory of a system (Warren et al.1979). Responses to disturbances, in turn, will depend on the frequency, size, and composition of the event. By altering natural disturbance regimes through land-use practices and fire-suppression, we may be fundamentally changing the direction and nature of this responsive change. Warren and Liss (1980) noted that short of extinction, the most profound effect that managers can have upon a fish population is to alter its potential and realized adaptive capacities. Land use practices by changing environmental conditions, affects the adaptive potential of aquatic populations. Unfortunately, we have limited knowledge of how altering the natural disturbance regimes will affect the long-term environmental capacity of a system.

CONCLUSIONS

Summary

This study indicates that forest practices, in the form of clearcuts and roads, are associated with an increase in the frequency and magnitude of landslides that initiate debris flows, an increase in the length of stream channel affected by debris flows, and an alteration in the composition of debris flow deposits. By altering these aspects of natural disturbance regimes through land-use practices, there may be unforeseen and adverse impacts on aquatic ecosystems.

It is important to keep in mind that the results of this study only apply to a sub-set of the landslides and debris flows on the landscape. The only failures detected during this study where debris flows that reached larger mid-order streams and valley floors. Debris flows that deposited in tributaries or landslides that did not propagate into debris flows were not evaluated, and these failures could have very different characteristics.

The question asked regarding the initiation sites of debris flows was, is there a difference in the quantity, magnitude, or location of initiation sites in forests compared to clearcuts? Landslides in clearcuts were found to have a higher frequency and greater magnitude than landslides in mature forests. The number of landslides per unit area showed a 10-fold increase for clearcuts compared to mature forests. The average sediment volume of shallow landslides in second growth and clearcuts was over twice the average sediment volume for shallow landslides in mature forests. The type of landslide was similar across forest types. No difference was found in the site characteristics of initiation sites, both forests and clearcuts had the same range of slopes and soil depths. Road initiated landslides had a higher number of landslides per unit area and an order of magnitude larger initiation volume than non-road related landslides. These landslides often occurred on high slope positions, which resulted in longer travel distances and greater sediment accumulation.

The question asked of the runout zone of the debris flow was, does the debris flow behave differently if it travels through a forested vs. clearcut riparian area? While the proportion of the runout zone that was in erosional and depositional zones was consistent across forest types, debris flows that travel through clearcuts had a higher cumulative runout length. Mature forests had the largest estimated sediment accumulations, and the narrowest range of conditions, in low-order channels that were scoured by debris flows. It was not possible to address the question relating to the likelihood of debris flows getting smaller or larger as they traveled due to the presence of multiple failures into a single channel.

The question asked regarding the debris flow deposits was, is there a difference in the composition of the deposit, expressed by the volume of sediment and wood delivered to the receiving channel, from debris flows through forested vs. clearcut basins? Deposits from debris flows through clearcuts had only a slightly lower volume of wood, with an equal diameter distribution but shorter length class when compared to debris flows from mature forests. These deposits largely reflect the legacy of previous forest stands because the size class of wood in the deposit was not well correlated to the size class of trees currently growing on the surrounding hillslopes, except in basins with mature forests. Debris flows from clearcuts, and those initiated at roads, transported a greater volume of sediment, which caused the formation of larger deposits. Debris flows through clearcuts also had a greater proportion of the total sediment coming from hillslope sources, whereas debris flows through mature forests had a greater proportion of the total sediment coming from the eroded low-order stream channel.

The mixed forest stand category was difficult to interpret and was biased toward larger failures. Debris flows that travel farther had a greater probability of running into a different forest or clearcut patch because of the fragmentation of forested landscapes in the Oregon Coast Range.

Recommendations for Future Research

Additional research is required to better understand the role of debris flows in the long-term delivery of wood and sediment to higher-order mountain streams. Little is known about how this wood and sediment, which is currently stored in discrete locations in the channel and valley floor, is re-distributed and how it will affect channel morphology and the potential to form high-quality aquatic habitat over time.

Research is also needed to gain insight into how forest practices in the Oregon Coast Range are affecting the frequency, magnitude, and composition of landslides and debris flows. For example, this study identifies 'composition' as an important characteristic of natural disturbances, and one that could be increasingly altered by land use. If these essential linkages of routing wood and sediment are disrupted by land management, it could adversely affect the potential of the channel and the life-history strategies of aquatic biota. The composition of future debris flow deposits, which lack the current legacy of large wood stored in the channels and valley floors, may have a very different structure and function.

Following a debris flow, the low-order channel will go through a series of recovery stages, where the channel will slowly re-accumulate sediment and wood. This recovery path may be drastically altered by the lack of large riparian trees, which will function to store sediment in these steep, bedrock-dominated channels.

This study also brings to light the issue of reference sites. All comparisons in this study were made against the present-day mature forest. Mature forests are sites that typically have not been recently disturbed. Using a site that has experienced a disturbance more recently, such as a large stand-resetting fire, may be more insightful for understanding how land use can alter the natural disturbance regime.

Recommendations for Forest Managers

Recommendations for forest managers is often limited by the relatively small number of studies on debris flow interactions with land management and the small geographic scope of previous studies. However, this study suggests that the frequency, magnitude, and composition of debris flows is altered by past and present land management activities. The risk associated with these activities must be managed to reduce adverse impacts to natural resources and society.

Increasing the rotation age of forests in low-order basins represents a management approach that may assure that future debris flows will contain the essential elements for producing high quality aquatic habitat and recovery of the system. The presence of LWD in low-order streams is vital for sediment storage, is an important component of the debris flow deposit, and may affect the recovery of the low-order channel after scouring by the debris flow.

The entire drainage area of zero-order basins plays a role in the timing and abundance of water routed to unstable areas. While, streamside buffers are becoming a common practice in the Pacific Northwest, the hydrology and sediment transport dynamics of zero-order basins is poorly understood. Buffers are also susceptible to increased blowdown and may not cover side slopes that are also prone to failure. Buffers or headwall leave areas may not provide the desired function for reducing landslide risk, due to these factors. However, when the site does fail they will contribute wood to the debris flow.

Road-initiated debris flows had the highest sediment volumes and may be occurring in places on the landscape that are not susceptible to debris flows under natural conditions or roads may be exacerbating failures on naturally unstable sites. Roads in upper mid-slope positions, especially those with large volumes of fill, should be managed to reduce the risk of failure. Extreme caution should be taken if new roads are constructed in this particularly sensitive position on the landscape.

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