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CLASSES IN THE CENTRAL OREGON COAST RANGE

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DEBRIS FLOWS THROUGH DIFFERENT FOREST AGE CLASSES IN THE CENTRAL OREGON COAST RANGE¹

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ABSTRACT: Debris flows in the Pacific Northwest can play a major role in routing sediment and wood stored on hillslopes and in first-through third-order channels and delivering it to higher-order channels. Field surveys following a large regional storm event investigated 53 debris flows in the central Oregon Coast Range to determine relationships among debris flow characteristics and the age class of the surrounding forest. The volume of sediment and wood delivered by debris flows was strongly correlated with runout length. Debris flows that initiated at roads were significantly longer than nonroad related failures, and road related landslides were an order of magnitude larger than nonroad related landslides. Clearcuts and roads tended to have more numerous contributing landslides relative to second growth and mature forests. No statistically significant difference in the average debris flow runout length was detected among the forest age classes, although debris flows initiating in clearcuts and mixed forest and at roads occasionally supported extremely long runout lengths that were outside the range of variability observed in completely forested basins. The size of wood in deposits was not correlated with the size of trees on the adjacent slopes, suggesting that the majority of wood in debris flow deposits was from remobilization of wood previously stored in low order channels.

(KEY TERMS: erosion; sedimentation; landslides; debris flows; aquatic ecosystems; forestry; roads; large woody debris.)

INTRODUCTION

Erosion and sedimentation are often viewed negatively from a biological perspective; however, these geomorphic processes are essential to the ecological functioning of aquatic and terrestrial communities because they provide the sources and surfaces necessary for habitat formation (Naiman *et al.*, 1992). In conjunction with nutrient and energy dynamics, the delivery and routing of water, sediment, and wood to stream channels comprise key processes that determine the ecological health of watersheds in the Pacific Northwest coastal ecoregion (Swanson *et al.*, 1982;

Naiman *et al.*, 1992). In addition to more frequent and chronic processes such as bank erosion and soil creep, episodic disturbances (e.g., large scale and infrequent processes such as mass wasting) in steep mountainous terrain play a major role in delivering wood and sediment to stream networks (Keller and Swanson, 1979; Swanson *et al.*, 1982; Benda and Dunne, 1997). Debris flows form a critical link between hillslope and fluvial processes in many mountain streams because this process episodically transports large volumes of hillslope derived sediment and wood, and redistributes material that has been stored in small streams for decades or even centuries.

First- and second-order channel segments (referred to hereafter as low order channels) (Strahler, 1964) can represent 60 to 80 percent of the cumulative channel length in mountainous terrain (Shreve, 1969). Many of these low-order streams are naturally susceptible to debris flows because they are adjacent to steep, landslide prone slopes and because the channels are narrow and high gradient (Swanson *et al.*, 1982; Benda and Dunne, 1997; Naiman *et al.*, 1992). Relatively little sediment and wood are transported by chronic fluvial processes in low-order channels (Swanson *et al.*, 1982). Instead, these channels undergo long periods of storage of sediment and wood that is punctuated by episodic transport by debris flows. Because of their abundance and position in the channel network, low order channels can be viewed as important conduits for water, sediment, and wood routed from hillslopes to higher order rivers (Naiman *et al.*, 1992; Benda and Dunne, 1997).

The majority of studies on the interaction between timber harvest and mass wasting focus on hillslope characteristics at the initiation site (O'Loughlin, 1972; Swanson and Dyrness, 1975; Swanson *et al.*,

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STUDY AREA

1977; Gresswell *et al.*, 1979). Research on the downstream consequences of landslides is limited. 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 based on interpretation of aerial photographs. The increased rates of mass wasting in clearcuts was greater for debris flows than for landslides, with the frequency of debris flows increasing as much as 8.8 times. In a ground based investigation, Ketcheson and Froehlich (1978) reported that debris flows through clearcuts traveled 1.7 times farther than in forested watersheds. These authors observed that 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.

Following a large regional storm event during the winter of 1996, many questions were raised regarding interactions between timber harvest, roads, and regional flood events and how these interactions may affect aquatic ecosystems. The objective of this study was to document characteristics of the initiation site, runout path, and deposition of debris flows that traveled through different forest stand ages or that were initiated at a road.

The Oregon Coast Range extends in elevation from sea level to 1,200 m. Basins selected for this study (Figure 1) were located in the Siuslaw River drainage (2,010 km²), which is underlain primarily by Tertiary marine sedimentary rocks of the Tye formation (Baldwin, 1964). The Tye formation is composed of massive, rhythmically bedded sandstones with interbeds of siltstones and mudstones. The topography is characterized by a dense, dendritic drainage pattern in first- and second-order streams that drain short, steep hillslopes. At the confluence between low-order and higher-order streams, there is typically an abrupt slope break onto a broad alluvial valley floor. Hillslopes in this area commonly exceed 65 percent slope, and some exceed 100 percent (Robison *et al.*, 1999).

The soils in the region are well drained and range from loams to clay loams with generally high nutrient levels. Soils on steep slopes are prone to mass movement, especially during high intensity rainstorms. Rocks from the Tye sandstone are mechanically weak and break apart rapidly during transport (Benda, 1994).

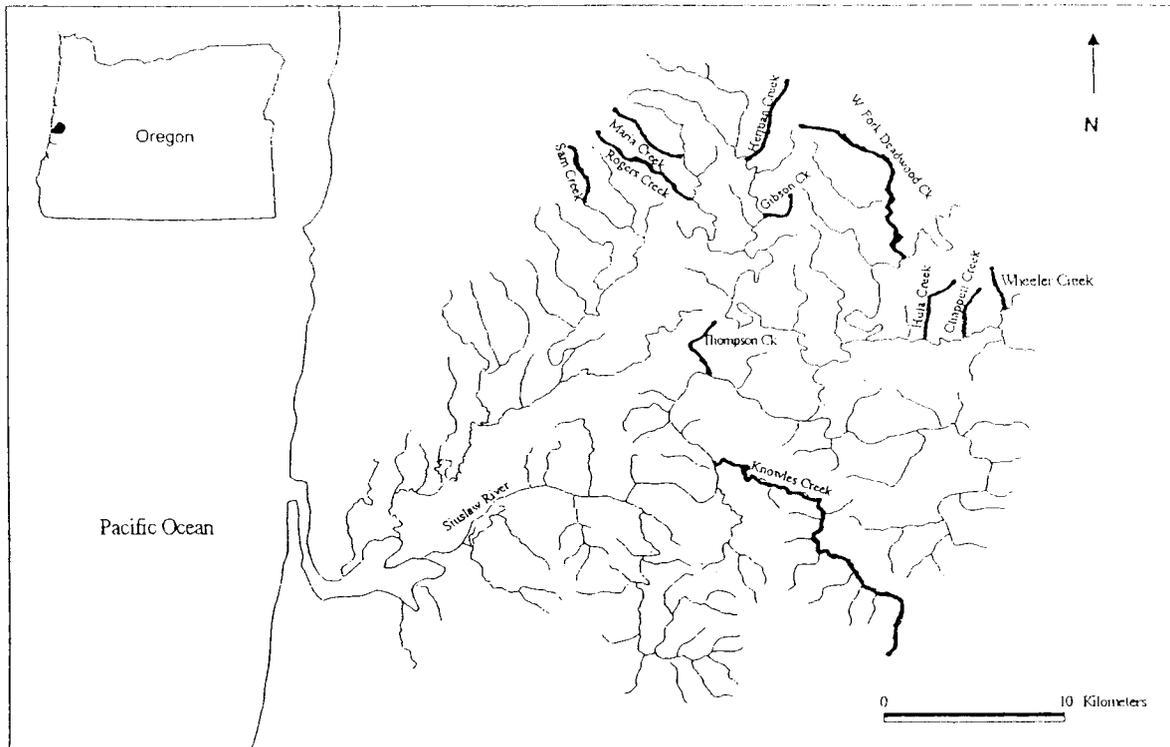


Figure 1. Streams Selected for Debris Flow Surveys in the Siuslaw River Basin.

METHODS

Dense Douglas-fir (*Pseudotsuga menziesii*) and western hemlock (*Tsuga heterophylla*) forests dominate the central Oregon Coast Range, which is located in the *Tsuga heterophylla* zone (Franklin and Dyrness, 1973). Red alder (*Alnus rubra*) is often found in riparian areas and in areas of recent disturbance and is the most common deciduous species. The heavy ground cover of shrubs consists mostly of salmonberry (*Rubus spectabilis*), thimbleberry (*Rubus parviflorus*), vine maple (*Acer circinatum*), swordfern (*Polystichum munitum*), salal (*Gaultheria shallon*), and huckleberry (*Vaccinium parvifolium*).

The Oregon Coast Range has a maritime climate characterized by wet and relatively warm winters and dry summers. Normal annual precipitation ranges from 1,650 mm to 2,230 mm, falling mostly as winter rain. Strong orographic effects and a patchy distribution of storm cells produce highly varied localized effects, resulting in a wide range of rainfall intensity, duration, and volume (Surfleet, 1997). In February 1996, a large regional storm event produced sustained precipitation for several days. Small scale spatial variability in the timing and intensity of rainfall was tremendous. Portions of the region received record rainfall during this long duration subtropical storm (Taylor, 1997). For example, Laurel Mountain in the Coast Range received a four-day total rainfall of 708 mm. Recurrence intervals of flood flows were highly variable and ranged from 30 to more than 100 years in many rivers in Oregon, Washington, and Idaho (Swanson *et al.*, 1998).

Eleven third-order through fifth-order streams (referred to hereafter as mid-order streams) within the Siuslaw River drainage with previous stream inventory data (Oregon Department of Fish and Wildlife, unpublished data) and a broad range of forest age classes were selected for this study (Figure 1). Debris flows within these 11 basins were located by field investigation, and all debris flows that delivered material to the mid-order stream or valley floor were included in the sample (Table 1). Debris flows that deposited higher up in tributaries or landslides that did not propagate into debris flows were not detected by this study because they were not visible to the observer due to dense vegetation.

Forest age classes were characterized by estimating the average diameter at breast height (dbh) of trees along the perimeter of the debris flow path. Debris flow paths that had trees with an average dbh less than or equal to 10 cm were classified as clearcuts. Debris flow paths that had greater than 75 percent of the trees between 20 and 50 cm dbh were classified as second growth forests. When 75 percent of the trees along the perimeter of the runout zone were greater than 50 cm dbh, the debris flow path was classified as mature forest. All other debris flows that ran through patches with various forest ages were classified as mixed aged forest stands. These forest age classes were only intended to represent the history of timber harvest. All stands classified as second growth had stumps present, and all stands classified as mature forests were naturally regenerating,

TABLE 1. Basins Investigated for Debris Flows and Associated Forest Characteristics. In-stream large wood was estimated for the entire mid-order stream length, along with the relative contribution of wood from recent debris flows.

Basin	Mid-Order Stream Length (km)	Percent of Basin Clearcut	Percent of Basin in Mature Forest	Number of Debris Flow	Total In-Stream Wood Volume (m ²)	Percent of Wood in Debris Flow Deposits
Chappel	1.7	54	16	3	836	59
Gibson	1.2	16	21	2	243	28
Herman	3.5	1	23	6	574	30
Hula	1.7	25	12	4	1304	59
Knowles	15.1	27	32	20	3001	42
Maria	3.3	11	35	5	519	26
Rogers	6.9	15	28	3	844	11
West Branch Sam	1.7	26	30	3	459	36
Thompson	1.0	10	29	1	438	57
West Fork Deadwood	1.7	8	7	2	574	37
Wheeler	1.8	23	29	4	587	22

unharvested forests. The proportion of each study basin in the different forest age classes was determined from aerial photo interpretation.

Debris flow surveys began at the deposit and traversed up the runout path until the initiating landslide scar was encountered. The landslide type was classified, and the dimensions and slope of the failure surface were measured. Landslides were classified as shallow rapid failures, earth flows or road related failures. Road related landslides came directly off a forest road or road drainage feature or occurred within 20 m of the road surface. The runout length of debris flows was measured using a hip chain along the axis of the runout zone or parallel to the runout path when extremely hazardous terrain was encountered. In some instances it was not possible to traverse the head scarp of the landslide, in which case the dimensions were visually estimated.

For the purposes of this study, each debris flow deposit in the mainstem river was counted as a single debris flow. However, numerous debris flows within the tributary basin often coalesced to form a large debris flow complex (Figure 2). When multiple landslides and debris flows coalesced into a larger debris flow complex, two different measurements of the runout length were necessary. The “primary channel runout length” was measured from the landslide that

initiated farthest upstream of the deposit (i.e., the longest single channel of the runout path). All additional contributing failures were defined as secondary debris flow channels. The “cumulative runout length” included primary and secondary runout lengths.

Longitudinal segments within the runout path were delineated at every major morphological change (e.g., abrupt changes in slope or valley width) or at a maximum length of 150 m. Each segment was classified as being in either the erosional or depositional zone of the debris flow or in a transitional zone between the two extremes (Figure 2). Erosional segments were located in the upper portion of the runout path and were classified either as “bedrock” (> 75 percent exposed bedrock on the valley floor) or “incised” (< 75 percent exposed bedrock on the valley floor). Depositional segments were classified as “discrete deposits” (sediment wedges formed upstream of large wood accumulations or on debris flow fans) or “gradual deposition.”

The average debris flow width and height was measured within each of the longitudinal segments of the runout path (Figure 3). Measurements were not taken on corners or constrictions, where debris flows hyper-elevate. The valley floor width and the erosional or depositional surface width were measured with meter tapes when possible or visually estimated when

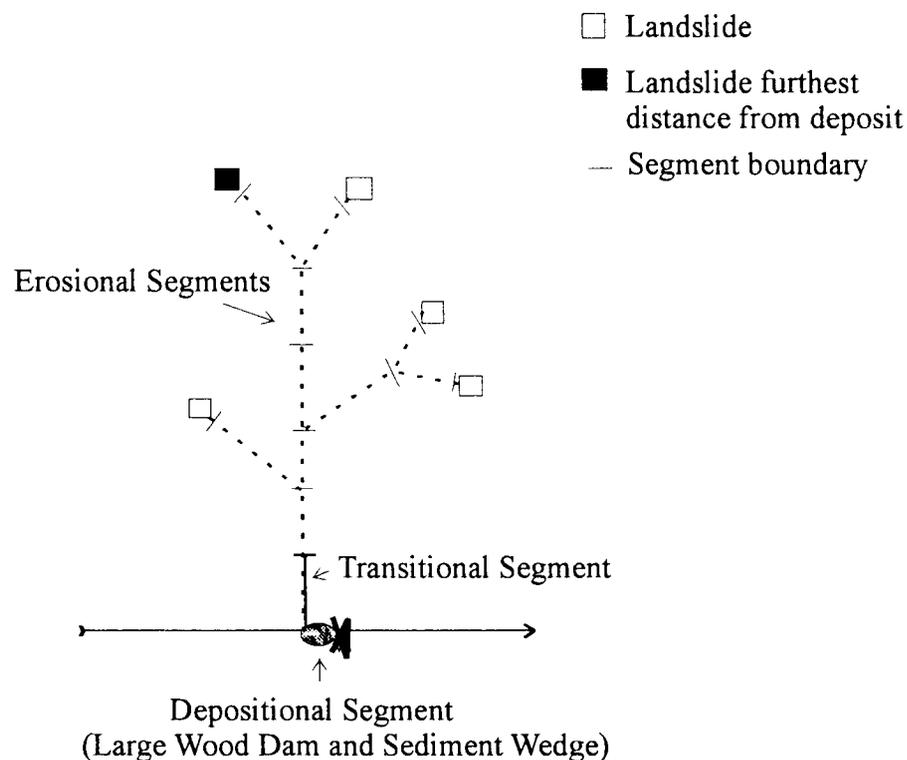


Figure 2. Schematic of Debris Flow Runout Path.

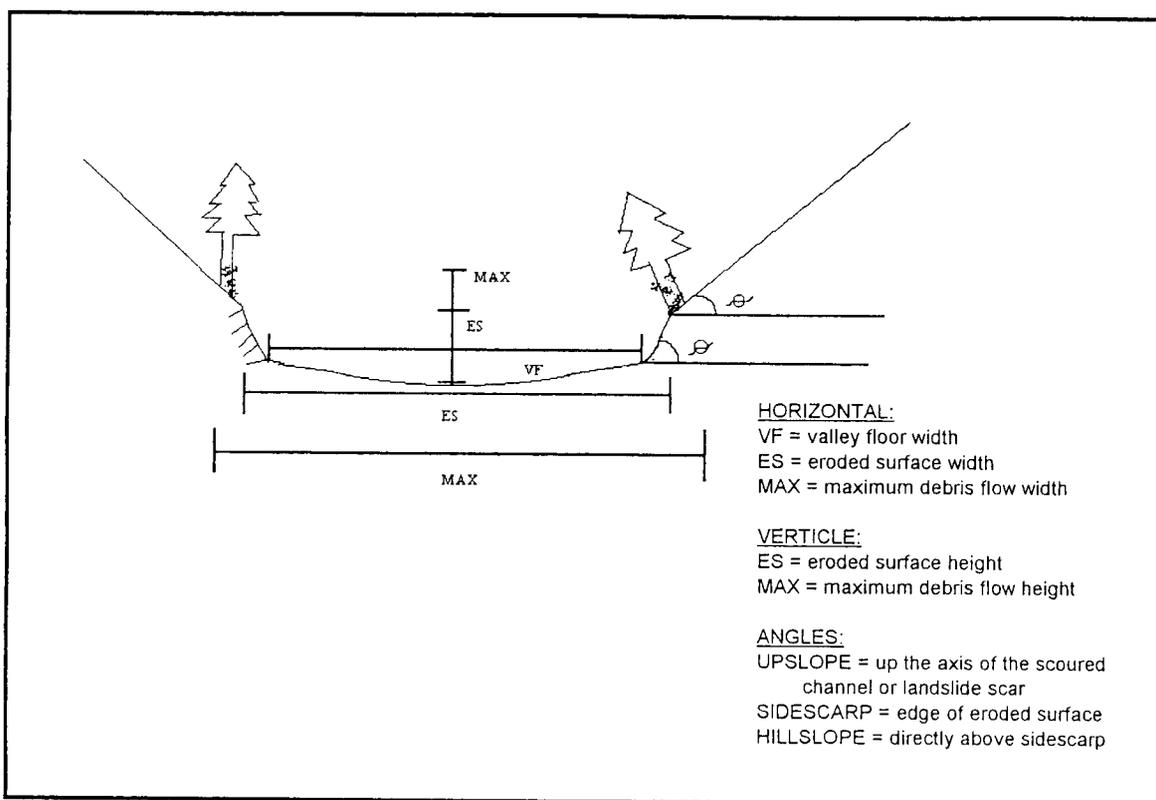


Figure 3. Cross Section Measurements Taken in the Field During Surveys of the Erosional Zones of Debris Flows.

necessary. Height of the erosional or depositional surface was measured using a survey rod or by visual estimation.

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 to two meters up the hillslope along the perimeter of the runout zone. A survey rod was used as a level with the clinometer set on top, and the angle was measured from the side dial of the instrument. This method was used when it was possible to climb the sides of the runout zone. Visual estimation was frequently used because of difficult terrain.

Estimates of the Eroded Sediment Volume From Low-Order Streams

Many of the debris flow deposits had been substantially reworked by the associated flood flows in the mainstem rivers; therefore, the observed deposit volume was not an accurate measure of the total volume

of sediment mobilized by the debris flow. Consequently, a consistent method of approximation was needed to estimate the volume of sediment scoured from the erosional zone of the low order stream channel (May, 1998).

For the extremely narrow, hillslope constrained, upper extent of first-order channels triangular geometry was used to estimate sediment volumes. It was assumed that the volume of sediment in the channel was equivalent to the amount of sediment that would be present if the hillslope angles were extended downwards. This approximation could not account for additional storage in the concave depression.

For most of the channel length, a second method of approximation was used. This approximation was based on a half-ellipse shape and was used to calculate the sediment volume in larger first-order channels, and in all second-order and third-order channels. A correction factor was used to remove 20 percent of the estimated elliptical volume to represent the channel area. An additional, weighted correction factor was used to reduce the estimated sediment volume for channels that were not scoured completely to bedrock; this coefficient was proportional to the percentage of the valley floor not scoured to bedrock. On a few occasions the height of the debris flow was

excessive (> 3 m), and based on field evidence, it was deemed necessary to adjust the approximation method. A maximum sediment depth of 2 m was imposed to avoid overestimating the in-channel sediment scoured by extremely large debris flows. If the eroded surface height was greater than 2 m, the additional sediment depth was assumed to be a relatively thin layer of hillslope sediment and not the thicker valley floor accumulation.

The estimation procedure is likely to underestimate the actual volume of sediment in the channel. Although the estimated sediment volumes cannot be considered absolute values, the approximations were consistent among all debris flows and are relative values for purposes of comparison. As a test of the accuracy of the estimated sediment volumes, a comparison was made between measured deposit volumes at two sites that appeared to have undergone little fluvial transport after deposition. The measured volume of two sediment wedges behind large wood debris dams underestimated the estimated volumes by 11 and 22 percent.

Estimates of the Volume of Wood in Debris Flow Deposits

In depositional zones, a single trained observer estimated the dimensions of all visible wood that was larger than 20 cm in average diameter and longer than 2 m. The volume of each piece was calculated as a cylinder. Dimensions of individual pieces of wood were estimated instead of measured because repeated climbing through deposits was extremely hazardous. Due to the massive quantity of wood present in large deposits, poor visibility in immense jams, and burial of wood under sediment, the actual volume of wood was underestimated.

The proportion of the wood in the receiving stream that was directly associated with debris flows from the winter of 1996 was estimated for third-order to fifth-order channels in the study basins. The volume of wood in contact with the bank-full channel for the entire length of the mainstem river was calculated, and pieces that were located in recent debris flow deposits were identified.

Statistical Analysis

Kruskal-Wallis one-way analysis of variance (ANOVA) was used to test for significant differences in landslide and debris flow characteristics among the forest age classes and for road related failures. For skewed distributions, the data were transformed to a

logarithmic scale and the geometric mean was calculated. Results were back-transformed and reported on the original scale.

Statistical power is the ability to detect a statistically significant difference if one exists. A retrospective power analysis cannot exceed 0.5 using the observed effect size and observed variance; otherwise, a statistically significant difference would have been detected. Therefore, it is more appropriate to use a pre-specified effect size and the observed variance (Thomas, 1997). Results of both forms of power analysis were reported. Statistical power was extremely low in this study because of the small sample size, relative to the high degree of variability observed in landslide and debris flow characteristics. The ability to detect differences was also affected by transforming the data to a logarithmic scale. Since the difference in means is assessed on a nonlinear scale, it is easier to detect differences for smaller numbers (i.e., greater spread on the log scale) than it is for large numbers (i.e., more compressed on the log scale).

To analyze for differences in the distributions of debris flow characteristics, a two-sided, two-sample Kolmogorov-Smirnov test was used. Kolmogorov-Smirnov test statistic (D) is a nonparametric measure of agreement of the absolute value of the largest vertical difference between the cumulative frequency distributions of two samples. Differences in the distribution are insightful because they represent the range of natural variability and potential deviations from it.

RESULTS

A total of 53 debris flows were observed in the 11 study basins. Eleven debris flows initiated and ran through clearcuts, ten debris flows initiated and ran through second growth forests, and five debris flows initiated and ran through mature forests. Fourteen debris flows ran through mixed aged forests that were associated with 41 landslides (51 percent initiated in clearcuts, 32 percent in second-growth forests, 5 percent in mature forests, and 11 percent initiated at roads). Thirteen debris flows initiated at roads.

Initiation Sites

Landslide density was not evenly distributed among the forest age classes (Table 2), and landslides tended to occur disproportionately to the basin area occupied by each forest age class. Clearcuts accounted for 24 percent of the basin areas and contained 46

percent of the 106 landslides observed during this study, resulting in the highest landslide density observed (4.3 landslides per km²). Mature forest accounted for 29 percent of the basin areas but contained only 6 percent of the observed landslides, resulting in the lowest landslide density observed (0.4 landslides per km²). Roads accounted for less than 1 percent of the basin area and initiated 16 percent of the observed landslides.

TABLE 2. Density of Landslides That Initiated Debris Flows in Tributaries to the Siuslaw River.

Forest Age Class	Area (km ²)	Percent of Total Area	Slides/km ²	Percent of Observed Landslides
Clearcut	11	24	4.3	46
Second Growth	22	47	1.6	32
Mature Forest	14	29	0.4	6
TOTAL	47	100		84*

* Remaining 16 percent of landslides were road related failures.

Multiple landslides in a basin frequently triggered numerous small debris flows that coalesced into a larger debris flow complex. The average number of landslides per debris flow (Table 3) was highest for clearcuts (2.6 landslides per debris flow) and roads (2.4 landslides per debris flow). In completely forested basins, there were never more than three landslides contributing to a debris flow complex; however, there were up to nine landslides per debris flow complex in clearcut basins.

TABLE 3. Landslide Density for Debris Flows in Tributaries to the Siuslaw River.

Forest Age Class	Number of Debris Flows	Number of Landslides Per Debris Flow Average	Range
Clearcut	11	2.6	1 to 9
Second Growth	10	1.2	1 to 3
Mature Forest	5	1.6	1 to 3
Mixed Age Forest	14	2.1	1 to 5
Road Related	13	2.4	1 to 6
TOTAL	53		

Debris flows were initiated by shallow rapid landslides in hollows or on planar sideslopes (88), earth flows (3), road related landslides (15), and three

debris flows had no identified hillslope failure. Because of extremely hazardous terrain it was not possible to estimate the landslide volume for 13 of the 106 landslides encountered during this study. Road related landslides were associated with a landslide volume an order of magnitude larger than nonroad related landslides (one-way ANOVA, p-value < 0.01) (Figure 4). Mean landslide volume in clearcuts (180 m³) and second-growth forests (210 m³) was approximately double the mean landslide volume in mature forests (90 m³). For nonroad related shallow rapid failures, no significant differences in landslide volume were detected among the different forest age classes (one-way ANOVA, p-values > 0.1). The chance of detecting a difference of the magnitude observed during this study, if one existed, was only 15 percent (power analysis, observed effect size and variance, alpha = 0.05). The chance of detecting a 100 percent mean increase in landslide volume for one of the forest age classes relative to the mean volume in mature forests was 33 percent (power analysis, prespecified effect size and observed variance, alpha = 0.05).

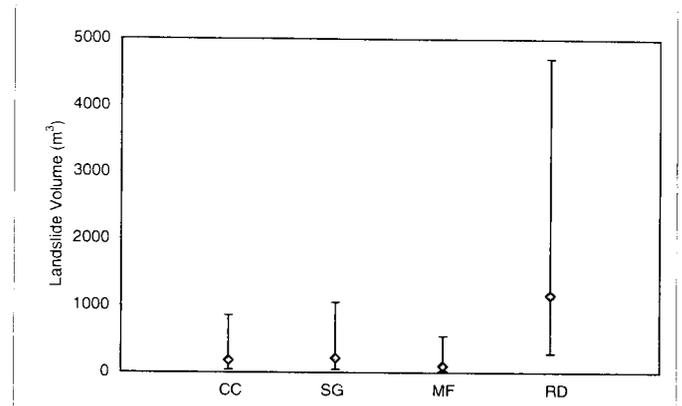


Figure 4. Geometric Mean of Shallow Rapid Landslide Volumes by Forest Age Class for Failures Contributing to Debris Flows in Tributaries to the Siuslaw River. Error bars represent one standard deviation. CC = clearcut, SG = second growth, MF = mature forest, and RD = road related.

Runout Zones

A broad range in the distribution of channel slopes was observed for initiation sites, erosional zones, transitional zones, and depositional zones of the runout path (Figure 5). Distributions of channel slope for discrete deposits and gradual deposits were significantly different (Kolmogorov-Smirnov statistic, p-value < 0.05). Slope measurements of discrete deposits were overestimated because the slope measurement included large accumulations of sediment

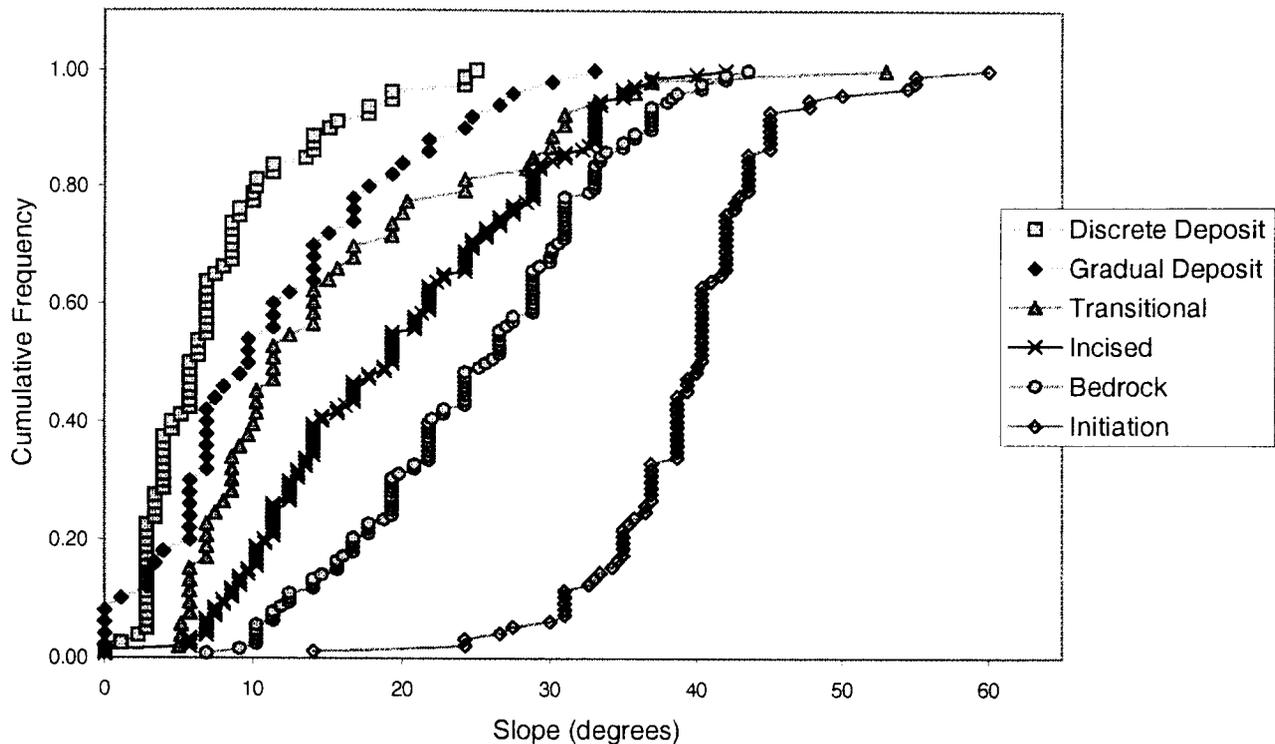


Figure 5. Slope Distributions for Depositional Zones (discrete and gradual), Transitional Zones, Erosional Zones (incised and bedrock), and Initiation Sites for Debris Flows.

and wood, which masked the prior surface slope. Distributions of channel slope for gradual deposits and transitional zones were similar (Kolmogorov-Smirnov statistic, p -value > 0.1). All other distributions were significantly different from one another (Kolmogorov-Smirnov statistic, p -value < 0.02). No relationship was observed between channel slope and debris flow width (slope of regression line was not significantly different from zero).

The mean primary channel runout length (Figure 6) was longest for debris flows that initiated at roads (580 m), which is 3.1 times farther than the mean runout length of debris flows through mature forests, and the distribution of runout lengths were significantly different (Kolmogorov-Smirnov statistic, p -value < 0.05). For debris flows that initiated and ran through a single forest type, the mean runout length was longest for debris flows in clearcuts (280 m) and second growth forests (290 m), which is approximately 1.5 times longer than runout lengths in mature forests (190 m). The distribution of runout lengths among the forest age classes were not significantly different from one another (Kolmogorov-Smirnov statistic, p -value > 0.1). One-way analysis of variance also detected no statistically significant difference in runout length among the forest age classes (p -value > 0.1). There was a 33 percent chance of

detecting a difference of the observed magnitude if one existed (power analysis, observed effect size and variance, $\alpha = 0.05$). The chance of detecting a 100 m mean increase in primary runout length for one of the forest age classes relative to the mean length for mature forests was 15 percent (power analysis, pre-specified effect size and observed variance, $\alpha = 0.05$).

The cumulative runout length of debris flows in second growth and mature forests corresponded with the primary channel runout length. In contrast, the variation in the primary channel and cumulative runout lengths showed the greatest deviation in clearcuts and mixed-aged forests and for road-related failures. This resulted from numerous landslides in a low-order basin that caused multiple debris flows, which coalesced into a larger debris flow complex. The mean primary channel runout length in clearcuts was only 280 m, although the mean cumulative runout length was 450 m. Furthermore, the maximum cumulative runout length was more than 2 km for both clearcuts and road related failures. However, the maximum cumulative runout length in second growth and mature forests was less than 1 km.

If one of the forest age classes was associated with a mean increase in the cumulative runout length of 100 m above the mean length for mature forests, a

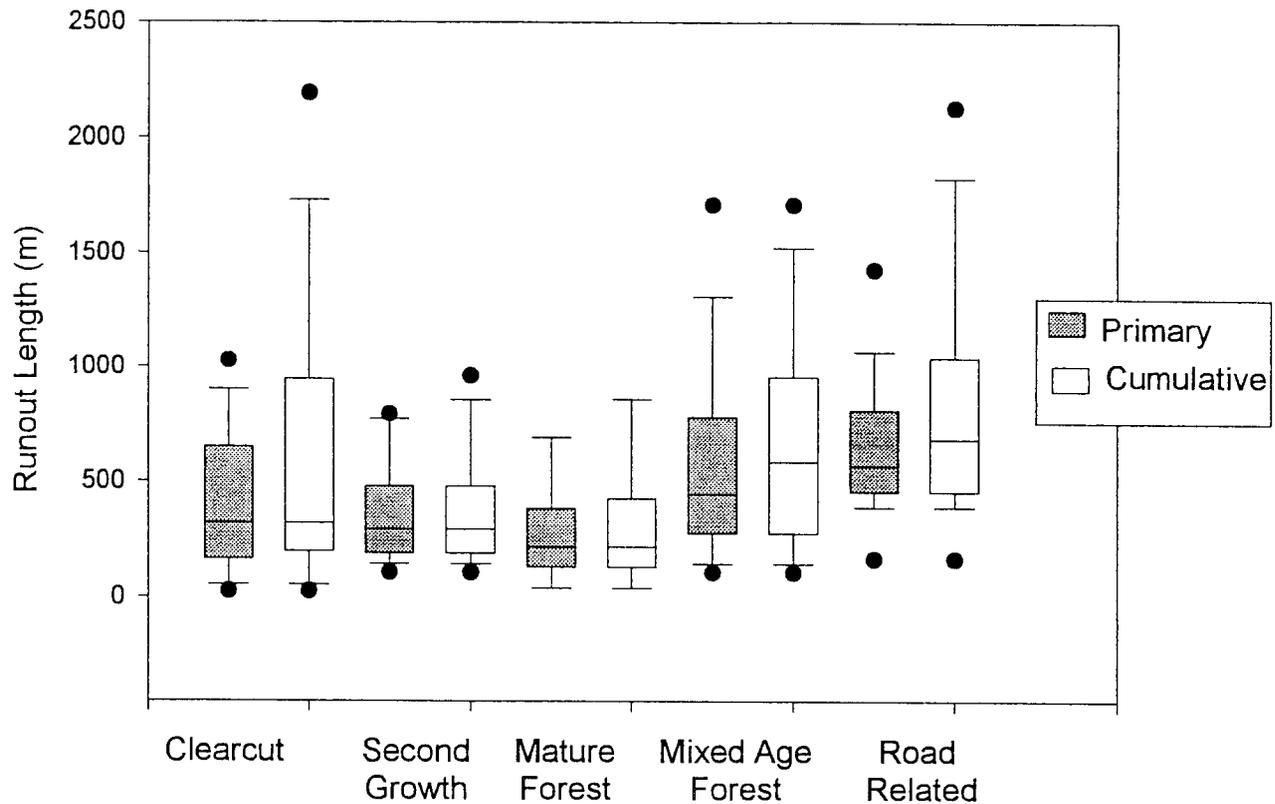


Figure 6. Box-and-Whisker Plots of the Primary Channel and Cumulative Runout Length for Debris Flows in Tributaries to the Siuslaw River. Lower boundary of box represents the 25th percentile, mid-line represents the median, and upper boundary of box represents the 75th percentile. Lower whisker represents the 10th percentile, upper whisker represents the 90th percentile, and circles represent outlying points.

sample size of 90 debris flows in each forest age class would be necessary to detect a statistically significant difference (sample size determination, $\alpha = 0.05$, $\beta = 0.20$). There was a 13 percent chance of detecting a difference of this magnitude with the sample size obtained during this study. Alternatively, if the minimum detectable difference for one of the forest age classes was associated with a mean increase in the cumulative runout length of 200 m above the mean length for mature forests, a sample size of 30 debris flows in each forest age class would be required (sample size determination, $\alpha = 0.05$, $\beta = 0.20$). The power to detect a difference of this magnitude with the sample size obtained during this study was 31 percent.

Sediment Volume Eroded from Low-Order Streams

The estimated volume of sediment eroded from the low order streams was highest for debris flows

through mature forest and for road related failures (Figure 7). Debris flows through mature forest had the smallest range of sediment volumes, whereas road related debris flows had the widest range of values. Debris flows through clearcuts, second growth, and mixed-aged forests had similar eroded stream channel sediment volumes, which were lower on average and more variable than debris flows through mature forest. No statistically significant differences were detected among the different forest age classes or for road related failures (one-way ANOVA, p -values > 0.3). There was a 32 percent chance of detecting a difference of the observed magnitude if one existed (power analysis, observed effect size and variance, $\alpha = 0.05$). If mature forests were associated with a 50 percent mean increase in the volume of sediment eroded from low-order streams compared to the other forest age classes, this study would have a 50 percent chance of detecting a difference if one existed (power analysis, prespecified effect size and observed variance, $\alpha = 0.05$).

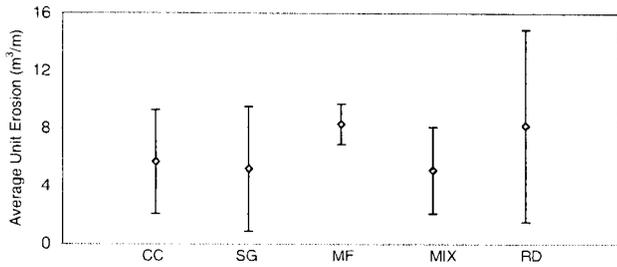


Figure 7. Average Volume of Sediment Eroded From Low Order Stream Channels Scoured by Debris Flows in Tributaries to the Siuslaw River. Volume estimates were scaled to the length of erosional segments in the runout path. Error bars represent one standard deviation. CC = clearcut, SG = second growth, MF = mature forest, MIX = mixed forest, and RD = road related.

Total Sediment Volume Delivered by Debris Flows

The total sediment volume of the debris flow included the volume of the initiating landslide(s) and the estimated volume of sediment eroded from the low order stream channel(s). The cumulative runout length was strongly correlated ($r^2 = 0.72$) with the total volume of sediment (Figure 8). Debris flows associated with clearcuts and roads had a greater proportion of the sediment derived from landslides on

hillslopes, in contrast to mature forests, where a greater proportion of the sediment was derived from the eroded stream channels (Table 4). The ratio of the volume of wood to the volume of sediment in debris flow deposits was highest for mature forests (Table 4).

TABLE 4. Ratio of Large Wood to Sediment in Debris Flow Deposits, and the Proportion of the Total Debris Flow Sediment Volume Accounted for by the Initial Landslide(s) Volume.

Forest Age Class	Ratio Wood: Sediment	Initial/Total Sediment Volume
Clearcut	0.04	48
Second Growth	0.08	19
Mature Forest	0.14	12
Mixed-Age Forest	0.04	24
Road Related	0.04	42

The mean total sediment volume (Figure 9) was highest for road related debris flows (4,800 m³). For nonroad related debris flows, the mean sediment volume was highest for mixed-aged forests (2,800 m³); however, this forest class may be biased to include debris flows with longer runout lengths due to the fragmentation of the forested landscape. Debris flows

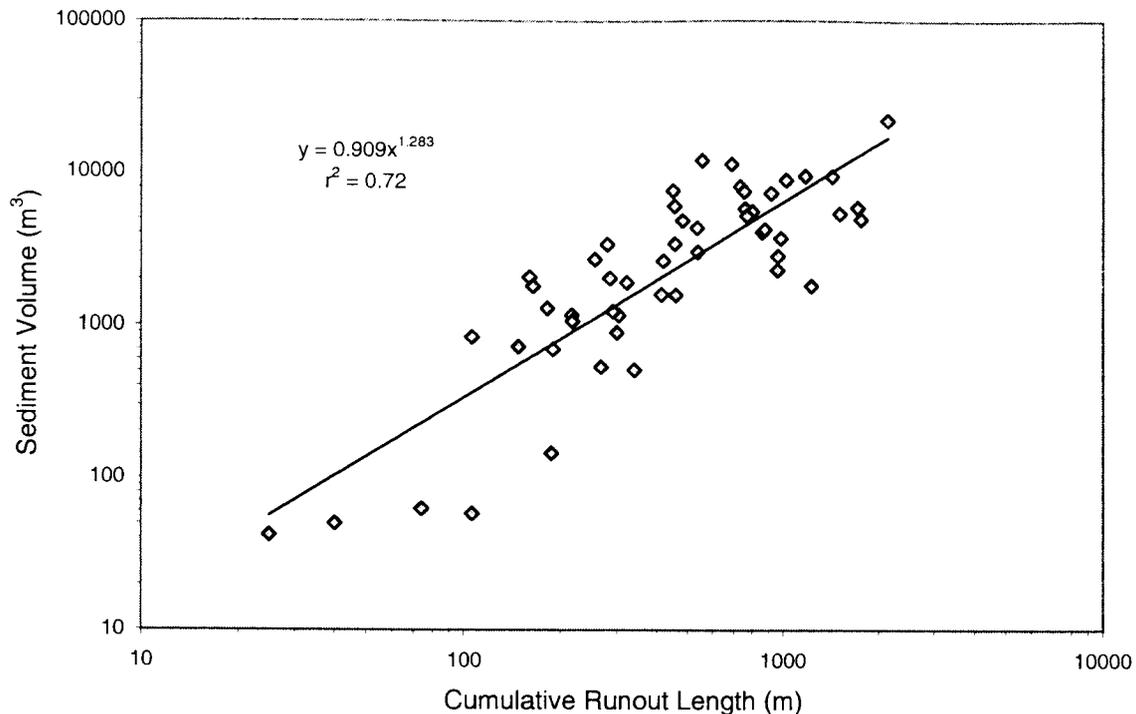


Figure 8. Total Sediment Volume Delivered by Debris Flows as a Function of Runout Length in Tributaries to the Siuslaw River.

that travel farther may have a greater probability of encountering a patch with a different forest stand age. In clearcuts (1,700 m³), the mean sediment volume was 70 percent greater on average than in mature forests (1,000 m³). Clearcuts were also associated with the greatest variability in the volume of sediment transported by a debris flow. The only statistically significant differences detected were between mature forests and road related failures and between second growth forests and road related failures (one-way ANOVA, p -values < 0.05). For nonroad related failures, this analysis had only a 21 percent chance of detecting a significant difference if one existed (power analysis, observed effect size and variance, $\alpha = 0.05$). If one of the forest age classes was associated with a 100 percent increase in the mean sediment volume above the mean for mature forests, this study only had a 13 percent chance of detecting a significant difference if one existed (power analysis, prespecified effect size and observed variance, $\alpha = 0.05$).

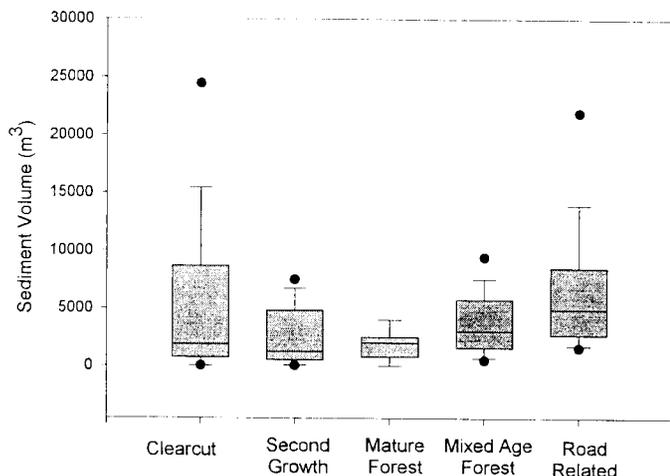


Figure 9. Sediment Volume Delivered by Debris Flows in Tributaries to the Siuslaw River. Error bars represent one standard deviation. CC = clearcut, SG = second growth, MF = mature forest, MIX = mixed forest, and RD = road related. Lower boundary of box represents the 25th percentile, mid-line represents the median, and upper boundary of box represents the 75th percentile. Lower whisker represents the 10th percentile, upper whisker represents the 90th percentile, and circles represent outlying points.

Large Wood Abundance

The volume of wood in debris flow deposits was strongly correlated with the cumulative runout length of the debris flow path (Figure 10). To assess the potential a debris flow had to accumulate wood as it

traveled, the volume of wood was scaled to runout length for each forest age class (Figure 11). Debris flows through mature forests consistently had the highest volume of wood per unit length of runout, and both minimum and maximum wood volumes were higher than other forest age classes. However, no statistically significant differences were detected among the forest age classes ($p > 0.1$, ANOVA).

The diameter distribution of wood in debris flow deposits was similar among the forest age classes ($p > 0.1$, Kolmogorov-Smirnov two-sided, two-sample test). Consequently, the diameter of wood in deposits was typically larger than the diameter of trees currently present on the surrounding hillslopes in clearcut and second-growth forests.

Among the study basins, the proportion of wood delivered by debris flows compared to the total volume of wood in the mainstem river channel ranged from 11 to 59 percent (Table 1). Six debris flow deposits were remobilized by flood flows in the mainstem river, and therefore wood from these debris flows could not be identified. Twelve debris flows formed large valley spanning dams of wood in the mainstem river, and an additional eight deposits formed discrete accumulations of wood in the mainstem but did not dam the channel. The remaining 27 debris flows formed deposits on existing fans or terraces before reaching the mainstem.

DISCUSSION

Initiation Sites

Road related failures had a high density of landslides relative to the proportion of the basin they occupied and these landslides were an order of magnitude larger than nonroad related failures. Swanson *et al.* (1981) reported a similar trend for this region, with rates of soil erosion from road rights-of-way exceeding forest rates by 26 to 350 times. Road failures often occurred on unusually high slope positions near the ridge, which resulted in longer travel distances and greater sediment accumulation for the associated debris flows. Furthermore, not all failures were associated with stream crossings, so predicting potential debris flow initiation sites may be difficult.

Landslides that initiated debris flows in clearcuts tended to occur in higher densities than landslides in mature forests. The average sediment volume of shallow landslides in second growth forests and clearcuts was more than twice that of shallow landslides in mature forests. However, the landslide volumes were highly variable, and the power to detect statistically

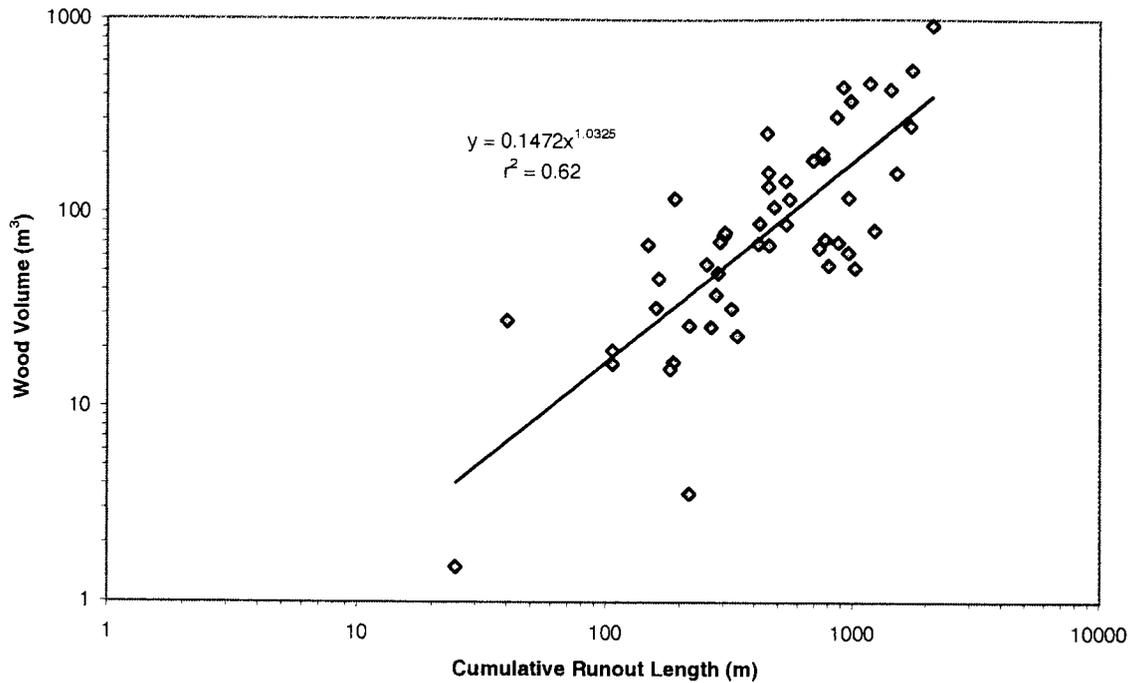


Figure 10. The Volume of Large Wood in Debris Flow Deposits as a Function of the Cumulative Runout Length of the Debris Flow Path.

significant differences was extremely low. Although clearcuts and mature forest accounted for a similar proportion of the total basin areas, clearcuts contained 40 percent more landslides and more than twice the number of debris flows. Robison *et al.* (1999) performed a ground-based study of landslides in the nearby Mapleton area of the Siuslaw basin during this period and reported a higher overall density of landslides. Forest stand ages of zero to nine years had a landslide density of 8.1 landslides per km², and forests greater than 100 years old had a landslide density of 5.2 landslides per km² for all nonroad related failures (Robison *et al.*, 1999). These authors detected no statically significant differences in landslide density or landslide erosion (volume of sediment per unit area).

The only landslides identified by this study were failures that triggered debris flows, which is not a complete inventory of all landslides in the basin. Furthermore, it was not possible to determine if the area in each forest age class was equivalent in regard to its potential to initiate and transport debris flows. Site factors such as the distribution of bedrock hollows, local root strength, rainfall intensity, and numerous other factors have the potential to influence landslide density. Each of the mid-order basins investigated had a range of forest age classes, so large geographic distances did not separate comparisons among the different forest age class. Additionally, the slope and soil depth at landslide scars were similar among the

forest age classes (one-way ANOVA, p-values > 0.4), suggesting that landslides were occurring on equivalent sites.

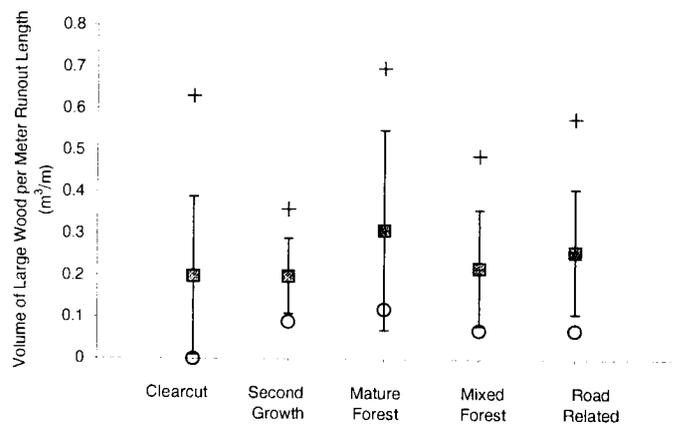


Figure 11. The Volume of Large Wood Transported by Debris Flows Through the Different Forest Age Classes. Error bars represent one standard deviation, open circles represent minimum values, and plus signs represent maximum values.

Runout Zones

The distribution of channel slopes within the runout path are useful for models that attempt to predict debris flow behavior and for identifying portions

of the channel network that are likely to be scoured to bedrock by debris flows. The continuum of distributions from erosional to depositional zones had substantial overlap for many of the slope classes; however, the distributions were significantly different (except gradual deposits and transitional zones). Discrete deposits had slopes ranging from 0 to 20°. Channels scoured to bedrock occurred on slopes that exceeded 10°.

The distribution of runout lengths in all forest age classes had a positive skew. The majority of debris flows were relatively small, and large debris flows were less frequent and extended the right tail of the distribution. The distribution of road related debris flows was unique, in that few small debris flows were observed. For example, 80 percent of the runout lengths of debris flows in mature forests were less than 400 m, whereas only 8 percent of the runout lengths of road related debris flows were less than 400 m. The range of runout lengths was the narrowest for mature forests and second-growth forests, where cumulative runout lengths were less than 1 km. The greatest range in the distribution was observed for debris flows through clearcuts and from roads where cumulative runout lengths exceeded 2 km.

The valley floors of third-order and higher-order streams in this portion of the Coast Range are typically wide and low gradient and present an abrupt transition from the narrow, high gradient tributaries. This abrupt change in slope, width, and direction of travel promotes rapid deposition of debris flows at the tributary junction. The runout distance of debris flows in this study is therefore based on the distance of the initiating landslide to a mid-order stream or valley floor. Debris flows that may have held up higher in the drainage network before they reached the mid-order stream were not detected by this study. The Oregon Department of Forestry (ODF) also investigated debris flows in this region and all streams less than 40 percent slope within the ODF study areas (Robison *et al.*, 1999). The distribution of runout lengths for this study (Figure 12) was similar to the ODF study (D. Montgomery, University of Washington, personal communication regarding additional analysis not present in the ODF report). Landslides that initiated in mature forest in the ODF study areas had 80 percent of their runout lengths less than 300 m (100 percent were < 800 m), and 80 percent of the primary channel runout lengths in this study were also less than 300 m (100 percent were < 700 m). Landslides that initiated in recent clearcuts and young forests (< 50 years) in the ODF study areas had 80 percent of runout lengths less than 500 m (100 percent were < 1,500 m), and 80 percent of the primary channel runout lengths in clearcuts in this study were

less than 700 m (100 percent were < 1,100 m). Results from both studies suggest that debris flows initiating in mature forest stands were associated with shorter runout lengths than debris flows initiated in clearcuts and young forests.

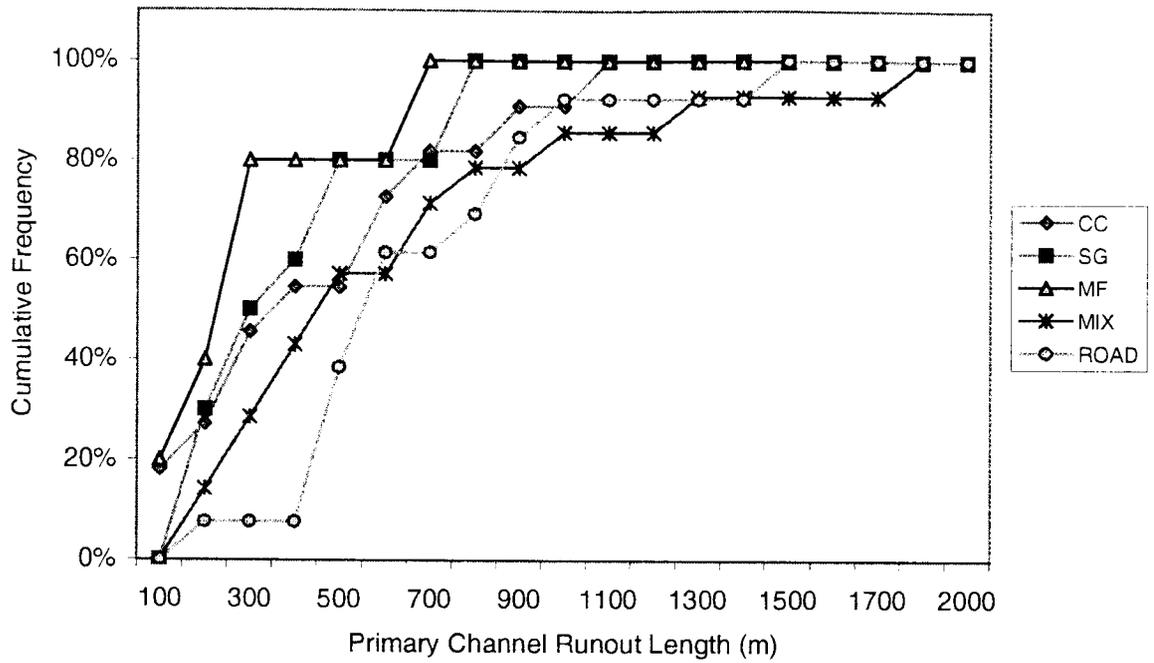
The cumulative runout length was highly correlated with the volume of sediment and wood accumulated as the debris flow traveled through the stream network. The cumulative runout length is also important for determining the proportion of the drainage network affected by debris flows. In basins where large debris flow complexes occurred, almost the entire drainage network in the low order basin was transformed into a bedrock state. In mature forests, only a small proportion of the channel network was scoured by debris flows. These patterns of disturbance could have vastly different ecological implications. When only a small portion of the drainage network is scoured by debris flows, refuges for stream dwelling biota (such as amphibians and invertebrates) and storage sites for wood and sediment persist within the low-order basin. When the entire drainage network is scoured by debris flows, there may be little refuge for stream dwelling biota that could recolonize the disturbed areas. This resulted in a homogeneous pattern of severely disturbed habitat, with few residual storage sites for wood and sediment in the network. By changing the distribution of disturbance and refuge patches within the stream network, the biotic response and physical template may be greatly altered. The legacy of this altered disturbance pattern may continue for decades to centuries as these small streams refill with sediment and wood and are recolonized by stream and riparian biota.

Total Sediment Volume Delivered by Debris Flows

The majority of the sediment mobilized by debris flows in mature forests originated from the eroded stream channel. In contrast, road related debris flows and debris flows in clearcuts were associated with a greater proportion of the sediment originating from landslides. This resulted from a higher landslide density and size, which increased the proportion of the total sediment volume being derived from hillslope sources as compared to in-stream sources.

Road related debris flows had the highest total sediment volume delivered by the debris flows, which averaged 4.8 times larger than nonroad related debris flows. Debris flows that initiated and ran through clearcuts also tended to have relatively high total volumes of sediment, with an average of 1.7 times more sediment than debris flows through mature forests. An increase in landslide density resulted in greater cumulative runout lengths of the debris flows and

(a)



(b)

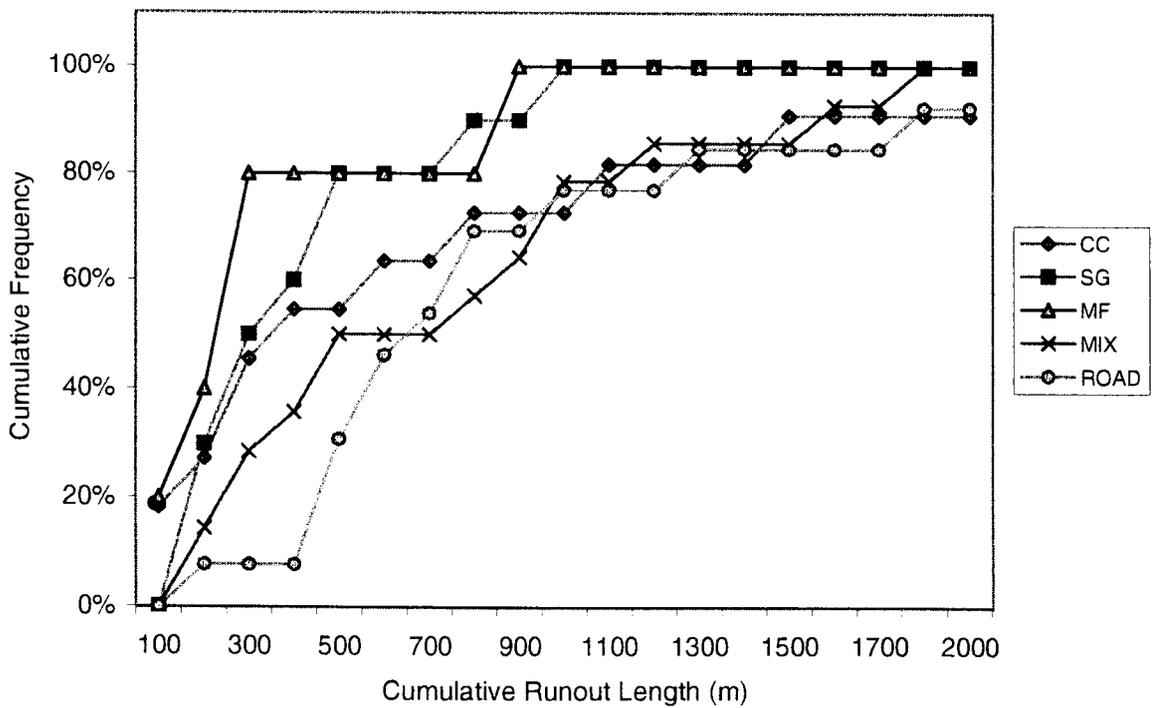


Figure 12. Distribution of Runout Lengths for Debris Flows in Selected Tributaries of the Siuslaw River: (a) Primary Channel Runout Length and (b) Cumulative Runout Length (CC = clearcut, SG = second growth, MF = mature forest, MIX = mixed forest).

therefore a greater potential for the debris flow to accumulate sediment as the debris flow traveled through the stream network. Mixed aged forest stands also tended to have relatively long runout paths and large sediment volumes, but debris flows that traveled farther had a greater probability of running into a patch with a different forest age class. Timber harvest has greatly increased the fragmentation of the forested landscape, and caution should be taken when interpreting results of this category.

Factors that kept the total 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. However, the eroded stream channels contained more sediment. Sediment accumulation in low-order channels is governed by the time since the last debris flow, the storage capacity of the channel, and the rate of sediment production in the basin. Therefore, the frequency and magnitude of debris flows are directly linked (Benda and Dunne, 1997). Results from this study suggest that debris flows may be occurring more frequently under the current management scenario, because the volume of sediment eroded from the runout path was frequently lower and more variable in harvested basins. The interval between disturbance events may be of great importance to native biota that are adapted to the natural disturbance regime.

Large Wood Abundance

Runout length had a strong influence on the potential a debris flow had to accumulate wood as it traveled, regardless of the age of the surrounding forest. If the majority of wood was being recruited directly from the forest growing along the runout path, then debris flows through recent clearcuts would be lacking large wood. Furthermore, the size of wood in deposits was not correlated with the size of trees growing along the runout path in clearcut and second-growth forests. These results suggest that debris flows are primarily a mechanism for redistributing wood from the previous forest stand, that was stored in the channel network. The term "legacy wood" can be used to describe pieces of wood that are unrelated in species or in size to the present day forest. Based on the presence of this legacy wood, basins that have recently undergone extensive timber harvest potentially still store large volumes of wood in small streams. This legacy wood cannot persist indefinitely, and management actions should consider the long-term replenishment of wood to this portion of the channel network.

The relative contribution of wood delivered by debris flows, as compared with the volume of wood already present in the channel, was highly variable among the study basins. The proportion of the basin clearcut was positively correlated with the relative contribution of wood from debris flows (correlation coefficient, $r = 0.61$). The relative contribution of wood from debris flows could increase in harvested basins if logging has depleted other sources of wood in the riparian zone or if debris flows are larger or more numerous in clearcuts.

Debris Flow Composition

Sediment and wood delivered by debris flows typically form discrete deposits in the vicinity of tributary junctions (Benda and Cundy, 1990; May, 1998). The composition of the deposit is important for aquatic habitat formation and for persistence of the depositional feature. A ratio of the volume of wood in deposits to the total sediment volume reflects a change in the composition of deposits among the different forest age classes (Table 4). The highest value of the ratio was associated with debris flows through mature forests and indicates that deposits contain less sediment and/or more wood. Lower values of the ratio indicate more sediment and/or less wood in deposits.

The proportion of wood and sediment in the debris flow that was delivered to the receiving stream, and therefore the structure and function of the deposit, varied by valley floor width. In narrow valley floors, the debris flows always had direct contact with the receiving channel. In broad valley floors, the majority of material transported by the debris flow was deposited on existing fans and terraces.

Management Implications

Landuse practices can affect watershed responses to flooding through the influences of managed vegetation patterns and roads on the delivery of water, sediment, and wood to streams (Swanson *et al.*, 1998). Forest road construction and timber harvest have replaced wildfire as major disturbances in much of the Pacific Northwest (Reeves *et al.*, 1995). 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). 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. By altering these aspects of the natural disturbance regime, landuse practices may have unforeseen and adverse impacts on aquatic ecosystems. Management practices need to ensure that when anthropogenic disturbances do occur, the essential linkages (e.g., coarse sediment and large wood inputs, nutrient and fine organic matter transfers, floodplain connections) that promote habitat recovery are not disrupted (Ebersole *et al.*, 1997).

Landslide risk and the potential consequences of debris flows should be considered prior to timber harvest or road construction on steep slopes. Preventive strategies could include removing large volumes of road fill that may initiate or be incorporated into debris flows. Other strategies include increasing the rotation age in low-order basins to reduce the time a basin is in a more sensitive state and providing riparian buffers along low-order streams to ensure an adequate supply of large wood to the channel.

Identifying the role of disturbance in the dynamics of sediment and large wood in headwater streams is important for understanding watershed processes and for aquatic conservation plans. Small streams are often directly impacted by landuse activities, but policy and management historically have not placed much consideration on the values of these streams and their associated riparian habitats (Beschta and Platts, 1986). Although low-order streams do not directly support fish, they may play a major role in habitat formation within the larger watershed (Reeves *et al.*, 1995). Because debris flows are a major disturbance process in steep mountainous terrain, this process should be recognized as an integral component of any long-term management strategy if native organisms and complex aquatic habitats are to persist (Reeves *et al.*, 1995).

CONCLUSIONS

Results of this study described how current and past forest management activities influenced characteristics of the initiation site, runout zone, and deposition of debris flows. Road related failures were associated with significantly longer runout lengths, larger landslide volumes, and greater total sediment volumes compared to debris flows through mature forests. Statistical power to detect differences among the forest age classes was extremely low because of the small sample size in relation to the high degree of variability observed in landslide and debris flow characteristics. It is incorrect to infer that failure to detect

a statistically significant difference indicates that no difference exists; it can only be concluded that statistical results were inconclusive. Furthermore, the extremely large sample size required to detect a statistically significant difference is likely to prohibit studies that can provide results with a high degree of certainty. Despite the uncertainty inherent in interpreting the results of studies with low statistical power, there is high ecological and social risk associated with landslide and debris flow processes, suggesting that trends in the data may be useful for management decisions. Clearcuts tended to be associated with increases in the density of landslides that initiated debris flows, and as a result, the length of stream channel affected by debris flows was occasionally greater than in mature forests. Debris flows through mature forests tended to have fewer and smaller landslides, shorter runout lengths, and the highest wood to sediment ratios in deposits. The cumulative runout length was the strongest predictor of the volume of sediment and wood transported by debris flow.

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