Debris Flows and Flood Disturbance in Small, Mountain Watersheds

by

Kai U. Snyder

A THESIS

submitted to

Oregon State University

in partial fulfillment of
the requirements for the
degree of

Master of Science

Presented July 12, 2000
Commencement June 2001

AN ABSTRACT OF THE THESIS OF

Kai U. Snyder for the degree of Master of Science in Forest Science presented on July 12, 2000. Title: Debris Flows and Flood Disturbance in Small, Mountain Watersheds.

Abstract approved: ____

Frederick J. Swanson

This study examined debris flows occurring in a 125 km^2 study area in the Blue River watershed in the western Cascade Mountains of Oregon over a 50-year period. Debris flow occurrence was found to be concentrated in a distinct zone of high activity occupying approximately half of the study area, characterized by weak rock, low elevation, and steep slopes. Three quarters of the total of 91 inventoried debris flows occurred during two seasons, in the winters of 1964-1965 and 1995-1996. Clearcutting appeared to increase debris flow initiation by 3-7 times relative to forest areas. Increases in initiation frequency from roads ranged from 11-50 times more frequent than forested areas. While land use activity was associated with an increase in debris flow frequency, it was not associated with changes in the elevation, slope steepness, and geologic site conditions of initiation. Stream network structure was a significant factor influencing the spatial distribution of debris flows and their disturbance of stream and riparian systems. Patterns of disturbance that were partially controlled by stream network structure were speculated to affect aquatic and riparian biota, perhaps influencing rates of recolonization following severe disturbance events.

LIST OF FIGURES

LIST OF TABLES

Debris Flows and Flood Disturbance in Small Mountain Watersheds

1. INTRODUCTION

Large flood events are one of the most significant forms of natural disturbance in the Pacific Northwest. Large floods in mountainous terrain are usually accompanied by debris flows, which are one of the primary drivers of landscape evolution in this region. Debris flows are rapid movements of water-charged soil, sediment, and wood down steep slopes (Dyrness 1967, Swanson et al. 1998). Debris flows are commonly initiated in headwater drainages, and may flow down channels, scouring streambeds and banks, and ultimately depositing sediment and organic debris in third- to fifth-order streams, or on terraces and fans (Benda 1990).

Flood events are of particular interest to scientists and managers not only as geomorphic sculptors, but also because flood-related processes rearrange the physical and biological structure of stream ecosystems, and cause damage to roads, stream-crossings, and buildings. Flood-related disturbance processes, including debris flows, are common throughout the world in steep and mountainous terrain (Sidle et al. 1985). Debris flows may serve as a link in a chain-reaction of disturbance processes, sometimes referred to as a disturbance cascade, in which an uphill process, such as a road-bed failure, initiates a debris flow, which may then trigger a subsequent downstream disturbance process (Nakamura et al. in press.)

To characterize temporal and spatial patterns of debris flows in a mountain landscape, I conducted a historical study of debris flow occurrence from 1946 through 1996 in the Lookout Creek and upper Blue River drainage basins in the Cascade Range, Oregon. Field data collected in previous studies by Dyrness (1967), Swanson and Dyrness (1975), Marion (1981), and Wallenstein and Swanson (1996) were compiled and analyzed. The overall objectives of this study were to characterize the spatial and temporal patterns of debris flows from 1946 through 1996, and to examine the associations between land use practices and debris flow occurrence. Specific objectives were to examine the frequency of debris flow occurrence by land use and geologic/topographic factors. Special attention was given to events in the natural forest to gain an understanding of the debris flow behavior in the absence of land use activity. Characteristics of debris flows associated with land use were compared with natural forest debris flows. Finally, relationships between patterns of disturbance and stream network structure were examined.

2. BACKGROUND

2.1 Debris flow initiation

Large flood events in the Pacific Northwest usually result from storms characterized by high intensity rainfall and associated melting of a pre-existing snowpack, producing high peak flows (Fredriksen 1965, Swanston and Dyrness 1973, Harr 1981, Jones and Grant 1996). Most mass soil movements, including debris flows, occur during these large storms (Swanston and Dyrness 1973, Harr 1981, Swanson et al. 1998). Since the designation of the H. J. Andrew Experimental Forest in 1948, there have been three large flood events: December 1964, January 1965, and February 1996. The December 1964 and January 1965 storms are often not distinguished in retrospective studies of soil mass movements, because the effects of the two storms cannot be separated in most cases. Consequently, these storms are considered a single event in this study. The storm of February 1996 produced 280 mm of rain in 4 days, while the December 1964 storm produced more than 330 mm in 4 days (Fredriksen 1965, Dyrness et al. 1996). However, four-day storms that deliver 330 mm are not considered unusual (Fredriksen 1965). According to the historical record, the 1964 flood was one of the most severe of six that have occurred in the Willamette Valley since 1861, an average of one every 17 years between 1861 and 1964 (Fredriksen 1965). However, streamflows from the storms of 1996 and 1964 exceeded recorded peak flows of the prior 50 years in streams in the Willamette Valley (Dyrness et al. 1996, Fredriksen 1965).

2.2 Floods and aquatic biota

Debris flows and other flood-related disturbance processes can have major, diverse effects on stream and riparian systems. In one study of stream biota recovery following a debris flow, trees and understory plants were removed for a distance of 5 to 15 m back from the stream banks over the entire length of a debris flow path (Lamberti et al. 1990). This canopy opening greatly increased solar radiation reaching the stream, and reduced litter fall to the stream from adjacent forest. High irradiance levels and reduced grazing by macroinvertebrates contributed to a rapid accrual of benthic algae, which formed the bioenergetic basis for ecosystem. Trout populations were locally decimated immediately following the debris flow, but by the second and third years following the disturbance, trout densities had increased markedly. By the fall of the third year, densities in the disturbed reaches were about double those in the undisturbed upstream reach. Nonetheless, despite the generally rapid recovery of the biota, most populations showed broad temporal fluctuations in abundance, suggesting that ecosystem stability was diminished by the debris flow (Lamberti et al. 1990).

2.3 Spatial characteristics of debris flow disturbance

Debris flow disturbance varies across the landscape, creating spatial complexity in the ecosystem. First- and second-order channels are source areas for sediment and woody debris, which is delivered to higher-order channels by debris flows and other processes. In the absence of debris flows, stream flow velocities in first- and second-order streams are commonly insufficient to disrupt and transport the coarse armor layer that protects the underlying sediment from stream erosion (Benda 1990). Third- through fifth-order valleys are typically deposition areas for debris flows. Along these streams, debris flow deposits form fans, levees, and boulder accumulations, and thus may control the distribution of very large boulders in the channel. These boulders, as well as organic debris, enhance the structural complexity of channels. Deposition of debris flows in third- through fifth-order streams may influence patterns of alternating scour and deposition along the channel. In the Oregon Coast Range, one researcher found that deposition of one or more debris flows in alluvial channels promotes a gravel-bed morphology (Benda 1990).

The importance of the spatial complexity of landforms and habitats to the persistence of aquatic biota has been well established in theory (Sedell et al. 1990, Dunning et al. 1992), and increasingly is finding support in empirical studies (e.g. Pearsons et al. 1992). The episodic contribution of sediment, boulders, and coarse woody debris by mass movements maintains the complex physical characteristics of stream networks, and may contribute to the habitat diversity important for aquatic organisms (Swanson and Lienkaemper 1978; Reeves et al. 1995; Bisson et al. 1996). Examples of mechanisms that enable persistence of aquatic biota despite disturbance include the recolonization of affected streams or reaches by populations of organisms through dispersal from local or internal refugia, and stabilizing effects that emerge from complex life histories (Rieman and Clayton 1997).

2.4 Factors associated with debris flow occurrence

While rainfall and snowmelt influences when debris flows occur, topographic, geologic and soil-cohesion factors strongly influence where they occur. Debris flows commonly initiate from debris slides that reach a stream channel. Landslides and debris flows result from soils of low internal strength, sufficient water for saturation or near-saturation, and at least moderately steep slopes (Sidle et al. 1985). In the western Cascades, Dyrness (1967) and Swanson and Dyrness (1975) found that more than 98% of the slides they inventoried occurred on soil types with very high concentrations of expansive clays. Parent material structure and rooting structures of trees and understory vegetation also affect soil stability (Swanston and Dyrness 1973).

Previous studies have found slope steepness to be the most significant factor in determining probable locations of occurrence (Dyrness 1967, Swanston and Dyrness 1973, Sidle et al. 1985). In a study in the western Cascades, two thirds of failures occurred on slopes between 38^{o} and 45^{o} (Dyrness 1967). Only about one-sixth occurred on slopes with a gradient less than 25^{o}. No failures in clearcuts were found on slopes under 30^{o} (Dyrness 1967). In the Coast Range, Gresswell et al. (1979) report that 95% of all failures occurred on slopes greater than 35^{o}, while Ketcheson and Froehlich (1978) found that half of the failures in undisturbed drainages and nine-tenths in clearcuts occurred on slopes of 38^{o} or greater. According to Ketcheson and Froehlich (1978), all natural failures were on slopes between 32^{o} and 47^{o}, while Gresswell et al. (1979) found that the greatest number of natural and road-related events occurred on slopes greater than 38^{o} (77% of natural failures and 81% of road-related failures). This corresponds to the upper limit of the angle of internal friction for inorganic silts in the absence of water (Gresswell et al. 1979).

Shallow, coarse-grained soils low in clay-size particles that have little or no cohesion are prone to sliding (Ketcheson and Froehlich 1978, Swanston and Dyrness 1973). In the western Cascades mass movements occur much more frequently in soils derived from pyroclastic rocks (tuffs and breccias) than in basalt or andesitic lava flow rock types. Dyrness (1967) reported that 94% of the events occurred in areas with tuff or breccia, even though only 37% of the total study area was made up of these rocks.

Aspect has not been found consistently to be an important factor contributing to mass soil movements in the Pacific Northwest. No significant relationship has been found between failure frequency and aspect (Ketcheson and Froehlich 1978, Gresswell et al. 1979, Dyrness 1967). In the Oregon Coast Range slightly over half of the failures in natural forest have been reported to originate in northwest and northeast aspects (Ketcheson and Froehlich 1978), but generally, landslides are nearly equally distributed between northerly and southerly slopes (Gresswell et al. 1979). In at least one study in the Cascades, mass movements are less common on slopes with a south or southwest aspect, possibly because rock weathering and soil formation proceeds much more slowly on the drier aspects. Southerly slopes are characterized by dry ravel and high fire frequency, facilitating soil loss by non-mass movement processes. The resulting shallow soils and less deeply weathered rocks may give rise to a greater degree of stability (Dyrness 1967). However, in both Coast and Cascade Range examples, geologic factors also vary with aspect, so it is difficult to separate influences of the various factors.

2.5 Land use and debris flows

Land use can strongly affect occurrence of debris flows by altering the hydrologic regime and vegetation of forested hillslopes. Roads and clearcuts may increase the frequency and size of debris slides. Debris flows commonly are initiated by debris slides; so increased rates of debris sliding are usually accompanied by a higher frequency of debris flows.

Roads have been identified as one of the greatest causes of recent mass movements in the western states (Sidle et al. 1985). Road construction disrupts the basic equilibrium of steep slope forest soils through alteration of slope drainage, slope loading, creation of uncompacted fills, and slope undercutting. Rainfall is intercepted and concentrated on roads by compacted road surfaces, ditches, bench cuts, and road fills. Ditches may carry water from cut slopes and road surfaces into marginally stable fills. This encourages saturation, development of positive pore pressure, and increased unit weight both in fillslope material, and potentially in soils upslope and downslope from the road cut. Poor drainage and plugged culverts may magnify these problems by ponding water on the upslope side of the road. In addition, slope undercutting by benching along oversteepened slopes removes support for the upslope soil, increasing the potential for cutslope slides (Swanston and Dyrness 1973).

Clearcutting has been associated with increases in both the frequency and size of debris slides, which in turn leads to a higher frequency of debris flows. Increases in the rate of sliding in clearcuts may range from 1.9 to 3.7 times when compared with undisturbed forest (Sidle et al. 1985). In addition, slope failures have been found to travel

1.7 times farther in clearcuts than in undisturbed watersheds in the Oregon Coast Range (Ketcheson and Froehlich 1978). Forest removal by clearcutting has been shown to reduce rooting strength and alter the hydrologic regime (Gresswell et al. 1979, Sidle et al. 1985). Vegetative cover helps control the amount of water reaching the soil and the amount held in the soil, while the root systems of trees and other vegetation contribute to the shear strength of unstable soils. However, the direct effect of interception by vegetation on the soil water budgets is probably not large, especially in areas of high total rainfall, and during large storms when most soil mass movement occurs (Swanston and Dyrness 1973).

The absolute and relative rates of sliding from land use affected sites appear to change as land use practices change. In a study in the Coast Range, for example, slides from clearcuts were found to be 5.7 times more frequent than from roads (Gresswell et al. 1979). Of all slides, only 14% were road-associated. This relatively low frequency of road failures may be directly related to the implementation of an intensive road and culvert maintenance program, and improved road design, location, and construction techniques. Nonetheless, road-related failures, while fewer in number, were by far the largest, averaging 660 cubic meters per failure, or about seven-fold higher in volume than natural failures (Gresswell et al. 1979). However, in making such comparisons it is important to note potential differences between physiographic provinces. For example, Swanson et al. (1981) observed large differences between average volumes of non-road slides between Coast Range and Cascades sites, but volumes of road-related slides were similar in size distribution.

3. METHODS

3.1 Study area

The study area included the Lookout Creek watershed and a portion of the upper Blue River watershed, which are located in the Willamette National Forest about 65 km east of Eugene. Lookout Creek watershed encompasses the H.J. Andrews Experimental Forest, a Long-Term Ecological Research (LTER) site sponsored by the National Science Foundation and the U.S.D.A. Forest Service. Three tributary sub-watersheds of the upper Blue River drainage basin, Cook Creek, Quentin Creek, and Mann Creek, were excluded from this study due to the lack of comprehensive data prior to 1996. Together, the Lookout Creek and upper Blue River watershed study area occupy 125 km^2.

Winters in the study area are usually cool and wet, while summers are dry and warm (Strahler and Strahler 1998). Precipitation is highly seasonal, occurring mostly during the period from November to April. Average annual precipitation exceeds 2500 mm, which usually falls in the form of snow above 1000 m, and as rain below 400 m. Rainfall, augmented by snowmelt, can deliver high levels of water to the soil and streams in this transient-snow zone (Harr 1981). Watershed elevations range from 300 m to 1600 m, and slopes are commonly steeper than 30^o. At low elevations, the soils are predominately derived from tuffs and breccias, while at higher elevations the soils are

Figure 1. Location of the study area including Lookout Creek watershed and Blue River watershed (south of the dashed line), in the state of Oregon.

derived from andesite lava flows and volcanic ash (Swanson and James 1975, Priest 1988, Walker and Duncan 1989). The native forest vegetation is dominated by Douglas-fir (*Pseudotsuga menziesii*) and western hemlock (*Tsuga heterophylla*) at low to mid-elevations, and Pacific silver fir (*Abies amabilis*) and noble fir (*Abies procera*) at high elevations. Clearcut logging has created a patchwork of plantations 30 to 50 yrs old, occupying about 25% of the watershed.

The upper Blue River is a sixth-order stream, and Lookout Creek is a fifth-order stream network (c.f., Strahler 1952). Eighty-nine percent the length of the stream network of Lookout Creek and upper Blue River is comprised of first- through third- order streams. Fourth- through sixth-order streams make up 11% of the network.

In this study, fourth- through sixth-order streams were commonly referred to as 'mainstem streams', while first- through third- order basins that drain to a mainstem stream were referred to as 'sub-basins'. Debris flow occurrence was often calculated in terms of the 'longest single channel length' (cf., May 1999), which was defined as the longest single stream channel or debris flow track from a channel head to the mouth of a sub-basin. This term was useful in preventing ambiguity where debris flow tracks overlap, and as a generalized indication of the relative size of a sub-basin.

3.2 Data acquisition

3.2.1 Field data

All field data, except termination site data, were gathered in previous studies by Dyrness (1967), Swanson and Dyrness (1975), Marion (1981), and Swanson and Wallenstein (1996). Termination site data were interpreted by this author and Fred Swanson using field observations, photo interpretation, and notes of previous workers. Field surveys involved combinations of driving the full road network, walking parts of the stream network, and examining aerial photographs to locate events. Measurements were taken on-site for each event. Overall, methodologies were fairly consistent across studies. Attributes of landslides that were measured in the field included:

1) year of occurrence
2) slope steepness at initiation site
3) volume of initiating landslide
4) land use at initiation site
5) topographic setting at initiation site
6) termination site location (for some events)

Data collection methods for each were as follows:

Year of occurrence: Due to the seasonal nature of debris flow activity, debris flow events were reported in this study according to the "water year", which was defined as the period beginning October 1 of the prior calendar year and ending September 30 of the current calendar year. The abbreviation “WY” is used throughout for water year.

For the majority of the events, a researcher or forest manager discovered the debris flow in the field in the year that it occurred, so the year of occurrence was known. In the cases of the December 1964, January 1965, and February 1996 events, inventories were conducted of these specific storms. However, in instances when the year of occurrence was not certain, the original researchers used aerial photos to bracket the probable date. Additionally, tree-ring analysis was used to age the debris slide event when possible.

Slope steepness: Slope steepness at the initiation site was measured in the field using a clinometer. Field slope measurements were compared against Digital Elevation Model (DEM) -derived measurements. Overall, DEM-derived slope values were 8^{o} more gentle than field-measured slope values. For more information see Appendix B.

Volume of initiating landslide: The volume of the landslide that initiated the debris flow was calculated from length, width, and depth measurements taken in the field using a tape measure or rangefinder.

Land use: Land use at the debris flow initiation site was determined in the field by the respective researcher who conducted the field work. Land uses included natural forest, plantation, or road. Additional distinctions included plantation age and particular influence of roads, such as cut and fill slopes and drainage.

Topographic setting: Topographic setting was also determined in the field by the researcher. Topographic settings were lumped into three categories for this study: channel head, planar hillslope, and streamside slide. Channel head sites included bedrock hollows and locations in which the landslide occurred in a topographic region characterized by convex contour lines draining to an established stream channel. Planar hillslope sites were defined as locations where the hillslope was neither convex nor concave along the contour. Streamside slides occurred characteristically on the oversteepened stream banks within 20 m of the stream, and commonly had width greater than height.

Termination site: A debris flow termination site was defined as the location where the majority of the large boulders, rocks, and woody debris was deposited. In most cases the termination site was a distinct deposit or a site where debris flow material was thoroughly redistributed after entering a fourth-order or larger channel. The termination site was determined by reviewing field notes from the past studies, examining aerial photographs, and field investigation. Termination site types included: floodplain, fan, terrace, small stream (first- through third-order stream channel), large stream (fourth- or higher-order tributary junction), and road.

3.2.2 GIS data

The Arc/Info and ArcView GIS software (Environmental Systems Research Institute, Redlands, CA) were used for spatial analysis of debris flows, land use, geologic, and topographic variables. The GIS data analyzed in this study included:

1) debris flow tracks
2) hydrography
3) geology
4) elevation

5) slope steepness
6) land use

Debris Flows: George Lienkaemper, then of the USDA Forest Service PNW Research Station (Forestry Sciences Laboratory, Corvallis, Oregon), originally digitized the debris flows. I subsequently corrected the location of several events and added a few that had been overlooked, based on interpretation of air photos. Debris flow length was calculated from the debris flow layer in Arc/Info. Hydrography was derived from the USGS 1:24,000 topographic maps and subsequently modified by George Lienkaemper during field investigations. The effectiveness of identification of debris flow events was examined in greater detail in Appendix B.

Geology: The geology layer was created by Fred Swanson and George Lienkaemper, based on earlier research (Swanson and James 1975, Priest et al.1988, Walker and Duncan 1989). Geological units were grouped into three distinct zones representing weak, moderate and strong rock types. Weak rock types included volcaniclastic rocks, especially tuffs and breccias, 18-25 million years old; moderate-strength rocks included volcaniclastics approximately 14 million years old (predominantly ashflows); and strong rock types were composed of ridge-capping lava flows, 4-8 million years old.

Elevation: Elevation was derived from 10 m Digital Elevation Models (DEMs) in Arc/Info. Three elevation zones were defined: 400 m to 750 m, 751 m to 1000 m, and 1000 m to 1700 m.

Slope Steepness: Slope steepness was also derived from 10 m DEMs. Slope steepness was divided into two zones: a gentle slope category of 0-20^o; and a steep slope category of >20^o.

Land use: Land use was created in Arc/Info by overlaying a buffered roads layer with the vegetation layer (created by the Willamette National Forest from aerial photos and SPOT satellite imagery). Roads were buffered by 16 m to account for the total average width of the roadbed including ditches (c.f. Silen and Gratkowski 1953; Wemple 1994).

3.3 Methods of analysis

3.3.1 Data pretreatment

Multicolinearity between slope steepness, geology, and elevation was investigated using analysis of variance (ANOVA). All two-way comparisons were examined. Strong rock types occur in high elevations, although there was no evidence for an association between elevation and weak and moderate rock types ($p = 0.0006$, ANOVA, N=91). There was insufficient evidence to identify an association between elevation and the DEM-based slope steepness at the initiation site ($p = 0.08$, ANOVA, N = 83). There was no evidence that DEM-based slope steepness of the initiation site is associated with rock type ($p = 0.68$, ANOVA, N=91).

3.3.2 *Statistical analyses*

Analysis of Variance (ANOVA) was used for several analyses. A log-transformation was necessary for the length variable. Comparisons were as follows:

Elevation X Initiation Site Land Use

Slope X Initiation Site Land Use

Length X Initiation Site Land Use

Length X Initiation Site Land Use (non-mainstem events only)

Length X Transportation Land Use

3.3.3 Qualitative comparisons

Whenever possible, comparisons were made on a unit-area basis. For natural forest, the number of events per percent-area was used in order to make comparisons across multiple years when the extent of the forest was being reduced over time. The distribution of topographic and geologic variables in natural forest remained relatively similar during the study period, although the overall area was reduced by approximately 30%. When unit-area calculations were not possible, the percentage of the total number of events was compared.

Frequency of occurrence was calculated using a GIS by overlaying debris flow events with land use, geology, elevation, and slope steepness layers to determine the number of events per hectare for each class. For topographic position, percentage of occurrence was calculated.

For rock type, elevation, and slope steepness class, debris flow frequency was calculated cumulatively over the whole study period as well as in WY 1965 and WY 1996 separately. For plantation- and road-associated land uses, frequency of occurrence was calculated in WY 1965 and WY 1996 only. The amount of area in plantation and road land uses changed dramatically during the study period, so multi-year unit-area calculations were not practical.

Three debris flow disturbance zones were defined in the stream network: primary, secondary, and tertiary. Primary disturbance zones refer to debris flow transportation tracks. Secondary disturbance begins at the termination site of a debris flow track, and ends at the confluence with a mainstem stream. Consequently, if a debris flow terminates at a mainstem stream, there is no secondary disturbance zone. Secondary disturbance zones are characterized by disturbance to riparian vegetation and deposition of sediment by fluvial processes subsequent, and unique from, the upstream debris flow event. The tertiary disturbance zone refers to the length of mainstem stream below the entry of a debris flow. The tertiary zone may experience stream channel and riparian disturbance that is accentuated by the contribution of sediment and wood delivered by the debris flow.

The mapped locations of debris flow transportation tracks were used to identify the primary disturbance zone. Secondary and tertiary disturbance zones were delineated by referencing the location of debris flow termination sites in the overall stream network structure. The length of each zone was summed by stream order.

4. RESULTS

4.1 Initiation

Between 1946 and 1996 91 inventoried debris flows occurred in the study area. Debris flows occurred in 12 of the 50 years, and 75% of inventoried debris flows took place in 1996. The rate of debris flow initiation in all other years was very low; no more than 4 events occurred in a single year (Figure 2, Figure 3).

The frequency of debris flows over the 50 year study period in weak rock types was 2.3 times greater than moderate-strength rock types, and a little more than 7 times greater than strong rock types (Table 1). Debris flow initiation sites ranged 530 m to 1045 m in elevation. The average elevation at the initiation site was 727 m. Approximately three-quarters of the initiation sites (68 debris flows) were located in the lowest quartile elevation zone (400 m to 700 m).

Based on field-measured slope values, initiation occurred on slopes ranging from 19 ^{o} to 50 ^{o}. The average slope angle was 35^{o}. Sixty-four percent of all events occurred on slopes between 31 ^{o} and 40 ^{o}. Only one event occurred in the gentle (<20^{o}) slope category (Table 1).

Of the three topographic settings, 57% of the initiation sites were located on planar hillslope settings, 30% initiated from channel heads, and 10% were triggered by streamside slides. The topographic setting of 3% (3 events) was unknown (Table 1).

Figure 2. Debris flows in the H.J. Andrews Experimental Forest and upper Blue River watershed, 1946-1996.

Figure 3. The pattern of debris flow initiation by year, WY 1946 - WY 1996.

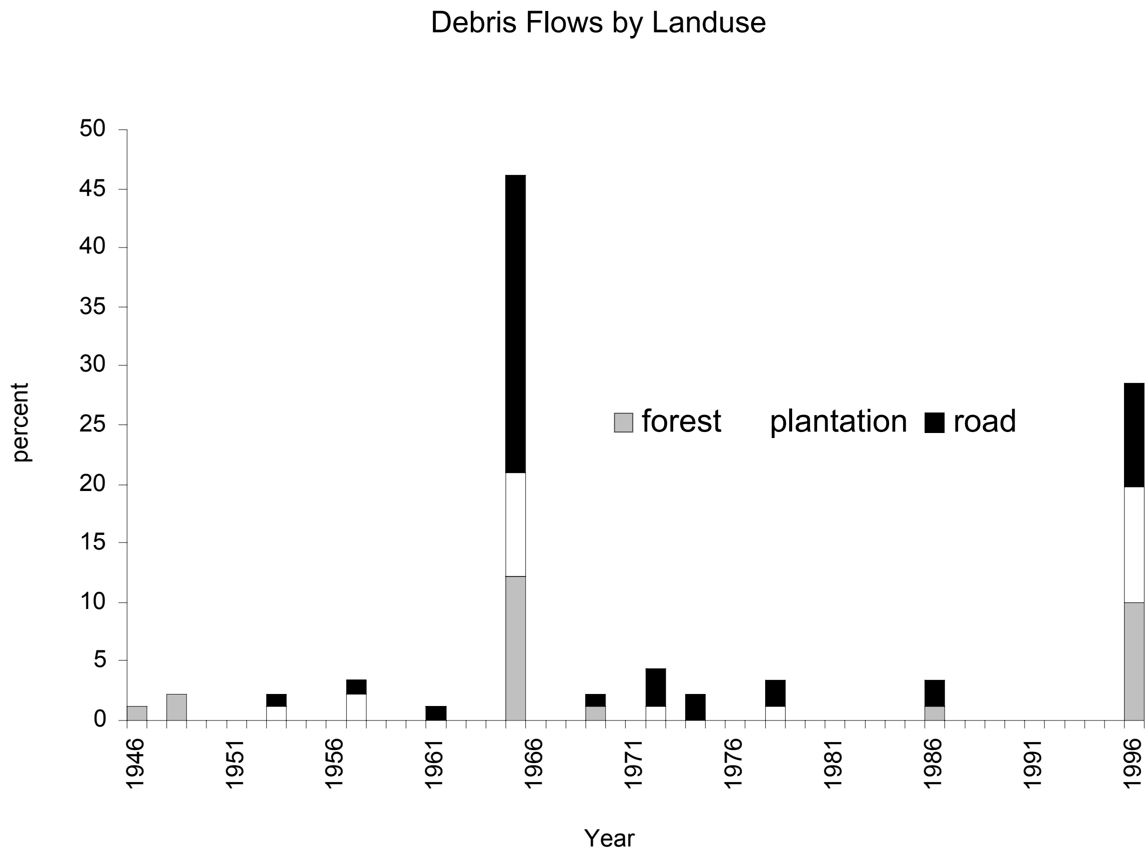


Table 1. An overview of debris flow occurrence WY 1946- WY 1996: cumulative density over the study period, and the number and percentage of events by land use.

Cumulative Density of debris flows										
	All Events				Natural Forest		Plantations		Roads	
Geology	# dfs	%df	ha	#/ha	#	%	#	%	#	%
weak	22	24	1090	0.0202	9	10	3	3	10	11
moderate	56	62	6470	0.0087	11	12	18	20	27	30
strong	13	14	4840	0.0027	6	7	1	1	6	7
					26	29	22	24	43	47
Elevation										
400-699m	40	44	2430	0.0165	10	11	14	15	16	18
700-999m	50	55	4960	0.0101	16	18	8	9	26	29
1000-1699m	1	1	5010	0.0002	0	0	0	0	1	1
					26	29	22	24	43	47
Slope										
0^o - 19^o	1	1	6060	0.0002	0	0	1	1	0	0
20o +	90	99	6340	0.0142	26	29	21	23	43	47
					26	29	22	24	43	47
Topo. Setting										
channel head	27	30	n/a	n/a	6	7	11	13	10	11
planar hillslope	52	57	n/a	n/a	14	16	10	11	28	32
stream-side	9	10	n/a	n/a	5	6	1	1	3	3
unknown	3	3	n/a	n/a	1	1	0	0	2	2
					26	29	22	24	43	47

In natural forest, 26 debris flows (29% of the total) occurred during the study period (Table 1). Natural forest events occurred in 6 of the 12 debris flow-producing years. Debris flow initiation frequency in weak rock types in natural forest was 5 times greater than in moderate and strong geologic types, on a number per percent-area basis (Table 2). Thirty-five percent were from weak, 42% moderate, and 23% from strong rock types.

Initiation site elevations in natural forest ranged from 605 m to 990 m, with an average of 763 m. Initiation frequency was similar for the 400-699 m and 700-999 m zones during the study period, with 0.5 and 0.4 events per percent-area, respectively. No events occurred between 1000-1699 m in natural forest.

The range of slope steepness at natural forest initiation sites was 23° to 50°. The average slope angle was 36°. There were no debris flows in natural forest in the gentle (<20°) slope category (Table 2).

Planar hillslope events were by far the most frequent (54%) in natural forest. Only 6 events initiated from channel heads in natural forest, while 5 events initiated from streamside areas. Topographic setting was unknown for 3 events.

In natural forest, debris flows initiated in a narrower band of elevations than the overall historical range of elevations. The minimum initiation elevation in natural forest was 75 m higher, and the maximum initiation elevation was 55 m lower than the overall historical initiation elevations. The average elevation in natural forest was 1.6% higher than the overall average. Similarly, the minimum slope angle of initiation was 4° higher in natural forest than the overall minimum slope angle. The average initiation slope angles were virtually the same; the average was 1% higher for natural forest.

The range of values for site characteristics at the initiation point in natural forest, including geology, elevation, slope steepness and topographic position, varied slightly from the overall pattern. The density of initiation on weak rock when compared to moderate rock was nearly 5 times greater in natural forest than the overall rate. However, the difference in the density of initiation between weak and strong rock types was similar for natural forest as the overall initiation density.

The distribution of initiation sites by topographic position was very similar for natural forest versus all debris flow events. Three percent fewer initiation sites were located on planar hillslopes in natural forest. At channel heads there were 7% fewer events, while there were 9% more from the stream-side in natural forest than overall. The number of unknown sites was about the same; there were 1% more unknown sites in natural forest.

Table 2. Debris flow occurrence in natural forest for all years combined, and for all years combined, and for WY 1965 and WY 1996 separately.

Natural Forest										
	All years (1946 area)				WY 1965			WY 1996		
Geology	#	%	%area	#/%area	#	%area	#/%area	#	%area	#/%area
weak	9	35	9	1.02	5	8	0.66	3	8	0.38
mod	11	42	52	0.21	5	52	0.10	2	48	0.04
strong	6	23	39	0.15	1	40	0.02	4	44	0.09
Elevation										
400-699	10	38	20	0.51	4	17	0.24	3	16	0.18
700-999	16	62	40	0.40	7	40	0.18	6	37	0.16
1000-1699	0	0	40	0.00	0	43	0.00	0	46	0.00
Slope										
0^o - 19^o	0	0	49	0.14	0	0	0.00	0	46	0.00
20^o +	26	100	51	0.37	11	53	0.21	9	54	0.17
Topo. Setting										
chan. head	6	23	n/a	n/a	0	n/a	n/a	5	n/a	n/a
hillslope	14	54	n/a	n/a	7	n/a	n/a	3	n/a	n/a
stream-side	5	19	n/a	n/a	3	n/a	n/a	1	n/a	n/a
unknown	1	4	n/a	n/a	1	n/a	n/a	0	n/a	n/a

In WY 1965, 19% of the debris flows initiated from plantations, while 26% initiated from natural forest. Plantation-associated initiation in WY 1996 accounted for 35% of the debris flows, the same percentage as natural forest in that water year (Table 3, Figure 4). However, the frequency of debris flow initiation was 7 times greater in plantations than in natural forest in WY 1965, and 3 times greater in plantations than in natural forest in WY 1996 on a unit-area basis (Figure 5, Table 3).

On a percentage basis, 47% of the debris flows during the whole study period originated from roads, whereas 29% originated from natural forest. However, debris flow initiation was approximately 50 times more frequent from roads than from natural forest in WY 1965, on a unit-area basis. In WY 1996 the frequency of road-related debris flow initiation was more than 11 times that of natural forest (Figure 4, Table 3).

Figure 4. Debris flow frequency by land use, WY 1965 and WY 1996.

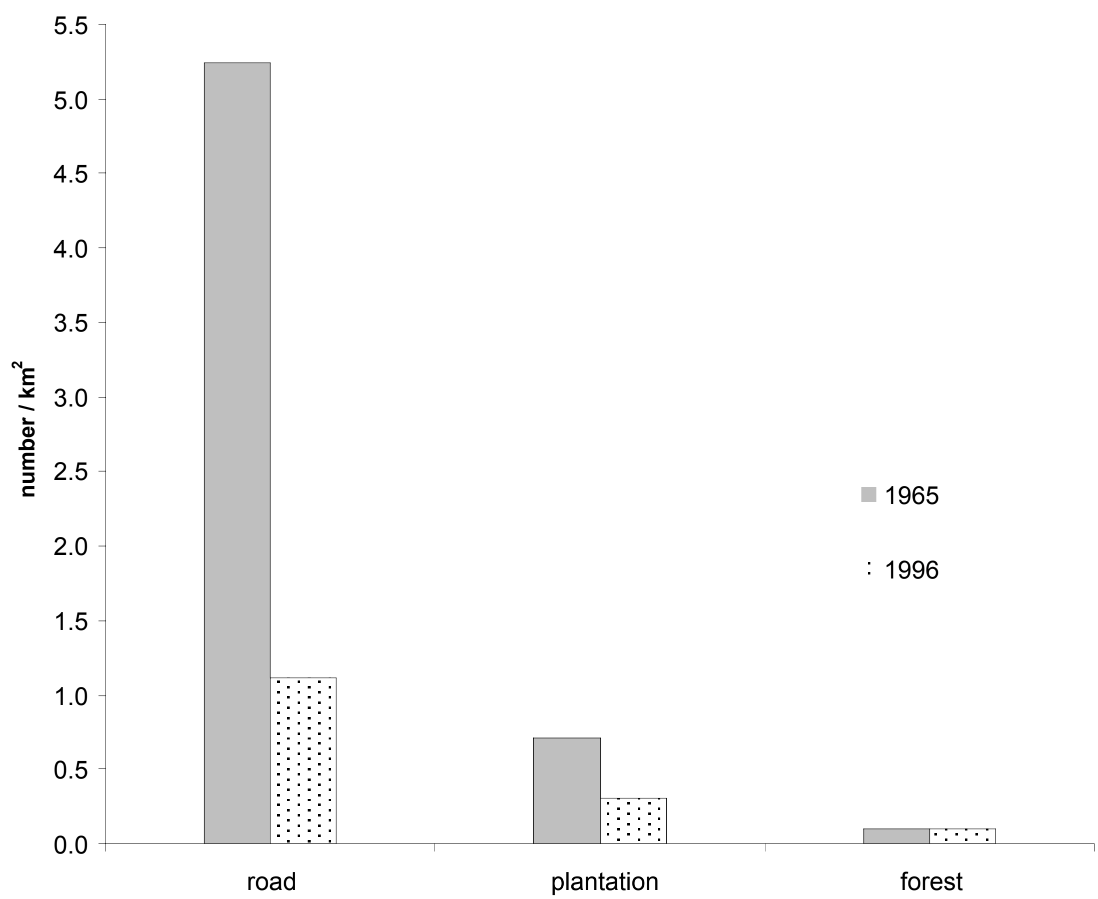


Table 3. Debris flow initiation WY 1965 and WY 1996. The number of events, percentage of each year's total, and density (#/km^2) are represented for geology, elevation, slope, and topographic position.

	water year 1965									water year 1996								
	forest			plantation			road			forest			plantation			road		
Geology	#	%	#/km^2	#	%	#/km^2	#	%	#/km^2	#	%	#/km^2	#	%	#/km^2	#	%	#/km^2
soft	5	12	0.60	1	2.4	0.59	7	17	7.78	3	12	0.44	0	0	0.00	3	12	3.00
mod	5	12	0.09	6	14	1.02	13	31	5.65	2	7.7	0.18	9	35	0.48	3	12	0.73
hard	1	2.4	0.02	1	2.4	0.29	3	7.1	2.73	4	15	0.40	0	0	0.00	2	7.7	1.00
Total:	**11**	**26**	**0.10**	**8**	**19**	**0.73**	**23**	**55**	**5.35**	**9**	**35**	**0.10**	**9**	**35**	**0.30**	**8**	**31**	**1.13**
Elevation																		
400-699	4	10	0.22	4	10	0.98	12	29	6.32	3	12	0.21	8	31	0.98	2	8	1.00
700-999	7	17	0.16	4	10	0.89	11	26	0.06	6	23	0.18	1	4	0.07	6	23	1.94
1000-1699	0	0	0.00	0	0	0.00	0	0	0.00	0	0	0.00	0	0	0.00	0	0	0.00
Total:	**11**	**26**	**0.10**	**8**	**19**	**0.73**	**23**	**55**	**5.35**	**9**	**35**	**0.10**	**9**	**35**	**0.30**	**8**	**31**	**1.13**
Slope																		
0° - 19°	5	12	0.10	2	4.8	0.33	9	21	2.65	0	0	0.00	2	7.7	0.13	4	15	0.74
20° +	6	14	0.10	6	14	1.20	14	33	15.56	9	35	0.19	7	27	0.48	4	15	2.35
Total:	**11**	**26**	**0.10**	**8**	**19**	**0.73**	**23**	**55**	**5.35**	**9**	**35**	**0.10**	**9**	**35**	**0.30**	**8**	**31**	**1.13**
Topo. Position																		
channel head	0	0	n/a	5	13	n/a	5	13	n/a	5	19	n/a	4	15	n/a	2	7.7	n/a
hillslope	7	18	n/a	3	7.5	n/a	17	43	n/a	3	12	n/a	4	15	n/a	6	23	n/a
streamside	3	7.5	n/a	0	0	n/a	0	0	n/a	1	3.8	n/a	1	3.8	n/a	0	0	n/a
unknown	1	1	n/a	0	0	n/a	1	0	n/a	0	0	n/a	0	0	n/a	0	0	n/a
Total:	**11**	**26**	**0.10**	**8**	**19**	**0.73**	**23**	**55**	**5.35**	**9**	**35**	**0.10**	**9**	**35**	**0.30**	**8**	**31**	**1.13**

Debris flows from plantations originated at lower elevations, on average, than from natural forest (p=0.002, df=2., F=6.5, ANOVA). The mean elevation of the initiation site for debris flows in plantatations was 90 m lower than natural forest. There was no evidence that debris flows originated on more gentle slopes in plantations, on average, than in natural forest (p=0.52, ANOVA).

On a percentage basis, debris flows initiated from channel head topographic settings in plantations at nearly twice the rate of natural forest, although the number of observations was small (n=14). The rate of initiation from planar hillslopes was similar for plantations (13%) and natural forest (16%).

During the entire period of record, 62% of plantation-initiation occurred in the first 9 years following harvest. No plantation events in WY 1965 occurred in plantations more than 14 years old. Initiation from plantations in WY 1996 was distributed fairly evenly across the range of plantation ages, with 3 events occurring in plantations 30 to 34 years old. In WY 1996, 3 of the 9 events originated in plantations that were clearcut in WY 1965 or earlier. The frequency of initiation in WY 1996 was approximately half the frequency of WY 1965, although there were more events in WY 1996 than in WY 1965 (Figure 5).

Figure 5. Debris flow initiation following plantation establishment. The number and frequency of WY 1965 and WY 1996 events that initiated in plantations are presented in 5-year increments by plantation age at the time of the flood event. Density is calculated based on the total area of plantations at the time of the flood event.

		WY 1965			WY1996	
Plantation Age (yrs)		#	#/ha		#	#/ha
0 - 4		2	0.0018		-	-
5 - 9		3	0.0027		3	0.0010
10 - 14		3	0.0027		-	-
15 - 19		-	-		1	0.0003
20 - 24		-	-		2	0.0007
25 - 29		-	-		-	-
30 - 34		-	-		3	0.0010

There were too few data for statistically meaningful unit-area comparisons between roads and natural forest within rock type, elevation, slope steepness, and topographic position categories. Consequently, the following comparisons between road and natural forest initiation are reported only by percentage of the total number of events that occurred during the study period.

Debris flow initiation in moderate-strength rock types was 2.5 times more frequent from roads than from natural forest (Table 1). Thirty percent of all debris flows on moderate-strength rock types originated from roads, while 12% originated from natural forest. The rate of initiation from weak and strong geologic types was similar for roads and natural forest. The rate of initiation from the 700-999 m elevation class was 1.6 times higher for roads than for natural forest. Twenty-nine percent of all debris flows originated from roads at elevations ranging 700-999 m, while 18% originated from natural forest. Of the total of 91 debris flows, the only event that originated above 1000 m was from a road (Table 1).

The rate of a debris flow initiation on hillslope topographic settings for road-associated events was double that of natural forest events. Thirty-two percent initiated from hillslopes on roads, while 16% originated on hillslopes in natural forest. The rate of initiation from roads on steep slopes (DEM slope >=20^{o}) was similar to that of natural forest. Twenty-seven percent of the road-initiated events originated on steep slopes, whereas 21% originated from natural forest on steep slopes.

4.2 Debris flow transportation

Based on the longest single channel lengths, the median debris flow transportation track length was 490 m, with a range of 100-1550 m. Twenty-four percent of the 91 debris flow initiation sites merged with at least one other debris flow transportation track. Within a single first- to third-order sub-basin, the range of debris flow tracks that merged was from 2 to 4. In all sub-basins that experienced multiple debris flows, the debris flow tracks merged. Of the debris flows that did not terminate at a mainstem stream, on average 63% of the total length of the longest single channel experienced primary debris flow disturbance (Figure 6).

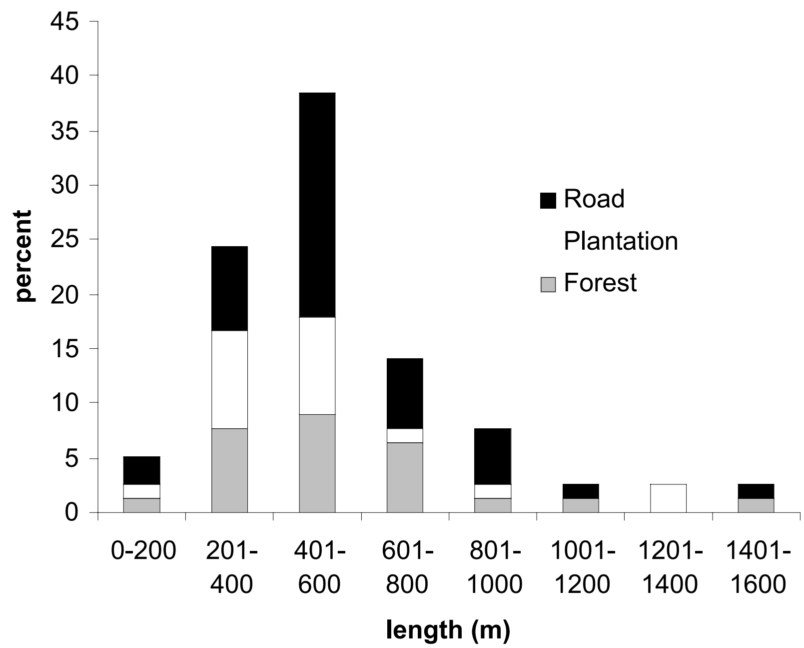
The majority of the debris flow tracks (63%) were relatively short (<600 m), and did not encounter a tributary junction. Of those that did cross tributary junctions, 29% crossed only one tributary junction, and only 7% crossed more than 2 tributary junctions. All debris flows that terminated at a tributary junction terminated at the confluence with a mainstem stream.

There were 18 debris flow tracks that both initiated and transported through natural forest. The range of natural forest track lengths was from 180 to 1550 m (median track length = 430 m). In only one case did debris flow tracks converge in natural forest (Figure 6).

There was no evidence of a statistically significant difference in the log-transformed mean debris flow length between events that initiated in natural forest, plantations, and roads (p=0.75, ANOVA). The median track lengths for plantation-, road-, and natural forest-associated initiation sites were, 443 m, 517 m and 429 m, respectively.

Land use along the transportation track did not have a detectable influence on the likelihood of a debris flow reaching a mainstem stream. Fourteen debris flow transportation tracks passed exclusively through plantations, and 20 tracks passed exclusively through natural forest. In plantations, 8 events (57%) reached a mainstem stream, while in natural forest 11 events (55%) reached a mainstem stream. However, the small number of observations limited the strength of this analysis.

Figure 6. Debris flow track length, based on longest single channel length, by land use.



4.3 Termination

A total of 78 debris flow termination sites were inventoried. Twenty-eight percent (22 sites) terminated at a mainstem stream tributary, 24% (19 sites) terminated in a first- through third-order channel, 28% (22 sites) terminated at a road, and 10% (8 sites) terminated on a floodplain, terrace, or a fan. The termination setting of 9% (7 sites) was indeterminable.

Nineteen percent of the debris flow termination sites (15 sites) resulted from events that initiated, transported, and terminated in natural forest. Of these, the majority (7 events) terminated at a mainstem stream, 4 events terminated in a first- to third-order stream, and 2 events terminated on a fan. The topographic setting of termination was unknown for 2 events. No natural forest sub-basin experienced more than one debris flow initiation event in a single year, and only one experienced a second debris flow during the study period.

The percentage of events that reached a mainstem stream was slightly lower for debris flows that passed through plantations compared with debris flows that passed through natural forest, although the number of observations was small. Forty-three percent of the debris flows that passed through plantations (6 events) reached the mainstem stream, while 55% of the natural forest debris flows (11 events) reached the mainstem.

4.4 Flood disturbance and the stream network

Forty-three percent of all sub-basins in the study area (63 sub-basins) experienced debris flow activity during the study period. Among those sub-basins affected by debris flows, three-quarters experienced one debris flow. Only 3% had more than 3 debris flows during the study period (Table 4).

Fifty-four percent (34) of the sub-basins that experienced a debris flow were first-order sub-basins (Table 4). Second-order sub-basins accounted for 36.5% (23 sub-basins), and third-order sub-basins comprised 9.5% (6) of the debris flow impacted sub-basins.

Table 4. Debris flows by sub-basin. The number and percentage of sub-basins that experienced 1, 2, 3, and >3 debris flows, and the number of sub-basins that did not experience any debris flows during the study period is shown by sub-basin stream order.

	Sub-basins by Stream Order							
	First-		Second-		Third-		Total	
# df's	#	%	#	%	#	%	#	%
1	30	48	14	22	4	6.3	48	76
2	4	6	5	8	0	0.0	9	14
3	0	0	3	5	1	1.6	4	6
>3	0	0	1	1.5	1	1.6	2	3
Sub-Total	34	54	23	36.5	6	9.5	63	100
zero df's	50	60	18	21	16	19	84	100
Grand Total	84	57	41	28	22	15	147	100

Primary disturbance affected 15% of the length of the stream network between 1946-1996 (Table 5). Over half of the length of all second- and third-order streams combined was impacted by primary disturbance during the study period. However, only 12% of the length of first-order streams was affected by primary disturbance.

Secondary disturbance was far less prevalent in the network than primary disturbance, impacting only 3% of the total stream length. Only 1.9% of the length of first-order channels experienced secondary disturbance, while 6.6% and 4.2% of second- and third-order streams were affected, respectively.

Tertiary disturbance affected 10% of the length of the stream network. The entire length of fifth- and sixth-order streams was influenced by tertiary disturbance, while 67% of the length of fourth-order streams was impacted. Only 8.6% of the length of third-order channels experienced tertiary disturbance (Table 5).

Table 5. Length and percent of stream in primary, secondary, and tertiary debris flow zones are shown by stream order. The total length and percentage of debris flow disturbed channel, as well as the total length and percentage of the entire stream network are also presented by stream order.

Length in debris flow disturbance zone (m)									Stream Net	
stream	primary		secondary		tertiary		total df	total %	total str.	total %
order	m	%	m	%	m	%	length	df dist.	net lngth	str. net
1	23980	12.4	3710	1.9	0	0	27690	14	193530	59.4
2	16820	22.5	4940	6.6	0	0	21760	29	74770	22.9
3	7680	34.4	940	4.2	1910	8.6	10530	47	22330	6.9
4	0	0	0	0	12680	67	12680	67	18920	5.8
5	0	0	0	0	14940	100	14940	100	14940	4.6
6	0	0	0	0	1440	100	1440	100	1440	0.4
Total	48480	15	9590	3	30970	10	89040	27	325930	100

Stream network structure at the sub-basin scale ranged in complexity from single first-order to branching third-order streams (Table 4). First-order sub-basins were characterized by a single channel flowing directly into the mainstem stream, and were the most common (57% of all sub-basins). Second- and third-order streams were less common. The pattern of debris flow disturbance among first- to third-order sub-basins revealed the highest frequency of activity in first-order sub-basins (54% of all debris flow –affected basins), a moderate frequency of activity in second-order sub-basins (37%), and a relatively low frequency in third-order sub-basins (10%). However, when viewed in terms of the number of debris flow-affected sub-basins (34) in relation to the total number of sub-basins of the same order (84), 40% of the first-order basins experienced debris flows, whereas 56% (23) of the all second-order basins (41) were affected by debris flows. Only 27% (6) of the all third-order sub-basins (22) experienced debris flows.

Sub-basin stream-order was an effective measure of the complexity of stream disturbance. In first-order sub-basins, the spatial pattern of debris flow disturbance was the most simple: four possibilities existed. First, the entire stream was scoured, from channel head to mainstem tributary junction (Figure 7b, numbered feature 1). Second, the debris flow did not reach a mainstem stream, leaving a zone of secondary disturbance between the debris flow termination site and the junction with the mainstem stream (Figure 7b, numbered feature 2). Third, the debris flow initiated below the channel head and flowed all the way to the mainstem stream, leaving an unaffected stretch of stream above the initiation site (Figure 7b, numbered feature 3). Fourth, the debris flow initiated below the channel head, but did not reach the mainstem stream, creating both a secondary disturbance zone, as well as leaving an undisturbed section above the initiation site (Figure 7b, numbered feature 4).

For second- and third- order streams, patterns of disturbance were propagated in the same manner as first-order streams, with the added complexity of multiple channels, which allowed for the possibility of multiple debris flows, merging at tributary junctions as they traveled downstream (Figure 7b, 5). Consequently, network properties such as the number of tributary junctions, tributary junction angles, and sinuosity of the stream channel all potentially influenced the spatial pattern stream disturbance.

At the scale of the fifth-order stream network (the entire study area), primary disturbance (debris flows) occurred in first- through third-order tributary streams at the edges of the stream network. Secondary disturbance occurred on the mainstem valley floor, between debris flow termination sites and mainstem streams. Tertiary disturbance occurred in the lower portion of the network, in the fourth- and fifth-order channels. Consequently, contours of disturbance intensities and types of processes generally followed stream-order breaks, and progressed outward and upward from the bottom of the drainage basins. At the top of the watershed was a zone of very low disturbance, corresponding with high elevations and hard rock types.

Although debris flows usually initiated on first-order streams, these streams experienced far less primary disturbance than second- and third-order streams (Table 4). This was due to the dendritic nature of the stream network: second- and third-order streams may have numerous first-order channels upstream, each potentially providing the conditions for debris flow initiation. Consequently, the recurrence interval of primary disturbance was much shorter in second- and third-order channels than in first-order ones.

Figure 7. Patterns of debris flow disturbance in the stream network.

5. DISCUSSION

5.1 The influence of site condition variation on debris flow initiation

The history of debris flow occurrence between 1946 and 1996 revealed a distinct zone of high debris flow activity, which was associated with weak rock, low elevations (<1000 m), steep slopes (DEM slope >20°), and land use (roads and plantations). Overall, this zone of debris flow activity remained constant throughout the study period, despite variation in storm intensity. Increases in storm intensity did not result in significant increases of the spatial extent of the debris flow zone, but rather an increase in the frequency of debris flow initiation within the confines set by rock strength, elevation, and slope steepness.

Although land use was associated with changes in the frequency of debris flow initiation, contrary to expectations, land use did not significantly influence the types of sites at which initiation occurred based on rock type, elevation, and slope steepness. Comparison of events that initiated in natural forest- with road- and plantation-initiated debris flows did not, in general, reveal differences in the rock strength, elevation, or slope steepness at the initiation site. The geographic distribution, as well as the range of conditions under which debris flows occurred, was similar between natural forest and land use-associated events.

However, in two specific instances land use did appear initially to influence site conditions, but further examination revealed alternate explanations for the apparent association. First, the high density of initiation from weak rock types that was observed in natural forest is likely due to uneven spatial distribution of roads and plantations by rock type, and reflects the disproportionate spatial association between moderate rock types and land use. Consequently, it may not reflect a land use-associated increase in the likelihood of debris flow initiation that is *specifically* related to moderate rock types, but rather a general increase associated with land use, which happened to occur on moderate rock types.

Second, there was evidence that the average elevation of initiation was lower for plantations than for road or natural forest sites. However, plantations are concentrated in the low and middle elevations in these watersheds. Consequently, this finding cannot be associated with an alteration of debris flow processes resulting from forest regeneration practices. Nonetheless, the density of plantations in the low and middle elevations may represent a concentration of disturbance that is divergent from the historical natural disturbance regime, which had less frequent disturbance at low elevations (cf. Weisberg 1998).

The fact that there were no debris flows in plantations older than 15 years in WY 1965 was quite possibly because there were no plantations older than 15 years old in the study area in WY 1965. The relatively low proportion of events that initiated in plantations that were less than 10 years old in WY 1996 may have been due to the fact that the plantations during the earlier part of the study period occurred in the more debris-flow prone portion of the watershed, at low elevations and on weak rock. The low frequency and higher overall number of plantation-associated debris flows in WY 1996 was probably a reflection of the increased proportion of the study area occupied by plantations in WY 1996 (30%) compared with WY 1965 (11%).

The frequency of debris flow initiation for events originating in natural forest versus those from roads and plantations was very different. The cumulative pattern of debris flow initiation (which includes all events from all years) in plantations, as well as the single-season records from WY 1965 and WY 1996, show a pattern of higher frequencies of initiation in plantations when compared with natural forest. The frequency of debris flow activity originating from roads in WY 1965 exceeds all other land use-associated observations by an order of magnitude. These findings corroborate the results of numerous past studies of landslides and debris flows (e.g. Swanson and Dyrness 1975, Marion 1981, Sidle et al. 1985, May 1999, Robison et al. 1999). There can be little doubt that the historical practices of road construction and clear-cut logging increased the frequency of debris flow initiation above levels that would have been expected in natural forest under the same conditions.

A marked drop in the frequency of debris flows was observed for events originating from roads in WY 1965 and WY 1996. In addition, more road-associated debris flows came from low elevations than moderate elevations in WY 1965, but the opposite was true in WY 1996. Past studies have speculated that improvements in road construction practices resulted in a reduction in the number of road-associated landslides in 1996 in western Oregon (e.g. Robison et al. 1999).

While initially it appeared that the reduction in road-associated events could be associated with improvements in road construction practices in my study area, closer examination suggests a lack of evidence to support this hypothesis. The history of road construction in relation to the timing of the WY 1965 and WY 1996 floods indicates that this study area is not well suited to a test of this hypothesis.

First, road construction in the study area began in the mainstem valley bottom in the 1950s and 1960s, and subsequently was extended up the hillslopes to the ridgetops. Only a few miles of road were constructed after 1970 (Wemple 1994). Second, approximately half of the road-associated debris flows from 1996 originated from roads constructed in the 1950's and 1960's. Third, changes in road-construction policy did not result in significant changes in road construction methods in the study area. While in other areas, early roads were constructed using the sidecast method (Robison et al. 1999), in this study area all roads, including the early ones, were full-bench roads (Wemple 1994). Thus, when the WY 1965 flood event occurred, it encountered a newly constructed road network, whereas in WY 1996 the road network was several decades old and had experienced approximately 5-6 large storm events. Virtually all road-associated debris flows in this study area originated from roads constructed using a single construction method during the first half of the study period. The occurrence of road-related slides for decades after construction reveals the important legacy effects of old practices.

5.2 The influence of the stream network on spatial patterns of debris flow and stream disturbance

Stream network structure played an influential role in determining the spatial pattern of debris flow disturbance. Characteristics of the network, such as the location and pattern of low-order streams in steep terrain, tributary junction angles, and stream-order connectivity patterns, affected the distribution of stream disturbance.

Results from this study, in conjunction with inherent properties of network structure, suggest that the likelihood of a debris flow terminating in a mainstem stream is greater for stream networks characterized by numerous first-order streams connecting directly to a fourth- or fifth-order mainstem channel. In a highly dendritic network, the order of streams meeting at tributary junctions is similar (e.g., a first-order stream joining a first- or second-order stream). Networks with a higher bifurcation ratio (i.e., the ratio the number of streams in a given stream-order to the number in the next highest stream-order), allow for a more spatially uniform distribution of low-order channels, and are more likely to have undisturbed channel segments upstream that may function as source areas of recolonization of downstream stretches. Consequently, bifurcation ratio may serve as an indication of the likelihood of debris flow connectivity with mainstem streams (given that other influential factors are similar).

The interplay of stream network structure and stream disturbance likely has significant implications for aquatic and riparian biota. Watershed-specific patterns of disturbance, and the presence or absence of potential sources of recolonization, may influence ecosystem recovery. Stream channels above the initiation site of debris flows that are relatively undisturbed may function as source-areas for the recolonization of some species in the downstream debris flow transportation zone (Figure 7b).

Habitat conditions for upstream recolonization from the mainstem stream may be very different for debris flows emerging from first-order sub-basins than from third-order sub-basins. Potentially different interfaces that occur between aquatic invertebrate communities in an orderly first-, second-, third-order, etc. dendritic structure with a stream network that is characterized by first-order streams joining fifth-order streams.

One might hypothesize that a debris flow scouring a first- to fifth-order junction might require a substantially greater time for recolonization than a scoured channel that ends at a first- to second-order tributary junction. Likewise, if debris flow initiation begins below the channel head, and an upstream portion of stream remains undisturbed, the potential for rapid recolonization of that channel may be greater.

5.3 Suggestions for research and management

The relationship between spatially variable landscape conditions, such as rock type, elevation, and slope gradient, and the spatial distribution of suitable growing conditions for marketable tree species may result in patterns of disturbance across the landscape that are different from those produced by the natural disturbance regime. To the extent that management is based on historical disturbance regimes (e.g. Cissel et al. 1999), the spatial and temporal patterns of human-induced disturbance would be expected to be as similar to natural disturbance as possible. More research needs to be conducted on the patterns of historical disturbance regimes, and the type and degree of deviation between debris flows in managed versus wild landscapes.

More investigation of the relationship between stream network structure and physical and biological processes is needed. While much attention has been given to the linear / longitudinal properties of stream networks (e.g., the River Continuum Concept, Vannote et al. 1980), and patchwork properties of landscapes (Pickett and White 1985), relatively little investigation of the implications of stream network structure has been conducted. One specific area of further research is the possible application of stream network metrics to physical and biological processes, such as bifurcation ratio as an indicator of the likelihood of debris flow connectivity with mainstem streams. Also, more investigation of the significance of the stream order of channels meeting at tributary junctions, in terms of the variability of physical conditions and biological communities, is warranted.

Results from this study suggest that careful attention should be given to the placement of roads and plantations with respect to factors that create high potential for debris flows, such as rock strength and/or elevation, and slope gradient. Zones of high debris flow activity are probably fairly static spatially, so limiting and carefully designing management activity in these areas may successfully prevent accelerated disturbance rates.

Finally, the coincidence of strong rock with high elevations made it difficult to determine which factor most influenced debris flow initiation. Further study on this topic, perhaps in other regions, is warranted.

6. Literature Cited

Benda, L. 1990. The influence of debris-flows on channels and valley floors in the Oregon Coast Range, USA Earth Surface Processes and Landforms 15: 457-466.

Bisson, P. A., G. H. Reeves, R. E. Bilby, and R. Naiman. 1996. Desired future conditions? pp. 447-474 In D. P. Stouder, P. A. Bisson, and R. Naiman (eds). Pacific salmon and their ecosystems. Chapman and Hall, New York.

Cissel , J. H., F. J. Swanson, and P. J. Weisberg. 1999. Landscape management using historical fire regimes: Blue River, Oregon. Ecol. Appl. 9(4): 1217-1231.

Dunning, J. B., B. J. Danielson, and H. R. Pulliam. 1992. Ecological processes that affect populations in complex landscapes. Oikos 65: 169-175.

Dyrness, C. T. 1967. Mass soil movements in the H. J. Andrews Experimental Forest. Pacific Northwest Range and Experiment Station, USDA Forest Service Research Paper PNW-42. 12 pp.

Dyrness, C. T., F. J. Swanson, G. E. Grant, S. V. Gregory, J. A. Jones, K. Kurosawa, A. Levno, D. L. Henshaw, and H. Hammond 1996. The flood of 1996 in the Andrews Forest. World Wide Web. Http://www.fsl.orst.edu/lter/pubs/spclrpfr.htm.

Fredriksen, R. L. 1965. Christmas storm damage on the H. J. Andrews Experimental Forest. USDA Forest Service Research Note PNW-29. 11 pp.

Gresswell, S., D. Heller, and D. N. Swanston. 1979. Mass movement response to forest management in the central Oregon Coast Ranges. USDA Forest Service Resource Bulletin PNW-84. 26 pp.

Harr, R. D. 1981. Some characteristics and consequences of snowmelt during rainfall in western Oregon. J. Hydr. 53: 277-304.

Ketcheson, G., and H. A. Froehlich. 1978. Hydrologic factors and environmental impacts of mass soil movements in the Oregon Coast Range. Water Resources Research Institute, Oregon State University. Report WRRI-56. 94 pp.

Lamberti, G. A., S. V. Gregory, L. R. Ashkenas, R. C. Wildman, and K. M. Moore. 1990. Stream ecosystem recovery following a catastrophic debris flow. Can. J. Fish. Aquat. Sci. 48:196-208.

Marion, D. A. 1981. Landslide occurrence in the Blue River drainage, Oregon. M.S. thesis. Oregon State University, Corvallis, Oregon. 114 pp.

May, C. L. 1999. Debris flow characteristics associated with forest practices in the central Oregon Coast Range. M.S. Thesis. Oregon State University, Corvallis, Oregon. 121 pp.

Nakamura, F., F. J. Swanson, and S. Wonzell.2000. Disturbance processes in stream and riparian systems – a disturbance cascade perspective. Manuscript in press, Hydrol. Proc.

Pearsons, T. N., H. W. Li, and G. A. Lamberti. 1992. Influence of habitat complexity on resistance to flooding and resilience of stream fish assemblages. Trans. Amer. Fish. Soc. 121:427-736.

Pickett, S.T.A., White, P.S., eds. 1985. The ecology of natural disturbance and patch dynamics. Academic Press, Inc. Orlando, FL 472 pp.

Priest, G. R., G. L. Black, N. M. Woller, and E. M. Taylor. 1988. Geologic map of the McKenzie Bridge quadrangle, Lane Co., Oregon. Oregon Dept. of Geology and Mineral Industries Geologic Map Series GSM-48, scale 1:62,500.

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

Rieman, B. E., and J. C. Clayton. 1997. Wildfire and native fish: issues of forest health and conservation of native fishes. Fisheries 22(11): 6-15.

Robison, G. E., K. Mills, J. Paul, L. Dent, A. Skaugset. 1999. Storm impacts and landslides of 1996: final report. Forest Practices Technical Report No. 4. Oregon Dept. of Forestry, Salem, OR. 145 pp.

Sedell, J. R., G. H. Reeves, F. R. Hauer, J. A. Stanford, and C.P. Hawkins. 1990. Role of refugia in recovery from disturbances: Modern fragmented and disconnected river systems. Env. Manage. 14:711-724.

Sidle, R. C., A. J. Pearce, and C. L. O'Loughlin. 1985. Hillslope stability and land use. Washington DC: American Geophysical Union.Water Resources Monograph No. 11. 140 pp.

Silen, R. R., and H. J. Gratkowski. 1953. An estimate of the amount of road in the staggered-setting system of clear cutting. USDA Forest Service, Pacific Northwest Forest and Range Experimental Station, Res. Note 92. Portland, OR. 4 pp.

Strahler, A. N. 1952. Hypsometric (area-altitude) analysis of erosional topography. Bull. Geol. Soc. Am. 63:1117-42.

Strahler, A. N. and A. Strahler. 1998. Introducing physical geography. John Wiley and Sons.

Swanson, F. J., and C. T. Dyrness. 1975. Impact of clearcutting and road construction on soil erosion by landslides in the western Cascade region, Oregon. Geology 3: 393-396.

Swanson, F. J., and M. E. James. 1975. Geology and geomorphology of the H. J. Andrews Experimental Forest, western Cascades, Oregon. Portland, OR, USDA Forest Service.

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

Swanson, F. J., and Wallenstein, M. 1996. Unpublished data.

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

Swanston, D. N., and C. T. Dyrness. 1973. Stability of steep land. J. For. 71:264-269.

Vannote, R. L., G. W. Minshall, K. W. Cummins, J. R. Sedell, and C. E. Cushing. 1980. The River Continuum Concept. Can. J. Fish. Aquat. Sci. 37:130-137.

Walker, G. W., and R. A. Duncan. 1989. Geology of the Salem 1x2 degree quadrangle, western Oregon. USGS Miscellaneous Investigations Series Map I-1893, scale 1:250,000.

Weisberg, P. J. 1998. Fire history, fire regimes, and development of forest structure in the central western Oregon Cascades. Ph.D. Thesis. Oregon State University, Corvallis, Oregon. 256 pp.

Wemple, B. C. 1994. Hydrologic integration of forest roads with stream networks in two basins, western Cascades, Oregon. M.S. Thesis. Oregon State University, Corvallis, Oregon. 85 pp.

Wemple, Beverly C. 1998. Investigations of runoff production and sedimentation on forest roads. Ph.D. Thesis. Oregon State University, Corvallis, Oregon. 168 pp.

APPENDICES

Appendix A: Examination of aerial photography

Inventories of landslides and debris flows based on aerial photography have received substantial criticism recently. Concerns have been raised regarding the detectability of landslides on air photos, especially in mature forest. A report issued by the Oregon Department of Forestry found that only about half of the landslides in recent plantations were visible in photos at the 1:6,000 scale (Robison et al. 1999). In mature and old-growth forest, the air photos revealed 5%, at most, of the ground surveyed slides.

In order to verify the historical data sets used in this study, and to determine the efficacy of identifying debris flows by using air photos, I conducted an independent air photo-based debris flow inventory. Results from the inventory were compared against the mapped debris flows from the historical studies (Dyrness 1967, Swanson and Dyrness 1975, Marion 1981, and Swanson and Wallenstein 1996). This investigation was conducted at the beginning of my study, in order to refine the data set.

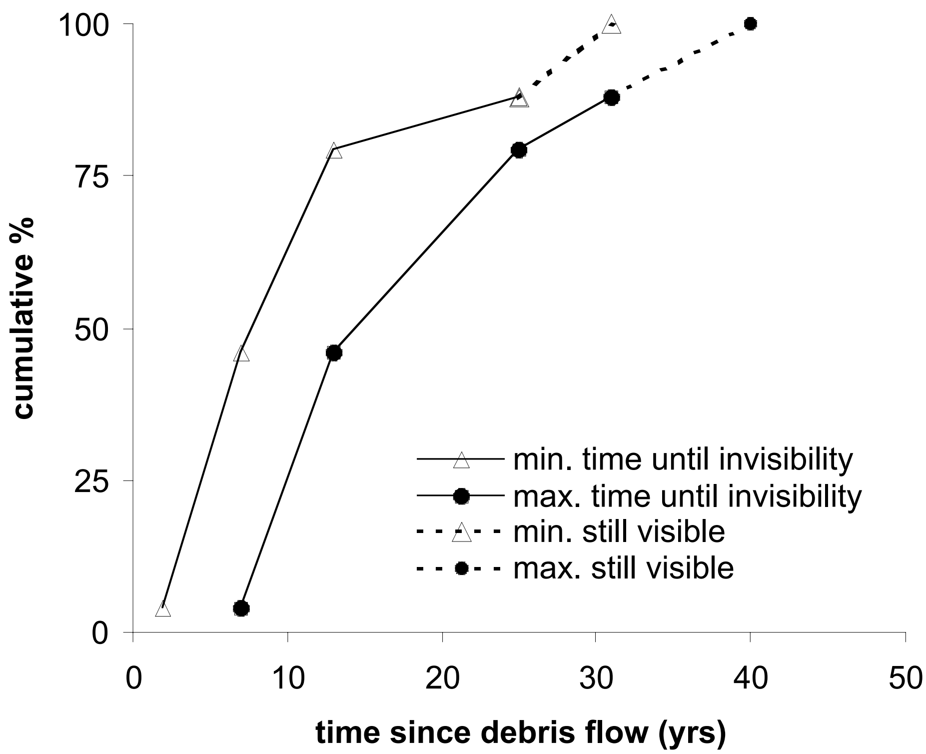
Characteristics of debris flows from this investigation included the initiation site, scoured stream channel, and the deposition site. Every debris flow that was identified on the air photos was evaluated for visibility and vegetation re-growth, which was tracked chronologically from each photo time-step to the next. 'Visibility' was a measure of the likelihood of detection, indicating the degree of brightness, contrast, color difference, and vegetative regrowth between the debris flow scar and surrounding landscape. Three classes of visibility were defined: highly visible, moderately visible, and scarcely visible. Highly visible events were uniformly bright, of a color and contrast entirely different from surrounding forest, and usually contained little or no vegetative re-growth.

Moderately visible events were characterized by a lack in intensity and uniformity of brightness, contrast, and color variance in the disturbed area, and were often approximately 50% covered with vegetative re-growth. Scarcely visible events were only slightly different from neighboring forest in terms of brightness, contrast and color, and often 100% covered with vegetative re-growth.

Of the 83 historical debris flow sites that were examined, 20% were never visible on aerial photographs. These events initiated from landslides that were 42% smaller in volume than the visible debris flows. Two-thirds of the invisible events occurred in mature and old-growth forest, while 33% were located in plantations. Of the 68 events that were detectable on the air photos, 64% were highly visible in the photo set closest to the time of occurrence, 19% were moderately visible, and 15% were scarcely visible. Visibility endured approximately 8 to 14 years for 50% of the WY 1965 events. Thirteen percent of these (3 events) remained visible in 1996 (Figure 8).

Ground-surveys in the ODF study found rates of sliding to be 1.6 to 2.8 times higher in plantations than in mature and old-growth forest (Robison et al. 1999, p. 26). Results from the historical record debris flow occurrence in this study area found rates of debris flow initiation to be 3 times higher in plantations than mature and old-growth forest (natural forest) during the same storm, supporting the contention that the historical data utilized in this study did not substantially underestimate rates of sliding in older forest. It appears that the combination of ground, road, and air photo-based inventory was successful in identifying debris flows in both plantations and natural forest.

Figure 8. Time (years) that debris flow scars remained visible for WY 1965 events (N=24).



Appendix B: DEM accuracy

Accuracy of Digital Elevation Model (DEM) elevation values was verified against high-resolution Global Postioning System (GPS) monuments in the H.J. Andrews Experimental Forest (Table 6). GPS monument measurements have an estimated accuracy of 10 cm. The DEM elevation values differed from the GPS values between 0.14-12 m, with a median value of 3.7 m and a standard deviation of 3.3 m.

Table 6. GPS monument vs. DEM elevation values. Elevation values are compared for 30 m and 10 m DEMs against the high resolution GPS monument locations.

	Elevation (m)			10m DEM vs GPS	30m DEM vs GPS	30m DEM vs. 10m DEM
SITE	30m DEM	10m DEM	GPS	difference (m)	difference (m)	difference (m)
HJAA	442	446	436	10	7	3.90
HJAB	525	525	536	12	11	0.53
HJAC	668	668	675	8	7	0.56
HJAD	1352	1355	1354	1	2	3.07
HJAE	1245	1245	1246	1	1	0.12
HJAF	1131	1132	1131	0	0	0.33
HJAG	1393	1396	1403	7	10	2.87
HJAH	1511	1512	1515	3	3	0.44
HJAI	942	938	945	7	4	3.60
HJAJ	978	979	973	6	5	1.48
HJAK	832	831	828	3	4	1.11
HJAL	764	765	758	7	6	0.17
HJAM	759	756	758	2	1	3.19
HJAN	442	442	439	3	3	0.18
HJAO	811	814	821	7	10	2.45
HJAP	670	670	673	2	3	0.59
HJAQ	1299	1299	1296	4	3	0.53
HJAR	1195	1195	1192	4	3	0.80
HJAS	902	901	900	1	2	0.83
HJVL	1260	1260	1268	8	8	0.03

DEM-derived slope gradient measurements were found to be consistently lower than field measurements of slope, and consequently the DEM slope values were adjusted to the field value. Field slope steepness measurements were gathered with a clinometer, and were presumed to be more accurate than the DEM slope values. Slope values derived from a 10 m DEM were 8° more gentle, on average, than field-measured slope values (Figure 9. DEM vs. field-measured slope gradient).

Figure 9. DEM vs. field-measured slope gradient. The dotted line shows field-measured slopes plotted on both the x and y axes, while the solid line shows field-measured slope values on the x-axis and DEM-derived slopes on the y-axis. DEM slope values were 8° more gentle, on average, than field-measured slope values.