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Made in United States of America
Reprinted from Journal of the American Water Resources Association
Vol. 36, No. 1, February 2000

JOURNAL OF THE AMERICAN WATER RESOURCES ASSOCIATION
VOL. 36, NO. 1 AMERICAN WATER RESOURCES ASSOCIATION FEBRUARY 2000

LANDSLIDE INITIATION, RUNOUT, AND DEPOSITION WITHIN CLEARCUTS AND OLD-GROWTH FORESTS OF ALASKA[1]

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ABSTRACT: More than 300 landslides and debris flows were triggered by an October 1993 storm on Prince of Wales Island, southeast Alaska. Initiation, runout, and deposition patterns of landslides that occurred within clearcuts, second-growth, and old-growth forests were examined. Blowdown and snags, associated with cedar decline and "normal" rates of mortality, were found adjacent to at least 75 percent of all failures regardless of land use. Nearly 50 percent of the landslides within clearcuts occurred within one year following timber harvest; more than 70 percent of these sites had hydrophytic vegetation directly above failures. In following the runout paths of failures, significantly more erosion per unit area occurred within clearcuts than in old-growth forests on slopes with gradients from 9 to 28° (16 to 54 percent). Runout length, controlled by hillslope position within deglaciated valleys, was typically longer in old-growth forests than in second growth and clearcuts (median values were 334, 201, and 153 m, respectively). Most landslides and debris flows deposited in first- and second-order channels before reaching the main stem channels used by anadromous fish. Slide deposits in old-growth forests were composed of a higher proportion of woody debris than deposits derived from slides in second growth or clearcuts.

(KEY TERMS: landslides; debris flows; land use planning; erosion and deposition; woody debris; deglaciated valleys; Alaska; anadromous fish.)

INTRODUCTION

The link between mass-wasting and valuable downstream resources, including salmonid habitats, suggests a need to assess both the triggering mechanisms and runout paths of these landslide events. Landslides typically occur in conjunction with major storms in mountainous terrain of the Pacific Northwest of the United States. These events are exacerbated by natural factors such as fire (Krammer, 1965; Rice, 1973; Swanson, 1981; Benda and Dunne, 1997; Benda *et al.*, 1998), wind (Swanston, 1979; Harris, 1989; Kramer, 1997; Nowacki and Kramer, 1997), natural declines in forest species (Johnson and Wilcock, 1997), or by human factors such as clearcutting and road building (Bishop and Stevens, 1964; Wu *et al.*, 1979; Sidle, 1985; Swanston, 1991). Previous studies conducted in the glaciated terrain of southeast Alaska have indicated that there is a two- to four-fold increase in landslide frequency associated with timber harvest (Bishop and Stevens, 1964; Swanston, 1974, 1979; Sidle 1985; Swanston, 1991; Swanston and Marion, 1991) and decline of yellow-cedar (*Chamaecyparis nootkatensis*) (Johnson, 1993, 1997).

In this study, characteristics of landslide initiation are presented, including an assessment of forest health and hydrology as indicated by vegetation. In addition, the volume of material eroded or deposited along landslide flow paths is examined. These factors are assessed for landslides initiated during a single storm event within various land use types including old-growth, second-growth, and clearcut forests. From these analyses, the underlying factors that may exacerbate the effects of land use on landslide occurrence and runout are evaluated.

STUDY AREA

Prince of Wales Island is about 40 kilometers west of Ketchikan, Alaska and at 578,000 hectares is the largest island of the Alexander Archipelago. The landslides sampled occurred during a single storm on October 26-27, 1993. More than 300 individual

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[1] Paper No. 98140 of the *Journal of the American Water Resources Association*. **Discussions are open until October 1, 2000.**

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landslides occurred primarily in the central and eastern central portions of the island at approximately 55°30´N,133°E (Figure 1).

The island is dominated by rocks of the Alexander Terrain, a large accretionary fragment, consisting of granodiorites, greywackes, conglomerates, limestones, and sandstones. Metasedimentary mudstones, greywackes, shales, slates, metavolcanic diorites and granodiorite dominate the study area. Most of the bedrock below 1000 m elevation is covered by till

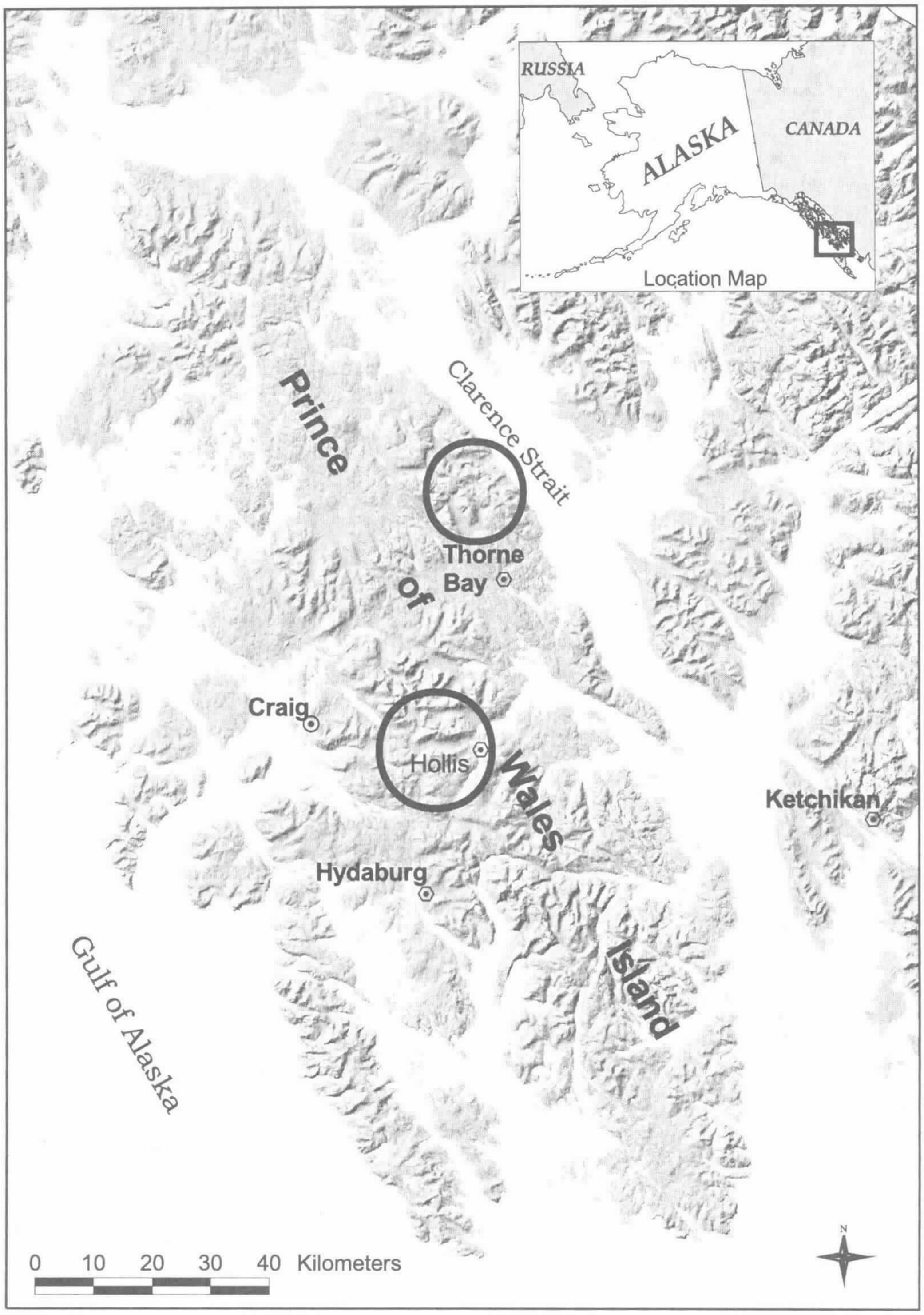

Figure 1. The Two Regions of High Landslide Frequency Associated with the October 1993 Storm on Prince of Wales Island.

associated with the late Wisconsinan glacial advance (Swanston, 1969).

Landslides were initiated in soils derived from glacial till classified as Spodosols (87 percent), and regions of exposed rock where soils include Inceptisols (10 percent) and Entisols (3 percent). The spodisols are sandy with an internal angle of friction of 35° and an effective cohesion of 8 kPa (Shroeder, 1983). They are classified primarily as typic humicryods, which are moderately-well to well-drained soils, typically greater than 60 cm in depth.

Precipitation was recorded in Hollis, central Prince of Wales Island. Precipitation for eight consecutive days preceding the storm event initiating the landslides totaled approximately 160 mm. During the storm that initiated these landslides, an additional 209 mm of rain fell. Weather stations at sea level recorded near freezing conditions, so some wet snowfall and associated rapid snowmelt also may have occurred. In addition, a 2 percent increase in rainfall for every 30 m rise in elevation near Hollis has been documented in previous storms (Walkotten and Patric, 1967). Personal accounts indicate local periods of high intensity rainfall and wind. Storm cells were documented in several areas near high landslide activity. The closest weather station that measured wind speeds was located 128 km NE in Petersburg, Alaska, where wind speeds of 18.4 m/s were reported.

The forests on Prince of Wales Island are dominated by stands of western hemlock (*Tsuga heterophylla*), Sitka spruce (*Picea sitchensis*), red cedar (*Thuja plicata*), Alaska yellow-cedar (*Chamaecyparis nootkatensis*), and shore pine (*Pinus contorta*). Yellow-cedar decline, a natural mortality of old-growth forests exists in some of the areas. The decline has been associated with change in soil temperature, chemistry, and/or change in hydrology as opposed to an association with pests or pathogens (Hennon *et al.*, 1990; Hennon and Shaw, 1997). Understory species include red huckleberry (*Vaccinium parvifloium*), Alaska blueberry (*Vaccinium alaskaense*), rusty menziesia (*Menziesia ferruginea*), and devil's club (*Opopanax horridus*). Skunk cabbage (*Lysichitom americanus*), and false helbore (*Veratrum eschscholtzii*) grow in the wettest areas. Windthrow is the dominant forest disturbance (Harris *et al.*, 1974; Harris, 1989; Nowacki and Kramer, 1997). Clearcutting of the old-growth forests has occurred since the 1950s resulting in a mosaic of clearcuts, second growth, and old growth patches. In this study, forests are identified as old growth if no harvesting has occurred, second growth if harvested before 1985, and clearcut if harvested after 1985.

METHODS

A total of 45 landslides were labeled and randomly selected using a random number generator from inventories conducted by the Ketchikan area of the Tongass National Forest (Johnson, 1993; Landwehr, 1993). These inventories were developed through low-elevation (less than 300 m) aerial reconnaissance surveys and road surveys. Fifteen landslides were randomly selected from clearcuts, second-growth, and old-growth forests, respectively. We use landslides as a descriptive term for all rapid soil failures. Debris flows are specified if it was apparent that the initial failure mass became liquefied as indicated by flow deposits.

Each landslide and debris flow was examined from the point of initiation to the point of deposition to evaluate initiation, runout, and deposition characteristics. Characteristics of the initiation zones included land use, indicators of hydrology, plant disturbance, and terrain configuration controlling slope stability. Initiation zones were defined as the locations where groundwater seepage converged in subsurface depressions or "hollows." Head scarps of failures may have migrated upslope following failure, but for the most part, initiation zones were characterized by a clear headwall and rapid downslope channeling into preexisting gullies, which transported resulting debris downslope. Indicator vegetation conditions at the immediate vicinity of landslide initiation included the presence of blowdown, decayed stumps, standing dead trees, cedar decline, split trees, leaning or "pistol butted" trees (tree trunks bending in downhill direction at ground level), logging disturbance, and presence of hydrophytic vegetation such as skunk cabbage. Indicator terrain conditions analyzed included elevation at the landslide initiation zone, distance to the ridgeline, slope, mean soil depth of failure mass within the failure zone, width of failed soil mass, and eroded volume.

The runout of landslides and debris flows was defined as the affected region between the initiation zone and the final deposition zone. Analysis of runout included a description of the changes in land use encountered along the landslide or debris flow path, measurements of runout widths and lengths, and erosional and depositional trends. These trends were described for runout segments, divided and sorted according to slope gradient category. Segment length ranged from 3 to 100 m, averaging 28 m with 4 to 21 segments per landslide. The fraction of total runout length occurring per slope gradient category is presented in conjunction with the range of volumes of erosion or deposition per unit runout area. Analysis of variance and t-tests were used to statistically analyze differences in erosion or deposition per slope gradient category. Differences were judged to be statistically significant at P = 90 percent ($p = 0.10$).

Final, or terminal deposits at the end of the landslide runout tracks were characterized by depositional slope, composition, volume, and location. For deposits in streams, order and stream type were determined. Stream type was defined as Class I if the stream supported anadromous fish populations, Class II if supporting resident fish such as cutthroat trout, and Class III and IV if without fish populations (USDA, 1997). Size and number of logs were counted at some of the landslide deposits.

A comparison of woody debris to soil volume ratios for clearcuts and old-growth forests was estimated using the following equation:

$$A\,(Tr)\,Vtr : A\,(d)$$

where, A = area of landslide; Tr = average number of trees per area; d = average depth of soil; and Vtr = average tree volume.

From this ratio, comparisons were made between old-growth and clearcut forests. Tree densities used in this calculation were 255 trees per ha with an average volume of 2.2 m^3 per tree, values typical for a productive, well drained forest in southeast Alaska (Rogers and van Hees, 1992). Within clearcuts, stump volume was assumed to be 1/20 the size of an entire tree, or 0.11 m^3. Woody debris on the forest floor was not included in this calculation because it varied considerably across sites.

RESULTS

Initiation

The areas of initiation (head scars) for 40 of the 45 landslides and debris flows in the random sample were greater than 200 m^2 (volumes greater than 77 m^3) except one slope failure within clearcut forests, and two failures within old-growth and second-growth forests. This has been the minimum size consistently observed under the old-growth forest canopy of southeast Alaska at the photographic scale of 1:12,000 (Swanston and Marion, 1991). Other studies in coastal regions of Oregon (Oregon Department of Forestry, 1998) have found that the minimum observable size of landslide initiation zones under forest canopy was 418 m^2 (roughly 15 by 27 m) using 1:6,000 and 1:12,000 scale aerial photographs. Although we believe our sample is unbiased, we acknowledge that some bias toward larger landslides within old-growth forests may have occurred. As a result, failure rates and volumes per area per landuse were not calculated.

Initiation of landslides was closely associated with landforms. At least 40 out of 45 (89 percent) of the failures initiated in bedrock hollows (bedrock depressions where colluvium, woody debris and water collect), a phenomenon common in the Pacific Northwest (Dietrich and Dunne, 1978). The remainder occurred on planar slopes. Till was the primary failure material in at least 75 percent of the sites. Slope and soil depth at landslide initiation sites were similar for all land use types (Table 1). Initiation aspects differed. Nine out of 15 of landslides in old growth trended to the northeast and southeast, 11 out of 15 landslides in clearcuts occurred on west and southwest aspects, and 10 out of 15 of the landslides within second growth occurred on south-facing slopes.

Springs and seepage were found at most of the landslide scarps at the soil/till (bedrock) contacts (Table 2). Approximately 90 percent of the sites had two or three seeps that converged at the base of the bedrock/till hollow. Hydrophytic vegetation was more common at clearcut sites (7 out of 15) than in old-growth (3 out of 15) or second-growth (2 out of 15) sites. Five of the seven sites within clearcuts having hydrophytic vegetation were harvested less than a year before the landslides occurred. Root deterioration was apparent at 10 out of 15 sites within each of the land use types.

Residual logging disturbance was apparent in 7 out of 15 second-growth sites and in 5 out of 15 sites in clearcuts, typically in the form of corridors where logs were dragged along and across the failure scarp. In addition, at several of the sites above the headwall, rotten logs directed water to the hollow where failure occurred.

Runout

At least one-third of the sampled landslides traveled from one land use type into another land use type, and were thereby affected by road crossings, change in woody debris loading, and change in the size of standing timber (Figure 2). In lieu of this complexity, details of runout were described solely for the landslides that remained consistently within the forest type in which they initiated (nine within each landuse type).

The majority of failures (5 out of 9) within old growth split just below the zone of initiation. These landslides split when standing trees (greater than 0.3 m in diameter) impeded the flow path of the failure mass and forced it to shift into several channels. Two

TABLE 1. Summary of Landslide Initiation Site Characteristics (n = 15 for each land use type).

Landuse Type	Mean Value	Maximum	Minimum	Standard Deviation
OLD GROWTH				
Soil Depth (m)	1.2	2.0	0.5	0.5
Width (m)	19	32	10	6
Slope (degrees)	38	55	31	7
Elevation (m)	370	608	172	115
Distance to Ridgeline (m)	234	701	50	198
Eroded Volume (m3)	382	855	25	274
SECOND Growth				
Soil Depth (m)	1.1	2.2	0.4	0.7
Width (m)	17	49	7	13
Slope (degrees)	34	45	27	5
Elevation (m)	256	396	183	85
Distance to Ridgeline (m)	282	1037	46	296
Eroded Volume (m3)	633	3952	20	1037
CLEARCUTS				
Soil Depth (m)	1.2	2.0	0.6	0.4
Width (m)	13	35	5	9
Slope (degrees)	36	47	25	6
Elevation (m)	391	500	195	83
Distance to Ridgeline (m)	165	671	61	157
Eroded Volume (m3)	347	1332	104	322

TABLE 2. Conditions at Sites of Landslide Initiation (n = 15 per condition per land use type).

Site Condition	Clearcuts	Second Growth	Old Growth
Blowdown	3	3	8
Pistol Butted Trees	6	6	7
Split Trees	1	0	3
Leaning Trees	2	0	3
Decayed Stumps and Decayed Snags	9	11	9
Cedar Decline (CD)	3	0	2
Standing Dead (other than CD)	1	0	4
Yarding Disturbance	5	7	0
Groundwater Seepage	15	13	13
Hydrophytic Vegetation	7	2	3

of those five landslides turned into channelized debris flows and followed pre-existing gullies. Another two landslides flowed out onto planar slopes and upon splitting, appeared to undercut the adjacent slopes causing additional slides. One landslide split initially and then returned to the other flow path leaving an island of trees. Only one of the five landslides inventoried had a majority of deposition in a steep channel. At this site, the flow path crossed a steep (21°, 37 percent) channel with a junction angle of 70°, and the majority of the flow stopped in the channel. Of the remaining four landslides that did not split, two flowed into channels and two remained wide and unchannelized.

Unlike landslides in old-growth forests, those in second growth and clearcuts did not split. Four out of nine landslides and debris flows in second growth flowed into steep channels (> 20°, 36 percent), the rest

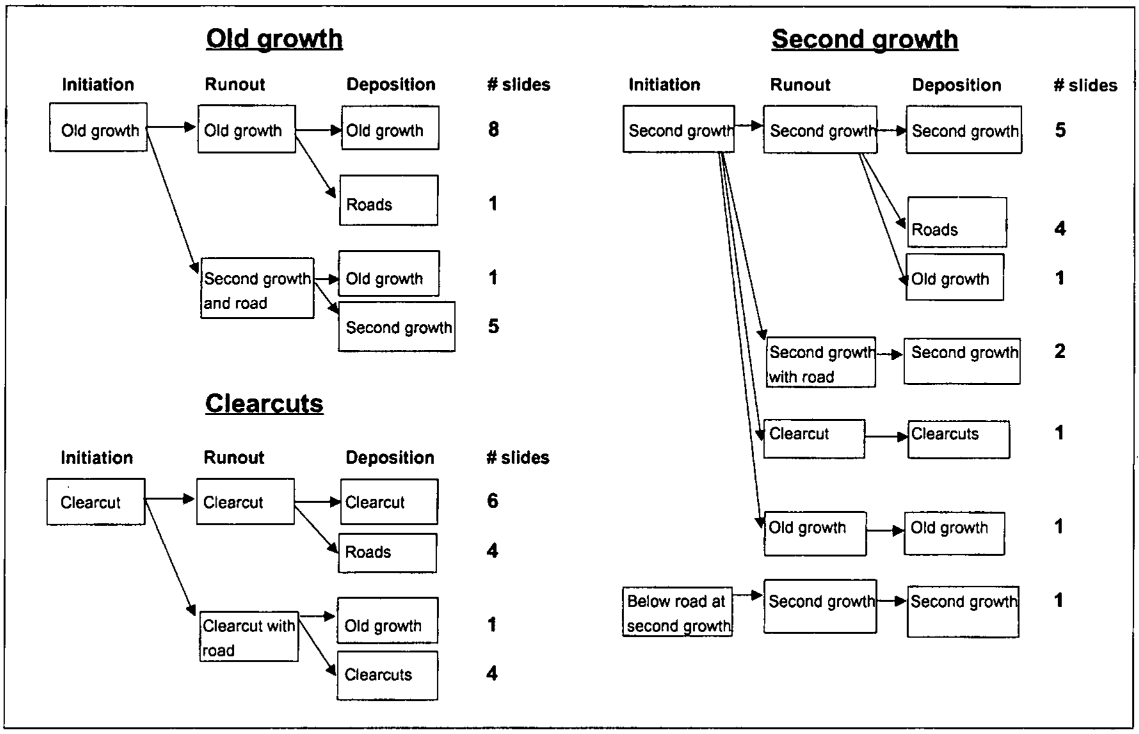

Figure 2. The Initiation and Runout of Landslides on Prince of Wales Island with Changes in Land Use Indicated. Note that for at least one-third of the landslides, runout passed into a different land use.

were wide and unchannelized. All of the landslides and debris flows in clearcuts flowed into steep first-order through third- order channels (>20°, 36 percent).

The longest runout segments occurred within old-growth forests followed by those in clearcuts and second growth. Five out of nine of the failures in old growth had large widths (> 20 m) for the first 75 m whereas only two large-width landslide within clearcuts traveled 25 m before decreasing in width (Figure 3d). The majority of landslides within clearcuts had runouts that initially were medium widths (10-19 m) and did not travel distances exceeding 400 m (Figure 3c). Small-width landslides within second growth, clearcuts, and old growth traveled ≤ 200, ≤ 300, and ≤ 600 m, respectively (Figure 3b). Two failures in second growth started with large widths and an additional two landslides became large in width. Five runout segments from these four landslides had runout distances exceeding 101 m (Figure 3d).

Deposition within the runout of debris flows and landslides occurred on slopes as steep as 38° (78 percent) in old growth and second growth (Figure 4a). Deposition occurred as berms along the flow path and piles of soil and woody debris that had been backed-up behind standing trees. For old-growth forests, the amount of erosion was nearly equal to the amount of deposition on slopes from 19 to 28° (34 to 54 percent). These slopes accounted for thirty-three percent of the total runout distance occurring in old-growth forests (from Figure 4d).

Although landslides and debris flows in old growth were generally larger in size than landslides in second growth and clearcuts, there was more erosion per area in clearcuts than in old growth. Erosion was dominant, as indicated by median, upper and lower quartile values, on slope gradients greater than 29° (56 percent) in old growth (Figure 4a) and second growth (Figure 4c), and greater than 19° in clearcuts (Figure 4b). These slope gradients accounted for 38 percent, 29 percent, and 55 percent of the total runout lengths, respectively (Figure 4d). In other words, there was a tendency for more erosion to occur along the majority of the runout lengths within clearcuts. Slope gradients from 19 to 23° (34 to 42 percent) had significantly more erosion per unit area in clearcuts than in old growth (t-tests; $p = 0.02$). On these slope gradients, mean erosion was 0.28 m^3/m^2 (volume per area) in clearcuts ($n = 12$) while in old-growth ($n = 16$), deposition was dominant with a mean volume of 0.16 m^3/m^2. A significant difference was also found on 9 to 28° (16 to 54 percent) slope gradients ($p = 0.08$). Here, 0.03 m^3/m^2 was eroded in clearcuts ($n = 50$), and in old growth ($n = 57$), 0.15 m^3/m^2 was deposited.

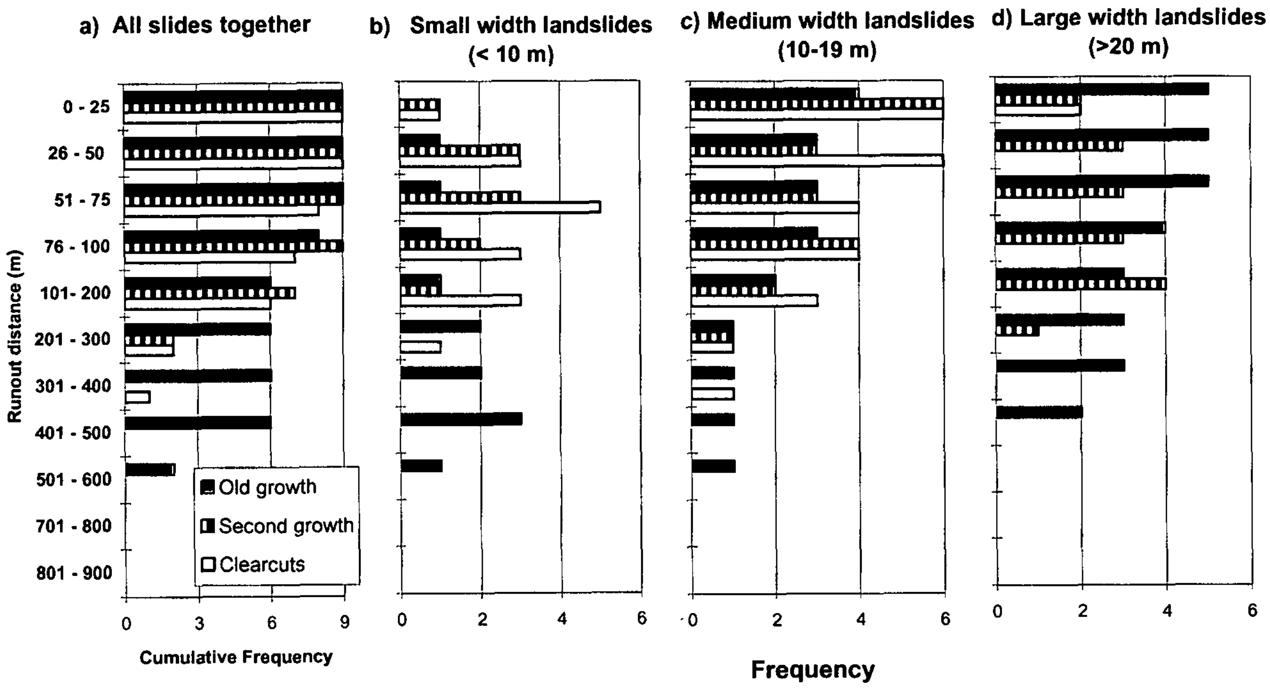

Figure 3. Landslide Runout Width and Length for: (a) All Landslides Together, (b) Small Width Landslides, (c) Medium Width Landslides, and (d) Large Width Landslides.

Deposition

Final, or terminal deposits were located at the end of the runout tracks. Maximum and mean deposit volumes were largest in old-growth forests and the smallest in clearcuts (Table 3). The slope upon which the final deposits were located ranged from 2.5 to 19° (5 to 34 percent). Depositional processes appeared to be enhanced by large standing trees (> 0.3 m diameter), a lack of channelization, and runout onto road surfaces on slopes less than 15° (27 percent). Four of the nine landslides and debris flows that traveled through second growth and clearcuts ended at or near roads (Figure 2).

Twenty out of 27 terminal deposits occurred in first-order and second-order stream channels on 4 to 19° slopes (7 to 34 percent) with a mean of 10° (16 percent) (Table 4). Two sites (in a clearcut and second growth) did not deposit in channels. The remaining five slides deposited in third- and fourth-order channels on slopes ranging from 2.5 to 9° (5 to 16 percent) slopes with a mean slope of 6° (10 percent). Two landslides/debris flows in old growth deposited in a fourth-order, Class I, or anadromous fish bearing channel. Only one of these failures had a major impact on the channel by introducing over 100 m^3 of sediment and woody debris, while the other slide deposited approximately 10 m^3 of sediment and wood. Two debris flows deposited in muskeg ponds (wetland bogs or fens) that are classified as Class II due to use by resident fish. The remainder of the debris flows deposited in Class III and Class IV channels without fish. In contrast, all of the landslides in clearcut and second-growth forests deposited in Class III and Class IV channels, except for one landslide in second growth that deposited in a Class II stream (Table 4).

The relative proportion of woody debris to sediment in the landslide deposits was greater in old growth than clearcuts. Deposits in clearcuts consisted of sediment, woody debris fragments and stumps with rootwads, as compared to slides in old growth which were composed of sediment, entire trees and woody debris fragments. Slide deposits in old growth often had a snout of woody debris on the downward side. Deposits in second growth deposits were similar to those in clearcuts if the second growth was relatively young, and more similar in composition to old growth with increasing age. Deposits in old-growth forests had from 98 to 300 logs (with diameters from 0.2 to 2.0 m). When a large snout of wood existed within a single deposit, smaller woody debris and sediment was often backed-up behind it. Lacking a large woody debris snout, the unimpeded sediment freely moved greater distances in the downstream or downslope direction.

The estimated percentage of woody debris derived from 0.25, 0.5, and 1.0 ha landslides and debris flows

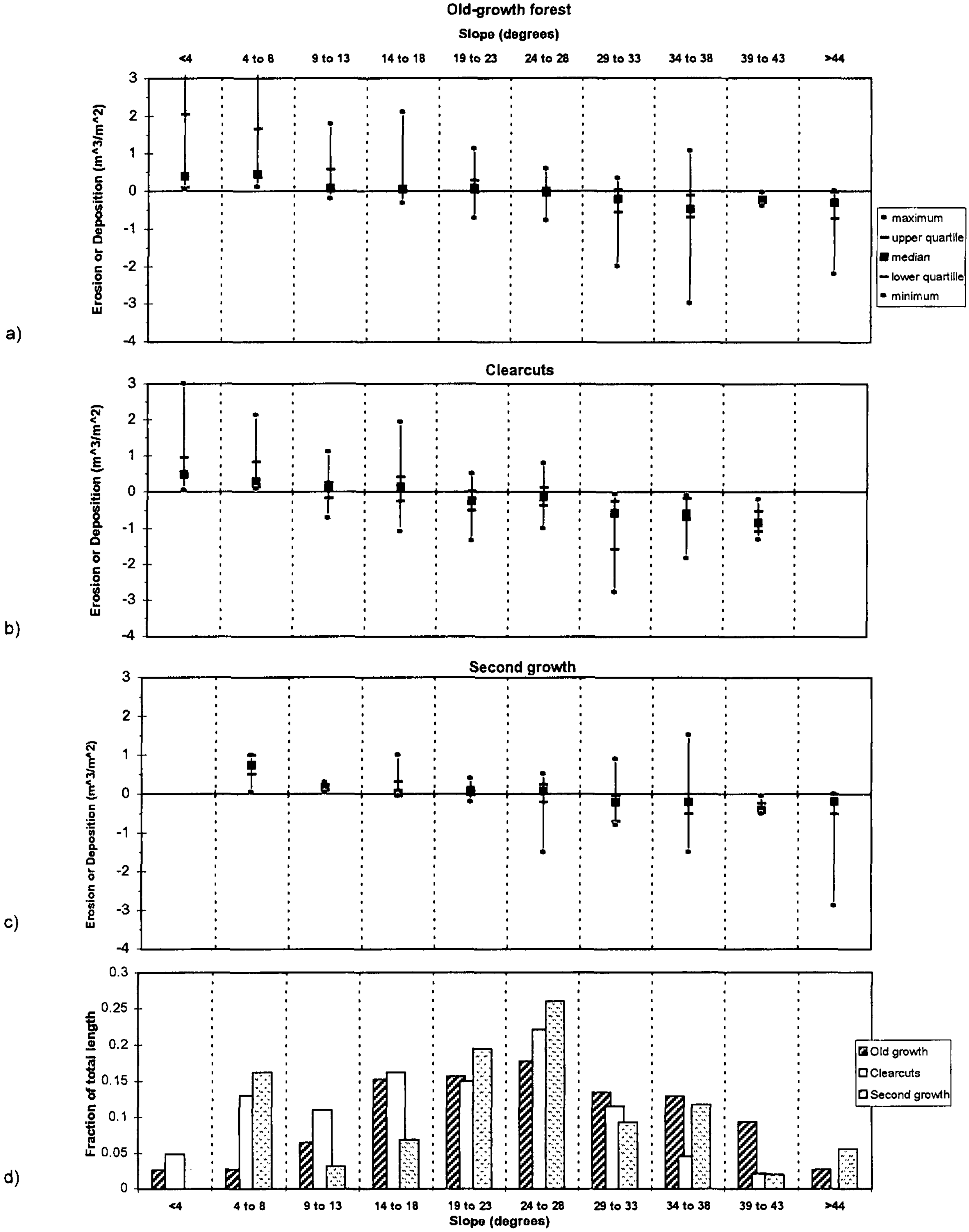

Figure 4. Distributions (box and whisker plots) of Erosion and Deposition in: (a) Old Growth, (b) Clearcuts, and (c) Second Growth by Slope Category, and (d) Fraction of Total Runout Length per Slope Category (deposition is indicated by positive volumes and erosion by negative volumes along the Y-axis). Note more erosion in clearcuts.

TABLE 3.Characteristics of Landslide Terminal Deposits (n = 9 for each land use type).

Landuse Type	Mean Value	Maximum	Minimum	Standard Deviation
OLD GROWTH				
Slope (degrees)	10	19	2.5	5
Width (m)	26	72	5	24
Volume (m^3)	756	2649	10	958
SECOND GROWTH				
Slope (degrees)	13	17	4	10
Width (m)	21	53	7	14
Volume (m^3)	514	2268	100	692
CLEARCUTS				
Slope (degrees)	7	12	3	3
Width (m)	11	20	5	5
Volume (m^3)	187	724	13	197

TABLE 4. Number of Landslide Terminal Deposits Per Stream Order and Stream Class [Class I, anadromous fish; Class II, resident fish; Class III and IV, without resident fish populations (U.S.D.A., 1997)] with Average Slope Indicated in Parentheses (total n = 27).

Landuse	First Order Class IV	Second Order Class III	Third Order Class II	Fourth Order Class I
Old Growth	2 (14°, 25%)	3 (8°, 12%)	2 (7°, 12%)	2 (2.5°, 5%)
Second Growth	5 (15°, 27%)	2 (6°, 10%)	1 (7°, 12%)	0
Clearcuts	4 (12°, 21%)	4 (10°, 18%)	0	0
Totals	**11**	**9**	**3**	**2**

with average soil depths of 0.1, 0.2 and 0.5 m indicates that the proportion of woody debris in a deposit was greatest when landslides derived from clearcuts and old growth were large and soils were shallow (Figure 5). Landslide deposits in old-growth forest typically had ten times the woody debris volume of deposits originating in clearcuts.

DISCUSSION

While our selection of landslides was random, the pattern of land use distribution was not. In southeast Alaska, clearcuts are often located in mid-slope and upper-slope regions of wide, U-shaped glacial valleys whereas areas of remaining old growth typically occur in steep V-shaped valleys above clearcuts or in steep canyons. In addition, old growth is common on valley side-slopes due to economic and regulatory reasons. Second-growth sites are generally lower in elevation than clearcut or old-growth sites, due mainly to earlier removal of easily reachable, high value timber. These land use pattern differences not only relate to differences in forest hydrology and forest health which may be associated with the initiation of landslides, but also affect runout length. Although it is difficult to directly compare landslides within the different landuse types because of differences in hillslope location, some trends are apparent.

Initiation

Seven of 15 landslides occurred within one year of forest harvest on clearcut sites, in contrast to the general 2-5 year delay found by others (Zeimer and Swanston,1977; Zeimer, 1981; O'Loughlin and Zeimer, 1982). This difference could be due to the magnitude of the storm and site conditions, including the condition of roots and preponderance of site saturation. Landslides in clearcuts may have been initiated

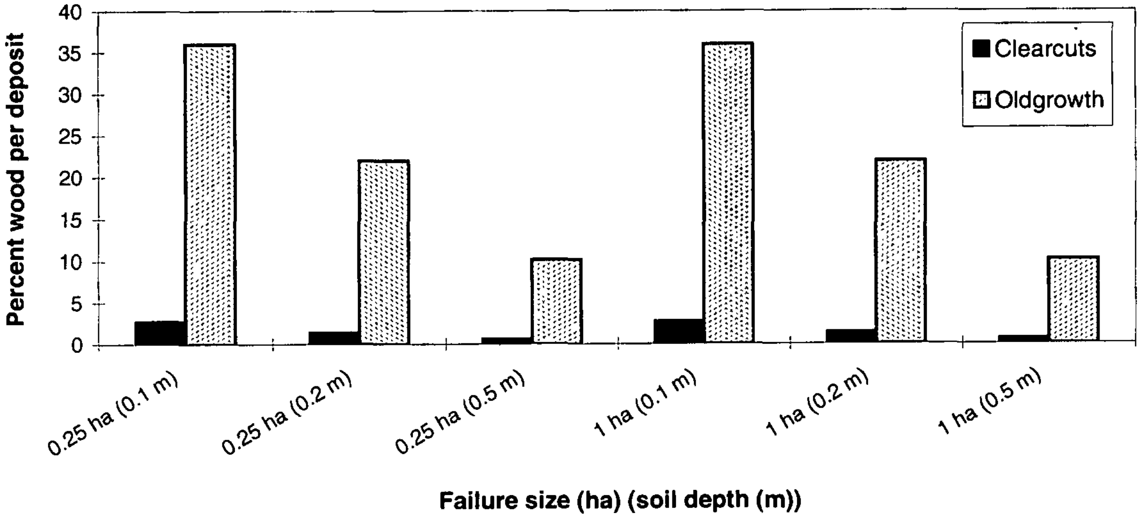

Figure 5. Estimated Proportion of Woody Debris in Clearcut and Old Growth Landslide Deposits. Calculations are plotted by size of landslide scar and by depth of erosion (in parenthesis). Woody debris diameters are greater than 23 cm.

regardless of storm and harvest timing due to preharvest hydrologic and root conditions predisposing some sites to failure. Five out of seven landslide scarps within clearcuts having failures within one year of forest harvest had a preponderance of rotted roots that pre-dated harvest activities and hydrophytic vegetation, specifically skunk cabbage. Skunk cabbage is indicative of a high water table (Minore, 1969) and is also well-correlated with topographic convergence (area where ground water concentrates).

Topographic models such as TOPOG (O'Loughlin, 1986) and TOPMODEL (Beven and Kirkby, 1979) quantify the degree to which ground saturation due to rising ground water is possible. These models have been linked to stability models (Montgomery and Dietrich, 1994), but are dependent on detailed topographic scale. Lacking the appropriate topographic data, we suggest that the prevalence of wetland vegetation in conjunction with steep slopes, convergent topography, and bedrock hollows, are indicative of high landslide potential. These indicators of landslide hazard, when combined with a decrease in overstory canopy, may markedly alter the magnitude and timing of peak pore pressures in convergent topography following major rainstorms. For example, in southeast Alaska, as much as 22 percent of the rainfall (where rainfall for one storm was 203 mm) is intercepted by hemlock and spruce forests (Patric, 1966). Loss of forest not only results in a decrease in root strength, but also increases the amount of precipitation directly reaching the ground, decreases evapotranspiration, and may decrease the time it takes for the groundwater table to rise to the soil surface.

A reduction of root strength as well as a lack of overstory vegetation may have played a key role in triggering some landslides as blowdown, rotted roots, or cedar decline occurred on 93 percent of old-growth locations, 73 percent of clearcut sites, and 80 percent of second-growth forests. Within clearcuts, skunk cabbage was present on a minority of the landslide sites that occurred 2-6 years post harvest (13 percent). Skunk cabbage was found in 20 percent of old-growth sites and in 13 percent of second-growth sites. Factors besides topographic control on hydrology, perhaps including yarding disturbance and changes in root strength, may have triggered these landslides. If all other variables are similar, roots have a greater relative role in the stability of hillslopes when soil depths are shallow (Johnson and Wilcock, 1997).

Runout and Deposition

Wide valleys and trellis drainage systems of Prince of Wales Island, characteristic of glaciated systems, controlled patterns of runout and deposition. In this recently deglaciated landscape, channel development is relatively young (generally less than 10,000 ybp), compared to older, nonglaciated landscapes in Oregon and California where drainage systems are dendritic. A comparison of measured and predicted runout lengths with corresponding change in elevation for both of these landscapes (Benda, personal communication; Montgomery and Dietrich, 1994) indicates that in nonglaciated systems the average runout slope is approximately 14° (25 percent) whereas it is approximately 23° (42 percent) in glaciated systems. Linear relationships for change in elevation and runout length indicate differences in runout trends for landslide occurring within different geomorphic regions (Figure 6).

Channel gradients at landslide deposits ranged from 3 to 19° (5 to 34 percent); a higher range than that found in Oregon, California, and Japan where depositional slopes range from 1 to 10° (2 to 18 percent) (Ikeya, 1981; Benda and Cundy, 1989). Benda and Cundy (1989) found that deposition typically occurs on 8° (14 percent) slope gradients in third-order channels and 1° slope gradients in fifth-order channels. In Alaska, deposition occurred on slopes averaging 10° (18 percent) in first-order and second-order channels. Differences in deposition location may be due to the lack of channel confinement in Alaska as compared to other regions. The rapid decrease in low-order stream gradients found in Alaska as compared a gradual decrease in channel gradients elsewhere, may also contribute to higher slopes of deposition. In both areas, higher depositional slopes may be attributed to lower water content (Johnson, 1984), increased woody debris content, higher angle tributary junctions, and/or smaller basin area (Ikeya, 1981; Benda and Cundy, 1990).

Because the location of landslide occurrence is associated with landscape form, the location of any particular land use within a landform affects both occurrence and deposition of landslides. Slides in old-growth forest tend to deposit within a range of stream orders whereas slides in second growth and clearcuts tended to deposit in lower order (higher class) channels within the valley floor. Slides in second growth and clearcuts tended to flow from the slopes of wide U-shaped valleys and deposit in valley floors, likely because they lacked the momentum to reach the higher order, lower gradient mainstem channels. All of the landslides that moved into higher order channels occurred in steeper portions of the landscape more dendritic in form. The difference in erosion and deposition processes within runouts was largely due to the effect of large standing trees in old-growth and second-growth forests that blocked the flow of oncoming debris. In addition, sediment and woody debris were backed-up behind large fallen logs in old-growth derived deposits.

The size and pattern of deposits of fine sediment and large woody debris can impact fisheries habitat (Swanson and Lienkaemper, 1978; Bisson *et al.*, 1992). While the majority of landslide/debris flow deposits do not reach higher order, main stem channels (habitat for many anadromous fish populations), the composition of deposits has important implications for fisheries habitats. First, large woody debris retained temporarily in deposits and released during subsequent storms is an important source of woody debris recruitment to stream channels. Secondly, steep tributaries that are contiguous with main stem channels provide debris and sediment recruitment conduits. Third, main and tributary channels may be particularly sensitive to inputs of fine sediment introduced from channels flowing across and through

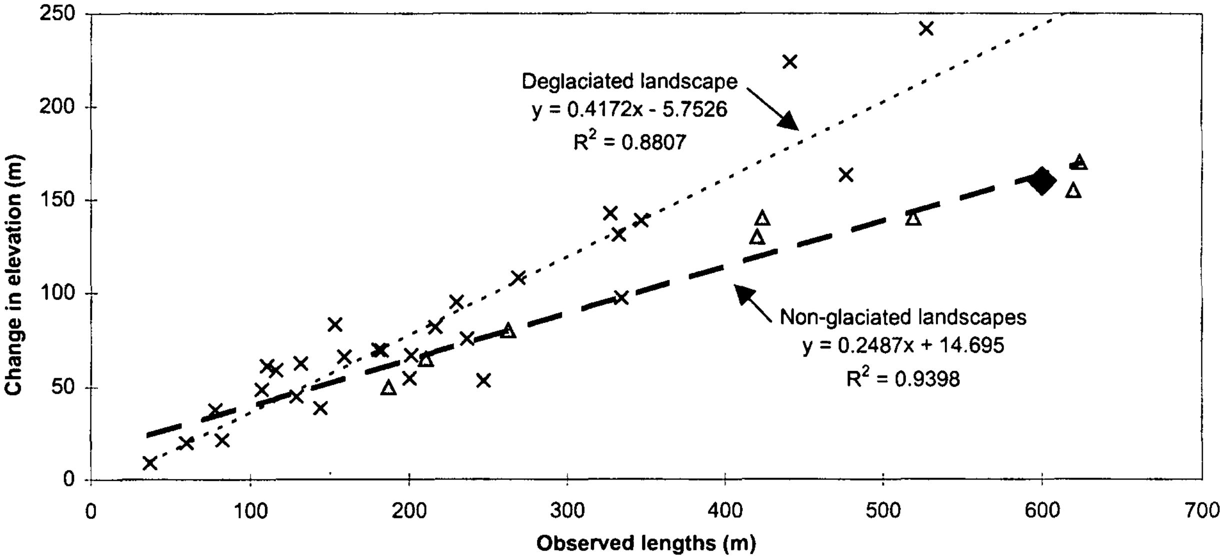

Figure 6. Change in Elevation Plotted as a Function of Observed Length of Landslides Occurring on Prince of Wales Island (shown as X's), Oregon (average value from Benda, personal communication, shown as diamond), and in California (Montgomery and Dietrich, 1994, shown as triangles).

landslide deposits – particularly if the sediment is not backed-up behind woody debris. This lack of back-up is the typical case for landslides occurring within clearcuts. These implications suggest that understanding the recruitment and storage of sediment and large woody debris in time and space at a landscape scale is essential to interpreting the variability of landslide impacts within a watershed context (Benda *et al.*, 1998).

CONCLUSIONS

Examination of a random sample of landslides within a deglaciated landscape in southeast Alaska indicated that natural site conditions, evidence of past blowdown, and hillslope position largely determined locations of landslide initiation and position of final deposition. We found that 89 percent of initiation sites had rotted roots, convergent topography, evidence of blowdown, and wetland vegetation which predated any human-related disturbances. Runout of landslides appeared to be affected by drainage pattern. A trellis form, typical of glaciated terrain in southeast Alaska, tended to induce deposition in first- or second-order channels in wide U-shaped valleys with slopes averaging 9° (18 percent), leaving main stem channels unaffected. Less typically, debris flows crossed mainstem channels at 90° angles. In contrast, the uppermost regions of glaciated systems, as well as the dendritic drainage systems characteristic of nonglaciated systems, typically had longer runouts and a lower average depositional slope. This feature was due to the existence of acute angles at stream junctions and gradual slope change encountered as the debris flows moved into higher order channels from lower order channels.

When effects of clearcutting were superimposed on natural site conditions, several factors appeared to contribute to the enhancement or suppression of landslide and debris flow impacts. These factors included an increase in triggering mechanisms associated with loss of forest canopy and loss of soil strength due to root cohesion. In addition, there was a significant difference in erosion and deposition characteristics of runout due to loss of the roughness effects provided by standing trees. For example, on slopes ranging from 19 to 23° (34 to 42 percent), erosion (with a mean of 0.28 m^3/m^2) was dominant in runout paths of debris flows in clearcuts while deposition (mean of 0.16 m^3/m^2) was dominant in old growth. Different patterns of erosion and deposition may have affected composition of final deposits in old growth and clearcut stands. To illustrate, we estimated that the composition of deposits originating from old-growth forests had five times the woody debris volumes of deposits originating from clearcuts. Lacking large woody debris volumes, fine sediment from clearcuts tended to migrate further down tributary channels to the receiving main stem channels, possibly to the detriment of anadromous fish habitats.

Before an understanding of the effects of land management on landslide initiation and runout can be developed, the underlying routing of sediment and large woody debris need to be understood in a landscape context. In the glaciated systems of Prince of Wales Island, most deposits from landslides or debris flows do not immediately reach main stem channels that are important habitats for anadromous fish. Hence, management of this habitat will benefit from an understanding that desirable levels of woody debris may occur as a result of recruitment from natural hillslope failure routed through the few steep reaches contiguous to the main stem channels. In addition to these inputs, woody debris recruitment occurs as a result of direct inputs from riparian forest adjacent to the main stem channel and as a result from recruitment from tributaries. Input mechanisms, in addition to landslides, include blowdown, bank erosion, and inputs due to forest mortality; natural processes largely controlled by topography and climate. Finally, management plans may benefit through the acknowledgement and integration of historical correlations between these naturally occurring disturbance processes and the habitats they create.

ACKNOWLEDGMENTS

Funding for this study was provided by the U.S.D.A., Forest Service, Ketchikan Area of the Tongass National Forest and PNW Research Station, Juneau, Alaska. Soil scientists Roger Johnson and Dennis Landwehr produced the landslide inventories from which our sample was derived, and aided immensely in the field work. We also thank Richard Woodsmith, Rachel Baker, Dave Mongomery, Terry Shaw, and three anonymous reviewers for their extremely useful editing and critiques of the manuscript.

LITERATURE CITED

Benda, L. E. and T. W. Cundy, 1990. Predicting Deposition of Debris Flows in Mountain Channels. Can. Geotech. J. 27:409-417.

Benda, L. E. and T. Dunne, 1997. Stoicastic Forcing of Sediment Supply to Channel Networks from Landsliding and Debris Flows. WRR 33(12):2849-2863.

Benda, L. E., D. J. Miller, T. Dunne, G. H. Reeves, and J. K. Agee, 1998. Landscape Dynamics. *In:* Ecology and Management of Streams in the Pacific Northwest Ecoregion, R. Naiman and R. Bilgy (Editors). Springer-Verleg, pp. 261-288.

Beven, K. and M. J. Kirkby, 1979. A Physically Based, Variable Contributing Area Model of Basin Hydrology. Hydrol. Sci. Bull. 24:43-67.

Bishop, D. M. and M. E. Stevens, 1964. Landslides in Logged Areas in Southeast Alaska. U.S.D.A. Forest Service Research Paper NOOR-1, Northern Forest Experimental Station, Juneau, Alaska, 18 pp.

Bisson, P. A., T. P. Quinn, G. H. Reeves, and S. V. Gregory, 1992. Best Management Practices, Cumulative Effects, and Long-Term Trends in Fish Abundance in Pacific Northwest River Systems. *In:* Watershed Management, R. J. Naiman (Editor). Springer-Verlag, pp. 127-188.

Dietrich, W. E. and T. Dunne, 1978. Sediment Budget for a Small Catchment in Mountainous Terrain. Zietshrift fur Geomorphologie, Suppl. Bd. 29:191-206.

Harris, A. S., 1989. Wind in the Forests of SE Alaska and Guides for Reducing Damage. USFS-PNW-GTR-244.

Harris, A. S., O. K. Hutchison, W. R. Meehan, D. N. Swanston, A. E. Helmers, J. C. Hendee, and T. M. Collins, 1974. The Forest Ecosystem of Southeast Alaska. 1. The Setting, U.S.D.A. For. Ser. Gen. Tech. Rep. PNW-12.

Hennon, P. E., E. M. Hansen, and C. G. Shaw, 1990. Dynamics of Decline and Mortality of *Chamaecyparis nootkatensis* in Southeast Alaska. Canadian Journal of Botany 68(3):651-662.

Hennon, P. E. and C. G. Shaw, 1997. The Enigma of Yellow-Cedar Decline. Journal of Forestry 95(12):4-10.

Ikeya, H., 1981. A Method for Designation for Areas in Danger of Debris Flow,. *In:* Erosion and Sediment Transport in Pacific Rim Steeplands. IAHS Spec. Publ. 132, pp. 576-588.

Johnson, A. C., 1993. The Association Between Landslides and Yel-Low Cedar Decline in Southeast Alaska. EOS, Trans. Amer. Geophysical Union, 74:315.

Johnson, A. C., 1997. Hillslope Stability in Cedar Decline Forests of Southeast Alaska. Unpubl. Master's Thesis, Johns Hopkins Univ., Baltimore, Maryland, 52 pp.

Johnson, A. C. and P. Wilcock, 1997. Effect of Root Strength and Soil Saturation on Hillslope Stability in Forests with Natural Cedar Decline in Headwater Regions in SE Alaska. *In:* Headwaters – Water Resources and Soil Conservation, M. Haigh, J. Krecek, G. S. Rajwar, and M. P. Kilmartin (Editors). A.A. Balkema, Rotterdam, Netherlands, pp. 381-390.

Johnson, A. M., 1984. Debris Flow. *In:* Slope Stability, D. Brunsden and D. B. Prior (Editors). Wiley and Sons, New York, New York, pp. 257-361.

Johnson, R., 1993. Inventory and Analysis of Landslides Caused by the October 25-26 Storm Event on the Craig Ranger District, Ketchikan Area Watershed Group. Unpublished U.S.D.A. Inventory.

Kramer, M. G, 1997. Abiotic Controls on Windthrow and Forest Dynamics in a Coastal Temporate Rainforest, Kuiu Island, Southeast Alaska. Unpublished Master's Thesis, Montana State University, Bozeman, Montana, 79 pp.

Krammer, J. S., 1965. Seasonal Debris Movement from Steep Mountain Side Slopes in Southern California. Proceedings, Federal Interagency Sediment Conference, 1965, Paper 12, in U.S.D.A. Misc. Pub. 970, pp .85-88.

Landwehr, D. J., 1993. Inventory and Analysis of Landslides Caused by the October 25-26 Storm Event on the Thorne Bay Ranger District. Ketchikan Area Watershed Group, U.S.D.A., Forest Service, Ketchikan, Alaska, Unpublished Report.

Minore, D., 1969. Yellow Skunk-Cabbage (*Lysichitum americanum* Hult and St. John) – An Indicator of Water-Table Depth. Ecology 50(4):737-739.

Montgomery D. R. and W. E. Dietrich, 1994. A Physically Based Model for the Topographic Control on Shallow Landsliding. Water Resour. Res. 30(4):1153-1171.

Nowacki, G. J. and M. G. Krammer, 1997. The Effects of Wind Disturbance on Temperate Rain Forest Structure and Dynamics of Southeast Alaska. *In:* Conservation and Resource Assessments for the Tongass Land Management Plan Revision, U.S.D.A., PNW Research Station, Gen Tech. Report 421.

O'Loughlin, E. M., 1986. Prediction of Surface Saturation Zones in Natural Catchments by Topographic Analysis. Water Resour. Res. 22(5):794-804.

O'Loughlin, C. L. and R. R. Zeimer, 1982. The Importance of Root Strength and Deterioration Rates Upon Edaphic Stability in Steepland Forests. *In:* Carbon Uptake and Allocation in Subalpine Ecosystems as a Key to Management. Proceeding of an I.U.F.R.O. Workshop, August 2-3, 1982, pp. 70-78.

Oregon Dept. of Forestry, 1998. 1996 Storm Impacts Monitoring Project – Preliminary Report.

Patric, J. H., 1966. Rainfall Interception by Mature Coniferous Forests of Southeast Alaska. Journal of Soil and Water Conservation.

Rice, R. M., 1973. The Hydrology of Chaparral Watersheds. Proc. Symp. Living with Chaparral. Sierra Club, Riverside, California, pp. 27-33.

Rogers, G. and W. W. S. van Hees, 1992. Timber Resource Statistics for the Ketchikan Area of the Tongass National Forest, Alaska, U.S.D.A. Forest Service , PNW-RB-184, 18 pp.

Schroeder, W. L., 1983. Geotechnical Properties of Southeast Alaskan Forest Soils. Oregon State University Civil Engineering Department, U.S.D.A. Forest Service, 46 pp.

Sidle, R. C, 1985. Factors Influencing the Stability of Slopes. Proceedings of a Workshop on Slope Stability: Problems and Solutions in Forest Management. U.S.D.A. Forest Service, Gen. Tech. Rep. PNW 180, pp 17-25.

Sidle, R. C. and D. N. Swanston, 1982. Analysis of a Small Debris Slide in Coastal Alaska. Can. Geotech. J. 19:167-174.

Swanson, F. J., 1981. Fire and Geomorphic Processes. *In:* Fire Regimes and Ecosystem Properties. Proceedings of the Conference, H. A. Mooney, T. M. Bonnicksen, N. L.Christensen, J. E. Lotan, and W. A. Reinerset (Editors). USDA For. Serv. Gen. Tech. Rep. WO-26, pp.401-420.

Swanson, F. J. and G. W. Lienkaemper, 1978. Physical Consequences of Large Organic Debris in Pacific Northwest Streams. U.S.F.S. Gen. Tech. Rep., PNW-69, PNW Forest and Range Experiment Station, Portland, Oregon.

Swanston, D. N., 1969. Mass Wasting in Coastal Alaska. U.S.D.A. Forest Service Research Paper PNW-83, Institute of Northern Forestry, Juneau, Alaska, 15 pp.

Swanston, D. N., 1970. Soil-Water Piezometry in a Southeast Alaska Landslide Area. Res. Pap. PNW-103, For. Serv., U.S.D.A., Portland, Oregon, 17 pp.

Swanston, D. N., 1974. The Forest Ecosystem in Southeast Alaska, Soil Mass Movement. U.S.D.A., Forest Service Gen. Tech. Bull. PNW-17, 21 pp.

Swanston, D. N., 1979. Landslide Prediction and Assessment Interpreting Stability Problems for the Land Manager. Proceedings of Workshop of Scheduling Timber Harvest for Hydrologic Concerns, U.S.D.A. Forest Service, Pacific Northwest Region, PNW Forest and Range Experiment Station.

Swanston, D. N., 1991. Natural Processes. *In:* Influences of Forest and Rangeland Management on Salmonid Fishes and Their Habitats, W. Meehan (Editor). American Fisheries Society Special Pulblication 19:139-179.

Swanston, D. N. and D. A. Marion, 1991. Landslide Response to Timber Harvest in Southeast Alaska. *In:* Proceedings of the Fifth Interagency Sedimentation Conference, Federal Energy Regulatory Commission, Las Vegas, Nevada.

U.S.D.A., 1997. Land and Resource Management Plan, Tongass National Forest. Forest Service Publication, Alaska R10-MB-338dd, pp. 4-8 to 4-12.

Walkotten, W. J. and J. H.Patric, 1967. Elevation Effects of Rainfall Near Hollis, Alaska. USDA Forest Service Research Paper PNW-53, Institude of Northern Forestry, Juneau, Alaska, 8 pp.

Wu, T. H., W. P. McKinnel, and D. N.Swanston, 1979. Strength of Tree Roots on Prince of Wales Island, Alaska. Can. Geotech. J. 16 (1):19-33.

Zeimer, R. R., 1981. Roots and the Stability of Slopes. Int. Assoc. Hyd. Sci., Publ. 132:43-357.

Zeimer, R. R. and D. N. Swanston, 1977. Root Strength Changes After Logging in SE Alaska. Res. Note PNW 306, For. Serv., U.S. Department of Agric., Portland, Oregon, 10 pp.