AN ABSTRACT OF THE DISSERTATION OF

Christine L. May for the degree of Doctor of Philosophy in Fisheries Science presented on November 13, 2001. Title: Spatial and Temporal Dynamics of Sediment and Wood in Headwater Streams in the Oregon Coast Range.

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Robert E. Gresswell

Channels that were scoured to bedrock by debris flows provided unique opportunities to calculate the rate of sediment and wood accumulation, to make inferences about processes associated with input and transport of sediment, and to gain insight into the temporal succession of channel morphology following disturbance. In an intensive investigation of 13 channels the time since the previous debris flow was estimated using dendrochronology. The volume of wood in the channel was positively and linearly correlated with the time since the previous debris flow. The pattern of sediment accumulation was non-linear and appeared to increase as the storage capacity of the channel increased through time. Wood stored the majority of the sediment in these steep headwater streams, and landslides and wind throw were the dominant mechanisms for delivering wood to the channel. With an adequate supply of wood, small streams have the potential to store large volumes of sediment in the interval between debris flows and can function as one of the dominant storage reservoirs for sediment in mountainous terrain.

In an extensive investigation of 125 headwater streams, the spatial and temporal patterns of debris flow occurrence and deposition were investigated. The temporal distribution of debris flow occurrence varied with network structure and drainage area of the tributary basin. Network structure may affect the frequency of debris flows delivered to the mainstem river valley because it reflects the number of potential landslide source areas and the routing ability of the channel. Tributary basins with larger drainage areas and more convergent topography had a greater proportion of channels in the younger, post-debris flow age-classes compared to smaller basins with less convergent topography. The flux rate of material delivered to the confluence with the larger river also influenced the development of debris flow fans. Fans at the mouth of tributary basins with smaller drainage areas had a higher likelihood of being eroded in the interval between debris flows, while larger, more persistent fans were present at the mouth of bigger basins. Valley floor width of the mainstem river typically constrained fan development and was also an important predictor of fan size.

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Spatial and Temporal Dynamics of Sediment and Wood in Headwater Streams

in the Central Oregon Coast Range

by

Christine L. May

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Christine L. May, Author

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Spatial and Temporal Dynamics of Sediment and Wood in Headwaters Streams in the Oregon Coast Range

1. Introduction

Small headwater streams in steep mountainous terrain represent an important linkage between hillslope and fluvial processes, and between terrestrial and aquatic ecosystems. Many of the small colluvial channels in soil-mantled landscapes are susceptible to erosion and deposition by debris flows. Debris flows of relatively low frequency and high magnitude are one of the dominant sediment transport processes in the Pacific Northwest and are a major disturbance agent in the aquatic ecosystem.

Debris flows have the potential to scour sediment and wood that has been stored in small streams for decades to centuries and episodically deliver this material to larger alluvial rivers. The number of potential landslide source areas and the routing ability of the channel network may play an important role in the frequency of debris flow delivery to the mainstem river. The flux rate of sediment and wood from small streams can be important for determining the size and persistence of deposition surfaces, for structuring the morphology of the receiving the stream, and for determining the frequency of disturbance to aquatic communities. During the interval between debris flows these small streams are important for routing water from the hillslopes to the larger river system and for the storage of sediment and wood. Although the majority of the channel network is composed of these small colluvial channels, little is known about the structure and function of small streams or about the key processes associated with the creation and maintenance of stream channel structure. The influence of wood and sediment availability on channel development following disturbance by debris flows is critical to landscape modeling and for understanding the dynamics of these systems.

Small colluvial channels can be an important storage reservoir for sediment delivered from the adjacent hillslopes. The routing of sediment through this portion of the drainage network depends on the storage capacity of the channel and the frequency of debris flows. Wood can be especially important for creating and maintaining sediment storage sites in these steep, high energy channels. Many studies have shown the important role large wood plays in the structure and function of coastal streams; however, little is known about the relative contribution of wood delivered by processes occurring in the local riparian area compared to upstream and upslope sources of wood. Input processes of wood may vary spatially in a basin because of differences in stream size, the degree of hillslope constriction, dominant geomorphic processes, and forest stand characteristics. Understanding the multiple pathways that recruit and redistribute wood in the channel network is important because it provides insight into the physical and biological linkages between streams, riparian zones, and uplands.

The spatial and temporal patterns of disturbance are important for understanding watershed processes and for designing aquatic conservation plans. These patterns provide insight into the disturbance history of a watershed, which affects the distribution of channel states and processes that interact to shape the distribution. Debris flows transport sediment and wood stored in low-order channels, and leave behind an erosional zone that is typically scoured to bedrock. These bedrock channels provided a unique opportunity to calculate the rate of wood and sediment accumulation, and to gain insight into the processes that refill the channel with sediment and wood in the interval between debris flows. Process rates are important for predicting the state of the channel and for understanding the development of the channel morphology following disturbance. At the basin scale, the availability of wood and sediment may be important factors in the temporal dynamics of channel development. At the regional scale, the underlying geology and the occurrence of fires and large storms may be important factors in disturbance frequency and magnitude.

The goals of this study were to (1) investigate the processes and rates of sediment and wood accumulation in headwater streams; (2) document the spatial and temporal patterns of debris flow deposition; and (3) quantify the relative importance of different wood recruitment and redistribution processes, and how they vary spatially in the network. Each chapter of the dissertation addresses one of these goals.

2. Processes and Rates of Sediment and Wood Accumulation in Headwater Streams of the Oregon Coast Range, U.S.A.

Christine L. May and Robert E. Gresswell

ABSTRACT

Channels that have been scoured to bedrock by debris flows provide unique opportunities to calculate the rate of sediment and wood accumulation in low-order streams, to understand the temporal succession of channel morphology following disturbance, and to make inferences about processes associated with input and transport of sediment. Dendrochronology was used to estimate the time since the previous debris flow and the time since the last stand-replacement fire in a sample of unlogged basins in the central Coast Range of Oregon. Substantial debris flow activity occurred in both the post-fire and inter-fire time periods. Changes in sediment and wood storage were quantified for 13 streams that ranged from 4 to 144 years since the previous debris flow. The volume of wood in the channel was strongly correlated with the time since the previous debris flow, and the accumulation rate was linear. The pattern of sediment accumulation was non-linear and appeared to increase as the storage capacity of the channel increased through time. Wood stored the majority of the sediment in these steep headwater streams. In the absence of wood, channels that have been scoured to bedrock by a debris flow may lack the capacity to store sediment and could persist in a bedrock state for an extended period of time. With an adequate supply of wood, low-order channels have the potential of storing large volumes of sediment in the interval between debris flows and can function as one of the dominant storage reservoirs for sediment in mountainous terrain.

KEY WORDS: debris flows; sedimentation; large wood; dendrochronology; bedrock streams

INTRODUCTION

First- and second-order streams (Strahler, 1964; referred to hereafter as low-order streams) can represent 60 - 80% of the cumulative channel length in mountainous terrain (Schumm, 1956; Shreve, 1969; Benda, 1988). Because of their abundance and distribution throughout the channel network, low-order streams can be viewed as a primary conduit for water, sediment, and wood routed from hillslopes to higher-order rivers (Niaman *et al.*, 1992). Many low-order streams in the Oregon Coast Range are naturally prone to episodic disturbance by debris flows because they drain steep, landslide-prone hillslopes. Past studies in the Oregon Cascade Range (Swanson *et al.*, 1982) and in central Idaho (Megahan and Nowlin, 1976) indicate that relatively little sediment and wood is transported by chronic fluvial processes in low-order streams. Instead, many low-order streams undergo long periods of net increase in the storage of sediment and wood that is punctuated by episodic transport by debris flows (Dietrich and Dunne, 1978; Swanson *et al.*, 1982; Benda and Cundy, 1990). Sediment that is entrained as a debris flow travels through the low-order channel network can account for over 80% of the volume of debris flow deposits (May, 1998).

Unlike larger rivers, sediment storage sites, such as point bars and floodplains, are absent in steep low-order streams because they are tightly constrained by the surrounding hillslopes. Thus, large wood may account for a much greater portion of the total sediment in storage in the headwater streams (Keller and Swanson, 1979). For example, large wood stored 49% of the sediment in seven small Idaho watersheds (Megahan, 1982), and 87% of the sediment in a small stream reach in New Hampshire (Bilby, 1981). By increasing the sediment storage capacity of the channel, large wood buffers the sedimentation impacts on downstream reaches when pulses of sediment enter headwater streams (Swanson and Lienkamper, 1978).

Debris flows transport sediment and wood stored in low-order channels and leave behind an erosional zone that is typically scoured to bedrock (Swanson and Lienkamper, 1978; May, 1998). The erosion of the channel to bedrock provides a unique opportunity to calculate the rate of wood and sediment accumulation, and to gain insight into the processes that refill the channel with sediment and wood in the interval between debris flows. In low-order streams, the size of wood is typically large in relation to the size of the channel (Bilby and Ward, 1989; Bilby and Bisson, 1998), and it can be assumed that fluvial processes transport very few pieces of wood in the interval between debris flows. Conversely, the sediment transport capacity of the channel may be high immediately following a debris flow because bedrock channels are typically straight, steep, and have a high hydraulic radius and low roughness. Therefore, immobile pieces of wood can form a physical obstruction to sediment transport that may be critical for sediment accumulation in this portion of the drainage network.

The goal of this study was to investigate changes in sediment and wood storage volumes, and associated changes in channel morphology, in low-order streams that are prone to erosion by debris flows. We used a space-for-time substitution approach to align spatially separated states along a temporal sequence (Welch, 1970). Specific objectives were to: (1) quantify the rate of wood and sediment accumulation in second-order streams that are prone to erosion by debris flows; (2) identify the mechanisms for storing sediment in high-gradient, low-roughness channels; (3) assess the relative importance of debris flow-prone tributaries as storage reservoirs for sediment in the drainage basin.

STUDY AREA

Two third-order basins with a limited history of timber harvest and road construction were selected for this study (Table 2.1, Figure 2.1). Sediment production and transport processes in the basins were considered typical of debris flow terrain in the central Coast Range of Oregon. Skate Creek has a drainage area of 2.5 km^2 and Bear Creek has a drainage area of 2.3 km^2, both are located in the Siuslaw River drainage. A ridge top road and small clearcut units are located at the upper extent of both basins. Tributaries that were influenced by timber harvest activities were not investigated.

The study basins are underlain by Tertiary marine sedimentary rocks of the Tyee Formation (Baldwin, 1964). The Tyee Formation is composed of massive, rhythmically bedded sandstones with interbeds of siltstones and mudstones. The drainage network is characterized by a dense, dendritic drainage pattern in first- and second-order streams that drain short, steep hillslopes. The low elevation (< 500 m) mountains are unglaciated and have a topography similar to the 'ridge and ravine topography' described by Hack (1960). The soils are well drained and range from loams to clay loams.

Mature stands of Douglas-fir *(Pseudotsuga menziesii)* and western hemlock (*Tsuga heterophylla*) forest are present in the study basins, which are located in the western hemlock zone (Franklin and Dyrness, 1973). Red alder *(Alnus rubra)* is typically found in riparian areas, or in areas of recent disturbance, and is the most common deciduous species. A thick ground cover of shrubs consists mostly of salmonberry

Table 2.1. Channel and basin characteristics of Skate and Bear Creeks.

Tributary	Total Channel Length (m)	Erosional Zone Length (m)	Erosional Zone Drainage Area (km^2)	Average Erosional Zone Slope (%)	Average Valley Floor Width (m)
Skate T3	384	344	0.15	29	4.0
Skate T4	714	584	0.15	30	3.9
Skate T5	313	265	0.11	25	3.4
Skate T6	354	296	0.09	32	3.3
Skate T8	290	290	0.12	38	4.5
Bear T3	252	215	0.06	32	4.4
Bear T4	445	254	0.08	32	5.0
Bear T5	315	239	0.08	34	3.2
Bear T7	486	389	0.09	35	4.3
Bear T9	514	462	0.09	25	4.4
Bear T11	399	242	0.15	22	4.8
Bear T12	420	420	0.11	26	4.8
Bear T13	489	261	0.20	41	2.8

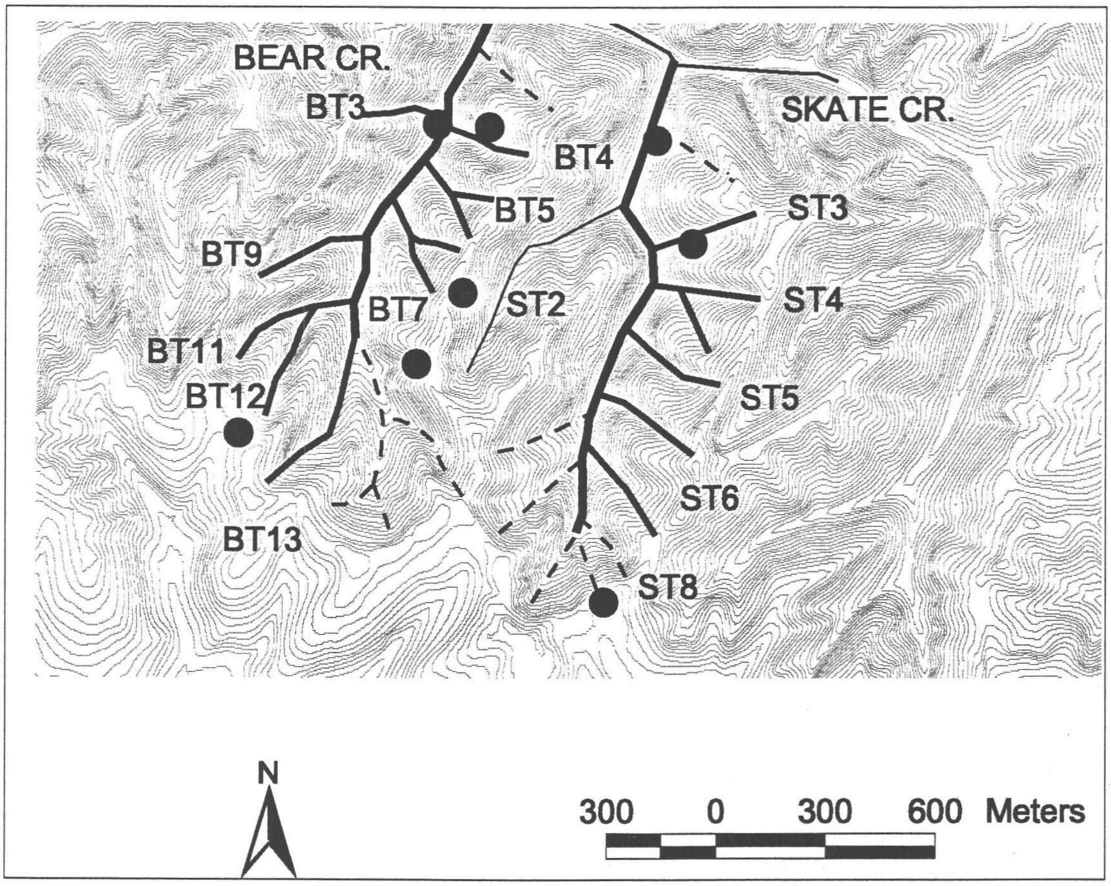

Figure 2.1. Site map of Skate and Bear Creeks, Siuslaw River drainage in the central Oregon Coast Range. Dark solid lines represent channels investigated for wood and sediment storage. Dashed lines represent colluvial tributaries impacted by timber harvest and not investigated. Thin solid line (ST2) is the only tributary with no evidence of delivering debris flows to the mainstem. Numerous first-order channels throughout the network are not highlighted and are not well represented on low-resolution topographic data. Solid circles represent sample sites for the dendrochronology-based fire history reconstruction. Contour intervals = 10 m.

(Rubus spectabilis), thimbleberry *(Rubus parviflorus)*, vine maple *(Acer circinatum)*, swordfern *(Polystichum munitum)*, salal *(Gaultheria shallon)*, and huckleberry *(Vaccinium parvifolium)*. These shrubs rapidly colonize landslide scars, and the dense understory significantly limits visibility.

METHODS

Second-order channels prone to debris flows were identified by the presence of either a current or remnant depositional feature at the tributary junction with the mainstem. The stratigraphy of debris flow deposits was differentiated from alluvial deposits by the dominance of poorly sorted, angular colluvium in the former. All of the channels we investigated were also predicted to deliver debris flows to the mainstem river by an empirical model based on tributary junction angle and channel gradient (Benda and Cundy, 1990).

The erosional zone of the channel was defined at the downstream end by a consistent slope of > 20%, or the presence of continuos reaches of exposed bedrock. The transition between the erosional and depositional zone was further distinguished by the presence of a large boulder lag that is typically deposited at the tail end of the debris flow. Channels were ascended until a pair of first-order channels were encountered at the upper extent of the second-order channel.

Time since the previous debris flow was estimated by aging trees currently growing on the valley floor of channels in the erosional zone. Trees in the depositional zone were not dated because of a greater likelihood that older trees survived the previous debris flow. Tree cores were extracted < 1m above the base of the tree on the uphill side, with a 46-cm-long increment bore. Cores were air-dried, mounted, planed, and sanded until cell structure was clearly visible. The time since the previous debris flow was expressed in years before 2000. Additional years were added to the tree ring count to correct for the number of years required for the tree to grow to the height at which it was sampled (Agee, 1993). The oldest date acquired for a particular channel was used in the analysis; however, dates can only be considered a minimum time since the previous debris flow because limited information is available on the time required for tree establishment or for successional lags among species.

The time since the previous stand-replacement fire was investigated by coring trees at eight sample sites in the study basins. Two distinct size classes of trees were observed on aerial photographs. The larger size class of trees was located in the low elevation valley floors, and the smaller size class was located on mid- and upper-hillslope positions. This pattern was consistent in both Bear and Skate drainages. Sampling focused on four topographic positions: (1) ridge tops, (2) upper-slope positions were landslides initiated debris flows, (3) mid-slope positions that approximated the runout zone of debris flows, and (4) along the low elevation valley floors of Bear and Skate Creeks. Two sample sites were located in each zone (Figure 2.1), and four to six trees were sampled at each site.

Measurements of Wood and Sediment Accumulation

The volume of wood was assessed by surveying the entire length of the second-order channel in each tributary for pieces of wood with an average diameter > 20 cm and length > 2 m. Only pieces that were in contact with the channel or valley floor were measured, and wood that was suspended > 2 m above the channel was not recorded. The volume of each piece was calculated as a cylinder using the average diameter and total piece length. Pieces of wood that were actively storing sediment were documented.

Sediment accumulations were measured if they were at least equal in length to the active channel width. The volume of sediment was estimated by measuring the valley floor width, the length of the sediment accumulation, and the average thickness of the sediment accumulation above bedrock. For discrete deposits formed behind obstructions, the volume of the sediment was calculated as a wedge, assuming a constant bedrock slope beneath the deposit. For more continuous accumulations of sediment, a rectangular volume of sediment was calculated, also assuming a constant bedrock slope beneath the deposit. Because patches of bedrock were frequently present and layers of sediment were typically thin and discrete, it was possible to reliably estimate sediment depth. The particle size of the surface layer of sediment was assessed by visually estimating the proportion of the streambed covered by fine sediment (< 2 mm), gravel (2 – 64 mm), cobble (65 – 256 mm), boulder (> 256 mm), and bedrock in each sediment accumulation patch.

Sediment accumulation rates were only calculated for the erosional zone of the channel; however, sediment storage throughout the Skate Creek basin was investigated. Sediment storage was measured in all second- and third-order channels in the unlogged portion of Skate Creek (Figure 2.1). Sediment storage could not be measured in tributaries that had been harvested for timber in previous decades because the abundance of logging debris substantially impaired access to the streambed, and sediment depth could not be reliably estimated. The volume of sediment stored in terraces along the mainstem of Skate Creek was calculated as a trapezoid with the volume of the bank-full channel removed. The height of the terrace above bedrock in the streambed, terrace width on each side of the channel, and the hillslope angles were measured at 50 m intervals. The perimeter, height above the streambed, and the distance from the apex of the fan (i.e. the hillslope constriction of the tributary) to the mainstem channel edge was measured at each debris flow fan. Fan volume was calculated as half an ellipse because this shape was a good approximation of the actual, two-dimensional shape of fans developed within the constraints of a relatively narrow valley floor. This calculation underestimated the actual volume because the sloping surface of the fan was not accounted for.

Predicting Sediment Input

Observations of sediment storage in channels can be used to make inferences about input and transport processes. Bedrock hollows act as local traps for a portion of the colluvium transported down hillslopes, and erosion rates can be calculated using the age and size of the contributing source area (Reneau and Dietrich, 1991). Reneau and Dietrich (1991) used two methods to estimate erosion rates in the Oregon Coast Range. The first method used colluvial infilling rates, based on the age and size of bedrock hollows (3.6×10^{-3} m^3/m/yr; Reneau and Dietrich, 1991). We used this value to predict sediment input to channels; however, this prediction assumes that all input is from local diffusive processes. Diffusive processes move soil gradually downslope, including mechanisms such as soil creep, animal burrowing, tree throw, and rainsplash (Roering *et al.*, 1999). This infilling rate is likely to underestimate the actual volume of sediment stored in channels because it does not account for all sources of sediment, such as landslides and fluvial transport from upstream.

The second method for predicting a sediment input rate to a channel used an inferred bedrock lowering rate (1.1×10^{-4} m/yr; Reneau and Dietrich, 1991) and a soil to bedrock bulk density ratio of 0.5 (Reneau and Dietrich, 1991; Heimsath *et al.*, 2001). The bedrock lowering rate was inferred from the volume of colluvium stored in dated bedrock hollows. Using the contributing basin area and the density of weathered bedrock, the accumulated colluvium was mathematically spread over the adjacent hillslopes to calculate an equivalent average bedrock lowering rate. This inferred rate was consistent with calculations of the maximum bedrock exfoliation rate (0.9×10^{-4} m/yr; Reneau and Dietrich, 1991). The maximum bedrock lower rate was also in close agreement with the catchment-averaged erosion rate of 1.2×10^{-4} m/yr estimated by Heimsath *et al.* (2001) in this area. The underlying assumption of using this method for predicting input to the channel is that all sediment from bedrock lowering over the entire contributing drainage area is delivered to the channel, and none is lost to downstream transport. This method is likely to overestimate the actual volume of sediment stored in the channel because some portion of the sediment produced in the basin is stored on hillslopes and in hollows, and some sediment that is delivered to the channel is exported.

Both methods for predicting sediment input are approximations, but they provide reasonable estimates in the absence of a feasible method to directly calculate sediment input to the channels we investigated. The values reported by Reneau and Dietrich (1991) were determined on a longer time scale than in this study; therefore, short-term pulses of sediment delivery may not be represented by the long-term average. The direction and relative magnitude of these predictions can be compared to the observed volume of sediment stored in the channels to make inferences about processes associated with sediment input, storage, and transport.

RESULTS

Dendrochronology

Estimates for the ages of the 13 debris flow runout paths ranged from 4 to 144 years since the previous debris flow (Table 2.2). In order to estimate the lag time between debris flow occurrence and tree establishment, two debris flows with a known time of occurrence were compared with the age of tree cores sampled from the erosional zone. Bear T11 (Figure 2.1) had an even age cohort of alders that ranged from 18 to 20 years of age. No debris flow was detected in this tributary on 1972 aerial photographs; however, a debris flow runout path was observed on 1979 aerial photographs. A large storm event in November-December 1975 triggered numerous landslides and debris flows in the area (Swanson and Swanson, 1977). If the debris flow in Bear T11 was associated with the 1975 storm, there was a lag time of up to 5 years in the tree ring record. A debris flow in Cedar Creek, also in the Siuslaw River drainage, also had a known time of occurrence in 1975 (Swanson and Swanson, 1977). The age of alder trees in the erosional zone ranged from 18 to 22 years, indicating a lag time of 3 to 7 years for tree establishment. Additional error was inherent in estimating precise dates from tree core samples. The most common source of error in our analysis was underestimation of the actual age when the exact center point of the tree was not encountered during sampling; thus, the first few years of growth may have been missed.

Table 2.2. Particle size of streambed surface layer and average length of bedrock reaches.

Time Since Debris Flow (yr)	Tree Species	Tributary	Percent Channel Area by Substrate Size					Average Length of Bedrock Reaches (m)
			Fines	Gravel	Cobble	Boulder	Bedrock	
4	-	BT13	1	7	3	3	86	57
20	Red Alder	BT11	4	24	7	2	62	22
36	-	ST6	0	6	4	0	89	85
88	Hemlock	BT12	3	23	11	5	58	17
84	Red Alder	ST5	4	20	11	13	52	32
114	Hemlock	BT5	11	29	14	22	24	11
121	Douglas Fir	ST4	2	35	14	11	36	13
123	Douglas Fir	ST3	3	28	11	14	45	28
124	Douglas Fir	BT9	5	39	18	19	20	9
127	Douglas Fir	BT4	7	38	12	12	32	14
129	W. Red Cedar	BT3	14	35	12	17	21	7
143	W. Red Cedar	ST8	3	45	12	9	30	9
144	Douglas Fir	BT7	10	35	20	22	13	9

No trees were growing in the erosional zone of two of the channels in our study basins. The debris flow in Bear T13 was known to have occurred during a large storm event in 1996. No trees had become established in the erosional zone in the 4 years since this debris flow; however, young alder seedlings had rapidly recolonized the deposit. Skate T6 was heavily shaded and also had no trees present in the erosional zone, and this channel had extremely low volumes of wood and sediment. A landslide near the channel head was visible on air photos from 1968; therefore, it was assumed that this debris flow occurred during an extremely large storm in 1964.

Trees established since the previous stand-replacement fire on mid- and upper-elevation hillslopes were younger than trees growing on the low elevation valley floors. All trees sampled on mid- and upper-hillslopes were < 148 years of age. The average age of tree cores from these slope positions was 133 ± 11 years (± one standard deviation), and the average diameter was 85 ± 23 cm (± one standard deviation). The maximum tree ring count from the low elevation valley floors of Skate and Bear Creeks was 315 years, the average was 251 ± 54 years (± one standard deviation), and the average diameter was 163 ± 30 cm (± one standard deviation). The age of tree cores extracted from the extremely large trees growing on the low elevation valley floor surfaces are only a partial age based on the number of tree rings counted. Only the outer 46 cm of these large diameter trees could be extracted, and the center of the tree could not be sampled; therefore, the reported age underestimates the actual age.

Accumulation Rates

The estimated time since the previous debris flow was used to calculate accumulation rates for sediment and wood. A linear fit to the wood volume and age data yielded a constant accumulation rate of wood per stream length of 0.008 $m^3/m/yr$, based on the slope of the linear regression equation (Figure 2.2). Time since the last debris flow accounted for 57% of the observed variance in wood volume ($p < 0.01$). In contrast, the sediment accumulated at a non-constant rate (Figure 2.3). A lower accumulation rate was observed immediately following a debris flow, whereas a higher accumulation rate was observed as the time since the previous debris flow increased. The nonlinear fir to the data ($p < 0.001$, $r^2 = 0.91$) had a better fit than the linear model ($p < 0.001$, $r^2 = 0.79$). Drainage area and channel gradient were not significant variables for predicting the volume of sediment in the channel when compared with the age data in a multiple linear regression model ($p > 0.1$). Regression analysis performed for this study were subject to high leverage because most of the data were in the > 100 year age range and data in 50 to 100 year period were sparse.

A temporal succession of changes in channel morphology can be perceived for the erosional zones of past debris flows (Figure 2.4). Immediately following a debris flow the channel was typically bedrock, with no sediment or wood in storage. Thirty to sixty years following a debris flow, small discrete patches of sediment were stored behind individual logs, but the channel was predominantly bedrock. Ninety years after a debris flow, almost half of the channel length was still exposed bedrock. Approximately 120 years after a debris flow, discrete patches of stored sediment coalesced to form larger, more continuous patches. After 150 years the channel was continuously covered with sediment, with very little exposed bedrock.

The decrease in average length of bedrock reaches with increased age depicts how these discontinuous patches of sediment coalesced through time (Table 2.2). As the

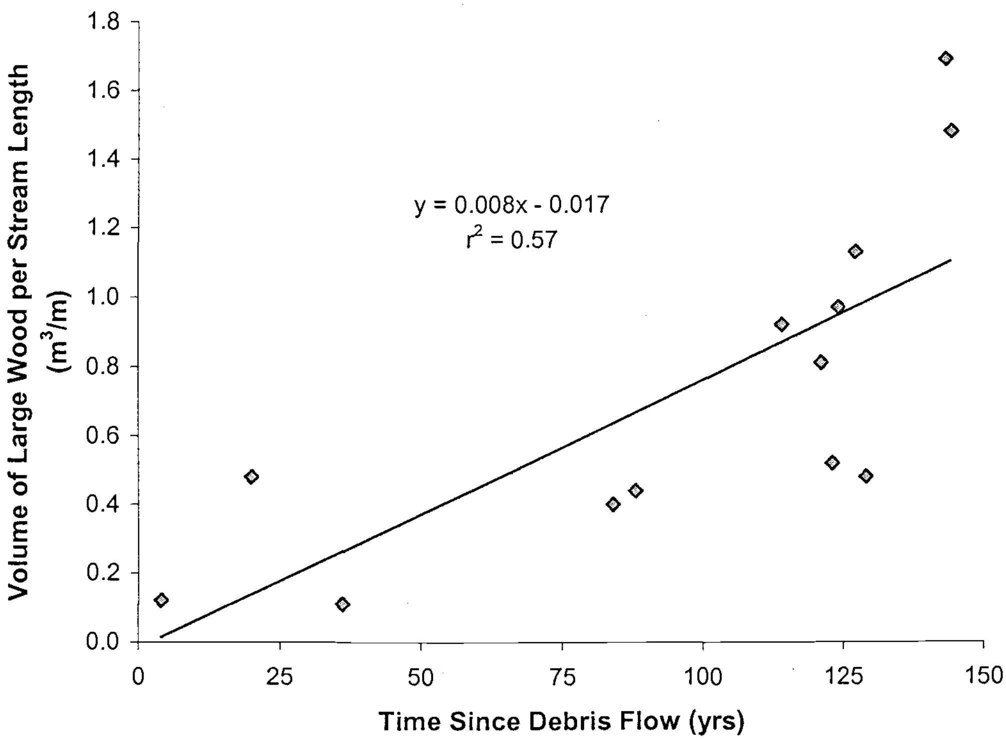

Figure 2.2. Volume of large wood in the study streaams based on the time since the previous debris flow as estimated by dendrochronology.

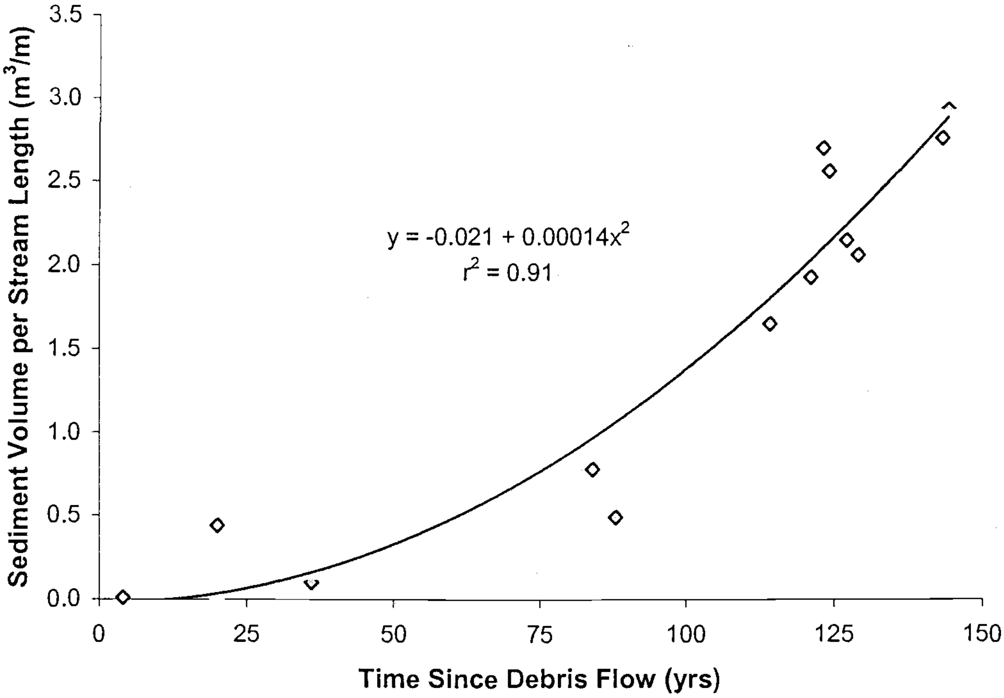

Figure 2.3. Sediment accumulation in the study streams based on the time since the previous debris flow as estimated by dendrochronology.

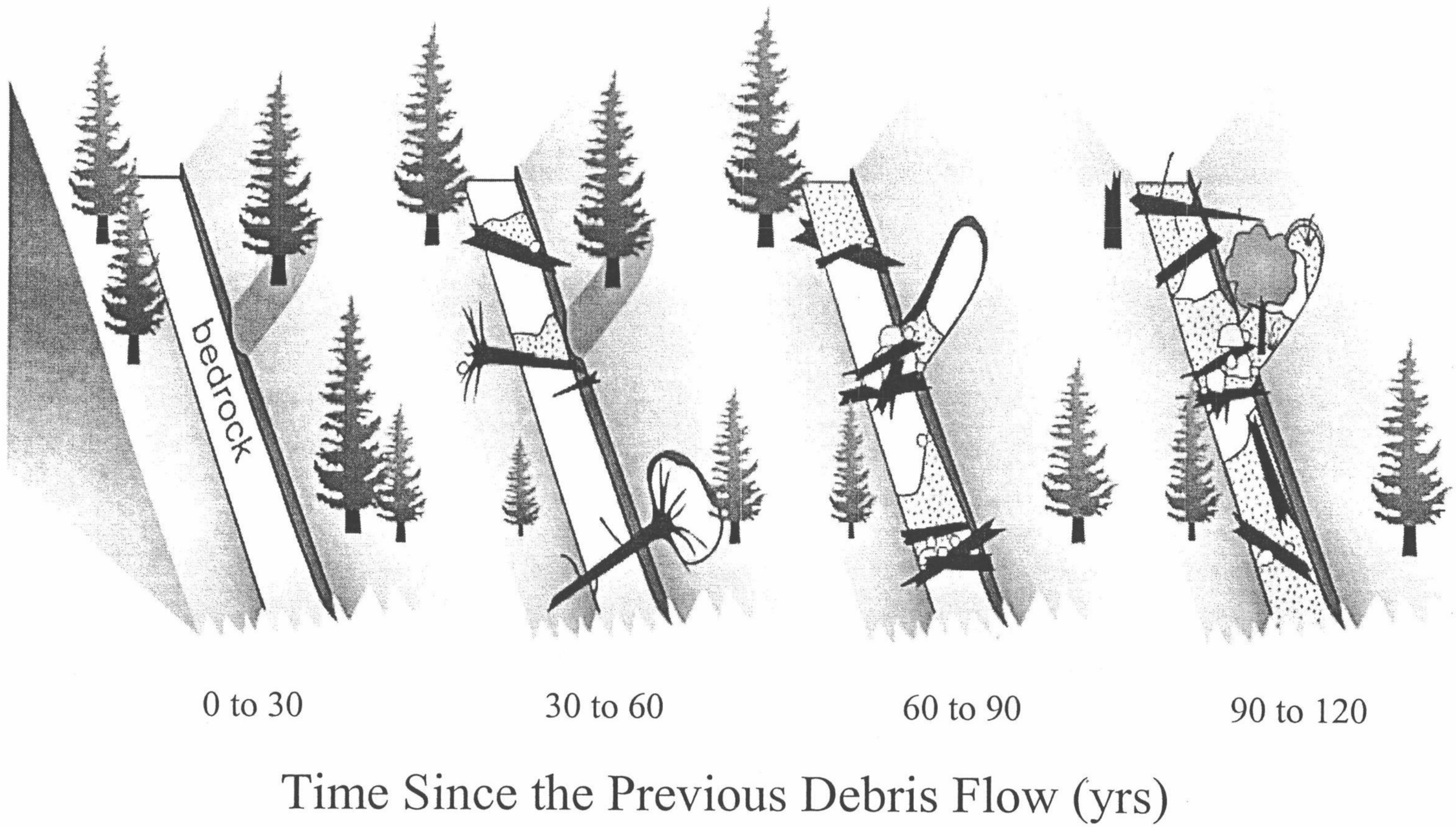

Figure 2.4. Conceptual diagram of changes in channel morphology based on the time since the previous debris flow.

proportion of the channel area with exposed bedrock decreased through time, the proportion of gravel in the surface layer increased (Table 2.2). Field observations indicated the development of an armor layer; therefore, the proportion of fine sediment stored in these channels was underestimated by observations of the surface layer. Similarly, Benda and Dunne (1987) observed that below a surface pavement, the texture of sediments in low-order channels consisted of colluvium that had undergone little to no sorting by fluvial transport.

Using the observed sediment accumulation trend (Figure 2.3), we calculated an average accumulation rate for a channel with the longest time since the previous debris flow (144 years post-debris flow). The observed accumulation rate of sediment to a channel in this age class (2.0×10^{-2} $m^3/m/yr$) was an order of magnitude higher than the average colluvial infilling rate predicted from dated bedrock hollows (3.6×10^{-3} $m^3/m/yr$, Reneau and Dietrich, 1991). Consequently, the observed volume of sediment stored in the channels we investigated was substantially higher than predicted by the equivalent years of colluvial infilling to bedrock hollows (Table 2.3, Figure 2.5). This discrepancy may be related to inputs from landslides from bedrock hollows and planar sideslopes, which were observed to be a major source of sediment to the channels we investigated. Unfortunately, it was not possible to quantify the long-term contribution of sediment delivered from landslides because landslide scars were rapidly vegetated, and only failures that occurred in the last decade could be detected. Where landslide scars could be detected, the scar was measured, and this volume accounted for an average of 19% of the sediment stored in the channels.

Table 2.3. Measured sediment volumes and predicted sediment volumes from colluvial infilling rates from dated bedrock hollows and an inferred bedrock lowering rate.

Tributary	Time Since Debris Flow[a] (yrs)	Erosional Zone Sediment Volume[b] (m^3)	Sediment Volume Predicted from Colluvial Infilling[c] (m^3)	Sediment Volume Predicted from Bedrock Lowering[c] (m^3)
Skate T3	123	939	305	1005
Skate T4	121	1110	509	1012
Skate T5	84	223	160	503
Skate T6	36	27	77	180
Skate T8	143	800	299	947
Bear T3	129	443	199	443
Bear T4	127	546	232	582
Bear T5	114	394	196	529
Bear T7	144	1138	403	737
Bear T9	124	1183	412	611
Bear T11	20	106	35	165
Bear T12	88	208	266	544
Bear T13	4	27	8	44

[a] Time since debris flow determined by dendrochronology.

[b] Measured sediment volume.

[c] Average colluvial infilling rates from dated bedrock hollows and inferred bedrock lowering rates from Reneau and Dietrich (1991).

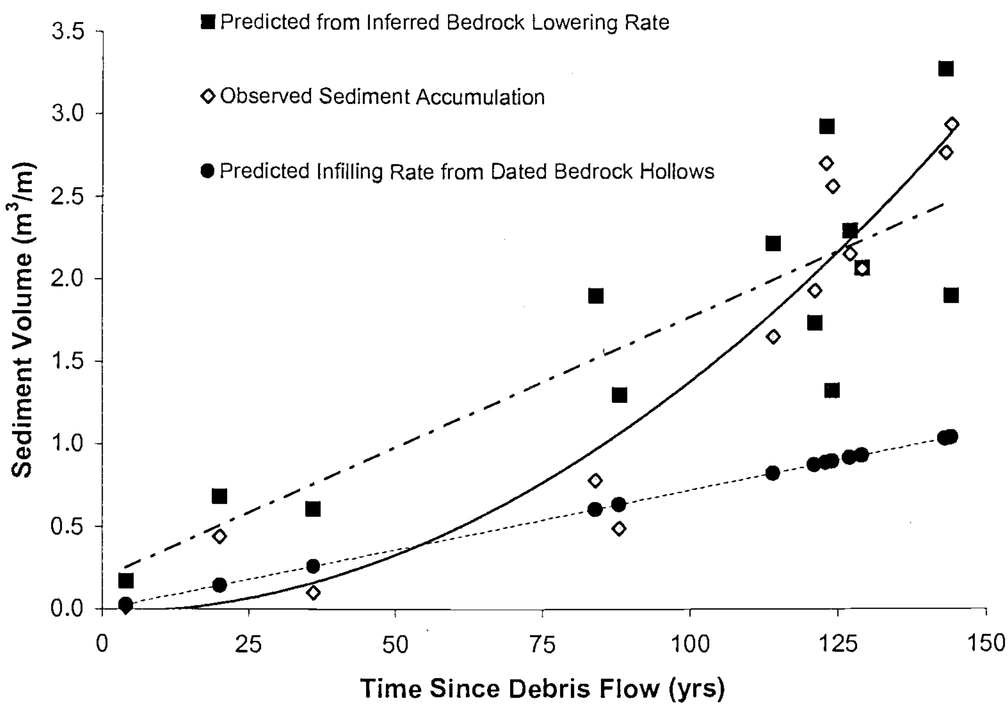

Figure 2.5. Measured sediment accumulation and predicted sediment input from dated bedrock hollows and from an inferred bedrock lowering rate (Reneau and Dietrich, 1991). The observed sediment accumulation rate was based on field measurements from our study streams, solid line regression equation $y = -0.021 + 0.00014x^2$, $r^2 = 0.88$. Predicted sediment input from dated bedrock hollows was 3.6×10^{-3} $m^3/m/yr$, dotted line regression equation $y = 0.0072x$, $r^2 = 1.0$. Predicted sediment input from an inferred bedrock lowering rate was 1.1×10^{-4} m/yr multiplied by the drainage area and a soil to bedrock bulk density ratio of 0.5, dashed line regression equation $y = 0.016x + 0.168$, $r^2 = 0.70$.

The observed volume of stored sediment in the channel was also contrasted with the predicted input rate calculated from the maximum bedrock lowering rate (1.1×10^{-4} m/yr) and a soil to bedrock bulk density ratio of 0.5 estimated by Reneau and Dietrich (1991). For the decades following the latest debris flow event the observed volume of sediment stored in the channel was generally less than predicted from the bedrock lowering rate (Table 2.2, Figure 2.5). As the time since the previous debris flow increased, the observed volume of sediment accumulated in the channel exceeded the average input volume. Because the bedrock lowering rate is based on drainage area and not linear channel length, it may provide a better representation of the average annual input than the previous method.

A rough estimate of the volume of sediment lost to fluvial export was estimated from the rates of sediment input and accumulation. The accumulation rate of sediment in our study streams ($y = -0.021 + 0.00014x^2$, Figure 2.3) was subtracted from the sediment input rate ($y = 0.016x + 0.168$, Figure 2.5) predicted from the bedrock lowering rate (Reneau and Dietrich, 1991). From these values it was possible to back-calculate the volume of sediment presumably lost to fluvial export (Figure 2.6). Because total sediment storage increased proportional to time squared it implies that the accumulation rate increases in time in a linear fashion, in proportion to the volume of wood in the channel. Approximately 110 years post-debris flow the average accumulation rate was higher than the average input rate; therefore, it was not possible to estimate sediment dynamics beyond this point in time. Furthermore, the fluvial export rate we calculated may underestimate the actual rate if sediment input was higher than average immediately following a debris flow.

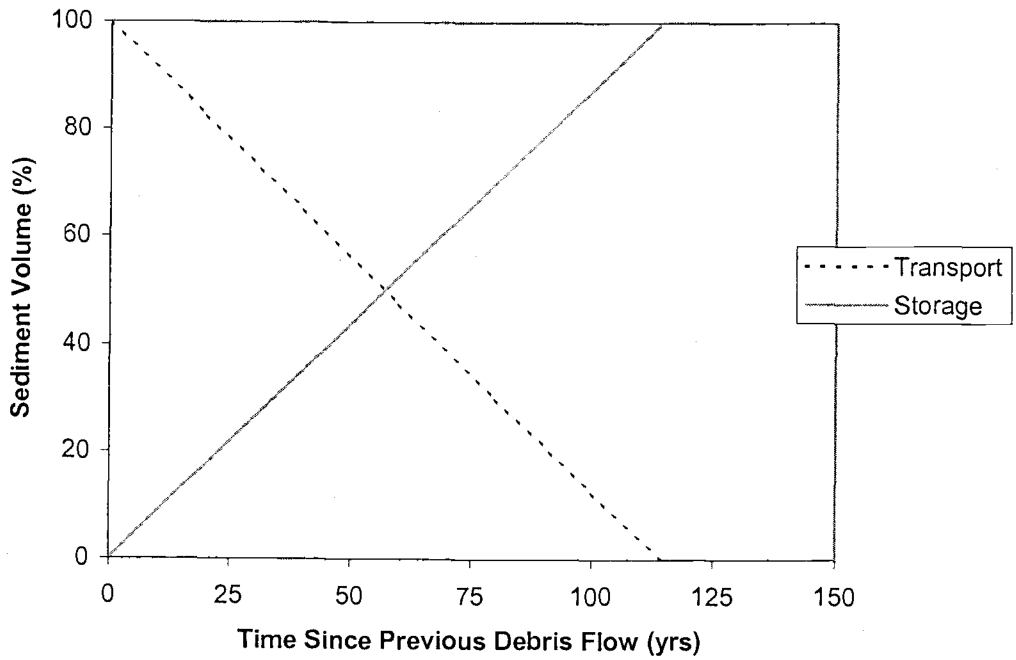

Figure 2.6. A rough estimate of the percent of sediment input that was stored in the channel and the percent lost to transport. The observed sediment accumulation rate ($y = -0.021 + 0.00014x^2$) was subtracted from the inferred input rate ($y = 0.016x + 0.168$) to determine the volume lost to transport.

The approach to estimating sediment and wood accumulation rates had several underlying assumptions: (1) Previous debris flows evacuated all sediment and wood from the erosional zone. There is no direct evidence that all the channels we investigated were completely scoured to bedrock; however, field observations from a previous study of 53 debris flows triggered during a large regional storm event in 1996 in this area indicated that incomplete evacuation of material stored in high gradient channels is uncommon (May, 1998). Benda and Cundy (1990) also documented that channels with slopes > 10° were scoured to bedrock by debris flows in almost all streams that were investigated. (2) Dates derived from tree cores were a reasonable estimate of the actual time since the last debris flow. The lag time in tree establishment appears to be relatively short (3-7 years); however, there is no information available on a potential lag-time among species related to successional patterns. (3) The space-for-time substitution is only reasonable when other site factors had a minimal effect on the observed patterns. Channel gradient and drainage area of the erosional zone were not significant explanatory variables for the volume of sediment in storage in a multiple linear regression analysis. This result supports the assumption that the time since the previous debris flow was the primary mechanism behind the observed pattern. (4) Sediment production and transport processes in the study basins are typical of debris flow terrain in the central Oregon Coast Range. The observed processes of sediment input and transport are consistent with previous studies (Dietrich and Dunne, 1978); however, the observed process rates may vary with topography and network structure. Basins with more highly dissected topography potentially have more landslide source areas and may infill faster and/or scour more frequently. Additionally, the observed accumulation rate of large wood might be relatively high because a mature forest stand was investigated. Accumulation rates might be lower in younger forests because the trees are smaller and may decompose more rapidly.

Basin-Scale Sediment Storage

The quantity of sediment stored in debris flow runout paths was contrasted with the volume of sediment stored in the mainstem channel and valley floor landforms of Skate Creek. Wood provided a physical obstruction to sediment transport, and 73% of the sediment in tributaries that are prone to debris flows was stored directly behind wood (Figure 2.7). Large wood stored 59% of this sediment, and small wood (pieces < 2 m in length and < 20 cm average diameter) stored 14%. A total of 389 pieces of wood was measured in debris flow-prone tributaries to Skate Creek, and 37% of these pieces stored sediment. Wood > 15 m in length accounted for only 22% of the number of pieces, but accounted for 78% of the total volume of wood. Despite this inconsistency, the number of pieces explained 60% of the variance in the volume of wood in the channels (Figure 2.8). Only 4% of sediment in the tributaries was stored in the absence of wood and boulders.

Large wood was also a major component of sediment storage in the mainstem of Skate Creek (Figure 2.7); however, < 0.5% of the sediment in the mainstem was stored by small wood. In contrast to the tributaries, the mainstem had low-gradient reaches (1 – 5% slope) where sediment was stored in the absence of wood or boulders.

Wood influenced channel morphology on multiple spatial scales. Individual pieces, or small accumulations of wood, functioned to store sediment at small spatial scales (10^0 - 10^1 m). These individual pieces were relatively abundant and broadly

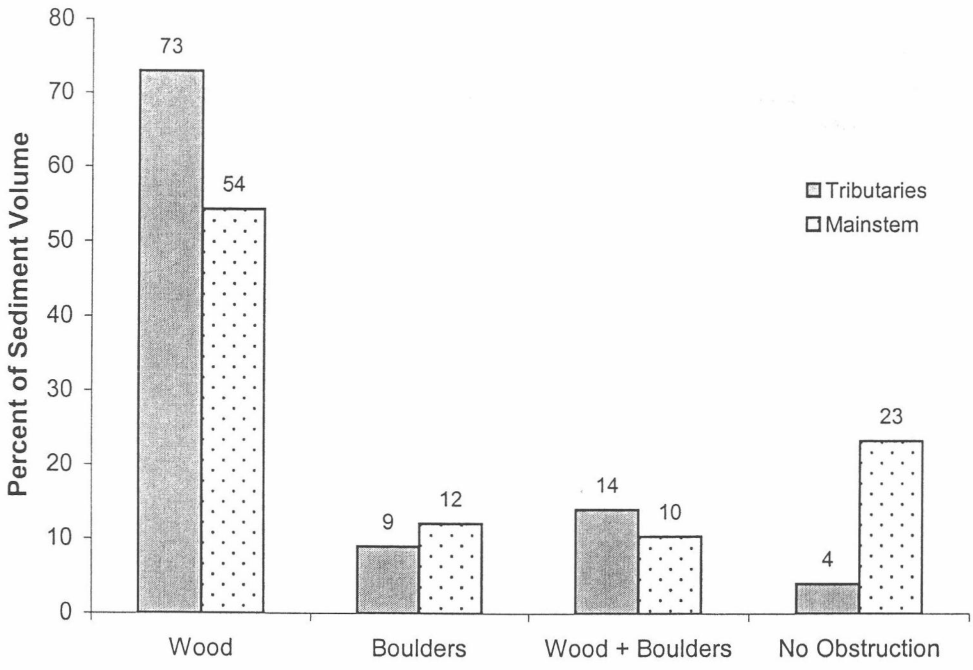

Figure 2.7. Sediment storage in the channel network of Skate Creek. Numbers represent the percent of stored sediment.

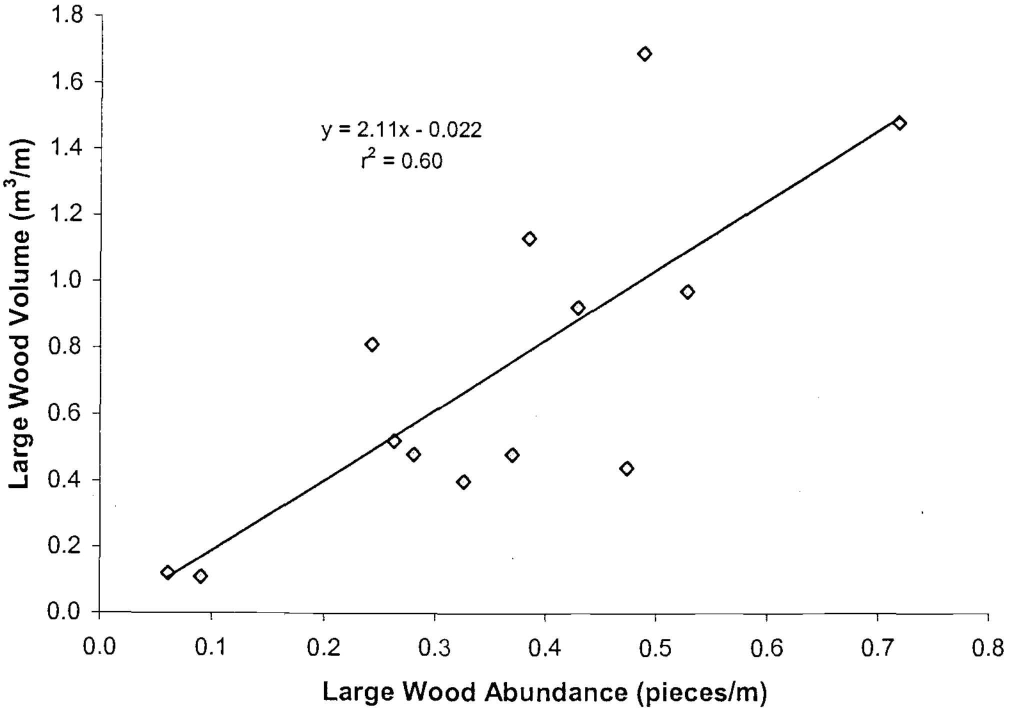

Figure 2.8. The association between large wood abundance and volume in Skate and Bear Creeks.

distributed spatially throughout the channel network. In contrast, large, valley-spanning wood dams formed by debris flows stored sediment on larger spatial scales ($10^1 - 10^2$ m) and inundated entire stream reaches and valley floor surfaces. These large dams were infrequent and were discretely located near tributary junctions. Two large, valley spanning wood dams formed by debris flows in the last 30 years were located in the mainstem of Skate Creek. These debris flows originated in the upper portion of the basin where timber was harvested in the mid-1970s. The channel was actively incising the wedge of sediment upstream of the debris dam, resulting in the formation of continuous terraces along the channel. These large dams stored 32% of the sediment in the mainstem, and individual pieces of wood and small accumulations accounted for 22%.

A total length of 6860 m was surveyed in the channel network of Skate Creek, and a total volume of 21,950 m^3 of sediment in storage was estimated in this portion of the channel network. Numerous first-order channels throughout the network were not investigated; therefore, the proportion of the network in low-order colluvial channels was substantially underrepresented. The majority of sediment in the network was stored in tributaries (72%) that also comprised 69% of the channel length investigated. Debris flow-prone tributaries stored 56% of the total sediment in the network, and the remaining 16% was stored in the single tributary with no evidence of delivering debris flows to the mainstem (Figure 2.1). The third-order mainstem of Skate Creek was 2100 m long, had an average channel gradient of 5.7%, an average valley floor width of 18 m, and an average bank-full channel width of 5 m. The average depth of alluvium in the mainstem streambed was < 40 cm, which represented 28% of the sediment currently in storage in the channel network.

In addition to the channel network, 47,560 m^3 of sediment were stored in valley floor landforms along the mainstem of Skate Creek. Terraces contained 76% and debris flow fans contained 24% of this sediment. These valley floor landforms along the mainstem stored 2.2 times more sediment than the entire channel network; however, the residence time for this sediment is typically longer than sediment stored in the channel network (Dietrich and Dunne, 1978). The combined volume of sediment in the channel network and on the valley floor was equivalent to 491 years of annual soil production based on a bedrock lowering rate of 1.1×10^{-4} m/yr and a soil to bedrock bulk density ratio of 0.5 (Reneau and Dietrich, 1991).

DISCUSSION

Sediment Dynamics

Evaluating stream channel structure over broad time scales provides insight into large-scale patterns that are not manifested at smaller time scales. The approach of using a space-for-time substitution provided a means for examining stream channel structure over longer time scales than direct observation could permit. This approach acknowledges that small colluvial channels are dynamic and that patterns of channel structure could not be interpreted without information on the disturbance history. The underlying assumption of the space-for-time approach is that individual channels were similar except for the time since disturbance. We attempted to investigate channels with similar characteristics by constraining the portion of the channel network we examined to high-gradient, second-order streams in close proximity to each other.

Over a time scale of multiple decades, a linear pattern of wood recruitment was documented; however, the pattern of sediment accumulation was non-linear. This non-linear pattern suggests that immediately following a debris flow the sediment transport capacity of the channel is relatively high, and the storage capacity is low. Field evidence suggests that debris flows cause an extended pulse of secondary erosion by undercutting the base of the adjacent hillslopes. This pulse of sediment input is not reflected in the sediment accumulation data because bedrock channels in this portion of the network have a high unit stream power and may lack the potential for storing sediment in the absence of large obstructions.

Large wood was the focal point for sediment accumulation because it provided a physical obstruction to sediment transport. Sediment accumulation appeared to increase in proportion to the volume of wood in the channel, expressed as time squared. Over time, as more wood was recruited to the channel, the storage capacity of the channel increased and a series of positive feedbacks could be initiated. Sediment that was stored behind wood in the channel increased the streambed roughness, decreased the local slope of the channel, and reduced the capacity for sediment transport. As a greater proportion of the streambed was covered by sediment, roughness continued to increase and more of the water could begin to flow subsurface, further decreasing surface water velocities. In addition, vegetation became established and root networks held the sediment in place. Dietrich and Dunne (1978) documented a similar pattern of non-linear sediment accumulation for bedrock hollows that were infilling by local diffusion.

The short-term pattern of sediment accumulation in channels of Skate and Bear Creeks did not correspond with estimated input rates predicted by the long-term average infilling rates of dated bedrock hollows (Reneau and Dietrich, 1991). As expected, this method underestimated sediment input to the channel because it does not account for all sources of sediment. Debris flows undercut the toeslopes of the adjacent hillsopes, and thus can trigger an accelerated pulse of erosion from the near-stream area that can persist for multiple decades.

The inferred bedrock lowering rate (Reneau and Dietrich, 1991) was a better predictor of the observed volume of sediment stored in the channels of Skate and Bear drainages because it was averaged over the entire catchment. This method represented a broader array of processes and was not as heavily biased when the near-stream area was contributing a disproportionate amount of sediment in the short term.

The direction and relative magnitude of the error in predicting sediment input from these two methods can provide insight into mechanisms of sediment transport and storage. The high degree of underestimation derived from predicting sediment input from colluvial infilling of dated bedrock hollows suggests that a large proportion of the sediment was coming from sources other than local diffusion. The degree of overestimation derived from predicting input from inferred bedrock lowering rates suggests that a substantial volume of sediment was being stored upslope or was lost to transport.

A rough estimate of the proportion of the sediment lost to fluvial export suggested that sediment storage exceeded fluvial transport approximately 60 years after a debris flow (Figure 2.6). Similarly, Grant and Wolf (1991) observed that the proportion of sediment lost to fluvial export was relatively minor during the interval between debris flows in low-order streams in the Cascade Mountains of Oregon. Swanson *et al.* (1982)

deduced that low-order streams might be aggrading on a time scale of years and decades, while experiencing net degradation on a longer time scale. The long-term history of degradation is apparent in the incised topography of these steep-sided, V-notch valleys.

Wood Dynamics

Currently, there is little information on how wood abundance is linked to landscape processes that typically have temporal cycles of activity of decades to centuries (Benda and Sias, 1998). A confounding problem is that field measurements are commonly taken at a single point in time in highly variable systems governed by stochastic processes. Bilby and Ward (1989) observed that the frequency of wood pieces decreased as stream size increased. Examination of their data also revealed that the absolute variability in the abundance of wood increased as stream size decreased (R.E. Bilby, personal communication, 2001). A high degree of variability in wood abundance was also observed in the low-order streams we investigated; however, the time since the last debris flow explained 57% of the variance. By providing a disturbance-based context for field measurements taken at a single point in time, large-scale influences on channel structure can be better understood. For example, the observed volume of wood and sediment may be relatively low a few decades following a debris flow. In contrast, if the same channel was observed over a century following a debris flow, the volume of wood and sediment might be high and exposed bedrock would be virtually absent.

Large wood can play a vital role in channel morphology in mountainous terrain because it provides the cornerstone for sediment accumulation in channels that would otherwise be bedrock dominated (Montgomery *et al.*, 1996). Bilby and Ward (1989) suggested that small streams cannot transport large wood by chronic fluvial processes, and therefore, recruitment processes in the adjacent hillslopes and riparian areas determine the spatial distribution of wood in the channel. In higher-order streams, the distribution of large wood depends both on local recruitment and upstream sources. During the interval between debris flows, low-order streams had the to potential store an abundance of wood delivered from the local hillslopes. As individual sediment accumulations coalesced and sediment depth increased, wood that had previously fallen into the channel became buried. Wood that was buried could decay slower and therefore have a longer residence time in the channel (Hyatt and Naiman, 2001).

A relatively small proportion of wood pieces (37%) were actively storing sediment, and small pieces of wood were more frequently associated with sediment storage as stream size decreased. Similarly, Bilby and Ward (1989) observed that nearly 40% of pieces of wood in channels less than 7 m wide were associated with sediment accumulations, and the proportion of pieces storing sediment decreased as channel width increased.

Wood can influence the morphology of the channel at multiple spatial scales (Table 2.4). At the microhabitat scale (Frissell *et al.*, 1986) small wood or portions of individual logs can influence substrate composition and can force local convergence and divergence of streamflow. At the habitat unit scale individual logs and small accumulations of wood can store patches of sediment in the channel, or scour pools and streambanks. Large accumulations of wood influence the channel and modify the valley floor of entire stream reaches. Individual logs and small accumulations of wood may have a greater overall influence on channel morphology than debris dams because they are more evenly distributed spatially throughout the network; however, large wood dams

Table 2.4. The influence of wood at multiple spatial scales.

Spatial Scale (m)	Habitat Scale [1]	Wood Configuration	Wood Function	Sediment Storage Reservoir	Persistence (yrs)
10^{0}	Microhabitat	Small wood or portions of individual pieces that interact with streamflow and sediment	Substrate composition; Local flow convergence or divergence; Cover and substrate for biota	'transient' storage of small, mobile patches	10^{0} - 10^{1}
10^{1}	Habitat Unit	Individual pieces of large wood and small accumulations	Streambed scour; Streambank scour; Sediment storage; Increase in channel width or depth; Creation of steps that influence the local slope	'active' sediment storage in the channel	10^{1}
10^{2}	Reach	Large jams and dams	Formation of terraces, side channels, and islands; Aggradation associated with increased valley width and decreased valley slope; Lateral channel migration and sinuosity; Forced pool-riffle sequences; Riparian stand regeneration	'intermediate' sediment storage in the channel and 'long-term' storage in valley floor landforms	10^{1} - 10^{2}
10^{3}	Segment	Numerous pieces distributed throughout the low-order channel	Cornerstone for sediment accumulation; Mass of wood forms resistance to flow during a debris flow	'long-term' sediment storage in colluvial tributaries	10^{2}

[1] Habitat scales from Frissell et al. 1986.

formed by debris flows can function as an important storage reservoir for sediment. Furthermore, wood stored in large jams may be particularly susceptible to congested transport (Braudrick *et al.*, 1997; Johnson *et al.*, 2000) if batches of wood are released when the jams break apart. Wood can also influence channel morphology at the segment scale in the low-order channels because it is the cornerstone for sediment accumulation in the interval between debris flows and because the mass of wood may cause resistance to movement during a debris flow event (Lancaster *et al.*, 2001).

Small streams in forested basins are often the most directly impacted by land-use activities (Beschta and Platts, 1986); however, policy and management historically placed less emphasis on these small, often ephemeral, tributary channels and their associated riparian habitats. If low-order basins are managed for timber harvest on a short rotation age or if no streamside buffers are retained, recruitment of wood to the channel can be diminished. If these low-order streams are depleted of present or future sources of large wood, the sediment storage capacity of the basin may be drastically reduced. Without the input of wood, channels that have been transformed into a bedrock state may persist in this state for a greater length of time. Because there is no sediment storage in bedrock channels, these channels become an efficient conveyor of sediment delivered from the hillslopes. This would represent a major shift in processes, with low-order channels becoming a chronic source of sediment to downstream areas instead of an episodic source.

Basin-Scale Sediment Storage

The volume of sediment stored in the channel network and valley floor landforms of Skate Creek was equivalent to 491 years of estimated annual soil production. As expected for unglaciated terrain, this finding suggests that the channels and valley floor surfaces are in equilibrium with the present-day climate and vegetation. Currently, the majority of sediment in the channel network of Skate Creek is stored in the low-order tributaries; however, valley floor surfaces alongside the mainstem contained 2.2 times more sediment than the channel network. If a large-scale disturbance such as an extremely large storm event, catastrophic wildfire, or timber harvest were to occur, the distribution of sediment storage sites could shift. A pulse of debris flow activity in the basin could force most of the sediment into the mainstem and valley floor surfaces, and relatively little sediment would remain in the tributaries. These episodic inputs of sediment in steep mountainous terrain can dominate long-term sediment yields (Kirchner *et al.*, 2001).

The occurrence of debris flows in relation to forest fires is an issue of concern in steep, mountainous terrain. Several researchers have proposed that large-scale, severe fires are associated with pulses of debris flow activity (Swanson, 1981; Meyer *et al.*, 1992; Benda and Dunne, 1997a). Charcoal in sediment from Little Lake in the Oregon Coast Range suggests that under the climate conditions of the past 9000 years, the mean fire interval in this area has been 230 years (Long *et al.*, 1998). Alternatively, a dendrochronology-based study that directly overlapped the Little Lake basin suggested that the natural fire rotation for large-scale, stand-replacement fires was 452 years during the pre-settlement period (Impara, 1997). The low elevation valley floors of Skate and Bear Creeks had not experienced a stand-replacement fire for > 315 years. Tree ring data from mid- and upper-elevations of the basins suggest that the time since the previous stand-replacement fire was approximately 148 years. A fire reconstruction study located only 10 km north of our study basins documented a large-scale, high severity wildfire in 1852 (Impara, 1997). Although this fire was recorded as the fire episode of 1852 in the dendrochronology record (Impara, 1997), local historical records documented a fire event in 1849 that reportedly burned >2000 km^2 (Morris, 1934).

Our study indicates that a pulse of debris flow activity occurred following the last stand-replacement fire on mid- and upper-slope positions. During the 30 years following the 1849 fire event, 54% of the tributaries we investigated experienced a debris flow (Figure 2.9). Similarly, Swanson (1981) suggested that fire-induced accelerated erosion may persist for 20 to 30 years in western Oregon. Although 30 years appears to be an extended time period for fire effects to be manifested, our age dates may be underestimated by up to 10 years.

Our data also documented substantial debris flow activity in the inter-fire period. In the absence of fire and land management activities, high intensity rainstorms triggered debris flows that ran through 46% of the tributaries investigated. These recent debris flows would have erased evidence of earlier post-fire events. It is also important to note that first-order streams route debris flows to the second-order streams; therefore, the second-order channels we investigated may experience debris flows more frequently than any individual first-order stream (Swanson and Lienkaemper, 1978).

Past fires did not burn homogenously in the study basins. In mid- and upper-elevations, where landslides initiate debris flows, fires may burn more frequently than low elevation valley floors that provide habitat for fish. Impara (1997) observed a similar pattern of greater fire frequency on mid- and upper-hillslope positions compared to low elevation valley floors, and fire occurrence was not influenced by aspect. Although the

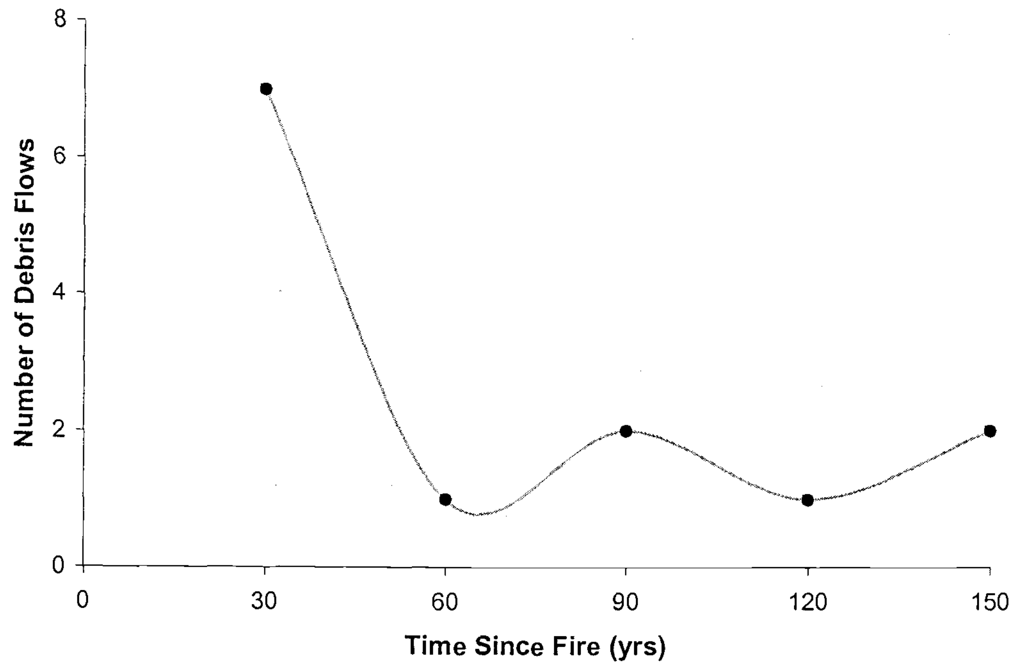

Figure 2.9. Temporal distribution of debris flows in the immediate post-fire and inter-fire time periods in Skate and Bear Creeks. Data are grouped into 30 year age classes.

most recent fire in the upper slopes of our study basins did not directly impact the low elevation channels and valley floors (i.e. the fish-bearing portion of the channel network), the disturbance was propagated through the network by debris flows in the tributaries.

In the inter-fire time period large storm events sporadically triggered debris flows in individual tributaries. The potential for debris flow deposits to eliminate or create in-stream habitat may be a function of the age of the deposit (Hogan *et al.*, 1998). The asynchronous timing of debris flows in the inter-fire period may create a greater variety of deposit ages, and therefore a higher diversity in the structure and function of deposits. More extensive refuges for aquatic biota may also be present during debris flow triggering storms than might be expected in the immediate post-fire period.

Previous studies have also documented that debris flows can be an important source of wood and sediment to many alluvial streams in the Pacific Northwest (Keller and Swanson, 1979; Benda and Dunne, 1997a; May, 1998). These episodic pulses of wood and sediment can affect channel morphology (Everest and Meehan, 1981; Benda and Dunne, 1997b; Hogan *et al.*, 1998) and fish community composition (Reeves *et al.*, 1995).

Results of this study provide insights into a temporal succession of channel morphology following disturbance, and the sediment retention capacity of debris flow-prone channels. A cycle of sediment and wood accumulation in low-order streams was punctuated by episodic evacuation by a debris flow. As sediment and wood loading in the channel changed, so did the structure of the habitat and perhaps the aquatic community composition. These small streams provide habitat for numerous aquatic invertebrates and amphibians that may reestablish populations in waves of recolonization.

Initial recolonization may favor species that are well adapted to bedrock substrate and homogenous habitat conditions. Later reconolization may favor species suited for course substrate and require more heterogeneous habitat conditions.

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REFERENCES

Agee JK. 1993. *Fire Ecology of Pacific Northwest Forests*. Island Press, Washington D.C.

Baldwin EM. 1964. *Geology of Oregon*. University of Oregon, Eugene, Oregon.

Benda LE. 1988. *Debris Flows in the Tyee Sandstone Formation of the Oregon Coast Range*. M.S. Thesis, University of Washington, Seattle, Washington.

Benda LE, Cundy TW. 1990. Predicting deposition of debris flows in mountain channels. *Canadian Geotechnical Journal* **27**:409-417.

Benda LE, Dunne T. 1987. Sediment routing by debris flows. In *Erosion and Sedimentation in the Pacific Rim*, Beschta RL, Blinn T, Ice GE, Swanson FJ (eds). IAHS **165**: 213-223.

Benda LE, Dunne T. 1997a. Stochastic forcing of sediment supply to channel networks from landsliding and debris flows. *Water Resources Research* **33**(12):2849-2863.

Benda LE, Dunne T. 1997b. Stochastic forcing of sediment routing and storage in channel networks. *Water Resources Research* **33**(12):2865-2880.

Benda LE, Sias JC. 1998. *Landscape Controls on Wood Abundance in Streams*. Earth Systems Institute, Seattle, Washington.

Beschta RL, Platts WS. 1986. Morphological features of small streams: significance and function. *American Water Resources Bulletin* **22**(3):369-379.

Bilby RE. 1981. Role of organic debris dams in regulating the export of dissolved and particulate matter from a forested watershed. *Ecology* **62**:1234-1243.

Bilby RE, Bisson PA. 1998. Function and Distribution of Large Woody Debris. In *River Ecology and Management: Lessons from the Pacific Coastal Ecoregion*, Niaman RJ, Bilby RE (eds). Springer-Verlag, New York; 324-346.

Bilby RE, Ward JW. 1989. Changes in characteristics and function of woody debris with increasing size of streams in western Washington. *Transactions of the American Fisheries Society* **118**:368-378.

Braudrick CA, Grant GE, Ishikawa Y, Ikeda H. 1997. Dynamics of wood transport in streams: a flume experiment. *Earth Surface Processes and Landforms* **22**:669-683.

Dietrich WE, Dunne T. 1978. Sediment budget for a small catchment in mountainous terrain. *Zeitschrift fur Geomorphologie N.F.* 29:191-206.

Franklin JF, Dyrness, CT. 1973. Natural vegetation of Oregon and Washington. *USDA Forest Service General Technical Report*, PNW-8.

Frissell, C.A., Liss W.J., Warren C.E., and M.D. Hurley. 1986. A hierarchical framework for stream habitat classification. *Environmental Management* **10**: 199-214.

Grant GE, Wolff AL. 1991. Long-term patterns of sediment transport after timber harvest, western Cascade Mountains, Oregon, USA. In *Proceedings of the Vienna Symposium,* IAHS **203**:31-40.

Hack JT. 1960. Interpretation of erosional topography in humid temperate climates. *American Journal of Science* **258**-A: 80-97.

Heimsath AM, Dietrich WE, Nishiizumi K, Finkel RC. 2001. Stochastic processes of soil production and transport: erosion rates, topographic variation and cosmogenic nuclides in the Oregon Coast Range. *Earth Surface Processes and Landforms* **26**:531-552.

Hogan DL, Bird SA, Hassan M. 1998. Spatial and temporal evolution of small coastal gravel-bed streams: influence of forest management on channel morphology and fish habitats. In *Gravel-Bed Rivers in the Environment*, Klingeman PC, Beschta RL, Komar PD, Bradley JB (eds). Water Resources Publications, Highlands Ranch, Colorado; 365-392.

Hyatt TL, Naiman RJ. 2001. The residence time of large woody debris in the Queets River, Washington, USA. *Ecological Applications* **11**(1):191-202.

Impara, PC. 1997. *Spatial and Temporal Patterns of Fire in the Forests of the Central Oregon Coast Range*, Ph.D. Dissertation, Oregon State University, Corvallis, Oregon.

Johnson SL, Swanon FJ, Grant GE, Wondzell WM. 2000. Riparian forest disturbances by a mountain flood: the influence of floated wood. *Hydrological Processes* **14**:3031-3050.

Keller EA, Swanson FJ. 1979. Effects of large organic material on channel form and fluvial processes. *Earth Surface Processes* **4**:361-380.

Kirchner JW, Finkel RC, Riebe CS, Granger DR, Clayton JL, King JG, Megahan WF. 2001. Mountain erosion over 10 yr, 10 k.y., and 10 m.y. time scales. *Geology* **29**(7): 591-594.

Long CJ, Whitlock C, Bartlein PJ, Millspaugh SH. 1998. A 9000-year fire history from the Oregon Coast Range, based on a high-resolution charcoal study. *Earth Surface Processes and Landforms* **28**: 774-787.

May CL. 1998. *Debris Flow Characteristics Associated with Forest Practices in the Central Oregon Coast Range*, M.S. Thesis, Oregon State University, Corvallis, Oregon.

Megahan WR. 1982. Channel sediment storage behind obstructions in forested drainage basins draining the granitic bedrock of the Idaho batholith. In *Sediment Budgets and Routing in Forested Drainage Basins*, FJ Swanson, R. Janda, T Dunne, DN Swanston (eds). USDA Forest Service General Technical Report, PNW-141; 114-121.

Megahan WF, Nowlin, RA. 1976. Sediment storage in channels draining small forested watersheds in the mountains of central Idaho. In *Proceedings of the Third Federal Interagency Sedimentation Conference*, Water Resources Council: Denver, Colorado; **4**:115-126.

Meyer GA, Wells SG, Balling RC, Jull AJT. 1992. Response of alluvial systems to fires and climate change in Yellowstone National Park. *Nature* **367**:147-149.

Montgomery DR, Abbe TB, Buffington JM, Peterson NP, Schmidt KM, Stock JD. 1996. Distribution of bedrock and alluvial channels in forested mountain drainage basins. *Nature* **381**:587-589.

Morris, WG. 1934. Forest fires in western Oregon and western Washington. *The Oregon Historical Quarterly* Vol. XXXV: 313-339.

Naiman RJ, Beechie TJ, Benda LE, Berg DR, Bisson PA, MacDonald LH, Steel EA. 1992. Fundamental elements of ecologically healthy watershed in the Pacific Northwest coastal ecoregion. In *Watershed Management: Balancing Sustainability and Environmental Change*, RJ Niaman (ed). Springer-Verlag, New York; 127 – 188.

Reeves GH, Benda LE, Burnett KM, Bisson PA, Sedell J.R. 1995. A disturbance-based ecosystem approach to maintaining and restoring freshwater habitats of evolutionary significant units of anadromous salmonids in the Pacific Northwest. In *American Fisheries Society Symposium*: Bethesda, Maryland; **17**:334-349.

Reneau SL, Dietrich WE. 1991. Erosion rates in the southern Oregon Coast Range: evidence for an equilibrium between hillslope erosion and sediment yield. *Earth Surface Processes and Landforms* **15**: 307-322.

Roering JJ, Kirchner JW, Dietrich WE. 1999. Evidence for nonlinear, diffusive sediment transport on hillslopes and implications for landscape morphology. *Water Resources Research* **35**(3): 853-870.

Schumm SA. 1956. Evolution of drainage systems and slopes in badlands at Perth Amboy, New Jersey. *Bulletin of the Geological Society of America* **67**:597-646.

Shreve RL. 1969. Stream lengths and basin areas in topologically random channel networks. *Journal of Geology* **77**:397-414.

Strahler AN. 1964. Quantitative geomorphology of drainage basins and channel networks. In *Handbook of Applied Hydrology*, Chow VT (ed). McGraw Hill, New York; 40-74.

Swanson FJ. 1981. Fire and ecosystem processes. USDA Forest Service, General Technical Report WO-26.

Swanson FJ, Fredricksen RL, McCorison FM. 1982. Material transfer in a western Oregon forested watershed. In *Analysis of Coniferous Forest Ecosystems in the Western United States*, Edmonds RL (ed). Hutchinson Ross, New York; 233-266.

Swanson FJ, Lienkaemper GW. 1978. Physical consequences of large organic debris in Pacific Northwest streams. *USDA Forest Service, General Technical Report* PNW-69.

Swanson FJ, Swanson MM. 1977. Inventory of mass erosion in the Mapleton Ranger District Siuslaw National Forest. *USDA Forest Service, Final Report.*

Welch DM. 1970. Substitution of space for time in a study of slope development. *Journal of Geology* **78**:234-238.

3. Spatial and Temporal Patterns of Debris Flow Deposition in the Oregon Coast Range, U.S.A.

Christine L. May and Robert E. Gresswell

ABSTRACT

Patterns of debris flow occurrence were investigated in 125 headwater streams in the Oregon Coast Range. Time since the previous debris flow was established using dendrochronology, and the distribution of ages varied with network structure and drainage area of the tributary basin. Estimates of debris flow frequency ranged from 98 to 357 years in the colluvial tributaries. Tributary basins that had larger drainage areas and more convergent topography had a higher proportion of trunk channels in younger post-debris flow age-classes compared to smaller basins with less convergent topography. The flux rate of material delivered to the confluence with a larger river influenced the development of debris flow fans. Fans at the mouth of tributary basins with smaller drainage area had a higher likelihood of being eroded by the mainstem river in the interval between debris flows, compared to bigger basins that had larger, more persistent fans. Valley floor width of the receiving channel also influenced fan development because it determined the space available to accommodate fan formation. Of 63 recent debris flow deposits (< 30 years old), 52% delivered sediment and wood directly to the mainstem river, 30% were captured on an existing fan before reaching the mainstem, and 18% deposited within the confines of the tributary valley before reaching the confluence. Spatial variation in the location of past and present depositional surfaces indicates that sequential debris flow deposits do not consistently form in the same place, suggesting that other temporally variable factors may be important for determining deposit location.

KEYWORDS: Landslides, Debris flows, Alluvial fans, Sedimentation, Coast Range, Dendrochronology

INTRODUCTION

Debris flows strongly influence the structure and function of many headwater streams in mountainous terrain. These small ephemeral and intermittent channels do not directly support fish but they can have a strong influence on the rate of sediment and wood delivered to the larger rivers. Riparian areas have long been recognized as an important transition zone between terrestrial and aquatic ecosystems (Swanson *et al.*, 1982b; Naiman and Decamps, 1990; Gregory *et al.*, 1991). Similarly, small headwater streams in steep mountainous terrain can be viewed as the transition zone between hillslope and fluvial processes.

Small unchannelized valleys, also termed bedrock hollows (Dietrich and Dunne, 1978), are areas of topographic convergence that accumulate sediment and are particularly susceptible to mass movement as shallow rapid landslides. Landslides in hollows are widely recognized as the most common initiation site for debris flows in steep soil-mantled landscapes (Dietrich and Dunne, 1978; Reneau and Dietrich, 1987; Benda, 1988; May, 1998). Bedrock hollows occur at the upper extent of all first-order channels (referred to hereafter as 'channel-heads') and on hillsides along channels of any order (Dietrich and Dunne, 1978). The estimated areal density of hollows in Rock Creek drainage of the Oregon Coast Range was 22 per km^2, half of which were located at channel-heads (Dietrich and Dunne, 1978).

Landslides and debris flows are important processes in landform development because they influence incision of the channel system into the underlying bedrock

(Dietrich and Dunne, 1978). Many first- and second-order channels (Strahler, 1964) in the Oregon Coast Range are effective at transporting debris flows because the valleys are narrow and high gradient (Swanson *et al.*, 1982a; Benda and Dunne, 1997b). These low-order streams typically have ephemeral or intermittent stream flow, and fluvial export of sediment may be minor relative to the volume of sediment in storage. For example, in a 30-year history of sediment production from a small experimental watershed that has experienced repeated debris flows, fluvial processes account for < 15% of the total sediment yield (Grant and Wolff, 1991). Instead, these channels can undergo long periods of storage of sediment and wood that is punctuated by episodic transport by debris flows (Swanson *et al.*, 1982a). Estimates of sediment yield at millennial time scales further suggests that 70% - 97% of the long-term sediment delivery in steep mountainous terrain is from episodic inputs, which are unlikely to be captured by decadal scale observations (Kirchner *et al.*, 2001).

Channel confluences represent a critical component of drainage system geometry and are points at which river morphology and hydrology can change drastically (Mosley, 1976). One of the dominant valley floor landforms at channel confluences are alluvial fans that consist of debris flow deposits and/or fluvially transported sediments. The surface of the fan forms a segment of a cone that radiates downslope from the point where the stream emerges from the mountain front (Bull, 1963). The primary requisite for fan formation is a large supply of sediment and a depositional environment that can retain the delivered sediment, commonly a lowland valley (Schumm, 1977).

Alluvial fans are frequently found in arid and semi-arid regions with tectonically active mountains where there is an abundant supply of sediment; however, alluvial fans also occur in humid-temperate, subtropical, arctic, and alpine environments (Lecce, 1990). Only recently have alluvial fans in humid-temperate regions received attention (Kochel and Johnson, 1984). In a sub-humid mountain region two distinct fan types have been observed (Kostaschuk *et al.*, 1986). Large low-gradient fans dominated by fluvial processes were associated with bigger drainage basins with a lower ruggedness ratio (defined as drainage basin height divided by the square root of drainage basin area; Melton, 1965). In contrast, small steep fans dominated by debris flow processes were associated with smaller drainage basins with a higher ruggedness ratio. Similarly, the size, degree of dissection, and composition of fans was related to the mainstem valley floor width, and area, relief, and bedrock geology of the tributary basins in the Cascade Range of Oregon (Swanson and James, 1975).

Relatively small, yet well-formed fans, or remnants of older fans are present at the confluence of low-order colluvial channels and higher-order alluvial channels in many drainage basins in the Oregon Coast Range. Examination of the stratigraphy in cut-banks along the larger rivers indicates that the fans build over time by a series of debris flow episodes. Similarly, Kochel and Johnson (1984) documented that fans in central Virginia were formed primarily by debris flows and debris avalanches triggered by high intensity precipitation events. Debris flows in arid regions have been observed to both build (Beaty, 1963; Beaty, 1970) and erode (Hunt and Mabey, 1966) fan surfaces.

Fans can strongly influence the routing of debris flows through the channel network (Benda and Dunne, 1997b) and are recognized as important, long-term storage reservoirs for sediment in drainage basins (Dietrich and Dunne, 1978). Fans that have not been incised by the tributary channel can trap debris flows. In contrast, fans that are substantially incised can laterally confine the flow and effectively route debris flows through the fan and to the mainstem river (Denny, 1967; Swanson and James, 1975). When the flow is not laterally confined the debris flow can spread over the fan surface and thus, increase the frictional resistance to flow, promoting deposition on the fan surface.

Although debris flows are widely recognized as one of the dominant geomorphic process in the steep mountainous terrain (Dietrich and Dunne, 1978; Swanson et al., 1982; Benda and Dunne, 1997b), little is known about the frequency of debris flows or the persistence of depositional landforms. Network structure of the tributary basin may affect the frequency of debris flows delivered to mainstem river valley by influencing the number of potential landslide source areas and the routing ability of the channel. The frequency of debris flows influences the structure and function of the channel in the runout path, the potential magnitude of the event, and the development of depositional features. Understanding the spatial and temporal patterns of debris flow deposition can provide insight into the sediment flux rate and long-term patterns of channel network development.

The objectives of our study were to: (1) determine the frequency of debris flow delivery from colluvial tributaries to the mainstem river and assess how network structure of the tributary influenced this frequency; (2) determine if fan size was correlated with the flux rate of sediment delivered to the confluence; (3) document the proportion of debris flow deposits that were captured by the fan before reaching the mainstem.

STUDY BASINS

Five study basins in the Oregon Coast Range were selected that had mature forest stands and a minimal history of timber harvest and road construction (Table 3.1, Figure 3.1). Franklin, Harvey, and Wassen Creeks are adjacent basins that are located approximately 30 km south of Skate and Bear Creeks. All the study basins are underlain by Tertiary marine sedimentary rocks of the Tyee Formation (Baldwin, 1964). The Tyee Formation is composed of massive, rhythmically bedded sandstones with interbeds of siltstones and mudstones. The drainage network is characterized by a dense, dendritic drainage pattern in first- and second-order streams that drain short, steep hillslopes. The low elevation (< 600 m) mountains were never glaciated and have a topography similar to the 'ridge and ravine topography' described by Hack (1960). Large deep-seated earthflows were not observed in the study basins; however, they are common along geologic contacts between basalt and sandstone formations and near igneous dikes in other portions of the Coast Range (Graham, 1985).

The Oregon Coast Range has a maritime climate, characterized by wet and relatively warm winters and dry summers. Normal annual precipitation ranges from 165 cm to 229 cm, coming mostly as fall and winter rain. Douglas-fir *(Pseudotsuga menziesii)* and western hemlock (*Tsuga heterophylla*) forests dominate the central Oregon Coast Range, which is located in the *Tsuga heterophylla* zone (Franklin and Dyrness, 1973). Red alder *(Alnus rubra)* is typically found in riparian areas or in areas of recent disturbance, and it is the most common deciduous species. Estimates of the natural fire rotation for large-scale, stand-replacement fires in the region range 230 years (Long *et al.*, 1998) to 452 years (Impara, 1997). Bear, Skate, and Franklin Creeks all

Table 3.1. Basin and network characteristics of the study area.

Basin	Catchment	Drainage Area (km^2)	Total Network Length (km)	Percent of Network in First- and Second-Order Channels	Number of Tributaries Investigated
Bear Creek	Siuslaw River	2.2	9.1	75	12
Franklin Creek	Umpqua River	18.5	88.5	76	23
Harvey Creek	Umpqua River	23.0	109.5	78	52
Skate Creek	Siuslaw River	2.5	8.8	76	9
Wassen Creek	Smith River	6.8	31.5	79	29

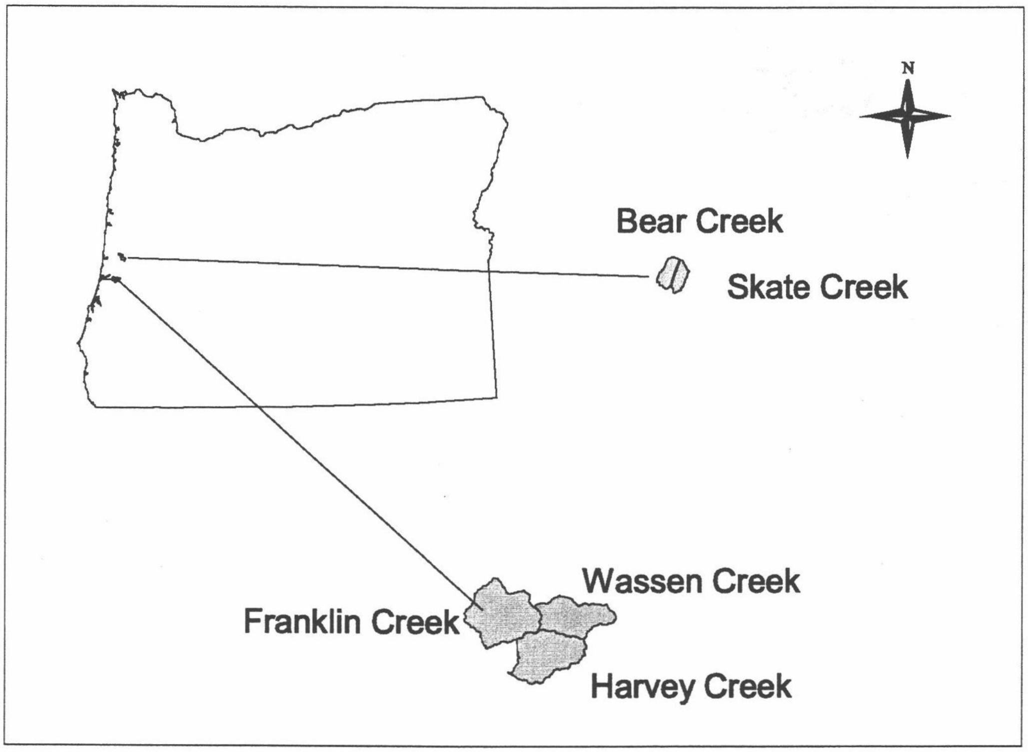


Figure 3.1. Location of study basins in the Oregon Coast Range.

experienced a large stand-replacement fire in 1849 (Morris, 1934; see Chapter 1). Harvey Creek also burned in 1849, but there is some indication that the basin burned again approximately 50 years later (Reeves *et al.*, 1995). Upper Wassen Creek reportedly burned in 1868 (Morris, 1934). Timber harvest occurred in 19 of the 125 tributary basins investigated, and typically consisted of small patch cuts in the upper elevations. These tributary basins contained 11of the 63 recent debris flows that were inventoried. The only roads in the study basins were located on ridge tops.

Two extremely large storm events occurred in this region in February and November of 1996. Portions of the region received record rainfall during these long duration subtropical storms (Taylor, 1997). The maximum four-day precipitation during the February storm exceeded the previous precipitation record in many parts of western Oregon, and many rivers experienced record-setting peak flows (Taylor, 1997).

METHODS

Channel Types

Three distinct categories of debris flow prone tributary channels were classified on the basis of network structure and were defined by the abundance of first-order streams and dominant tributary junction angle. Simple networks had ≤ 3 first-order channels that typically entered at low (< 70°) tributary junction angles (Figure 3.2.a). Complex networks had ≥ 4 first-order channels, the majority of which entered at low tributary junction angle (Figure 3.2.b). Trellis networks also had ≥ 4 first-order channels; however, the majority of first-order channels had high (> 70°) tributary junction angles (Figure 3.2.c).

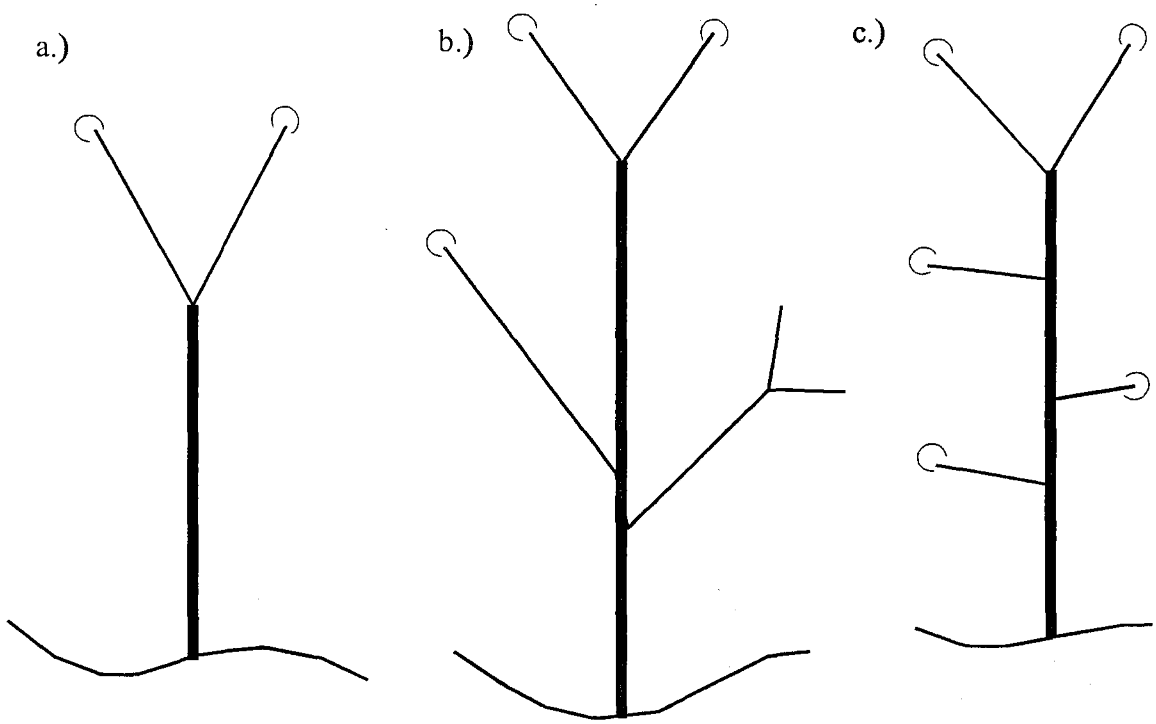


Figure 3.2 Channel network classification based on the abundance of first-order streams and the dominant tributary junction angles; (a) simple networks had < 4 first-order streams, (b) complex networks had > 4 first-order streams with predominantly < 70 degree tributary junction angles, (c) trellis networks had > 4 first-order streams with predominantly > 70 degree tributary junction angles. Trunk channels had direct contact with the mainstem river and are represented with bold lines.

Only the second- or third-order trunk channel of each tributary basin was investigated in the field. We defined the trunk channel of the tributary basin as the channel that directly drained into a larger mainstem river (Figure 3.2). Sampling was limited to the trunk channels because they provided information on the frequency that debris flows potentially reached the mainstem. Channel length, slope, and valley width were measured in the field, and the location of all debris flow deposits was recorded. The valley floor width of the mainstem river was measured in the field upstream of the fan at the confluence. Tributary junction angle was measured using compass bearings.

Dendrochronology was used to estimate a minimum time since the previous debris flow. A 46 cm increment bore was used to extract cores from trees growing in the erosional zone of the trunk channel. Erosional zones were considered to be channels that had a consistent slope > 20%. The transition between the erosional and depositional zone was further distinguished by the presence of a large boulder lag that is typically deposited at the tail end of the debris flow. Trees in the depositional zone were not dated because of a greater possibility that older trees survived the previous debris flow. Whenever possible, tree cores were extracted less than 1m above the base of the tree.

Cores were air-dried, mounted, planed, and sanded until cell structure was clearly visible. An age correction factor that compensated for the difference in age between the core height and the ground level was added to the tree ring count (Agee, 1993). The time since the previous debris flow was expressed in years before 2000. The oldest date acquired for an individual channel was used in the analysis; however, dates can only be considered a minimum time since the previous debris flow. Kolmogorov-Smirnov, one-sided, two-sample test was used to assess the absolute difference in the cumulative frequency distribution of ages among channels with different network structure.

Several sources of error are inherent in using tree ring analysis to estimate the time since the previous debris flow. The reported dates underestimate the actual dates because there may be a lag between debris flow occurrence and tree regeneration (see Chapter 1), and the lag time may depend on local site conditions. Additionally, core samples did not always encounter the exact center point of the tree so the first few years of growth may have been undetected.

A qualitative estimate of the proportion of channel with exposed bedrock, average length of bedrock reaches, and volume of sediment and wood stored in the channel was used to classify the channels into 30-year age-classes (see Chapter 1 and Figure 3.3). Estimated age-classes were compared with tree ring data in order to test the consistency of previously documented rates of sediment and wood accumulation (see Chapter 1). Channels classified in the 0 - 30 year age-class had > 80% of the channel in long, continuous reaches of exposed bedrock. Channels in the 30 - 60 year age-class had < 60% of channel length in exposed bedrock, with extremely low volumes of wood and sediment in storage. Channels in the 60 - 90 year age-class had < 40% of the channel in exposed bedrock and discrete accumulations of sediment and wood. Channels in the 90 - 120 year age-class had < 20% exposed bedrock, sediment accumulations were coalescing, and wood was present in various states of decay. The only exposed bedrock in channels > 120 years since the previous debris flow were vertical bedrock steps, and the channel had continuous accumulations of sediment. Highly decayed wood and pieces buried in sediment accumulations were also present in the > 120 year age-class. In 22 of

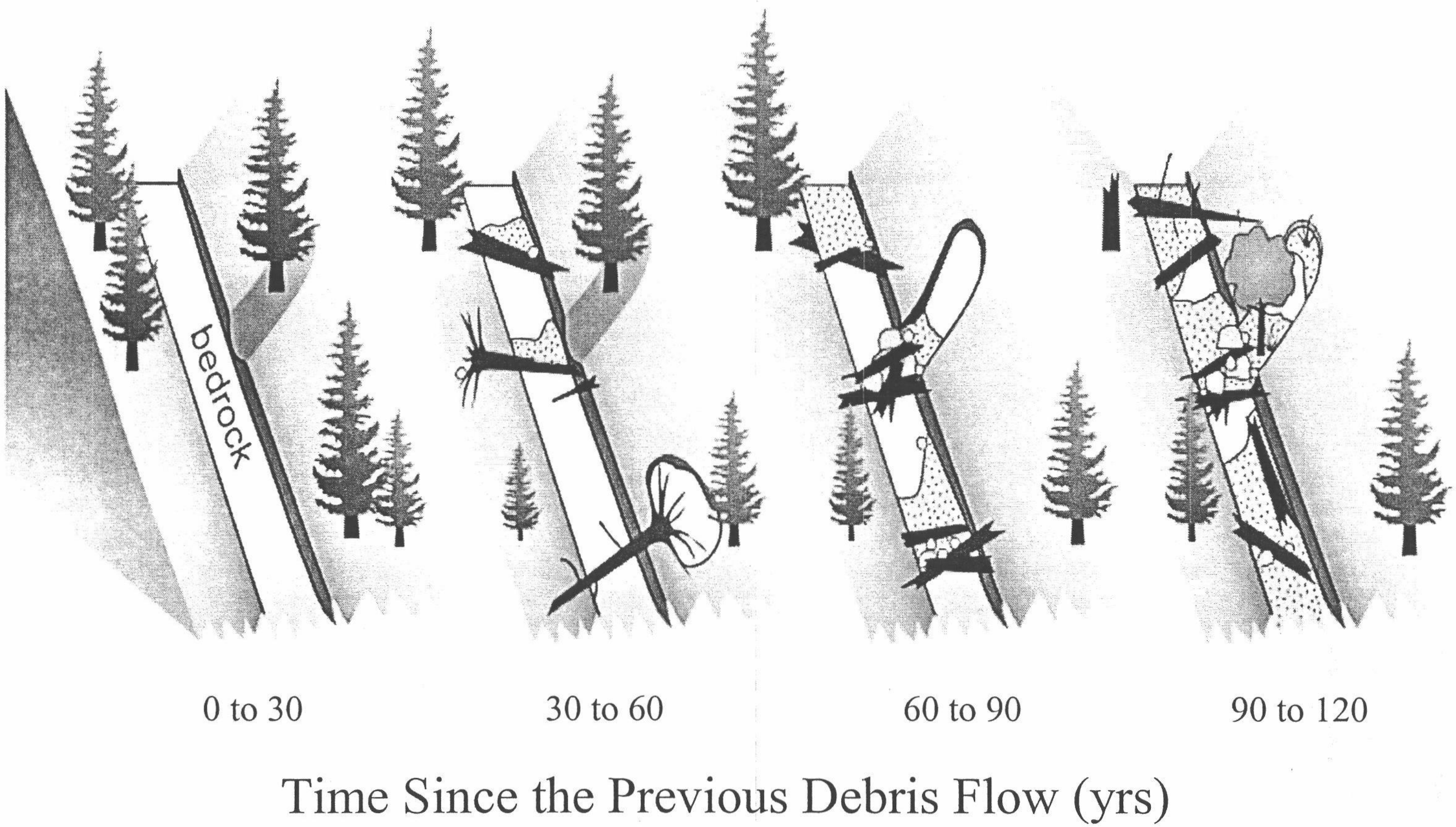


Figure 3.3. Conceptual diagram of changes in channel structure based on the time since the previous debris flow.

the channels investigated no trees were growing in the erosional zone, presumably due to a high degree of shading by the steep topography and the closed canopy of the surrounding forest stand. For these tributaries the subjective classification was the only criterion used to determine the age-class of the tributary.

Estimates of Debris Flow Frequency

An estimate of the frequency of debris flow occurrence in the trunk channels was constructed from the age-class data. In the absence of recurrence interval data, a mathematical model analogous to the 'fire cycle' was used. This model is defined as the average stand-age of a forest whose age distribution fit a specified mathematical distribution that was used to characterize the recurrence of the last stand-replacement disturbance on the landscape (Agee, 1993).

Our estimate of debris flow frequency can be interpreted as the average time since the previous debris flow in the trunk channels, where the age distribution fit a negative exponential distribution, expressed as:

$$f(x) = pe^{-px}$$

f(x) is the frequency of age-class x, e is the base of natural logarithms, and p is the annual probability of an event (Van Wagner, 1978). Using a negative exponential distribution, the mean age of all tributaries (C, referred to hereafter as interval) is equal to 1/p, and the median age can be determined from the distribution as 0.693*C.

The negative exponential is the most appropriate for this type of reconstruction because it is a 'random selection' model. The underling assumption is that channels have an equal probability of experiencing a debris flow regardless of the time elapsed since the previous failure. This assumption appears reasonable because landslides typically initiate debris flows, and potential landslide sources areas are abundant in steep soil mantled landscapes (Dietrich and Dunne, 1978; Montgomery *et al.*, 2000). However, this assumption could be violated if the volume of wood and sediment stored in the channel increased the resistance to flow, resulting in a reduction in the runout length of the debris flow and a decreased probability that the trunk channel was scoured (Lancaster *et al.*, 2001).

Debris Flow Fans

Debris flow fans were identified by poorly-sorted, angular and sub-angular colluvium in a matrix-supported framework (Figure 3.4). The perimeter of the fan was measured in the field with a reel tape. The radius of the fan was measured along the centerline from the fan edge to the hillslope constriction of the tributary valley. Height of the fan edge was measured at the upstream, center, and downstream ends of the fan. The height of the fan edge could only be measured as the height above the streambed in the mainstem river, therefore, the actual volume of the fan may be underestimated if the lower portion of the fan was buried in modern alluvium. Fan height at the apex was calculated from the average fan edge height, fan slope, and centerline distance. Fan slope was measured from the top of the fan edge to the fan apex using a clinometer. Fan area was calculated as a sector of a circle,

$$\text{Area} = \theta\, r^2 / 2$$

where θ was calculated by dividing the perimeter length by the distance to the hillslope along the centerline of the fan (r). Fan volume was calculated by multiplying the area by the average height of the fan.

Figure 3.4. Debris flow fan deposit observed along the channel bank of the mainstem river, with modern alluvium at base. Arrow indicates an abrupt transition between layers, indicating sequential debris flow deposits.

Multiple regression was used to investigate the relationship between fan size and basin characteristics. Drainage area and drainage density were used as explanatory variables, and values were derived from 10-m resolution digital elevation models. Stream layers were created from digital elevation models using a 75 ha threshold for channel initiation (unpublished data, Coastal Landscape Analysis and Modeling Study). Our estimates of the extent of the channel network were dependent on the resolution of the topographic data and unfortunately, digital elevation models usually predict a coarse, inaccurate portrayal of the fine-scale features at which many of the processes of interest operate (Dietrich and Montgomery, 1998). Distributions of drainage area, mainstem valley floor width, fan area, and fan volume were positively skewed and were transformed to logarithmic scale. Interaction terms among the explanatory variables were tested but were not reported if they were not statistically significant ($p > 0.05$).

Deposit Types

Five types of debris flow deposits were categorized based on the location of the deposit relative to the fan and mainstem river channel (Figure 3.5). Debris flows that deposited in the confines of the tributary valley had no direct contact with the fan or mainstem river channel (Figure 3.5.a). Three deposit types interacted with existing debris flow fans. Perched deposits stopped when they reached an existing fan or in the area immediately upstream of the fan (< 100 m) that had been back-filled with sediment (Figure 3.5.b). In this case, all of the depositional material was out of reach of the mainstem channel. Lobed deposits had one or several lobes that cut a path through the fan, but only a portion of the material reached the mainstem channel (Figure 3.5.c). Overrun deposits delivered the majority of their mass to the mainstem channel and

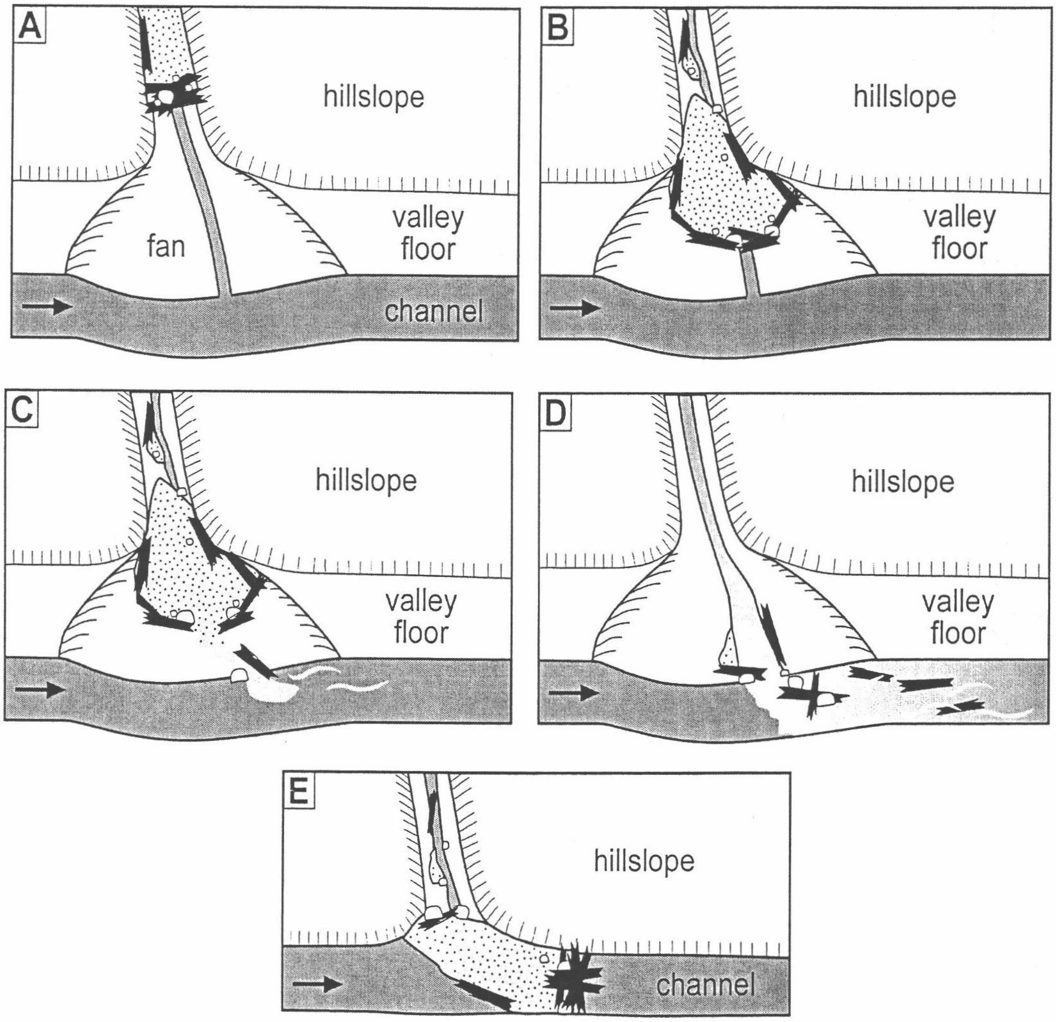


Figure 3.5. Debris flow deposit types: (a) debris dam and sediment wedge formed in tributary valley, (b) deposit perched on fan surface, (c) lobe of perched deposit overran fan, (d) deposit overruns fan surface, (e) debris dam formed in the mainstem river in narrow valley floor that prevented fan formation. Fan surfaces in the Oregon Coast Range have a dense forest cover; however, vegetation was not shown for purposes of illustration.

scoured the surface of the existing fan (Figure 3.5.d). The remaining deposit type did not interact with a debris flow fan, and instead formed a large debris dam in the mainstem river channel (Figure 3.5.e). These deposits typically entered the mainstem where the valley floor was narrow, which prevented the formation of a fan and allowed direct access of the debris flow to the mainstem.

Debris flows that may have deposited higher in the basin were not detected because field investigation was limited to the trunk channel; therefore the confluences of all the first-order streams in the network were not investigated. These confluences are potential depositional areas for debris flows that do not continue to travel down the trunk channel (Benda and Cundy, 1990). In some cases the entire length of the trunk channel could not be investigated because vertical bedrock cliffs blocked access.

All of the debris flow deposits we investigated were predicted by an empirical model (Benda and Cundy, 1990) to reach the confluence with the mainstem river except deposits in channels with a trellis network structure. The model constructed by Benda and Cundy (1990) is based on reach-scale slope estimates from digital elevation models ($> 3.5°$) and tributary junction angles above the mainstem confluence ($< 70°$). The location of debris flow deposits was documented in the field and compared with distance from the confluence of the tributary and the mainstem channel. Deposit location relative to the confluence was compared for channels with different slope classes. Slope class was defined by the gradient of the erosional zone directly upstream of the depositional zone. All of the deposits included in this analysis had a debris flow fan at the confluence, and all deposits were formed in straight reaches, either in the tributary valley or on the fan.

RESULTS

Channel Network Characteristics

A total of 125 second- and third-order tributaries prone to debris flows were investigated in the five study basins. Drainage area for these small colluvial channels ranged from 0.1 to 1.1 km^2. Drainage area was correlated with the length of the channel network (Figure 3. 6) and the number of first-order streams per tributary basin (Figure 3.7). Because the channel network reflects the degree of topographic dissection of the landscape, drainage area can be a useful predictor of the extent of convergent topography. Relative relief ratio (Figure 3.8), plotted as the maximum elevation change of a tributary basin divided by the length of the basin (Schumm, 1956), was similar among the study basins.

Drainage density is the ratio of total length of channel in the basin divided by drainage basin area, and is typically expressed as a power function.

$$L_d = cA_d^{\,b}$$

Where L_d is the total channel length, A_d is drainage basin area, and b and c are constants. Data from debris flow prone tributaries in the study basins yielded a power function of $3.63x^{0.904}$ (Figure 3.6), and confidence interval estimates for b indicated that the exponent was significantly different from 0.5 (lower 95% confidence interval = 0.832, upper interval = 0.976).

Channel Types

Debris flow prone tributaries with a simple network structure were the most abundant channel type, and accounted for 65% of the tributaries investigated (Table 3.2).

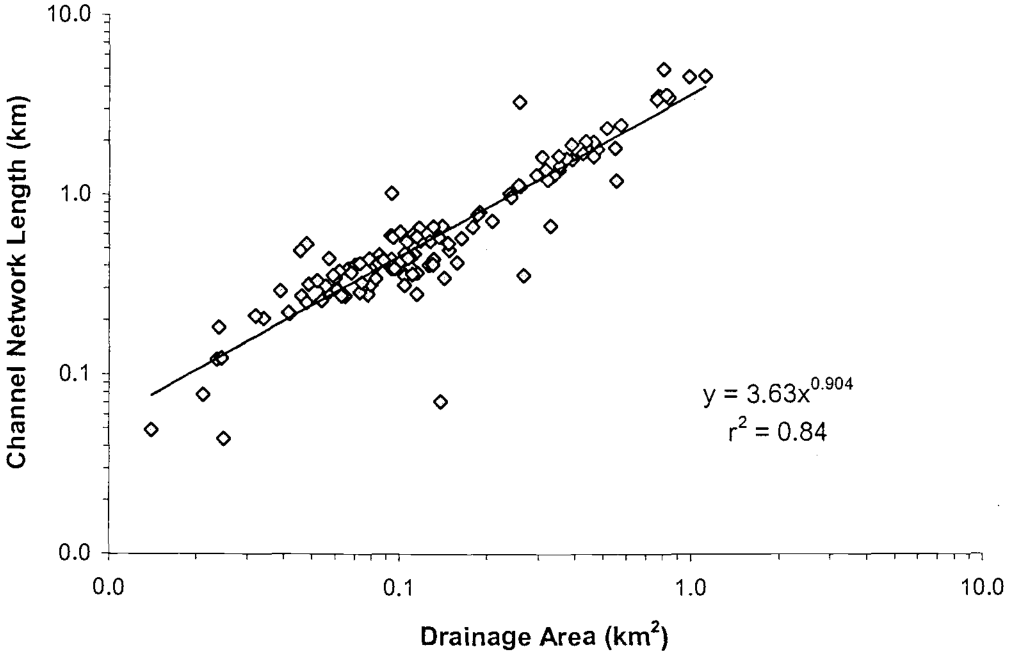


Figure 3.6. Drainage density of debris flow prone tributaries in the study basins. Data was obtained from 10 m resolution digital elevation models.

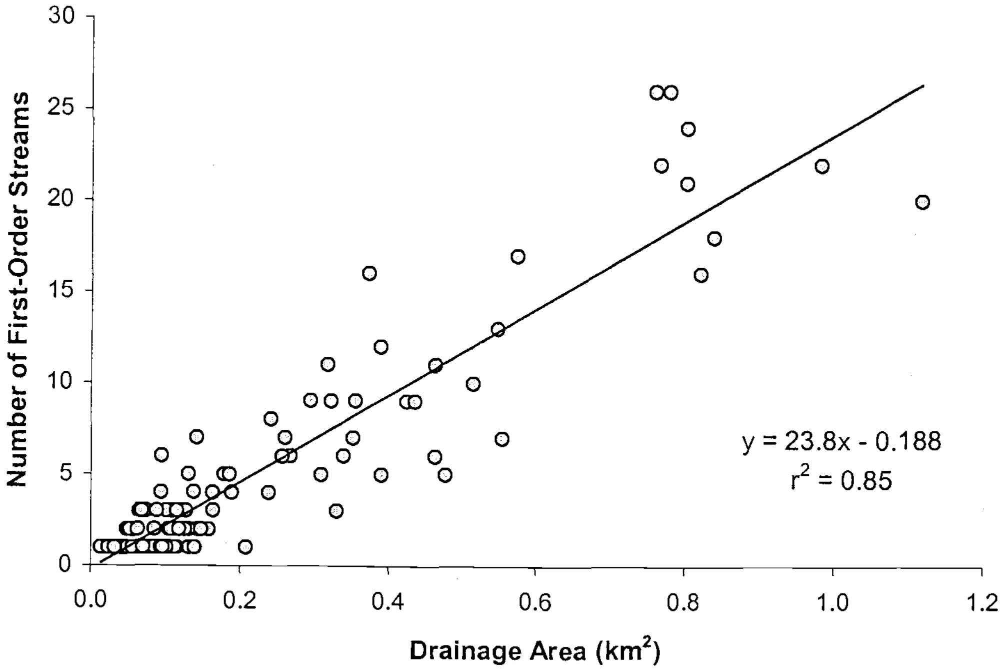


Figure 3.7. Association between the number of first-order streams and drainage area of debris flow prone tributaries in the study basins. Data was obtained from 10 m resolution digital elevation models and a 75 ha threshold for channel initiation.

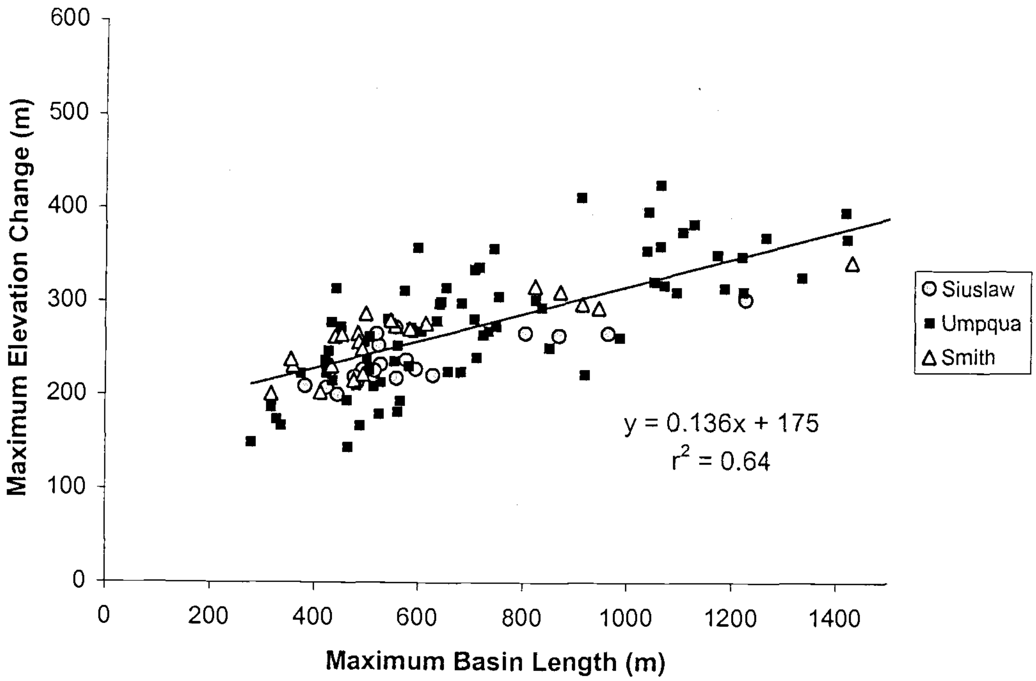


Figure 3.8. Relative relief, plotted as the maximum elevation change of a tributary basin divided by the maximum basin length, for debris flow prone tributaries in the study basins.

Table 3.2. Tributary basin and debris flow fan characteristics of the three channel network types.

	Channel Netowork Type		
	Simple	Complex	Trellis
Number of tributaries	81	36	8
Percent of trunk channels with recent debris flow	34	74	100
Average drainage area (km^2)	0.08	0.42	0.36
Range of drainage areas (km^2)	0.01 - 0.55	0.09 - 1.12	0.13 - 0.55

Tributaries with a complex network structure were less abundant (29%), but a greater proportion of these channels had experienced a debris flow during the past 30 years. Tributaries with a trellis network structure were infrequent (6%) and recent debris flow deposits were present in all of the trunk channels. Trellis channels typically did not deliver debris flows to the mainstem, instead large valley-floor-spanning wood dams backed up a large wedge of sediment and formed steps that ranged in height from 2 m to 5.5 m (Figure 3.9).

Estimates of Debris Flow Frequency

Distributions of time since the previous debris flow were significantly different between channels with simple and complex network structure ($p < 0.01$; Kolmogorov-Smirnov, one-sided, two-sample test). Tributaries with a simple network structure had fewer recent debris flows and a greater proportion of the channels were in the older, post-debris flow age-classes compared to tributaries with a complex network structure (Figure 3.10).

A comparison of the estimated time since the previous debris flow using dendrochronology and the subjective classification (Figure 3.3; see Chapter 1) indicated that 90% of the tributaries were classified correctly. The greatest source of error was for tributaries that had an abundance of near vertical bedrock steps that resulted in the proportion of exposed bedrock being greater than expected for its age-class.

Debris flow frequency in the trunk channels was estimated using two configurations of the age-class data and the model developed from the negative exponential distribution. The full model contained all of the data and resulted in an interval of 98 years and a median age of the tributaries of 65 years. This model

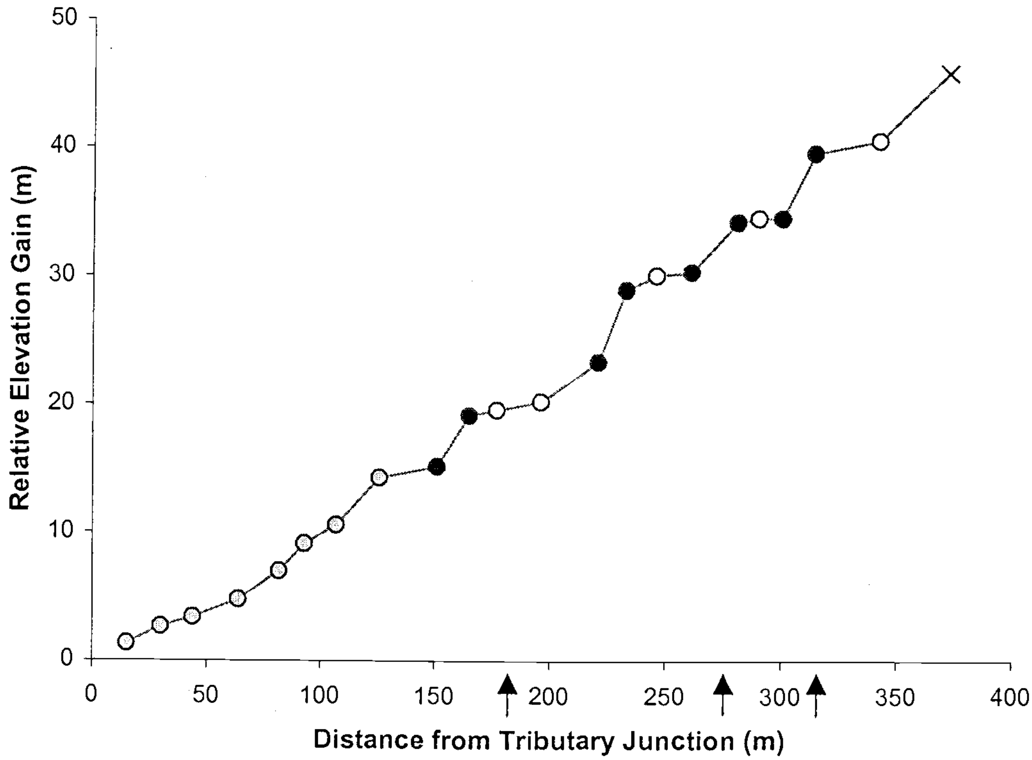


Figure 3.9. Longitudinal profile of a trunk channel in a tributary basin with a trellis network structure. Gray symbols represent gradual deposits, pairs of closed symbols represent the top and bottom of a large valley spanning debris dam, open symbols represent sediment wedges discretely deposited above debris dams, and X symbols represent bedrock reaches. Arrow represents the confluence of a first-order channel entering at > 70 degrees.

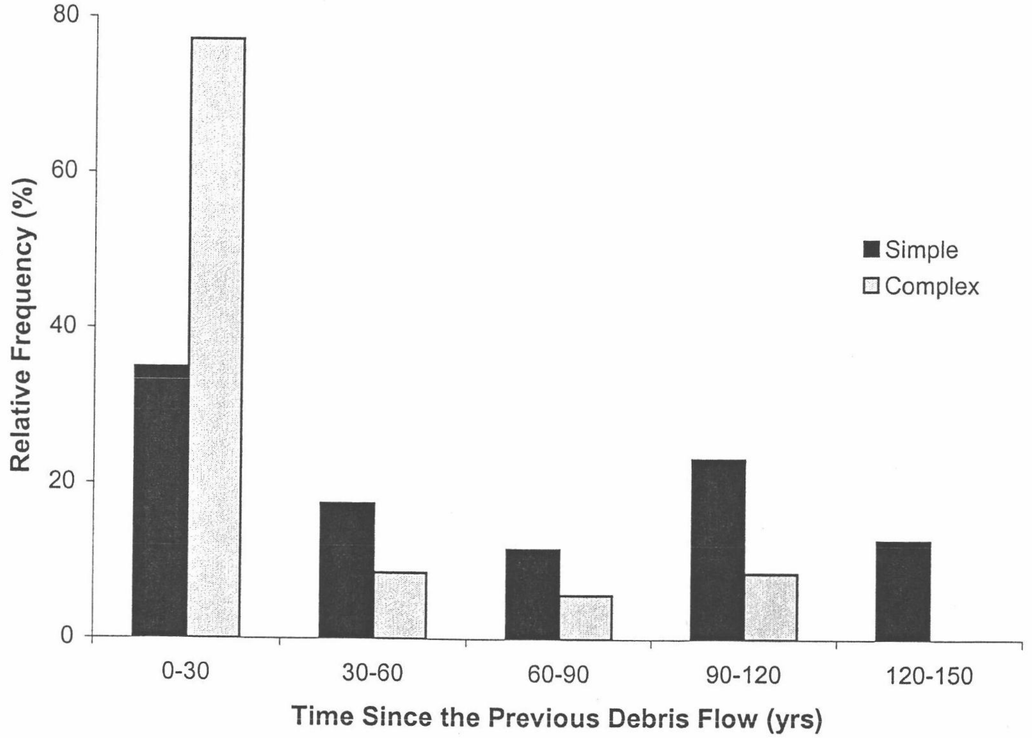


Figure 3.10. Distribution of ages for the time since the previous debris flow in channels classified as having a simple or complex network structure.

overestimated the frequency of debris flows because it was heavily biased by the numerous debris flows triggered during the 1996 flood events. The reduced model excluded the youngest age-class (0 to 30 years), and resulted in an interval of 357 years and a median age of 247 years.

No consistent pattern was observed among the study basins for debris flow activity in the decades following the last stand-replacement fire (Figure 3.11). Skate and Bear Creeks had a pulse of debris flow activity in the 30 years following the last stand-replacement fire; however, this pattern was not observed for Franklin, Harvey, and Wassen Creeks. The pattern of debris flow occurrence in these basins was dominated by recent debris flows that would have erased any evidence of debris flow activity in the immediate post-fire period.

Debris Flow Fans

Debris flow fans in the Oregon Coast Range were relatively small and steep. Adjacent fans usually did not coalesce and fan development was frequently constrained by narrow valley floors in the mainstem river valleys. Fan slope typically ranged from 5° to 10°, and the internal structure was composed of unsorted colluvium, with particles ranging from clay size to large boulders. Fluvial erosion of the fans occurred along the perimeter by the mainstem river and to a lesser extent through the body of the fan by headcut erosion of the tributary channel. Fan incision was minor in large, well-developed fans but was substantial in remnant fans that had not received a debris flow deposit in > 100 years.

All fans investigated were < 9000 m^2 in area and < 96,000 m^3 in volume. A total of 28 km of mainstem channel length was investigated in the five study basins, and 28%

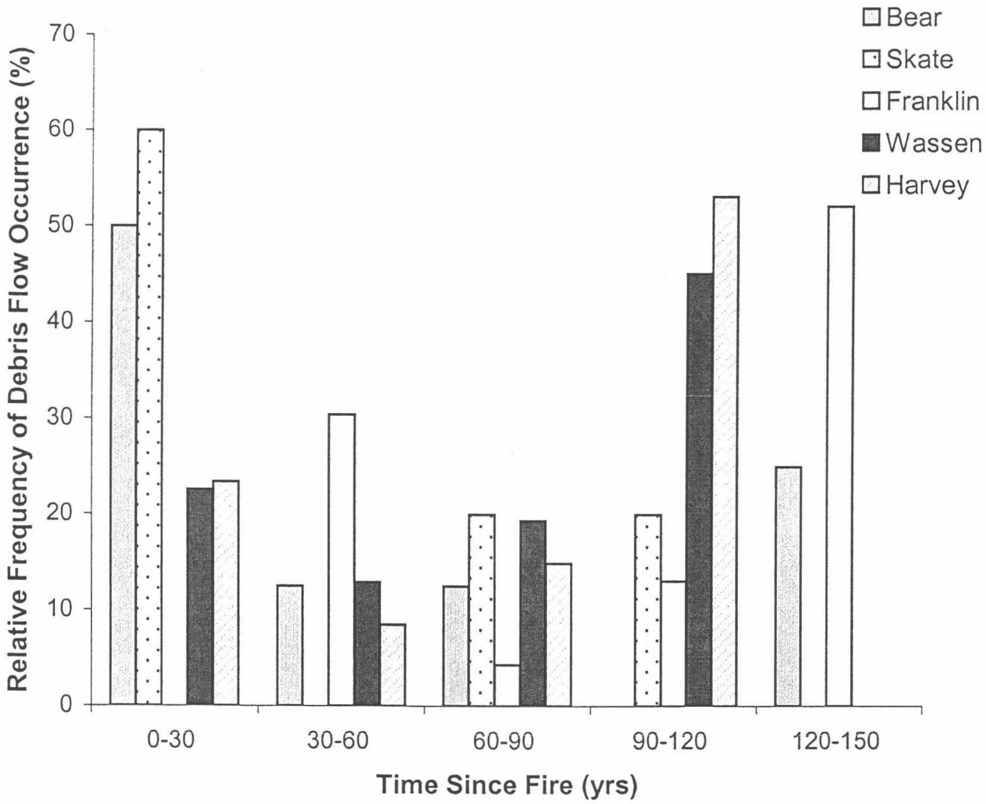


Figure 3.11. Debris flow occurrence relative to the time since the previous stand-replacement wildfire. The most recent fire occurred 151 years bp in Skate, Bear, and Franklin Creeks, approximately 132 years bp in Wassen Creek, and approximately 101 years bp in Harvey Creek.

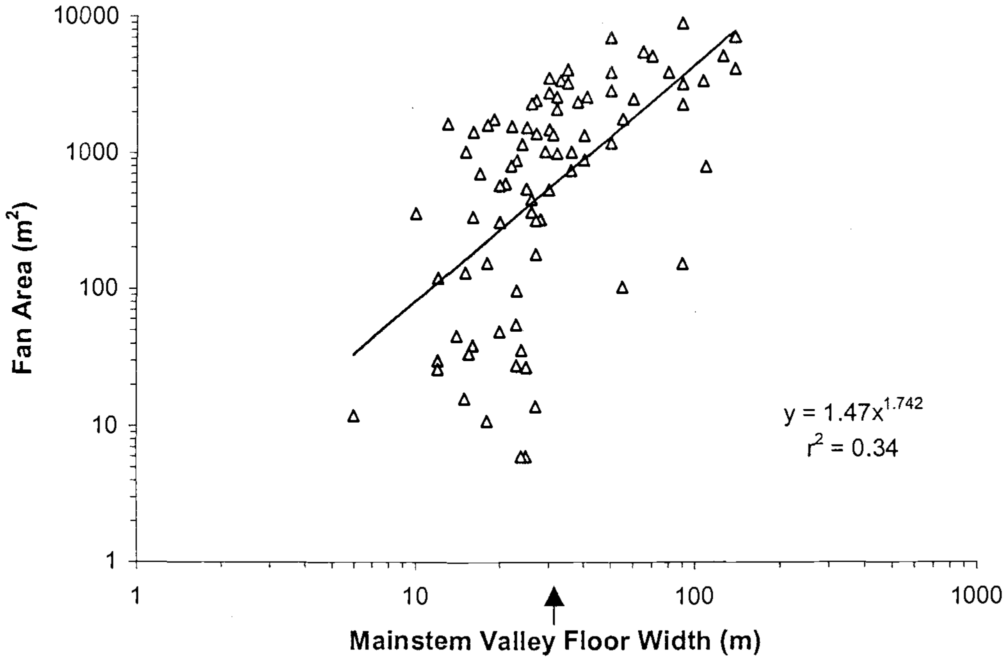
± 8% (one standard deviation) of the length of the mainstem was in direct contact with a fan. Thirty-four tributaries did not have a fan at the confluence, and 79% of these tributaries entered the mainstem where the valley floor width was < 30 m. Where valley floors were narrow, deposits frequently entered the mainstem river and did not form fans. When fans did form they were highly susceptible to erosion by the mainstem river. In valleys > 30 m, valley floor width was a better predictor of fan size (Figure 3.12).

Bull (1964) observed a morphometric relationship between fan area and drainage basin area in the form of a power function.

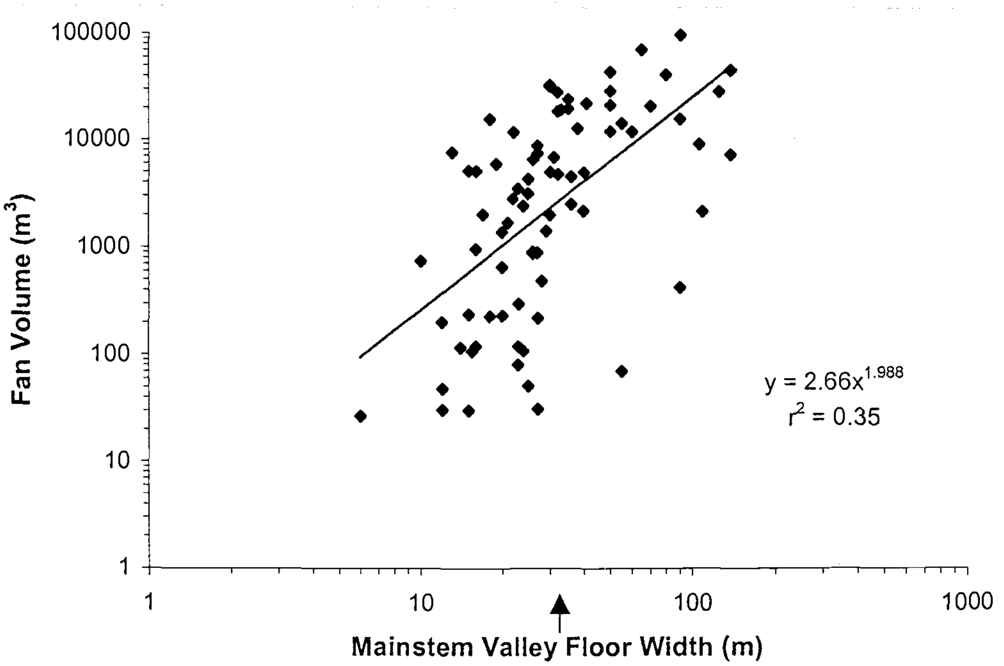
$$A_f = cA_d^{\,b}$$

Where A_f is fan area, A_d is drainage basin area, and b and c are empirically determined coefficients. The exponent b is a constant whereas c varies geographically (Denny, 1967; Hooke, 1968). The exponent b represents the constant of proportional change in the ratio of fan area to drainage basin area (Church and Mark, 1980). When $b = 1.0$, proportional change is constant and no scale-related distortion of geometry occurs (Church and Mark, 1980). The isolated morphometric relationship of drainage area to fan area was statistically significant in our study basins ($p = 0.01$), but results were highly variable and the area relationship explained very little of the observed variance ($r^2 = 0.07$). This relationship yielded a power function of $0.61x^{0.578}$, but the confidence interval for the exponent was extremely broad (lower 95% confidence interval = 0.127, upper interval = 1.029), and resulting statistical relationships between drainage area and fan area were inconclusive.

Multiple linear regression analysis suggested that the combined effects of basin characteristics and the temporal sequence of debris flows influenced fan size. Drainage



a.)



b.)

Figure 3.12. The relationship between the mainstem valley floor width and (a) fan area and (b) volume. Arrows highlight 30 m wide valley floors, below this value fan size was more variable and above this value fan size had a stronger correlation.

area of the tributary basin on the logarithmic scale (*a*) ($p < 0.02$), mainstem valley floor width on the logarithmic scale (*b*) ($p < 0.01$), and the occurrence of a debris flow in the trunk channel during the past 30 years (*c*) ($p < 0.01$) were significant explanatory variables in a multiple linear regression analysis of fan area on the logarithmic scale ($R^2 = 0.51$).

$$\mathrm{Log}_{10}\ (\text{fan area}) = 0.612 + 0.371a + 1.590b + 0.402c$$

The same three variables were also significant explanatory variables ($p < 0.05$) in a multiple linear regression model of fan volume on the logarithmic scale ($R^2 = 0.46$).

$$\mathrm{Log}_{10}\ (\text{fan volume}) = 0.682 + 0.421a + 1.925b + 0.483c$$

All coefficients were positive values, indicating that increases in any of the explanatory variables resulted in an increase in fan area and volume. Although the combined influence of these variables was a better predictor of fan size than any single factor, the explained variance was still relatively low.

Deposit Types

Of the 63 recent debris flow deposits, 33 delivered material as a large, instantaneous pulse to the mainstem. The deposits occurred in narrow valley floors that prevented the formation of a fan ($n = 15$) or where debris flows overran the existing fan ($n = 18$). Nineteen debris flow deposits were captured on the fan surface or in aggraded reaches immediately upstream of the fan. These deposits were perched on the fan surface ($n = 12$) in their entirety or a minor portion of the deposit crossed the fan as a lobe ($n = 7$). The remaining 11 deposits were captured within the confines of the tributary valley above the influence of a fan. Channels with a trellis network structure ($n = 8$) had multiple deposits from first-order channels entering the trunk channel at > 70° junction angles. These deposits created large-scale steps in the channel profile the tributary valley (Figure 3.9). Additionally, there were three tributaries that had a deposit > 100 m upstream of the fan environment (n = 3). Because we only investigated the trunk channel, debris flows that may have deposited higher in the network were not detected.

We hypothesized that a high gradient reach directly upstream of the fan would result in a higher probability of the deposit overriding the fan and reaching the mainstem (Figure 3.13). Negative values in the following comparison indicate deposits that stopped within the confines of the tributary valley before reaching the confluence (Figure 3.5.a) and positive values indicate deposits that entered the mainstem valley (Figure 3.5.b through d). Tributary channels that had a low gradient reach (< 5° field measured slope) immediately upstream of the depositional reach had the broadest range in deposit location relative to the confluence (-540 to 60 m) (Figure 3.14). Channels that had a high gradient reach (>10° field measured slope) upstream of the depositional reach had the narrowest range in deposit location (-30 to 40), and the majority of deposits reached the mainstem valley. Without the presence of a fan there was a higher likelihood that a debris flow would deliver to the mainstem, regardless of slope-class. Of the 15 recent debris flows in tributaries that did not have a fan at the confluence, 14 of the deposits directly entered the mainstem and one deposited in a tributary valley.

The ratio of the mainstem gradient to the gradient of the tributary above the hillslope constriction point varied with tributary junction angle (Table 3.3). Channel gradient for this analysis was determined from digital elevation models for channel reaches that ranged from 100 to 150 m in length. Lower ratios were documented for tributaries with a high junction angle, indicating a more abrupt change in slope at the

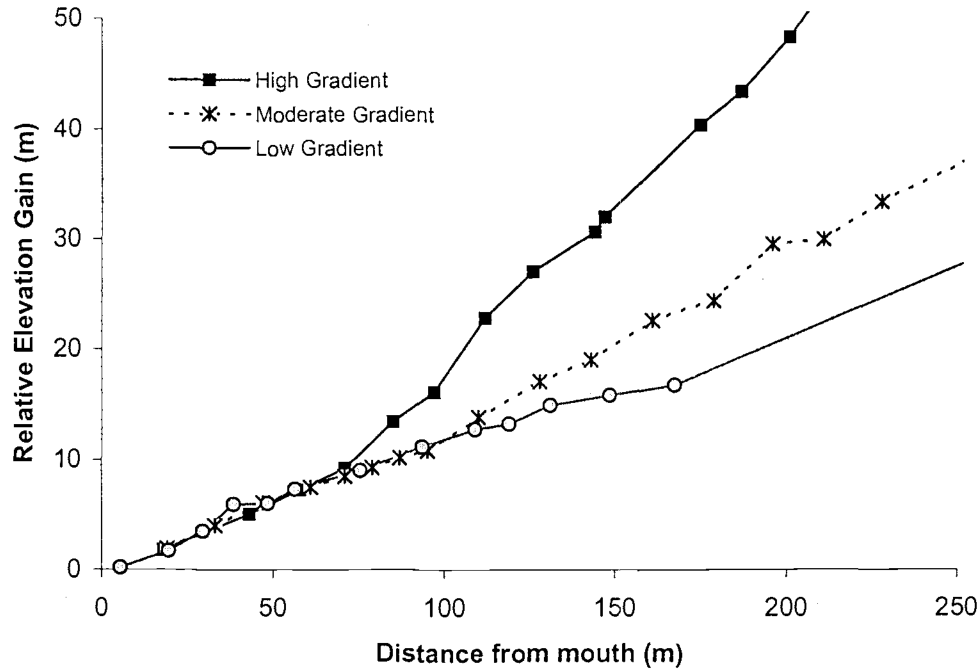


Figure 3.13. Examples of longitudinal profiles from channels with a low gradient reach (< 5 degrees), moderate gradient reach (5 - 10 degrees), and high gradient reach (> 10 degrees) immediately upstream of the depositional zone.

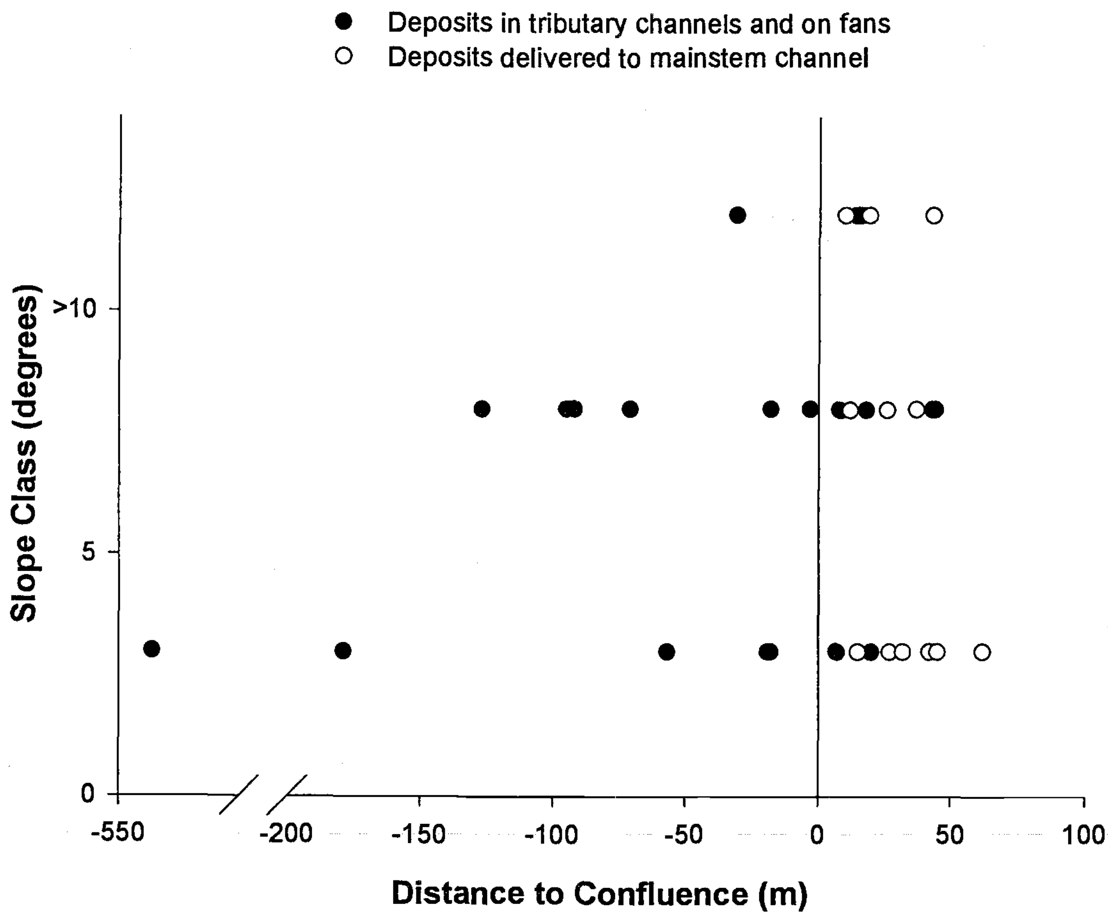


Figure 3.14. Debris flow deposit location. Zero on the x-axis represents the end of the hillslope constriction of the tributary valley and the beginning to the valley floor of the mainstem river. Negative values represent deposits that formed inside the confines of the tributary valley before reaching the confluence with the mainstem, and positive values represent debris flows that deposited in the mainstem valley. Each data point represents a seperate debris flow deposit in a trunk channel.

Table 3.3. The distribution of tributary junction angles at the confluence of debris flow prone tributaries and mainstem rivers. Gradient ratio is the mainstem gradient divided by the gradient of the tributary channel, measured from 10 m resolution digital elevation models.

	Junction Angle (degrees)				
	45 & 50	60	70	80	90
Number of tributaries	12	8	10	27	68
Mean gradient ratio (sd)	0.79 (0.27)	0.31 (0.22)	0.41 (0.24)	0.29 (0.34)	0.12 (0.12)

confluence. Higher ratios were documented for tributaries with a low junction angle, indicating a more gradual change in slope. All of the tributaries that we investigated that had a junction angle of 45° were located at the upper extent of the of the third-order segment (i.e. at the confluence of two second-order channels); however, sampling was constrained to low-order tributaries that entered higher-order streams.

DISCUSSION

Channel Network Characteristics

Drainage area of the tributary basin was highly correlated with the length of the channel network and the number of first-order streams per tributary basin. These relationships can be expected in landscapes with a uniform spacing between ridges and valleys, and were instructive because fine-scale valley density is poorly and inconsistently depicted on moderate resolution topographic data (Dietrich and Montgomery, 1998). Because drainage area is a reasonable proxy for the number of first-order streams, it may be a useful measure for predicting the density of convergent topography, and therefore, the abundance of potential landslide source areas.

The drainage density relationship, expressed as a power function, resulted in the coefficient b being statistically significant from 0.5. When $b = 0.5$, the ratio of basin area and channel length is constant across scales, consistent with fractal analysis of landscape form (Church and Mark, 1990; Montgomery and Dietrich, 1992). When $b > 0.5$ the relationship is not scale independent, and channel network length extends out of proportion with drainage basin area (Church and Mark, 1990). Our results are consistent with the findings of Montgomery and Dietrich (1992), who empirically defined a topographic threshold for channel-head locations, and thus a finite extent of the channel network in steep, soil mantled landscapes.

Similarity in relative relief among the study basins suggests that the coarse-scale potential energy of debris flow paths was equivalent. This is of interest because there is a strong latitudinal gradient in turbidite sequences in bedrock underlying the Oregon Coast Range (Ryu, 1995). Thicker, more resistant sandstone layers occur in the south (in the vicinity of Franklin, Harvey, and Wassen Creeks), and become progressively thinner to the north (in the vicinity of Skate and Bear Creeks). Because of the inherent difference in the underlying topography there may be a difference in landslide and debris flow frequency or potential runout length.

Channel Types

Channels with a simple network structure (Figure 3.2.a) tended to have smaller drainage areas, lower drainage density, and fewer channel-head areas that potentially could initiate a debris flow. Distributions of the age of debris flow runout paths suggest that these tributaries deliver debris flows less frequently than channels with a complex network structure. If debris flows occur less frequently, the trunk channel may accumulate a larger volume of sediment and wood during the interval between debris flows. Because the frequency and magnitude of debris flows are linked (Benda and Dunne 1997b), simple channels may deliver debris flows on a lower frequency, but the debris flows may be relatively large in volume because they can accumulate more material that has been stored in the low-order streams.

Channels with a complex network structure (Figure 3.2.b) tended to occur in larger drainage basins, with more numerous landslide source areas and potentially a greater routing ability of the channel network. The majority of the trunk channels were in a bedrock state and few channels were in older age-classes, indicating a higher frequency of scour than channels with a simple network structure. Tributaries with a complex network structure may deliver smaller debris flow volumes because the interval between debris flows is less; however, the net volume may be compensated if the channels are longer and the potential runout length is greater. Individual first-order streams in these tributary basins may accumulate sediment and wood for centuries; however, the dominant state for the second- or third-order trunk channels appeared to be bedrock. These channels may also be incising more rapidly into the underlying bedrock if the frequency of scour and the exposure time is greater.

Channels with a trellis network structure (Figure 3.2.c) were infrequent. The trunk channels typically stored deposits delivered from numerous first-order channels that entered at high junction angles (> 70° junction angles). Deposits tended to form large-scale steps in the channel profile. The presence of debris flow fans at the confluence with the larger river suggests that deposits are occasionally scoured from the trunk channel and delivered to the confluence with the mainstem. First-order channels at the upper extent of the trunk channel enter at low junction angles and may be capable of transporting a debris flow to the mainstem (Benda and Cundy, 1990).

Estimates of Debris Flow Frequency

An estimate of the frequency of scour was calculated by determining the annual probability of debris flow occurrence in the trunk channels, but this type of event reconstruction has several limitations. First, the interval between debris flows was not observed. Instead, the length of time since tree establishment was estimated for riparian vegetation. Van Wagner (1978) described a similar approach, using the distribution of stand-ages to infer fire history. A second limitation of this method for estimating debris flow frequency is that recent events erased evidence of prior events. The resulting frequency estimates only represent one point in time that was strongly influenced by the recent history of fires and high-intensity rainstorms and should not be considered a fixed rate.

The estimated debris flow frequency was defined as the average time required for debris flows to occur in abundance equal to the number of trunk channels in the study area. During this interval, some channels may not experience a debris flow and others may experience more than one, therefore the interval is not equivalent to each channel failing once. Because our estimate of debris flow frequency could only be made for one instance in time, it was instructive to construct two models. The full model contained all of the data, and yielded an interval of 98 years. This estimate is biased towards a younger age because the numerous debris flows that occurred during the 1996 flood events may have obliterated older age-classes. The reduced model omitted recent events (0 - 30 year age-class), and yielded an interval of 357 years. This estimate is biased toward an older age because it removed data from channels that may typically be observed in younger age-classes because they are inherently prone to more frequent debris flows. Despite the limitations, these estimates provide upper and lower bounds of the debris flow interval. Estimates of debris flow frequency were not calculated for the individual channel types because the sample size was too small.

In order to make comparisons with previous studies, and to compare the frequency of debris flows in basins of different size, we also calculated an area-dependant average of the annual probability of failure. For the 144 years of record there was an average of 0.016 debris flows km^{-2} yr^{-1} in the study basins. This annual probability of debris flow occurrence was similar to the value observed by Swanson et al. (1982a) in the Cascade Range of Oregon (0.017 debris flows km^{-2} yr^{-1}). These rates of debris flow occurrence concur with the range of long-term landslide rates estimated for bedrock hollows in the Oregon Coast Range (0.01 – 0.03 landslides km^{-2} yr^{-1}; Montgomery et al., 2000). From our results, the average return interval of one debris flow in a small basin (0.1 km^2) was 611 years, and in a larger basin (0.5 km^2) was 122 years. Because the entire basin area is not prone to debris flow occurrence and because the entire channel network was not investigated, the estimated return interval is highly inflated.

It has been suggested that pulses of debris flow activity may occur in the decades following a large, stand-replacement wildfire (Swanson, 1981; Meyer *et al.*, 1992; Benda and Dunne, 1997a). This pattern may be anticipated if high-intensity rainstorms occur during the time when the root network of the previous forest stand is decaying and before the root network of the regenerating stand becomes established (Ziemer, 1981). The premise of current models of debris flow activity is that almost all landslides occur immediately post-fire (Benda and Dunne, 1997a; Lancaster *et al.*, 2001). In addition to fire-related loss of root strength, forest gaps and hardwood patches are common in mature forest stands and result in areas of local reduction in root strength that can increase landslide susceptibility (Schmidt *et al.*, 2001). In our study, debris flow activity during the inter-fire time period was substantial, and 78% of the trunk channels experienced a debris flow > 30 years post-fire (Figure 3.12). Although no consistent pattern of debris flow occurrence in the post-fire period was observed among the study basins, interpretation was confounded by recent debris flow activity that erased evidence of previous events.

Debris Flow Fans

Fans store sediment and wood that is episodically deposited by debris flows and release this material at a slower rate to the mainstem rivers. Material stored in the fans can be accessed over time by bank erosion and high flow events. This material also can be incorporated into subsequent debris flows that are large enough to entrain earlier deposits. Because fans provide an intermediate storage compartment for sediment and wood they can function to dampen the effects of episodic inputs to the larger rivers. Similarly, in southeast Alaska, debris flows typically deposited on broad fans in U-shaped glacial valleys, which limited the transport of sediment and wood from small streams to the larger channels (Swanston and Marion, 1991).

Our study did not document a strong correlation between fan area and drainage area; however, this relationship was confounded by the constrained valley floors that limited the size of fans and by erosion of the fan during the interval between debris flows. Furthermore, not all debris flows delivered material to the fan surface. Debris flows that deposited before encountering the fan, or deposits that overran the fan, did not function to increase the size of the fan.

It has been argued that morphometric relationships with basin area and fan area are only of interest if they can provide insight into the underlying mechanisms that determine why the correlations occur (Church and Mark, 1980). Because larger tributary basins may have more numerous landslide source areas and a greater routing ability of the channel network, the flux rate of sediment and wood to the confluence is higher. If larger tributary basins have a greater frequency of debris flows delivery to the confluence, larger more persistent fans can develop. In smaller drainage basins the interval between debris flows appeared to be longer and fans had a greater likelihood of being eroded by the mainstem. The combined influences of drainage area, mainstem valley floor width, and the presence of a recent debris flow deposit were found to be statistically significant explanatory variables in multiple linear regression models of fan area and volume; however, the explained variance was low.

Mainstem valley floor width determined the potential of the fan for developing within the confines of the surrounding hillslopes. Valley width generally tended to increase as the distance from the drainage divide increased (Figure 3.15); however, variance in valley width increased substantially with increasing drainage area. Benda (1988) investigated debris flow deposits in the Oregon Coast Range and concluded that the erosion rate of a deposit was directly related to drainage area of the mainstem. In our study, valley floor width ($r^2 = 0.35$, $p < 0.01$, F-ratio = 40.6) explained more of the observed variance in fan volume than drainage area of the mainstem ($r^2 = 0.26$, $p < 0.01$, F-ratio = 27.6). In narrow valley floors (< 30 m), deposits frequently entered the mainstem and did not form a fan. If fans were formed in these narrows they were highly susceptible to erosion by the mainstem river. In wider valley floors (30 – 100m), well-formed fans were developed, and the channel was pushed to the opposite side of the valley. In broad valley floors (> 100 m) debris flow fans did not have contact with the mainstem, and therefore were not being eroded.

In addition to being an important storage reservoir for sediment, debris flow fans bordered an average of 28% of the mainstem channel length in the study basins. Fans

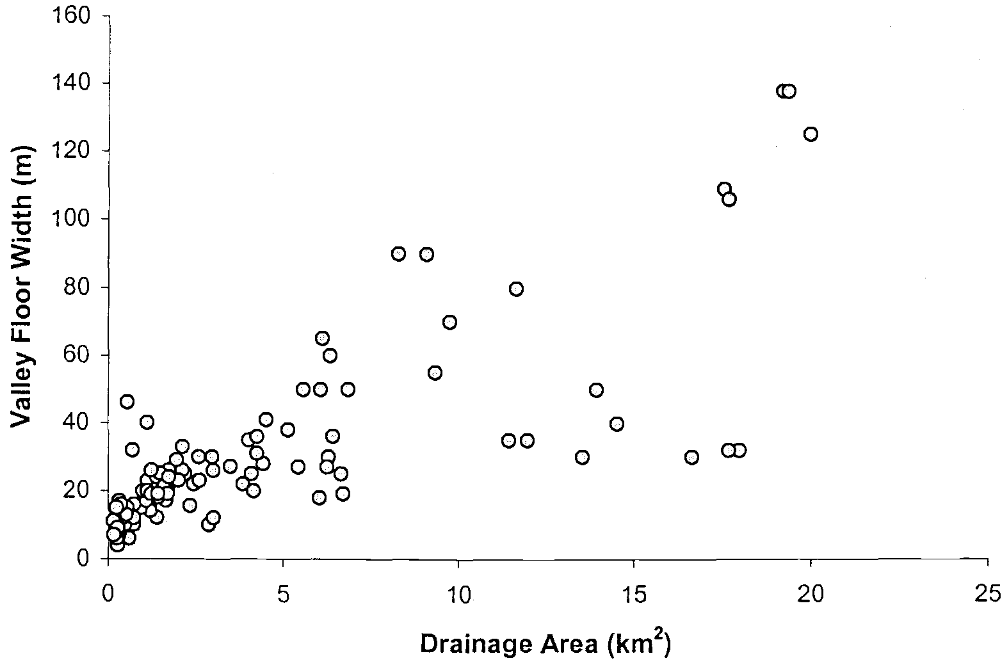


Figure 3.15. The relationship between drainage area and the mainstem valley floor width using data from all five study basins. Each data point represents a field measurement of valley floor width taken above the influence of a fan.

can influence the morphology of the mainstem channel in a variety of ways. Benda (1988) documented that 65% of the meander bends in a fifth-order stream in the Oregon Coast Range were created by debris flow fans. Fans can maintain these meander bends because they create streambanks that may be less erodable than the surrounding terraces due to the abundance of large cobbles and boulders in deposited on the fans. Alternatively, fans can occasionally block the mainstem river and create large ponds upstream (Everest and Meehan, 1981). Over time these ponds can become filled with sediment and create broad, unconstrained reaches with an active floodplain and low-gradient channel. The mainstem river channel can also dissect the fan surface and create islands (May, 1998).

Deposit Type

Half of the tributaries investigated during this study were recently scoured to bedrock by a debris flow. These recent debris flows occurred in the absence of fire, and 52 of the 63 debris flows occurred in the absence of land management activities in the tributary basin. The two extremely large storm events in 1996 undoubtedly left a strong signal of recent debris flows in the basins.

The type of deposit formed was important for determining the downstream consequences of sediment and wood delivered by the debris flow and the rate at which this material was accessed by the mainstem river. Deposits that were captured on the fan surface can be accessed over time by bank erosion and high flow events in the mainstem river. Wood deposited on the fan surface is likely to decay in place before the larger stream can access it, unless it is buried by subsequent debris flows and the decay rate is reduced (Hyatt and Naiman, 2001). Lobed deposits delivered a portion of the wood and sediment to the mainstem river; however, the majority of material was deposited on the fan surface. Deposits that overran the fan, or tributaries that delivered directly to the mainstem without the presence of a fan, delivered a large, instantaneous pulse of wood and sediment to the mainstem river.

Debris flows that deposited in the confines of the tributary valley had the potential to be scoured by future debris flows; however, these deposits usually formed broad flat surfaces that created ideal depositional environments that may halt the runout of future debris flows. Similarly, aggraded reaches were frequently observed above the fan apex, suggesting that sediment is being backed-filled into the tributary channels. These aggraded reaches created relatively low gradient areas that could promote deposition of future debris flows. Channels that had a high gradient reach upstream of the depositional reach appeared to have a higher likelihood of debris flows reaching the mainstem. Channels that had a low gradient reach upstream of the depositional reach had the potential of reaching the mainstem; however, deposit location was more variable.

The magnitude of variation of deposit location in the vicinity of the confluence with the mainstem suggests that a simple spatially explicit model may not be adequate to predict debris flow delivery to the mainstem rivers. Although the variation in the distance may be relatively short (50 to 100 m), this distance determines whether the debris flow delivers material to the larger river as an instantaneous pulse or if the material is transferred into long-term storage on the valley floor. The expected results of the Benda and Cundy (1990) model was a synchronous pulse of material entering the receiving stream; however, our results found that only half of the debris flows reached the mainstem river. The lack of a spatially deterministic relationship of deposit location and network geometry supports field evidence that sequential debris flows do not consistently deposit in the same location. Most channels with debris flow deposits that formed in straight reaches of the trunk channel also had a fan present at the confluence, indicating that past debris flows had reached the confluence. This suggests that other time-dependent variable such as water and sediment concentrations (Whipple, 1992), the mass of wood in transport (Lancaster *et al.*, 2001), or the presence of other deposits that may act as barriers to transport can be important for determining runout length and deposit location.

Tributary junction angle has long been recognized as an important factor in predicting debris flow deposition (Benda and Cundy, 1990); however, valley floor landforms at the confluence have not been previously considered. The distribution of tributary junction angles for the debris flow prone tributaries was highly skewed toward 90° tributary junction angles. Horton (1945) recognized that where there is an abrupt transition in slope between the tributary and mainstem, the tributary joined at almost a right angle to the mainstem. In contrast, where the tributary and mainstem gradient are similar, the tributary will enter at a low junction angle. In the study basins, all of the debris flow deposits that encountered a fan in a broad valley floor deposited in straight reaches, suggesting that the abrupt change in slope or valley width promoted deposition. This is contrary to previous findings that suggested debris flows deposited at confluences with high junction angles because the debris flow dissipated energy when contacting the opposite valley wall, forcing the debris flow to turn a sharp corner (Benda and Cundy, 1990).

CONCLUSIONS

Network structure and drainage area influenced the frequency of debris flow delivery to the mainstem rivers in the study basins. Larger tributary basins with more convergent topography may have a higher probability of experiencing a debris flow during a storm event because the number of potential landslide source areas is greater than in smaller basins with less convergent topography. The frequency of debris flows influenced the structure of the tributary channel and the flux rate of sediment and wood delivered to the confluence with the larger river. Debris flow fan formation was effected by this flux rate and the valley width of the mainstem river. At the mouth of small basins, with less convergent topography and less frequent debris flows, fans were more likely to be eroded during the interval between debris flows. Where the valley floor was wide enough, persistent and well-developed fans formed at the mouth of larger tributary basins. Debris flow fans stored sediment and wood that was episodically transported by debris flows. This material can be accessed over time by bank erosion and high flow events, substantially dampening the stochastic input from debris flows. In narrow valley floors that may have prevented the formation of a fan, debris flows were more likely to deliver a large pulse of sediment and wood directly to the mainstem river. Valley width can therefore be seen as an important predictor of the connectivity between tributaries and mainstem rivers.

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REFERENCES

Agee, JK. 1993. *Fire Ecology of Pacific Northwest Forests*. Island Press, Washington D.C.

Baldwin EM. 1964. *Geology of Oregon*. University of Oregon, Eugene, Oregon.

Beaty CB. 1963. Origin of alluvial fans, White Mountains, California and Nevada. *Annals, Association of American Geographers* **53**:516-535.

Beaty CB. 1970. Age and estimated rate of accumulation of an alluvial fan, White Mountains, California, U.S.A. *American Journal of Science* **268**:50-70.

Benda LE. 1988. *Debris Flows in the Tyee Sandstone Formation of the Oregon Coast Range*. M.S. Thesis, University of Washington, Seattle, Washington.

Benda LE, Cundy TW. 1990. Predicting deposition of debris flows in mountain channels. *Canadian Geotechnical Journal* **27**:409-417.

Benda LE, Dunne T. 1997a. Stochastic forcing of sediment supply to channel networks from landsliding and debris flows. *Water Resources Research* **33**(12):2849-2863.

Benda LE, Dunne T. 1997b. Stochastic forcing of sediment routing and storage in channel networks. *Water Resources Research* **33**(12):2865-2880.

Bull WB. 1963. Alluvial-fan deposits in western Fresno County, California. *Journal of Geology* **71**:243-251.

Bull WB. 1964. Geomorphology of segmented alluvial fans in western Fresno County, California. *U.S. Geological Survey Professional Paper*, **352**:89-129.

Church M, Mark DM. 1980. On size and scale in geomorphology. *Progress in Physical Geography* **4**(3):342-390.

Denny CS. 1965. Alluvial fans in the Death Valley region, California and Nevada. *U.S. Geological Survey Professional Paper*, **446**.

Denny CS. 1967. Fans and pediments. *American Journal of Science* **265**:81-105.

Dietrich WE, Dunne T. 1978. Sediment budget for a small catchment in mountainous terrain. *Zeitschrift fur Geomorphologie N.F.* **29**:191-206.

Dietrich WE, Montgomery DR. 1998. Hillslopes, channels and landscape scale. In *Scale Dependence and Scale Invariance in Hydrology*, G Sposito (ed). Cambridge University Press, New York; 30-60.

Everest FH, Meehan WR. 1981. Forest management and anadromous fish habitat productivity. In *Transactions of the 46th North American Wildlife and Natural Resources Conference*. Wildlife Management Institute, Washington D.C.; 521-530.

Franklin JF, Dyrness, CT. 1973. Natural vegetation of Oregon and Washington. *USDA Forest Service General Technical Report*, PNW-8.

Graham JD. 1985. *Mass Movement Dynamics, Geomorphology and Their Relationship to Geology in the North Fork Siuslaw River Drainage Basin, Oregon Coast Range*, M.S. Thesis, Oregon State University, Corvallis, Oregon.

Grant GE, Wolff AL. 1991. Long-term patterns of sediment transport after timber harvest, western Cascade Mountains, Oregon, USA. In *Proceedings of the Vienna Symposium,* IAHS **203**:31-40.

Gregory SV, Swanson FJ, McKee WA, Cummins KW. 1991. An ecosystem perspective of riparian zones. *BioScience* **41**:540-551.

Hack JT. 1960. Interpretation of erosional topography in humid temperate climates. *American Journal of Science* **258**-A: 80-97.

Hooke RL. 1968. Steady-state relationships on arid-region alluvial fans in closed basins. *American Journal of Science* **266**:609-629.

Horton RE. 1945. Erosional development of streams and their drainage basins: hydrophysical approach to quantitative morphology. *Geological Society of American Bulletin* **56**:275-370.

Hunt CB, Maybe DR. 1966. Stratigraphy and structure, Death Valley, California. *U.S. Geological Survey Professional Paper* **494**-A: 1-162.

Hyatt TL, Naiman RJ. 2001. The residence time of large woody debris in the Queets River, Washington, USA. *Ecological Applications* **11**(1):191-202.

Impara, PC. 1997. *Spatial and Temporal Patterns of Fire in the Forests of the Central Oregon Coast Range*, Ph.D. Dissertation, Oregon State University, Corvallis, Oregon.

Johnson EA, Van Wagner CE. 1984. The theory and use of two fire history models. *Canadian Journal of Forest Research* **15**: 214-220.

Kirchner JW, Finkel RC, Riebe CS, Granger DR, Clayton JL, King JG, Megahan WF. 2001. Mountain erosion over 10 yr, 10 k.y., and 10 m.y. time scales. *Geology* **29**(7): 591-594.

Kochel RC, Johnson RA. 1984. Geomorphology, sedimentology, and depositional processes of humid-temperate alluvial fans in central Virginia, U.S.A. *Canadian Society of Petroleum Geologists Memoir* **10**:109-122.

Kostaschuk RA, MacDonald GM, Putnam PE. 1986. Depositional process and alluvial fan-drainage basin morphometric relationships near Banff, Alberta, Canada. *Earth Surface Processes and Landforms* **11**:471-484.

Lancaster ST, Hayes SK, Grant GE. 2001. Modeling sediment and wood storage and dynamics in small mountainous watersheds. In *Geomorphic Processes and Riverine Habitat*, Dorava JM, Montgomery DR, Palcsak BB, Fitzpatrick FA (eds). American Geophysical Union, Washington, 85-102.

Lecce, SA. 1990. The alluvial fan problem. In *Alluvial Fans: A Field Approach*, Rachocki AH, Church M (eds). John Wiley and Sons, New York, 3-24.

Long CJ, Whitlock C, Bartlein PJ, Millspaugh SH. 1998. A 9000-year fire history from the Oregon Coast Range, based on a high-resolution charcoal study. *Earth Surface Processes and Landforms* **28**: 774-787.

May CL. 1998. *Debris Flow Characteristics Associated with Forest Practices in the Central Oregon Coast Range*, M.S. Thesis, Oregon State University, Corvallis, Oregon.

Melton MA. 1965. The geomorphic and paleoclimatic significance of alluvial deposits in southern Arizona. *Journal of Geology* **73**: 1-38.

Meyer GA, Wells SG, Balling RC, Jull AJT. 1992. Response of alluvial systems to fires and climate change in Yellowstone National Park. *Nature* **367**:147-149.

Montgomery DR, Dietrich WE. 1992. Channel initiation and the problem of landscape scale. *Science* **255**:826-830.

Montgomery DR, Schmidt KM, Greenberg HM, Dietrich WE. 2000. Forest clearing and regional landsliding. *Geology* **28**(4): 311-314.

Morris WG. 1934. Forest fires in western Oregon and western Washington. *The Oregon Historical Quarterly* Vol. XXXV: 313-339.

Mosley MP. 1976. An experimental study of channel confluences. *Journal of Geology* **84**:535-562.

Naiman RJ, Decamps H. 1990. Aquatic-terrestrial ecotones: summary and recommendations. In *Ecology and Management of Aquatic-Terrestrial Ecotones*, Naiman RJ, Decamps H (eds). UNESCO, Paris, and Parthenon Publishing Group, Carnforth, UK, 295-301.

Reeves GH, Benda LE, Burnett KM, Bisson PA, Sedell J.R. 1995. A disturbance-based ecosystem approach to maintaining and restoring freshwater habitats of evolutionary significant units of anadromous salmonids in the Pacific Northwest. In *American Fisheries Society Symposium*: Bethesda, Maryland; **17**:334-349.

Reneau SL, Dietrich WE. 1991. Erosion rates in the southern Oregon Coast Range: evidence for an equilibrium between hillslope erosion and sediment yield. *Earth Surface Processes and Landforms* **15**: 307-322.

Ryu I. 1995. *Stratigraphy, Sedimentology, and Hydrocarbon Potential of Eocene Forearc and Subduction Zone Strata in the Southern Tyee Basin, Oregon Coast Range*, Ph.D. Dissertation, Oregon State University, Corvallis, Oregon.

Schmidt KM, Roering JJ, Stock JD, Dietrich WE, Montgomery DR. 2001. The variability of root cohesion as an influence on shallow landslide susceptibility in the Oregon Coast Range. *Canadian Geotechnical Journal* (in press).

Schumm SA. 1956. Evolution of drainage systems and slopes in badlands at Perth Amboy, New Jersey. *Bulletin of the Geological Society of America* **67**:597-646.

Schumm SA. 1977. *The Fluvial System*. John Wiley and Sons, New York.

Strahler AN. 1964. Quantitative geomorphology of drainage basins and channel networks. In *Handbook of Applied Hydrology*, Chow VT (ed). McGraw Hill, New York; 40-74.

Swanson FJ. 1981. Fire and ecosystem processes. USDA Forest Service, General Technical Report WO-26.

Swanson FJ, James ME. 1975. Geomorphic history of the lower Blue River-Lookout Creek area, western Cascades, Oregon. *Northwest Science* **49**(1):1-11.

Swanson FJ, Fredricksen RL, McCorison FM. 1982a. Material transfer in a western Oregon forested watershed. In *Analysis of Coniferous Forest Ecosystems in the Western United States*, Edmonds RL (ed). Hutchinson Ross, New York; 233-266.

Swanson FJ, Gregory SV, Sedell, JR, Campbell, AG. 1982b. Land-water interactions: the riparian zone. In *Analysis of Coniferous Forest Ecosystems in the Western United States*, Edmonds RL (ed). Hutchinson Ross, New York; 267-291.

Swanston DN, Marion DA. 1991. Landslide response to timber harvest in Southeast Alaska. In *Proceedings of the Fifth Federal Interagency Sedimentation Conference*, Shou-Shan Fan, Yung-Huang Kuo (eds). Federal Energy Regulatory Commission, Washington D.C.

Taylor G. 1997. Causes of the flood and a comparison to other climate events. In *The Pacific Northwest Floods of February 6-11, 1996: Proceedings of the Pacific Northwest Water Issues Conference*, Laenen A, Ruff JD (eds). American Institute of Hydrology, St. Paul, Minnesota; 3-7.

Van Wagner CE. 1978. Age-class distribution and the forest fire cycle. *Canadian Journal of Forest Research* **8**:220-227.

Whipple KX. 1992. Predicting debris-flow runout and deposition on fans: the importance of the flow hydrograph. In *Erosion, Debris Flows and Environment in Mountain Regions: Proceedings of the Chengdu Symposium*, Walling D, Davies T, Hasholt B (eds). International Association of Hydrological Sciences **209**: 337-345.

Ziemer RR. 1981. Roots and the stability of forested slopes. In *Erosion and Sedimentation of the Pacific Rim Steeplands*, Davies TRH, Pearce AJ (eds). International Association of Hydrological Sciences. Institute of Hydrology, Wallingford, Oxfordshire; **132**: 343-361.

4. Large Wood Recruitment and Redistribution in Headwater Streams in the Southern Oregon Coast Range, U.S.A.

Christine L. May and Robert E. Gresswell

ABSTRACT

Large wood recruitment and redistribution mechanisms were investigated in a 3.9 km^2 basin with an old-growth *Pseudotsuga menziesii* and *Tsuga heterophylla* forest, located in the southern Coast Range of Oregon. Stream size and topographic setting strongly influenced processes that delivered wood to the channel network. In small colluvial channels draining steep hillslopes, processes associated with slope instability dominated large wood recruitment. In the larger alluvial channel, wind throw was the dominant recruitment process from the local riparian area. Consequently, colluvial channels received wood from further upslope than the alluvial channel. Input and redistribution processes influenced piece location relative to the direction of flow and thus, affected the functional role of wood. Wood recruited directly from local hillslopes and riparian area was typically positioned adjacent to, or spanned, the full width of the channel, and trapped sediment and wood in transport. In contrast, wood that had been fluvially redistributed was commonly located in mid-channel positions and was associated with scouring of the streambed and banks. Debris flows were a unique mechanism for creating large, valley spanning accumulations of wood in small streams that lacked the capacity for abundant fluvial transport of wood and for transporting wood that was longer than the bank-full width of the channel.

KEY WORDS: Large woody debris, Streams, Oregon Coast Range, Forestry, Landslides

INTRODUCTION

The transfer of large wood from forests to streams is a major linkage between terrestrial and aquatic ecosystems (Lienkaemper and Swanson 1987). Previous studies have shown the important role large wood plays in the structure and function of mountain streams (Keller and Swanson 1979; Harmon et al. 1986; Bisson et al. 1987; Ralph et al. 1994; Bilby and Bisson 1998); however, little is known about the relative contribution of wood delivered by processes occurring in the local riparian area compared to upstream and upslope sources of wood. Previous research on wood recruitment processes (Keller and Swanson 1979; Murphy and Koski 1989) and the source distance of wood to stream channels (McDade et al. 1990; Murphy and Koski 1989) have primarily focussed on wood recruited directly from the local riparian area in alluvial streams. In mountainous terrain of the Pacific Northwest, landslides on the hillslopes and debris flows in small colluvial channels also have the potential to deliver large quantities of wood to the larger alluvial streams (Swanson and Lienkaemper 1978; Keller and Swanson 1979; Benda and Sias 1998; May 1998). Information on wood recruitment and redistribution mechanisms, and how they vary spatially in a basin, may be useful for determining how and where to protect the sources of wood to streams (Martin and Benda, 2001).

In recent years it has become increasingly apparent that to maintain complex aquatic habitat, guidelines for forest practices require measures to preserve physical and biological linkages between streams, riparian zones, and uplands (IMST 1999). Upland forests and headwater streams can influence water quantity, water quality, invertebrate and detritus inputs, and physical habitat characteristics throughout the drainage network.

Small ephemeral channels typically do not directly support fish but they can have a strong influence on the rate of sediment and wood delivered to larger rivers that provide habitat for numerous aquatic organisms.

The majority of the channel network in mountainous terrain is composed of first- and second-order channels (Shreve 1969) that typically have ephemeral or intermittent streamflow and store large volumes of wood and colluvial sediment. Several studies have documented a systematic increase in large wood abundance with decreasing stream size, along with a corresponding decrease in the average size of pieces as stream size decreases (Keller and Swanson 1979; Bilby and Ward 1989; McDade et al. 1990). The frequency and residence time of log jams has also been observed to increase as drainage area decreases (Martin and Benda 2001).

Past studies in the Oregon Cascade Range (Swanson et al. 1982) and in central Idaho (Megahan and Nowlin 1976) have indicated that relatively little sediment and wood is transported by chronic fluvial processes in first- and second-order streams. Instead, low-order streams can undergo long periods of storage of sediment and wood that can be episodically transported by debris flows (Swanson and Lienkaemper 1978; May 1998). Because debris flows are a stochastic process, at any point in time or location in space, the relative importance of debris flow transported wood will vary greatly within and among basins (Benda and Sias 1998). In 11 third- through fifth-order streams in the Oregon Coast Range, the contribution of wood from debris flows ranged from 11-57% of the total volume of wood in the channel for basins that had a broad range of forest age classes (May, *in review*). Because debris flows are primarily a mechanism for redistributing in-stream wood (May 1998), it is important to understand the sources of wood to this portion of the network.

If past management practices have depleted other sources of wood to the larger alluvial rivers than the relative contribution of wood delivered by debris flows in the colluvial tributaries would be expected to increase. For example, if timber harvest has reduced the recruitment potential of wood from the local riparian area along alluvial rivers, or if wood was purposefully removed from the alluvial river channel, the relative contribution of wood from debris flows would be expected to increase. Wood delivery by landslides and debris flows would also be expected to increase if the removal of forest cover has increased the frequency of mass wasting. This increase in wood delivery would only be expected if legacy wood, such as wood stored in the colluvial channels, was available for transport.

The goal of this study was to gain insight into the relative contribution of processes that recruit and redistribute wood and to understand how these processes vary spatially in a basin. Specific research questions included: (1) Do processes that deliver and redistribute wood differ in small colluvial channels compared to larger alluvial channels? (2) Does the distance from the rooting site of the tree to the stream-bank differ for wood delivered from the local hillslopes and riparian areas in colluvial and alluvial channels? (3) How do input and redistribution processes influence the functional role of wood in the channel?

STUDY BASIN

The study was conducted in the North Fork of Cherry Creek Research Natural Area (Franklin 1972), a 3.9 km^2 basin in the southern Oregon Coast Range (Figure 4.1).

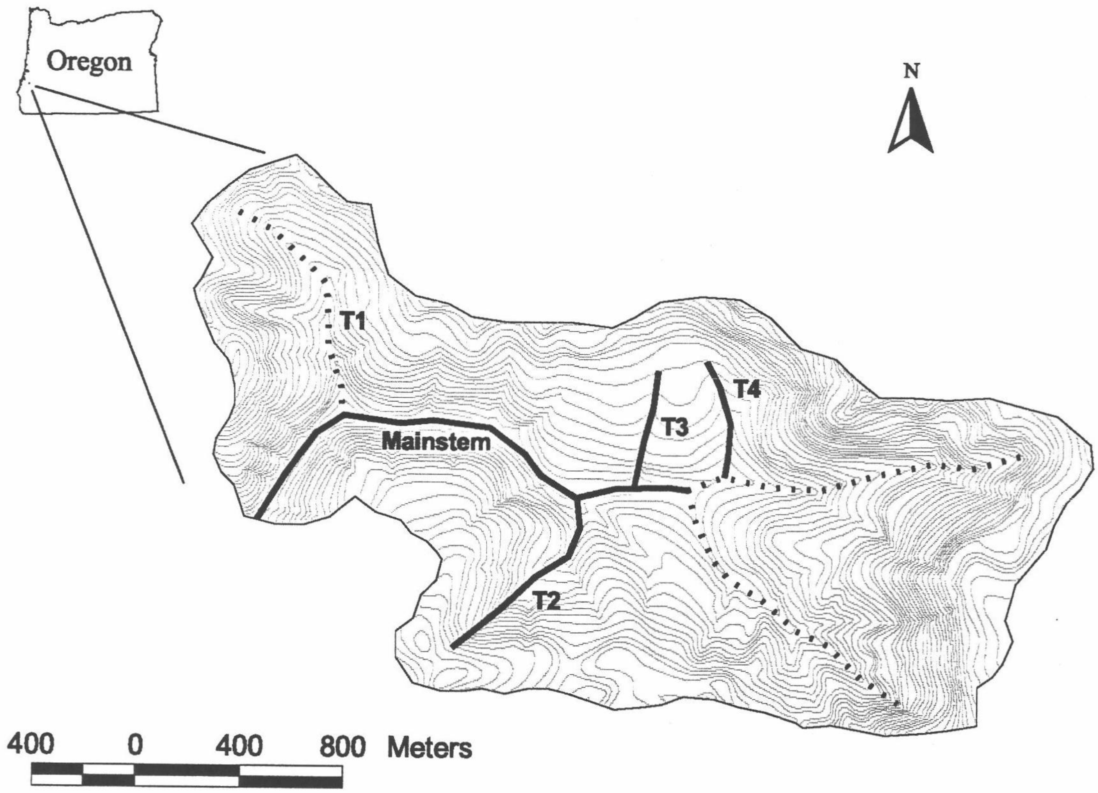


Figure 4.1. North Fork of Cherry Creek basin. Dark lines represent the study streams, dashed lines represent second-order channels with a history of timber harvest and not investigated, numerous first-order channels are poorly represented and are not highlighted. Contour interval = 10m.

This basin was selected because few large-scale disturbances, such as debris flows or fires, have occurred for several centuries. Old growth Douglas-fir *(Pseudotsuga menziesii)*, western hemlock (*Tsuga heterophylla*), and western red cedar (*Thuja plicata*) is present in the portion of the study basin investigated. The average age of Douglas-fir trees is in excess of 300 years, and the average diameter at breast height (dbh) ranges from 125 to 175 cm (Franklin 1972). Although tree size varies with site conditions and tree age, a typical old-growth Douglas-fir tree is 50 to 70 m in height (Franklin *et al.* 1981). The largest identified Douglas-fir tree in Oregon (294 cm dbh, 87 m height) was located on the low elevation valley floor of the mainstem, and tree ring analysis indicated the tree originated in the 1300s (U.S. Bureau of Land Management, personal communication). Human influences upon the area are related to road construction and clearcut logging operations in the upper elevations of the basin (Franklin 1972).

The Oregon Coast Range has a maritime climate, characterized by wet and relatively warm winters and dry summers. Annual precipitation averages 210 cm, coming mostly as fall and winter rain. The basin is underlain by Tertiary marine sedimentary rocks of the Tyee Formation and is bordered on the west by the Umpqua Formation (Baldwin 1964). The dominant substrate throughout the channel network was gravel and sand-sized particles. Soils in the basin are classified as Preacher-Bohannon Loams, which are characterized by deep to moderately deep, steep, gravelly and loamy soils that formed in colluvium and residiuum derived from sedimentary rock (Soil Conservation Service 1989). Umpcoos soils are present in the vicinity of rock outcrops that expose fractured, hard sandstone on steep side slopes. The basin ranges in elevation from 207 m to 451 m.

This study focused on a contrast between colluvial tributaries and the mainstem, alluvial channel because they had vastly different 'process domains' (Montgomery 1999). Process domains are spatially identifiable areas characterized by distinct suites of geomorphic processes, and systematic differences in the type and frequency of disturbance and habitat-forming events. Colluvial channels are high gradient and directly drain the steep hillslopes. These channels are tightly constrained by the adjacent hillslopes and have small drainage areas (< 1 km^2). Colluvial channels typically have ephemeral or intermittent streamflow and have poorly sorted, angular to sub-angular substrate and the absence of alluvial bedforms. Alluvial channels are low to moderate gradient, commonly have perennial stream flow, and have alluvial bedforms. Alluvial channels in the Oregon Coast Range are typically third-order or larger channels, with drainage areas > 1 km^2.

All colluvial channels investigated were second-order (Strahler 1964) ephemeral streams that drained steep hillslopes and were tributaries of the mainstem, alluvial channel. The determination of stream-order is highly contingent upon the resolution used to define first-order streams. For this study, first-order streams were delineated on topographic maps where distinct valleys were evident, and the extent of the network was verified in the field by the presence of a definable channel and evidence of fluvial scour. Therefore, first-order streams extended higher up in the drainage network than previous studies that have based stream order on stream lines from USGS topographic maps. Our field-based determination of stream order typically resulted in an increase of one stream order compared to map-based determinations. This distinction is important for comparison with other studies, and because second- and third-order streams in the study basin represent different process domains.

METHODS

Three colluvial tributaries and the entire mainstem of the North Fork of Cherry Creek were investigated (Figure 4.1). Tributary #1 was not surveyed because all of the wood in the channel had been removed by a debris flow that initiated several decades ago in a timber harvest unit at the channel head. Two tributaries in the upper basin were not surveyed because they had been harvested for timber in previous decades.

In the study streams, all downed wood that exceeded 20 cm in average diameter and was > 2 m in length that was in contact with the bank-full channel was measured. The average decay class of each piece was recorded and characterized by the following criteria: class (1) bark, branches, and twigs present; class (2) bark present, branches absent, bole sturdy; class (3) bark loose or absent, surface of bole slightly decayed; class (4) surface of bole deteriorating, center solid; class (5) bole and center disintegrating. Wood volume was calculated as a cylinder, using the average piece diameter and total length.

Large wood was categorized by the action that delivered it to its current position in the channel network: (1) delivered directly from the local hillslopes and riparian area, (2) fluvial redistribution, (3) debris flow transported, or (4) unidentified source. Specific recruitment processes for wood derived from the local hillslopes and riparian areas were identified by following the in-stream wood up the bole to the rooting location of the tree (Table 4.1).

Table 4.1. Criteria used to identify large wood recruited from processes in the local hillslopes and riparian areas.

Recruitment Process	Criteria for Classifying
Slope Instability	deposits associated with landslides in hollows and planar sideslopes, streamside landslides, and inner gorge areas with evidence of accelerated soil creep and surface erosion at the rooting site
Natural Mortality	broken boles of standing dead trees
Independent Wind Throw	single, uprooted tree
Dependent Wind Throw	numerous uprooted trees in a larger wind throw patch, often located further upslope and knocking down trees growing closer to the channel
Bank Erosion	undercut trees rooted in the channel bank
Unknown Process	bole extended into the local forest; however, no recruitment process could be identified

Fluvially redistributed wood was identified by the absence of a local growing point of the tree and by the physical trapping of the piece by obstructions in, or along, the channel that would result from transport to the site from upstream. Wood transported by debris flows in the tributaries was identified by deposit morphology, which included large, valley spanning debris dams and debris flow fans. Debris flow deposits were also in close proximity to a tributary that had been scoured to bedrock. The contribution of wood from debris flows may have been overestimated if fluvially transported wood had accumulated above the deposit. The original source and recruitment process of wood that had been redistributed in the channel could not be identified.

Identification of wood recruitment and redistribution mechanisms were categorized during a retrospective investigation, and therefore, were subject to several forms of ambiguity. The proportion of wood recruited and redistributed by mechanisms identified during this study may not represent the original source of wood if the action that delivered wood to its current position in the channel network was the result of multiple processes. The wood recruitment category with the greatest degree of uncertainty was wind throw. It was assumed that live trees were uprooted by wind throw, and that natural mortality resulted in fragmentation of a standing dead tree (Table 4.1). Wind throw may also cause trees to fall that have been weakened by competition or other mortality agents (e.g., insects and disease) that predispose the trees to toppling or breaking (Harmon et al. 1986; Franklin et al. 1987). Furthermore, trees rooted in the channel bank could have been delivered by the combined effects of bank erosion and wind throw (Lienkaemper and Swanson 1987); however, all wood from trees rooted in the bank was categorized as bank erosion. Our study was also limited to a single point in time in a dynamic system where the timing of tree death is highly variable and unpredictable (Franklin et al. 1987).

Source distance of wood derived from the local hillslopes and riparian areas was measured as the total slope distance from the edge of the bank-full channel, upslope to the growing point of the tree (McDade et al. 1990). Hillslope gradient from the active channel to the rooting site of the tree was measured with a clinometer. Pieces from broken trees that were in direct alignment were followed to the rooting location. If there was any uncertainty in the sequences of pieces, no source distance was recorded. The identified rooting location was used to quantify the source distance. If a single tree delivered multiple pieces of wood to the channel, all pieces were assigned the same source distance. The distance an individual tree slid downslope from the rooting location was not recorded. Because the exact rooting location could not be identified on landslides, the source distance for wood in landslide deposits was taken from the active channel edge to the headscarp of the landslide. This measurement may overestimate the actual source distance of individual trees previously growing on the landslide.

The location of wood, relative to the flow direction, was recorded for all pieces in contact with the active channel. Categories of piece location included pieces adjacent to the channel bank (categorized as 'side'), pieces suspended over the channel, mid-channel pieces, or pieces that spanned the full width of the channel. The geomorphic function of wood was classified by its interaction with streamflow and sediment. Pieces were classified as being associated with: (1) streambed scour, (2) stream-bank scour, (3) stream-bank armor, (4) sediment storage, (5) wood storage, (6) side channel formation, or

(7) no discernable geomorphic function. Wood storage included the physical trapping of branches and twig accumulations (i.e. small wood) and other pieces of large wood.

RESULTS

A total of 1205 pieces of large wood was measured in the channel network (Table 4.2). Wood derived from the local hillslopes and riparian area accounted for the majority of wood pieces (63%) in the small colluvial channels (Table 4.3). The larger alluvial channel received wood from a greater variety of sources, including recruitment from the local hillslopes and riparian area (36%), fluvial redistribution (9%), and debris flow transported wood (33%). In the colluvial tributaries, 36% of the pieces had an unidentified source; however, these pieces were typically small and only accounted for 10% of the total volume of wood. In the mainstem, alluvial channel 22% of the pieces had an unidentified source, but they were also small and accounted for only 6% of the total volume of wood. The majority of pieces with an unidentified source appeared to be broken branches or the tops of trees that experienced substantial breakage. The average length of wood in the tributaries was slightly longer than in the mainstem (Figure 4.2), but distributions were not significantly different ($p > 0.1$, Kolmogorov-Smirnov, two-sided, two-sample test). The distribution of piece diameter (Figure 4.3) was similar in tributaries and the mainstem ($p > 0.1$, Kolmogorov-Smirnov, two-sided, two-sample test).

Wood that was redistributed by fluvial processes had the smallest median volume per piece (Table 4.3). Pieces with an unknown source and those transported by a debris flow were intermediate in size, and pieces recruited directly from the local hillslopes and riparian area had the largest median volume. The median volume of wood pieces was significantly different among these sources ($p < 0.05$, Kruskal-Wallis Multiple

Table 4.2. Channel characteristics and large wood abundance in colluvial tributaries and the mainstem alluvial channel.

	Mainstem	Tributary 2	Tributary 3	Tributary 4
Stream Order (topographically determined)	3	2	2	2
Stream Order (USGS streamlines)	2	0	0	0
Stream Length Sampled (m)	2140	490	400	190
Mean Channel Width (m)	4.8	3.3	3.6	3.6
Mean Valley Floor Width (m)	16	6	5	6
Mean Channel Slope (%)	3	19	25	9
Large Wood (#) per 100m	34	48	42	37

Table 4.3. Sources of large wood in the North Fork of Cherry Creek basin.

	Wood Pieces (%)		Wood Volume (%)		
	Colluvial Tributaries	Alluvial Mainstem	Colluvial Tributaries	Alluvial Mainstem	Median Piece Volume (m^3)
Local Hillslopes and Riparian Areas	63	36	89	74	2.75
Fluvial Redistribution	1	9	1	2	0.25
Debris Flow Transported	-	33	-	18	0.77
Unknown Source	36	22	10	6	0.63

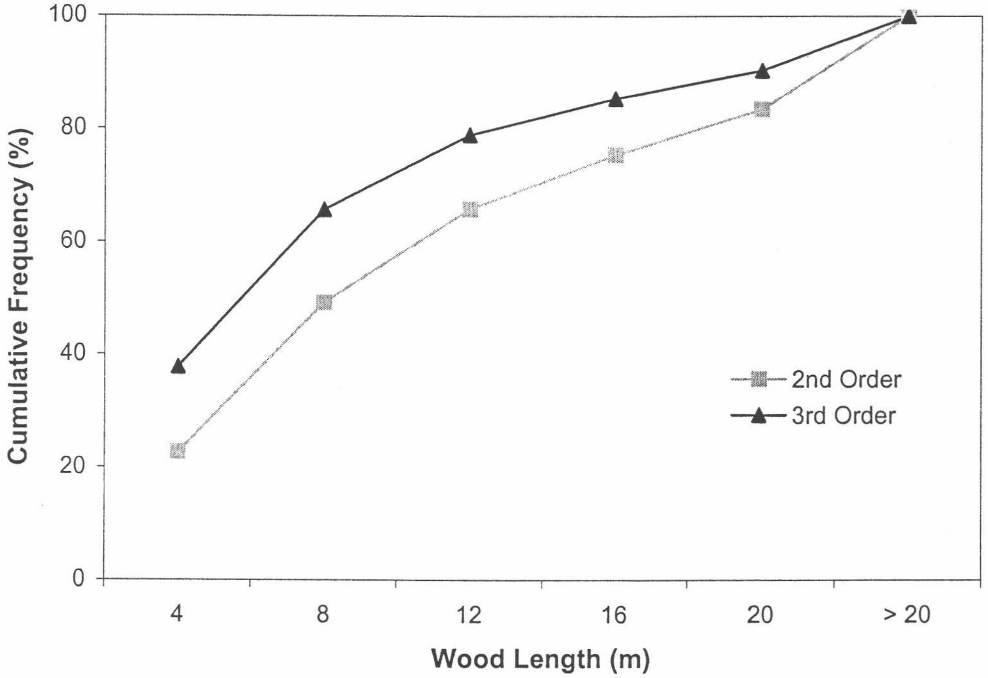


Figure 4.2. Distribution of piece length in the small colluvial tributaries (second-order) and in the mainstem channel (third-order).

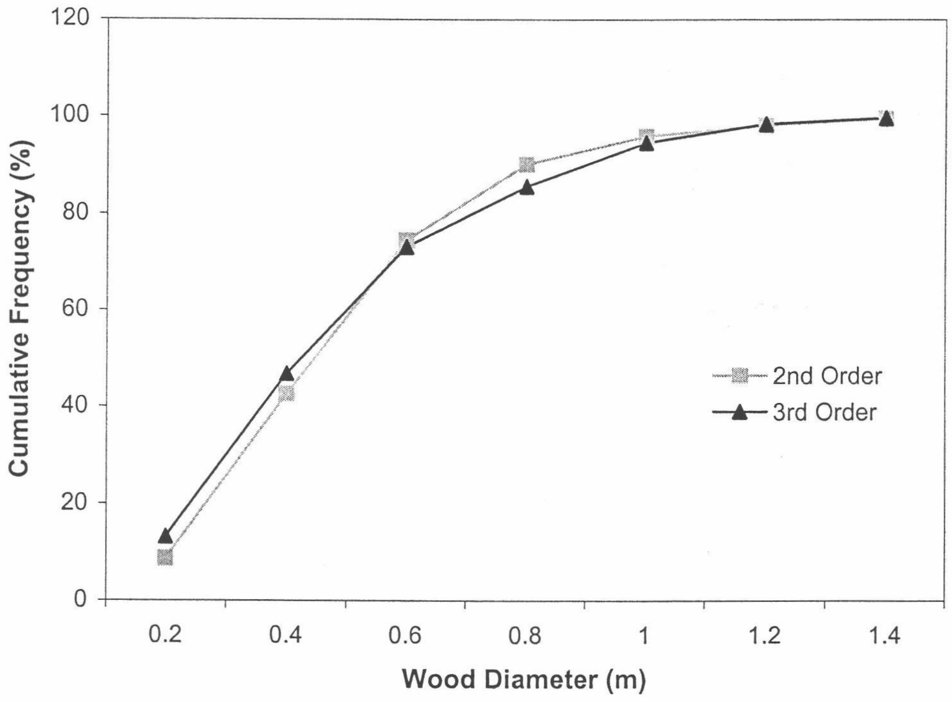


Figure 4.3. Distribution of piece diameter in the small colluvial tributaries (second-order) and in the mainstem channel (third-order).

Comparisons Test). Because larger pieces of wood were recruited from the local hillslopes and riparian areas, these sources of wood had a disproportionately large contribution to the volume of wood in the channel. For example, wood recruited from the local hillslopes and riparian areas accounted for 36% of wood pieces in the alluvial stream, which accounted for 74% of the total volume of wood.

Large Wood Recruitment from the Local Hillslopes and Riparian Areas

The dominant wood recruitment mechanisms in the small colluvial channels were processes associated with slope instability and wind throw (Figure 4.4). Wind throw was also the dominant recruitment process for wood derived from the local hillslopes and riparian area along the larger alluvial stream. The broad distribution of decay classes for in-stream wood recruited by wind throw suggests that input did not occur in a single, catastrophic event, but was spread over multiple decades (Figure 4.5).

Distributions of the source distance of wood pieces was significantly different between colluvial and alluvial channels ($p < 0.05$, Kolmogorov-Smirnov, one-sided, two-sample test) (Figure 4.6.a). The source distance of wood was also significantly different when comparing wood volume between colluvial and alluvial channel due to the extended tail of the distribution ($p < 0.05$, Kolmogorov-Smirnov, one-sided, two-sample test) (Figure 4.6.b). In colluvial streams, 80% of wood pieces and 80% of the total volume of wood originated from trees rooted within 50 m of the channel. In the alluvial channel, 80% of the pieces of wood originated from within 30 m of the channel; however, this accounted for only 50% of the total volume of wood. Source distance was poorly correlated with piece length ($r_s = 0.20$, Spearman's Rank Correlation),

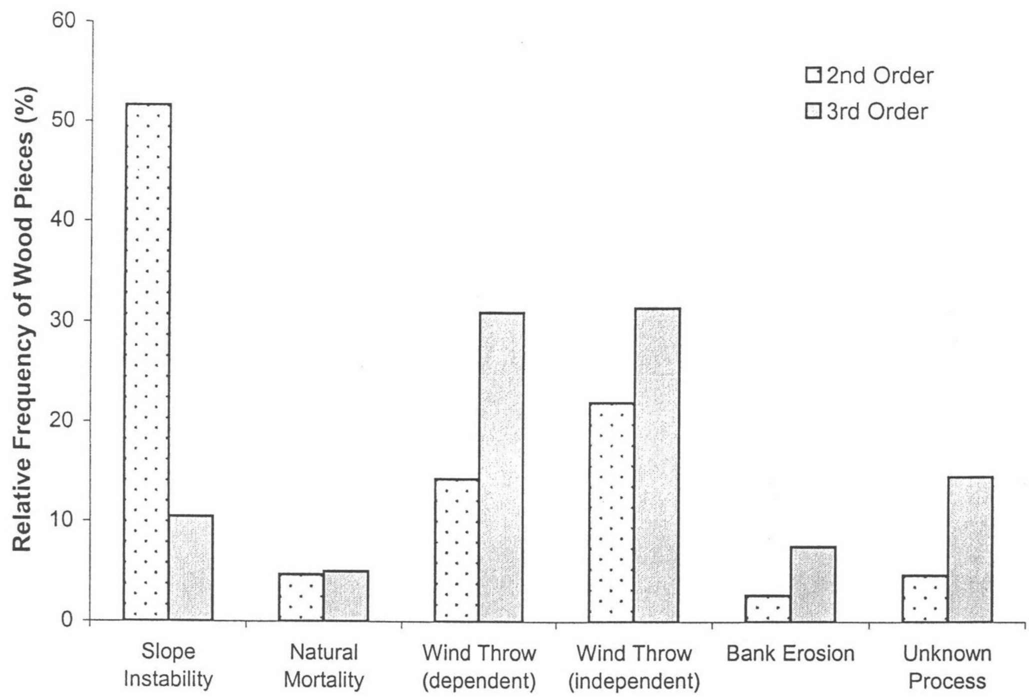


Figure 4.4. The relative contribution of different wood recruitment processes for pieces derived from the local hillslopes and riparian areas.

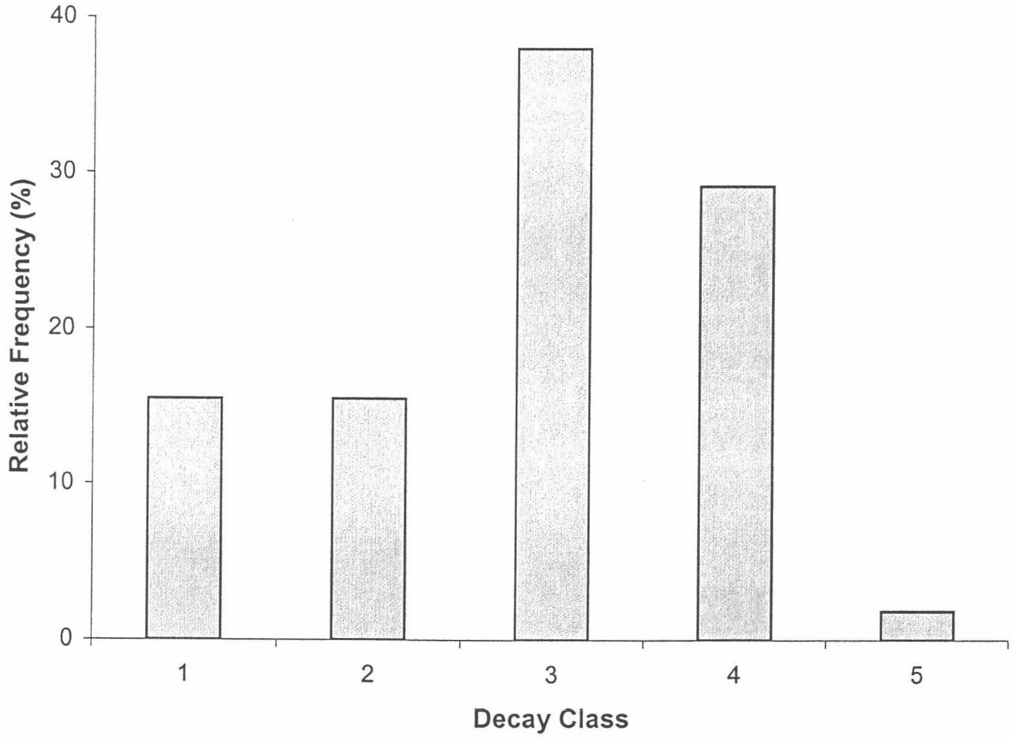
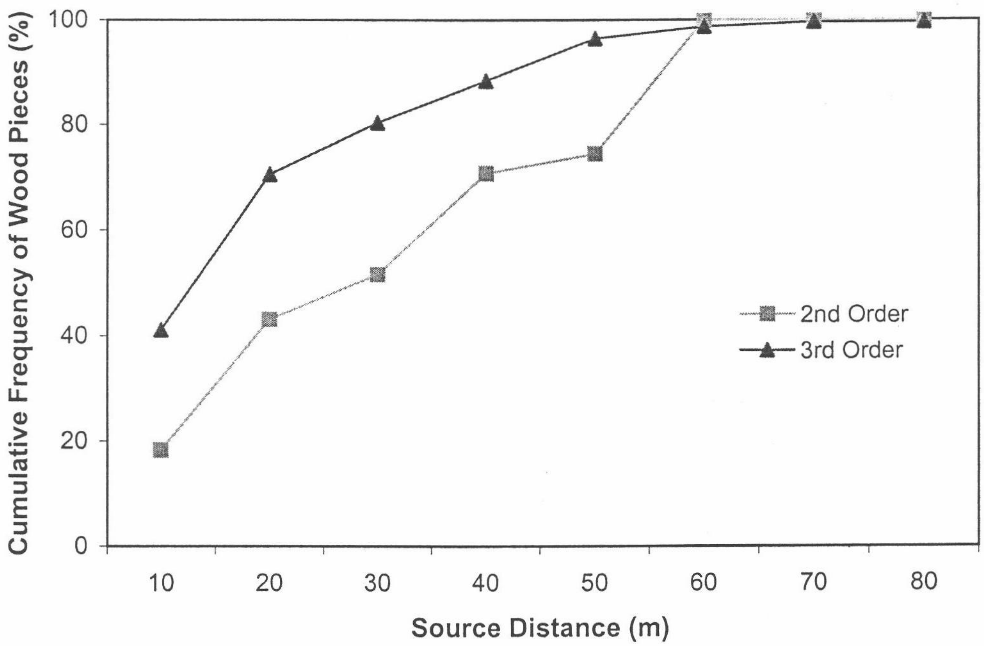
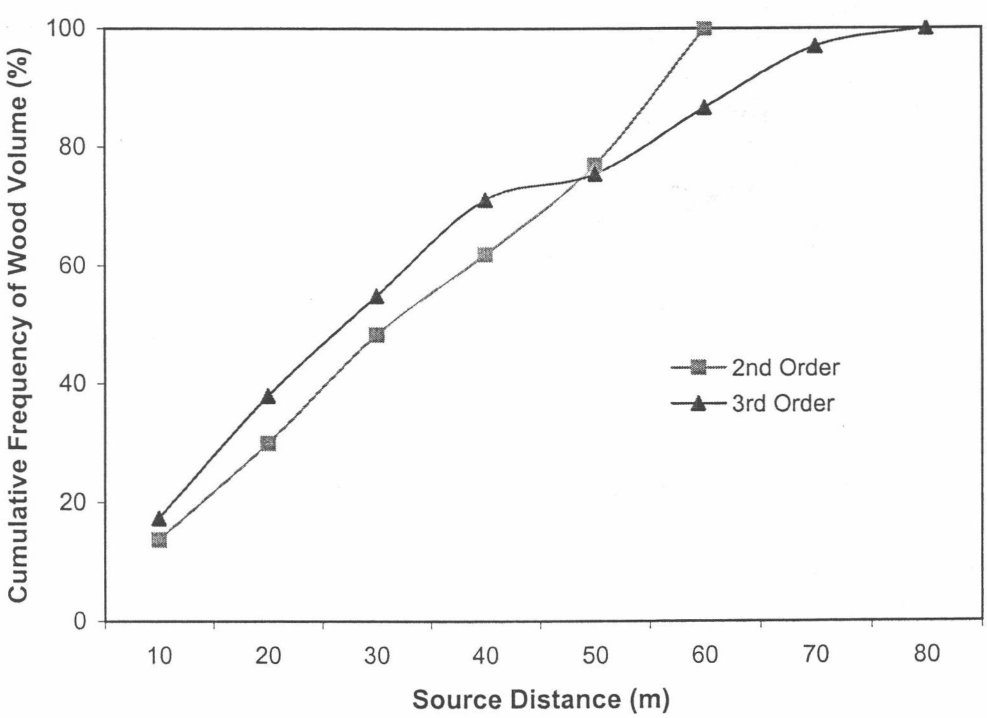


Figure 4.5. The range of decay classes observed for wood recruited by wind throw.



a.)



b.)

Figure 4.6. The source distance of large wood (a) pieces and (b) volume for second-order colluvial tributaries and the third-order mainstem channel in the North Fork of Cherry Creek basin.

diameter ($r_s = 0.23$, Spearman's Rank Correlation), and piece volume ($r_s = 0.26$, Spearman's Rank Correlation).

Breakage of fallen trees into multiple pieces was common. Piece diameter, source distance, and presence of a rootwad were significant explanatory variables ($p < 0.01$) in a multiple linear regression model of piece length from broken trees. Although this model was statistically significant it accounted for only 38% of the observed variability (adjusted R^2) in piece length. The gradient from the channel edge to the rooting location of the tree was not a significant explanatory variable associated with breakage ($p > 0.05$).

Processes associated with slope instability tended to deliver wood from further upslope than other processes (Figure 4.7). In both colluvial and alluvial channels sources of wood delivered by slope instability extended furthest from the channel (median = 40 m), followed by both independent and dependent wind throw (median = 20 m), natural mortality (median = 18 m), and for obvious reasons bank erosion occurred closest to the channel bank (median = 2 m). Slope instability and bank erosion had significantly different median source distances compared to all other recruitment processes ($p < 0.05$, Kruskal-Wallis Multiple Comparisons Test). Source distances of wood recruited by natural mortality and independent and dependent wind throw were similar ($p > 0.05$, Kruskal-Wallis Multiple Comparisons Test). There were no significant differences in the source distance of wood recruitment processes among stream orders, excluding wind throw ($p > 0.05$, Kruskal-Wallis Multiple Comparisons Test). The median source distance of wood recruited by independent wind throw was significantly longer in colluvial channels than in alluvial channel ($p < 0.05$, Kruskal-Wallis Multiple Comparisons Test).

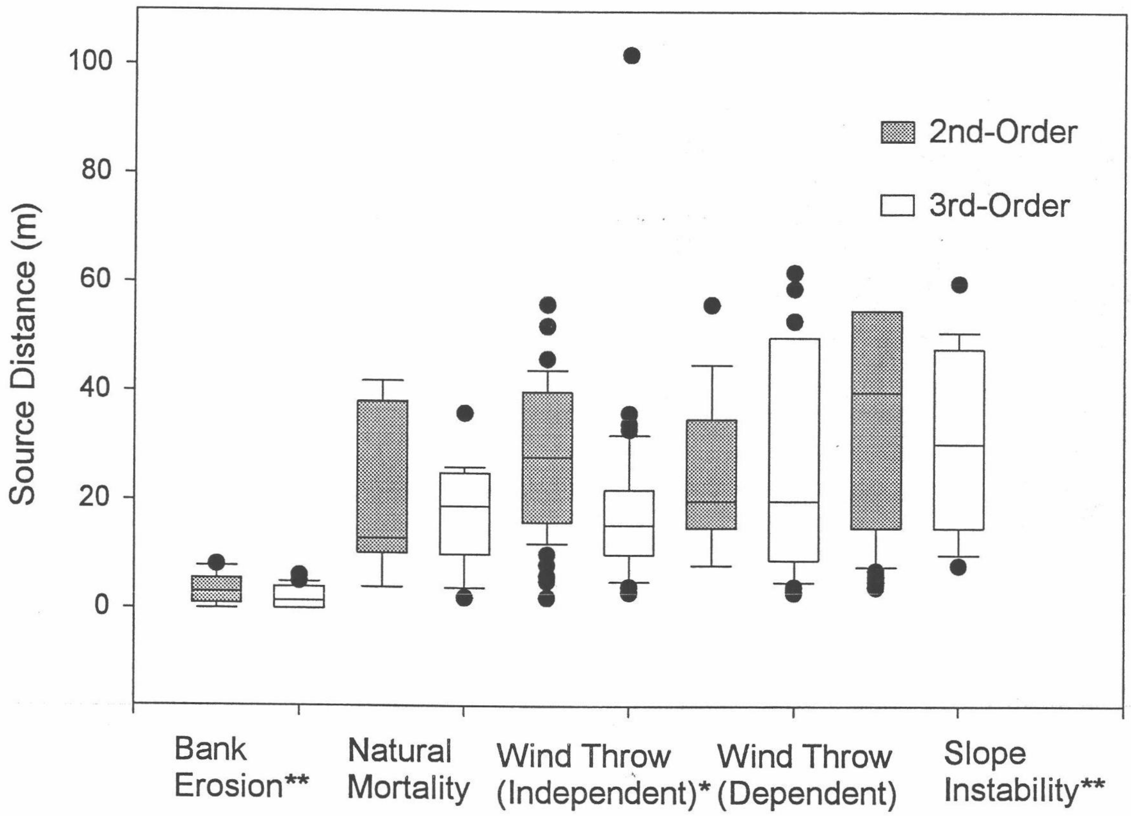


Figure 4.7. Box-and-whisker plots of the source distance of large wood with different recruitment mechanisms. Lower boundary of box represents the 25th percentile, mid-line represents the median, and upper boundary of box represents the 75th percentile. Lower whisker represents the 10th percentile, upper whisker represents the 90th precentile, and circles represent outlying points. * Median source distance significantly different in second- and third-order channels ($p > 0.05$, Kruskal-Wallis Multiple Comparisons Test). ** Median source distance significantly different from all other recruitment processes ($p > 0.05$, Kruskal-Wallis Multiple Comparisons Test).

Large Wood Redistribution

Fluvial redistribution of wood was infrequent in the channels we investigated (Table 4.3). In the mainstem alluvial channel 38% of all pieces were shorter than the average bank-full channel width, and 68% of pieces that were fluvially redistributed were shorter than the average bank-full channel width. In the colluvial tributaries 16% of pieces were shorter than the average bank-full channel width; however, only 1% of pieces were moved by fluvial transport. In contrast, a large proportion of debris flow transported wood (55% of pieces) were longer than the average bankfull width of the tributaries.

In the alluvial channel, wood that had been redistributed by fluvial processes or by debris flows had a patchy spatial distribution (Figure 4.8). A debris flow in Tributary 1 (Figure 4.1) initiated in a timber harvest unit in the 1960s. This debris flow deposit formed a large valley-spanning accumulation in the mainstem, and appeared to trap wood transported from upstream. In contrast, large wood derived from wind throw was more abundant and more evenly distributed spatially throughout the stream.

Large Wood Function

The primary function of wood in the small colluvial channels was sediment storage (40%) and small wood storage (20%); however, 37% of pieces had no interaction with streamflow or sediment (Table 4.4). A broader range of functions was observed in the alluvial channel, but the majority of pieces were associated with local scour of the streambed (26%) and stream-banks (26%). The size of pieces associated with each functional category was highly variable, and no consist pattern was observed.

Table 4.4. Geomorphic function of large wood in the North Fork Cherry Creek basin.

	Colluvial Tributaries		Alluvial Mainstem	
	Percent of Wood Pieces	Average Length of Pieces (m)[1]	Percent of Wood Pieces	Average Length of Pieces (m)[1]
Sediment Storage	40	9.8 (9.5)	14	8.8 (9.8)
Wood Storage	20	11.2 (10.1)	4	14.5 (12.0)
Streambed Scour	0	-	26	8.9 (8.7)
Bank Scour	3	14.8 (13.4)	26	10.8 (9.9)
Bank Armor	0	-	6	7.2 (7.6)
Side Channel	0	-	1	13.4 (5.1)
No Discernable Function	37	12.7 (9.9)	23	9.5 (9.0)

[1] numbers in parenthesis represent one standard deviation

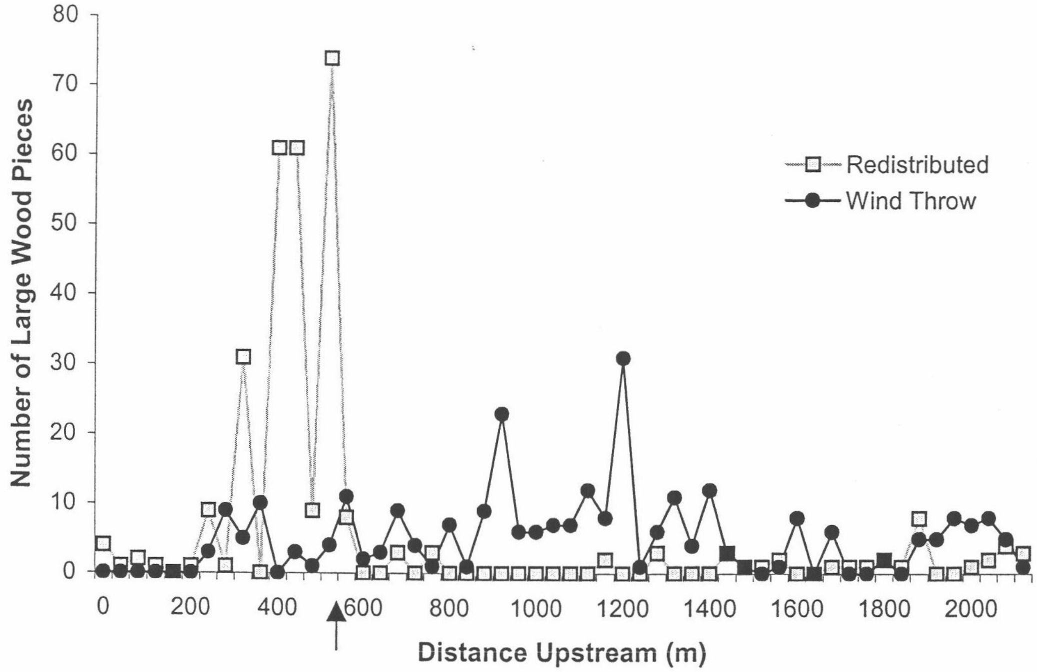


Figure 4.8. Spatial distribution of large wood along the third-order mainstem of the North Fork of Cherry Creek. Arrow indicates the confluence with Tributary 1.

Recruitment and redistribution processes influenced the position of the wood in the channel. In the alluvial channel, 73% of pieces that had been redistributed were located in mid-channel positions (Figure 4.9). Large wood derived from the local hillslopes and riparian area had a greater variety of positions, but over 56% of pieces were located adjacent to the channel bank.

Because the source of wood influenced piece location and size there was an interaction with wood source and functional category. Redistributed wood was typically smaller in size and was associated with local scour of the streambed (38%) and stream-banks (33%), and almost all (93%) pieces interacted with streamflow and sediment (Figure 4.10). Wood recruited directly from the local hillslopes and riparian areas, had a large proportion of pieces with no discernable interaction with streamflow and sediment (37%) apparently because pieces were located along the edge of the channel. A small number of pieces recruited directly from the local riparian area were important for storing other large wood pieces that had been redistributed fluvially (8%) and for side channel formation (3%), processes that were not associated with redistributed wood.

DISCUSSION

Large Wood Recruitment from the Local Hillslopes and Riparian Areas

Stream size and topographic setting strongly influenced processes that recruited and redistributed wood in the channel network (Table 4.3; Figure 4.4). Colluvial channels were high gradient, ephemeral tributaries that had small drainage areas and were tightly constrained by the surrounding hillslopes. The mainstem alluvial channel was in a moderate gradient, alluvial valley and had perennial streamflow. Processes of slope

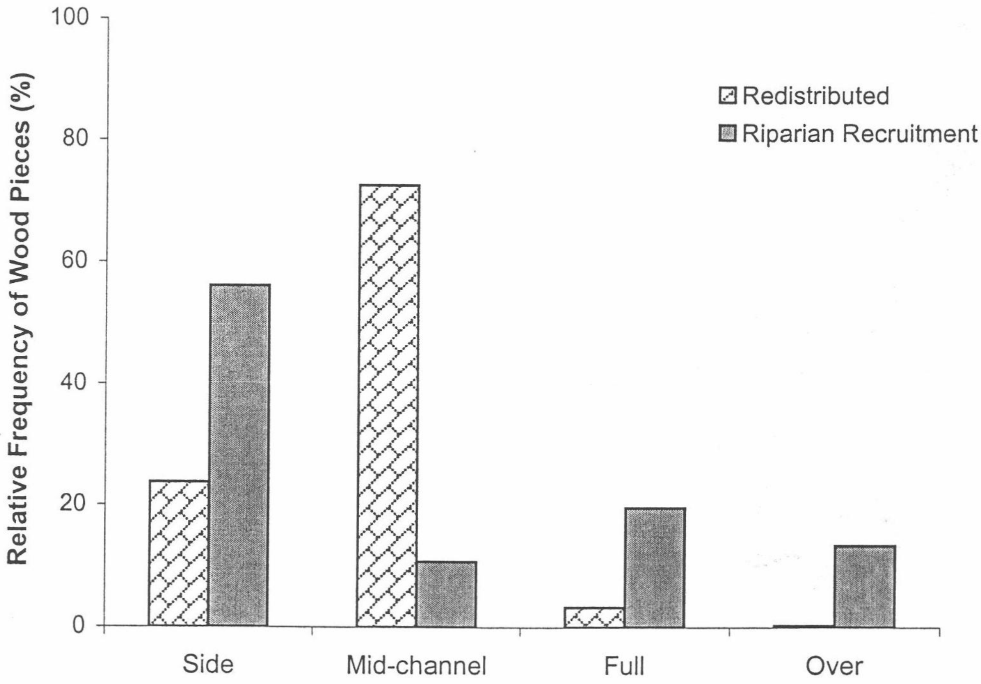


Figure 4.9. The position of large wood pieces that were recruited directly from the local riparian area and those redistributed by fluvial and debris flow transport in the third-order mainstem of the North Fork of Cherry Creek.

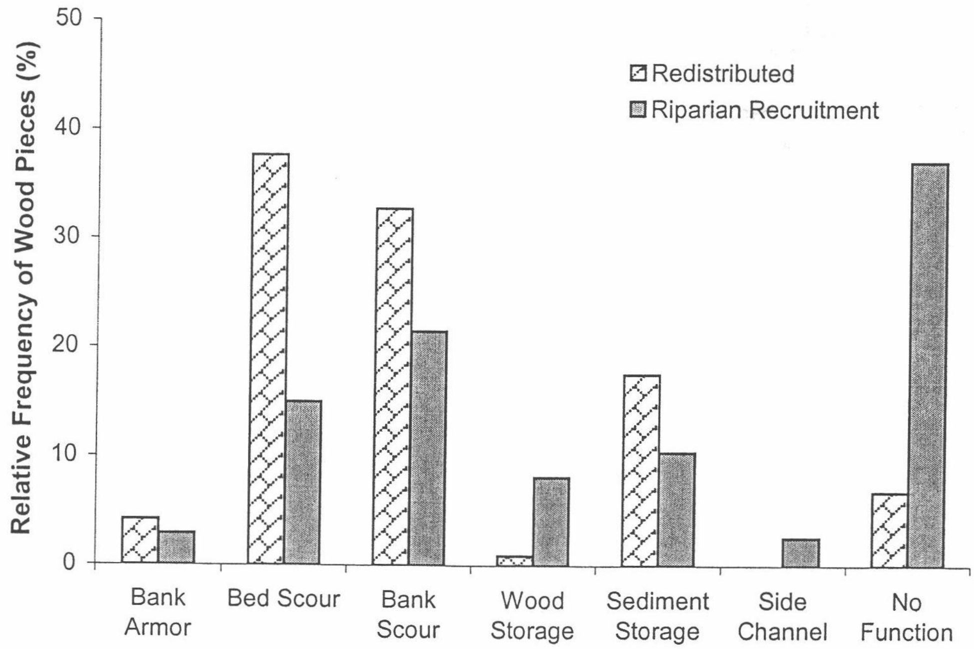


Figure 4.10. Geomorphic function of large wood that was recruited from the local riparian area in contrast to pieces that were redistributed by fluvial and debris flow transport in the third-order mainstem of the North Fork of Cherry Creek.

instability, which included landslides on planar hillslopes and in convergent hollows, streamside landslides, and small inner-gorges that had evidence of accelerated toe slope creep were important conveyors of wood from upland forests to small, colluvial channels. Wind throw was also an important process for delivering wood to the channel in both the tributaries and the mainstem. Input of wood from bank erosion was minimal in the study streams, presumably because lateral migration of the channel was limited by the small size of the streams and their contributing drainage area.

The recruitment of wood by wind throw included direct toppling of an individual tree and larger wind throw patches. Wind throw is a major form of disturbance in coastal forests, creating both small discrete and large diffuse disturbance patches (Greene et al. 1992). The occurrence of wind throw may depend on weather patterns, topographic position, and valley configuration. Regional gradients in the extent of wind damage to forest stands has been documented in the Pacific Northwest. Franklin et al. (1987) reported that wind-related mortality decreased from about 80% in coastal spruce-hemlock stands to < 15% in interior ponderosa pine stands. Because our study basin was located on the west-side of the Coast Range, approximately 34 km from the coastline, it is heavily influenced by Pacific frontal storms and may have a relatively high potential for wind throw. Tree species, size, age, height, and position in a stand also influence the susceptibility of trees to wind throw (Harmon et al. 1986).

Causal mechanisms of tree mortality in terrestrial forest stands influenced the relative contribution of various wood recruitment processes in the channel network. Although wind throw has been identified as one of the dominant causes of tree mortality in forests of the Coast Range and Cascade mountains of Oregon and Washington

(Franklin and DeBell 1988), insects and disease cause mortality in < 1% of trees in forest inventory areas in this region (Harmon et al. 1986). The relative contributions of these agents of mortality in the terrestrial forest stands translated into similar patterns in wood recruitment to the channels. Wind throw and natural mortality are dispersed throughout the stand, but landslides typically impact a relatively small, discrete patch of the forest and are an efficient conveyor of material downslope to the channel. Bank erosion is concentrated along the channel and can result in an abundance of wood being recruited to the channel; however, it may account for only a small portion of the mortality in the larger forest stand. Martin and Benda (2001) estimated that channel processes (i.e., bank erosion) exceeded the maximum mortality of the surrounding forest stands (including wind throw and natural mortality) in drainage areas larger than 20 km^2.

Forest community composition can vary with distance from the stream (Pabst and Spies 1999; Nierenberg and Hibbs 2000); therefore, the source distance of wood needs to be placed in context of how tree species and size change with increasing distance from the channel. Conifers were dominant along the colluvial channels we investigated. In contrast, the low elevation floodplain along the alluvial channel was easily accessible by high flow events, and young alders (< 40 years) dominated the near-stream environment. The majority of wood pieces with source distances < 10 m in the alluvial channel were young hardwoods. Beyond the floodplain and terrace surfaces, large conifers could be recruited, and this relationship may explain the higher volume of wood associated with increased source distances. Contrary to model predictions by Van Sickle and Gregory (1990), trees entering the channel from a short distance did not contributed longer or larger pieces than wood delivered from a greater distance. In our study basin the size of individual pieces was poorly correlated with source distance, and breakage of large trees was common.

Successional stage can affect the size, species, amount, decay class, and distribution of large wood (Harmon et al. 1986; Spies et al. 1988). If younger forests were investigated, suppression mortality might have played a stronger role in wood recruitment during the stem exclusion phase, or if early successional species with a short life span were present. Old-growth forests contain the highest levels of deadwood in the terrestrial environment, compared to young and intermediate age forests (Spies et al. 1988). If forests with shorter stature were examined, the source distance of wood might be less because taller trees can deliver wood from further away (Harmon et al. 1986; McDade et al. 1990; Van Sickle and Gregory 1990). Conversely, if larger, laterally migrating rivers were investigated, bank erosion and fluvial transport would be expected to play a stronger role in wood recruitment. Murphy and Koski (1989) observed that bank erosion and wind throw were the most frequent processes that recruited wood from the local riparian area in low-gradient alluvial rivers in Alaska.

Upslope processes may dominate wood recruitment at the upper extent of the drainage network, whereas processes in the near-stream environment become more important downstream. In a study of wood input to streams in the Cascade mountains, wood in small streams was recruited from areas not influenced by the channel, but in intermediate-sized streams wood was recruited from a variety of sites equally distributed between areas proximal and distal to the stream-banks. In larger streams the majority of wood was recruited from the channel banks (Lienkaemper and Swanson 1987). Martin and Benda (2001) also reported that wood recruitment from windthrow and chronic mortality was dominant in small drainage basins; however, wood recruitment from bank erosion increased systematically with increasing drainage area. Similar results were observed during our study, where landslides and windthrow dominated wood recruitment from upslope forests adjacent to small tributaries, but wood was recruited from a greater variety of sources in the intermediate-sized mainstem channel (Table 4.3; Figure 4.2).

Comparison with Previous Research on the Source Distance of Wood

McDade et al. (1990) is the only other study that empirically determined the source distance of wood to small streams in mountainous terrain. There were several differences between these studies; McDade et al. (1990) (1) defined stream order using USGS stream lines, resulting in a lower resolution of the channel network, (2) included smaller wood in the sample (minimum diameter greater than 10 cm at the small end and length greater than 1 m), (3) focused on large wood directly associated with identifiable rooting locations and may have excluded landslide derived wood, (4) assessed the number of pieces recruited but not the volume of wood, (5) investigated short stream reaches and not the entire network, and (6) only 2 of the 39 streams investigated were in the Oregon Coast Range.

The source distance of wood for the third-order alluvial channel in our study was similar ($p > 0.1$, Kolmogorov-Smirnov, one-sided, two-sample test) to the results of McDade et al. (1990). McDade et al. (1990) found no significant association between source distance and stream order; however, small colluvial channels were not consistently defined. In contrast, results of our study suggest that wood recruitment occurred over greater distances in small colluvial channels (second-order) than on larger alluvial channels (third-order).

McDade et al. (1990) could not determine the source for 48% of the pieces encountered. If landslide-derived wood were excluded from our study because it could not be directly associated with an exact rooting location, we would have excluded 52% of wood pieces in second-order colluvial streams and 10% in third-order alluvial streams. Additionally, the spatial distribution of wood recruited from landslides and debris flow is patchy, and therefore, studies that only investigate short channel reaches may underestimate these recruitment mechanisms because the probability of encountering a patch during sampling is low.

Large Wood Redistribution

The spatial distribution of wood in the channel was determined by patterns of wood recruitment in the local hillslopes and riparian area due to low transport capacity of the channel. Fluvial transport of wood typically becomes greater in larger streams and rivers because mobile pieces are usually shorter than the bank-full width (Lienkaemper and Swanson 1987). Small streams commonly lack the capacity to transport large wood by chronic fluvial processes; therefore, recruitment from the adjacent hillslopes and riparian areas has a greater influence on the spatial distribution of wood in the channel (Bilby and Ward 1989; Bilby and Bisson 1998). In higher-order streams, the distribution of large wood depends on both local recruitment and upstream sources (McGarry 1994). The channels we investigated were small (< 5 m wide) relative to the size of wood in the channels (Figure 4.2). Fluvial redistribution of wood was relatively minor in our study streams, and the spatial distribution was patchy. Although the number and volume of pieces was small, fluvially transported wood in the alluvial channel was commonly associated with scouring of the streambed and stream-banks. Because wood can force streamflow to converge, causing scour of the streambed and banks, it may be important for pool formation.

Debris flows in colluvial tributaries can be another important source of wood to larger, alluvial channels. Colluvial channels lack the capacity to transport wood by fluvial redistribution, and therefore, small streams often store large volumes of wood that can be episodically transported by debris flows. Many first- and second-order colluvial channels in the Oregon Coast Range are susceptible to episodic scouring by debris flows because they drain steep, landslide-prone hillslopes, and the channels are narrow and high gradient. Debris flows deliver sediment, boulders, and wood that can structure the morphology of the receiving channel and are often an important influence on the long-term potential for aquatic habitat development (Everest and Meehan 1981; Reeves et al. 1995; Benda and Dunne 1997; Hogan et al. 1998). Wood delivered by landslides and debris flows may increase in steep V-shaped valleys with high connectivity between hillslopes and channels and between headwater streams and larger rivers, and decrease in broad U-shaped glacial valleys (Martin and Benda 2000).

The median volume of pieces differed for the various recruitment and redistribution processes. Wood that was redistributed by fluvial processes had the smallest median volume per piece (Table 4.3). Pieces with an unknown source and those transported by a debris flow were intermediate in size, and pieces recruited directly from the local hillslopes and riparian area had the largest median volume. If fires occur more frequently on mid- and upper-elevation hillslopes than on the low-elevation valley floors in the Coast Range (Impara 1997), then riparian zones of the larger alluvial rivers may contain the largest trees in the basin. This pattern of fire occurrence suggests that wood recruited and redistributed by debris flows may be smaller because mid- and upper-elevation stands burned more frequently and therefore are typically younger. Debris flows also exert great force on the wood being transported, resulting in substantial breakage.

Large Wood Function

The effect of large wood on channel form and process varies from insignificant to nearly complete control of channel morphology (Keller and Swanson 1979). Results of our study indicated that large wood played an important role in storing sediment and small wood in colluvial channels. Similarly, large wood was responsible for the storage of 49% of the sediment in seven small Idaho watersheds (Megahan 1982) and 87% of the sediment in a small stream reach in New Hampshire (Bilby 1981). Large wood may be the cornerstone for storing sediment in steep headwater streams because it provides a physical obstruction to transport in high-energy environments. In the absence of wood, small headwater streams may become a chronic source of sediment to downstream areas. By increasing the sediment storage capacity of the channel, large wood buffers the sedimentation impacts on downstream reaches when pulses of sediment enter headwater streams (Swanson and Lienkamper 1978). In larger alluvial streams, large wood had a broader array of geomorphic functions and was particularly important in pool formation. In both channel types, a large proportion of wood pieces had no discernable interaction with streamflow and sediment at the time of this study; however, these pieces still functioned to increase roughness, create cover and substrate for aquatic organisms, and were a source of nutrients and organic matter.

Landslides and debris flows were capable of forming large accumulations of wood at points in the network where fluvial processes may not be competent to transport large quantities of wood. In channels that are narrow or that have a small drainage area, it may not be possible to transport large wood by flotation during high flows (Swanson and Lienkaemper 1978; Martin and Benda 2001). Therefore, landslide and debris flow deposits can provide a unique structure to the channel by forming extremely large accumulations of wood in small streams. When large accumulations of wood break apart during extreme flood events, they can become highly susceptible to congested transport (Braudrick et al. 1997). Congested transport of wood during floods can be associated with a higher intensity disturbance to the channel and riparian area than floods without batches of wood in transport (Johnson et al. 2000).

Management Implications

There is a critical need to restore ecological processes that produce and deliver large wood to streams from riparian and upslope areas in the Pacific Northwest (IMST 1999). Upland forests and headwater streams can influence water quantity, water quality, invertebrate and detritus inputs, sediment retention, and physical habitat characteristics throughout the drainage network. Because these small streams are so abundant and tightly coupled with the steep hillslopes, they can form an important link between hillslope and fluvial processes and between terrestrial and aquatic ecosystems. These small colluvial channels are characterized by a distinct suite of geomorphic processes, and patterns of wood recruitment and redistribution are different than in the larger alluvial streams.

Source distance of wood recruited directly from the local hillslopes and riparian area varied by position in the network because of differences in processes, degree of hillslope constriction, and slope steepness. Colluvial channels that drain steep hillslopes are more susceptible to mass wasting and recruited wood from further upslope than larger alluvial channels. As wood is scoured from these small streams, replenishment of similar size wood may not be possible in intensively harvested basins that lack streamside buffers. If timber harvest reduces future recruitment of wood in the interval between debris flows, subsequent failures could be lacking large wood. Forest management that relies primarily on recruitment of wood from riparian buffers along the larger, fish bearing streams may result in much lower levels of wood recruitment than the historic range of conditions (IMST 1999). A restoration approach focused on restoring and managing watershed processes rather than individual habitat characteristics (Beechie and Bolton 1999; Ebersol et al. 1997; Kauffman et al. 1997) may be more effective in producing complex stream channel structure because it provides for complex processes and linkages between processes.

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REFERENCES

Baldwin E.M. 1964. Geology of Oregon. University of Oregon Press, Eugene, Oregon.

Beechie, T., and Bolton, S. 1999. An approach to restoring salmonid habitat-forming processes in Pacific Northwest watersheds. Fisheries **24**(4): 6-14.

Benda, L.E., and Dunne, T. 1997. Stochastic forcing of sediment supply to channel networks from landsliding and debris flow. Water Resour. Res. **33**(12): 2849 – 2863.

Benda, L.E., and Sias, J.C. 1998. Landscape controls on wood abundance in streams. Earth Systems Institute, Seattle, Washington.

Bilby, R.E. 1981. Role of organic debris dams in regulating the export of dissolved and particulate matter from a forested watershed. Ecology **62**: 1234-1243.

Bilby, R.E., and Bisson, P.A. 1998. Function and distribution of large woody debris. *In* River Ecology and Management: Lessons from the Pacific Coastal Ecoregion, *Edited* by R.J. Niaman, and R.E. Bilby. pp. 324-346.

Bilby R.E., and Ward, J.W. 1989. Changes in characteristics and function of woody debris with increasing size of streams in western Washington. Trans. Am. Fish. Soc. **118**: 368-378.

Bisson, P.A., Bilby, R.E., Bryant, M.D., Dolloff, C.A., Grette, G.B, House, R.A., Murphy, M.L., Koski, K.V, and Sedell, J.R. 1987. Large woody debris in forested streams in the Pacific Northwest: past, present, and future. *In* Streamside Management: Forest and Fishery Interactions, *Edited* by E.O. Salo, and T.W. Cundy, University of Washington , Institute of Forest Resources, Seattle. pp. 143-190.

Braudrick, C.A., Grant, G.E., Ishikawa, Y., and Hiroshi, I. 1997. Dynamics of wood transport in streams: a flume experiment. Earth Surf. Processes Landforms **22**: 669-683.

Ebersole, J.L., Liss, W.J., and Frissell, C.A. 1997. Restoration of stream habitats in the western United States: restoration as reexpression of habitat capacity. Environ. Manage. **21**(1): 1-14.

Everest, F.H., and Meehan, W.R. 1981. Forest management and anadromous fish habitat productivity. *In* Transactions of the 46th North American Wildlife and Natural Resources Conference. Wildlife Management Institute, Washington D.C. pp. 521-530.

Franklin, J.F. 1972. Cherry Creek Research Natural Area. *In* Federal Research Natural Areas in Oregon and Washington: a guidebook for scientists and educators. USDA For. Serv. Pacific Northwest Forest and Range Experiment Station, Portland Oregon.

Franklin, J.F., Cromack, K. Jr., Denison, W., McKee, A., Maser, C., Sedell, J., Swanson, F., and Juday, G. 1981. Ecological characteristics of old-growth Douglas-fir forests. USDA For. Serv. Gen. Tech. Rep., PNW-118, 48pp.

Franklin, J.F., and DeBell, D.S. 1988. Thirty-six years of tree population change in an old-growth Pseudotsuga-Tsuga forest. Can. J. For. Res. **18**: 633-639.

Franklin, J.F., Shugart, H.H., and Harmon, M.E. 1987. Tree death as an ecological process. BioScience **37**(8): 550-556.

Harmon, M.E., Franklin JF, Swanson FJ, Sollins P, Gregory SV, Lattin JD, Anderson NH, Cline SP, Aumen NG, Sedell JR, Lienkaemper GW, Cromack K, Cummins KW. 1986. Ecology of course woody debris in temperate ecosystems. Adv. Ecol. Res. **15**: 133-302.

Hogan, D.L., Bird, S.A., and Hassan, M. 1998. Spatial and temporal evolution of small coastal gravel-bed streams: influence of forest management on channel morphology and fish habitats. *In* Gravel-Bed Rivers in the Environment, *Edited* by P.C. Klingeman, R.L. Beschta, P.D. Komar, and J.B. Bradley, Water Resources Publications, Highlands Ranch, Colorado. pp. 365-392.

Impara, PC. 1997. Spatial and Temporal Patterns of Fire in the Forests of the Central Oregon Coast Range. Ph.D. Dissertation, Oregon State University, Corvallis, OR.

Independent Multidisciplinary Science Team (IMST). 1999. Recovery of wild salmonids in western Oregon forests: Oregon Forest Practices Act Rules and the Measures in the Oregon Plan for salmon and watersheds. Tech. Rep. 1999-1.

Johnson, S.L., Swanson, F.J., Grant, G.E., and Wondzell, S.M. 2000. Riparian forest disturbances by a mountain flood: the influence of floated wood. Hydrological Processes **14**: 3031-3050.

Kauffman, J.B., Beschta, R.L., Otting, N., and Lytjen, D. 1997. An ecological perspective of riparian and stream restoration in the western United States. Fisheries **22**(5): 12-24.

Keller, E.A., and Swanson, F.J. 1979. Effects of large organic material on channel form and fluvial processes. Earth Surf. Processes Landforms **4**: 361-380.

Lienkaemper, G.W., and Swanson, F.J. 1987. Dynamics of large woody debris in streams in old-growth Douglas-fir forests. Can. J. For. Res. **17**:150-156.

Martin, D.J., and L.E. Benda. 2001. Patterns of instream wood recruitment and transport at the watershed scale. Trans. Am. Fish. Soc.**130**:940-958.

May, C.L. 1998. Debris flow characteristics associated with forest practices in the Central Oregon Coast Range. M.S. thesis, Oregon State University, Corvallis, OR.

May, C.L. (*in review*) Accumulation rates of wood and sediment in headwater streams of the central Oregon Coast Range. Journal of Geomorphology.

McDade, M.H., Swanson, F.J., McKee, W.A., Franklin, J.F., and Van Sickle, J. 1990. Source distances for coarse woody debris entering small streams in western Oregon and Washington. Can. J. For. Res. **20**: 326 – 330.

McGarry, E.V. 1994. A quantitative analysis and description of the delivery and distribution of large woody debris in Cummins Creek, Oregon. Research Report, Geosciences Department, Oregon State University, Eugene, Oregon.

Megahan, W.R. 1982. Channel sediment storage behind obstructions in forested drainage basins draining the granitic bedrock of the Idaho batholith. *In* Sediment Budgets and Routing in Forested Drainage Basins, *Edited* by F.J. Swanson, R. Janda, T. Dunne, and D.N. Swanston. USDA Forest Service General Technical Report, PNW-141; 114-121.

Megahan, W.F., and Nowlin, R.A. 1976. Sediment storage in channels draining small forested watersheds in the mountains of central Idaho. *In* Proceedings of the Third Federal Interagency Sedimentation Conference, Water Resources Council: Denver, Colorado. 4: 115-126.

Montgomery, D.R. 1999. Process domains and the river continuum. J. Am. Water Resour. Assoc. **35**(2): 397-410.

Murphy, M.L., and Koski, K.V. 1989. Input and depletion of woody debris in Alaska streams and implications for streamside management. North American Journal of Fisheries Management **9**: 427-436.

Nierenberg, T.R., and Hibbs, D.E. 2000. A characterization of unmanaged riparian areas in the central Oregon Coast Range of western Oregon. Forest Ecology and Management **129**: 195-206.

Pabst, R.J., and Spies, T.A. 1999. Structure and composition of unmanaged riparian forests in the coastal mountains of Oregon, U.S.A. Can. J. For. Res. **29**: 1557-1573.

Ralph, S.C., Poole, G.C., Conquest, L.L., and Naiman, R.J. 1994. Stream channel morphology and woody debris in logged and unlogged basins of western Washington. Can. J. Fish. Aquat. Sci. **51**: 37-51.

Reeves, G.H., Benda, L.E., Burnett, K.M., Bisson, P.A., and Sedell, J.R. 1995. A disturbance-based ecosystem approach to maintaining and restoring freshwater habitats of evolutionalry significant units of anadromous salmonids in the Pacific Northwest. *In* American Fisheries Society Symposium **17**:334-349.

Shreve, R.L. 1969. Stream lengths and basin areas in topologically random channel networks. J. Geol. **77**: 397-414.

Soil Conservation Service. 1989. Soil Survey of Coos County, Oregon. United States Department of Agriculture.

Spies, T.A., Franklin, J.F., and Thomas, T.B. 1988. Coarse woody debris in Douglas-fir forests of western Oregon and Washington. Ecology **69**(6):1689-1702.

Strahler, A.N. 1964. Quantitative geomorphology of drainage basins and channel networks. *In* Handbook of Applied Hydrology, *Edited* by V.T. Chow. McGraw Hill, New York. pp. 40-74.

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

Swanson, F.J., Fredricksen, R.L., and McCorison, F.M. 1982. Material transfer in a western Oregon forested watershed. *In* Analysis of Coniferous Forest Ecosystems in the Western United States, *Edited* by R.L. Edmonds, Hutchinson Ross, New York. pp. 233-266.

Van Sickle, J., and Gregory, S.V. 1990. Modeling inputs of large woody debris to streams from falling trees. Can. J. For. Res. **20**: 1593-1601.

4. Summary

The findings of this research contribute to the understanding of channel networks and disturbance processes in mountainous terrain. Information on the spatial and temporal patterns of disturbance, and the interactions among disturbance processes, provides insights that may be useful for formulating management strategies that are based on natural disturbance regimes. This research is also of interest for long-term ecosystem management and aquatic habitat conservation. One of the most pervasive impacts of climate change on ecosystem structure and function may be the alteration of the timing, intensity, and resilience to disturbance. The interaction of fire and large storms on landslide and debris flow occurrence may be greatly affected if the frequency or magnitude of fires or floods undergoes dramatic change, or if extent and duration of snow accumulation is altered.

Results of the intensive study of stream channel structure in the erosional zone of past debris flows suggests that wood is the cornerstone for sediment accumulation in high energy, low-roughness channels. With an adequate supply of wood, small colluvial channels were found to be an important sediment storage component of the channel network. If the removal of forest cover leads to an increase in landslide and debris flow occurrence, the flux rate of sediment and wood could increase in conjunction with the abundance of bedrock channels. Furthermore, if wood is not available to the channel following a debris flow, channels that have been scoured to bedrock may persist in this state for an extended period of time. This suggests that basins intensively managed for timber harvest without adequate leave areas may be experiencing a shift in channel form and function, if bedrock channels are becoming more frequent and persistent.

In the extensive investigation of debris flow occurrence and deposition, network structure of the tributary basin was found to be an important determinant of the flux rate of sediment and wood. Small tributary basins with less convergent topography had a longer interval between debris flow occurrences in the trunk channel, resulting in a reduced flux rate of sediment to the confluence with the larger river when compared to larger tributary basins with more convergent topography. Drainage area, valley floor width, and the timing of debris flows influenced the size and persistence of debris flow fans. Because the structure and function of erosional and depositional landforms changes through time, the timing of debris flow occurrence throughout a watershed can have a major influence on channel morphology, habitat availability, and the resilience of biotic communities.

BIBLIOGRAPHY

Agee JK. 1993. *Fire Ecology of Pacific Northwest Forests*. Island Press, Washington D.C.

Baldwin EM. 1964. *Geology of Oregon*. University of Oregon Press, Eugene, Oregon.

Beaty CB. 1963. Origin of alluvial fans, White Mountains, California and Nevada. *Annals, Association of American Geographers* **53**:516-535.

Beaty CB. 1970. Age and estimated rate of accumulation of an alluvial fan, White Mountains, California, U.S.A. *American Journal of Science* **268**:50-70.

Beechie T, Bolton, S. 1999. An approach to restoring salmonid habitat-forming processes in Pacific Northwest watersheds. *Fisheries* **24**(4): 6-14.

Benda LE. 1988. *Debris Flows in the Tyee Sandstone Formation of the Oregon Coast Range*. M.S. Thesis, University of Washington, Seattle, Washington.

Benda LE, Cundy TW. 1990. Predicting deposition of debris flows in mountain channels. *Canadian Geotechnical Journal* **27**:409-417.

Benda LE, Dunne T. 1987. Sediment routing by debris flows. In *Erosion and Sedimentation in the Pacific rim*, Beschta RL, Blinn T, Ice GE, Swanson FJ (eds). IAHS **165**: 213-223.

Benda LE, Dunne T. 1997a. Stochastic forcing of sediment supply to channel networks from landsliding and debris flows. *Water Resources Research* **33**(12):2849-2863.

Benda LE, Dunne T. 1997b. Stochastic forcing of sediment routing and storage in channel networks. *Water Resources Research* **33**(12):2865-2880.

Benda, LE, and Sias JC. 1998. *Landscape Controls on Wood Abundance in Streams*. Earth Systems Institute, Seattle, Washington.

Beschta RL, Platts WS. 1986. Morphological features of small streams: significance and function. *American Water Resources Bulletin* **22**(3):369-379.

Bilby RE. 1981. Role of organic debris dams in regulating the export of dissolved and particulate matter from a forested watershed. *Ecology* **62**:1234-1243.

Bilby RE, Bisson PA. 1998. Function and Distribution of Large Woody Debris. In *River Ecology and Management: Lessons from the Pacific Coastal Ecoregion*, Niaman RJ, Bilby RE (eds). Springer-Verlag, New York; 324-346.

Bilby RE, Ward JW. 1989. Changes in characteristics and function of woody debris with increasing size of streams in western Washington. *Transactions of the American Fisheries Society* **118**:368-378.

Bisson PA, Bilby RE, Bryant MD, Dolloff CA, Grette GB, House RA, Murphy ML, Koski KV, Sedell JR. 1987. Large woody debris in forested streams in the Pacific Northwest: past, present, and future. In *Streamside Management: Forest and Fishery Interactions*, Salo EO, Cundy TW (eds). University of Washington , Institute of Forest Resources, Seattle; 143-190.

Braudrick CA, Grant GE, Ishikawa Y, Ikeda H. 1997. Dynamics of wood transport in streams: a flume experiment. *Earth Surface Processes and Landforms* **22**:669-683.

Bull WB. 1963. Alluvial-fan deposits in western Fresno County, California. *Journal of Geology* **71**:243-251.

Bull WB. 1964. Geomorphology of segmented alluvial fans in western Fresno County, California. *U.S. Geological Survey Professional Paper*, **352**:89-129.

Church M, Mark DM. 1980. On size and scale in geomorphology. *Progress in Physical Geography* **4**(3):342-390.

Denny CS. 1965. Alluvial fans in the Death Valley region, California and Nevada. *U.S. Geological Survey Professional Paper*, **446**.

Denny CS. 1967. Fans and pediments. *American Journal of Science* **265**:81-105.

Dietrich WE, Dunne T. 1978. Sediment budget for a small catchment in mountainous terrain. *Zeitschrift fur Geomorphologie N.F.* **29**:191-206.

Dietrich WE, Montgomery DR. 1998. Hillslopes, channels and landscape scale. In *Scale Dependence and Scale Invariance in Hydrology*, G Sposito (ed). Cambridge University Press, New York; 30-60.

Ebersole JL, Liss WJ, Frissell CA. 1997. Restoration of stream habitats in the western United States: restoration as reexpression of habitat capacity. *Environmental Management* **21**(1): 1-14.

Everest FH, Meehan WR. 1981. Forest management and anadromous fish habitat productivity. In *Transactions of the 46th North American Wildlife and Natural Resources Conference*. Wildlife Management Institute, Washington D.C.; 521-530.

Franklin JF. 1972. Cherry Creek Research Natural Area. In *Federal Research Natural Areas in Oregon and Washington: a Guidebook for Scientists and Educators*. USDA Forest Service Pacific Northwest Forest and Range Experiment Station, Portland Oregon.

Franklin, J.F., Cromack, K. Jr., Denison, W., McKee, A., Maser, C., Sedell, J., Swanson, F., and Juday, G. 1981. *Ecological Characteristics of Old-Growth Douglas-fir Forests*. USDA Forest Service General Technical Report, PNW-118.

Franklin JF, and DeBell DS. 1988. Thirty-six years of tree population change in an old-growth Pseudotsuga-Tsuga forest. *Canadian Journal of Forest Research* **18**: 633-639.

Franklin JF, Dyrness, CT. 1973. Natural vegetation of Oregon and Washington. *USDA Forest Service General Technical Report*, PNW-8.

Franklin JF, Shugart HH, Harmon ME. 1987. Tree death as an ecological process. *BioScience* **37**(8): 550-556.

Frissell, C.A., Liss W.J., Warren C.E., and M.D. Hurley. 1986. A hierarchical framework for stream habitat classification. *Environmental Management* **10**: 199-214.

Graham JD. 1985. *Mass Movement Dynamics, Geomorphology and Their Relationship to Geology in the North Fork Siuslaw River Drainage Basin, Oregon Coast Range*, M.S. Thesis, Oregon State University, Corvallis, Oregon.

Grant GE, Wolff AL. 1991. Long-term patterns of sediment transport after timber harvest, western Cascade Mountains, Oregon, USA. In *Proceedings of the Vienna Symposium,* IAHS **203**:31-40.

Gregory SV, Swanson FJ, McKee WA, Cummins KW. 1991. An ecosystem perspective of riparian zones. *BioScience* **41**:540-551.

Hack JT. 1960. Interpretation of erosional topography in humid temperate climates. *American Journal of Science* **258**-A: 80-97.

Harmon ME, Franklin JF, Swanson FJ, Sollins P, Gregory SV, Lattin JD, Anderson NH, Cline SP, Aumen NG, Sedell JR, Lienkaemper GW, Cromack K, Cummins KW. 1986. Ecology of course woody debris in temperate ecosystems. *Advances in Ecological Research* **15**: 133-302.

Heimsath AM, Dietrich WE, Nishiizumi K, Finkel RC. 2001. Stochastic processes of soil production and transport: erosion rates, topographic variation and cosmogenic nuclides in the Oregon Coast Range. *Earth Surface Processes and Landforms* **26**:531-552.

Hogan DL, Bird SA, Hassan M. 1998. Spatial and temporal evolution of small coastal gravel-bed streams: influence of forest management on channel morphology and fish habitats. In *Gravel-Bed Rivers in the Environment*, Klingeman PC, Beschta RL, Komar PD, Bradley JB (eds). Water Resources Publications, Highlands Ranch, Colorado; 365-392.

Hooke RL. 1968. Steady-state relationships on arid-region alluvial fans in closed basins. *American Journal of Science* **266**:609-629.

Horton RE. 1945. Erosional development of streams and their drainage basins: hydrophysical approach to quantitative morphology. *Geological Society of American Bulletin* **56**:275-370.

Hunt CB, Maybe DR. 1966. Stratigraphy and structure, Death Valley, California. *U.S. Geological Survey Professional Paper* **494**-A: 1-162.

Hyatt TL, Naiman RJ. 2001. The residence time of large woody debris in the Queets River, Washington, USA. *Ecological Applications* **11**(1):191-202.

Impara, PC. 1997. *Spatial and Temporal Patterns of Fire in the Forests of the Central Oregon Coast Range*, Ph.D. Dissertation, Oregon State University, Corvallis, Oregon.

Independent Multidisciplinary Science Team (IMST). 1999. Recovery of wild salmonids in western Oregon forests: Oregon Forest Practices Act Rules and the Measures in the Oregon Plan for salmon and watersheds. Tech. Rep. 1999-1.

Johnson EA, Van Wagner CE. 1984. The theory and use of two fire history models. *Canadian Journal of Forest Research* **15**: 214-220.

Johnson SL, Swanon FJ, Grant GE, Wondzell WM. 2000. Riparian forest disturbances by a mountain flood: the influence of floated wood. *Hydrological Processes* **14**:3031-3050.

Kauffman JB, Beschta RL, Otting N, Lytjen D. 1997. An ecological perspective of riparian and stream restoration in the western United States. *Fisheries* **22**(5): 12-24.

Keller EA, Swanson FJ. 1979. Effects of large organic material on channel form and fluvial processes. *Earth Surface Processes* **4**:361-380.

Kirchner JW, Finkel RC, Riebe CS, Granger DR, Clayton JL, King JG, Megahan WF. 2001. Mountain erosion over 10 yr, 10 k.y., and 10 m.y. time scales. *Geology* **29**(7): 591-594.

Kochel RC, Johnson RA. 1984. Geomorphology, sedimentology, and depositional processes of humid-temperate alluvial fans in central Virginia, U.S.A. *Canadian Society of Petroleum Geologists Memoir* **10**:109-122.

Kostaschuk RA, MacDonald GM, Putnam PE. 1986. Depositional process and alluvial fan-drainage basin morphometric relationships near Banff, Alberta, Canada. *Earth Surface Processes and Landforms* **11**:471-484.

Lancaster ST, Hayes SK, Grant GE. 2001. Modeling sediment and wood storage and dynamics in small mountainous watersheds. In *Geomorphic Processes and Riverine Habitat*, Dorava JM, Montgomery DR, Palcsak BB, Fitzpatrick FA (eds). American Geophysical Union, Washington, 85-102.

Lecce SA. 1990. The alluvial fan problem. In *Alluvial Fans: A Field Approach*, Rachocki AH, Church M (eds). John Wiley and Sons, New York, 3-24.

Lienkaemper GW, Swanson FJ. 1987. Dynamics of large woody debris in streams in old-growth Douglas-fir forests. *Canadian Journal of Forest Research* **17**:150-156.

Long CJ, Whitlock C, Bartlein PJ, Millspaugh SH. 1998. A 9000-year fire history from the Oregon Coast Range, based on a high-resolution charcoal study. *Earth Surface Processes and Landforms* **28**: 774-787.

Martin DJ, Benda LE. 2001. Patterns of instream wood recruitment and transport at the watershed scale. *Transactions of the American Fisheries Society* **130**:940-958.

May CL. 1998. *Debris Flow Characteristics Associated with Forest Practices in the Central Oregon Coast Range*, M.S. Thesis, Oregon State University, Corvallis, Oregon.

May CL. (*in review*) Accumulation rates of wood and sediment in headwater streams of the central Oregon Coast Range. *Journal of Geomorphology*

McDade MH, Swanson FJ, McKee WA, Franklin JF, Van Sickle J. 1990. Source distances for coarse woody debris entering small streams in western Oregon and Washington. *Canadian Journal of Forest Research* **20**: 326 – 330.

McGarry EV. 1994. *A Quantitative Analysis and Description of the Delivery and Distribution of Large Woody Debris in Cummins Creek, Oregon*. Research Report, Geosciences Department, Oregon State University, Eugene, Oregon.

Megahan WR. 1982. Channel sediment storage behind obstructions in forested drainage basins draining the granitic bedrock of the Idaho batholith. In *Sediment Budgets and Routing in Forested Drainage Basins*, FJ Swanson, R. Janda, T Dunne, DN Swanston (eds). USDA Forest Service General Technical Report, PNW-141; 114-121.

Megahan WF, Nowlin RA. 1976. Sediment storage in channels draining small forested watersheds in the mountains of central Idaho. In *Proceedings of the Third Federal Interagency Sedimentation Conference*, Water Resources Council: Denver, Colorado; **4**:115-126.

Melton MA. 1965. The geomorphic and paleoclimatic significance of alluvial deposits in southern Arizona. *Journal of Geology* **73**: 1-38.

Meyer GA, Wells SG, Balling RC, Jull AJT. 1992. Response of alluvial systems to fires and climate change in Yellowstone National Park. *Nature* **367**:147-149.

Montgomery DR. 1999. Process domains and the river continuum. *Journal of the American Water Resources Association* **35**(2): 397-410.

Montgomery DR, Abbe TB, Buffington JM, Peterson NP, Schmidt KM, Stock JD. 1996. Distribution of bedrock and alluvial channels in forested mountain drainage basins. *Nature* **381**:587-589.

Montgomery DR, Dietrich WE. 1992. Channel initiation and the problem of landscape scale. *Science* **255**:826-830.

Montgomery DR, Schmidt KM, Greenberg HM, Dietrich WE. 2000. Forest clearing and regional landsliding. *Geology* **28**(4): 311-314.

Morris WG. 1934. Forest fires in western Oregon and western Washington. *The Oregon Historical Quarterly* Vol. XXXV: 313-339.

Mosley MP. 1976. An experimental study of channel confluences. *Journal of Geology* **84**:535-562.

Murphy ML, Koski KV. 1989. Input and depletion of woody debris in Alaska streams and implications for streamside management. *North American Journal of Fisheries Management* **9**: 427-436.

Naiman RJ, Beechie TJ, Benda LE, Berg DR, Bisson PA, MacDonald LH, Steel EA. 1992. Fundamental elements of ecologically healthy watershed in the Pacific Northwest coastal ecoregion. In *Watershed Management: Balancing Sustainability and Environmental Change*, RJ Niaman (ed). Springer-Verlag, New York; 127 – 188.

Naiman RJ, Decamps H. 1990. Aquatic-terrestrial ecotones: summary and recommendations. In *Ecology and Management of Aquatic-Terrestrial Ecotones*, Naiman RJ, Decamps H (eds). UNESCO, Paris, and Parthenon Publishing Group, Carnforth, UK, 295-301.

Nierenberg TR, Hibbs DE. 2000. A characterization of unmanaged riparian areas in the central Coast Range of western Oregon. *Forest Ecology and Management* **129**: 195-206.

Pabst RJ, Spies TA. 1999. Structure and composition of unmanaged riparian forests in the coastal mountains of Oregon, U.S.A. *Canadian Journal of Forest Research* **29**: 1557-1573.

Ralph SC, Poole GC, Conquest LL, Naiman RJ. 1994. Stream channel morphology and woody debris in logged and unlogged basins of western Washington. *Canadian Journal of Fisheries and Aquatic Sciences* **51**: 37-51.

Reeves GH, Benda LE, Burnett KM, Bisson PA, Sedell J.R. 1995. A disturbance-based ecosystem approach to maintaining and restoring freshwater habitats of evolutionary significant units of anadromous salmonids in the Pacific Northwest. In *American Fisheries Society Symposium*: Bethesda, Maryland; **17**:334-349.

Reneau SL, Dietrich WE. 1991. Erosion rates in the southern Oregon Coast Range: evidence for an equilibrium between hillslope erosion and sediment yield. *Earth Surface Processes and Landforms* **15**: 307-322.

Roering JJ, Kirchner JW, Dietrich WE. 1999. Evidence for nonlinear, diffusive sediment transport on hillslopes and implications for landscape morphology. *Water Resources Research* **35**(3): 853-870.

Ryu, I. 1995. *Stratigraphy, Sedimentology, and Hydrocarbon Potential of Eocene Forearc and Subduction Zone Strata in the Southern Tyee Basin, Oregon Coast Range*, Ph.D. Dissertation, Oregon State University, Corvallis, Oregon.

Schmidt KM, Roering JJ, Stock JD, Dietrich WE, Montgomery DR. 2001. The variability of root cohesion as an influence on shallow landslide susceptibility in the Oregon Coast Range. *Canadian Geotechnical Journal* (in press).

Schumm SA. 1956. Evolution of drainage systems and slopes in badlands at Perth Amboy, New Jersey. *Bulletin of the Geological Society of America* **67**:597-646.

Schumm SA. 1977. *The Fluvial System*. John Wiley and Sons, New York.

Shreve RL. 1969. Stream lengths and basin areas in topologically random channel networks. *Journal of Geology* **77**:397-414.

Soil Conservation Service. 1989. *Soil Survey of Coos County, Oregon*. United States Department of Agriculture.

Spies, T.A., Franklin, J.F., and Thomas, T.B. 1988. Coarse woody debris in Douglas-fir forests of western Oregon and Washington. *Ecology* **69**(6):1689-1702.

Strahler AN. 1964. Quantitative geomorphology of drainage basins and channel networks. In *Handbook of Applied Hydrology*, Chow VT (ed). McGraw Hill, New York; 40-74.

Swanson FJ. 1981. Fire and ecosystem processes. USDA Forest Service, General Technical Report WO-26.

Swanson FJ, Fredricksen RL, McCorison FM. 1982a. Material transfer in a western Oregon forested watershed. In *Analysis of Coniferous Forest Ecosystems in the Western United States*, Edmonds RL (ed). Hutchinson Ross, New York; 233-266.

Swanson FJ, Gregory SV, Sedell, JR, Campbell, AG. 1982b. Land-water interactions: the riparian zone. In *Analysis of Coniferous Forest Ecosystems in the Western United States*, Edmonds RL (ed). Hutchinson Ross, New York; 267-291.

Swanson FJ, James ME. 1975. Geomorphic history of the lower Blue River-Lookout Creek area, western Cascades, Oregon. *Northwest Science* **49**(1):1-11.

Swanson FJ, Johnson SL, Gregory SV, and Acker SA. 1998. Flood disturbance in a forested mountain landscape. *Bio Science* **9**: 681-689.

Swanson FJ, Lienkaemper GW. 1978. Physical consequences of large organic debris in Pacific Northwest streams. *USDA Forest Service, General Technical Report* PNW-69.

Swanson FJ, Swanson MM. 1977. Inventory of mass erosion in the Mapleton Ranger District Siuslaw National Forest. *USDA Forest Service, Final Report.*

Swanston DN, Marion DA. 1991. Landslide response to timber harvest in Southeast Alaska. In *Proceedings of the Fifth Federal Interagency Sedimentation Conference*, Shou-Shan Fan, Yung-Huang Kuo (eds). Federal Energy Regulatory Commission, Washington D.C.

Taylor G. 1997. Causes of the flood and a comparison to other climate events. In *The Pacific Northwest Floods of February 6-11, 1996: Proceedings of the Pacific Northwest Water Issues Conference*, Laenen A, Ruff JD (eds). American Institute of Hydrology, St. Paul, Minnesota; 3-7.

Van Sickle J, Gregory SV. 1990. Modeling inputs of large woody debris to streams from falling trees. *Canadian Journal of Forest Research* **20**:1593-1601.

Van Wagner CE. 1978. Age-class distribution and the forest fire cycle. *Canadian Journal of Forest Research* **8**:220-227.

Welch DM. 1970. Substitution of space for time in a study of slope development. *Journal of Geology* **78**:234-238.

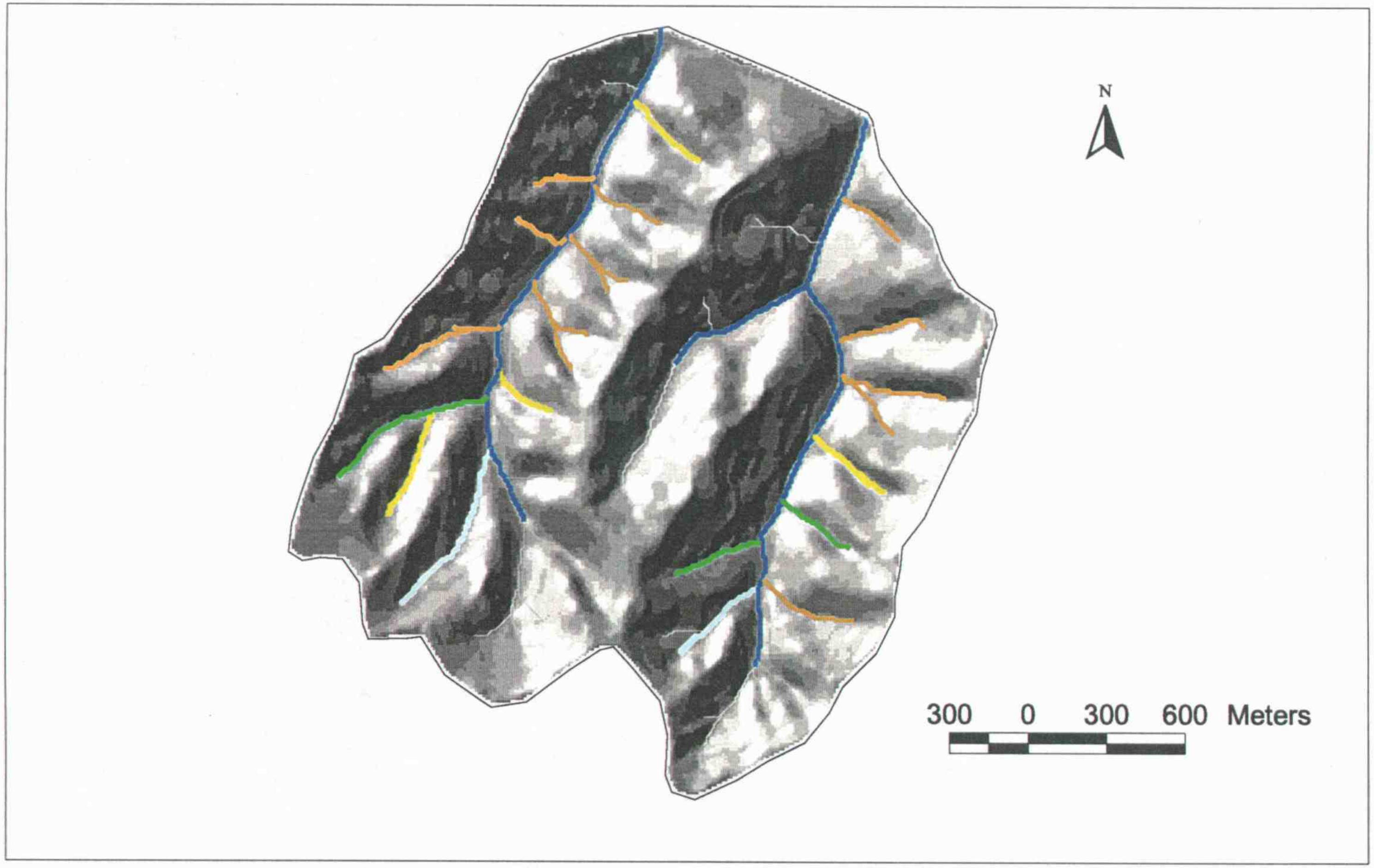
Whipple KX. 1992. Predicting debris-flow runout and deposition on fans: the importance of the flow hydrograph. In *Erosion, Debris Flows and Environment in Mountain Regions: Proceedings of the Chengdu Symposium*, Walling D, Davies T, Hasholt B (eds). International Association of Hydrological Sciences **209**: 337-345.

Ziemer RR. 1981. Roots and the stability of forested slopes. In *Erosion and Sedimentation of the Pacific Rim Steeplands*, Davies TRH, Pearce AJ (eds). International Association of Hydrological Sciences. Institute of Hydrology, Wallingford, Oxfordshire; **132**: 343-361.

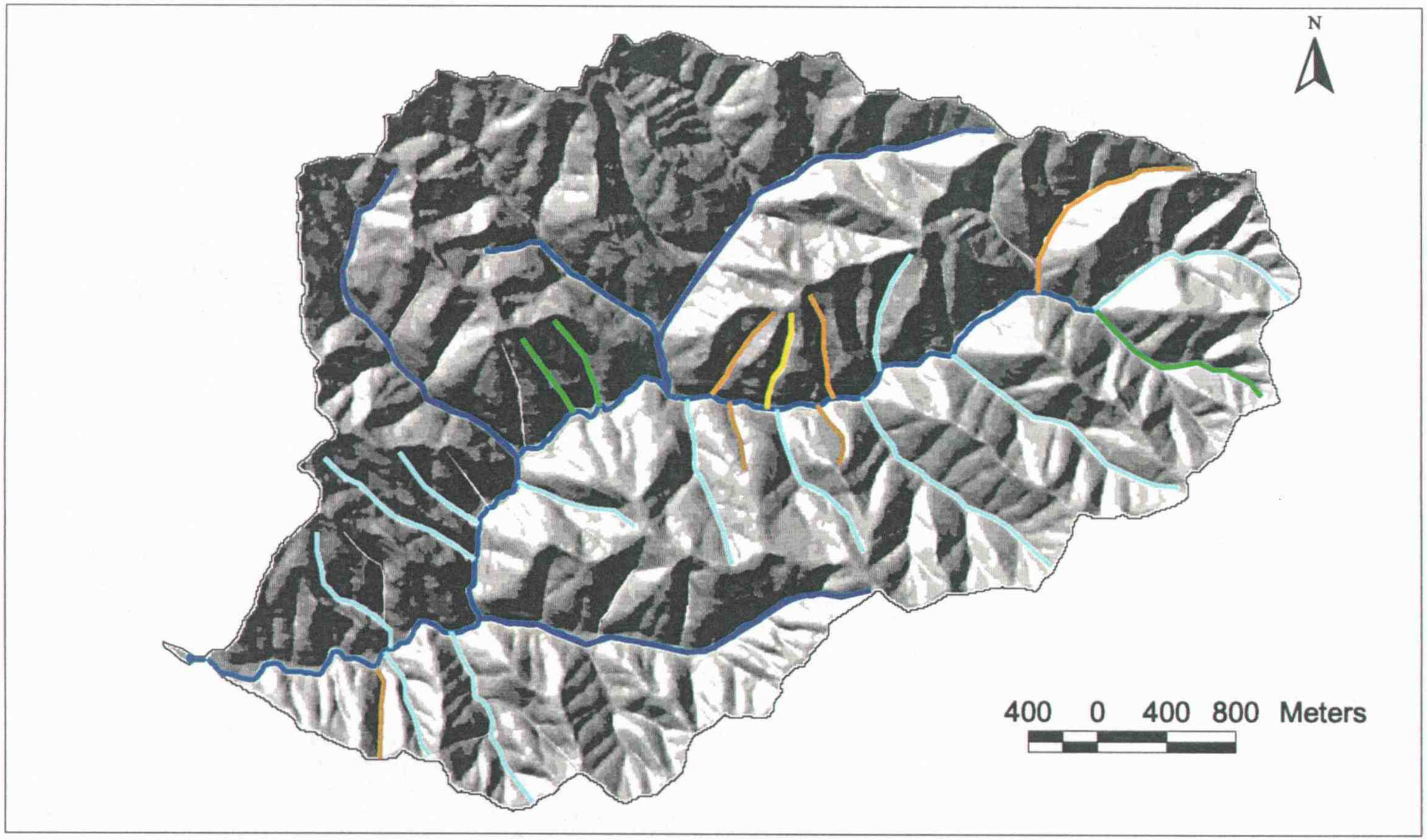
APPENDICES

Appendix A

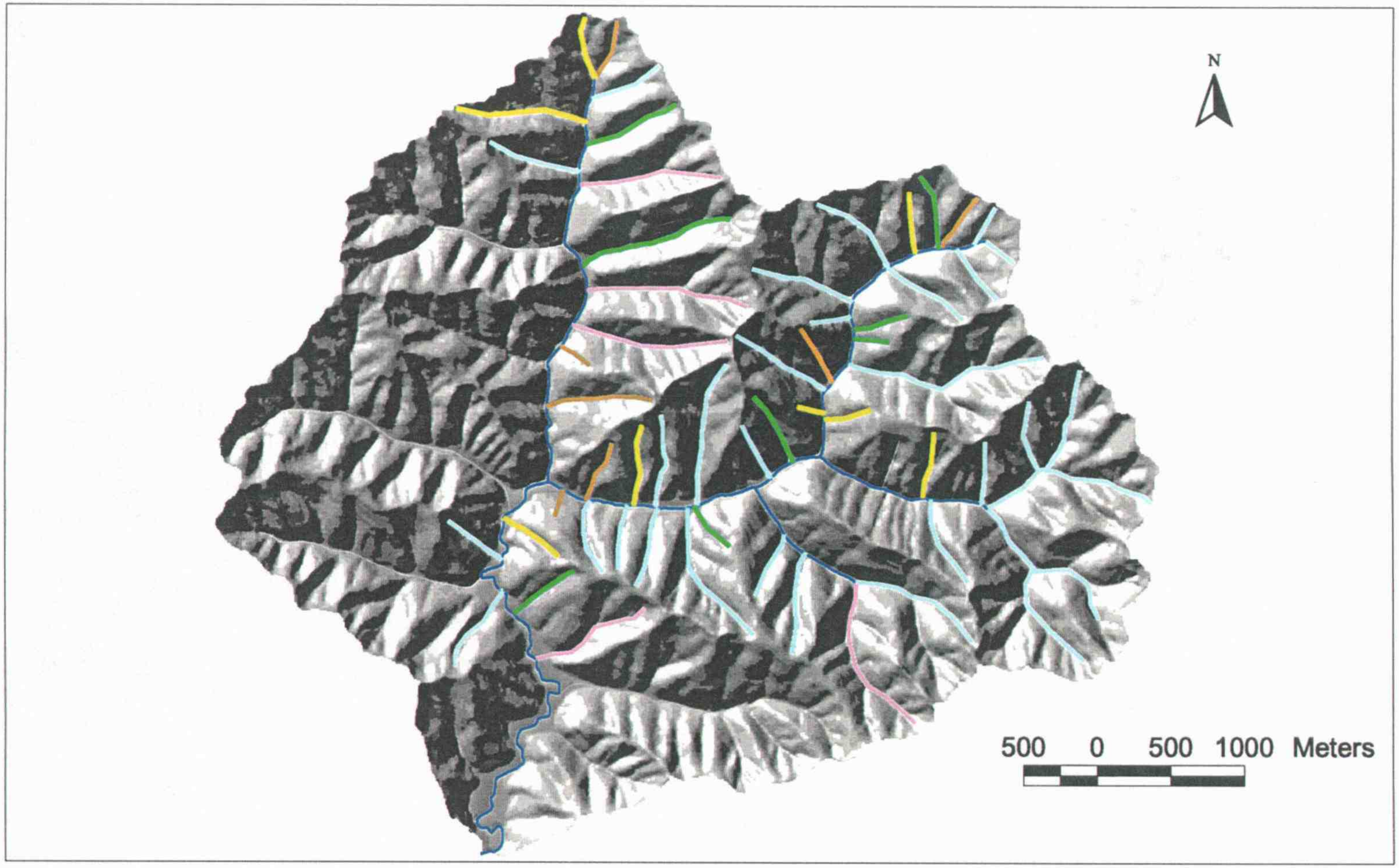
Map of the time since the previous debris flow for (I) Skate and Bear Creeks, (II) Franklin Creek, (III) Harvey Creek, and (IV) upper Wassen Creek. Light blue represents 0 to 30 year age class, green represents 30 to 60 year age class, yellow represents 60 to 90 year age class, brown represents > 90 year age class. Pink represents channels with a trellis network structure.



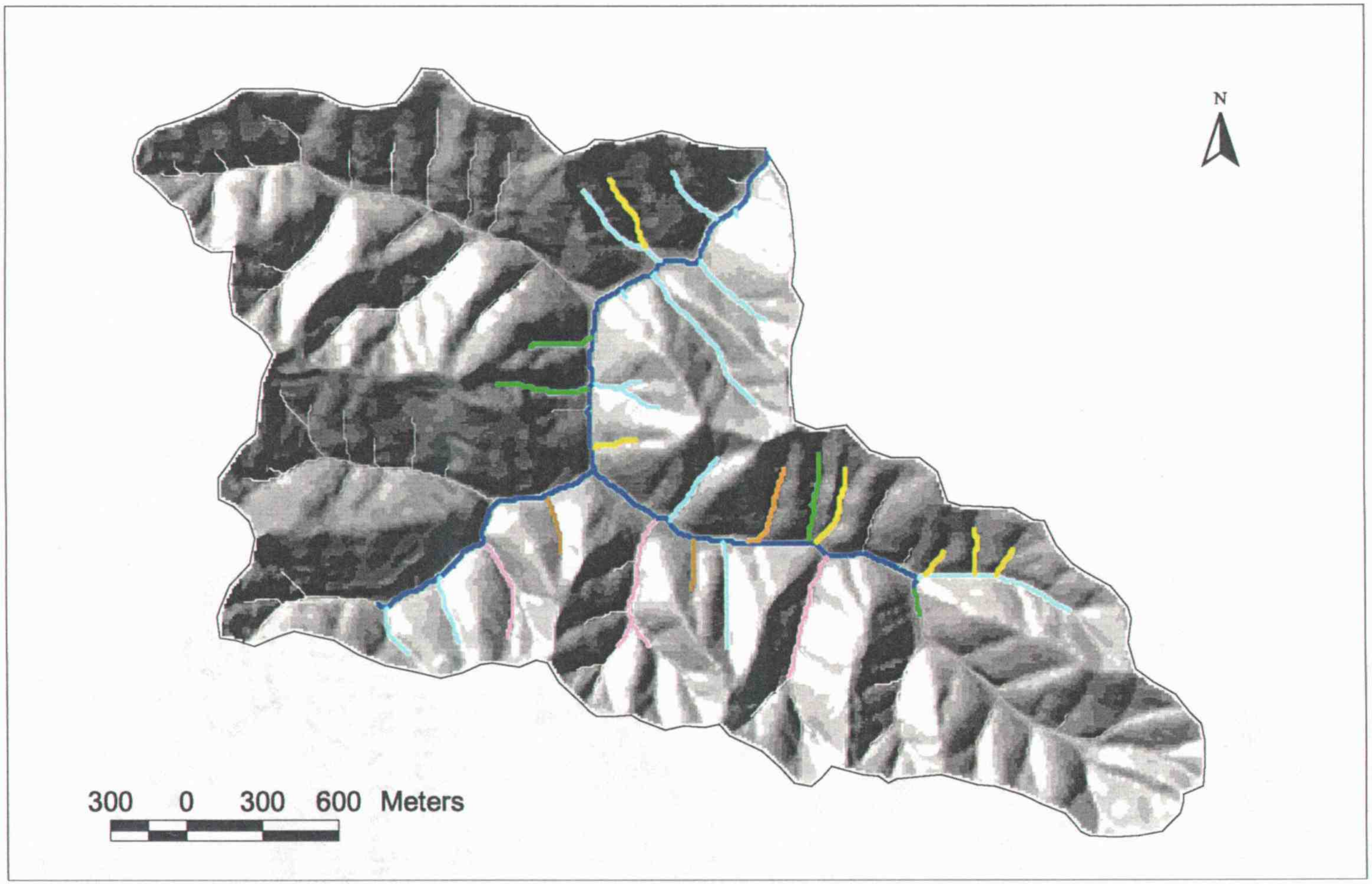
Appendix A.I. Map of the time since the previous debris flow for Skate and Bear Creeks. Light blue represents 0 to 30 year age class, green represents 30 to 60 year age class, yellow represents 60 to 90 year age class, brown represents greater than 90 years. Pink represents high angle channels.



Appendix A.II. Map of the time since the previous debris flow for Franklin Creek. Light blue represents 0 to 30 year age class, green represents 30 to 60 year age class, yellow represents 60 to 90 year age class, brown represents greater than 90 years. Pink represents high angle channels.



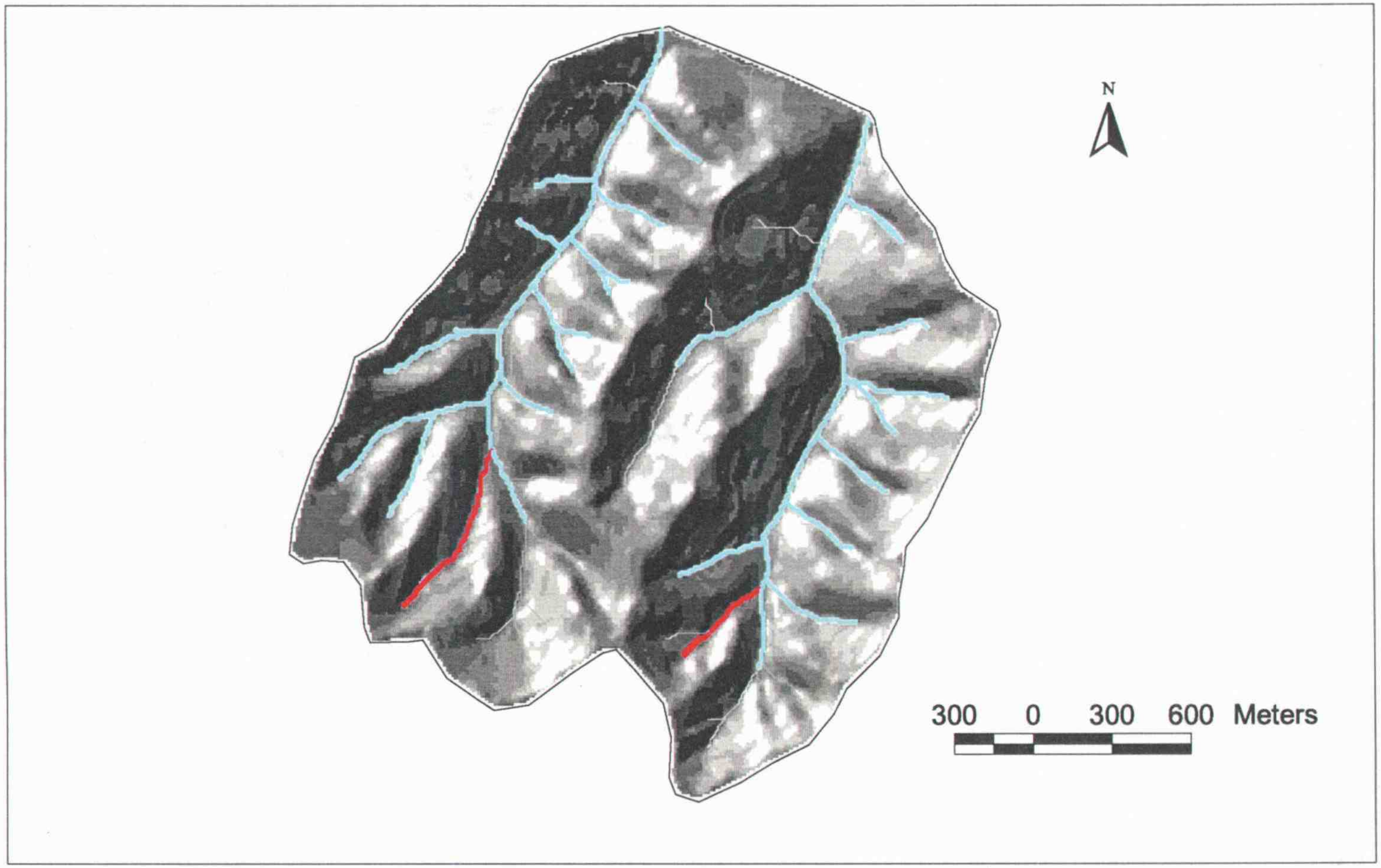
Appendix A.III. Map of the time since the previous debris flow for Harvey Creek. Light blue represents 0 to 30 year age class, green represents 30 to 60 year age class, yellow represents 60 to 90 year age class, brown represents greater than 90 years. Pink represents high angle channels.



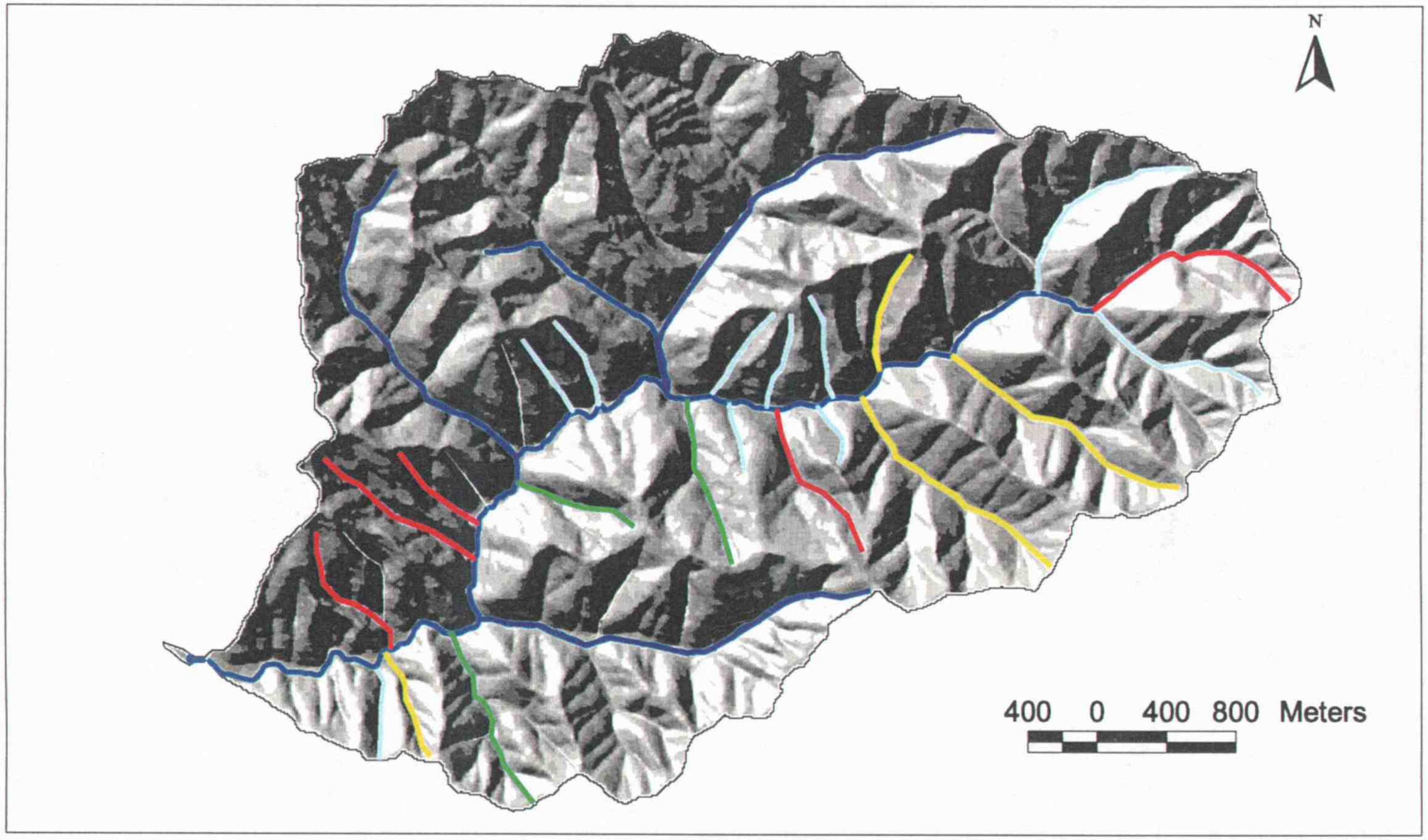
Appendix A.IV. Map of the time since the previous debris flow for upper Wassen Creek. Light blue represents 0 to 30 year age class, green represents 30 to 60 year age class, yellow represents 60 to 90 year age class, brown represents greater than 90 years. Pink represents high angle channels.

Appendix B

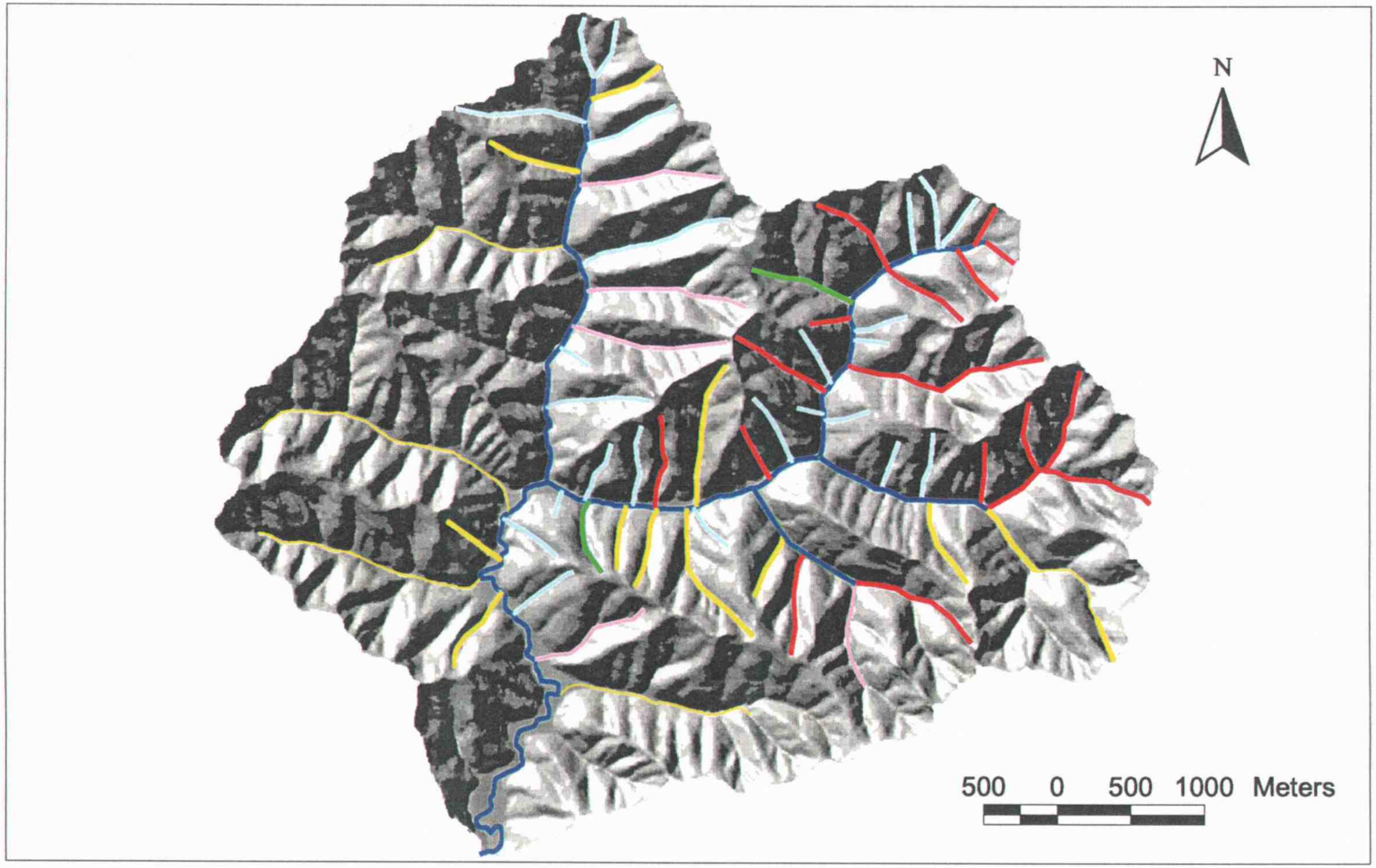
Map of debris flow deposit types in (I) Skate and Bear Creeks, (II) Franklin Creek, (III) Harvey Creek, and (IV) upper Wassen Creek. Yellow represents perched deposits, green represents lobed deposits, red represents overrun deposits. Pink represents channels with a trellis network structure. Light blue represents channels that have not had a debris flow in the trunk channel for > 30 years.



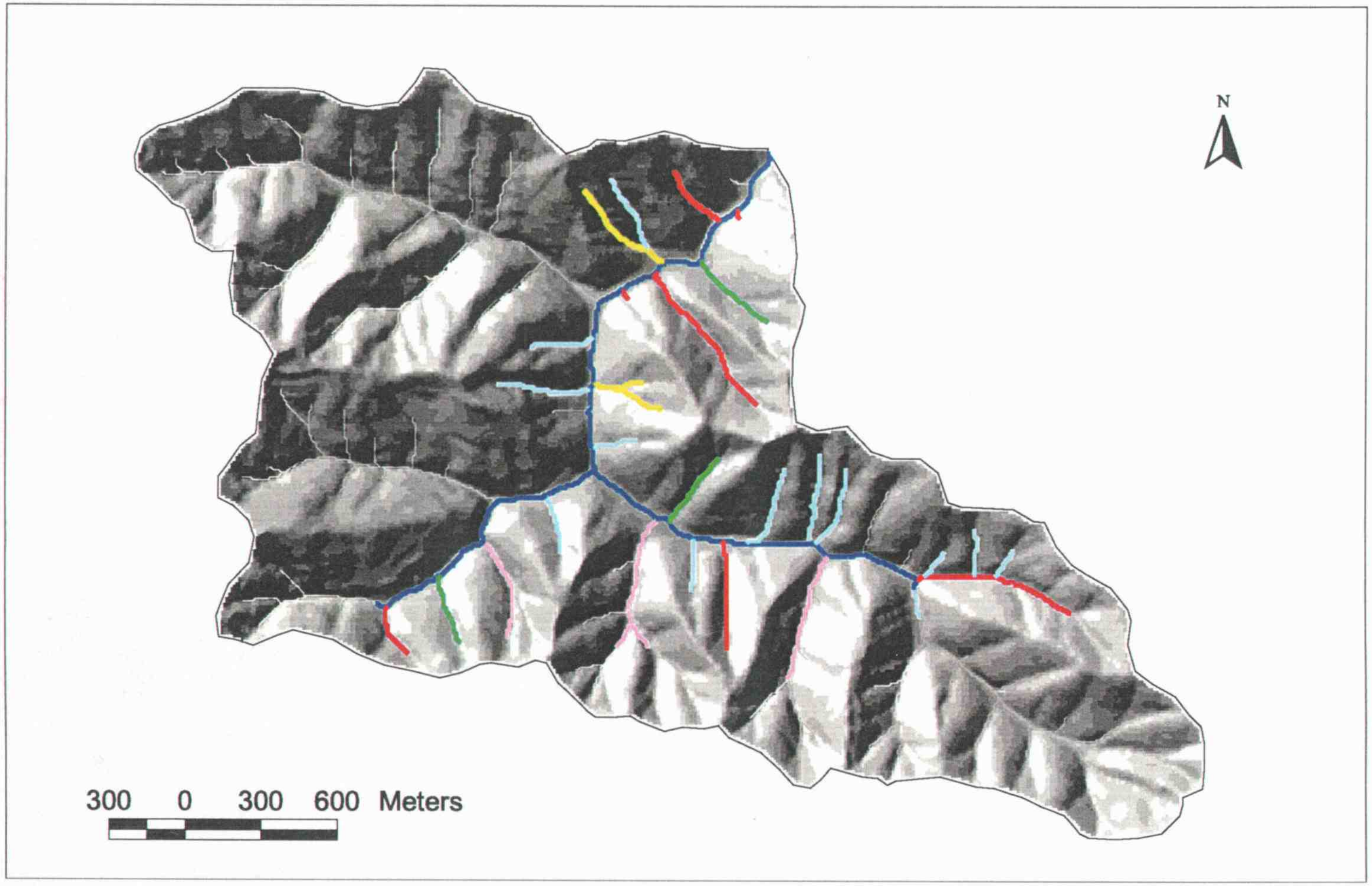
Appendix B.I. Map of debris flow deposit types in Skate and Bear Creeks. Yellow represents perched deposits, green represents lobed deposits, red represents overrun deposits. Pink represents high angle channels. Light blue represents channels that have not had a debris flow in the trunk channel for greater than 30 years.



Appendix B.II. Map of debris flow deposit types in Franklin Creek. Yellow represents perched deposits, green represents lobed deposits, red represents overrun deposits. Pink represents high angle channels. Light blue represents channels that have not had a debris flow in the trunk channel for greater than 30 years.



Appendix B.III. Map of debris flow deposit types in Harvey Creek. Yellow represents perched deposits, green represents lobed deposits, red represents overrun deposits. Pink represents high angle channels. Light blue represents channels that have not had a debris flow in the trunk channel for greater than 30 years.



Appendix B.IV. Map of debris flow deposit types in upper Wassen Creek. Yellow represents perched deposits, green represents lobed deposits, red represents overrun deposits. Pink represents high angle channels. Light blue represents channels that have not had a debris flow in the trunk channel for greater than 30 years.