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Spatial and temporal patterns of debris-flow deposition in the Oregon Coast Range, USA

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Abstract

Patterns of debris-flow occurrence were investigated in 125 headwater basins in the Oregon Coast Range. Time since the previous debris-flows was established using dendrochronology, and recurrence interval estimates ranged from 98 to 357 years. Tributary basins with larger drainage areas had a greater abundance of potential landslide source areas and a greater frequency of scouring events compared to smaller basins. The flux rate of material delivered to the confluence with a larger river influenced the development of small-scale debris-flow fans. Fans at the mouths of tributary basins with smaller drainage areas 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 limited the space available to accommodate fan formation. Of 63 recent debris-flows, 52% delivered sediment and wood directly to the mainstem river, 30% were deposited on an existing fan before reaching the mainstem, and 18% were deposited within the confines of the tributary valley before reaching the confluence. Spatial variation in the location of past and present depositional surfaces indicated that sequential debris-flow deposits did not consistently form in the same place. Instead of being spatially deterministic, results of this study suggest that temporally variable and stochastic factors may be important for predicting the runout length of debris-flows.

Keywords: Landslides; Debris-flows; Alluvial fans; Depositional environment; Drainage basins; Ephemeral streams

1. Introduction

Development of valley floor landforms and channel morphology in mountain streams is strongly influenced by processes that occur external to the alluvial channel (Grant and Swanson, 1995). Although debris-flows are widely recognized as one of the dominant geomorphic processes in steep mountainous terrain (Dietrich and Dunne, 1978; Swanson et al., 1982; Orme, 1989; Benda and Dunne, 1997a), little is known about the recurrence interval of these events and how this interval changes throughout the drainage network. Drainage area and network geometry of the tributary basin may affect the frequency of debris-flows delivered to mainstem river valleys by influencing the number of potential landslide source areas and the routing ability of the channel.

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Understanding the spatial and temporal patterns of debris-flow deposition can provide insight into the residence time of sediment stored in channels and fans, and long-term patterns of channel and landform development. Debris-flow fans are useful for gaining insight into the spatial and temporal patterns of mass wasting because fans preserve a record of past events that can be interpreted from their size and composition. Although the literature on fan morphology in arid regions is voluminous (Lecce, 1990), relatively few studies have been conducted in humid regions of the Pacific Northwest (Orme, 1989). In arid regions, a strong association between drainage basin area and fan area has long been recognized (Bull, 1964; Hooke, 1968). In humid mountain landscapes, this relationship may be related to the frequency of debris-flows delivered to the confluence. In addition, the accommodation space available for fan formation and preservation may be limited because fans occur within upland drainage basins rather than well-defined mountain fronts.

In mountainous terrain, fans can create a buffer between hillslope sediment sources and mainstem rivers by storing sediment delivered from headwater streams (Florsheim et al., 2001). This is particularly important in the Pacific Northwest because forest clearing has dramatically accelerated shallow landsliding (Montgomery et al., 2000). To predict the frequency of scouring events in headwater streams factors such as root cohesion at the initial site (Schmidt et al., 2001), the abundance of landslide source areas (Reneau and Dietrich, 1987), the volume of sediment and wood mobilized by the debris-flow (Lancaster et al., 2001), channel gradient in the runout path, and tributary junction angles need to be addressed (Benda and Cundy, 1990).

The objectives of this study were to (1) estimate the recurrence interval of debris-flows and determine if the interval varies systematically with drainage area; (2) determine if fan size was correlated with the frequency of debris-flows delivered to the confluence; and (3) document the effectiveness of fans for capturing debris-flow deposits before reaching the mainstem river.

2. Study basins

The study basins (Fig. 1) are underlain by Tertiary marine sedimentary rocks of the Tyee Formation (Baldwin, 1964). The low elevation mountains (< 600 m) were never glaciated and have topography similar to the 'ridge and ravine topography' described by Hack (1960). The drainage network is characterized by a dense, dendritic drainage pattern of headwater streams that drain short, steep hillslopes. Headwater streams typically have ephemeral or intermittent streamflow, and the fluvial transport of sediment is typically minor relative to the volume of material that is transported by debris-flows. These headwater streams are effective at transporting debris-flows because the valleys are narrow and high gradient. Small-scale fans typically form by a series of debris-flow deposits, which can be identified by poorly sorted, angular and sub-angular colluvium in a matrix-supported framework (Costa, 1984).

The Oregon Coast Range has a maritime climate, characterized by wet and relatively warm winters and dry summers. Normal annual precipitation ranges from 165 to 230 cm, falling mostly as winter rain. This coastal rainforest is dominated by Douglas-fir (*Pseudotsuga menziesii*) and western hemlock (*Tsuga heterophylla*). Estimates of the natural fire frequency for large-scale, stand-replacement fires range from 230 (Long et al., 1998) to 452 years (Impara, 1997). All of the study basins experienced a large stand-replacement fire in the past 100–150 years (Morris, 1934; Reeves et al., 1995; May, 2001). Timber harvest activities have occurred in 19 of the 125 tributary basins investigated, typically consisting of small patch cuts in the upper elevations. Tributaries with large clear cuts were not surveyed. The only roads in the study basins were located on ridge tops.

3. Methods

3.1. Recurrence interval estimates

First-order channels (Strahler, 1964) were identified by the presence of continuous valleys that were delineated on 10-m resolution digital elevation models. Trunk channels were defined as the highest-order channel in a tributary basin, which directly drained into a larger alluvial river (hereafter referred to as the mainstem river). Surveys were limited to second- and third-order trunk channels because these channels provided information on the frequency that debris-flows

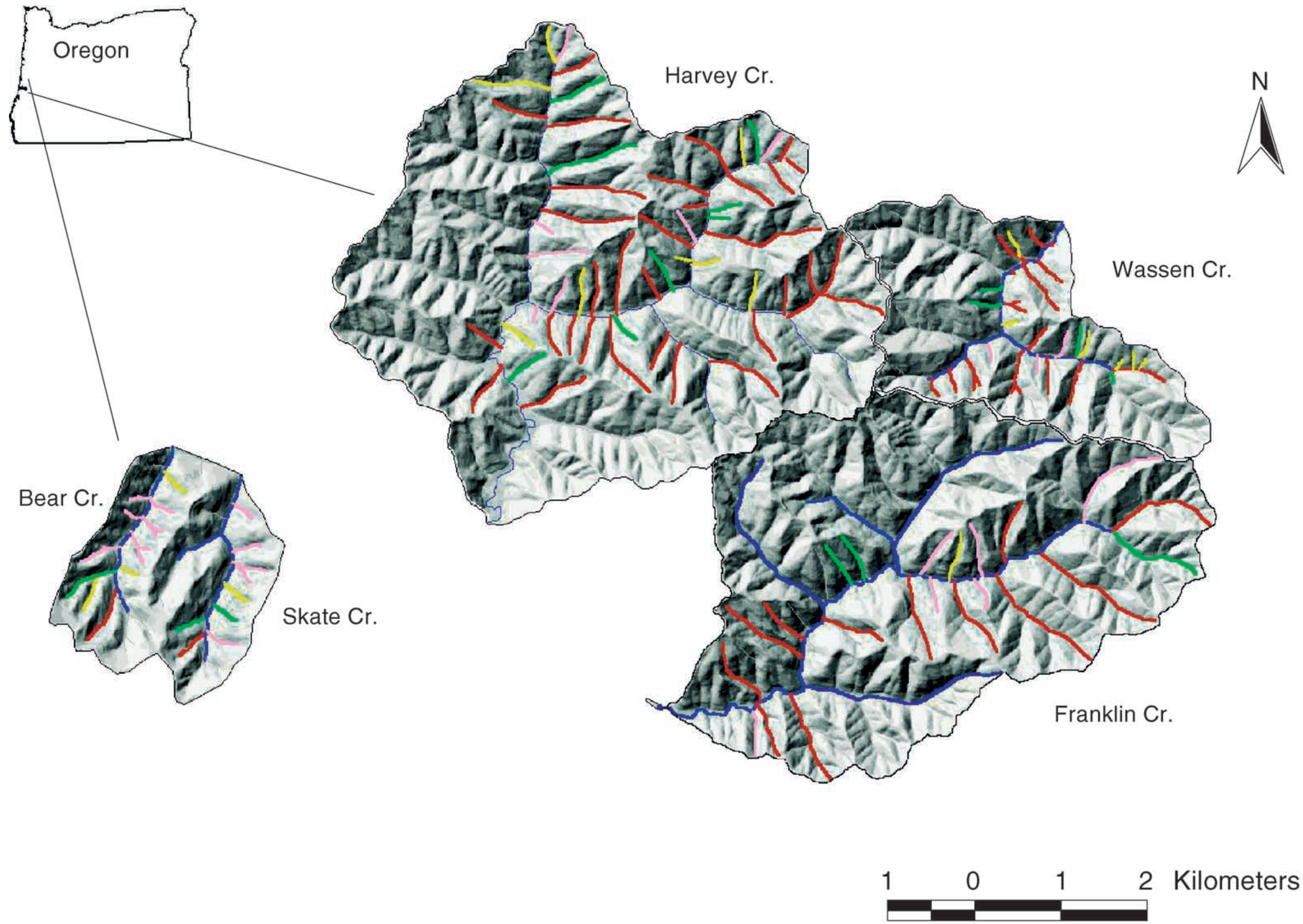

Fig. 1. Shaded relief maps and illustrations of the time since the last debris-flow in the surveyed stream channels. Red lines represent channels in the 0- to 30-year age-class, green represents 30- to 60-year age-class, yellow represents 60- to 90-year age-class, pink represents >90 years.

reached the mainstem river valley. Debris-flows that may have deposited higher in the network were not detected, and in a few cases, the entire length of the trunk channel could not be investigated because vertical bedrock cliffs blocked access. Because our search was limited, the recurrence interval estimates may underestimate the actual interval if all debris-flow deposits in the study area were not detected.

Debris-flows typically remove all vegetation in the valley bottoms (Costa, 1984); therefore, dendrochronology provides a useful tool for determining of the 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%. This value was consistent with the transition from colluvial channels to channels within alluviated valleys documented by Montgomery and Foufoula-Georgiou (1993), and the slope for channels that were typically scoured to bedrock by debris-flows identified by May (2002). 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 1 m 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. Previous research estimated a lag time of 3 to 7 years for tree establishment in the erosional zone of past debris-flows (May, 2001).

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 (Table 1). Prior investigations of the accumulation rates of sediment and wood (May, 2001) were used to define the criteria for each age-class. An especially good indicator of the age-class of the channel was the proportion of the channel length with exposed bedrock, which was highly correlated with the time since the last debris-flow ($r = 0.91$; May, 2001). In 21 of the channels investigated, no trees were growing in the erosional zone of channels that had no evidence of a recent debris-flow, presumably due to adverse growing conditions due to excessive 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. Estimated age-classes were also compared with tree ring data in order to test the consistency of previously documented rates of sediment and wood accumulation.

Table 1
Criteria used to classify debris-flow-prone channels into discrete age-classes

Age-class (years)	Percent bedrock (%)	Description
0–30	>80	Channel has long, continuous reaches of exposed bedrock
30–60	40–60	Extremely low volume of wood and sediment in storage, wood not substantially decayed
60–90	20–40	Discrete accumulations of wood and sediment in storage, wood in various states of decay
>90	< 20	Sediment accumulations coalescing to form continuous accumulations of sediment, wood highly decayed and often buried

An estimate of the recurrence interval for debris-flows in the trunk channels was constructed from the age-class data. In the absence of data on the time period between subsequent events, 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 fits a specified mathematical distribution that was used to characterize the recurrence of the last stand-replacement disturbance on the landscape (Agee, 1993).

Our recurrence interval estimates 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 for all debris-flow channels (C, referred to hereafter as the 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 increases the resistance to flow, resulting in a reduction in the runout length of the debris-flow and a decreased probability of the trunk channel being scoured (Lancaster et al., 2001).

3.2. Debris-flows fans

Fans at the confluence of a second- or third-order tributary to the mainstem river valley were surveyed. 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. Valley floor width of the mainstem river was measured upstream of the fan. Fan volume could not be estimated accurately because the height of the fan could only be measured as the height above the mainstem river, which was often buried in modern alluvium. 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).

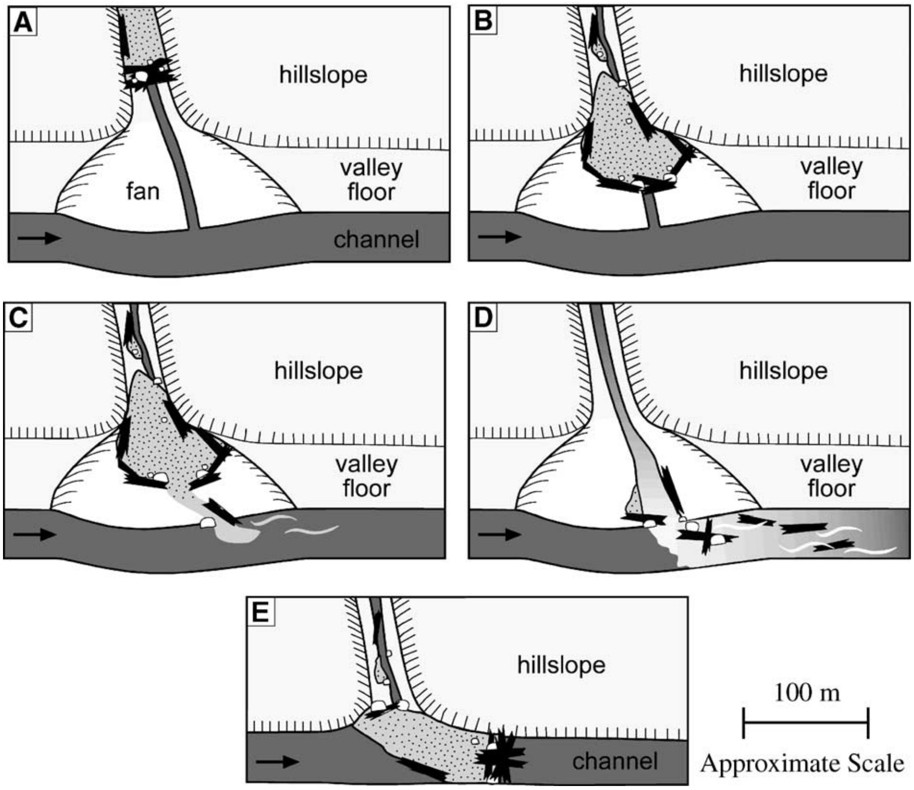

Fig. 2. Debris-flow deposit types: (A) debris dam and sediment wedge formed in tributary valley, (B) deposit perched on fan surface, (C) lobe of perched deposit overran fan, (D) deposit overran fan surface, (E) debris dam formed in mainstem river in narrow valley that prevented fan formation. Fan surfaces in the Oregon Coast Range have a dense forest cover; however, vegetation was not shown for purposes of illustration.

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 0.75-ha threshold for channel initiation (unpublished data, U.S.F.S. Coastal Landscape Analysis and Modeling Study). Distributions of drainage area, mainstem valley floor width, fan area, and fan volume were positively skewed and were transformed to logarithmic scale.

3.3. 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 (Fig. 2). Debris-flows that deposited in the confines of the tributary valley had no direct contact with the fan or mainstem river channel (Fig. 2A). Three deposit types resulted from interactions 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 (Fig. 2B). 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 (Fig. 2C). Overrun deposits delivered the majority of their mass to the mainstem channel and scoured the surface of the existing fan (Fig. 2D). The remaining deposit type did not interact with a debris-flow fan, and instead formed a large debris dam in the mainstem river channel (Fig. 2E). 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.

4. Results

4.1. Recurrence interval estimates

A total of 125 second- and third-order channels prone to erosion by debris-flows were investigated in the five study basins. Drainage areas for these small colluvial channels ranged from 0.1 to 1.1 km^2. Drainage area was highly correlated with the length of the channel network ($r = 0.92$) and the number of first-order streams per tributary basin ($r = 0.92$). Because drainage density was constant, drainage area was a useful proxy for the abundance of channel heads, and therefore the abundance of landslide source areas. Tributaries with smaller catchments had fewer recent debris-flows and a greater proportion of the channels were in older, post-debris-flow age-classes compared to tributaries with larger catchments (Fig. 3).

Comparisons of the estimated time since the previous debris-flow using dendrochronology and the subjective classification indicated that 90% of the tributaries were classified correctly (Table 2). The

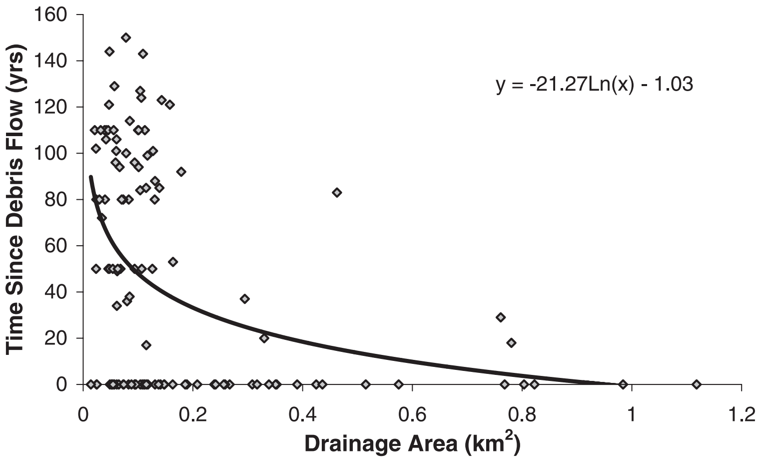

Fig. 3. The relationship between drainage area and the time since the last debris-flow.

Table 2
Comparison of the number of channels in each age-class using dendrochronology and the subjective classification

Age-class estimated from subjective classification (years)	Age-class calculated from dendrochronology			
	0–30 years	30–60 years	60–90 years	>90 years
0–30	63	0	0	0
30–60	0	7	1	4
60–90	0	1	6	4
>90	0	0	0	18

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 the appropriate age-class.

Recurrence interval estimates for debris-flows 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 underestimated the recurrence interval of debris-flows because it was heavily biased by the numerous debris-flows triggered during recent storm events. Two extremely large storm events occurred in this region during the winter of 1996, and portions of the region received record rainfall during these long duration subtropical storms (Taylor, 1997). The reduced model excluded these recent events (0- to 30-year age-class), and resulted in an interval of 357 years and a median age of 247 years.

Debris-flow activity in the immediate post-fire time period was relatively minor compared to debris-flow occurrence in the inter-fire time period (Fig. 4). Interpretation of this pattern is confounded because recent debris-flows may have erased any evidence of debris-flows activity in the immediate post-fire period. 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.

4.2. Debris-flow fans

Debris-flow fans were relatively small and steep, and all fans investigated occupied <9000 m^2. 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. Adjacent fans usually did not coalesce and fan development was frequently constrained by narrow valley floors in the mainstem river valleys. Fluvial erosion of the fans occurred along the perimeter by the mainstem river and to a lesser extent through the body of the fan

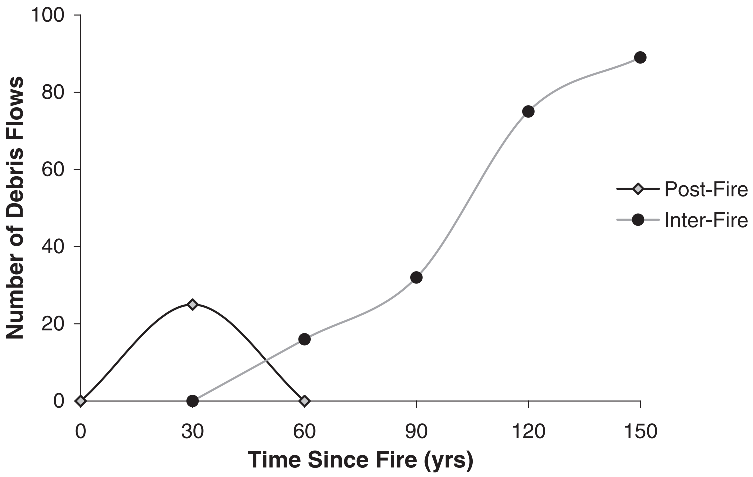

Fig. 4. Debris-flow occurrence relative to the time since the previous stand-replacement wildfire. Post-fire debris-flows occurred within a 30-year time period. All other debris-flows occurred in the inter-fire time period and were plotted as a cumulative function.

by headcut erosion of the tributary channel. Fan incision was minimal in large, well-developed fans but was substantial in remnant fans that had not received a debris-flow deposit in >100 years.

A total of 28 km of mainstem channel length was investigated in the five study basins, and an average of 28 ± 8% (one standard deviation) of the length of the mainstem was in direct contact with a fan. Of the 125 tributaries we investigated, 34 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. Fan area tended to increase with an increase valley floor width; however, the relationship was nonlinear (Fig. 5).

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

$$A_{\mathrm{f}} = cA_{\mathrm{d}}^{b}$$

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 (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). Kochel (1990) concluded that low values of the exponent b documented the restriction of fan growth in narrow valleys.

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 ($r = 0.26$). This relationship yielded a power function of $0.61 \times 10^{0.58}$, but the confidence interval for the exponent was extremely broad (lower 95% confidence interval = 0.12, upper interval = 1.03), 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 area of the tributary basin on the logarithmic scale (coefficient a; $p < 0.02$), mainstem valley floor width on the logarithmic scale (coefficient b; $p < 0.01$), and the presence (1) or absence (0) of a debris-flow in the trunk channel during the past 30 years (coefficient c; $p < 0.01$) were significant explanatory variables in a multiple linear regression analysis of fan area on the logarithmic scale ($R^2 = 0.51$).

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

All coefficients were positive values, indicating that increases in any of the explanatory variables resulted in an increase in fan area. 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.

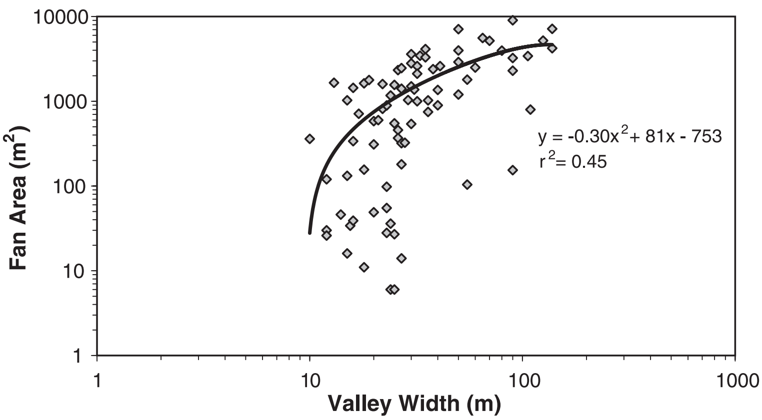

Fig. 5. The relationship between the mainstem valley floor width and fan area.

Table 3
Summary of debris-flow deposit types listed by increasing impact on the mainstem river channel

Deposit type	Number of deposits
Debris dam formed in tributary valley	11
Deposit perched on fan surface	7
Lobe of perched deposit overran fan	12
Deposit overran fan	18
Deposit directly entered mainstem river	15

4.3. Deposit types

Of the 63 recent debris-flow deposits, 33 delivered material as a large, instantaneous pulse to the mainstem (Table 3). These deposits occurred in narrow valley floors that prevented the formation of a fan or where debris-flows overran the existing fan. 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 in their entirety or a minor portion of the deposit crossed the fan as a lobe. The remaining 11 deposits were deposited within the confines of the tributary valley above the influence of a fan.

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. Negative values in the following comparison (Fig. 6) indicate deposits that stopped within the confines of the tributary valley before reaching the confluence (Fig. 2A) and positive values indicate deposits that entered the mainstem valley (Fig. 2B–D). Only tributaries that entered the mainstem valley at nearly a right angle and deposits that were not remobilized by the mainstem river were included in this comparison. 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). 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

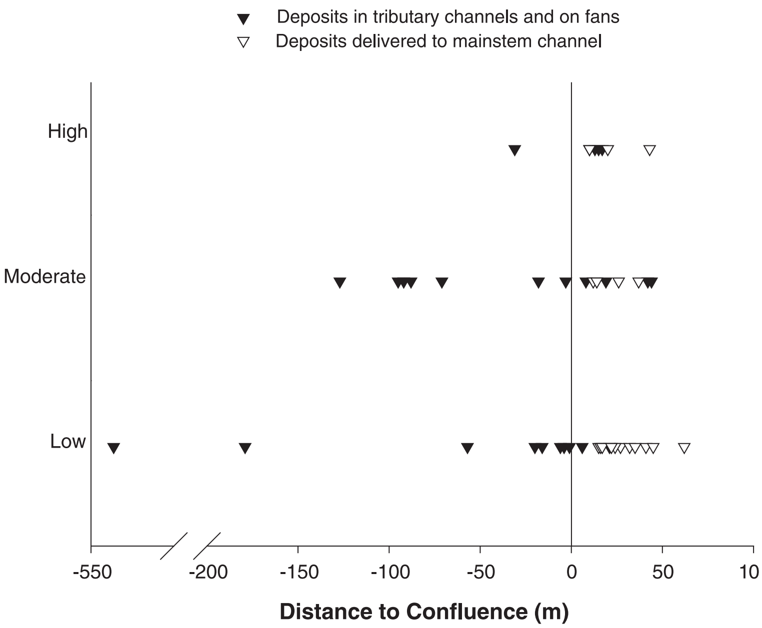

Fig. 6. Summary of debris-flow deposit locations for tributaries that entered the mainstem valley at nearly right angles. Slope classes for tributary channels characterized as 'low' were >5°, 'moderate' slopes ranged from 5° to 10°, and 'high' slope classes exceeded 10°. Zero on the *x*-axis represents the end of the hillslope constriction of the tributary valley and the beginning of 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.

reached the mainstem valley. No statistically significant differences in the distributions were determined (p>0.05, Kolmogorov–Smirnov two-sided test); however, the sample size was small relative to the observed variance. The lack of a spatial deterministic pattern suggests that other temporally variable factors may be important for predicting the runout length of the debris-flows.

No fans formed at confluences that entered the mainstem valley at $<65°$ junction angles. All tributary junctions $<65°$ occurred at the upper extent of the mainstem river, at the confluence of two second-order streams. 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 was deposited within a tributary valley.

5. Discussion

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; Montgomery et al., 1998). Bedrock hollows are areas of topographic convergence that accumulate sediment and are particularly susceptible to mass movement as shallow rapid landslides (Dietrich and Dunne, 1978). Bedrock hollows occur at the upper extent of first-order channels (i.e. channel heads) and on hillsides along channels of any order (Dietrich and Dunne, 1978).

In landscapes with a uniform spacing between ridges and valleys, such as the Oregon Coast Range, drainage density is relatively constant. This pattern indicates that drainage area is a reasonable proxy for the abundance of channel heads, therefore, it is a useful measure for predicting the relative abundance of potential landslide source areas. Using drainage area as a proxy for the relative abundance of landslide source areas is necessary because fine-scale valley density is poorly and inconsistently depicted on moderate resolution topographic data (Dietrich and Montgomery, 1998).

Tributaries with smaller catchment basins had fewer potential landslide source areas and these channels delivered debris-flows less frequently than tributaries with larger drainage basins. If debris-flows occur less frequently, the trunk channel may accumulate a larger volume of sediment and wood during the interval between debris-flows. Therefore, the recurrence interval places a limit on the mass of material that can be mobilized by a debris-flow because the frequency and magnitude of these events are directly linked (Dunne, 1991; Benda and Dunne, 1997a). Smaller catchments with longer recurrence intervals may deliver debris-flows that are relatively large in volume because they can entrain more material that has been stored in the low-order channels.

Larger catchments had a greater abundance of hollows and can receive debris-flows from multiple first-order channels. The majority of the trunk channels in these catchments were in the youngest age-class, indicating a higher frequency of scour than smaller catchments. Larger catchments may deliver debris-flows with less volume because the interval between debris-flows is shorter; 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 morphology for the second- or third-order trunk channels appeared to be bedrock. These channels may be incising more rapidly into the underlying bedrock if the frequency of scour and the exposure time is greater.

5.1. Recurrence interval estimates

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 recurrence intervals is that recent events erased evidence of prior events. The resulting recurrence interval estimates only represent one point in time that was strongly influenced by the recent history of high-intensity rainstorms and should not be considered a fixed rate.

For this study, the estimated recurrence interval for debris-flows 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 recurrence intervals 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 lower recurrence interval because numerous debris-flows were triggered during the 1996 flood events, which would have obliterated any 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 a longer recurrence interval 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.

In order to make comparisons with the previous studies, and to compare the recurrence interval of debris-flows in basins of different size, an area-dependant average of the annual probability of failure was calculated. For the 144 years of record, there was an average of 0.016 debris-flows km^{-2} $year^{-1}$ in the study basins. This annual probability of debris-flow occurrence was similar to the value observed by Swanson et al. (1982) in the Cascade Range of Oregon (0.017 debris-flows km^{-2} $year^{-1}$). These rates of debris-flow occurrence concur also with the range of long-term landslide rates estimated for bedrock hollows in the Oregon Coast Range (0.01–0.03 landslides km^{-2} $year^{-1}$; 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. Reneau and Dietrich (1987) also suggested that debris-flow recurrence intervals probably decrease systematically as the number of upslope landslide sources increases, perhaps reaching the lowest recurrence interval in second-order channels. These authors inferred a rough estimate of debris-flow recurrence intervals from an average rate of landslide occurrence in hollows of 10,000 years. Based on this assumption, they estimated that a first-order basin with 10 landslide sources areas would have a recurrence interval of 1000 years, and a second-order channel that contained 50 landslide sources areas would have a recurrence interval of 200 years.

Several current models of debris-flow activity presume that almost all landslides occur immediately post-fire (Benda and Dunne, 1997b; Lancaster et al., 2001). This pattern may be anticipated if high-intensity rainstorms occur during the time when the root network of the previous forest stand has decayed, and before the root network of the regenerating stand becomes established (Ziemer, 1981). 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). Because fires occur so infrequently and high-intensity rainstorms are very common in this region, the long-term contribution of post-fire debris-flows activity may be insubstantial. Seventy-eight percent of the channels we investigated experienced a debris-flow that was not associated with fire. However, interpretation of this pattern was confounded by recent debris-flow activity that would have erased any evidence of previous events that may have occurred post-fire.

5.2. Debris-flow fans

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 fans that consist of debris-flow deposits and fluvially transported sediments. Drainage basin size and relief are major controls on the sedimentology of fans, with small, steep drainage basins producing fans composed primarily of debris-flow deposits (Harvey, 1984). Relatively small, yet well-formed fans, or remnants of older fans are present at confluences 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 confirmed that the fans built over time by a series of debris-flow episodes and locally these fans have been recognized as important, long-term storage reservoirs for sediment (Dietrich and Dunne, 1978).

Fans store sediment and wood that is episodically delivered by the tributary channel, and release this material to the mainstem river at a slower rate. 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).

Fans can also influence the routing of debris-flows through the drainage network. Fans that are substantially incised by the tributary channel can laterally confine the flow and effectively route debris-flows through the fan and to the mainstem river (Swanson and James, 1975). When the flow is not laterally confined, the debris-flows can spread over the fan surface, and thus increase the frictional resistance to flow, promoting deposition on the fan surface.

In contrast to a well-defined relationship between fan area and basin area (Bull, 1964), we found fan size to be highly variable. The poor statistical relationship and high standard deviation suggests that the accommodation space in the valley floor places a stronger control on fan development than the contributing source area. Previous research by in the Appalachian Mountains (Mills, 1987; Kochel, 1990) and the Canadian Rocky Mountains (Kostachuk et al., 1986) also found that valley width limited the size of fans. Field evidence indicated that substantial lateral erosion of the fan by the mainstem river occurred during the interval between debris-flows. Because fans were small, relative to their contributing drainage area, our results suggest that erosion by the mainstem river is keeping pace with fan development.

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 presumably have more numerous landslide source areas, the flux rate of sediment and wood to the confluence is higher. If larger tributary basins have a greater frequency of debris-flow 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; however, the explained variance was relatively low.

Mainstem valley floor width determined the potential the fan had for developing within the confines of the surrounding hillslopes. In narrow valley floors (< 30 m), deposits frequently entered the mainstem and did not form a fan. If fans were formed in these narrow valleys, they were highly susceptible to erosion by the mainstem river. In wider valley floors (30–100 m), well-developed fans were formed, and the channel was typically pushed to the opposite side of the valley. In broad valley floors (>100 m), debris-flows fans typically did not have contact with the mainstem, and therefore were not being eroded. These results were similar to the predictions by Ikeya (1981) that valley widths >25 m limit debris-flows contributions directly to mainstem river channels.

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 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 deposited in the fans. The highest density of boulders and the steepest channels can also occur where channels are bordered by fans and active landslides (Grant and Swanson, 1995). In contrast, fans can occasionally block the mainstem river and create large ponds upstream (Everest and Meehan, 1981). Over time, the ponds become filled with sediment and these backfilled valleys create broad, unconstrained reaches with an active floodplain and low-gradient channel.

5.3. Deposit type

Deposition of debris-flows on fan surfaces may be a common occurrence in this region because the majority (>75%) of tributary junctions of low-order streams that enter mainstem river valleys occur at nearly right angles (May, 2001). Tributary junctions with a high angle have an abrupt change in slope that can promote rapid deposition of debris-flows. In contrast, where the tributary and the mainstem river gradient are similar, the tributary will typically enter at a low junction angle (Horton, 1945). The abrupt change in slope at a right angle confluence, combined with a wide valley floor, creates the optimal condition for fan development.

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 located 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. The decay rate of buried wood is greatly reduced, which can result in the persistent of wood in the network for an extended period of time (Hyatt and Naiman, 2001). Lobed deposits delivered a portion of the wood and sediment to the mainstem river; however, the majority of the material were 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 valleys. These aggraded reaches created low-gradient areas that could promote deposition of future debris-flows.

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-flows 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-flows delivers material to the larger river as an instantaneous pulse or if the material is transferred into long-term storage on the valley floor. An empirical model by Benda and Cundy (1990) uses channel slope ($<3.5°$) and tributary junction angle (>70°) to predict debris-flow deposition. The expected result of this 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 temporally variable parameters 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.

6. Conclusions

Larger tributary basins may have a greater probability of experiencing a debris-flow during any given storm event because the number of potential landslide source areas is higher than in smaller basins with fewer landslide source areas. Debris-flow fan formation was affected by this flux rate and the valley width of the mainstem river. At the mouth of small basins, with fewer landslide source areas 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, J.K., 1993. Fire Ecology of Pacific Northwest Forests. Island Press, Washington, DC.

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

Benda, L.E., 1988. Debris-flows in the Tyee Sandstone Formation of the Oregon, Coast Range. MS Thesis, University of Washington, Seattle, WA.

Benda, L.E., Cundy, T.W., 1990. Predicting deposition of debris-flows in mountain channels. Canadian Geotechnical Journal 27, 409–417.

Benda, L.E., Dunne, T., 1997a. Stochastic forcing of sediment routing and storage in channel networks. Water Resources Research 33 (12), 2865–2880.

Benda, L.E., Dunne, T., 1997b. Stochastic forcing of sediment supply to channel networks from landsliding and debris-flows. Water Resources Research 33 (12), 2849–2863.

Bull, W.B., 1964. Geomorphology of segmented alluvial fans in western Fresno County, California. US Geological Survey Professional Paper 352, 89–129.

Costa, J.E., 1984. Physical geomorphology of debris-flows. In: Costa, J.E., Fleisher, P.J. (Eds.), Developments and Applications of Geomorphology. Springer-Verlag, New York, pp. 268–317.

Church, M., Mark, D.M., 1980. On size and scale in geomorphology. Progress in Physical Geography 4 (3), 342–390.

Dietrich, W.E., Dunne, T., 1978. Sediment budget for a small catchment in mountainous terrain. Zeitschrift fur Geomorphologie N.F. 29, 191–206.

Dietrich, W.E., Montgomery, D.R., 1998. Hillslopes, channels and landscape scale. In: Sposito, G. (Ed.), Scale Dependence and Scale Invariance in Hydrology. Cambridge Univ. Press, New York, pp. 30–60.

Dunne, T., 1991. Stochastic aspects of the relations between climate, hydrology and landform evolution. Transactions, Japanese Geomorphological Union 12, 1–24.

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

Florsheim, J.L., Mount, J.F., Rutten, L.T., 2001. Effect of baselevel change on floodplain and fan sediment storage and ephemeral tributary channel morphology, Navarro River, California. Earth Surface Processes and Landforms 26, 219–232.

Grant, G.E., Swanson, F.J., 1995. Morphology and processes of valley floors in mountain streams, western Cascades, Oregon. Natural and Anthropogenic Influences in Fluvial Geomorphology. Geophysical Monograph, vol. 89, pp. 83–101.

Hack, J.T., 1960. Interpretation of erosional topography in humid temperate climates. American Journal of Science 258-A, 80–97.

Harvey, A.M., 1984. Debris-flow and fluvial deposits in Spanish Quaternary alluvial fans: implications for fan morphology. In: Koster, E.H., Steel, R.J. (Eds.), Sedimentology of Gravels and Conglomerates. Canadian Society of Petroleum Geologists Memoir, vol. 10, pp. 123–132.

Hooke, R.L., 1968. Steady-state relationships on arid-region alluvial fans in closed basins. American Journal of Science 266, 609–629.

Horton, R.E., 1945. Erosional development of streams and their drainage basins: hydrophysical approach to quantitative morphology. Geological Society of America Bulletin 56, 275–370.

Hyatt, T.L., Naiman, R.J., 2001. The residence time of large woody debris in the Queets River, Washington, USA. Ecological Applications 11 (1), 191–202.

Ikeya, H., 1981. A method of designation of area in danger of debris-flows. International Symposium on Erosion and Sediment Transport in Pacific Rim Steeplands. IAHS Publication, vol. 132, pp. 576–588.

Impara, P.C., 1997. Spatial and Temporal Patterns of Fire in the Forests of the Central Oregon Coast Range, PhD Dissertation, Oregon State University, Corvallis, OR.

Kochel, R.C., 1990. Humid fans of the Appalachian Mountains. In: Rachocki, A.H., Church, M. (Eds.), Alluvial Fans: A Field Approach. Wiley, New York, pp. 109–129.

Kostachuk, R.A., MacDonald, G.M., Putnam, P.E., 1986. Depositional process and alluvial fan-drainage basin morphometric relationships near Banff, Alberta, Canada. Earth Surface Processes and Landforms 11, 471–484.

Lancaster, S.T., Hayes, S.K., Grant, G.E., 2001. Modeling sediment and wood storage and dynamics in small mountainous watersheds. In: Dorava, J.M., Montgomery, D.R., Palcsak, B.B., Fitzpatrick, F.A. (Eds.), Geomorphic Processes and Riverine Habitat. American Geophysical Union, Washington, pp. 85–102.

Lecce, S.A., 1990. The alluvial fan problem. In: Rachocki, A.H., Church, M. (Eds.), Alluvial Fans: A Field Approach. Wiley, New York, pp. 3–24.

Long, C.J., Whitlock, C., Bartlein, P.J., Millspaugh, S.H., 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, C.L., 2001. Spatial and Temporal Dynamics of Sediment and Wood in Headwater Streams in the Central Oregon Coast Range, PhD Dissertation, Oregon State University, Corvallis, OR.

May, C.L., 2002. Debris-flows through different forest age classes in the central Oregon Coast Range. Journal of the American Water Resources Association 38 (4), 1097–1113.

Mills, H.H., 1987. Debris slides and foot-slope deposits in the Blue Ridge province. In: Graf, W.L. (Ed.), Geomorphic Systems of

North America. Geological Society of America, Centennial Special, vol. 2, pp. 29–37.

Montgomery, D.R., Foufoula-Georgiou, E., 1993. Channel network source representation using digital elevation models. Water Resources Research 29 (12), 3925–3934.

Montgomery, D.R., Sullivan, K., Greenberg, H.M., 1998. Regional test of a model for shallow landsliding. Hydrological Processes 12, 943–955.

Montgomery, D.R., Schmidt, K.M., Greenberg, H.M., Dietrich, W.E., 2000. Forest clearing and regional landsliding. Geology 28 (4), 311–314.

Morris, W.G., 1934. Forest fires in western Oregon and western Washington. Oregon Historical Quarterly 35, 313–339.

Mosley, M.P., 1976. An experimental study of channel confluences. Journal of Geology 84, 535–562.

Orme, A.R., 1989. The nature and rate of alluvial fan aggradation in a humid temperate environment, NW Washington. Physical Geography 10, 131–146.

Reeves, G.H., Benda, L.E., Burnett, K.M., Bisson, P.A., 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. American Fisheries Society Symposium 17, 334–349 (Bethesda, MD).

Reneau, S.L., Dietrich, W.E., 1987. The importance of hollows in debris-flow studies; examples from Marin County, California. In: Costa, J.E., Wieczorek, G.F. (Eds.), Debris-flows/Avalanches: Process, Recognition, and Mitigation. Reviews in Engineering Geology, vol. 7. Geological Society of America, Boulder, CO, pp. 165–180.

Schmidt, K.M., Roering, J.J., Stock, J.D., Dietrich, W.E., Montgomery, D.R., Schaub, T., 2001. The variability of root cohesion as an influence on shallow landslide susceptibility in the Oregon Coast Range. Canadian Geotechnical Journal 38, 995–1024.

Strahler, A.N., 1964. Quantitative geomorphology of drainage basins and channel networks. In: Chow, V.T. (Ed.), Handbook of Applied Hydrology. McGraw-Hill, New York, pp. 40–74.

Swanson, F.J., James, M.E., 1975. Geomorphic history of the lower Blue River–Lookout Creek area, western Cascades, Oregon. Northwest Science 49 (1), 1–11.

Swanson, F.J., Fredricksen, R.L., McCorison, F.M., 1982. Material transfer in a western Oregon forested watershed. In: Edmonds, R.L. (Ed.), Analysis of Coniferous Forest Ecosystems in the Western United States. Hutchinson Ross, New York, pp. 233–266.

Swanston, D.N., Marion, D.A., 1991. Landslide response to timber harvest in Southeast Alaska. In: Shou-Shan, F., Yung-Huang, K. (Eds.), Proceedings of the Fifth Federal Interagency Sedimentation Conference. Federal Energy Regulatory Commission, Washington D.C.

Taylor, G., 1997. Causes of the flood and a comparison to other climate events. In: Laenen, A., Ruff, J.D. (Eds.), The Pacific Northwest Floods of February 6–11, 1996: Proceedings of the Pacific Northwest Water Issues Conference. American Institute of Hydrology, St. Paul, MN, pp. 3–7.

Van Wagner, C.E., 1978. Age-class distribution and the forest fire cycle. Canadian Journal of Forest Research 8, 220–227.

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

Ziemer, R.R., 1981. Roots and the stability of forested slopes. In: Davies, T.R.H., Pearce, A.J. (Eds.), Erosion and Sedimentation of the Pacific Rim Steeplands. International Association of Hydrological Sciences. Institute of Hydrology, Wallingford, Oxfordshire, vol. 132, pp. 343–361.