On Debris Flows, River Networks, and the Spatial Structure of Channel Morphology

Paul E. Bigelow, Lee E. Benda, Daniel J. Miller, and Kelly M. Burnett

Abstract: We evaluated the morphological effects of debris flows from headwater streams in larger, fish-bearing channels of the central Oregon Coast Range, including their influence on fans, wood recruitment, and channel morphology. Continuous channel surveys (6.4 km) were conducted in third- through fifth-order streams (drainage area <10 km^2 and slope $<7\%$) where debris fan effects at confluences were most evident. This basin size contains the majority of channels (67%) in the central Coast Range with gradients that are used by coho salmon (*Oncorhynchus kisutch* Walbaum). The close spacing between headwater tributaries susceptible to debris flows (118 m average) resulted in long continuous sections of fish-bearing streams that were bordered by debris fans (103 m average) and debris fans impinging on 54% of the total channel length surveyed. Debris flows also supplied the majority of wood (58% of pieces) to the surveyed fish-bearing channels. The highest values of large wood, boulders, and channel gradients were associated with debris fans at confluences with headwater tributaries, while deeper sediment deposits were often associated with fans but also extended up and downstream from fans. The spacing and network pattern of debris flow-prone headwater tributaries influenced the spatial structure of channel morphology and aquatic habitats leading to a high degree of physical heterogeneity and patchiness in channel environments. Our study contributes to a growing emphasis on the role of tributary confluences in structuring channel morphology and aquatic habitats in mountain drainage basins and argues for including a confluence component to stream classification and habitat typing schemes. FOR. SCI. 53(2): 220–238.

Keywords: landslides, tributary fan, confluence effects, aquatic habitat, channel classification

Although erosion is a ubiquitous and natural process that delivers sediment and wood to stream channels, its role in habitat formation is not well understood. Debris flows that originate from headwater first- and second-order streams (Strahler 1957) are a dominant erosion process in many regions of North America, ranging from the Appalachian mountains in the east (Hack and Goodlett 1960, Eaton et al. 2003) to arid (Wohl and Pearthree 1991, Robichard and Brown 1999), semi-arid (Meyer et al. 1995, Kirchner et al. 2001), and temperate rainforest (Dietrich and Dunne 1978, Swanson et al. 1982, Hogan et al. 1998) landscapes in the west. Typically, debris flows scour sediment and wood along steep headwater streams and deposit this material downstream, creating fans and accumulations of boulders, coarse sediment, and wood in lower gradient fish-bearing channels and valley floors (Hack and Goodlett 1960, Benda 1990, Grant and Swanson 1995, Hogan et al. 1998, Benda et al. 2003a). Studies of debris flows often focus on stream habitat degradation in managed forests and in rapidly developing areas. This is because sediments delivered to streams by debris flows can have obvious destructive effects, including burying existing habitat and biota (Everest and Meehan 1981), suffocating incubating salmon eggs (Everest et al. 1987), scouring smaller, headwater channels (Benda 1990), increasing bed mobility that destroys spawning beds in larger, downstream channels (Nawa and Frissell 1993), and reducing summer pool capacity for juvenile salmonids (May and Lee 2004). However, sediment and wood from debris flows also provide essential structural elements for habitat in mountain streams that can endure for decades to centuries. Debris fans at confluences with larger streams can force channel meanders, supply concentrations of boulders (Benda 1990), deposit wood (Everest and Meehan 1981, Hart 2002, Reeves et al. 2003), and create pools (Benda et al. 2003a). Thus, debris flows can have both biologically destructive and constructive effects (Reeves et al. 1995).

Emerging landscape perspectives of rivers (Fausch et al. 2002, Ward et al. 2002), particularly the emphasis on tributary confluences and disturbances at the scale of entire river networks (Benda et al. 2004), provide a conceptual framework for considering the potential role of debris flow erosion in unmanaged landscapes on the constructive aspects of channel morphology and aquatic habitats. Based on such a network perspective, we made continuous measurements of channel and valley attributes along multikilometer stretches of streams in small to medium size basins (<10 km^2) of the Oregon Coast Range, a landscape where debris flows are a dominant geomorphic process delivering sediment and wood from headwater channels to larger fish-bearing

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channels (Dietrich and Dunne 1978, Benda 1990, May and Gresswell 2003). This allowed us to address two primary study objectives along fish-bearing streams in mostly unmanaged forests: (1) evaluate how channel gradient, wood, boulders, and gravelly alluvium were affected by proximity to low-order (headwater) confluences prone to debris flow deposition, and (2) evaluate how headwater tributary debris fan spacing and size (fan perimeter) affected the spatial structure of channel morphology. Based on this work and related studies of confluence effects in rivers in western North America, we propose that stream classification and habitat typing systems include a confluence component.

Study Area and Methods

Study Area

Because our objective was to study the effects of debris flow deposits on channel morphology, we selected channels where debris flow effects at confluences would be strong. The study was conducted in four mostly unmanaged mountain basins (Unamid, Form, Harvey, and Golden Ridge Creeks) of less than 10 km^2 located in the central Oregon Coast Range (Figure 1, Table 1). Timber harvest within the study basins was limited to a few recent patch cuts visible on 1997 air photos and historical logging was not evident, as

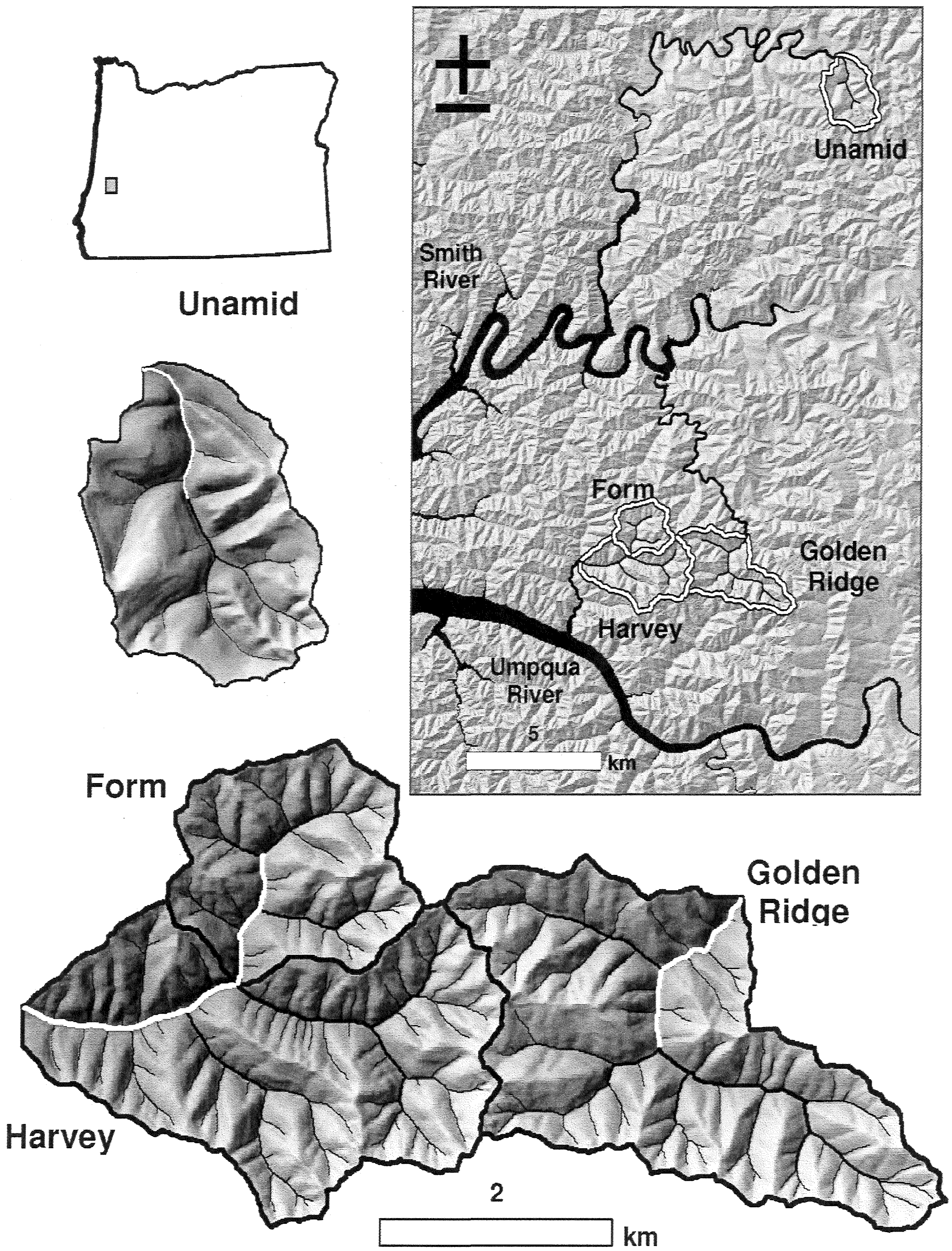

Figure 1. Location of study area, basins, and sections. Surveyed sections are shown in white.

Table 1. Physical characteristics of study sites

Variable	Site name			
	Form	Unamid	Golden Ridge	Harvey
Drainage area (km^2)	1.1–3.1	2.3–3.8	4.3–7.0	6.1–9.8
Stream order[a]	3rd–4th	4th	4th	5th
Avg channel gradient (%)	6.1	3.2	1.5	2.9
Avg channel width (m)	7.0	7.3	6.8	10.4
Avg valley width[a] (m)	46	27	68	81
Dominant substrate	bedrock	bedrock	gravel	cobble
Subdominant substrate	boulders	gravel	cobble	gravel
Survey length (m)	1,400	1,193	1,628	2,230
% of length bordered by debris fans	61	50	68	38
No. recent fans (<60 yr)	10	5	12	5
No. older fans (>60 yr)	7	2	3	10
Avg spacing between tributaries (m)	65	170	106	133
Avg continuous fan perimeter[b] (m)	106	99	123	83

[a] Derived from digital elevation model analysis (Miller 2003).
[b] Represents the average length of stream continuously bordered by a fan on either side of the stream (i.e., includes overlapping fans on opposite sides of the stream).

the canopy consisted of mature forest and younger age classes were not apparent. All roads were located on or very near to ridge tops (May and Gresswell 2004), and there were no midslope roads. Unmanaged forests in the central Oregon Coast Range averaged between 125 and 145 years of age (Nierenberg and Hibbs 2000), as stand-replacing fires occurred within the study basins within the past 100 to 150 years (Morris 1934, Reeves et al. 1995, May 2001). The maritime climate of the Oregon Coast Range consists of heavy winter precipitation (165–230 cm/yr annual) and dry summers. The coastal rainforest is dominated by Douglas-fir (*Pseudotsuga menziesii* [Mirbel] Franco) and western hemlock (*Tsuga heterophylla* [Raf.] Sarg.) on hillslopes and red alder (*Alnus rubra* Bong) and bigleaf maple (*Acer macrophyllum* Pursh) in riparian areas. Underlain by interbedded marine silt and sandstones, the basins are dissected by a dense dendritic network with short steep headwater streams bounded by steep hillslopes.

Although relatively small, the size of our study basins is ecologically important in the Oregon Coast Range. Basins of 10 km^2 or less contain the majority of channels with gradients used by salmonids in the Oregon Coast Range, including approximately 67% for coho salmon (*Oncorhynchus kisutch* Walbaum) (<7% gradient), 72% for steelhead (*O. mykiss* Walbaum) (<10% gradient), and 76% for resident rainbow (*O. mykiss irideus* Gibbons) and coastal cutthroat trout (O. *clarki clarki* Richardson) (<20% gradient). These estimates were derived for this study from US Forest Service data (www.fsl.orst.edu/clams/data index.HTML) over 5,727 km^2 in the central Oregon Coast Range. The channel gradient thresholds for fish use in the Oregon Coast Range are those reported in Burnett et al. (2007). Stream lengths for each species were estimated for all reaches below the downstream-most reach with a gradient exceeding the stated threshold.

Field Methods

The mature forest age-class and thick canopy obscured many debris flows on aerial photographs, requiring field detection of debris flows (e.g., Brardinoni et al. 2003). Thus, we collected attributes on channel and valley morphology continuously along 6.4 km of third- through fifth-order channels (Strahler 1957) in the four study basins (Figure 1) that ranged in size from 3 to 10 km^2 (Table 1). Channel orders were derived from digital elevation model analysis (Miller 2003) and are similar to the 1:24:000 stream layer available for the Siuslaw National Forest that encompasses the study area. Our surveys excluded the nonfish-bearing upper portions of the basins, which contained relatively continuous colluvial valley-fill deposits from debris flows (Benda and Dunne 1997, Lancaster et al. 2001) (Figure 2A). The field measurements focused on lower gradient portions of the valley floor (<7%) that contain numerous discreet debris flow deposits in the form of fans at headwater (first- and second-order) tributary confluences with larger fish-bearing channels (Figure 2A). There were two larger, third-order alluvial tributary confluences within the study basins.

The stream gradient and length of each reach were measured with a laser rangefinder and rod, with typical accuracies of approximately 1 to 2 m for distance and 0.1 degree for slope (www.ascscientific.com/impulse.HTML). The centerline and perimeters of debris fans (Figure 2C) were recorded during the surveys, the latter based on visual identification of lobate colluvial deposits, matrix supported debris in banks, boulders contained in deposits, and recent debris flows on surfaces of fans. Debris fan perimeters often overlapped each other on opposite sides of a channel, and occasionally on the same side of a channel.

We also evaluated the approximate ages of debris fans (i.e., the time since last debris flow) to help interpret the temporal influence of disturbance on channel morphology in our study area (Figure 2B). Ages of debris fans were categorized as recent (<60 years) or older based on physical evidence of debris flow deposition including ages of trees in depositional areas (measured using an increment borer), scour marks, and deposited logs. A debris flow was considered related to management if harvest units were apparent on 1997 1:12,000 air photos in tributary basins containing debris fans observed in the field.

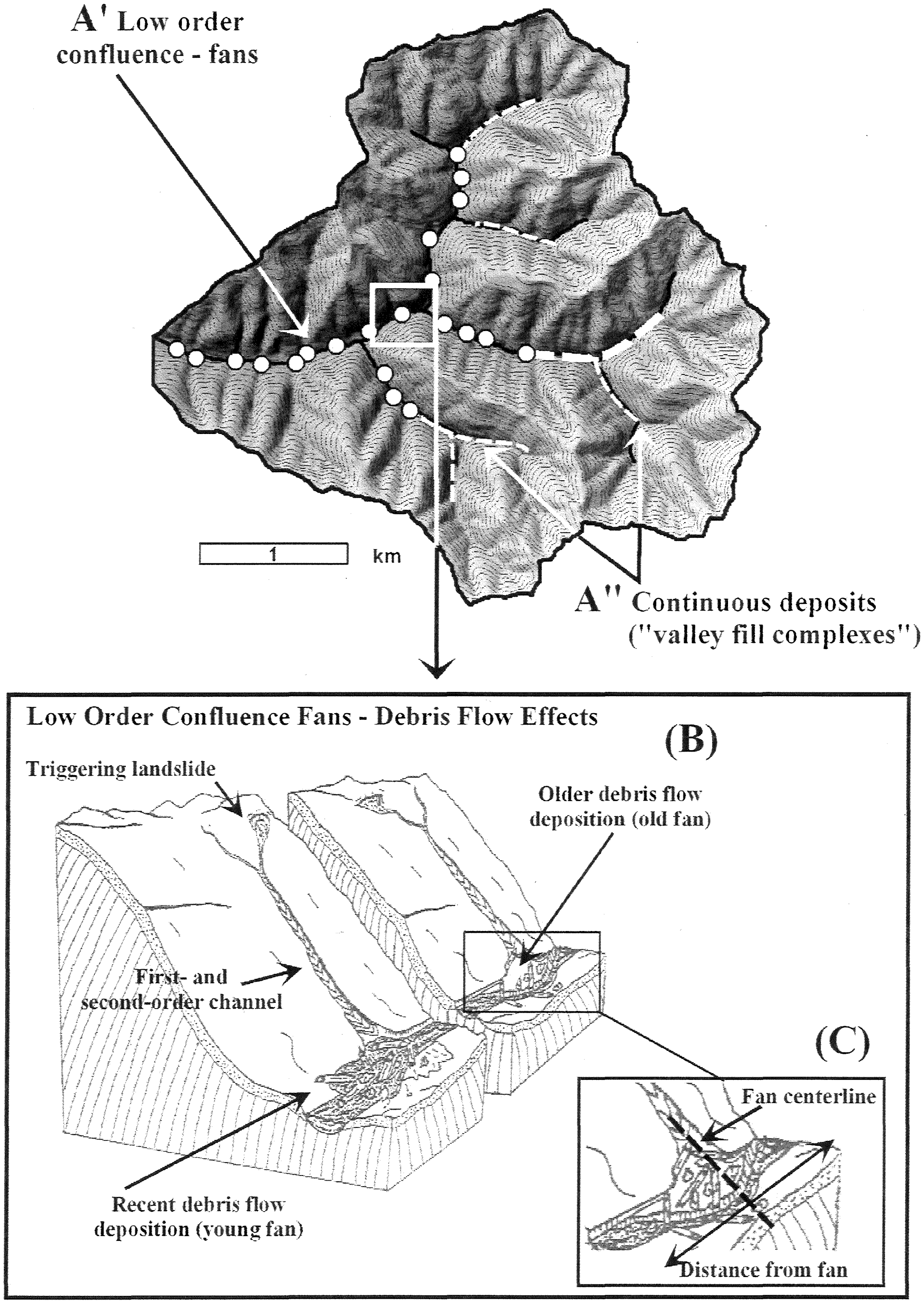

Figure 2. (A) Patterns of debris flow deposition in Harvey Creek basin. (A′) White dots represent observed debris flow deposits (debris fans) at confluences of first- and second-order headwater streams observed in the field and predicted using the model of Benda and Cundy (1990). (A″) Dashed white lines show colluvial valley fill complexes where debris flows create semicontinuous deposits and terraces along upper third-order channels as modeled by Benda and Dunne (1997). (B) Effects of deposits depend, in part, on their age. (C) Morphological effects of debris flows were evaluated according to the distance from nearest (upstream or downstream) "fan centerline."

Characteristics of channel morphology (gradient, boulders, sediment depth, and wood) that were measured in this study are important for salmonid habitat quality and abundance (Sullivan et al. 1987) and are hereafter referred to as channel parameters. Channel parameters were recorded for each reach (mean length 30 m, range 4–132 m), the length of which was based on breaks in channel gradient, changes in stream type and bed texture, or visibility (i.e., where overhanging vegetation, large wood jams, or meander bends precluded longer reach measurements with the rangefinder). The midpoints of all surveyed reaches were registered according to distance from the centerline of the nearest upstream or downstream fan, defined as the line drawn perpendicularly from the headwater tributary to the higher-order mainstem channel at the confluence (Figure 2C, Benda et al. 2003a). The proportion of streambed covered by boulders (>264 mm) was visually estimated. Average sediment depth through each reach was estimated (in 25-cm depth increments) by survey rod where channel bedrock was exposed. Where channel bedrock was not exposed and boulders were not observed, a minimum sediment depth of 2.5 m was recorded (we assumed that boulders were buried in the alluvium).

Wood pieces (>10 cm in diameter and 3 m in length) were counted within the channel and floodplain. Where feasible, the processes delivering large wood pieces to streams were identified, including bank erosion, tree mortality, or debris flow (Murphy and Koski 1989, Benda et al. 2002, May and Gresswell 2003). Wood recruited by bank erosion had roots connected to the stream bank, or the roots were in the channel and bank erosion was evident. Wood delivered by debris flows was located within or proximal to debris flow deposits. Wood recruited by forest mortality originated from within the riparian forest: broken pieces had a source snag or stump that was apparent, while intact pieces were still connected to roots and were likely a result of being blown down. Pieces classified as unknown had no obvious connection to the riparian stand, could not be identified to a recruitment source, and often showed signs of fluvial transport (abrasion, broken limbs or ends, or located in log jams).

Data Analysis

To aid in evaluating the spatial scale and structure of debris flow influences on fish-bearing channels and valley bottoms, we calculated the length of individual fan perimeters and coalescing fan perimeters (i.e., fans overlapping each other on the same side or from opposite sides of a channel), and the percentage of channel length bordered by fans in each basin. We also measured the distances separating tributary fans (at their centerlines, Figure 2C).

Statistical analysis of inherently variable channel environments with nonlinear patterns is difficult at best (e.g., Benda et al. 2003a, Kiffney et al. 2006) and consequently many confluence studies rely on visual plots of data (e.g., Benda et al. 2003b, Hoffman and Gabet 2007). To visually evaluate the spatial relationship between debris fans and channel parameters, we created scatter plots of channel parameters by distance from nearest fans and longitudinal profiles of channel parameters and associated debris fans.

We also evaluated the spatial relationship between channel parameters and tributary debris fans using histograms of the highest values of morphological features (hereafter referred to as "peak values") following a method similar to Kiffney et al. (2006). Histograms showing the number of peak values by distance from the nearest (upstream or downstream) fan provide a simple method to help determine whether headwater tributary fans create discontinuities in mainstem channel attributes (Kiffney et al. 2006) that reflect substantial changes in channel morphology. Although the resulting effects of tributary fans on channel parameters can vary in the upstream or downstream direction (see Grant and Swanson 1995, Benda 2003a, Kiffney et al. 2006), we evaluated parameters by distance from the nearest fan (upstream or downstream) because of the close spacing of headwater tributaries and overlapping debris fans in the study area. For each channel parameter, peak values consisted of the five highest values measured at each of the four study sections (roughly the highest 10% of channel parameters within each study basin), regardless of distance from a tributary. Approximately five values were needed from each study section to show a trend. In some cases there were ties in parameter peak values within each study section; to avoid having more than five values in such cases, the highest three or four unique values were selected. We did not select more than five peak values, because ties for some parameters would require selecting 10 or more values from each basin, defeating the intention of a peak value analysis. Peak values were grouped by distance from the nearest fan and data from all four study basins are combined. To normalize the reach distances from the nearest fan across the four study sections, the reach distances from fan were divided by the longest reach distance from fan within each of the four study sections. For example, the distance from the nearest fan for each reach in Harvey Creek was divided by the longest reach distance from the nearest fan encountered in that stream. Because of the close spacing of headwater tributaries, more reaches had midpoints closer to fan centerlines than further from fans (e.g., Benda et al. 2003a). Consequently, to maintain an equal number of reaches in each "distance from fan centerline group" for fair comparisons, the length scale of distance groups are not uniform (Benda et al. 2003a).

We also included an outlier analysis of channel parameters, which evaluates whether a peak value is within the range of variation expected for the basin (Kiffney et al. 2006). We used a typical definition of outliers (o):

$$o < \mathrm{Q1} - 1.5 * \mathrm{IQR} \quad \text{or} \quad o > \mathrm{Q3} + 1.5 * \mathrm{IQR},$$

where Q1 and Q3 are the first and third quartiles of a given parameter distribution within each study section, and IQR is the interquartile range (Q3–Q1).

Results

Scatter plots of channel parameters, such as wood pieces and boulders, by distance from nearest debris fan revealed distinct spatial patterns. Our most illustrative examples show that wood and boulders in Unamid and Harvey Creeks were generally more abundant near fans than further away (Figure 3, Appendix A). Longitudinal plots also revealed patches and spikes of wood near fan centerlines (Figure 4, Appendix B), particularly near recent fans. In many cases, frequencies of large wood associated with debris fans were hundreds of percent greater than frequencies at locations further from confluences with headwater tributaries (low-order confluences).

Although the scatter plots and longitudinal profiles of channel attributes provide visual evidence of the effects of low-order confluences on the spatial distribution of channel parameters, the analysis of peak values and outliers provides more quantitative support. The mainstem channel surveys revealed that values of channel gradients, boulders, and large wood were greater nearer to debris fans than farther away (Figure 5). Many of these peak values were outliers

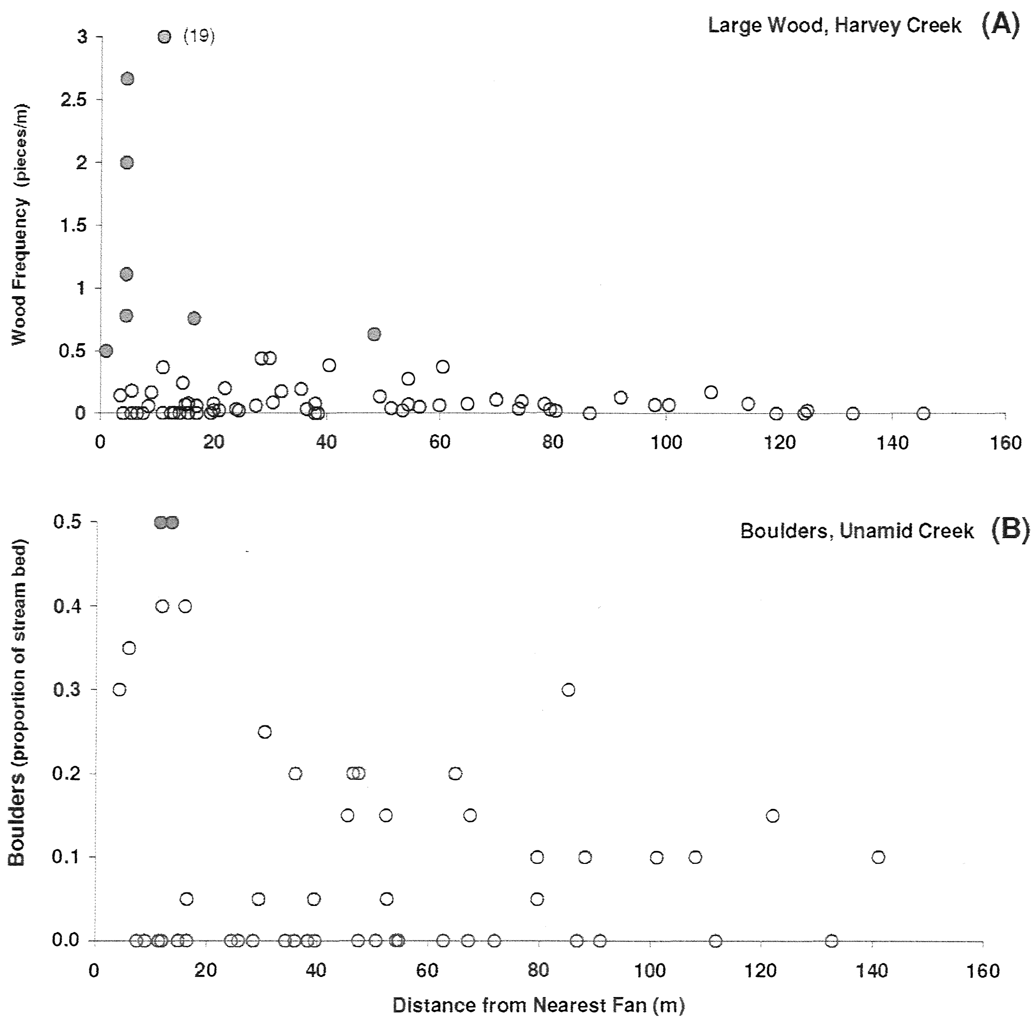

Figure 3. Scatter plots of (A) wood frequency in Harvey Creek, and (B) boulders in Unamid Creek; both plots showing higher and more variable magnitudes near fans. Outliers are shown in gray, maximum value shown in parentheses to maintain useful vertical scale. Similar patterns of boulders and wood concentrations are apparent in other study sections not shown here (Appendix A).

and essentially outside the range of variation expected from the distribution of values measured throughout the study basin. Discontinuities in peak values of parameters appear to spatially coincide; for example, several steps in the longitudinal profile of Form Creek (i.e., abrupt increase in channel gradient) are coincident with higher boulder concentrations near tributary fans (Figure 6). Although thicker wedges of sediment are nonuniformly distributed and frequently associated with increased boulder accumulations at fans, they also extended upstream and downstream from debris fans (Figure 7, Appendix C), and consequently were not detected in our peak value analysis. Other factors, such as log jams and local low gradient areas, store sediment in our study reaches, thereby limiting the alluvial sediment storage effect at headwater tributary confluences.

Debris flows played a major role in supplying wood to fish-bearing streams in the study area. Of the 1,311 wood pieces identified in the four study sections, 58% were from debris flow deposits, 13% were recruited by tree mortality (from within the local riparian forest), 2% were recruited by bank erosion, and 28% could not be identified to a recruitment process (unknown). Within each of the four study sections, debris flows recruited between 31 and 85% of the wood pieces, with lesser amounts recruited by mortality and bank erosion (Figure 8). These are conservative estimates because unknown sources are included in the total.

Each confluence with a headwater (first- or second-order) tributary had a debris fan, resulting in a total of 54 debris fans along the 6.4 km of the four study sections. Thirty-two of these fans were classified as recent deposits (<60 years) (Table 1) and 16 of these were estimated to have occurred within the past 10 years. Of these 16, three originated from harvested areas, the rest originated from mature, unmanaged forests.

The length of continuous fan perimeters (including overlapping or coalescing fans) ranged from 83 to 123 m and averaged 103 m (Table 1, Figure 9A). Relative to the perimeter length of the fans, the distance between headwater tributaries was shorter (65–170 m, average 118 m, Table 1, Figure 9B), as the perimeters of many fans overlapped each other on opposite sides of the stream, and occasionally on the same side of the stream. As a result, debris fans bordered

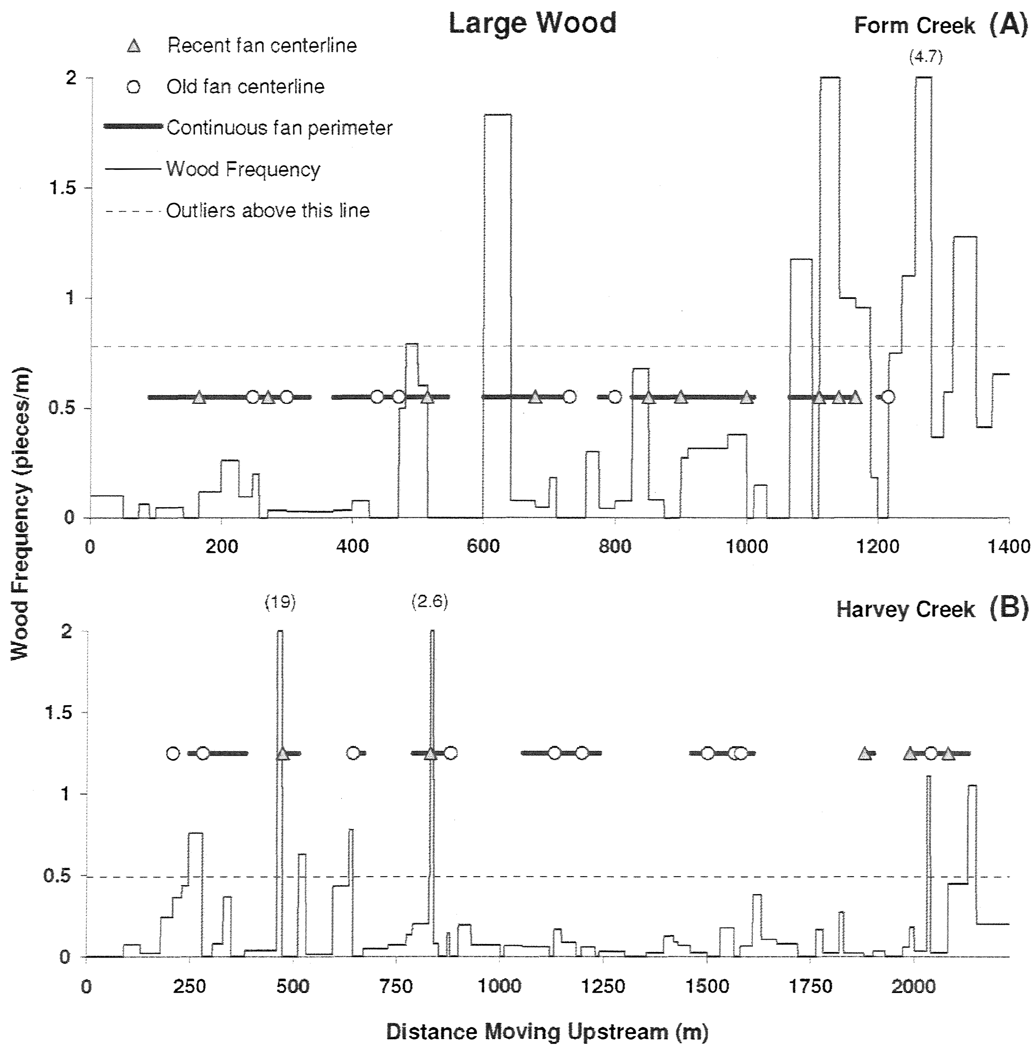

Figure 4. Long profiles of wood frequency along (A) Form Creek and (B) Harvey Creek showing patches and spikes of higher wood frequencies near and within debris fan perimeters, particularly recent fans. Maximum value shown in parentheses to maintain useful vertical scale. Higher wood frequencies at the top of Form Creek (~1,250–1,400 m section) are from two 1996 debris flows that enter the mainstem just above the study section. Similar patterns of wood concentrations near fans are also apparent in other study sections not shown here (Appendix B).

between 38 to 68 percent of the surveyed channel length (Table 1), averaging 54 percent across all four study sections.

Discussion

Debris Flow Deposits and Effects on Channel Morphology

Our findings of the morphological effects of debris flows on low-gradient, fish-bearing channels, such as accumulations of wood, boulders, and sediment at tributary confluences (Figures 3–8), are consistent with those of other studies in mountain channels of the Pacific Northwest (Swanson and Lienkaemper 1978, Hogan et al. 1998, Benda et al. 2003a), and suggest how debris flows may influence the development and spatial organization of aquatic habitats in small basins (<10 km^2) in the Oregon Coast Range. For example, many of the steep gradients near fans at low-order confluences are due to concentrations of boulders exhumed from debris flow deposits. These boulder concentrations persist over time because high flows in these small channels lack the competence to transport them. Other than debris flows, there are few additional sources of boulders in the study area, such as canyon walls. Higher concentrations of boulders, wood, and alluvial sediment near low-order confluences with debris fans also correspond with the general understanding of sediment and wood dynamics in mountain channels. Over time, boulders exhumed from debris flow deposits create higher in-channel roughness. Increased roughness from boulders causes increased storage of smaller, transportable sediment (Harrison and Keller 2003). Large boulders and debris fans tend to pinch channel width and locally reduce wood transport, increasing wood storage (Montgomery et al. 2003). The combination of higher roughness elements near fans, such as boulders and wood, in conjunction with deeper alluvial sediment, has potential for greater pool abundance over time (Benda et al. 2003a). Discreet alluvial sediment stores also appear to be spatially

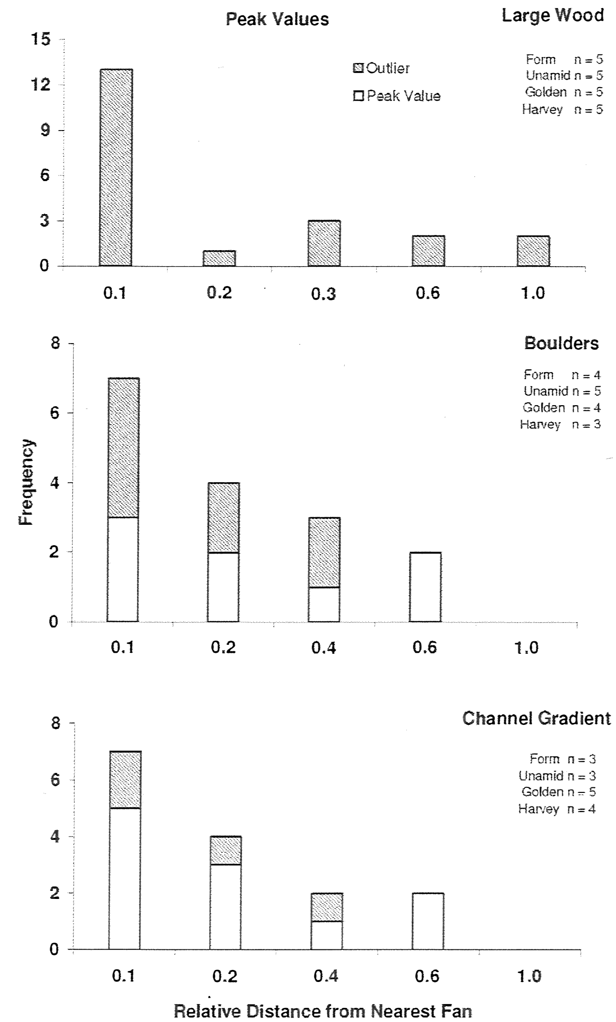

Figure 5. Frequency histograms of peak channel parameters by relative distance from nearest fan showing higher peak values near fans. The proportion of peak values that are also outliers are shown by hatch marks. To normalize the reach distances from nearest fan across the four study sections, the reach distances from fan were divided by the longest reach distance from fan within each of the four study sections (see Methods section), resulting in a relative distance from nearest fan for the *x* axis. While thicker wedges of sediment are often associated with increased boulder accumulations at fans, they also extended upstream and downstream from debris fans (Figure 7, Appendix C), and consequently were not detected in our peak value analysis and therefore not shown here.

coincident with headwater confluences in many cases (Figure 7, Appendix C). However, the extension of sediment wedges up and downstream of fan areas and the importance of other controls, such as log jams, obscured the effect in our analysis of peak values.

In the study basins, the occurrence of boulders in channels is partly related to the depth of alluvium within the channel. Where boulders were observed, the average depth of alluvial sediments (mixed grain size dominated by gravel) was always less than the mean boulder diameter. However, as sediment depth increases, boulders disappear beneath the alluvial cover. This is illustrated in the comparison between sediment depth and boulder concentrations in the middle section of Golden Ridge Creek (Figure 7A) and the bottom of Harvey Creek (Figure 7B), where sediment depth exceeds approximately 1 meter and boulders disappear despite the existence of low-order confluences with debris fans. The thickening wedge of alluvial sediment in the lower section of Harvey Creek appears to be related to network-wide aggradation, possibly from postwildfire erosion in the late 1800s that occurred in the study basins (Morris 1934, Reeves et al. 1995, May 2001). Upstream of that point, numerous alluvial terraces containing large amounts of burned wood suggests one or more cycles of aggradation followed by degradation (e.g., Miller and Benda 2000).

The analysis of peak values and outliers (Figure 5) further clarifies the debris flow effects on channel morphology observed in the scatter plots and longitudinal profiles. The close proximity and overlapping nature of low-order confluences and the skewed distributions of channel parameters confounded use of other statistical approaches. Similar difficulties in data analysis have been encountered in other tributary confluence studies of complex channel environments (Benda et al. 2003a, Kiffney et al. 2006). Typically, many confluence zones contain some of the highest values of channel parameters (Figure 5), while others may contain lower values (Figures 3, 4, 6, and 7). In addition, many reaches farther away from confluences may contain no boulders or wood (Figures 3, 4, and 7). Thus, confluence zones generally have higher variation in physical attributes.

To provide a landscape context for our results, it is important to note that debris flows may affect channel morphology differently across the Oregon Coast Range, depending on basin characteristics. In the steeper portions that are highly prone to debris flows, debris flow scour of sediment and wood occurs on channels slopes greater than approximately 10% (Benda and Cundy 1990) and in drainages up to 1 km^2 (Stock and Dietrich 2003). Debris flow deposits in channels with drainage areas less than about 3 km^2 tend to create valley fills and terraces (Figure 2A, Benda and Dunne 1997, Lancaster et al. 2001). Distinct fans at low-order confluences tend to form in mainstem valleys downstream from this point, as we found. Using an empirical debris flow model, approximately 85% of lengths of third-order channels in this landscape are characterized by discreet debris fans at low-order confluences, while 15% are characterized by semicontinuous colluvial debris flow deposits (Benda and Dunne 1997). The downstream extent of debris fan effects diminishes in channels with drainage areas larger than about 50 km^2 because the relative size of the tributary to the mainstem decreases and the higher stream power of the mainstem tends to quickly transport debris deposits (Benda et al. 2004). Within this domain of mainstem rivers where tributary debris fans form and persist (approximately 3–50 km^2 drainage area), which includes our study basins, the largest headwater tributaries should have the most geomorphically significant effects on receiving channels (e.g., Rice 1998, Benda et al. 2004). This is because larger headwater tributaries are more likely to have frequent and larger debris flows given the larger number of landslide and debris flow

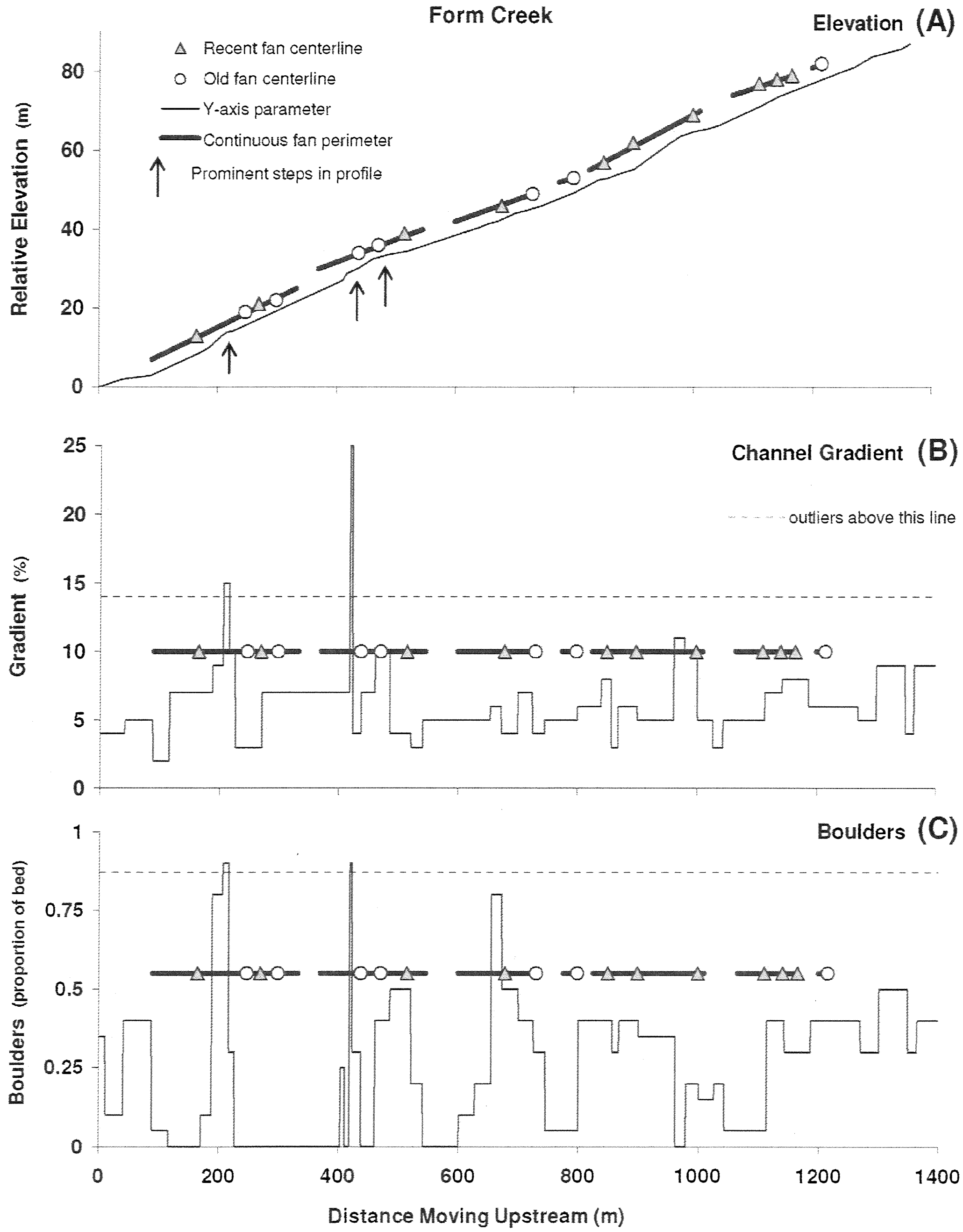

Figure 6. (A) Long profile of Form Creek shows several steps (abrupt changes in gradient) near tributary debris fans associated with (B) steeper gradients, and (C) concentrations of boulder deposits. Note that the first two steps are associated with gradients and boulders that are outliers.

source areas (Benda and Dunne 1997, May and Gresswell 2004).

We selected channels in the central Oregon Coast Range where debris flow effects at confluences would be strong. Because debris flow effects at confluences are ubiquitous in other mountain landscapes (Benda et al. 2003a, 2004 and references cited therein), our results should apply more generally to other mountain landscapes as well. However, our results would not apply to landscapes where other physical processes dominate (i.e., surface erosion, deep-seated landslides, earthflows, and bedrock).

Debris Flow Influences on Wood Recruitment to Streams

Wood recruitment from debris flows into low-gradient, fish-bearing streams in our study basins ranged from 31 to 85% (Figure 8) and 58% for all basins combined. The high estimates of wood recruitment from debris flows in our study likely results from two factors. First, the large 1996 storms triggered numerous debris flows in the central Oregon Coast Range (Robison et al. 1999), creating a spike in wood recruitment (this can be seen in the "recent" fans in

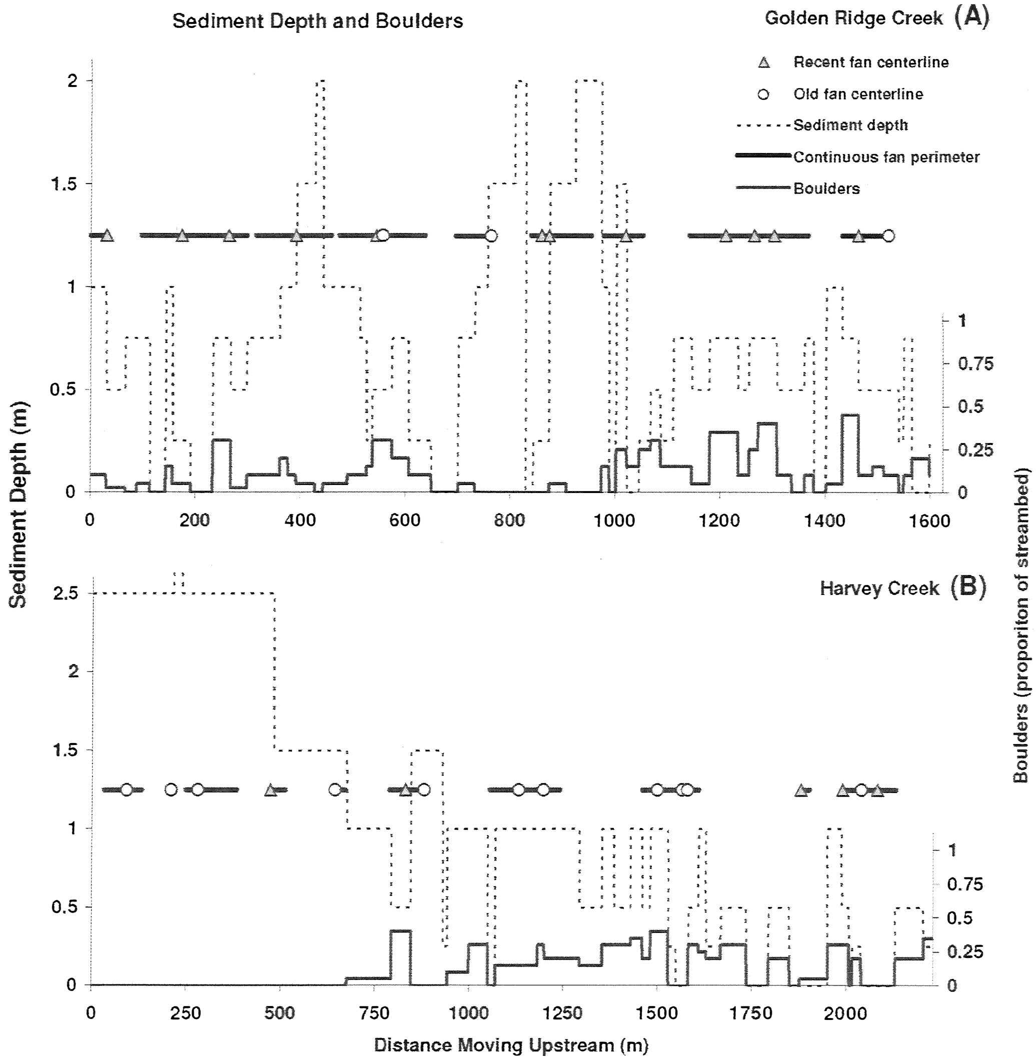

Figure 7. Long profiles of sediment depth and boulders in Golden Ridge and Harvey Creek basins showing generally higher concentrations of boulders near debris fans, with the exception of aggraded areas with thick sediment depths that apparently bury the boulders; for example, the (A) interval between 700 and 1,000 m in Golden Ridge Creek, and (B) bottom 700 meters in Harvey Creek. Thicker sediment depths also appear to be concentrated near fans in Golden Ridge Creek, particularly near recent fans. Similar sediment depth and boulder patterns were evident in Unamid and Form Creeks to a lesser degree (Appendix C).

Figure 4). Second, although we did not conduct a survey of riparian forest composition, other studies that included sites in unmanaged areas of the central Oregon Coast Range have documented low levels of mature conifer trees in the near streamside zone (Nierenberg and Hibbs 2000). Conifers may be more abundant in riparian areas near headwater streams (first-order) than along mid- and higher-order streams (e.g., Pabst and Spies 1999). Because streamflow in headwater streams is insufficient to transport large conifers that fall into small streams, debris flows are necessary to route wood derived from conifers in riparian areas along headwater streams to larger channels downstream. Conifers are also delivered directly to larger channels from adjacent riparian areas through local processes such as tree mortality and bank erosion (Van Sickle and Gregory 1990). In areas were debris flows are common and conifers along larger channels are sparse, debris flows are likely to be important sources of conifer wood to larger, fish-bearing channels in unmanaged forests.

Our observations of high wood recruitment from debris flows are similar to another *unmanaged* basin in the Oregon Coast Range where 65% of the wood pieces were delivered to the channel from upslope sources, most likely by mass wasting (Reeves et al. 2003). Other studies in unmanaged Coast Range basins have found lesser amounts of wood from debris flows in mainstem channels, including 33% of pieces (May and Gresswell 2003) and 3% of wood jams (Montgomery et al. 2003). The differences between studies are not unexpected, since wood storage is inherently highly variable, even within a basin, as shown in this study and others (Benda et al. 2002, May and Gresswell 2003, Comiti et al. 2006). Further differences between studies may be due to a variety of factors, including differences in terrain, time

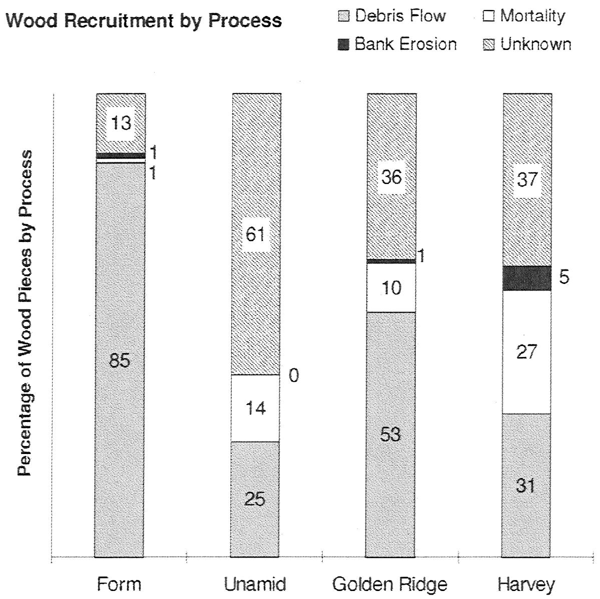

Figure 8. Percentage of wood pieces recruited by process in each study basin. This calculation includes pieces that could not be identified to a process (unknown) and therefore a minimum conservative estimate for recruitment by identified processes of debris flow, bank erosion, and mortality.

since last disturbance (debris flow, fire, floods), and methods. For example, Montgomery et al. (2003) examined the source of wood jams, rather than of total wood pieces, in two unmanaged stream reaches with few tributaries.

In modeling the long-term average percentage of wood delivered to fish-bearing streams by debris flows, Benda and Sias (2003) estimated 12% under natural conditions using an average recurrence interval of 500 years for the Oregon Coast Range (Benda and Dunne 1997) and full conifer canopy in the riparian forest. Using the same analysis, but with an updated recurrence interval estimate range of 98 to 357 years (May and Gresswell 2004), the long-term average contribution of debris flow wood increases to 25 to 60%. Knowledge about how debris flows influence stream channel morphology in unmanaged forests is of interest for many reasons, including interpreting effects attributed to land management. However, model results and available field studies, including ours, are insufficient for broad generalizations and must be recognized as incremental contributions to understanding a landscape where few opportunities remain for examining debris flows in unmanaged forests.

Role of River Network Geometry on Debris Flow Effects in Channels

The high spatial density of headwater channels susceptible to debris flows in the study basins (approximately 10 per km of fish-bearing channel) produces short interconfluence distances and average continuous fan perimeters of similar magnitude. This creates substantial contact between fans and fish-bearing channels (Figure 9, Table 1). That approximately 67% of low gradient channels used by coho salmon in the Oregon Coast Range lie in small basins (<10 km^2) with frequent debris flow deposits underscores the importance of this sizable coupling between debris fans and fish-bearing channels.

The proportion of channels impinged and influenced by fans should vary between basins based on differences in overall basin width, drainage density, valley wall steepness (i.e., tributary channel gradient), and valley width of receiving channels; these factors were not evaluated in our study. It is difficult to distinguish and make sharp demarcations between channels strongly influenced by debris flows at low-order confluences and channel reaches that are not because of the close proximity of confluence deposits and their overlapping nature, either on the same side of the valley or across the valleys. Nevertheless, apparent zones of confluence influence in the longitudinal plots of channel parameters are identifiable in Figures 4, 6, and 7.

Adding Confluence Environments to Stream Classification and Habitat Typing

Our field study points to the effects of low-order tributary confluences on the spatial distribution of channel morphology (particularly boulders, wood, and gravelly alluvium) and increasing morphological heterogeneity and patchiness along channels. Steeper channel gradients and higher concentrations of wood and boulders near low-order confluences create discontinuities in channel morphology that might not exist in the absence of such lateral inputs (e.g., Rice 1998, Benda et al. 2004, Ferguson et al. 2006, Hoffman and Gabet 2007). Longitudinal profiles of habitat parameters along individual study sections show clusters and spikes of wood (Figure 4) and clusters of boulders and zones of thicker sediment (Figures 6C and 7) associated with tributary debris fans. The size and spacing of these patches with higher morphological diversity is on the order of hundreds of meters (Figures 4, 6, and 7), larger than would be expected from habitat patches created by individual wood pieces, boulders, or channel meanders. The spacing of debris fans and any associated habitat patches is influenced by the distance between tributaries susceptible to debris flows, which ranged from 65 to 170 m (Table 1, Figure 9B) in the study basins.

It is feasible to use information such as the peak value analysis (Figure 5) to estimate a length scale of confluence effects. For illustration, one could select a zone 25 m in length extending up and downstream of fans to demarcate a potential confluence environment, while intervening areas could be classified as "nonconfluence zones", an approach conceptually similar to classifying active and inactive fans and floodplains in the Oregon Cascades used by Grant and Swanson (1995). Channels could then be classified according to confluence and nonconfluence zones (Figure 10A). Based on an estimated zone of confluence influence of 50 m and variation in spacing of headwater tributaries, potential confluence zones in Harvey Creek, for example, may range from 25 to 160 m, the larger size reflecting a coalescing of several tributary confluence zones (Figure 10A).

Presently, many stream classification systems (such as Rosgen 1994, Montgomery and Buffington 1997) and habitat typing schemes (such as Bisson et al. 1982, Hawkins et

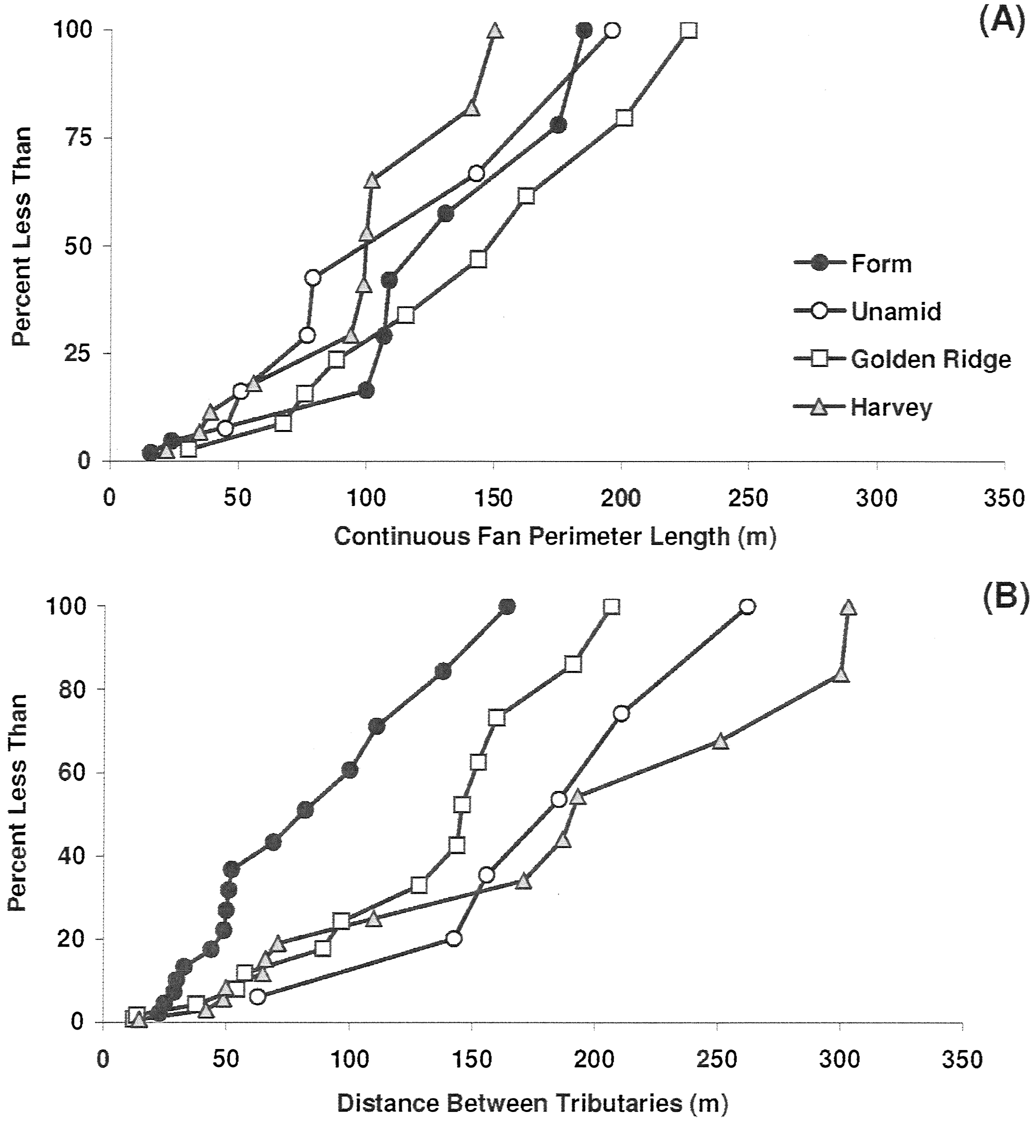

Figure 9. (A) Cumulative distributions of the continuous fan perimeters in the four study basins that average from 83 to 123 m and cumulatively border 54% of the fish-bearing channels in the area. Continuous fan perimeters are the length of stream continuously bordered by a fan, including fans that overlap each other on the same or opposite sides of the stream. (B) Cumulative distributions of the spacing between tributaries (fan centerlines) in the four study areas, with average spacing ranging from 65 to 170 m. Data are confined to low-order confluences.

al. 1993) do not formally address channel confluence zones. Based on our study and other work that has identified the importance of confluences on channel morphology and aquatic habitats (Mosley 1976, Best 1986, Church 1983, Benda 1990, Wohl and Pearthree 1991, Grant and Swanson 1995, Hogan et al. 1998, Rice et al. 2001, Benda et al. 2003a, Benda et al. 2004, May and Gresswell 2004, Kiffney et al. 2006, Rice et al. 2006), we propose that confluence zones be added to stream classification and habitat typing methods. The spatial pattern of confluence zones is expected to vary among basins of similar sizes due to topographic differences in drainage density, local network geometry (Benda et al. 2004) (Figure 9), erosion potential, and basin size (Figure 10B). Classification of confluence zones could be based on the relative size of tributaries to the mainstem channel (Rice 1998, Benda 2004), including erosion potential of tributary basins (Rice 1998), and on other factors such as valley width. Formally including confluence zones in stream classification and habitat typing (e.g., Figure 10A) may later help analysts elucidate structural patterns, sources, and forcing of different channel and habitat types. An example of integrating confluence environments into basin-scale predictions of habitat potential is provided in Benda et al. (2007).

Implications For Land Management

Watershed managers may wish to protect headwater tributaries prone to debris flows that are a substantial source of wood, coarse sediment, and boulders to fish-bearing streams

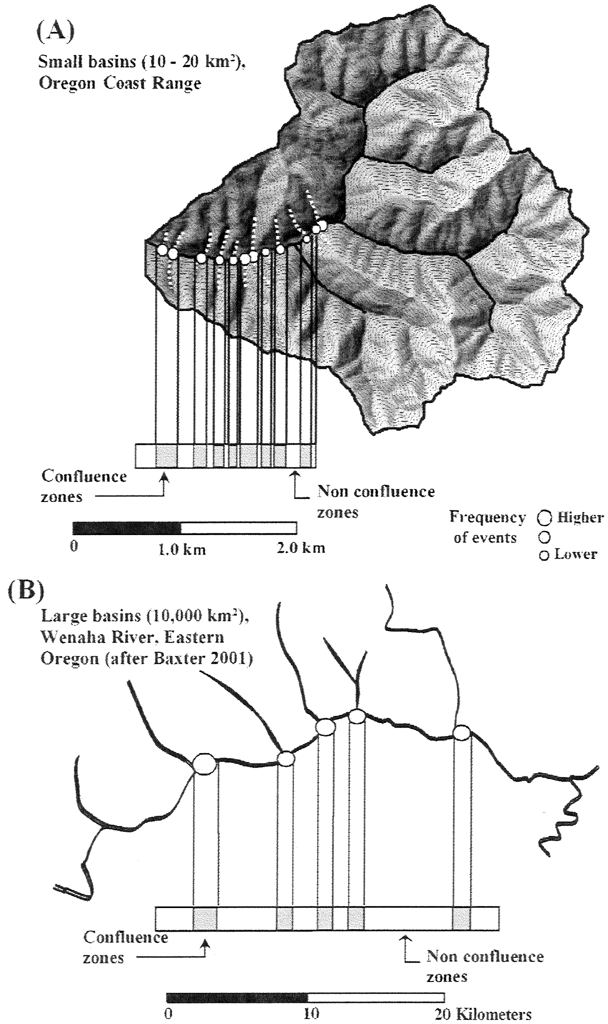

Figure 10. Confluence environments could become a component of stream classification and habitat typing methods. (A) In small to moderate size basins in the Oregon Coast Range (3–10 km^2), confluence environments are relatively short (25 to 160 m), closely spaced, and they have a distinct morphology compared to nonconfluence environments. (B) Classification of confluence environments could be extended to alluvial confluences in much larger basins (500 km^2) where geomorphically significant confluences are separated by multiple kilometers (Baxter 2001).

and potentially create patchy habitats. Because natural debris flows include both wood and sediment, protecting the sources of wood recruited to headwater channels that are periodically scoured by debris flows can be important in providing wood to larger, fish-bearing channels (Reeves et al. 1995, May and Gresswell 2003, Reeves et al. 2003). Such protection may be essential for salmonids in the Oregon Coast Range, where the majority of channels with gradients used by salmonids are within basins subject to frequent and persistent debris flow deposits. To this end, tools have been recently developed to help watershed managers identify basin-scale controls on habitat in general and debris flow sources of wood in particular (Benda et al. 2007, Miller and Burnett in press). Based on numerous field studies and models of landslide and debris flow erosion in the Oregon Coast Range, we propose the following four attributes of debris flows in unmanaged forests be considered relative to aquatic habitats when managing forests in montane areas.

1. Dual Nature of Debris Flows.—Debris flows can destroy habitat over short time periods, but may also construct and diversify habitats over longer time frames. The negative consequences of debris flows on habitats are always important to consider. However, a longer-term perspective over larger, landscape scales can provide insights on the distribution and abundance of habitat types and sensitivity (see Reeves et al. 1995, Benda et al. 1998, Swanson et al. 1988) and a context within which to interpret management effects. Such a perspective on debris flows would logically incorporate concepts of disturbance ecology and encourage forest practices based on dynamic, rather than static, landscape attributes (e.g., variable buffers based on sources of wood to streams versus uniform buffers). Acknowledging this twofold nature of debris flow disturbances (short- and long-term effects) provides the basis for rational dialogue in designing regulations and forest management strategies based on dynamic ecosystems.

2. Debris Flows Can Be an Important Source of Wood to Fish-Bearing Streams.—Transport of wood is a major factor in how debris flows contribute to aquatic habitats. Consequently, the composition of debris flows is critically important (Reeves et al. 1995, May and Gresswell 2003). Because clearcutting along ephemeral headwater channels over multiple rotations likely depletes large wood stored in debris flow-prone channels, one strategy might include protection of trees recruited along headwater channels that have a high likelihood of delivering wood to fish-bearing channels (May and Gresswell 2003, Reeves et al. 2003). Trees left along headwater streams and on fans would also promote shorter runout distances (e.g., Lancaster et al. 2003).

3. Land Management Can Alter the Spatial and Temporal Dimensions of Debris Flows.—Naturally occurring fires in the Oregon Coast Range led to spates of landslides and debris flows before forest management (Benda and Dunne 1997). Forest clearcutting can also lead to elevated rates of landsliding and debris flows (Swanson and Dyrness 1975, Schmidt et al. 2001), but at different spatial and temporal scales than those associated with fire. Therefore, both the destructive and constructive effects of debris flows have spatial and temporal dimensions. Too many debris flows occurring over too short a time frame can lead to long-term deleterious effects to fish habitats. Consequently, spatial and temporal patterns of debris flows should be considered where some landslide risk may occur due to forestry activities, such as roads and clearcuts (e.g., Dunne et al. 2001).

4. Topographic Context Determines the Type of Debris Flows Effects.—Debris flow effects in channels, as documented in this and other studies, are confined to a specific set of basin and channel conditions. In the central Oregon Coast Range, localized effects at confluences are most pronounced in basins less than approximately 50 km^2, with mainstem channels of relatively low gradient and moderate valley widths to accommodate fan deposition. In other watersheds that have steeper mainstem channel gradients and larger drainage areas, effects of debris flows may be different (e.g., Grant and Swanson 1995). Thus, a landscape context is necessary when considering the role of debris flows in either unmanaged or managed forests.

Concluding Remarks

The higher frequency of peak concentrations of boulders, wood, and steep gradients we found near fans created discontinuities in channel morphology and associated variation. These confluence-driven discontinuities illustrate how disturbance can contribute structural elements of habitat and thus contribute to habitat heterogeneity in river systems. Empirical observations in this study support a perspective where climatic disturbances (fire and storms), interacting with a branched channel network, construct and organize a mosaic of habitat patches in fish-bearing streams, often concentrated near confluences, as predicted in previous modeling of the Oregon Coast Range (Benda and Dunne 1997, US Forest Service 2002). Consequently, certain aspects of aquatic habitats are ephemeral, driven by variation in the supply of materials to fish-bearing streams (Reeves et al. 1995).

Higher physical heterogeneity found near confluences due to debris flow disturbances in this study may also be linked to higher species diversity, assuming that structurally complex habitats provide more niches and access to environmental resources (Bazzaz 1975, Tews et al. 2004). Despite the observations of increased physical heterogeneity and patchiness near confluences, there are only a few emerging studies linking physical habitat at confluences with higher riverine species diversity (e.g., Rice et al. 2001, Fernandes et al. 2004, Kiffney et al. 2006). A recent Oregon Coast Range study suggests seasonal concentrations of cutthroat trout near some confluences (Gresswell et al. 2006), and further analyses of these relationships are underway (C. Torgersen, USGS Cascadia Field Station, Sept. 28, 2006 personal communication). Still, a series of hypotheses on the linkage between physical heterogeneity at confluences and aquatic diversity (see Benda et al. 2004, Rice et al. 2006) remain to be tested.

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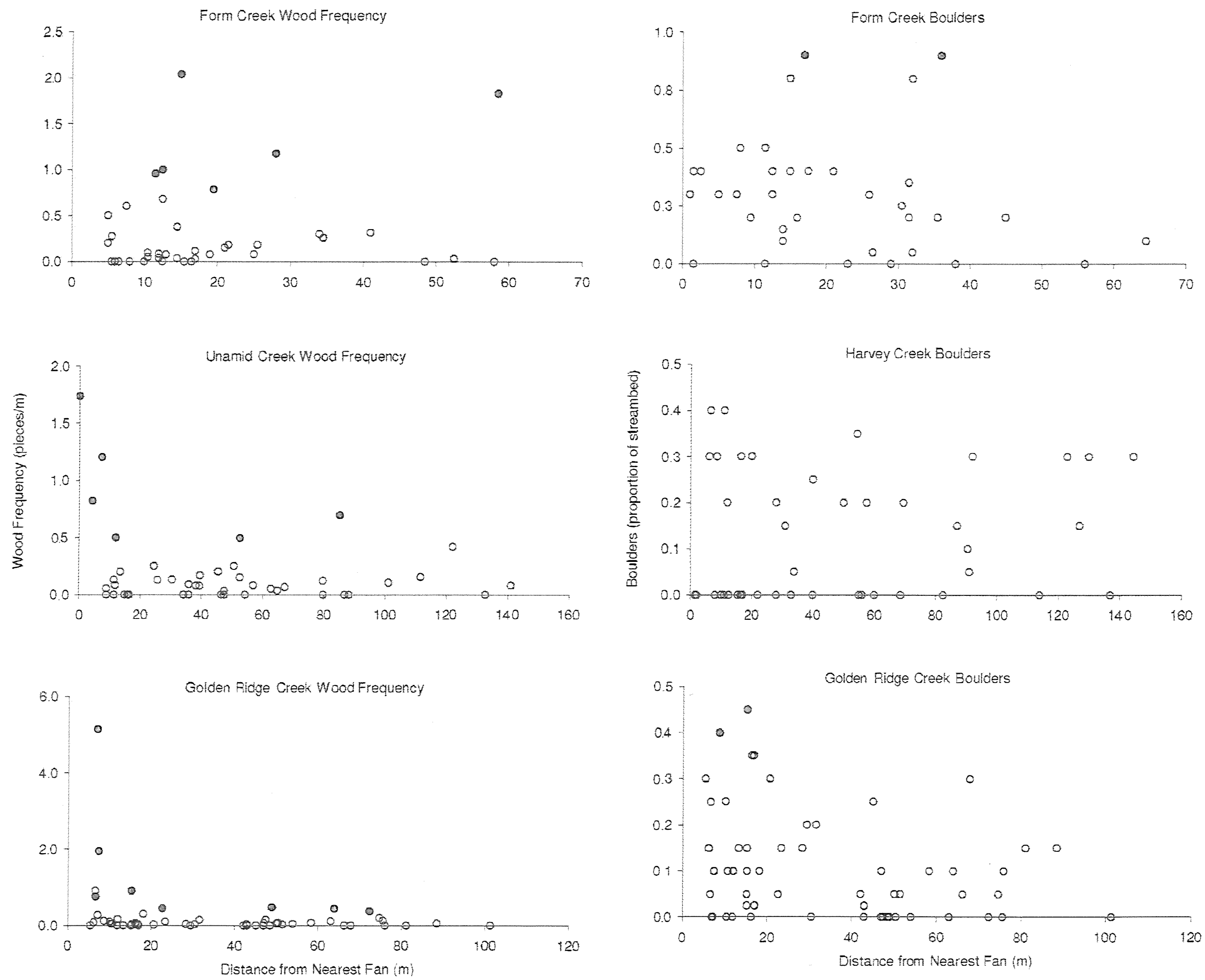
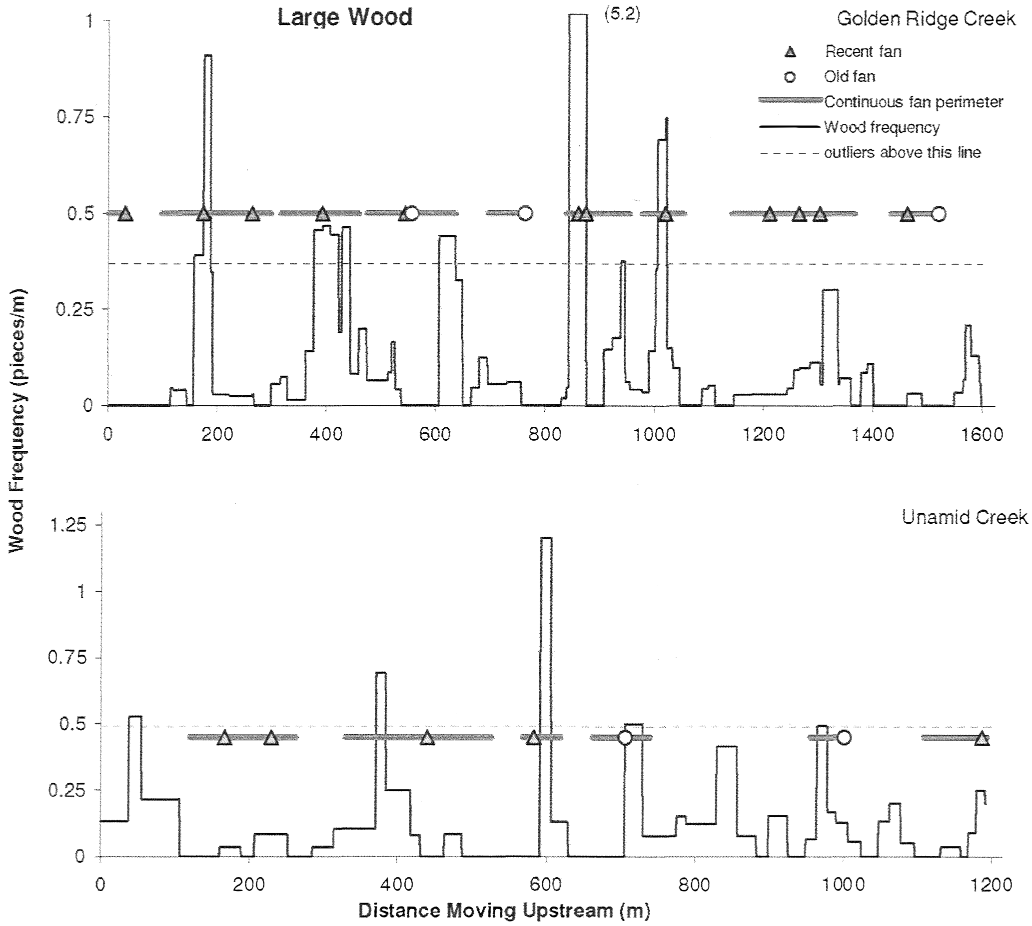
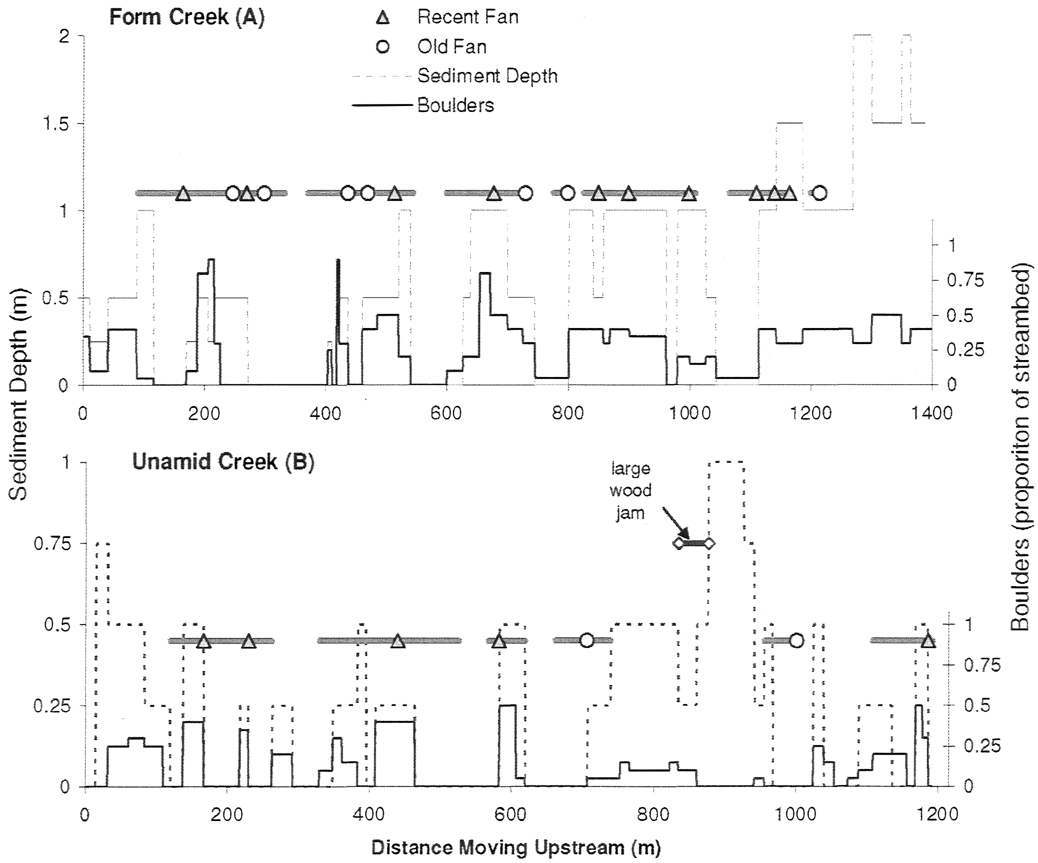
Appendixes



Appendix A. Scatter plots of wood frequency and boulders for study sections not shown in Figure 3. Outliers are shown in gray.



Appendix B. Long profiles of wood frequency for study sections not shown in Figure 4. Maximum value shown in parentheses to maintain useful vertical scale.



Appendix C. Long profiles of sediment depth and boulders not shown in Figure 7.