Debris flows as agents of morphological heterogeneity at low-order confluences, Olympic Mountains, Washington

Lee Benda[†]
Earth Systems Institute, 310 North Mount Shasta Boulevard, Suite 6, Mount Shasta, California 96067, USA
Curt Veldhuisen[‡]
Skagit System Cooperative, 25944 Community Plaza Way, Sedro Woolley, Washington 98284, USA
Jenelle Black[§]
Hart Crowser Incorporated, 1257 Main Street, Fortuna, California 95540, USA

ABSTRACT

Effects of tributary junctions on longitudinal patterns of riverine heterogeneity are relevant to both fluvial geomorphology and riverine ecology. We surveyed 10 km of small- to moderate-sized mountain channels in the Olympic Peninsula, Washington, to investigate how low-order confluences prone to debris flow deposition directly and indirectly influenced channel and valley morphology. In the Olympic Mountains, debris flows scour sediment and organic material from steep first- and second-order channels and create deposits (debris fans) at tributary junctions in higher-order streams. In lower-energy depositional environments there were statistically significant relationships among debris fans at low-order confluences and gravel substrate, wide channels, and numbers of logs and large pools. Effects of debris fans on channel morphology extended upstream and downstream of fan perimeters, indicating the importance of indirect (offsite) effects of debris flows. Consequently, certain aspects of channel morphology (e.g., pool density, substrate texture, and channel widths) were nonuniformly distributed, reflecting the role of network topology and disturbance history on the spatial scale of morphological heterogeneity. Moreover, heterogeneity of channel morphology increased in proximity to low-order confluences prone to debris flows. In contrast, confluence effects in higher-energy depositional environments were limited. Our field data and information from seven other studies indicate how variation in debris flow volume and composition, stream energy, and valley width at the point of deposition influence the relationship between low-order confluences and channel morphology.

Keywords: slope stability, fluvial geomorphology, debris flows, natural hazards.

INTRODUCTION

Effects of tributary confluences on morphology of streams and rivers have been recognized in a number of landscapes over the past half-century. Tributary junctions can affect development of floodplains and terraces, planform and hydraulic geometry, and substrate size in receiving channels, which may lead to increased physical heterogeneity. This aspect of fluvial geomorphology is directly relevant to emerging perspectives in riverine ecology that emphasize the role of physical heterogeneity in maintaining diverse and productive aquatic and riparian habitats. Fans created by debris flows, fire-induced erosion and sedimentation, and large floods also have implications for the principle of disturbance ecology, particularly as it pertains to the dynamics of habitat formation. The purpose of this paper is to evaluate the role of debris flow fans on channel heterogeneity along small- to moderate-sized channels in the Olympic Mountains, Washington. A further objective is to evaluate how stream energy affects debris fan impacts on channel morphology.

Changes in channel morphology occur downstream of alluvial and debris fans because of abrupt increases in discharge and sediment supply that are often accompanied by changes in the size of sediment delivered. Morphological changes also occur upstream of fans due to valley constrictions and fan-induced reductions in channel gradient that impede transport of sediment and organic material. Morphological effects upstream and downstream of alluvial and debris fans include forming steeper and shallower stream gradients, terraces, and wider floodplains (Small, 1973; Grant and Swanson, 1995; Schmidt and Rubin, 1995; Benda et al., in press), channel meanders and braids (Benda, 1990; Knighton, 1998), wider and deeper channels (Richards, 1980; Benda et al., in press), boulder deposits oftenleading to rapids (Wohl and Pearthree, 1991; Grimm et al., 1995; Griffiths et al., 1996), ponds (Everest and Meehan, 1981), mid-channel bars (Best, 1988), and log jams (Hogan et al., 1998). Channel effects are further differentiated according to whether fans form by debris flows (Benda, 1990; Wohl and Pearthree, 1991), flash floods—including those generated by accelerated post-fire erosion and sedimentation (Schmidt and Rubin, 1995; Benda et al., in press)—and less punctuated runoff-generated floods (Harvey, 1997).

Alluvial and debris flow fans can create morphological conditions in channels that differ from reaches located up- and downstream of confluences. As such, tributary confluences can be viewed as agents of morphological heterogeneity that affect characteristics of terraces, floodplains, bars, channel width, depth, substrate, and log jams. Heterogeneity arises simply due to the occurrence of different morphological conditions at and near junctions relative to areas upstream and downstream of them and also due to the increased range of conditions that can occur at junctions. Chang-

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[†] E-mail: leebenda@aol.com.
[‡] E-mail: cveldhuisen@skagitcoop.org.
[§] E-mail: jenelle.black@hartcrowser.com.

GSA Bulletin; September 2003; v. 115; no. 9; p. 1110–1121; 10 figures; 7 tables.

es in morphological heterogeneity at junctions have relevance for fluvial geomorphology, including sediment transport and storage (Schmidt and Rubin, 1995; Knighton, 1998), floodplain development (Grant and Swanson, 1995), and channel morphology (Best, 1988; Benda, 1990). Hence, certain aspects of fluvial geomorphology are affected by location and size of fans that impinge on channels.

The perspective of confluences as agents of morphological heterogeneity in streams and rivers is complimentary with emerging perspectives in riverine ecology. Specifically, physical heterogeneity is necessary for providing a range of habitats needed for species and population persistence (Reeves et al., 1995; Fausch et al., 2002; Weins, 2002; Poole, 2002). Moreover, morphological heterogeneity can be directly linked to biodiversity (Resh et al., 1988). In general, however, the role of branching networks in riverine ecology remains an outstanding question (Fisher, 1997), although recent fieldwork and modeling have specifically pointed to the importance of tributary confluences in fluvial geomorphology and aquatic ecology (Benda and Dunne, 1997b; Rice et al., 2001; Gomi et al., 2002).

The issue of confluence effects in river ecology also relates to the concept of ''disturbance,'' an ecological principle that recognizes the important role of dynamic watershed processes (i.e., fires, floods, landslides) in altering physical environments (Resh et al., 1988; Reeves et al., 1995; Poff et al., 1997). In this frame of reference, fans represent landforms generated by ''disturbances.'' Consequently, unique morphological conditions at confluences that link alluvial or debris fans directly to physical heterogeneity underscore the role of watershed disturbances in creating diverse habitats. In addition to the spatial dimension of confluence effects (i.e., size of area affected and spacing of confluences), the perspective of disturbance ecology is also concerned with the temporal frequency of fan construction and the longevity of their effects.

Although relevant to theoretical aspects of river ecology, effects of fans and the disturbances that create them also can be viewed from a more applied perspective. For example, there have been a series of partially conflicting studies regarding the role of debris flows on salmonid habitats in the Pacific Northwest for over two decades (Everest and Meehan, 1981; Scrivener and Brownlee, 1989; Benda, 1990; Reeves et al., 1995; Montgomery et al., 2003; Reeves et al., in press). In humid landscapes of the Pacific Northwest, debris flows scour sediment and logs from steep first- and second-order channels, commonly creating debris fans at low- to high-order confluences. Debris flow deposits can contribute to habitats, including forming of ponds that become occupied by fish and beaver (Everest and Meehan, 1981), releasing nutrients due to buried organics (Sedell and Dahm, 1984), depositing woody debris that creates sediment wedges and pools (Hogan et al., 1998), depositing boulders that trap sediments and create complex habitats (Reeves et al., 1995), and forming wider valley floors containing larger floodplains (Grant and Swanson, 1995). Spates of debris flows may also contribute to varying composition of riparian forests (Nierenberg and Hibbs, 2000) and to increased diversity of channel morphology (Nakamura et al., 2002).

Despite the constructive effects of debris flows, they also can have negative biological consequences. These include immediate burial of existing habitat and direct mortality of aquatic biota (Everest and Meehan, 1981), increased fine sediment in gravels onsite and downstream that suffocates fish eggs (Everest et al., 1987; Scrivener and Brownlee, 1989), and increased bedload transport and lateral channel movement due to heightened sediment supply that scours fish eggs (Tripp and Poulin, 1988).

The objective of this paper is to contribute to the growing body of research on confluence effects in rivers by examining the role of debris flow fans on small- to moderate-sized channels in a humid landscape. Of particular interest is the role of debris flows as agents of morphological heterogeneity and the spatial and temporal scales associated with it. Our field method examines both direct effects (i.e., immediately proximal to deposits) and indirect effects (i.e., extending upstream and downstream of deposits) of debris flows. We also endeavor to shed further light on the debate surrounding debris flows and fish habitats in the Pacific Northwest. We investigated how channel gradient, channel and floodplain width, substrate size, and wood and pool densities varied along streams that were impacted by recent and older debris flow deposits in basins in the Olympic Peninsula, Washington. In addition, we analyzed how channel morphology might vary over time since the last debris flow. Lastly, we compare our data to seven other field studies to help define the relationship between low-order confluences prone to debris flows and channel morphology.

STUDY AREAS

Sites were selected to evaluate the role of low-order confluences prone to debris flows on channel morphology in both low- and high-energy streams in managed and unmanaged basins on northwestern Olympic Peninsula. Study sites included 4 km of third- through fifth-order channels in Finley Creek Basin (Quinault River), Matheny Creek Basin (Quinault River), and Sitkum Creek Basin (Sitkum River). In those basins, landslides and their channel effects occurred in areas of primarily unmanaged forests. Study sites also included 6 km of channel in the Sekiu River Basin covered in second-growth forests (Fig. 1, Table 1). The majority of landslides inventoried in the Finley, Matheny, and Sitkum River Basins were triggered during a large storm in March of 1997 that generated flood flows with recurrence intervals of 10–50 yr (U.S. Geological Survey, 1997).

Study sites were selected where channel geometry encouraged deposition of debris flows at low- to higher-order confluences (Benda and Cundy, 1990). Across the study basins, annual precipitation averages 2800–4000 mm yr^{-1}, mostly as rain between October and April. Lithology varies between marine volcanic rocks to marine sandstones, siltstones, and mudstones. Steep and mass wasting-prone topography characterize the Olympic Mountains, and erosion is dominated by shallow landsides and debris flows (Reid, 1981).

The Sekiu study basins were logged beginning in the 1960s. At least some of the streams had been cleared of large wood following logging to improve fish passage. Deposits of wood and sediment from debris flows were not mechanically removed from any of the tributaries. In the Sekiu Basin, premanagement debris-flow deposits were also observed. However, the majority of debris flows over the past 40 yr occurred in proximity to timber harvest and logging roads (Washington Department of Natural Resources, 1998).

METHODS AND DATA ANALYSIS

Field Surveys

Fieldwork consisted of continuous surveys along channels that ranged in length from 0.4 km to 3 km; all 10 km of channels were surveyed during 1999 (Fig. 1; Table 1). The number of wood pieces (i.e., greater than 1.8 m in length and 0.15 m in diameter) residing within the bankfull channel and floodplain was tallied in 100 m reaches. Identifying the recruitment of wood by mass wasting was feasible only in the larger channels in which mass wasting occurred in the preceding few years (Finley and Matheny Creeks). In these basins, logs associated with mass wasting were either embed-

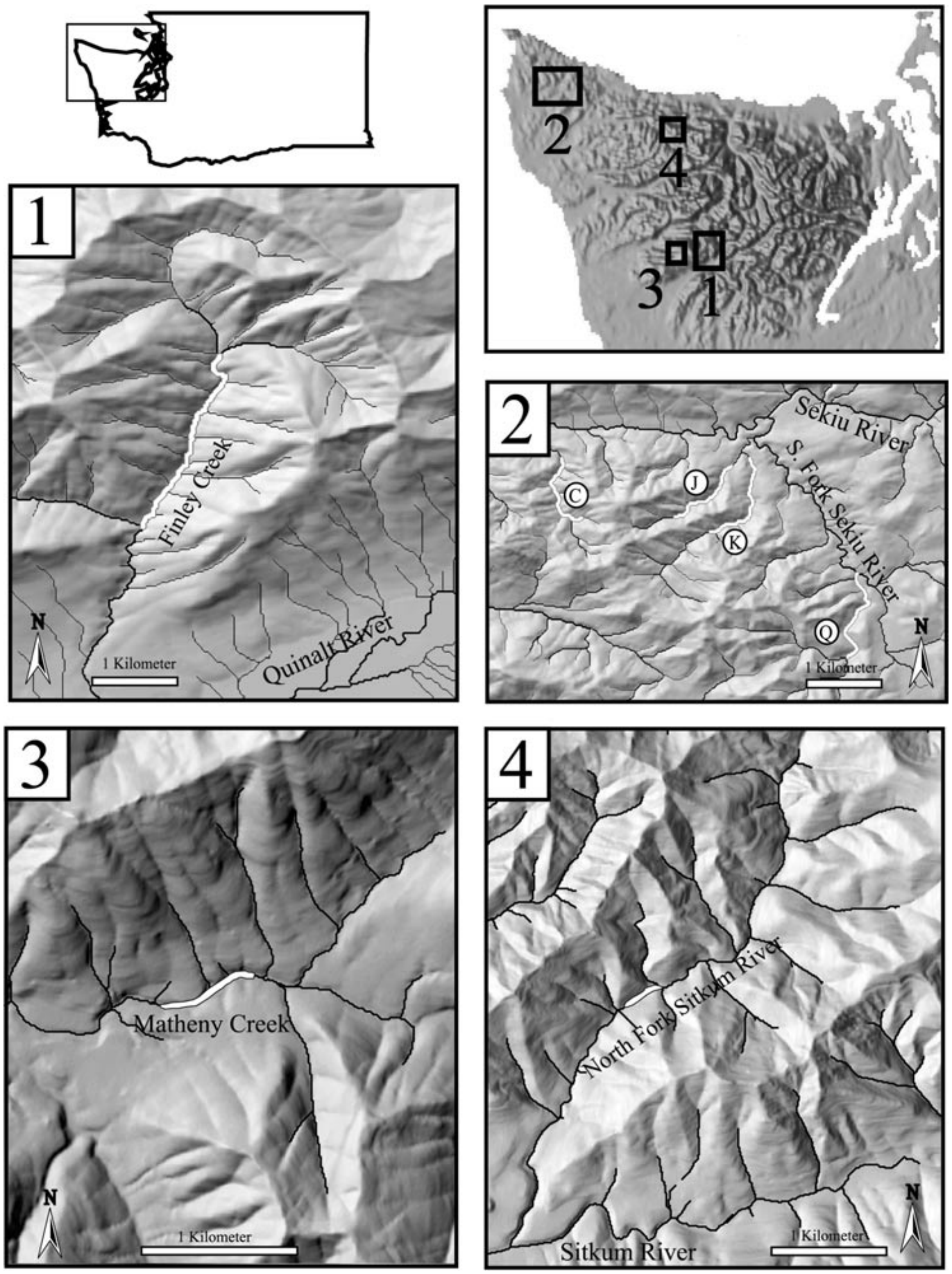

Figure 1. Three study sites (#1, 3, and 4) are located in primarily unmanaged forests in Quinault, Sekiu, and Queets River Basins, Olympic Peninsula, Washington. Four study sites (#2, Q, K, J, and C channels) are located in second-growth forests in Sekiu Basin.

ded in landslide deposits or located immediately below recent landslide scars. Pools were inventoried in the same 100 m reaches as the wood using a protocol that defined minimum residual pool depths (Lisle, 1987) and surface areas based on channel size (Schuett-Hames et al., 1994). Pools were also further identified as ‘‘deep pools’’ ($>$ 0.5-m residual depth), ‘‘large pools’’ ($>$ 30 m^2), and ‘‘wood-formed pools’’ (i.e., where wood was the dominant flow-impeding obstruction).

Channel and floodplain width, gradient, and substrate were measured at smaller reach scales (5–100 m, average 15 m) that reflected spatial variation in these parameters. Channel width was defined by the limits of vegetation-free surfaces. Floodplains were defined by lightly vegetated gravel bars littered with flood debris. In 521 individual study reaches, visual estimates of the proportion of channel covered by different substrate sizes (Hodgson, 1974) were used to determine bed texture following the Wentworth classification (Wentworth, 1922), with gravel defined as 2–64 mm (Platts et al., 1983). Ages of recent debris flow deposits in the second growth study sites (10–50 yr) were estimated by dating deciduous trees on fans using an increment borer and from historical aerial photography. On older fans that predated logging, tree rings were counted on several representative trees to approximate time since last debris flows. Because other factors could determine tree age, such as fire, ages represent minimum values. Debris flow volumes were estimated using scour length measured from aerial photographs multiplied by 5 m^3/m, an average rate of scour (e.g., Benda and Cundy, 1990).

Data Analysis Methods

Effects of debris flows on channel morphology can include ‘‘direct’’ effects, such as logs partially embedded in or proximal to deposits and any associated pools (Montgomery et al., 2003). However, ‘‘indirect’’ effects of debris flows may include the downstream transport and deposition of wood and sediment, including boulders, increased storage of sediment and wood upstream of deposits due to reduced material transport resulting from fan-induced reductions in channel gradients and constricted valley floors, and increased channel avulsions, bank erosion, and wood recruitment both upstream and downstream of deposits (Fig. 2). In lower-energy depositional environments in our study sites, debris flow effects extended upstream and downstream of confluences (defined by the intersection of the channel with the centerline of the low-order valley and fan margins, Fig. 3).

Locations of channel measurements were registered according to distance from debris-flow-prone, low-order confluences to circumvent the limitations imposed by measuring only direct effects and to reduce the need for subjective interpretation of cause and effect between debris fans and channel morphology. To relate channel attributes to individual low-order confluences, we assigned the midpoint of each 100 m study reach a distance upstream or downstream to the nearest intersecting low-order confluence, whichever was closest; this value is referred to as ‘‘nearest neighbor’’ (Fig. 3). Study reaches in the Sekiu Basins where this analysis was conducted, contained a total of 31 confluences. The 100 m reaches were then grouped into distance categories that were physically meaningful while maintaining approximately equal sample size for statistical analysis. Most reaches were near fans because of the relatively close spacing of

TABLE 1. SITE CHARACTERISTICS

Site	Legal[†]	Forest condition	Drainage area (km^2)	Segment length (m)	Channel gradient (Map %)	Lithology	Typical debris volume (m^3)
Finley Creek	T24N, R 9W, Sec 22, 23, 13, 12	Unmanaged	8–16	3000	3–7	MS[2]	∼500–2000
Matheny Creek	T24N, R9W, Sec 18	Unmanaged/ patch logged	4.4	800	3–6	MS[2]	3000–7000
Sitkum River	T29N, R11W, Sec 4	Unmanaged/ patch logged	11	600	8	MS[2]	∼100,000+
Sekiu—C Tributary	T32N, R14W, Sec 21, 20, 16, 17	Second Growth	1.5–2	1300	3	B[3]	∼1000–3000
Sekiu—J Tributary	T32N, R14W, Sec 21, 16, 28	Second Growth	1–1.5	1200	4	B[3]	∼1000
Sekiu—K Tributary	T32N, R14W, Sec 22, 28, 21	Second Growth	2.5–3.3	900	2.5	B[3]	∼1000
Sekiu—Q Tributary	T32N, R14W, Sec 35, 26, 27	Second Growth	3–4.5	2500	2.5	B[3]	∼1000

Note: MS[2]—marine sedimentary rocks, consisting of mudstones, sandstones, and siltstones. B[3]—the Crescent Formation, comprised of marine basaltic rocks.

[†] Description (relative to Willamette Meridian).

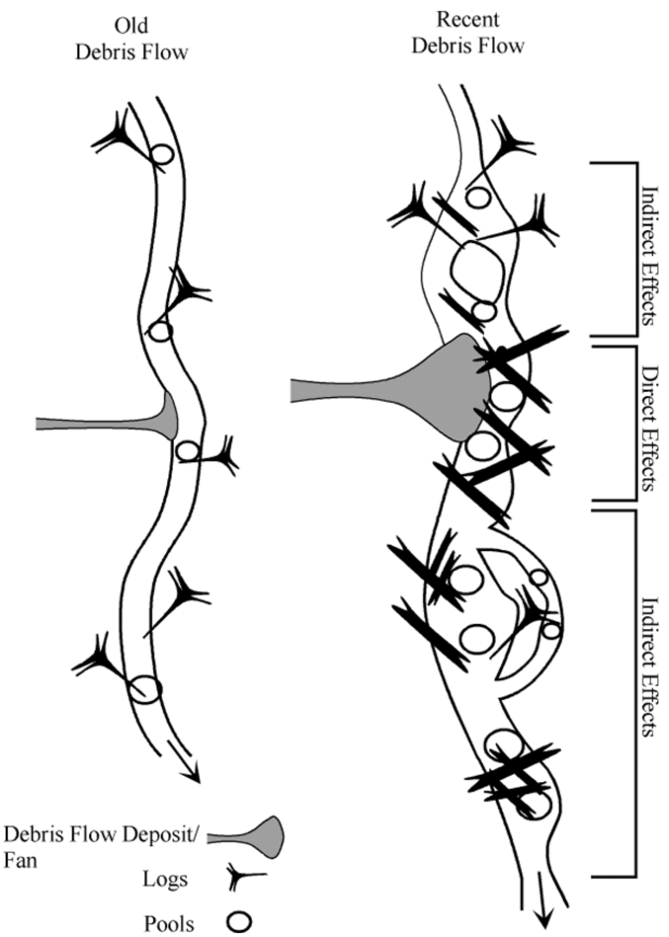

Figure 2. Schematic illustrating relatively isolated nature of "direct" effects compared to longitudinally and laterally more extensive "indirect" effects of debris flows and their fans on channel environments.

low-order tributaries (mean 180 m) and the average length of fan perimeters (85 m). Four distance categories were created that maintained approximately equal sample sizes: $\leq$25 m (closest to a confluence), 26–50 m (within fan margins), 51–150 m (increasing distance from confluence), and $>$151 m (furthest from confluence) (Fig. 3). Analysis of variance followed by multiple comparisons was used to test for differences in average wood and pool counts among the four distance categories. Analysis of variance assumes normally distributed data with equal variance among cells. The distribution of wood counts was skewed but approximately normal when log-transformed (Shapiro-Wilks test for normality, $p = 0.30$). Because pool counts (number of pieces/100 m) were neither approximately normal nor lognormally distributed, the nonparametric rankit transformation was used (Conover, 1980).

To study the effect of debris flow deposits on channel gradient, width, and substrate size, the smaller study reaches were grouped into approximately equal sample sizes. Contingency table analysis was applied to test for differences in reach characteristics among distance groups. In general, a significance level of 0.10 was used; the higher Type I error rate is justified because the physical complexities of channel impacted by debris flows strain the ability of statistical tests to identify relationships.

RESULTS

Low-Order Confluences and Channel Morphology

Our 6 km field surveys in second-growth Sekiu watersheds (Fig. 1, Table 1) revealed correlations among low-order confluences, debris-flow deposits, and channel morphology. For example, between 1100 and 1900 m in Q Creek, the largest concentrations of wood were located near six recent debris-flow deposits at low-order tributary junctions (Fig. 4). In addition, there were greater numbers of large pools ($>$ 0.5 m) in association with large wood counts between 1100 and 1900 m (Fig. 4). In contrast, the lowest wood and pool counts in Q Creek occurred between 0 and 1100 m, an area containing only two low-order confluences. In all, four study channels in the Sekiu Basin (drainage areas: 1–4.5 km^2; channel gradients: 2–4%) summary statistics indicated that densities of wood and pools were highest between 25 and 50 m from low-order confluences (Table 2). Specifically, average wood counts in reaches between 25 and 50 m

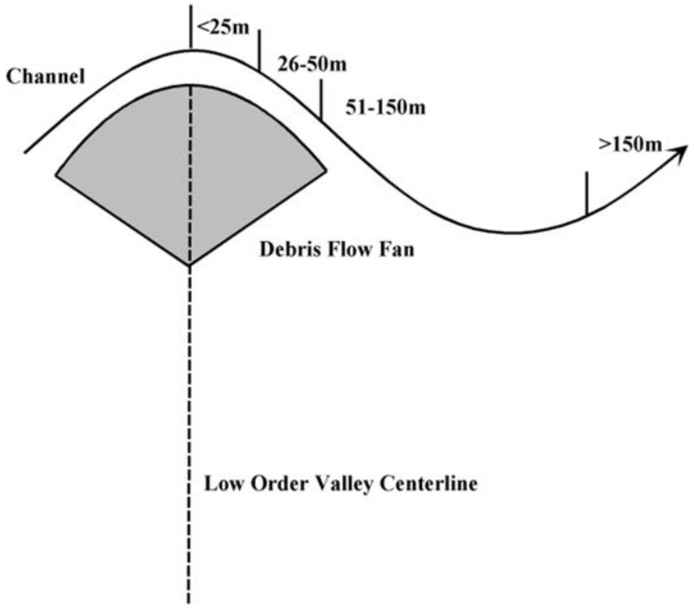

Figure 3. Schematic illustrating "nearest neighbor" analysis of channel attributes. Distances pertain to nearest tributary junction centerline in either up- or downstream direction.

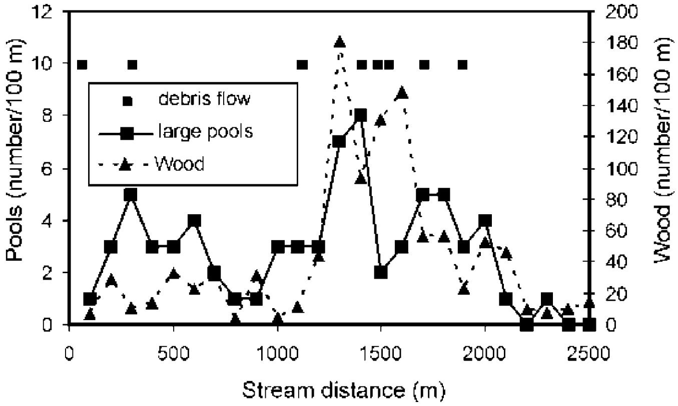

Figure 4. Variation in distribution of wood, large pools, and debris flow deposits occurs along 2500 m of Q channel, driven in part by location of debris fans at low-order confluences.

were significantly greater than the average in reaches further from confluences (analysis of variance, p = 0.01, Table 3, Fig. 5). However, of the pool categories (all, large, and wood-formed), only "large pools" showed statistical significance in their association with low-order confluences (analysis of variance, p = 0.09, Table 4, Fig. 5).

In the higher-energy, unmanaged Finley Creek Basin (drainage areas: 8–16 km^2; channel gradients: 3–7%), mass wasting (streamside landslides and debris flows) accounted for 80% of the wood where sources could be identified along the 3 km study reach (28% of the total wood) (Table 5). However, large (1–3 m) boulders created all pools, and hence pools were uniformly distributed and not associated with low-order confluences where debris fans were highly truncated.

We also surveyed an 800 m segment of Matheny Creek (drainage area: 4.4 km^2; channel gradients: 3–5%) to investigate the influence of a debris flow in a smaller, lower-gradient channel in a patch of unmanaged forest. Wood and pool surveys began 400 m upstream and continued 300 m downstream of the debris-flow deposit and recorded a large influx of wood (80–120 pieces/100 m); 72% of in-channel wood was attributed to that debris flow (Table 5). The debris flow in Matheny Creek dammed the narrow valley and created a 70-m-long pond and created a step in the longitudinal profile that was associated with local channel widening upstream of the deposit. We also surveyed another pond, 40-m in length, which was formed by a very large debris flow in the Sitkum River watershed on the Olympic Peninsula during this study (Table 1).

Other relationships were observed between low-order confluences, debris flow fans, and channel morphology in the second-growth Sekiu Basins. Average channel and floodplain widths (combined) increased with proximity to low-order confluences (Fig. 6). The percentage of reaches with channel and floodplain widths greater than 10 m was significantly greater nearer to low-order confluences (i.e., < 113 m from confluences) (Chi-square test, p value = 0.0001) (Table 6). With respect to substrate, the proportion of gravel ($\sim$2–64 mm) increased with proximity to low-order confluences (Pearson's Chi-squared test, p-value = 0.0008, Table 7, Fig. 7). The statistical analysis did not reveal a relationship between channel gradient and proximity to low-order confluences. Nevertheless, the longitudinal profiles indicate that at least in some locations, debris fans cause a steepening downstream of the fan and a decrease of gradient upstream (Fig. 8).

Despite the six debris flows and numerous, small streamside landslides inventoried in Finley Creek, stream erosion truncated all debris fans. Consequently, there were no measurable effects on channel gradient, width, and substrate sizes.

To estimate morphological heterogeneity, the range of observed values in a channel parameter, such as pool depths, was used as a proxy. Box-and-whisker plots for wood and pool counts (Fig. 5) and plots of floodplain widths (Fig. 6) revealed that heterogeneity of those aspects of channel morphology increased with proximity to low-order confluences. In addition, the observed differences in channel attributes near confluences versus in reaches farther away also represent increased physical heterogeneity linked to debris fans.

Time-Dependent Channel Morphology at Low-Order Confluences

The episodic nature of debris flows should impart a time-dependence to certain aspects of channel morphology, including heterogeneity

TABLE 2. WOOD AND POOL COUNT SUMMARY STATISTICS BY DISTANCE GROUP

Group	Sample size	Minimum	Median	Mean	Maximum
Wood					
≤25 m	19	3	50	51.5	156
25–50 m	13	11	57	106	324
50–150 m	17	4	29	43.6	181
>150 m	13	4	15	21.2	50
Pools					
≤25 m	19	1	4	5	14
25–50 m	13	1	7	7.38	15
50–150 m	17	1	6	5.76	15
>150 m	13	2	4	4.46	10
Large Pools					
≤ 25 m	19	0	1	2	8
25–50 m	13	0	3	3.69	10
50–150 m	17	0	3	2.41	7
>150 m	13	0	1	1.54	4
Wood Pools					
≤25 m	19	0	2	2.47	8
25–50 m	13	1	3	4.46	13
50–150 m	17	0	4	3.71	8
>150 m	13	0	3	2.31	5
Deep Pools					
≤25 m	19	0	1	1.37	6
25–50 m	13	0	2	2.15	8
50–150 m	17	0	1	1.41	5
>150 m	13	0	1	1.23	4

TABLE 3. RESULTS OF ANOVA GROUP COMPARISONS FOR WOOD (LOG TRANSFORMED)

	Df	Sum of Sq	Mean Sq	F Value	P value
Group	3	12.97	4.322	3.943	0.0125
Residuals	58	63.58	1.096		
	Mean difference	Std. error	Lower bound	Upper bound	
(<25 m)–(25–50 m)	−0.711	0.377	−1.59	0.172	
(<25 m)–(50–150 m)	0.165	0.35	−0.655	0.984	
(<25 m)–(>150 m)	0.681	0.377	−0.202	1.56	
(25–50 m)–(50–150 m)	0.876	0.386	−0.0283	1.78	
(25–50 m)–(>150 m)	1.39	0.411	0.429	2.35	****
(50–150m)–(>150 m)	0.516	0.386	−0.388	1.42	

Note: 90% simultaneous confidence intervals for specified linear combinations by the Tukey method. Intervals excluding 0 are flagged by ****. Df—degrees of freedom; Sq—squares.

at low-order confluences (Benda, 1990; Benda and Dunne, 1997b). Consequently, we compared our estimates of debris-flow fan ages to wood and pool densities. Since the effects of debris flow deposits were most pronounced within 50–100 m of confluences (Tables 2–7), only the study reaches located within 100 m of a confluence were used in the analysis. Although the data are sparse and the ages of debris flows are poorly constrained for older deposits, the data form an envelope in which the highest wood counts are associated with the youngest debris-flow deposits (Fig. 9A). For example, wood counts greater than 120 pieces/100 m ($n = $ five sites) were consistently associated with deposits less than 120 yr old. Four of the five segments with greater than 120 pieces were associated with deposits less than 60 yr old. In addition, there appears to be a general tendency for the highest densities of deep pools to occur in association with the youngest debris flow deposits (Fig. 10B). The clustering of many data points at young fans reflects the recent spate of debris flows that occurred in the second growth forests of the Sekiu Basin (i.e., debris flows less than ~40 yr old). The wide range of piece densities probably reflects the difficulty of relating wood to specific confluences and our measurement scale of 100 m.

DISCUSSION

Effect of Low-Order Confluences and Debris Flows on Channel and Valley Morphology

Effects of debris flows on channel and valley morphology in the second-growth Sekiu watershed were significant and varied. Deposits of debris flows at confluences of low-order (first- and second-order) with higher-order channels (third- and fourth-order) included fans, log jams, large pools, gradient breaks (nick points), wide channels and floodplains, and concentrations of gravel. Our findings are consistent with previous studies of debris-flow deposits that have documented the formation of fans, ponds, and logjams in other landscapes in the Pacific Northwest (Swanson and Lienkaemper, 1978; Everest and Meehan, 1981; Benda, 1990; Hogan et al., 1998), although our study provides considerable more detail.

Field surveys in the Sekiu watershed provides additional information on the role of debris flows on wood loading, pool formation, channel and floodplain width, and substrate. Counts of in-channel wood were significantly higher ($p = 0.01$, Table 3) near low-order confluences and debris fans compared to channel reaches located further away. High concentrations of wood associated with debris flow deposits are consistent with simulation models in which debris flows create the highest point loading of wood in landscapes that are prone to that form of erosion (Benda and Sias, 2003; United States Forest Service, 2003). Low wood counts immediately adjacent to debris flow fans (<25 m) was likely due to burial of valley floors with sediment. In addition, the number of large pools was significantly higher ($p = 0.1$, Table 4) near low-order confluences. There also were more deep pools in reaches 25–50 m from low-order confluences compared to reaches further from low-order confluences (Table 2). The differences among distance groups for "all pools" were not statistically significant (Table 4), presumably because "all pools" included numerous boulder-forced pools of all sizes.

A relationship between large wood and pools in the Sekiu watershed is consistent with previous studies that have documented pool formation driven by wood storage (30–50 pieces per 100 m) in channels generally less than 4% (Montgomery et al., 1995; Beechie and Sibley, 1997). The cited studies occurred in environments where wood was recruited primarily by mortality and bank erosion and fluvial reorganization of wood led to relatively small wood jams (and subsequent pool formation). In contrast, our study focused on extremely large pulses of wood that created valley-spanning logjams, both up- and downstream of debris flow fans. Our study documented an increase in pool frequency associated with high wood counts of between 50 and 100 pieces per 100 m, including in areas outside of fan perimeters (i.e., > 50 m). High wood loading apparently leads to a high concentration of certain types of pools along with, in some cases, an absence of intervening riffles or non-pooled areas. Hence, our study points to another mechanism of pool formation, in channels of between 3 and 6% in rel-

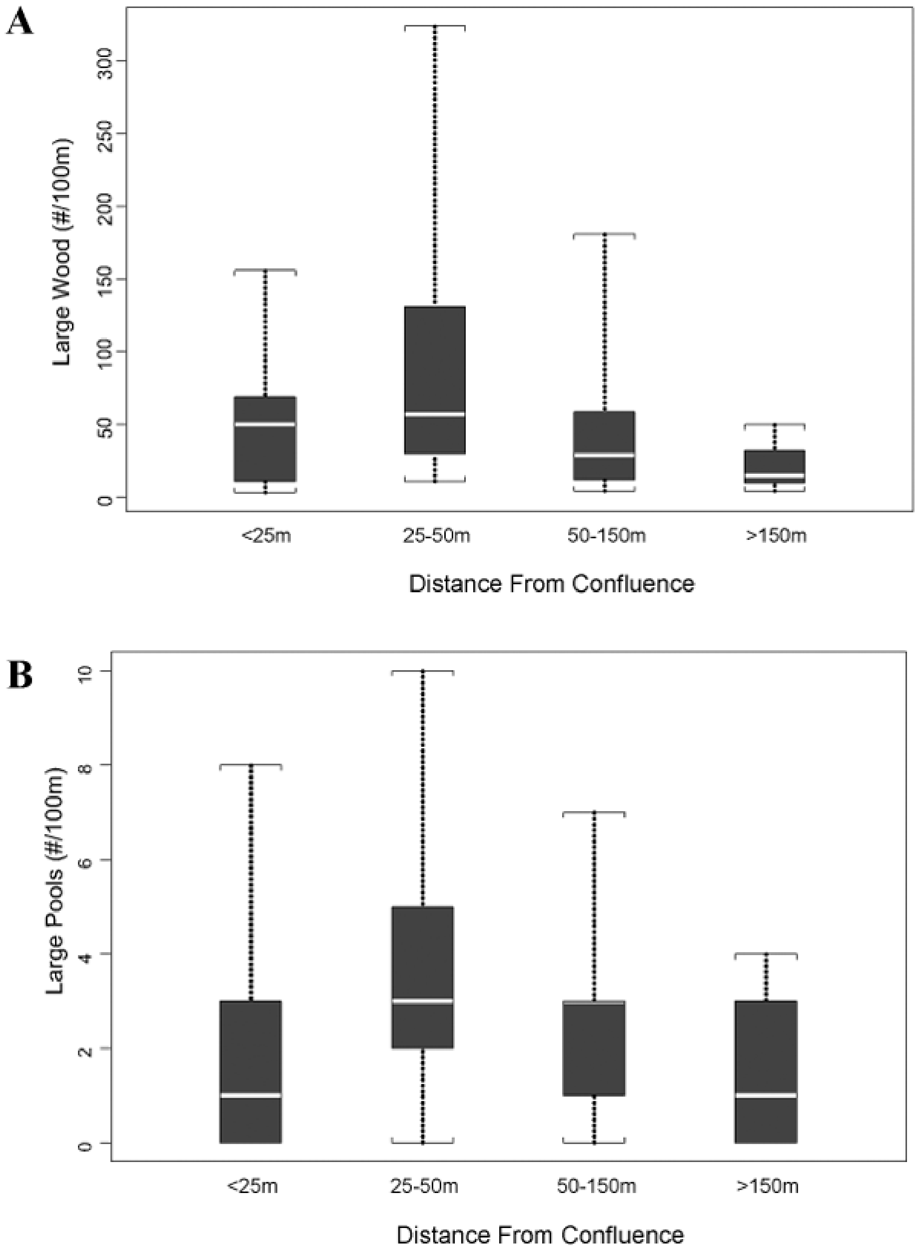

Figure 5. Box-and-whisker plots of wood (A) and pool counts (B) showing median (white line), inner quartiles (box), and ranges of data with increasing distance from low-order confluences (debris flow deposits) in Sekiu study basins.

atively small basins, that is linked directly to debris-flow deposits at low-order confluences.

Results in the Sekiu watershed indicating a prominent role of debris fans in forming wood jams, pools, wide channels, floodplains, and gravel deposits differ from the recent study of debris flows in the Oregon Coast Range reported by Montgomery et al. (2003). In the Montgomery et al. (2003) study, debris flows accounted for only 12–25% of logjams in two basins in managed forests and only 7% of all pools. In contrast, the highest counts of wood and pools in the Sekiu Basins were associated with debris-flow deposits near low-order confluences. Moreover, there was statistical significance among logs, large pools, and proximity to low-order confluences prone to debris flows in second-growth basins. The differing results between our study and that of Montgomery et al. (2003) may be partly explained by the two different methods of analysis employed. Montgomery et al. (2003) limited their analysis to ‘‘direct’’ effects of debris flows, which required that wood and pools be partially embedded within or proximal to debris-flow deposits (Fig. 2). The method also requires interpretation of how logs were deposited and pools were formed. However, debris flows can lead to numerous offsite or ‘‘indirect’’ effects, including the downstream transport and deposition of wood, sediment, and boulders; increased storage of sediment and wood upstream of deposits due to fan-induced reduction in channel gradients and valley constrictions; and increased channel avulsions, bank erosion, and wood recruitment both upstream and downstream of deposits (Fig. 2). In the Sekiu Basins, debris flow deposits extended both upstream and downstream of confluences and fans. Hence, we employed continuous surveys of channel attributes and simply registered them according to up- and downstream distance from low-order confluences to circumvent the limitations imposed by only measuring ‘‘direct’’ effects and to reduce the need for interpretation of cause and effect between debris flows and specific channel morphology. Moreover, our method limits the potential errors that might be associated with measuring only ‘‘direct’’ effects, such as interpreting a tree deposited into a channel by bank erosion as unrelated to a debris flow when channel migration that triggered bank erosion was actually due to increased sedimentation associated with debris flows.

Effects of debris flows in the higher-energy channels in unmanaged Finley Creek Basin were different compared to those in the Sekiu watershed. Our field study revealed a large proportion of wood (80%) originating from debris flows and streamside landslides during the last decade in the Finley Creek Basin in the Olympic National Park (Table 5). However, there was no relationship between wood and pools in Finley Creek because most pools occurred in association with boulders. The large debris-flow deposit in Matheny Creek, however, created a pond. Similarly formed ponds have been documented in second-growth forests in the Oregon Coast Range (Everest and Meehan, 1981). Because ponds fill with sediment or breach, they typically survive only a few years to a couple of decades (Benda, 1990).

Effects of debris flows on channel morphology and related physical heterogeneity of channels should vary with time since the last debris flow. The estimated ages of debris-flow deposits indicated that high wood storage may persist for a century or more following a debris flow in the small channels in the Sekiu Basin (Fig. 9). Our dates for older fans (100–200 yr) are consistent with estimates of century-scale recurrence intervals of debris flows in

TABLE 4. ANOVA RESULTS FOR POOLS

	Df	Sum of sq.	Mean sq.	F value	Pr(F)
All pools					
Group	3	3.734	1.245	1.384	0.2567
Residuals	58	52.15	0.899		
Large pools					
Group	3	5.287	1.762	2.217	0.0958
Residuals	58	46.11	0.795		
	Mean difference	Std. error	Lower bound	Upper bound	
(<25 m)–(25–50 m)	–0.677	0.321	–1.43	0.0747	
(<25 m)–(50–150 m)	–0.199	0.298	–0.897	0.498	
(<25 m)–(>150 m)	0.156	0.321	–0.596	0.908	
(25–50 m)–(50–150 m)	0.478	0.328	–0.292	1.25	
(25–50 m)–(>150 m)	0.833	0.35	0.0135	1.65	****
(50–150 m)–(>150 m)	0.355	0.328	–0.415	1.12	
	Df	Sum of sq.	Mean sq.	F value	Pr(F)
Deep pools					
Group	3	2.138	0.713	0.942	0.426
Residuals	58	43.87	0.756		
Wood–formed pools					
Group	3	5.121	1.707	2.027	0.120
Residuals	58	48.84	0.842		

Note: 90% simultaneous confidence intervals for specified linear combinations by the Tukey method. Intervals excluding 0 are flagged by ****. Df—degrees of freedom; Sq—squares; Std—standard.

TABLE 5. RECRUITMENT SOURCES OF WOOD ALONG FINLEY AND MATHENY CREEK STUDY REACHES

Location	Type	Mortality/bank erosion	Streamside landslides	Debris flow	Total
Finley Creek	Scattered	54	84	12	150
(3.0 km)	Accumulated	6	28	130	164
	Total	60 (19%)	112 (35%)	142 (45%)	314 (100%)
Matheny Creek	Scattered	55	0	19	74
(0.8 km)	Accumulated	98	0	372	470
	Total	153 (28%)	0 (0%)	391 (72%)	544 (100%)

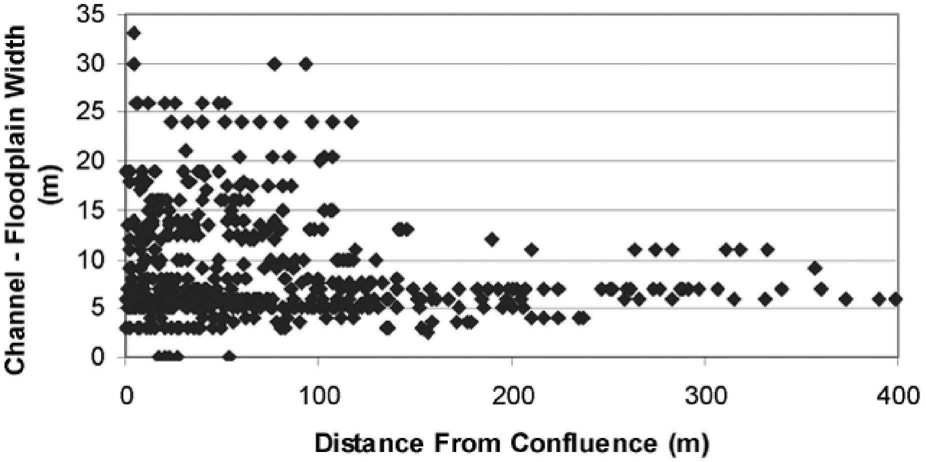

Figure 6. Combined channel and floodplain widths increase with proximity to debris fans at low-order confluences.

other Pacific Northwest landscapes (Swanson et al., 1982; Benda and Dunne, 1997a). The observed rate of wood loss over a century or more is also consistent with measured losses of wood in streams in the Pacific Northwest (including the processes of decay, abrasion, and transport) that ranged from 1% yr^{-1} to 6% yr^{-1} (Murphy and Koski, 1989; Bilby et al., 1999; Hyatt and Naiman, 2001). The loss of wood over time also appears to coincide with a loss of ''deep pools'' near confluences (Fig. 9).

The timber management history of the Sekiu watershed included harvest of all streamside forests. The loss of in-stream wood due to decay, abrasion, and stream transport, in the absence of streamside recruitment due to mortality and bank erosion, should have led to declines of in-channel wood. Moreover, some channels had been cleared of wood during logging to improve fish passage. These practices should have led to reductions in wood and an overall lower morphological diversity, including a decrease in pools (Bilby and Ward, 1989). Depressed morphological diversity prior to heightened debris flow activity (due to the destabilizing effects of roads and timber harvest) should exaggerate the morphological consequences of recent forest management-related debris flows at low-order confluences in the Sekiu watershed. Nevertheless, many watersheds in the Pacific Northwest and elsewhere have a similar history of timber harvest and channel impacts. In these situations, under certain valley floor conditions (discussed later), debris flows can increase morphological heterogeneity, including increased wood and pools near low-order confluences for decades or longer.

Debris flows also occur in unmanaged settings, as evidenced by the profusion of debris fans and other morphological signatures observed in the field and from aerial photography (Dietrich and Dunne, 1978; Swanson et al., 1982; Benda, 1990; Grant and Swanson, 1995; Hogan et al., 1998). Concentrations of debris flows entering larger channels in unmanaged basins on the Olympic Peninsula were documented in 1939 aerial photographs (see Fig. 11.1 in Benda et al., 1998) and in the Queen Charlotte Islands, British Columbia (Schwab, 1998). Hence, we anticipate that naturally occurring debris flows will have similar effects on channel morphology and physical heterogeneity of channels, although their effects may be somewhat less pronounced.

Channels Susceptible to Confluence Effects by Debris Flows

The morphological consequences of mass wasting at low-order confluences should be governed to a large degree by the volume and composition of the deposited material and by the size and energy of the channel that the debris enters. In our study in the Olympic Peninsula, coarse-textured debris flows (i.e., containing cobbles and boulders) ranged in volume from ~10^3 to 10^5 m^3 (Table 1) and entered relatively small third- and fourth-order valley floors. The result, with the exception of Finley Creek, was large morphological effects,

TABLE 6. CONTINGENCY TABLE: CHANNEL/FLOODPLAIN WIDTHS BY DISTANCE GROUP

Distance (m)[†]	Total	Number (≤10 m)	Number (>10 m)	Percent (>10 m)	Percent (>10 m)
<8	54	36	18	33%	
8–16	52	35	17	33%	
16–26	54	37	17	31%	
26–37	54	38	16	30%	
37–49	48	37	11	23%	32%
49–65	51	27	24	47%	
65–86	52	34	18	35%	
86–113	52	40	12	23%	
113–179	52	47	5	10%	
>179	52	44	8	15%	13%

[†] Distances are grouped into deciles (i.e., each group contains 10% of the reaches).

TABLE 7. CONTINGENCY TABLE: CHANNEL SUBSTRATE BY DISTANCE GROUP

Distance group	Bedrock, boulders, cobble, or sand[†]	Gravel[†]	Total[†]	Percent gravel
<25	51	102	153	67%
25–50	37	68	105	65%
50–100	58	59	117	50%
>100	72	62	134	46%

Note: Pearson's Chi-squared p-value = 0.0008.
[†] Number of sites.

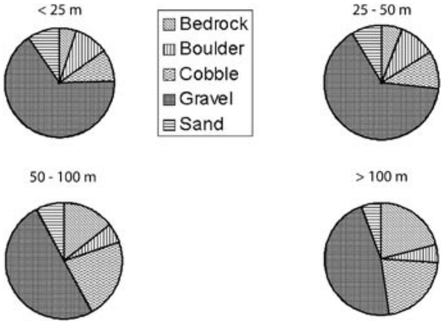

Figure 7. Channel substrate varies according to distance from debris fans at low-order confluences in Sekiu Basin. Proportion of gravel (2–64 mm) increases with proximity to low-order confluences.

including steps in the longitudinal profile (Fig. 8), ponds, concentrations of wood and deep pools (Figs. 4 and 5), gravel abundance (Fig. 7), and wider channels (Fig. 6).

To examine how our results compare with other field studies that have documented effects of debris flows on channels at points of deposition, we plotted the estimated volumes of debris flows against a measure of the size or energy of the channel it enters represented by channel slope multiplied by its drainage area. The latter is an index of the available stream power (Bagnold, 1966) approximating a channel's ability to transport and redistribute the mass wasting debris. Our fourth-order basins in the Sekiu and Matheny watersheds, which record a large range of morphological effects, represent an end member in our plot, where debris-flow volumes on the order of several thousand cubic meters enter relatively low-energy channels (Fig. 10). In contrast, the Finley Creek Basin exhibited few morphological effects because similar debris volumes entered a significantly higher energy channel. The higher-energy channel of the Sitkum River (drainage area: 11 km^2; channel gradient: 8%), also recorded large morphological effects, but the debris volume that was required was significantly greater (i.e., 10^5 m^3).

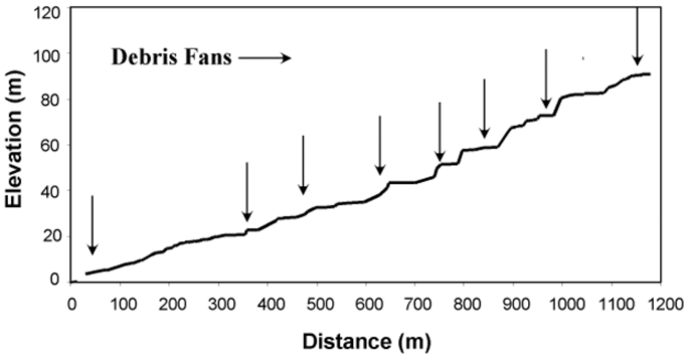

Figure 8. Gradient breaks (knick points) occur along longitudinal profile of J-channel near debris fans located at low-order confluences (arrows).

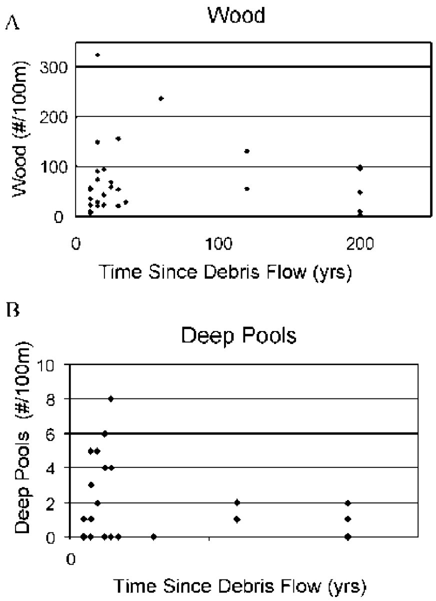

Figure 9. Estimated ages of debris flow fans in Sekiu Basin compared to wood and pool counts.

Other studies provide additional information for considering effects of debris flows on channel morphology at confluences. In the central Oregon Coast Range, coarse-textured debris flows of several thousand cubic meters commonly enter third- through fifth-order channels (drainage area: 3–40 km^2; channel gradient: 5–1%) where they form ponds, wood concentrations, boulder lag deposits, and meanders (Everest and Meehan, 1981; Benda, 1990). In addition, debris flows of similar volume in unmanaged basins in the Queen Charlotte Islands, British Columbia, formed wood jams and sediment wedges at low-order confluences in basins of comparable sizes (drainage area: 1–30 km^2; channel gradient: 0.3–8%) (Hogan et al., 1998). Examples from both the central Oregon Coast Range and the Queen Charlotte Islands plot close to the fourth-order Sekiu Basins in Figure 10. Collectively, all three studies indicate the general set of basin conditions under which coarse-textured debris flows of a volume of a few thousand cubic meters have large morphological consequences on channels and valley floors at low-order confluences.

To create large morphological effects in higher-energy channels requires larger magnitude landslides, as indicated by our Sitkum River example and a large debris flow fan impinging on the Siuslaw River in the central Oregon Coast Range (Fig. 10). Less pronounced effects of debris flows, including boulder deposits and valley widening, have

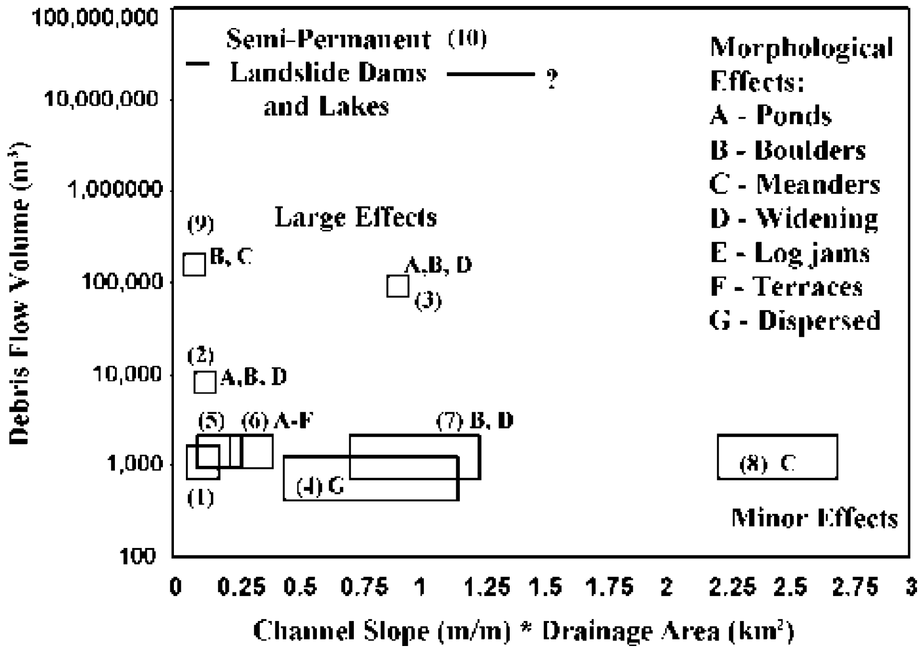

Figure 10. Effects of debris flows on morphology and heterogeneity of larger streams vary based on volume of debris and stream power of receiving channel. Data include this study (Sekiu Basin #1, Mathey Cr. #2, Sitkum #3, and Finley Creek #4), central Oregon Coast Range (#5, Benda 1990; Everest and Meehan, 1981), Queen Charlotte Islands, British Columbia (# 6, Hogan et al., 1998), Oregon Cascades (#7 and #8, Grant and Swanson, 1995), Suislaw River, Oregon (#9), and #10 (Costa and Schuster, 1988).

been reported in higher-energy channels (drainage area: 47–60 km^2; channel gradient: 2.2%) in the Andrews Experimental Forest, Oregon (Grant and Swanson, 1995). In that environment, debris flows have similar volumes compared to the Sekiu watershed and the Oregon Coast Range (Swanson et al., 1982). In even higher-energy channels of French Pete Creek in the Oregon Cascades (60–84 km^2, channel gradient: 4%), effects of debris flows are limited to boulder deposits at fans near low-order confluences (Fig. 10). Another end member is semi-permanent landslide dams and lakes that require 10^6 to 10^9 m^3 of debris and involve a range of channel sizes (Costa and Schuster, 1988).

Other factors affect debris flow impacts on channel morphology. For example, debris flows in certain parts of the Idaho Batholith are fine textured (lacking in cobbles and boulders) and deposits of volumes of 15,000 m^3 have little effect on channel morphology at points of deposition in large rivers (Meyer et al., 2001). In contrast, when debris flows in the same landscape contain large boulders (~1–3 m), armored fans are formed and rapids are created. Debris flows with volumes of 10,000–15,000 m^3 form rapids and create upstream sediment wedges in channels that have drainage areas of 1000–3000 km^2 and slopes of 0.006–0.007 (slope * drainage area = 6 to 26) in the South Fork Payette River in Idaho (Meyer and Pierce, 2003). Hence, debris flows containing large boulders can affect much larger channels than those plotted in Figure 10.

Effects of debris flows should decrease as valleys widen and delivery of material to rivers diminishes. In all of the examples given above (and plotted in Fig. 10), valley floors were relatively narrow and debris flows had sufficient access to river channels. Debris flows occurring in areas of wider valley floors will have a lower likelihood of impacting channel morphology; deposition will occur on fans, terraces, or wide floodplains. Examples of these environments include the larger river valleys on the Olympic Peninsula, as well as larger rivers throughout the region. Debris flows will also have limited access to channels where recent glaciation has widened valley floors, such as in southeast Alaska (Swanston and Marion, 1991; Johnson et al., 2000).

CONCLUSIONS

Our field study documents direct and particularly indirect effects of debris flow fans at low-order confluences, including wider channels and floodplains, increased gravel, and high densities of logs and large pools. Such effects of debris flows in low-energy depositional environments in the Olympic Peninsula may persist for at least a century. Debris-flow effects in higher-energy channels were limited. Our results from the Olympic Peninsula, combined with data from seven other studies, indicate how variations in debris-flow volume and composition, stream energy, and valley width at the point of deposition govern the extent of channel changes at confluences. For example, debris flows of several thousand cubic meters in low-energy channels or debris flows of much larger volumes in higher-energy fluvial environments can create steps in the longitudinal profile (nick points), ponds, log jams, boulder deposits, gravel accumulations, and pools up- and downstream of deposits. Effects of debris flows of several thousand cubic meters in high-energy environments are limited but may include boulder lag deposits and channel widening.

In the Olympic Peninsula, debris-flow deposits at confluences acted as sources of increased morphological heterogeneity. This is consistent with other studies that have documented morphological changes at confluences, even in much larger channels and involving alluvial fans (Small, 1973; Richards, 1980; Rice et al., 2001; Benda et al., 2003). In the Olympic Mountains, the spatial scale of heterogeneity was partially governed by drainage density where the characteristic spacing of low-order confluences is ~200 m. However, network topology also governs the spatial scale of heterogeneity. For example, variation in channel characteristics occurred at the 1000 m scale in Q Creek (Sekiu River) due to the topological controls on tributary spacing.

The role of morphological heterogeneity in riverine ecosystems underpins a new perspective among ecologists (Fausch et al., 2002; Wiens, 2002). Despite increased understanding of the role of tributary confluences on channel morphology and aquatic organisms (Minshall et al., 1985; Fisher, 1997; Benda and Dunne, 1997b; Rice et al., 2001; Poole, 2002; Gomi et al., 2002; Benda et al., 2003), integration of network geometry in river theory is limited. There continues to be uncertainty regarding how morphological characteristics of tributary environments form, how they evolve through time, and how variations in network topology relate to spatial organization of riverine habitats. Our study results in the Olympic Peninsula provide further clarification on confluence effects, including how network topology influences the spatial scale of heterogeneity and how effects evolve over time in small mountain channels in humid landscapes.

In a more applied perspective, improved understanding of how debris flows impact channel morphology could be integrated into models designed to predict watershed behavior, including effects of land management. For example, although there are several models for predicting shallow landslides and the transport distance of debris flows, none of them predicts ecological consequences. This, in part, fuels differing perspectives on the role of disturbance in stream channels in general and, specifically, effects of debris flows on aquatic habitats (Everest and Meehan, 1981; Reeves et al., 1995; Montgomery et al., 2003; Reeves et al., 2003). Although debris flows can have short-term negative consequences as demonstrated by numerous studies, they can also have longer-term constructive effects in channels, including increasing habitat heterogeneity, as evidenced in this and other studies. When evaluating effects of any form of mass wasting on channels, including debris flows, a longer-term perspective seems prudent, given that form of erosion's timescale and the potentially significant effects on channels and valley floors. Moreover, continuous surveys that target both direct and indirect effects are necessary when studying alluvial and debris fans and their effects on channels.

ACKNOWLEDGMENTS

This study was funded by the Earth Systems Institute and Crown Pacific Corporation. Reviews of earlier drafts by Steven Kite, Ellen Wohl, Tom Lisle, Jim Pizzuto, Dan Miller, and Paul Bigelow greatly improved various aspects of the manuscript.

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MANUSCRIPT RECEIVED BY THE SOCIETY 26 SEPTEMBER 2002
REVISED MANUSCRIPT RECEIVED 10 MARCH 2003
MANUSCRIPT ACCEPTED 18 MARCH 2003

Printed in the USA