Influence of debris flows and log jams on the location of pools and alluvial channel reaches, Oregon Coast Range

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ABSTRACT

We investigated the influence of debris-flow deposits and log jams on the location of pools and alluvial channel reaches in three Oregon Coast Range watersheds. Our surveys reveal differences in the type and location of log jams and the associated influences on pool formation and the extent of alluvial channel beds between channels flowing through old-growth and industrial forests. In channels we surveyed, debris-flow deposits formed 3% of log jams in reaches flowing through old-growth forest and 12% and 25%, respectively, in the two industrial forest channels. Pools formed by the direct effects of debris flows accounted for 4%–7% of all pools in reaches surveyed in both old-growth and industrial forest channels. Logs and log jams accounted for about half of the pools formed in old-growth reaches, but just 12%–13% of pools in reaches flowing through industrial forest. The distribution of bedrock and alluvial reaches was influenced by drainage area, channel-reach slope, sediment trapping by log jams, and boulders deposited by debris flows. Although debris-flow deposits can locally create or influence aquatic habitat, our field observations suggest general contrasts between old-growth and industrial forest in both log jam locations and the relative importance of debris-flow processes in the formation of pools and alluvial reaches.

Keywords: alluvial channels, debris flows, log jams, Oregon Coast Range, pools.

INTRODUCTION

Landslides are an important sediment transport process and ecological disturbance agent in mountain environments. In forested mountain drainage basins, debris flows scour steep headwater channels and deliver both sediment and wood debris to downstream channels, often creating log jams where they deposit. Log jams formed by deposition of debris flows, local recruitment of large logs from streamside forests, or recruitment of fluvially transported wood from upstream sources can store large amounts of sediment and increase the frequency and/or depth of pools through local bed scour (Keller and Swanson, 1976; Keller and Tally, 1979; Lisle, 1986; Andrus et al., 1988; Robison and Beschta, 1990; Swanston, 1991; Nakamura and Swanson, 1993; Abbe and Montgomery, 1996; Montgomery et al., 1995, 1996; Beechie and Sibley, 1997). Although the direct and indirect effects of debris flows can adversely impact salmonids (Everest and Meehan, 1981; Lamberti et al., 1991; Johnson and Jones, 2000), debris-flow deposited log jams also have been recognized as habitat-forming agents (Everest and Meehan, 1981; Reeves et al., 1995; Hogan et al., 1998). The ecological disturbance regime of mountain channels incorporates the frequency of debris-flow initiation, the extent of the downslope scour of valley bottoms, the distance debris flows travel before they deposit, and the characteristics of those deposits and their associated impacts on stream habitat. Although it is well established that forest cutting increases rates of landsliding in steep terrain (Swanston and Swanson, 1976; Sidle et al., 1985; Montgomery et al., 2000), far less is known about how land use, the size and characteristics of wood in channels, and streamside forest conditions influence the character of stream channels, and therefore, aquatic habitats in mountain drainage basins (Johnson et al., 2000a). Here, we examine the direct role of debris flows and log jams on the location of pools and alluvial channels, two fundamental characteristics of salmon habitat.

STUDY AREAS AND METHODS

From 1994 to 1999, we mapped the location and type of log jams and alluvial-channel reaches in three watersheds in coastal Oregon (Table 1; Fig. 1). Field work in each study area included walking the mainstem channel and mapping jam locations onto US Geological Survey 1:24,000 scale topographic quadrangles. We mapped channels that flow through old-growth forest in Cummins Creek and the headwaters of Knowles Creek. Both of these channels have an abundant supply of large in-channel wood debris, and to our knowledge, neither were splash dammed or otherwise cleared of debris. We also mapped channels that flow through industrial forests in the drainage basins of Larson and Sullivan creeks and the mainstem portion of Knowles Creek.

Surveys involved continuous mapping of log jams along the mainstem of each channel, and classifying each jam based on the process observed or interpreted to have triggered the jam formation. Prior studies have shown that the structure and morphology of a log jam can allow discrimination of jams formed by debris-flow deposition from those formed by progressive growth following emplacement of a stable key-member log (Abbe, 2000). In some cases, the spatial relation of a log to features such as an embayment in the stream bank or a tree-throw pit can provide definitive evidence for local recruitment of key logs upon which a log jam subsequently developed. Moreover, patterns of vegetation recolonization and the organization, or lack thereof, of the logs in a jam can bolster interpretation of whether it was formed by a debris flow. Jams founded on an identifiable key log (or logs)

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TABLE 1. STUDY AREA CHARACTERISTICS

Location	Basin size (km^2)	Lithology	Forest type
Sullivan and Larson Creeks	11	Sandstone	Industrial
Knowles Creek, mainstem	56	Sandstone	Industrial
Knowles Creek, headwaters	6	Sandstone	Old-growth
Cummins Creek	22	Basalt	Old-growth

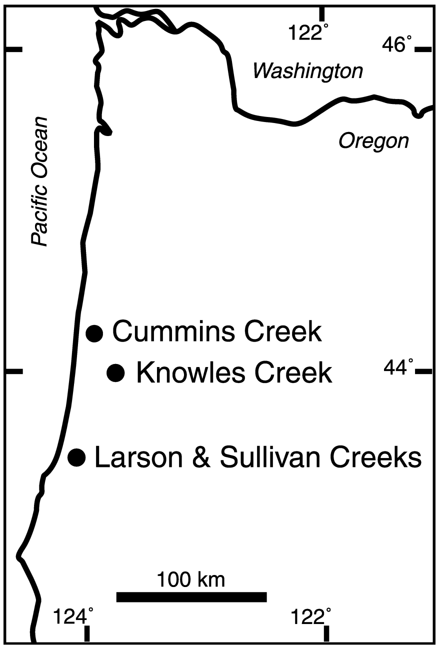

Figure 1. Location map for Oregon Coast Range study sites.

that functions as a stable foundation against which additional logs are deposited were classified as either having clear evidence of being initiated by local recruitment (through wind throw or bank erosion) or of fluvial origin in those cases where the key log was either clearly delivered from upstream or was not readily determined to have been recruited locally. We also noted whether each log or jam was part of or proximal to a debris-flow deposit or was built by humans as revealed by cables or other artificial elements. As it can be difficult to determine whether a fluvially-deposited log might have been originally introduced upstream as part of a debris flow, and then subsequently transported downstream, we do not address potential indirect effects of logs remobilized from debris-flow deposits.

In addition to mapping log jams and debris-flow deposits, we also inventoried pools following procedures and definitions adopted by Montgomery et al. (1995). We measured width, length, and residual depth of each pool and noted whether each pool was (1) freely formed by the interaction of flow and sediment transport, (2) forced by less than 5 pieces of wood debris, (3) forced by a log jam with >5 pieces of wood debris, (4) forced by a debris-flow deposit or debris-flow-deposited log jam, or (5) forced by bedrock outcroppings. We also recorded the size of each key piece and the presence or absence of a root wad for all wood-debris accumulations that influenced channel morphology within the bankfull channel.

Field surveys in each of the study basins included mapping and surveying reach-average channel slopes in a number of discrete bedrock- and alluvial-channel reaches spanning lengths of 10 to >20 channel widths. Following Montgomery et al. (1996), we considered alluvial reaches to be those with an alluvial bed in which the length of contiguous bedrock exposures (if any) extended downstream for less than the scale of the local channel width. Conversely, we considered bedrock-channel reaches to be those with a nearly continuous bedrock bed in which alluvial bed cover accounted for a downstream distance no more than the equivalent of a channel width. We did not survey mixed-morphology reaches that did not satisfy either definition. We did, however, survey bed surface and average valley slopes for alluvial reaches forced by deposition upstream of log jams and for reaches where boulder fields deposited by debris flows were associated with alluvial beds.

PATTERNS IN LOG JAM FORMATION

Comparison of field mapping from these watersheds reveals both similarities and differences in the type and location of log jams in channel systems that flow through old-growth and industrial forest (Fig. 2). Differences appear to be due to the relative abundance, distribution, and stability of wood large enough to function as key members, as well as the legacy of past splash damming and stream cleaning.

The frequency of log jams differed between industrial and old-growth forests (Table 2). The surveyed old-growth reaches of Cummins Creek and the headwaters of Knowles Creek, respectively, had 21.4 and 37.3 jams per km^{-1}. In contrast, the reaches flowing through industrial forest (Knowles mainstem, Sullivan, and Larson creeks) had 5.5 and 12.8 jams per km^{-1} not constructed by restoration activities, or one-seventh to one-half the jam frequency found in old-growth forest. In addition, one-third of the large log jams mapped in the industrial-forest reaches of Knowles Creek were constructed as part of channel restoration efforts, and in Sullivan and Larson Creeks, over half of all the large log jams (i.e., those with less than 5 pieces of wood debris) were formed by debris flows. In contrast, debris-flow deposits accounted for only 5% of the large log jams in Cummins Creek and one-sixth of the large log jams in the old-growth headwaters of Knowles Creek. In the two industrial forest study areas (Knowles Creek mainstem and Sullivan and Larson creeks), debris-flow deposits accounted for 12% and 25%, respectively, of all log jams that influenced channel morphology, whereas debris-flow-formed log jams accounted for only 3% of all log jams in old-growth channels (Table 3).

Log jams generally formed along the entire length of the reaches surveyed in old-growth forests. Most log jams mapped in our survey of Cummins Creek were founded on key logs either recruited from local sources or reworked by fluvial processes. Only one of the debris-flow-deposited log jams was located just downstream of a blue-line tributary junction; the other two deposited where they entered the mainstem channel at approximately right angles after flowing down small colluvial channels. All of the debris-flow jams mapped by Everest et al. (1981) in Cummins Creek appeared to have been breached or substantially modified by the time of our survey in 1999. The old-growth headwaters of Knowles Creek host many channel-spanning log jams distributed along the channel, with the largest two formed at the snout of debris-flow deposits.

In contrast to the pattern of log jams distributed along the whole length of the channel network in old-growth forest, log jams were concentrated at or near tributary junctions in industrial forests. We observed that log jams formed by debris flows in industrial forests can also create longitudinal steps in the channel profile by trapping large amounts of sediment. Along the mainstem of Knowles Creek, for example, jams either formed by debris-flow deposition or constructed as part of channel-restoration efforts trap gravel and create alluvial pools. Whereas log jams formed by debris flows along the mainstem of Knowles Creek are concentrated near tributary junctions, log jams formed by other processes are more widely distributed. Similarly, in the middle reaches of Larson and Sullivan Creeks, a se-

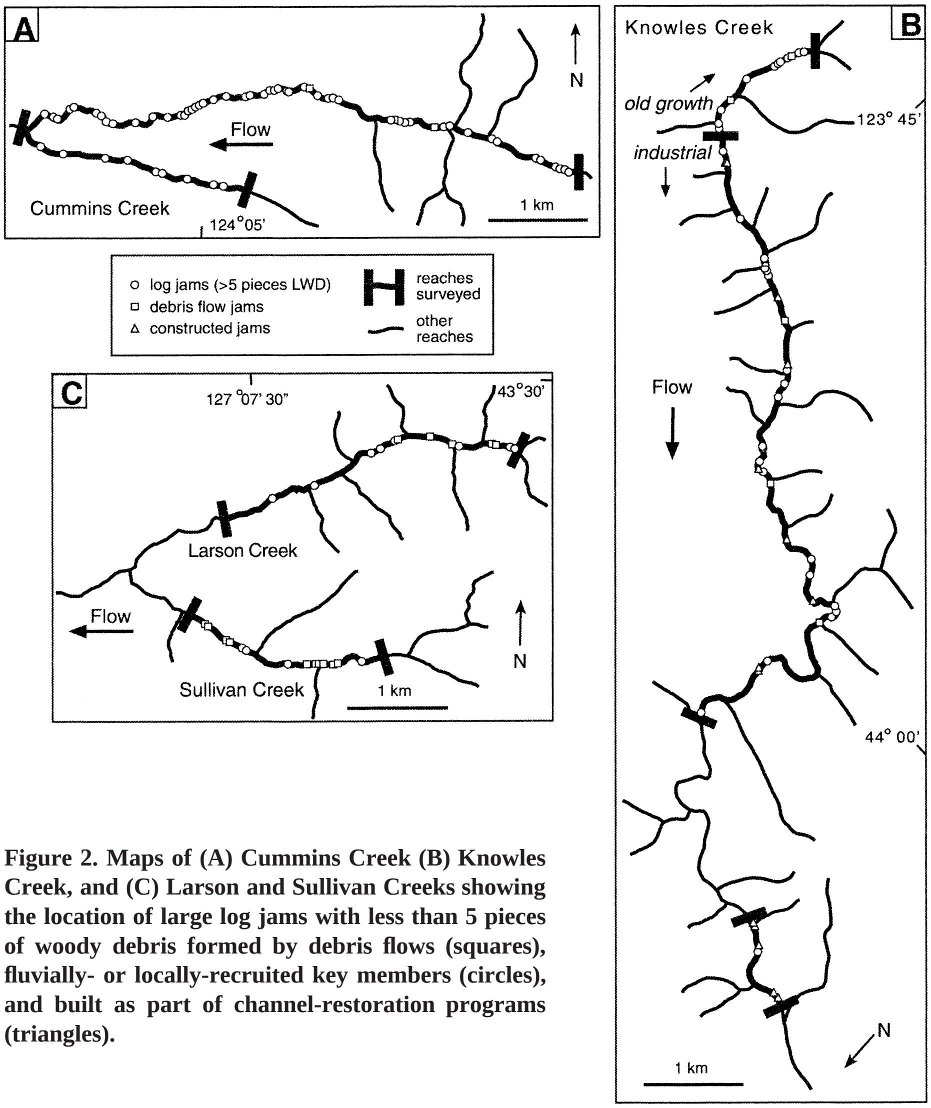

Figure 2. Maps of (A) Cummins Creek (B) Knowles Creek, and (C) Larson and Sullivan Creeks showing the location of large log jams with less than 5 pieces of woody debris formed by debris flows (squares), fluvially- or locally-recruited key members (circles), and built as part of channel-restoration programs (triangles).

quence of debris-flow-emplaced log jams coalesced to form a nearly continuous jam complex that resembles those founded on locally recruited logs in prior studies of channels in old-growth forest (Montgomery et al., 1996; Abbe, 2000) (Fig. 3). In the lower, alluvial reaches of Larson Creek, log jams founded on individual key members were the dominant type of log jam; debris-flow-jams only occurred in the upper portions of the watershed.

Distances between log jams with less than 5 pieces of large woody debris were greater in the industrial forest reaches of Knowles Creek than the other study watersheds (Fig. 4). The mean distance between large jams in the old-growth reaches of Cummins Creek and the headwaters of Knowles Creek were 126 ± 14 m and 101 ± 31 m, respectively. In industrial forest reaches, the mean distance between large jams was 172 ± 33 m in Sullivan and Larson creeks and 376 ± 83 m in the mainstem of Knowles Creek. P values for T-tests and F-tests for similarity in the mean and variance of the distributions of distances between large log jams among the study sites (Table 4) show that (1) the distributions among the old growth channels are not significantly different, (2) the distributions among industrial forest channels are significantly different, (3) the distribution in the mainstem of Knowles Creek differs from both old-growth forest channels, and (4) the distribution in Sullivan and Larson creeks is not significantly different from either of the old-growth study areas. Coupled with the differences in total jam frequency (i.e., not just large jams), the spacing between log jams is smaller in reaches flowing through old-growth forest than in industrial forest.

The frequency distribution of the distances upstream from large log jams to the next tributary junction portrayed by blue lines on 1:24,000 scale topographic maps provides an independent indication of the relative influence of debris-flow deposition at tributary confluences on log-jam formation for the study basins. The mean distance from large jams to upslope tributaries in Cummins Creek and the old-growth reaches of Knowles Creek were 966 ± 108 m and 286 ± 183 m, respectively. In industrial forest reaches, the mean distance between large jams was 249 ± 38 m in Sullivan and Larson Creeks and 242 ± 35 m in Knowles Creek. T- and F-tests of the distribution of distances to upslope blue-line tributaries indicate that the distribution from Cummins Creek differs from the other study areas, which do not differ from one another (α = 0.05). However, using the blue line stream network underrepresents the extent of small, debris-flow prone colluvial channels (Montgomery and Foufoula-Georgiou, 1993), and the portrayal of ephemeral colluvial channels as blue lines may differ among the study watersheds. Hence, the data from our our study basins can only suggest that log jams in

TABLE 2. LOG-JAM FREQUENCY IN OREGON STUDY AREAS (JAMS KM^{-1})

Location	USFS	DF	Other	Total
Industrial Forest				
Sullivan and Larson Creeks	0.0	3.2	9.7	12.9
Knowles Creek	1.9	0.7	4.8	5.5
Old-Growth Forest				
Cummins Creek	0.0	0.6	20.8	21.4
Knowles Creek	0.0	1.1	36.2	37.3

Note: USFS—constructed by U.S. Forest Service; DF—debris-flow-formed jams; other includes both local and fluvial categories. Totals do not include constructed jams.

TABLE 3. PERCENTAGE OF ALL LOG JAMS NOT CONSTRUCTED BY HUMANS INFLUENCING CHANNEL MORPHOLOGY WITH KEY MEMBERS EMPLACED BY DIFFERENT PROCESSES

Location	Debris flows	Local	Fluvial
Industrial Forest			
Sullivan and Larson Creeks	25	7	68
Knowles Creek	12	3	85
Old-Growth Forest			
Cummins Creek	3	24	73
Knowles Creek	3	2	95

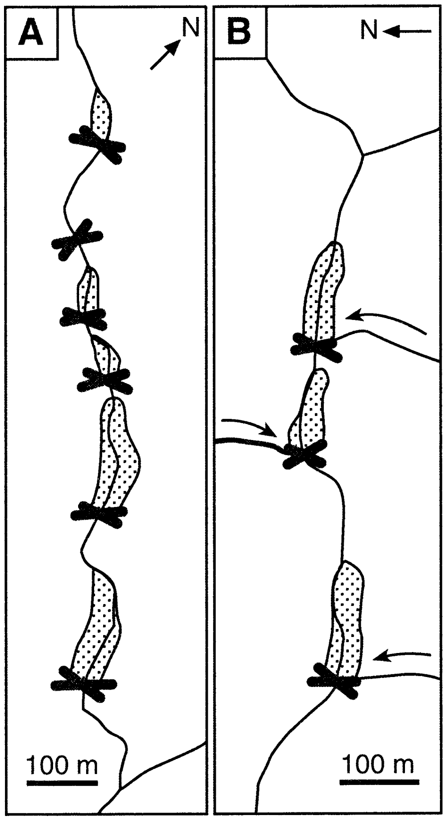

Figure 3. Maps of log jams and alluvial-valley flats in (A) Black Creek, a tributary of the West Fork Satsop River, Washington, where log jams were formed by proximal recruitment of large key-member logs from streamside forests (Montgomery et al., 1996); and (B) a portion of Larson Creek, Oregon, surveyed in 1995 and in which log jams were formed by deposition of debris-flow deposits at tributary junctions (arrows indicate direction of delivery down tributary channels). The middle jam shown in Figure 3B was initially mapped in 1994, but had breached prior to the 1999 field season, and the associated channel fill had eroded to bedrock. By the time of our 1999 resurvey, however, another debris-flow jam had formed between the old (1994) jam location and the next jam downstream.

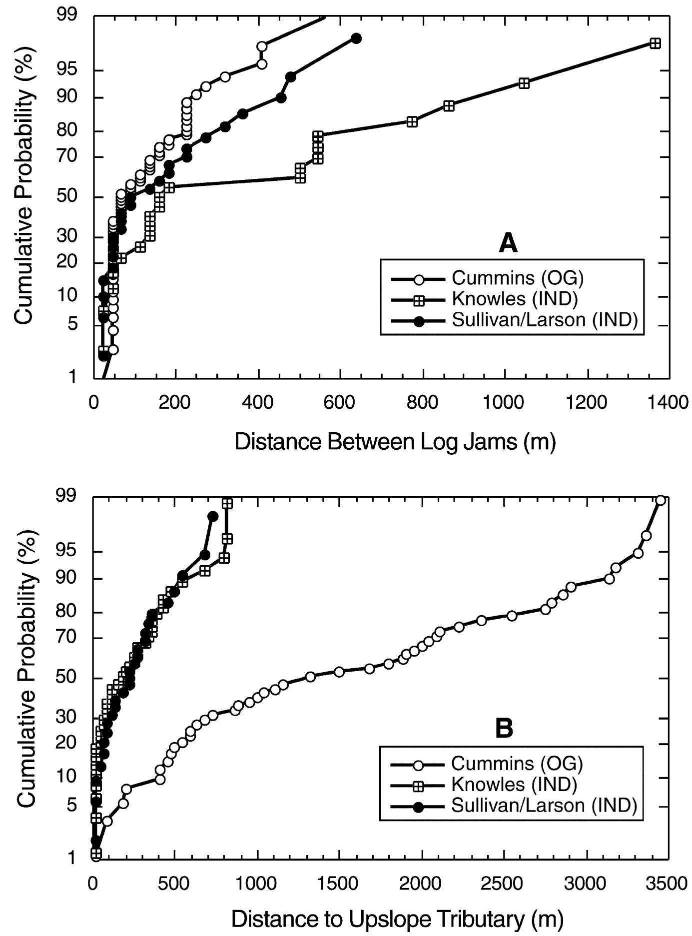

Figure 4. Cumulative probability distributions of (A) the distance between large log jams (i.e., less than 5 pieces LWD), and (B) the distance from large log jams to blue-line tributary junctions portrayed on 1:24,000 scale topographic maps; constructed jams in Knowles Creek were excluded from this analysis.

TABLE 4. P-VALUES FOR T- AND F-TESTS OF THE SIMILARITY IN THE MEAN AND VARIANCE OF DISTRIBUTIONS OF DISTANCES BETWEEN LARGE LOG JAMS

Location	T-test	F-test
Cummins (OG), Knowles (OG)	0.6163	0.7035
Cummins (OG), Knowles (I)	<0.0001	<0.0001
Cummins (OG), Sullivan/Larson (I)	0.1391	0.0226
Knowles (OG), Sullivan/Larson (I)	0.2440	0.0747
Knowles (OG), Knowles (I)	0.0288	<0.0001
Knowles (I), Sullivan/Larson (I)	0.0187	0.0003

Note: I—industrial forest, OG—old-growth forest.

industrial forests may be more highly concentrated near tributary junctions than jams formed in old-growth forests (Fig. 4B).

In both types of forest, there are many small log jams and few large ones. Frequency distributions of the number of pieces per jam followed inverse power relations (Fig. 5). Hence, the arrangement of logs into jams appears to exhibit some systematic self-organization independent of forest age. In total, 60% of the inventoried jams had 1–5 pieces, and 23% had 6–10 pieces, indicating that small jams with less than 10 pieces of wood dominated the population of log jams. Jams in unmanaged forests had a greater proportion of key logs with root wads across the full range of jam sizes.

POOL FORMATION

Data on pool-forming agents and pool dimensions were collected for 720 pools and 413 pieces of wood debris that influenced channel morphology by forming or modifying a pool. Substantial differences in pool-forming agents were found between industrial and old-growth forests (Table 5), with 12%–13% of pools being forced by wood in reaches flowing through industrial forest, as compared to 46%–51% in those flowing through old-growth forest. Pools formed by debris-flow deposits accounted for 4% of pools in old-growth-forest reaches and 4%–7% of pools in

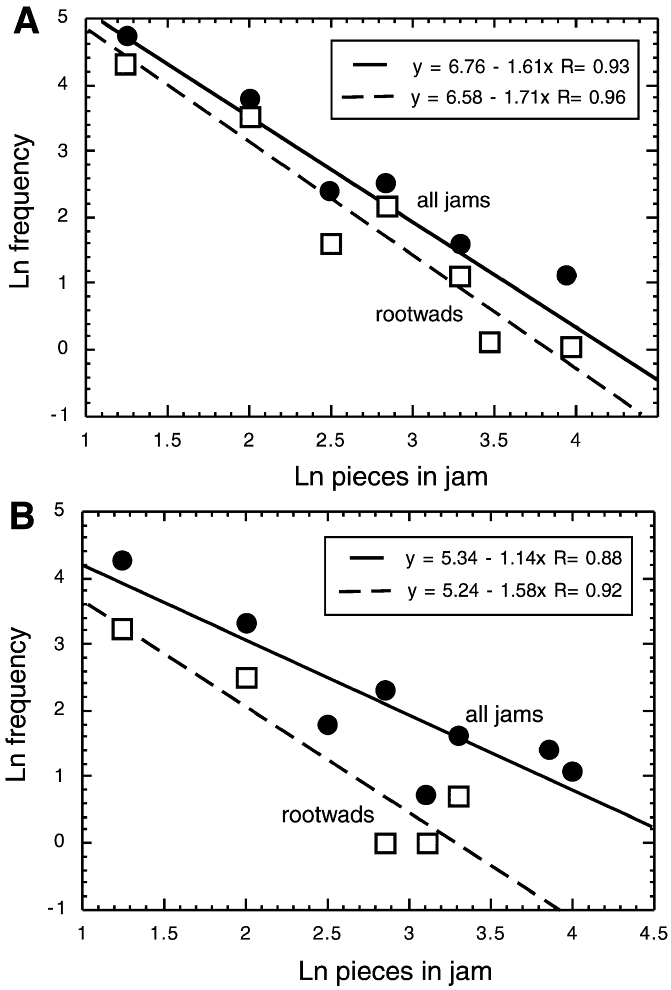

Figure 5. Frequency of log jams as a function of jam size expressed as the number of logs in a jam for both all log jams (circles and solid line) and only those log jams with a rootwad (squares and dashed line) for (A) unmanaged reaches, and (B) managed reaches.

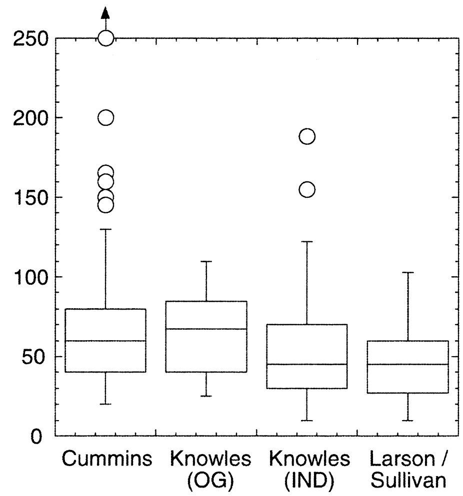

Figure 6. Distributions of key-log diameters for the study basins; OG—old growth forest; IND—industrial forest.

TABLE 5. PERCENTAGE OF POOLS SURVEYED FORMED BY DIFFERENT POOL-FORMING AGENTS, EXCLUDING THOSE POOLS ASSOCIATED WITH CONSTRUCTED LOG JAMS

Location	Bedrock	Jams/wood	Free	Debris flow
Industrial Forest				
Sullivan and Larson Creeks†	44	13	34	7
Knowles Creek	33	12	51	4
Old-Growth Forest				
Cummins Creek	25	51	20	4
Knowles Creek	7	46	43	4

†An additional 2% of pools in Sullivan & Larson Creeks were formed by beaver ponds.

TABLE 6. P-VALUES FOR T- AND F-TESTS OF THE SIMILARITY IN THE MEAN AND VARIANCE OF DISTRIBUTIONS OF KEY LOG SIZES

Location	T-test	F-test
Cummins (OG), Knowles (OG)	0.9068	0.1103
Cummins (OG), Knowles (I)	0.0081	0.2855
Cummins (OG), Sullivan/Larson (I)	0.0006	0.0013
Knowles (OG), Sullivan/Larson (I)	0.0028	0.4551
Knowles (OG), Knowles (I)	0.1077	0.3202
Knowles (I), Sullivan/Larson (I)	0.1262	0.0188

Note: I—industrial forest, OG—old-growth forest.

industrial-forest reaches. Log jams formed by debris-flow deposits created only a small proportion of the pools in both the industrial and old-growth watersheds that we surveyed. However, the nature of pool forming agents shifts from wood dominated in old-growth forests to bedrock dominated in industrial forests.

KEY LOG SIZE

Most key logs in old-growth channels were >0.60 m in diameter, whereas most key logs in industrial-forest channels were <0.45 m in diameter (Fig. 6). T-tests and F-tests indicate that the mean and variances of the distributions of key log sizes were not significantly different between Cummins Creek and old-growth portions of Knowles Creek (Table 6). Similarly, there was no significant difference between the mean key log size in the industrial forest channels of Larson and Sullivan creeks and the mainstem of Knowles Creek, although the Knowles Creek key logs had a larger variance. Distributions of key log size in the old-growth-forest reaches of Cummins Creek differed significantly from distributions from both industrial forest study areas. The mean and variance in the old growth and industrial reaches of Knowles Creek were not significantly different, but the mean key log size in the old-growth headwaters of Knowles Creek differed from that for the industrial forest reaches of Sullivan and Larson Creeks. The apparent difference in the size of key logs in old-growth and industrial-forest channels is all the more striking considering that the largest wood debris in the industrial forest reaches is ''legacy wood'' derived from now-harvested forest stands.

BEDROCK AND ALLUVIAL CHANNEL DISTRIBUTIONS

The development of a bedrock- or alluvial-reach morphology depends on the relation of local transport capacity to the bedload supply, a relationship that can be influenced by trapping of sediment by log jams and local variations in sediment supply or bedload-clast lithology (Montgomery et al., 1996; Massong and Montgomery, 2000). Previous studies in the Satsop and Willapa River Basins evaluated a model for the distribution of bedrock and alluvial reaches that predicts bedrock channels occur where the local bedload-transport capacity given by $q_b = kA^mS^n$ chronically exceeds the local bedload-sediment supply given by $q_s = cA^p$, where A is the upstream drainage area, S is channel gradient, k and c are empirical constants, and m, n, and p are scaling exponents (Montgomery et al., 1996). Hence, the critical gradient, S_c, for maintaining a bedrock reach morphology is given by

$$S_c \geq [c/k]^{1/n} A^{(p-m)/n}, \tag{1}$$

where $[c/k]^{1/n}$ is a constant that incorporates local geology and climate, and (p-m)/n reflects both sediment transport processes (through m and n) and sediment supply (through p). This framework predicts that a greater sediment supply would require a larger slope to sustain a bedrock channel for the same drainage area, whereas a greater runoff per unit area would yield the opposite result.

Previous studies confirmed the predicted threshold separating data from bedrock and free-formed alluvial channel reaches, as well as the local influence of log jams, sediment supply, and clast lithology (Montgomery et al., 1996; Massong and Montgomery, 2000). In the Satsop River, for example, log jams founded on large key member logs locally forced conversion of bedrock reaches to alluvial reaches by trapping bedload (Montgomery et al., 1996). In the Willapa River basin, log size, sediment supply, and bedload clast lithology all influenced the distribution of bedrock and alluvial reaches (Massong and Montgomery, 2000). Wood debris exerted little influence on bedrock and alluvial-reach distributions in channels with a legacy of stream cleaning, splash damming, and loss of streamside forest (and, therefore, a dearth of large wood). In contrast, bedload deposition forced by log jams dominated the distribution of alluvial reaches in channels where wood was delivered by debris flows or where second-growth forest contributed wood large enough to form stable key members.

Our new data from Oregon Coast Range channels also indicate that an inverse drainage area-slope relation separates bedrock reaches from free-formed alluvial reaches, which plot at lower reach-average slopes for a given drainage area. The Oregon watersheds further reveal similarities in the longitudinal variations in processes controlling alluvial channel-reach distributions, with downstream patterns in that debris-flow processes yield to greater log jam influences that, in turn, yield to freely-formed alluvial channels at the base of the catchment. But there are also key differences among the three Oregon watersheds that show how underlying geological controls influence the relative importance of log jams in the creation and maintenance of alluvial reaches in bedrock valley segments.

The data from Cummins Creek show a separation of the data derived from bedrock and free-formed alluvial reaches, but the total number of data points (which represents a sampling of the distribution of area-slope data along the stream profile) are not uniformly distributed about the relation that separates data from bedrock and alluvial reaches (Fig. 7A). At low slopes along the mainstem channel (corresponding to drainage areas >1 km²), all of the surveyed reaches have a free-formed alluvial morphology (and plot below the threshold). In contrast, data from channels with drainage areas <1 km² exhibit a wide variety of slopes, with about half of our observations plotting in the field defined by bedrock reaches (i.e., above the threshold). Hence, the mainstem of Cummins Creek should exhibit an alluvial bed morphology even without log jams, whereas debris-flow deposits and log jams are likely to be important in creating alluvial reaches in headwater channels in this watershed.

A drainage area-slope threshold also defines the general distribution of bedrock and free-formed alluvial reaches in Knowles Creek (Fig. 7B). But in contrast to Cummins Creek, the threshold almost evenly divides the composite drainage area-slope data set. In Knowles Creek, log jams and boulders deposited by debris flows influence the distribution of reach types along much of the mainstem channel. Reaches in which a gravel bed is associated with boulders deposited by debris flows plot above data from free-formed alluvial reaches indicating that, as found previously for log jams (Montgomery et al., 1996), debris-flow deposits can force creation of alluvial reaches in locations that otherwise would host bedrock channels. In addition, most of the data from Knowles Creek plot close to but above the locally-derived drainage area-slope relation that defines an apparent upper limit to free-formed gravel beds. Consequently, log jams, boulders, or debris-flow deposits appear to be essential for retaining alluvial channel beds in this stream.

In Sullivan and Larson Creeks, bedrock channels are found even in large reaches, and most of the surveyed reaches plot in the field of data from bedrock reaches across the entire data set (Fig. 7C). As in Knowles Creek, alluvial reaches forced by either log jams or boulders deposited along debris-flow tracks plot within the field of bedrock data. In addition, most of the free-formed alluvial reaches occur at the lower end of the watershed (at drainage areas >4 km²).

The position of the threshold separating bedrock and alluvial channels relative to the drainage areas and slopes of the channel system controls the importance of log jams and debris-flow deposits on the formation of alluvial reaches. This relationship differs among the three study watersheds. Whereas in Cummins Creek, most of the reaches surveyed plot below the threshold, in Knowles, Larson, and Sullivan Creeks, most plot above the threshold. Hence, wood debris exerts a much greater control on the extent of alluvial reaches in Knowles, Sullivan, and Larson Creeks than it does along most of the mainstem of Cummins Creek.

DISCUSSION

Our observations reveal differences in the relative importance of log jams and debris flows in creating pools and alluvial channel beds both between old-growth and industrial forests and in different geological contexts. But as the riparian forest contributing trees to a channel may differ from the average forest-stand condition in the watershed, simple classification of forests into old-growth and industrial can mask substantial variability in the relation between riparian forest conditions and in-stream wood loading. In addition, field interpretation of the nature of pool-forcing agents and the cause(s) of log-jam formation are not always straightforward, and channel network architecture can influence patterns of debris-flow deposition. Nonetheless, the patterns that we observed are consistent with other observations that lead us to propose that our observations reflect general tendencies in Oregon Coast Range channels.

Debris flows obviously occur in old-growth forests in steep terrain, yet we did not observe any debris-flow jams in our previous field surveys of log jams in the Satsop and Queets Rivers on the Olympic Peninsula, Washington

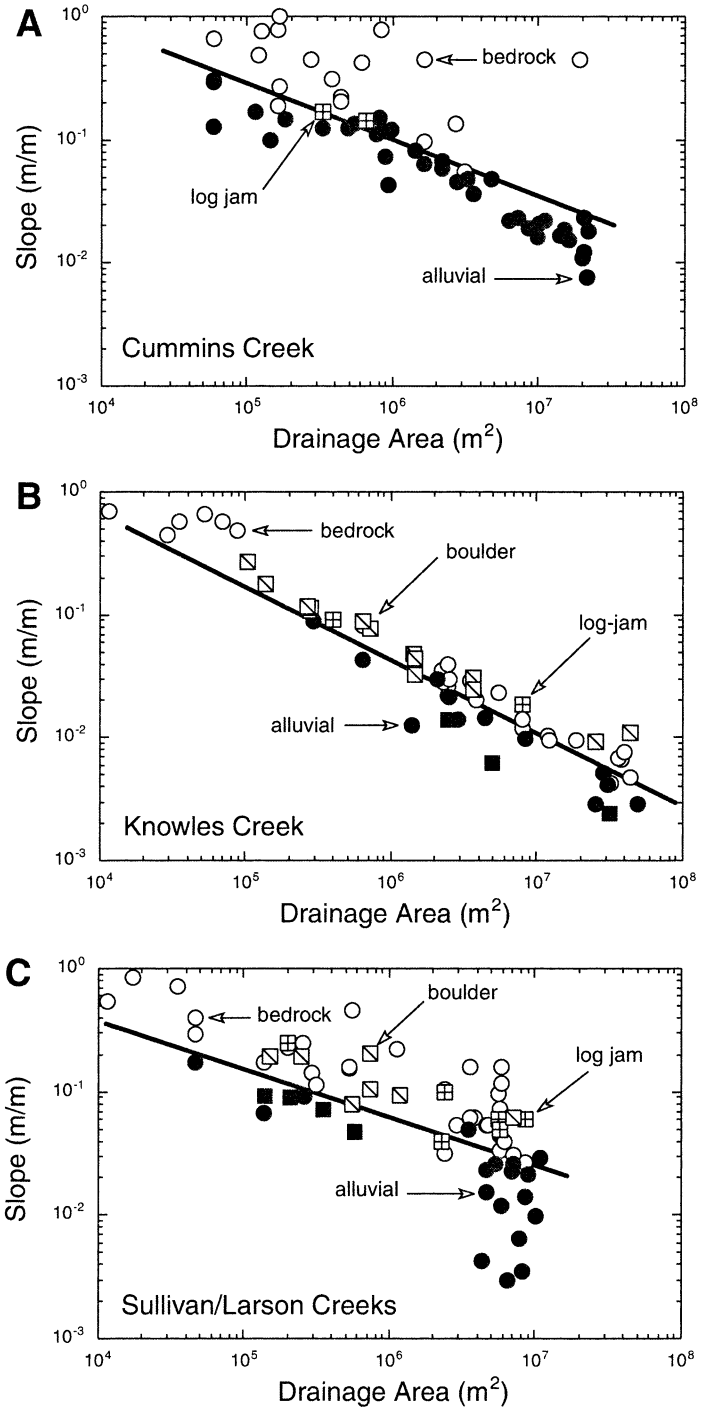

Figure 7. (A) Plot of drainage area versus reach average slope for bedrock reaches (open circles), free-formed alluvial reaches (solid circles), and reaches with an alluvial morphology forced by either wood debris (squares with internal cross) or debris-flow-deposited boulders (squares with internal diagonal slash) for (A) Cummins Creek, (B) Knowles Creek, and (C) Larson and Sullivan Creeks. Solid squares represent reaches where log jams and/or boulders locally trap sediment but do not control whether the channel has an alluvial bed at the scale of the entire reach. Lines represent threshold-like boundary between fields defined by data from bedrock and free-formed alluvial reaches.

(Abbe and Montgomery, 1996; Montgomery et al., 1996; Abbe, 2000). With one exception, all of the log jams mapped by Abbe (2000) in the Queets River were founded on key members either recruited from local streamside forests or transported some distance by fluvial processes. No debris-flow formed jams were found in channels with log-jam frequencies of >20 jams per km^{-1} (Abbe, 2000). This indicates that debris-flow-formed log jams are far less frequent than log jams formed by other processes in this relatively pristine river system.

Similarly, in the reaches of the Satsop River mapped by Montgomery et al. (1996), all of the surveyed log jams were founded on key-member logs that exhibited no evidence of having undergone transport through the channel network. None of the log jams were formed by debris flows; all of the jams consisted of logs racked up onto one or more key members recruited from the streamside forest. Most of the key members were in an advanced state of decay, however, as little key member recruitment had occurred since logging of the original streamside forest. Based on the map presented by Montgomery et al. (1996), the jam frequency founded on this mix of second growth and legacy old-growth wood was ≥10 jams per km^{-1}. The frequencies of log jams in the Queets and Satsop Rivers are similar to those found in our surveys of channels in old-growth forests in Oregon (Table 2).

In contrast, our previous surveys of the Willapa River (Massong and Montgomery, 2000) showed that reaches in which log jams forced an alluvial-bed morphology were associated with debris flows deposited at tributary junctions. Following their initial deposition, large quantities of fluvially-transported wood debris accumulated upstream of these jams. In addition, the scarcity of such large log jams (i.e., <2 jams per km^{-1}) reflects the small size of wood debris available both in the channel and from the riparian zone, and the systematic historic removal of large wood from channels. The concentration of log jams at tributary junctions in industrial forests found both in the present study and our previous work on the Willapa River contrasts with the pattern of frequent jams and almost continuous log steps in the reaches flowing through old-growth forest in the Queets River, tributaries to the West Fork Satsop River, headwaters of Knowles Creek, and in Cummins Creek.

We do not argue that debris flows were not an important sediment transport agent in the Oregon Coast Range prior to the onset of industrial logging. Neither do we argue that debris flows do not or did not transport substantial quantities of wood debris. Rather, we ask to what extent did debris-flow deposits influence the creation of pools and alluvial channel reaches in old-growth forests, and to what extent have those influences changed with modern logging practices. It may prove difficult to evaluate the indirect contribution of debris flows on downstream channels, as models that might be employed to address these issues typically involve large numbers of free parameters and can predict conflicting results depending upon the assumptions used to drive them (Benda and Dunne, 1997; Lancaster et al., 2001).

Our data on bedrock- and alluvial-reach distributions indicate that the relative importance of wood debris on habitat formation is to a large extent controlled by feedback among long-term processes that set the valley-long profile, processes in turn controlled by uplift rate and lithology. Although the three watersheds lie relatively close together in the Oregon Coast Range, differences in the relation between the river-long profile (as described by drainage area and slope) and the threshold controlling the distribution of bedrock and free-formed alluvial reaches likely reflect differences in bedrock lithology and perhaps variations in rock uplift rates. For example, if the bedrock is quite erodible when exposed, as is the case in the sandstone basins of the Oregon Coast Range, then the river profile should evolve such that its area-slope relationship and bedrock-alluvial threshold roughly coincide because prolonged exposure of bedrock in the streambed will lead to enhanced erosion. This will lower reach slopes and eventually stabilize an alluvial channel bed and thereby slow long-term erosion rates by shielding the underlying bedrock from erosion. Hence, the observation that in the sandstone basins of the Oregon Coast Range (Knowles, Sullivan, and Larson Creeks) the area-slope data for the channel network tend to plot well above the bedrock-alluvial threshold implies a system in which long-term bedrock erosion rates are damped by a forced-alluvial bed cover mediated by the dynamics of sediment storage elements associated with logs and log jams.

Clearly, substantial temporal variability in sediment supply could affect the extent and distribution of bedrock and alluvial reaches in mountain drainage basins (e.g., Kelsey, 1980; Madej and Ozaki, 1996). Although such variability might be expected in response to the delivery of a large pulse of sediment during storms, our data suggest that the effects of log jams and debris-flow-delivered boulders can be strong enough to substantially mask effects of stochastic temporal variability in sediment input and routing on the distribution of bedrock and alluvial channels when considered at the scale of the entire watershed. Boulder reaches created by debris-flow deposits apparently can reduce the local transport capacity (probably due to greater reach-scale hydraulic roughness) to the point where a former bedrock channel can develop an alluvial bed.

Each of the study watersheds has three distinct zones with different controls on the formation of alluvial channel reaches. The influences of debris flows, their deposits, and log jams on the formation of pools and alluvial channel reaches documented in our field surveys are consistent with three general process domains that define zones characterized by different styles of geomorphological influence on aquatic ecosystems in forested-mountain drainage basins: (1) an alluvial zone along the lower portions of mainstream channels, (2) a forced alluvial zone in the middle reaches of the channel network, and (3) a debris-flow-dominated zone in headwater channels. In each of our study watersheds, the debris-flow-dominated zone characterizes channels with drainage areas less than $\sim$1 km^2 and slopes $>$0.2. The extent of the middle zone of forced alluvial morphology varies among the three study watersheds, reflecting the relationship between the drainage area-slope characteristics of the river system and the basin-specific, critical-slope relation described by equation (1). The lower reaches of Cummins Creek are alluvial even without the effect of log jams or debris flows. Conversely, in Knowles, Sullivan, and Larson Creeks, the forced-alluvial zone extends over most of the mainstem length, and a free-formed alluvial morphology dominates the mainstem only near the basin outlet although the downstream arrangement of the three general process domains is similar, the extent of the channel network within each zone varies among the study watersheds.

Relation to Previous Studies

Several other studies from the Pacific Northwest support our interpretation that the habitat-forming role(s) of debris flows are more important in industrial forests than in old-growth forests. Our interpretation that most log jams and pools in Cummins Creek are formed by local recruitment of wood from the riparian forests is similar to the finding of a study using U.S. Forest Service survey data (McGarry, 1994). Although McGarry's terminology could lead one to conclude that debris flows were a major source of large woody debris for Cummins Creek, McGarry's study does not support this contention. Instead, McGarry (1994) reported that ''most wood tends to be nontransported,'' and concluded that ''debris torrents trap pieces of LWD at a limited number of locations, providing limited opportunities for good habitat'' (McGarry, 1994, p. 22).

Similarly, Dewberry et al. (1998) found that the role of debris-flow deposition in forming salmonid habitat along the mainstem of Knowles Creek was limited to near tributary junctions. Dewberry et al. (1998) noted that debris-flow deposition at tributary junctions formed alluvial reaches, which led them to build log jams along the mainstem and attempt to convert bedrock reaches to alluvial reaches. Their structures trapped extensive amounts of gravel, suggesting that the predominantly bedrock morphology of the mainstem of Knowles Creek is due primarily to limited sediment storage capacity rather than an inherently low sediment supply. Although the results of Dewberry's restoration efforts along Knowles Creek support our interpretation that the extent of bedrock channels found there today reflects a dearth of in-channel obstructions such as wood debris and boulders, much of the sediment trapped by Dewberry's structures may have been introduced to the channel system by the large, landslide-producing storms of 1996–1997.

Other stream channel restoration programs in the Oregon Coast Range provide additional evidence for the fundamental importance of sediment retention by wood debris on formation of aquatic habitat (House and Boehne, 1985, 1986, 1987; House et al., 1991; House, 1996). Numerous restoration projects that increased the extent of spawning gravel within a year of log-jam construction confirm that the extensive bedrock reaches in Oregon Coast Range streams reflect lack of sediment retention rather than low sediment supply. For example, the boulder-bed channel of Tobe Creek filled with coarse gravel during the first major winter freshet following construction of channel-spanning gabion and log structures (House and Boehne, 1986). Similar gabion and log barriers constructed in Lobster Creek resulted in a substantial decrease in the extent of bedrock along the bed in treated reaches during the first postconstruction high flows (House and Boehne, 1985; House, 1996). Fully- and partially-spanning log structures constructed in Elk Creek trapped sufficient bedload to increase the extent of gravel substrate by 44–50 fold (House et al., 1991). We conclude that the present abundance of bedrock reaches in the Oregon Coast Range arose not from a naturally low, depleted, or highly stochastic sedi-

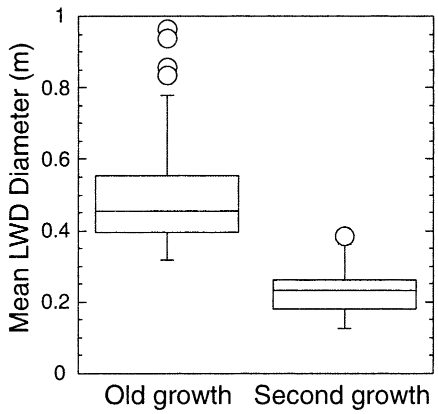

Figure 8. Box and whiskers plot showing the median diameter of in-channel wood debris derived from old-growth (n = 55) and second-growth (n = 47) forests reported by McHenry et al. (1998). T-tests and F-Tests indicate that the mean and variance of these distributions are significantly different ($p < 0.0001$).

ment supply, but rather from the loss of in-stream obstructions as a result of historic region-wide clearing of both log jams from channels and large trees from streamside forests.

We know of three additional data sets that can be used to address changes in the size of in-channel debris and streamside trees resulting from forest management. Key logs mapped by Montgomery et al. (1996) in tributaries of the West Fork Satsop River were from 0.6–2.0 m in diameter, a range that corresponds to that of the old-growth riparian stumps in the area. In contrast, the standing second-growth riparian forest has smaller trees that range from 0.1–0.9 m in diameter. McHenry et al. (1998) reported the mean diameter of LWD derived from old-growth and second-growth forests in 28 streams on the Olympic Peninsula, Washington. The frequency distribution of the data presented in their Tables 4 and 5 (Fig. 8) shows that the mean size of the wood derived from old-growth forests exceeded 0.5 m in diameter in almost half the reaches, but that the mean size of the wood derived from second-growth forests never exceeded 0.4 m. Long (1987) showed that in coastal Oregon, the size of in-channel debris recruited in the 60 yr after cutting was smaller than debris retained before harvest of the streamside forest, and much of the debris retained prior to cutting was >0.6 m in diameter, whereas none of the postcutting debris exceeded this size. We infer that the decreased size of wood debris associated with industrial forestry has led to a decrease in the frequency of stable log jams, which in turn has increased the importance of direct influences of debris-flow deposits in the creation of salmon habitat.

Additional support for our inference can be found in Kiem et al.'s (2000) finding that wood debris introduced to three Oregon Coast Range streams was not stable and had little lasting effect on channel morphology. The debris used in their experimental manipulations ranged from 0.15–0.81 m in diameter, with most pieces $\leq$0.3 m in diameter. The instability of this relatively small size debris supports our interpretation that the formation of stable log jams is inhibited by the small size of trees that can be recruited to channels from the riparian zones of contemporary industrial forests. Hence, one would expect debris-flow deposits to assume greater relative importance in log-jam formation in industrial forests due to the inability of locally-recruited wood debris to provide stable foundations upon which to initiate stable log jams.

Studies at the H.J. Andrews Experimental Forest in the Oregon Cascades provide further support for our interpretation of limited importance of debris-flow deposits as a habitat-forming mechanism in old-growth forests of this region. Johnson et al. (2000b) surveyed the effects of debris flows on wood transport and recruitment in channels flowing through old-growth forest but from which most of the in-stream wood had been removed following the 1964 storm. They found that high flows toppled and recruited trees from the streamside forest in reaches both influenced and uninfluenced by the direct and downstream (indirect) effects of debris flows. Although the proportion of the postflood wood loading that was due to debris-flow introduction is not explicitly presented in their paper, the relative proportion of wood delivered by debris flows was classified as ''high'' for only one of the eight channels studied (Johnson et al., 2000b). Johnson et al. (2000b) also found that the number of streamside trees toppled during that storm was not systematically related to debris-flow influences; in some reaches, more trees were toppled upstream of debris-flow influences than downstream of where debris flows entered the channel.

Implications for the Disturbance Ecology of Salmon

The disturbance associated with scour and passage of a debris flow generally is considered to negatively impact aquatic ecosystems, but debris-flow deposition can locally create or enhance fish habitat (Everest and Meehan, 1981; Reeves et al., 1995). Hence, an initially detrimental event could catalyze subsequent benefits for salmon populations. However, the net benefit or detriment to a salmon population will depend on the frequency of disturbance and the relative importance of debris flows in creating essential characteristics of salmon habitat. It would be naïve to suggest that salmon habitat can be described by only the extent of an alluvial-bed cover and pool frequency, but these are nonetheless important aspects of channel morphology of direct importance to salmon-habitat quality and abundance. Similarly, the larger-scale, longer-term interactions of debris-flow processes on valley-bottom morphology (Grant and Swanson, 1995), and as a source of sediment and wood to downstream channels, merit further study to evaluate the indirect effects of debris flows on salmon habitat.

Assessment of the relative role of debris flows on fish habitat needs to include consideration of the net effect of habitat destruction and creation. Although debris flows can create habitat where they deposit, the associated long zone of scour can obliterate habitat for fish and/or other organisms along the run-out path. An illustration of the importance of assessing the relative magnitude of the creation and destruction of habitat by debris flows is given by a dam-break flood on Black Creek, one of the tributaries of the West Fork Satsop River mapped by Montgomery et al. (1996). This event removed the log jams (most of which were founded on rotted key members) and transported all of the wood debris and stored sediment, incorporating them into a large log jam upslope of the confluence with the main channel. The net result was a complete scouring to bedrock and loss of an alluvial bed along much of the previously surveyed portion of the channel (Fig. 9).

Our observations suggest that the delivery of wood and gravel by debris flows may be advantageous to fish only in channels flowing through industrial forests where debris-flow deposits create diverse habitat in generally wood-poor reaches. Recognizing that salmon evolved in a dynamic environment does not necessarily imply that debris flows benefit salmon populations or that debris flows are an essential process that creates and maintains salmon habitat. An overall beneficial effect of habitat creation by debris flows may be restricted to wood-depleted channel systems. Consequently, debris-flow-formed log jams might provide high-quality habitat in a channel system in which few key logs are available, but our observations indicate that such jams were only marginally significant in creating and sustaining log jams and pools in the

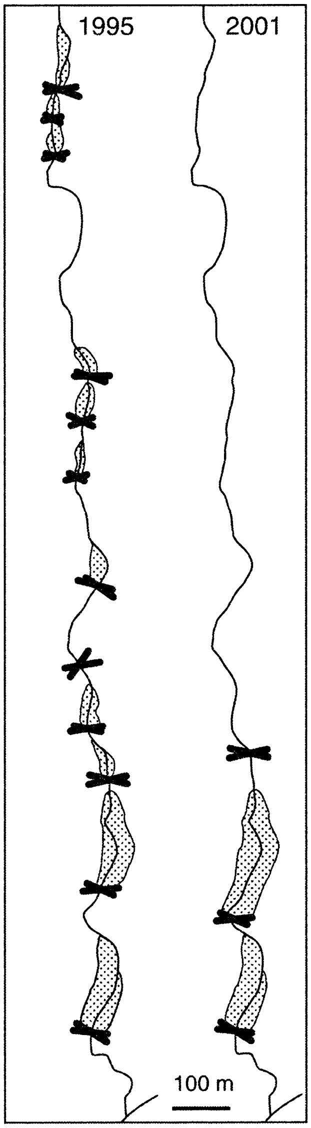

Figure 9. Maps of Black Creek in 1995 before and in 2001 after a dam break flood, showing locations of log jams and associated alluvial valley fills.

wood-rich systems in which the Pacific salmon evolved.

Salmon once thrived in the disturbance prone environment of the Pacific Northwest, and development of mountainous topography has been proposed as the driving force behind speciation of the Pacific salmon (Montgomery, 2000). But salmon-bearing streams tend to be low-gradient (i.e., <4% slopes) channel types (Montgomery et al., 1999), which in old-growth systems would be buffered somewhat from temporal variability in sediment and wood inputs because log jams function as sediment capacitors (Lancaster et al., 2001). The relatively limited role of debris flows as a habitat-forming process in old-growth forests suggested by our data indicates that models for the disturbance ecology of salmon need to take differences in the disturbance dynamics of old-growth and industrial forests into account in order to provide credible avenues for determining the risk associated with land management in steep forested terrain. In particular, management recommendations based on evolutionary interpretations that are themselves based on a disturbance model primarily applicable to industrial forests may prove misleading.

CONCLUSIONS

Our field surveys indicate that the degree to which debris-flow processes control log-jam formation appears to depend strongly upon land use and, more generally, on the presence of in-channel logs large enough to form key members capable of initiating stable log jams. Hence, interpretations of the importance of debris-flow deposits for aquatic habitat may be strongly conditioned by the specific geographic context in which those deposits occur. That log jams were originally abundant and widely distributed in Oregon Coast Range channels is consistent with descriptions of the extensive work required to clear channels for splash damming in the early twentieth century (Beckham, 1990). We suspect that historic reduction in the size and abundance of wood debris in Pacific Northwest channels has changed the nature of debris-flow influences on the structure and dynamics of salmon habitat. In primeval forests, locally-derived log jams primarily controlled habitat abundance through recruitment of large key-member-size logs from streamside and valley-wall forests. In contrast, the dearth of such large logs recruited to channels from contemporary industrial forests results in a greater direct influence of debris-flow deposits on habitat availability.

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