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Influence of large woody debris on channel morphology and dynamics in steep, boulder-rich mountain streams, western Cascades, Oregon

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Abstract

This study used 20-year records of stream channel change and wood to test hypotheses about the long-term influence of large woody debris (LWD) on channel morphology, channel stability, and sediment dynamics in a steep, boulder-rich mountain stream. We compared two nearly adjacent reaches of third-order Mack Creek over the period 1978–1997 after virtually all wood was removed from the channel of the lower reach in 1964. We assessed the long-term legacy of wood removal using repeated cross-section surveys, streamflow data, LWD inventory data, and detailed mapping and longitudinal profile surveys. At each of 11 cross sections in the upper reach and 19 in the lower reach, we calculated areas of scour and fill in response to the two largest floods in the record. We used quasi-likelihood logistic regression models to test the proportion of each reach that experienced change between consecutive surveys over the entire record (1978–1997) as a function of flood return periods. The longitudinal profile of the site without LWD was more variable than the reach with LWD at the finest scale (~ 1 m) due to a greater frequency of boulder steps, but the reach with LWD was more variable at the channel unit scale. LWD-created steps 1 to 2.5 m high in the wood-rich reach accounted for nearly 30% of the total channel fall and created low-gradient upstream channel segments one to three channel widths long. As a result, both reaches have the same average slope (about 9%), but nearly three times as much of the channel in the wood-rich reach had a slope of ≤ 5% as in the reach without wood (20.4% of total channel length vs. 7.5% of channel length). The reach with abundant LWD was less responsive to moderate streamflow events (return period < ~ 5 years), but it responded similarly to peak flows with a return period of about 10 to 25 years. Although the average magnitude of cross-section changes was the same during the largest flood in the record (25-year return period), the reach without LWD experienced scour and coarsening of the bed surface, whereas the reach with LWD experienced aggradation upstream of LWD features. Mack Creek may be representative of many steep mountain streams in which channel structure is strongly influenced by nonfluvial processes: a legacy of large boulders from glacial or mass movement processes and a legacy of dead wood from ecological processes. Sediment-limited mountain streams with large boulders, when deprived of LWD, appear to exhibit less morphological variation at the channel unit scale, to store less sediment, and to release it more readily than those with LWD.

Keywords: Woody debris; Channel stability; Stream cross sections; Longitudinal profile; Sediment

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1. Introduction

In steep mountain streams, large woody debris (LWD) is believed to create distinctive, persistent geomorphic features by affecting sediment dynamics. In narrow, steep-sided valleys, LWD (logs, branches, and wood fragments >10 cm in diameter and 1 m in length) contributes to the creation of a stepped longitudinal channel profile (Keller and Swanson, 1979; Nakamura and Swanson, 1993; Montgomery et al., 1996). LWD can create "forced" channel morphologies (e.g., pool-riffle or step-pool) in environments beyond the range of conditions in which they are normally found (i.e., at steeper gradients or lower sediment supply rates) (Montgomery and Buffington, 1997) and can even create alluvial channels where high bed shear stress and low sediment supply would otherwise be expected to create bedrock channels (Montgomery et al., 1996). LWD-created structures (e.g., steps and pools) retain sediment; increase the heterogeneity of bed elevation, water depth, and particle size; and reduce sediment transport relative to reaches without LWD. LWD accumulations diminish the probability of bed particle entrainment during competent flows and reduce the mean travel distance of entrained particles, thus reducing sediment transport efficiency (Heede, 1972a,b, 1975; Swanson and Lienkaemper, 1978; Beschta, 1979; Bilby, 1981; Megahan, 1982; Marston, 1982; Nakamura and Swanson, 1993; Thompson, 1995).

LWD structures create persistent, stable sediment storage sites that comprise the dominant sediment storage mechanism in many steep, forested mountain streams (Megahan and Nowlin, 1976; Thompson, 1995; Montgomery et al., 1996). Individual pieces or accumulations of LWD create storage sites for sediment accumulations amounting to as much as 10 to 15 times the annual sediment yield of some mountain streams (Megahan and Nowlin, 1976; Swanson and Lienkaemper, 1978; Megahan, 1982; Swanson and Fredriksen, 1982). Many channel-spanning LWD pieces or accumulations are stable for decades or longer (Swanson and Lienkaemper, 1978; Swanson et al., 1984; Hogan, 1987; Lienkaemper and Swanson, 1987). Based on the ages of trees growing on them, the minimum age of LWD jams averaged 50 years in third- to fourth-order streams in old-growth forest in Oregon sampled by Gregory (1991), with a maximum age of 150 years.

The influence of LWD on channel form and process is greatest in steep headwater streams where sediment supply is limited and where LWD is stable and provides the predominant, or only, source of large roughness elements able to retain sediment. In such streams, LWD may exert a dominant influence on the longitudinal channel profile. The proportion of total channel relief influenced by LWD in the Western Cascades ranges from 8–59% (Keller and Tally, 1979) to 30–80% (Keller and Swanson, 1979), while values as high as 100% have been reported for headwater streams of the Rocky Mountains in Colorado and the White Mountains in Arizona (Heede, 1972a,b, 1977). In larger gravel-bed rivers, LWD has less influence on the channel profile, although it may strongly influence other aspects of channel morphology (Abbe and Montgomery, 1996). However, in streams where sediment supply is not limited, spatial and temporal variations in sediment delivery and transport may in some cases overprint and obscure the effect of LWD on channel structure (Massong and Montgomery, 2000).

Large boulders contributed to stream channels by nonfluvial processes potentially complicate the role of LWD in channel morphology (Fig. 1). In highly resistant volcanic substrates such as those in the western Cascades, glacial action and mass movement processes (e.g., earthflows, debris slides, and debris flows) have left lag deposits of large (≥1 m diameter), persistent boulders whose threshold of mobility often exceeds the tractive force of contemporary fluvial events. Longitudinal variations in the frequency of large boulders in a channel may be an indicator of spatial variations in fluvial and hillslope processes that shape channel and valley floor morphology (Grant and Swanson, 1995; Lambert, 1997) and may be important in the stabilization of LWD jams (Likens and Bilby, 1982). Large boulders have at least two kinds of possible effects on sediment dynamics. First, they act as large roughness elements that may retain and release sediment comprising the stream's bed load. Chin (1989) noted a fining of bed material upstream and a coarsening downstream of boulder steps. Second, they may capture and stabilize key pieces of LWD, creating sediment wedges (Fig. 1). Alternatively, very large boulders may suspend LWD well above the active channel, effectively precluding it from interacting with the bed load.

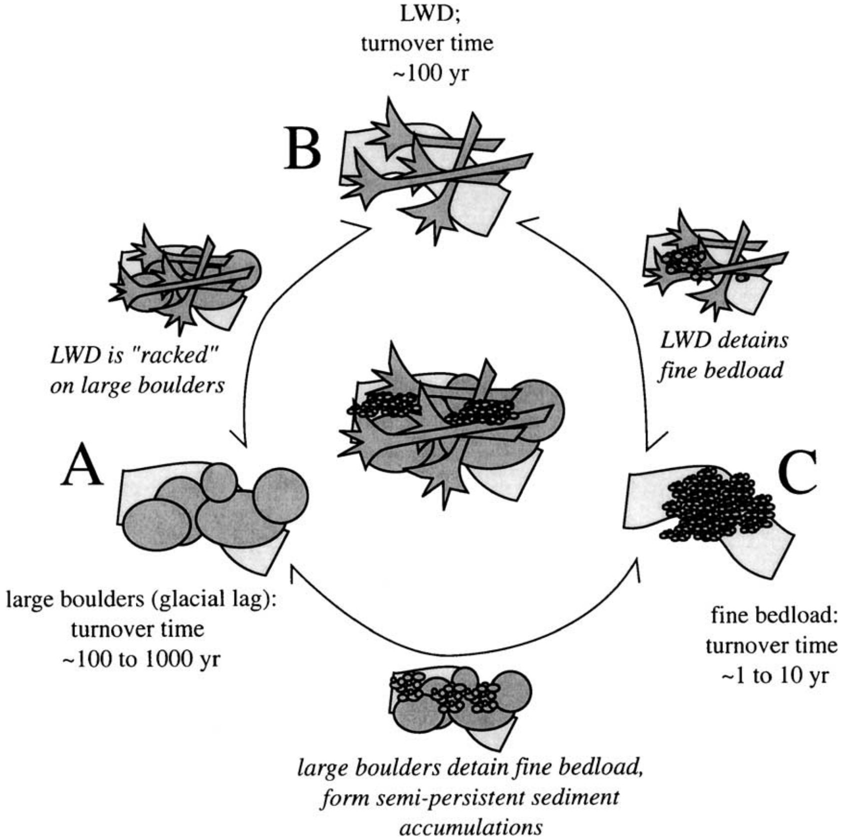


Fig. 1. Conceptual model for persistent features affecting sediment storage and turnover in supply-limited mountain stream channels. Sediment storage and transfer is a function of three kinds of interactions among large boulders (A), large wood (B), and bed load (C). Stream channels lacking in LWD may store and release fine bed load over shorter periods (e.g., Mack Creek clear-cut reach), whereas streams with LWD may store and release bed load over longer periods (e.g., Mack Creek old-growth reach).

The destabilizing effects of removing LWD from a channel have been well documented by experimental studies (Beschta, 1979; Bilby, 1981, 1984; Heede, 1985; Lisle, 1986, 1995; MacDonald and Keller, 1987; Smith et al., 1993a,b; Díez et al., 2000). In most of these studies, LWD removal has led to moderate to substantial erosion and a coarsening of the bed surface, presumably due to a decrease in channel roughness and a consequent increase in boundary shear stress available to transport sediment (Lisle, 1995). However, studies of geomorphic effects of wood removal have typically been short-term and have not addressed the long-term effects of LWD removal on channel stability. Few, if any, studies have directly addressed the question of whether LWD affects the temporal frequency or pattern of channel change. To our knowledge, no wood removal studies involved long-term monitoring of both LWD and channel structure.

This study examines the long-term effects of wood removal on channel morphology in a third-order mountain stream in the western Cascades characterized by abundant large boulders. It addresses two questions:

(i) Once a channel has adjusted to wood removal, does it have different channel structure and function than an otherwise similar channel that has LWD?
(ii) How does the presence of large boulders modify the long-term effects of removal of LWD?

We define two relevant attributes of wood interactions with stream channels: (i) the creation and persistence of features that permit sediment accumulation ("structure"); and (ii) the associated storage capacity and rates of sediment turnover ("function"). Although it is not possible to completely separate structure and function in stream channels, this distinction becomes important when evaluating long-term measurements. Measures of channel structure include channel width, depth, particle size, the presence/absence of LWD, wood volume, and the numbers and arrangement of geomorphic features (log steps, log jams, boulder steps). Measures of channel function include changes in any of the structural attributes over time in response to streamflow events.

This study tests hypotheses about the structure and function of LWD, using long-term data about both wood and channel structure to compare locations where wood was removed, and not removed, at both the within-reach (or channel unit) and between-reach scales. We tested these hypotheses:

(i) A reach that contains abundant LWD has many geomorphic features created by wood.
(ii) Channel-spanning LWD accumulations are associated with larger local departures from reach-average slope gradient than are large boulder accumulations.
(iii) Compared to reach-averaged particle sizes, channel-spanning LWD accumulations are associated with finer than average sediment upstream and coarser than average sediment downstream.
(iv) A reach with abundant LWD and large boulders will have more variable bed slope and a patchier, less uniform particle size distribution at the channel unit scale than an otherwise similar reach with large boulders but without LWD.
(v) Even after multiple flood events, a reach with abundant LWD is more stable, maintains a higher sediment storage capacity in the channel, and has lower bed load transport efficiency than a reach with only large boulders.

2. Methods

2.1. Study site and LWD treatments

The Mack Creek study site lies at an elevation of ~ 750 m within the H.J. Andrews Experimental Forest (Andrews Forest) (Fig. 2). Mack Creek is a third-order watershed with a drainage area of ~ 5.8 km^2 at the gaging station located about 1 km upstream of the junction with Lookout Creek. Since the mid-1970s, the lower portion of Mack Creek has been the site of intensive, long-term studies focusing on riparian forest dynamics and the fate and functions of LWD in fluvial systems (e.g., Swanson et al., 1976,

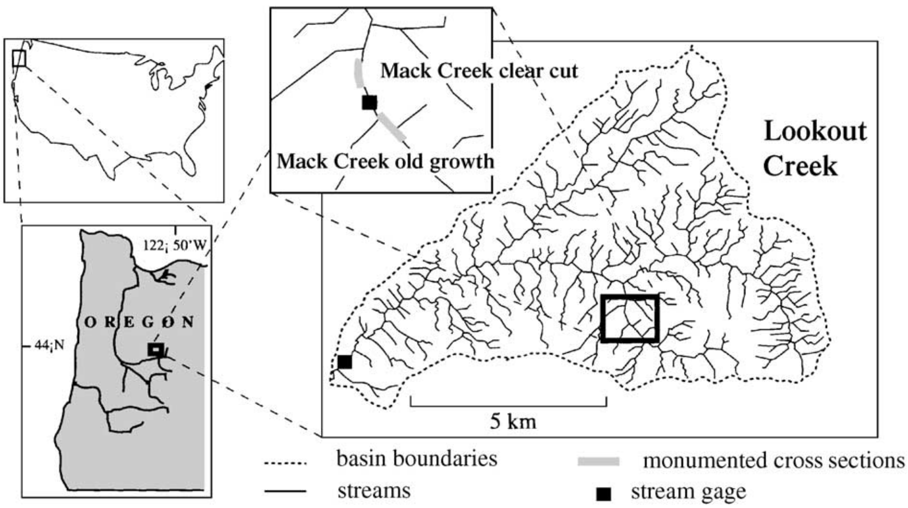


Fig. 2. Location of long-term cross-section monitoring sites and gaging stations in the Lookout Creek watershed used in this study (H.J. Andrews Experimental Forest).

1982a,b; Swanson and Lienkaemper, 1978; Lienkaemper and Swanson, 1987; Nakamura and Swanson, 1993).

This study capitalizes on some of those long-term monitoring data, including two sets of permanent reference channel cross sections in nearly adjacent, contrasting reaches. The upper reach (old-growth site) lies just upstream of the gaging station and a road crossing (Fig. 3); this reach contains 12 cross sections established in 1978 within an old-growth forest dominated by Douglas-fir (*Pseudotsuga*) with lesser amounts of western hemlock (*Tsuga*) and western redcedar (*Thuja*). The lower reach (clear-cut site) has 20 cross sections established in 1981 and lies immediately downstream of the gaging station. The hillslopes adjacent to the reach were clear-cut in 1964–1965, and most of the LWD remaining in the channel was flushed downstream by a major flood in December 1964. The distribution of LWD (all pieces ≥10 cm diameter and ≥1 m in length) has been monitored along an ~ 1-km stream reach encompassing the two cross-section sites since the mid-1980s. The two reaches have approximately the same channel gradient (~ 9%) and experience essentially the same discharge. No major tributaries enter within or between the two study reaches, although a first-order tributary with a drainage area of ~ 10 ha (unofficially designated Devil's Club Creek) enters the old-growth reach immediately upstream of cross section 5 (Fig. 3). LWD is abundant in the old-growth reach and largely absent in the clear-cut reach (Fig. 3). Also, the old-growth reach is confined by steep hillslopes in a

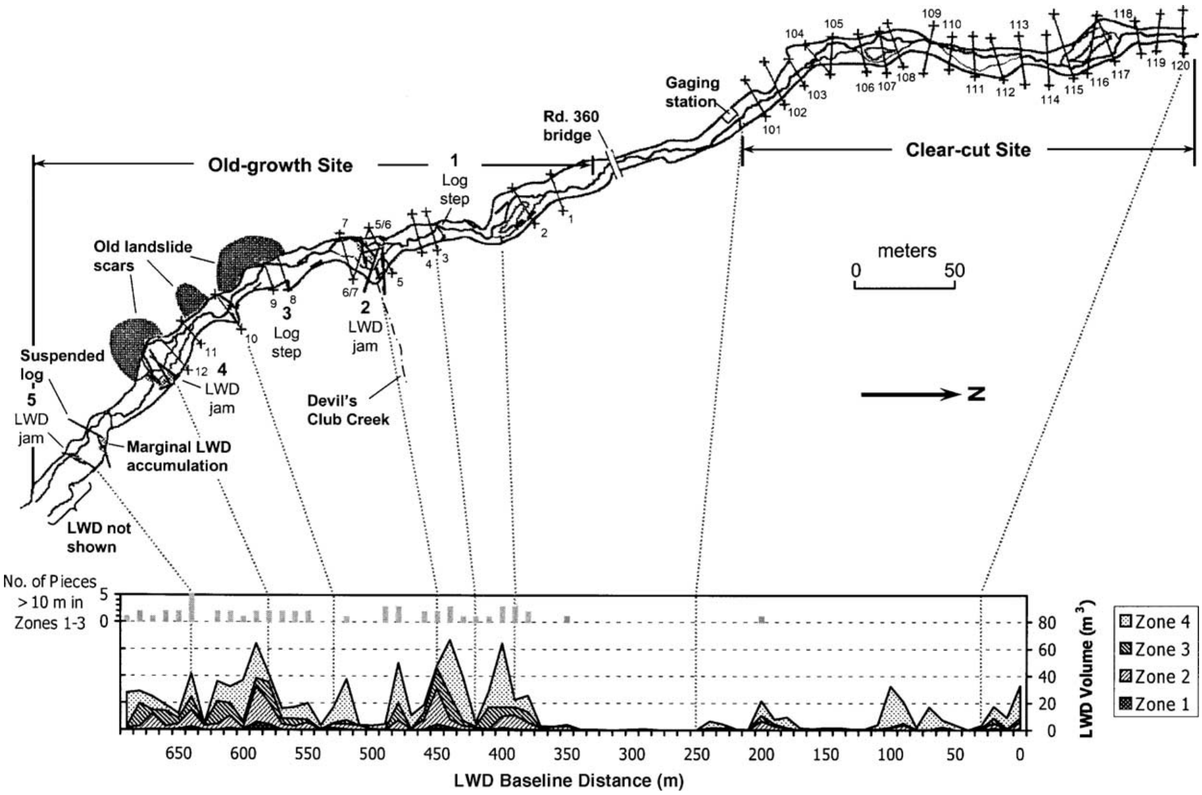


Fig. 3. Map of the Mack Creek old-growth and clear-cut cross-section sites showing LWD structures, cross-section locations, and longitudinal distribution of LWD (1996 data). Bars at top of lower plot show the number of pieces of LWD >10 m in length located at least partially within the channel, counted in 10-m channel segments. Bottom portion of lower plot shows the estimated volume LWD in 10-m channel segments within each of four zones relative to the channel: zone 1—within the low-flow active channel; zone 2—within the bankfull active channel outside or suspended above low-flow channel; zone 3—suspended above bankfull stage within the bankfull channel width; and zone 4—laterally outside the bankfull channel. LWD data are from Gregory (1998).

narrow valley, whereas in the clear-cut reach the valley floor is wider and not confined by adjacent hillslopes.

Compared to the clear-cut reach, the old-growth reach had approximately 8 times more LWD and 30 times more "key pieces" (Nakamura and Swanson, 1993) capable of forming significant structural elements in the channel in 1996 (Fig. 3). The estimated volume of LWD within the channel (zones 1–3; see figure caption) averaged 0.15 m^3/m (range: 0.00–1.08) within the clear-cut reach (40–260 m on the LWD baseline; Fig. 3) and 1.22 m^3/m (range: 0.05 to 4.6) in the old-growth reach (340–680 m on the LWD baseline). Only a single LWD piece >10 m in length was present within the channel in the clear-cut reach in 1996, compared with 51 pieces in the old-growth reach (Fig. 3); these values are equivalent to frequencies of 0.45 and 15 pieces per 100 m, respectively.

2.2. Historical data sets

Three sources of long-term data for the H.J. Andrews Experimental Forest (http://www.fsl.orst.edu/lter) were utilized in this study: (i) streamflow records, (ii) monitored cross sections and particle size data, and (iii) wood inventory data (Gregory, 1998). This study utilized peak flows from streamflow gages maintained since 1950 at Lookout Creek and since 1980 at Mack Creek (see Figs. 2 and 4). The magnitude and return period of the largest annual peak discharge between consecutive cross-section surveys were determined and used in an analysis of cross-section response to flood disturbance (Faustini, 2000 for details).

This study utilized data from two sets of reference cross sections, Mack Creek old growth and Mack Creek clear cut (Fig. 2), that are part of a larger set of channel cross sections established in the late 1970s in the Andrews Forest (Faustini, 2000). Cross sections were surveyed at the old-growth site only in 1978 and 1980 and at both sites in 1981–1986, 1988, 1990, and 1995–1997. Cross-section profiles were surveyed using rod and level, with measurements taken at 0.5-m intervals along the tape and at slope break points. The substrate at each rod position was also recorded as a two-letter code. The chief substrate categories (within the active channel) were boulder (>25 cm diameter), cobble (5 to 25 cm), gravel (2 mm to 5 cm), fine sediment (< 2 mm; typically sand), log, suspended log, and organic debris (woody debris < 10 cm in diameter). Modified Wolman (1954) pebble counts of 100 particles selected in a "random walk" from an ~ 2-m-wide band along each cross-section transect were performed beginning with the 1995 survey. For large, partially buried particles the length of the apparent intermediate axis of the exposed portion of the particle was measured.

This study utilized wood volume data for 1995 and 1996 from an annual inventory of wood in Mack Creek (Gregory, 1998). Tagging and tracking of LWD movement in Mack Creek was initiated in 1986 and is ongoing. Wood pieces ≥10 cm in diameter and 1 m in

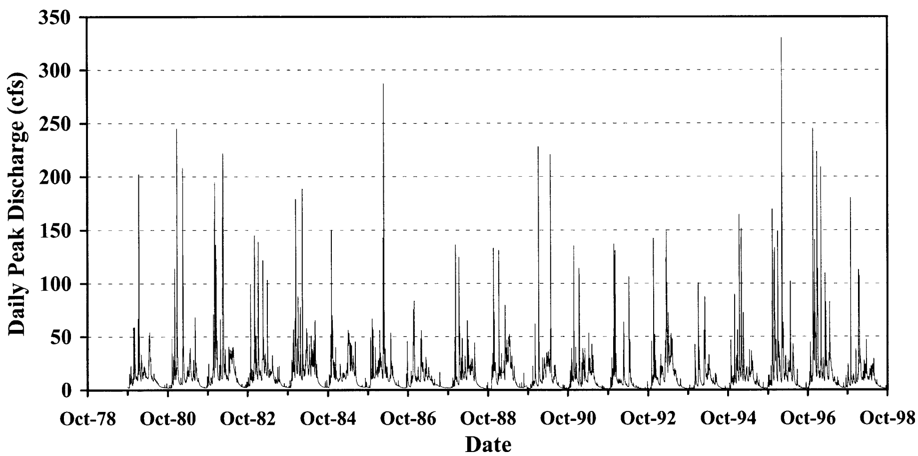


Fig. 4. Daily peak discharge at the Mack Creek gaging station, water years 1980–1998.

length are inventoried annually, and the position of each piece is noted in 10-m sections along a 1000-m transect extending upstream from the downstream end of the clear-cut reach (Fig. 3). In addition to LWD lying in or overhanging the channel, pieces lying on the bank or floodplain are included if they are judged to be close enough to the channel to interact with extreme floods. The length and average diameter of each piece are measured to the nearest 0.1 m and 1 cm, respectively, when the piece is first tagged and whenever it is determined to have moved. In addition, the percentage of the volume of each piece occupying each of four riparian zones (Robison and Beschta, 1990; see Fig. 3) is also estimated.

2.3. Field data collection

Additional field data were collected during the summer of 1997 (Faustini, 2000). Field work included (i) surveying the positions of the cross-section end-point stakes, (ii) surveying a high-resolution longitudinal profile of the channel thalweg, (iii) mapping the margins of the active channel floodway, (iv) counting the frequency of large boulders (≥1 m diameter) within the active channel floodway, and (v) mapping the locations of large logs and woody debris accumulations in the old-growth reach.

The map position and relative elevation of each cross-section end post were surveyed using a laser theodolite with an effective precision within ± 5 cm in 25 m in both the horizontal and vertical directions. A high-resolution longitudinal profile survey was conducted using the laser theodolite along the channel thalweg of ~ 1 km of Mack Creek, including both the old-growth and clear-cut sites. Both bed elevation and water surface elevation (these were baseflow conditions) were determined at each survey point. Survey points were selected along the main thalweg at intervals of ~ 1 m, or a smaller interval where necessary to characterize abrupt changes in channel slope or elevation. The longitudinal profile surveys consisted of 400 points at 0.96 ± 0.25-m intervals in the old-growth reach, and 412 points at 0.81 ± 0.23-m intervals in the clear-cut reach. Concurrently with the longitudinal profile survey, the margins of the active channel floodway were surveyed at intervals of ~ 5–10 m.

In both the old-growth and clear-cut reaches, the number of boulders with an intermediate (*b*-axis) diameter ≥ 1 m within each 20-m channel segment along the LWD baseline was counted. Boulders completely exposed and partially buried in the channel were counted if they met the size criterion. Boulders embedded in the bank were also counted if they could interact with a bankfull discharge or if they were undercut by the channel. In the old-growth reach, the locations of log jams and log steps were noted in the course of the longitudinal profile survey.

2.4. Data analysis

The structure and function of the old-growth and the clear-cut sites were compared for multiple time periods using a variety of analyses, depending upon data availability. Comparisons of structure between the old-growth and clear-cut sites were based on the 1997 longitudinal profiles and the 1995–1997 particle size data. Water depth and bed slope at several scales were calculated for each survey point ($n = 400$ in the old-growth reach, $n = 412$ in the clear-cut reach). Particle sizes were qualitatively compared between sites using graphs of cumulative particle size frequency distributions.

Sediment transport during the 1996 flood of record (Fig. 4) was inferred from changes between 1995 and 1996 in particle size distributions and in cross-section profiles at the old-growth and clear-cut sites. Statistically significant differences in bed surface particle size between reaches or between years at the same reach were determined using Student's *t*-tests of the differences in D_{16}, D_{50}, and D_{84} values for groups of cross sections ($n = 11$ for the old-growth reach, $n = 17$ for the clear-cut reach). Channel responses to the two largest floods in the record—February 22, 1986 and February 7, 1996—were compared between the old-growth and clear-cut sites by calculating the areas of fill and scour in each cross section between 1985 and 1986 and between 1995 and 1996. First, data points corresponding to logs lying on or suspended above the channel bed were filtered out so that the cross-section profiles would represent the configuration of the channel boundary exclusive of LWD (Faustini, 2000). Then a public-domain software package, WinXSPRO (Grant et al., 1992; USDA Forest Service, 1998), was used to calculate the area between cross-section profiles from consecutive survey dates to determine the cross-sectional area of channel scour and fill. These quantities may be thought of as the net volume per unit channel length of bed material eroded from (scour) or deposited within (fill) the channel. From this perspective, each cross section represents a single sample point for channel response in a longitudinal transect of the stream channel.

We used estimates of scour and fill to define net and total cross-section changes at each cross section. The *net cross-section change* is the algebraic sum of scour (a negative value) and fill (a positive value). A negative value for the net cross-section change represents a net loss of bed and/or bank material, or net scour, while a positive value represents a net gain of bed/bank material, or net deposition at a cross section. The *total cross-section change* is the sum of the absolute values of scour and fill, and is an estimate of the minimum absolute magnitude of channel response (volume of sediment reworked per unit channel length) at a single cross section. Estimates of scour, deposition, net change, and total change for all cross sections at a site (i.e., old growth or clear cut) were averaged to yield a reach-average response.

Channel responses to all events in the record were compared between the old-growth and the clear-cut site based on quasi-likelihood logistic regression models (Faustini, 2000). The dependent variable was defined as the number of cross sections in a reach that surpassed a threshold of total cross-section change between consecutive cross-section survey dates. To facilitate comparison between streams of different size, this threshold was scaled by channel width (Fig. 5). Significant change was defined as scour and/or fill ≥ 0.2 m deep over $\geq 10\%$ of the channel width, or ≥ 0.15 m deep over at least 20% of the channel width, in a pair of cross-section profiles from consecutive survey dates at the same location (Fig. 5). This was the smallest cross-section change that could be consistently identified over the entire historical data set (Faustini, 2000). The independent variable was defined as the estimated return period of the largest instantaneous stream discharge measured at the Mack Creek stream gage during the time interval between consecutive cross-section surveys. The logistic model estimates the proportion of cross sections in each reach exhibiting change exceeding the detection threshold as a function of the estimated peak flow return period. Alternately, the site response may be characterized as the peak flow magnitude (return period) required to produce a given level of cross-section response (e.g., 50% of cross sections exhibiting a response, or, equivalently, a 50% probability of observing a response at a randomly selected cross-section location). Logistic regression models were compared between the old-growth and clear-cut sites based on approximate 95% confidence intervals (Faustini, 2000).

3. Results

3.1. Channel structure

Mean channel width is greater for the old-growth site (13.0 m, $n = 17$) than for the clear-cut site (10.7 m, $n = 11$), a difference that is marginally statistically significant (one-sided p-value = 0.044; t-test). The

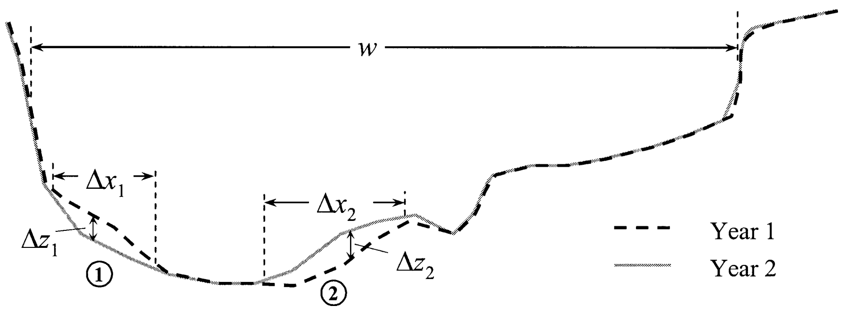


Fig. 5. Definition sketch showing criteria for inferring significant channel change based on consecutive cross-section surveys for logistic regression analysis. The detection threshold for change was defined as an average vertical displacement between profiles, Δz, of at least 0.2 m over at least 10% of the channel width, w, or $\Delta z \geq 0.15$ m over at least 20% of the channel width. That is $\Sigma \Delta x_i \geq 0.1\, w$ for $\Delta z_i \geq 0.2$ m or $\Sigma \Delta x_i \geq 0.2\, w$ for $\Delta z_i \geq 0.15$ m, where Δx_i is the length of an individual erosional or depositional feature (e.g., 1 or 2, respectively).

valley floor widens downstream of the road crossing (Fig. 3); hence, the old-growth reach has a wider channel despite being noticeably more constrained by its valley walls. Channel widths at the two log step locations are close to the reach average (9.5 and 15 m), while widths at the three LWD jam locations average 19.7 m, or 52% greater than the reach average. Within the clear-cut reach, the channel tends to bifurcate frequently, with mid-channel bars separating the main or low-flow channel from a secondary channel active only during high flows, whereas within the old-growth reach, only a short (~ 30 m) length of channel has a divided channel (Fig. 3).

The longitudinal channel profile (Fig. 6) reveals some important, albeit subtle, differences between the old-growth and clear-cut reaches in 1997. The reach-average channel slope is nearly identical in the two reaches (9.2% in the old growth vs. 9.3% in the clear cut). Water depth during low flow conditions was also similar in the two reaches, averaging 0.24 ± 0.15 m in the old-growth and 0.25 ± 0.12 m in the clear cut, although deep pools (water depth >0.5 m) were more common in the old growth (11 pools >0.5 m deep, or about 2.8/100 m) than in the clear cut (6 pools, or about 1.8/100 m) (Fig. 7). Absolute value of micro-scale channel slope (measured between adjacent points on the longitudinal profile, with an average spacing about 1 m) exceeded 1.0 at six locations in the old-growth reach (1.5/100 m) and 20 locations (6/100 m) within the clear-cut reach (Fig. 7). These locations correspond to small-scale boulder or log steps in the channel profile. Thus, by this measure the clear-cut

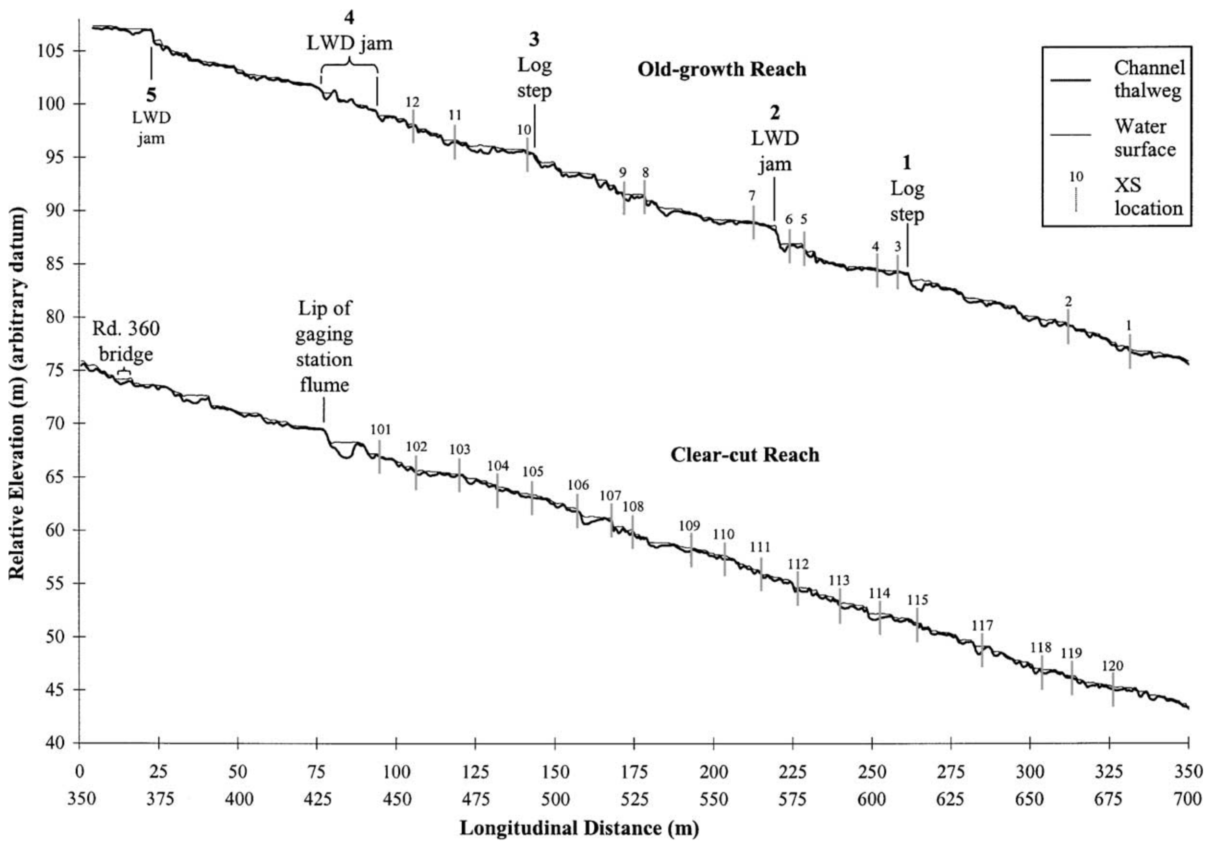
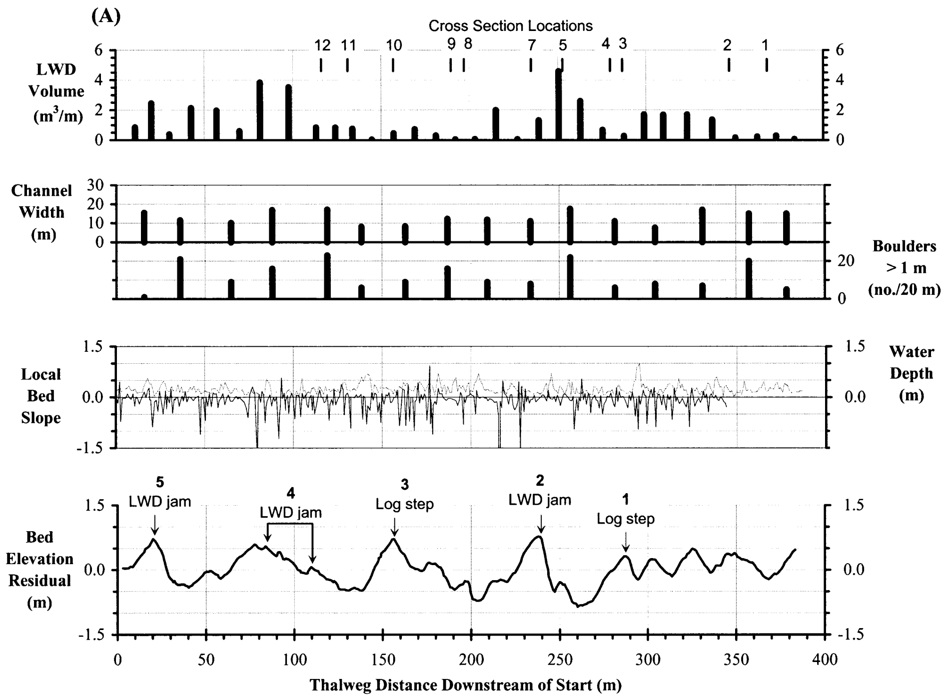
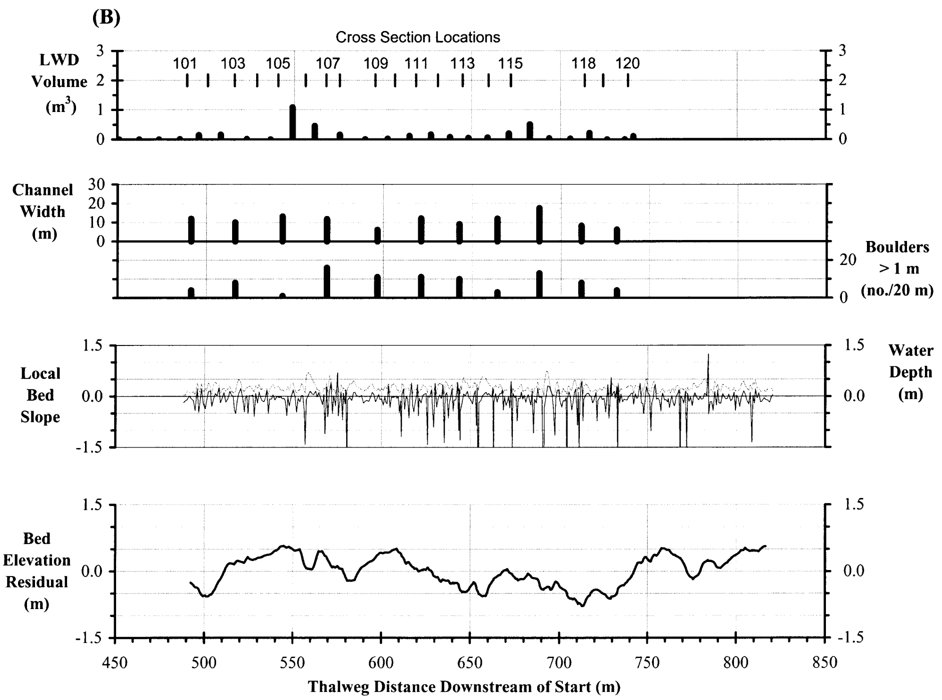


Fig. 6. Longitudinal profile for the portion of Mack Creek shown in Fig. 3. The longitudinal distance is based on an 11-point moving average of the *x*- and *y*-coordinates of the surveyed points along the channel thalweg, but the vertical coordinate has not been smoothed. The upper row of labels for the horizontal (longitudinal distance) axis apply to the upper plot (old-growth reach), while the lower row of labels apply to the lower plot (clear-cut reach). Numbered features correspond to numbered LWD structures in Fig. 3.


(A)
Cross Section Locations
12 11 10 9 8 7 5 4 3 2 1
LWD Volume (m³/m)
Channel Width (m)
Boulders >1 m (no./20 m)
Local Bed Slope
Water Depth (m)
5 LWD jam
4 LWD jam
3 Log step
2 LWD jam
1 Log step
Bed Elevation Residual (m)
Thalweg Distance Downstream of Start (m)


(B)
Cross Section Locations
101 103 105 107 109 111 113 115 118 120
LWD Volume (m³)
Channel Width (m)
Boulders >1 m (no./20 m)
Local Bed Slope
Water Depth (m)
Bed Elevation Residual (m)
Thalweg Distance Downstream of Start (m)

site has approximately four times the frequency of small-scale (boulder) steps as the old-growth site. However, the old-growth reach exhibits larger-scale step features associated with log steps (1 to 1.5 m in height) and LWD jams (1.5 to 2.5 m in height), which account for nearly 30% of the total channel fall (Fig. 6). LWD-caused steps in the longitudinal profile of the old-growth reach are significantly larger than most boulder-related steps in either reach. A few boulder steps in the clear-cut reach (e.g., at XS106 and 107, Fig. 6) have a height similar to the log steps (LWD structures 1 and 3, Fig. 6). However, the boulder steps are not associated with the 20- to 40-m-long segments of low-gradient channel that are found upstream of the LWD structures.

The effect of these larger-scale, wood-created step features on the longitudinal channel profile is clearly shown in the bed elevation residual plots [Fig. 7, lower plots in (A) and (B)], which reveal channel unit scale variations in bed slope. Peaks in the residual plots correspond to inflection points between channel segments with below-reach-average slope (upstream) and above-reach-average slope (downstream); these are more pronounced in the old-growth reach, where they correspond to LWD structures (Fig. 7). As a result of the wood-created steps, local channel slope measured at a scale approximating average channel width (about 10 m) has a frequency distribution skewed toward low slopes in the old-growth reach, compared to an approximately normal distribution for the clear-cut reach (Fig. 8). Nearly three times as much of the channel had a slope of 5% or less in the old-growth reach (20.4% of total channel length) as in the clear-cut reach (7.5% of total channel length) based on slopes calculated over a 10-m interval on a 5-point moving average of the longitudinal profile in Fig. 6.

Boulders $\geq$1 m in diameter were slightly more frequent in the old-growth reach (58/100 m) than in the clear-cut reach (40/100 m; Fig. 7). These average values are similar to the *maximum* frequency of $\sim$ 0.5 boulders per meter found by Lambert (1997) in first- to fifth-order Lookout Creek. The highest boulder frequencies in the old-growth reach were consistently found to occur at or downstream of LWD jams (Fig. 7A). While channel width was greatest at LWD jams (though not at log steps), the higher boulder frequency in the vicinity of LWD jams was not simply due to greater streambed area. For example, large boulders were much less abundant upstream than downstream of the uppermost LWD jam (structure 5 in Fig. 7A), even though the channel width was greater upstream than downstream of this structure. Also, exposed boulders meeting the size criterion were more frequent at the base and immediately downstream of LWD structures.

Bed material in low-gradient portions of the old-growth reach sampled by cross sections just upstream of log steps and LWD jams was finer than the reach average particle size, but particle size just downstream of LWD structures did not differ consistently from the reach average. The D_{84} at XS3, just upstream of a log step (see Fig. 6) was 152 mm in 1995 and 136 mm in 1996, compared to reach average D_{84} of 302 mm in both years. In 1997, the D_{84} values at XS3 and XS10, just upstream of log steps, were 222 and 190 mm, respectively, compared to a reach average of 370 mm. The D_{84} at XS7, just upstream of a log jam, was 234 mm in 1995 and 184 mm in 1996, compared to the reach average of 302 mm in both years, and 250 mm compared to a reach average of 370 mm in 1997. However, D_{84} particle sizes at the old-growth site were not consistently coarser than the reach average in steeper-than-average sections just downstream of LWD jams. The D_{84} at XS5 and XS12, just downstream of log structures 2 and 4, respectively (see Figs. 3 and 7) were 558 and 105 mm, respectively, in 1995 and 494 and 251 mm, respectively, in 1996, compared to a reach average D_{84} of 302 in both years. In 1997, the D_{84} values at XS5 and XS12 were 803 and 400 mm, respectively, compared to a reach average of 370 mm. For all 3 years in which particle size counts were conducted (1995–1997), the coefficient of variation in D_{84} and D_{50} particle sizes was greater for the old-growth site (0.453–0.549) than for

Fig. 7. Longitudinal plot showing quantity of LWD and channel characteristics at Mack Creek: (A) old-growth site; (B) clear-cut site. For each site, top plot shows volume of LWD (1996 data) within or suspended above the channel; the second pair of plots show a count of boulders with b-axis diameter $\geq$ 1 m within 20-m channel segments and the channel width at the midpoint of each segment; the third plot shows water depth in meters along the channel thalweg (gray line) and the local channel slope (dark line) calculated between adjacent points along the longitudinal profile (average spacing $\sim$ 1 m); and the bottom plot shows the residual from a linear regression of bed (thalweg) elevation vs. distance. The bed elevation residual plot has been smoothed by applying a 9-point moving average to filter out high frequency oscillations.

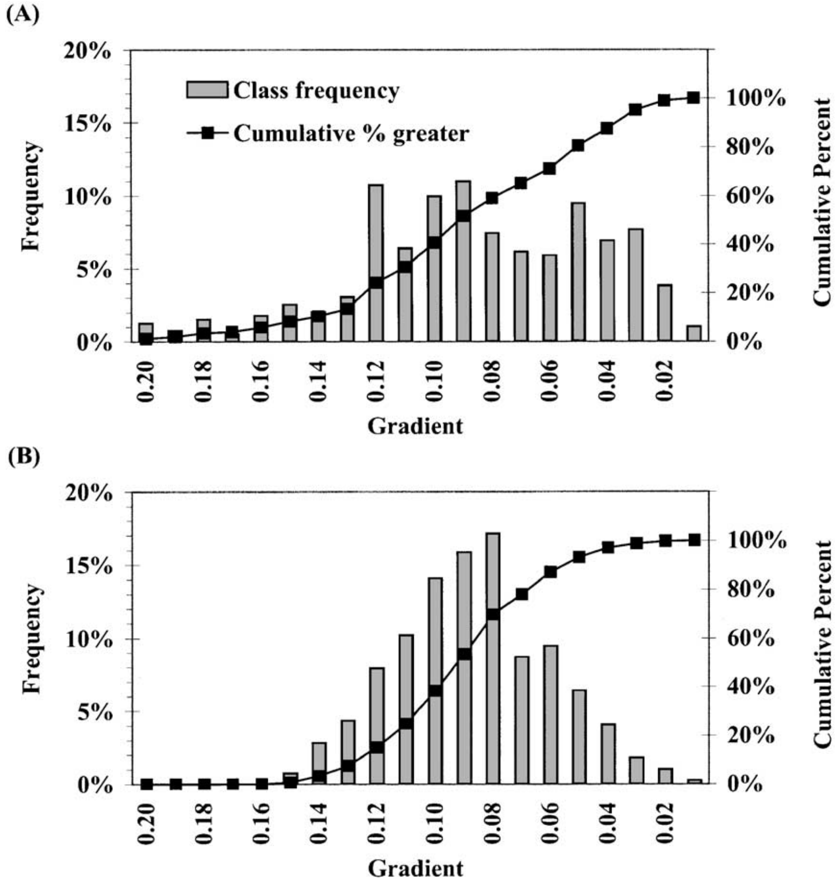


Fig. 8. Frequency distribution for the local low-flow water surface gradient in Mack Creek, binned in 1% slope increments: (A) old-growth site; (B) clear-cut site. Water surface slope was calculated over a 10-m interval centered on each point in a 5-point moving average of the longitudinal profile in Fig. 6.

the clear-cut site (0.166–0.378). Thus, the old-growth site exhibited greater variability in bed material size at the channel unit scale than did the clear-cut site.

3.2. Channel function

The February 1996 flood was associated with scour and coarsening of the bed surface in the clear-cut reach, compared to aggradation upstream of LWD features in the old-growth reach. Six of eighteen cross sections in the clear-cut reach for which change could be determined experienced substantial (≥ 3 m^2) scour, 8 exhibited at least moderate (≥ 2 m^2) scour, and 13 exhibited ≥ 1 m^2 scour. Only 6 of 18 cross sections experienced ≥ 1 m^2 of fill, and two experienced ≥ 2 m^2 fill (Fig. 9). In contrast, all three cross sections immediately upstream of channel-spanning LWD within the old-growth reach (XS3, 7, and 10) experienced ≥ 3 m^2 fill. Three cross sections not closely associated with existing LWD structures (XS1, 2, and 11) experienced ≥ 2 m^2 scour, and eight cross sections exhibited ≥ 1 m^2 scour (Fig. 9). At the reach scale, the old-growth and clear-cut sites experienced essentially the same total change, but *net* channel change was negligible at the old-growth site and strongly negative at the clear-cut site (Fig. 10). Cross-section changes between 1995 and 1996 were not spatially correlated with the magnitude of wood stored in the channel (Fig. 9), nor were they associated with changes in distribution of LWD volume within the channel (zones 1 to 3) for the same period. Of the old-growth cross sections that experienced the greatest

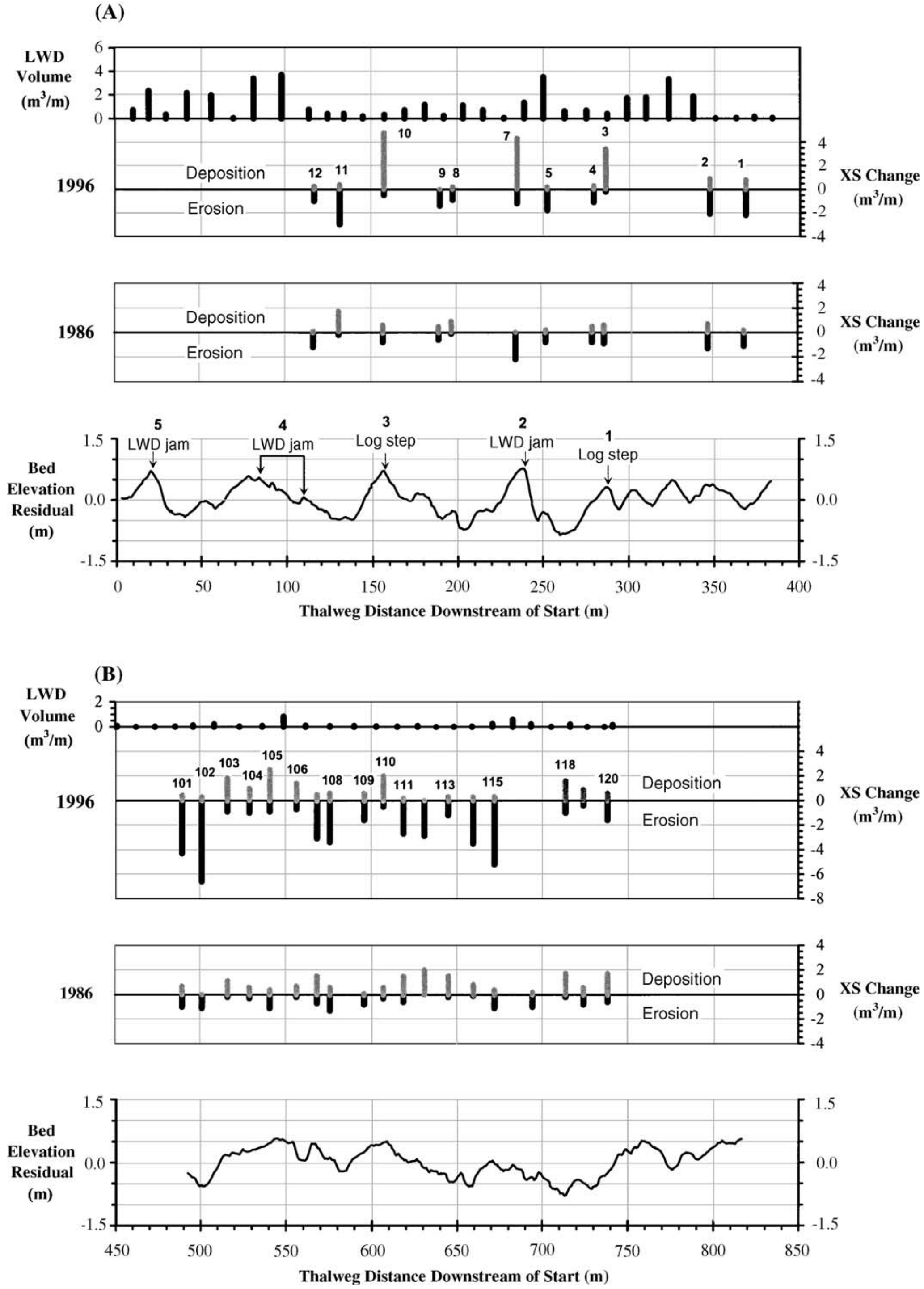


Fig. 9. Longitudinal plot showing volume of in-channel LWD (1995 data), cross-section scour and fill associated with large peak flow events in February 1996 and February 1986, and bed elevation residual for the Mack Creek cross section sited: (A) old growth; (B) clear cut.

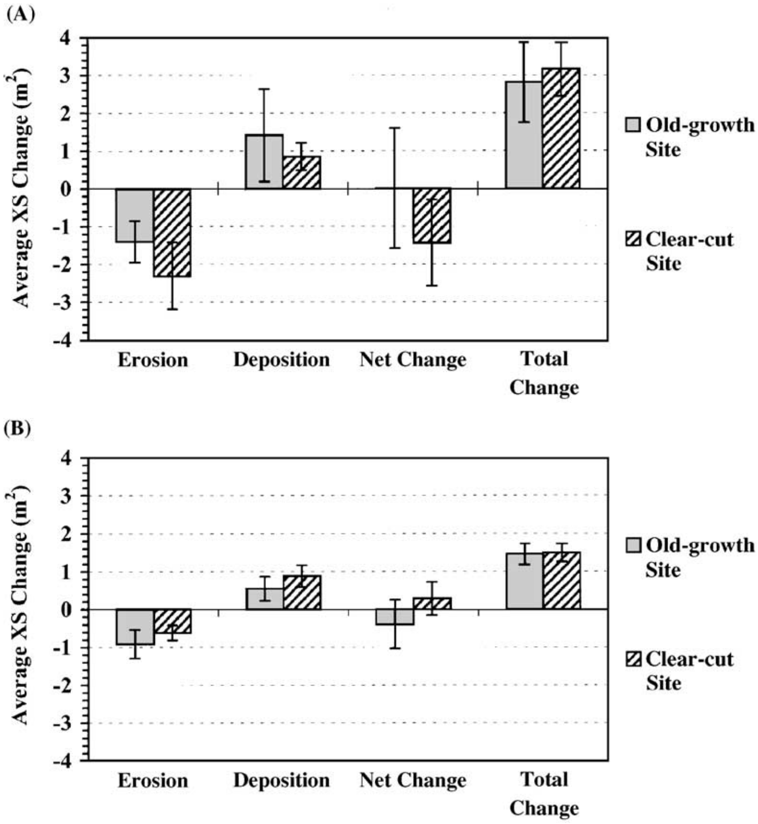


Fig. 10. Comparison of average cross-section changes (scour, fill, net change, and total change; see text for explanation) at the Mack Creek old-growth and clear-cut sites for (A) 1995–1996 and (B) 1985–1986. Error bars show 95% confidence intervals.

scour (XS1, 2, and 11) or fill (XS3, 7, and 10), only two (XS2 and 7) were proximal to large changes in LWD volume within the channel.

Bed surface particle size within the clear-cut site, especially large particle size fractions, increased significantly following the 1996 flood. The D_{84} increased from 224 mm in 1995 to 396 mm in 1996 ($p < 0.0001$); the D_{50} increased from 61 to 95 mm ($p < 0.003$); and the D_{16} increased from 15 to 20 mm ($p < 0.02$). In contrast, no significant changes of particle size occurred at the old-growth site. Here, the D_{84} was 280 mm in 1995 and 273 mm in 1996; the D_{50} was 81 mm in 1995 and 62 mm in 1996; and the D_{16} was 19 mm in both 1995 and 1996. In 1995, the D_{16} at the clear-cut site (15 mm) was significantly finer than at the old-growth site (20 mm, $p < 0.05$). By 1996, however, differences in D_{16} between sites were not significant, but the D_{50} and D_{84} were significantly coarser in the clear-cut reach than in the old-growth reach ($p < 0.04$ and $p < 0.02$, respectively).

The February 1986 flood, which had a peak discharge 87% as large as the 1996 flood (Fig. 4), produced a quite different pattern of cross-section responses that were disproportionately smaller than the 1996 cross-section changes. In general, scour was slightly greater than deposition in the old-growth reach in 1986 while fill predominated modestly over scour in the clear-cut reach, the opposite of the 1996 flood response (Figs. 9 and 10). In the old-growth reach, only a single cross section (XS7) exhibited ≥ 2 m^2 of scour in 1986, and only 5 of 11 (45%) exhibited either scour (four cross sections) or fill (one cross section) exceeding 1 m^2 (Fig. 9A). In the clear-cut reach, as in the old-growth reach, only a single cross section exhibited change of ≥ 2 m^2 (XS112, fill), but 13 of 19 (68%) exhibited either scour (six cross sections) or fill (seven cross sections) exceeding 1 m^2 (Fig. 9B).

Over the period of the cross-section record (1978–1997 for the old-growth reach and 1981–1997 for the clear-cut reach), the clear-cut reach experienced greater channel response to small to moderate peak flows than the old-growth reach, but this difference in channel response decreased for larger, less frequent events (Fig. 11). Based on the approximate 95% confidence intervals, this difference is significant for events with a return period of about 5 years or less. For the largest events (e.g., the 1986 and 1996 peak flows), the cross-section response was similar at both sites. Peak flows capable of producing a detectable response in 50% of cross sections have a return period of 4.0 years (approximate 95% confidence interval: 2.9 to 5.7 years) in the clear-cut reach vs. 5.8 years (approximate 95% confidence interval: 4.4 to 8.6 years) in the old-growth reach (Fig. 11).

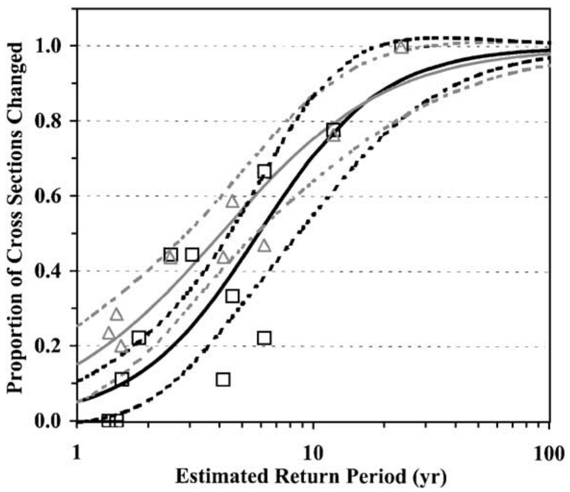


Fig. 11. Proportion of cross sections at the Mack Creek old-growth and clear-cut sites exhibiting change versus the estimated return period of the maximum instantaneous peak discharge in Mack Creek during the interval between consecutive cross-section surveys. Solid lines show quasi-likelihood logistics regression fit (old growth—dark line; clear cut—gray line); dashed lines show approximate 95% confidence intervals (± 2 standard errors). Each data point represents the proportion of cross sections at either the old-growth site (dark squares) or the clear-cut site (gray triangles) that exhibited change exceeding the specified detection threshold between one pair of consecutive survey dates, plotted vs. the estimated return period for the largest peak flow event during the interval between the surveys. For peak flows with a return period less than about 5 years, the clear-cut reach exhibited a greater degree of channel response by this measure than did the old-growth reach (i.e., the clear-cut data points [triangles] generally plot above the old-growth data points [squares] for peak flows with same estimated return period).

4. Discussion

The findings of this study generally supported hypotheses relating an abundance of LWD to increased geomorphic features, local variability in channel gradient and bed surface particle size, and increased channel stability and bed load retention. In the old-growth reach, boulders interact with LWD to form channel-spanning structures that retain large wedges of sediment, creating larger-scale steps in the channel profile and greater variability in local bed slope at the channel unit scale than are found in the reach lacking LWD. Bed material was generally finer upstream of the LWD steps, due to the reduced local channel gradient, so that median bed particle size sampled at the channel unit scale was more variable in the reach with abundant LWD. LWD also strongly influenced channel function: the clear-cut reach exhibited greater bed mobility than the old-growth reach in response to floods with a recurrence interval of <5 years, even decades after removal of LWD from the channel. Channel-spanning LWD structures in the old-growth reach appeared to store more sediment for longer periods than storage sites behind boulders or along channel margins in the reach lacking LWD.

It is important to keep in mind the particular features of this study when attempting to generalize the results. This study examined longitudinal channel structure and the response of the channel to streamflow events with up to 25-year return periods, capable of mobilizing the majority of the bed material but not large boulders or most LWD. Channel structure and function at the study site are strongly influenced by boulders that are rarely mobile under the current hydrologic regime (Grant et al., 1990; Grant and Swanson, 1995) and by the interaction of these boulders with LWD. Boulders ≥1 m in diameter occur at a frequency of about 0.5/m of channel length in Mack Creek, which is more frequent than in much of the remainder of the Lookout Creek system (Lambert, 1997).

The monumented channel cross sections in Mack Creek may be considered a "reference" for steep, forested stream systems elsewhere in the Pacific Northwest that have a legacy of large, relatively immobile boulders delivered to the channel by nonfluvial processes. Similar long-term channel cross-section studies also are underway at Redwood Creek (Madej, 1999) and Mount St. Helens (Simon, 1999), but these systems have orders-of-magnitude higher sediment yields and higher levels of disturbance from forest harvest and volcanic eruption than Mack Creek. In this study, little or no detectable change was observed in either reach of Mack Creek during events with 1- to 2-year return periods. However, both the old-growth and clear-cut reaches experienced significant channel change in several moderate to large events with 10- to 25-year return periods. These channel changes were not consistently associated with movement of wood nor with identifiable changes in sediment supply.

Large boulders and coarser bed load increase sediment–wood interaction (Fig. 1) by providing more potentially stable LWD accumulation sites, and coarse sediment is more easily trapped by LWD than fine sediment. The total elevation drop controlled by LWD in Mack Creek (~ 30%) is similar to values reported for other headwater streams in the Pacific Northwest (Keller and Swanson, 1979; Keller and Tally, 1979), but it is several times greater than in the Oregon Coast Range (Marston, 1982). Channel steps created by LWD were also more frequent in Mack Creek (five within 300 m) than in the Coast Range (4/km; Marston, 1982). The lower frequency of LWD structures in the Coast Range streams is likely due to the finer bed load and absence of large boulders, which reduce the frequency of stable LWD storage sites and the sediment trapping efficiency of LWD.

LWD accumulations and individual large pieces of LWD appear to act as large roughness elements that reduce reach-average flow velocity during moderate flow events, hence reducing boundary shear stress available to transport bed material. However, this effect diminishes as flow depth increases. The study reach with abundant LWD was less responsive to moderate streamflow events than the reach from which wood was removed in the 1960s, but it responded similarly to the highest observed flows. This effect is explained by the observation that removal of LWD increases flow velocity and boundary shear stress at low flows (Shields and Smith, 1992). However, the effect of LWD is reduced or eliminated with increasing discharge as flow depth becomes large relative to the size of flow obstructions associated with LWD (Lisle, 1986; Hecht and Woyshner, 1987; Shields and Smith, 1992; Gippel, 1995).

LWD structures appear to retain more sediment over the long term than large boulders. The study reach with LWD retained more sediment than the reach without LWD during the largest observed streamflow event, although little difference was exhibited in reach scale response to the second largest observed event. At the channel unit scale, aggradation occurred only upstream of LWD structures in the reach with LWD during the 1996 flood. Previous studies have shown that LWD can retain the annual sediment yield of a stream (Marston, 1982) or >10 times the annual sediment yield (Megahan and Nowlin, 1976; Swanson and Lienkaemper, 1978; Swanson and Fredriksen, 1982). In contrast, Grant et al. (1990) observed that steep channel units (lacking wood) can store little sediment other than "framework particles" that seldom move.

In this study, LWD removal was associated with long-term effects on channel structure and function, despite spatial and temporal variations in sediment supply (Massong and Montgomery, 2000). Faustini (2000) inferred that fine bed load was released from the lower end of the old-growth reach and contributed to the clear-cut reach during the 1996 flood due to the removal of a culvert at the road crossing in summer 1994. Nevertheless, the clear-cut reach experienced coarsening and degradation of the bed in response to the 1996 flood.

Our study demonstrates that even in a channel that has abundant large boulders (i.e., where LWD is not the only large roughness element), LWD has an important influence on channel structure and function. We infer that large boulders delivered to stream channels by nonfluvial processes can create "forced alluvial" reaches in steep, sediment-limited streams that would otherwise be expected to have bedrock channels, analogous to the effect of LWD in the channels studied by Montgomery et al. (1996) and Massong and Montgomery (2000). Montgomery et al. (1996) described the importance of LWD in steep, sediment-limited channels without large boulders, where the presence or absence of LWD could determine whether alluvial or bedrock channels would be present. They posited that the critical slope threshold between bedrock and alluvial channels in the absence of LWD depends upon geology and climate. Massong and Montgomery (2000) reported that the critical slope threshold depended not just upon the underlying bedrock geology but also upon the lithology of the alluvial material due to its influence on clast size. They found that stream reaches flowing over siltstone bedrock but dominated by basalt clasts had coarser bed material than reaches flowing over siltstone bedrock but dominated by siltstone clasts in the Willapa River basin, Washington. As a consequence, the basalt-dominated alluvial reaches over siltstone bedrock occurred at slopes above the critical slope threshold for siltstone-dominated alluvial reaches (Massong and Montgomery, 2000). Further research might seek to assess the relative frequency of LWD and large boulders and their relative importance in determining both the distribution of bedrock and alluvial channels in the landscape and the structure and function of alluvial channels.

We suggest that a positive interaction exists between LWD and boulders, leading to LWD being "racked" on boulders (Fig. 1). Such an interaction would explain the persistence of wood features in Mack Creek, which have been dated at 50 to 150 years (Swanson and Lienkaemper, 1978; Swanson et al., 1984; Gregory, 1991). It also might explain the higher frequency of channel-spanning wood with sediment wedges in the old-growth study reach compared to the Coast Range. It would be interesting to explicitly incorporate LWD–boulder interaction into existing channel unit classification systems (e.g., Rosgen, 1996; Montgomery and Buffington, 1997) to explore how widespread and how significant such interactions are.

Channel structure in the steep mountain streams in this study is strongly influenced by nonfluvial processes: a legacy of large boulders from glacial or mass movement processes and a legacy of large, dead wood from ecological processes. The record of channel changes from Mack Creek is consistent with the idea that most "effective work" is done by relatively infrequent events in these systems. Systems whose structure is controlled by legacies of geomorphic and ecological processes would be expected to behave differently than the fluvially controlled systems described by Wolman and Miller (1960) and more similarly to the hybrid systems described by Wolman and Gerson (1978).

In summary, sediment-limited mountain streams with large boulders, when deprived of LWD, appear to form fewer large features, to store less sediment, and to release it more readily than those with LWD. These findings are restricted to the range of streamflows large enough to mobilize the bed load but not large enough to mobilize most LWD or the large boulders. The functional differences between the two study reaches emerged most clearly when the full 20-year record was examined. More generally, the legacies from past geomorphic and ecological processes and their interactions add variability to stream channel behavior. Considering the spatial distribution of such legacies in the landscape may help to improve our geographical predictions of stream channel structure and function in the landscape.

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