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EFFECTS OF COARSE WOODY DEBRIS ON MORPHOLOGY AND SEDIMENT STORAGE OF A MOUNTAIN STREAM SYSTEM IN WESTERN OREGON

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ABSTRACT

Effects of coarse woody debris (CWD) on channel morphology and sediment storage were investigated at five sites, representative of first-order to fifth-order streams. In the steep and bedrock-confined stream (first–second order), interaction between the channel and CWD was limited, except where breakage upon falling produced CWD pieces shorter than channel width. Channel widening, steepening and sediment storage associated with CWD were observed predominantly in third- to fifth-order streams. Variation in channel width and gradient was regulated by CWD. In the fifth-order stream, most of the CWD pieces derived from the riparian forest interacted directly with the channel without being suspended by sideslopes. In this system CWD promoted lateral channel migration, but sediment storage was temporary, with annual release and capture.

KEY WORDS Fluvial geomorphology Coarse woody debris Channel morphology Sediment storage Debris flow Flood

INTRODUCTION

Studies of the geomorphic effects of coarse woody debris (CWD) on stream channels can be grouped according to their focus on (1) input processes (Swanson and Lienkaemper, 1978; Sedell *et al.*, 1988; McDade *et al.*, 1990); (2) in-channel effects (Zimmerman *et al.*, 1967; Heede, 1972; Keller and Swanson, 1979; Megahan, 1982); and (3) fluvial transport (Shimizu *et al.*, 1985; Lienkaemper and Swanson, 1987). These three categories are related, and each process varies depending upon stream size relative to CWD size. This paper focuses on the second category, namely the effects of CWD on channel morphology and sediment storage.

Effects of CWD on channel morphology have been examined in terms of longitudinal and cross-sectional profiles of the streambed and formation of pools and riffles, which are important for fish habitat (Bisson *et al.*, 1982; Harmon *et al.*, 1986). These studies in general conclude that a large percentage of steps in the longitudinal profile is influenced by CWD obstructions. Further, the influence of CWD in the widening of low-order channels and lateral shifts of high-order streams has been clearly observed. The effects of CWD on sediment storage have been estimated as the ratio of stored sediment volume associated with CWD to the total sediment volume on the streambed, and as the volume of stored sediment in relation to annual export (Megahan, 1982). The sediment volume stored by individual CWD obstructions varies as a function of CWD

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structure and size, whereas the total volume of sediment in storage is controlled by the interaction among CWD obstructions, channel morphology, and sediment production and discharge.

Interactions between CWD and the stream channel vary, and depend in large part on channel form and streamflow regime. In this paper, the effects of CWD are discussed in relation to stream order. Interactions between CWD and stream channels in a fifth-order drainage basin are quantified, and the effects of CWD on channel morphology are examined with respect to stream size. In addition, the effects of structure and size of CWD accumulations and of channel morphology on the volume of stored sediment are examined. Finally, the interaction of size and decay class of CWD with the stream channel are discussed.

STUDY SITES AND METHODS

The Lookout Creek drainage basin is located at the eastern edge of the western Cascade Range, in the Willamette National Forest, Oregon, U.S.A. (Figure 1). The watershed area is 64 km^2 and elevation ranges from 412 to 1630 m. Douglas-fir (*Pseudotsuga menziesii*), western hemlock (*Tsuga heterophylla*) and western red cedar (*Thuja plicata*) are dominant at lower elevations, and Pacific silver fir (*Abies amabilis*) is dominant at upper elevations. Annual precipitation averages 2500 mm and is concentrated in the fall and winter. Seasonal snowpacks are common above 1000 m. Little rain falls during summer.

Five sites within the Lookout Creek drainage basin were selected to represent a range of channel size (Figure 1, Table I). The term 'Channel' used in this paper refers to the valley floor area inundated by bankfull flow. In all sites except Watershed 1, old-growth Douglas-fir forest (Franklin *et al.*, 1981) borders the stream. Vegetation of Watershed 1 is regrowth since 1962–1966, when the old-growth forest was clear-cut. Sediment discharge from Watersheds 1 and 3, located at the downstream end of the Lookout Creek basin, has been measured annually since 1956 (Grant and Wolff, 1991). Debris slides, debris flows and windthrow are the major events that supply CWD to these low-order streams. Debris flows in Watershed 3 in 1964 dramatically altered CWD conditions by flushing CWD from the channel and undercutting side slopes so that fresh CWD fell into the channel. The Upper Lookout Creek site is pinched by an active earthflow, which has moved

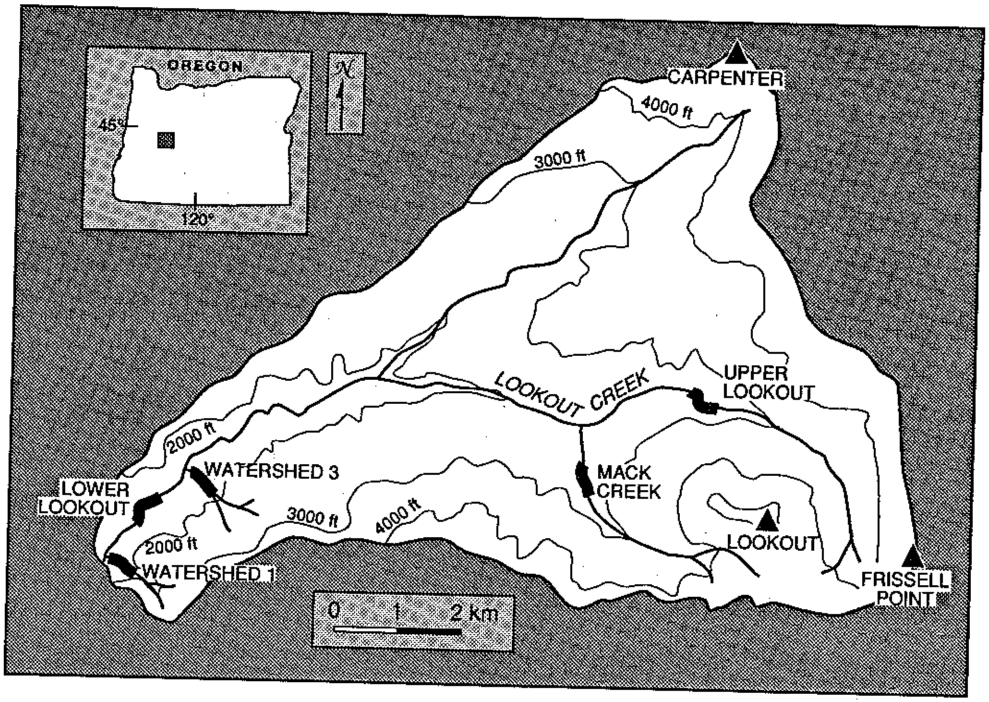

Figure 1. Locations of study sites in the Lookout Creek drainage basin, Oregon

Table I. General characteristics of study sites

Characteristic	Watershed 1	Watershed 3	Mack Creek	Upper Lookout	Lower Lookout
Watershed area (km^2)	0.96	1.01	5.49	10.7	60.5
Stream order	2	2	3	3	5
Length of study reach (m)	500	500	500	500	450
Average channel width (m)	10.9	7.6	18.1	15.6	24.0
Stream gradient in study reach (per cent)	18	21	11	7	3
Spacing of measurements:					
Width (m)	10	10	20	20	20
Gradient (m)	–	–	20	20	–
Volume of CWD (m^3 ha^{-1})*	–	–	570	340	230
Average number of CWD pieces produced by breakage of individual trees	–	–	3.3	3.5	2.7

* From Lienkaemper and Swanson (1987).

about 10 cm yr^{-1} since 1974 (Pyles *et al.*, 1987). Sediment and CWD have been introduced into Upper Lookout Creek by earthflow movement and streamside slides, especially during the 1964 flood. The Mack Creek site is a third-order stream, where CWD is contributed primarily by windthrow and slope failures associated with bank and sideslope erosion. In the Lower Lookout Creek site, located near the mouth of the Lookout Creek basin, CWD is supplied from stream banks by lateral channel migration and tree-fall from the riparian forest. Annual measurements of surveyed cross-sections of the Lower Lookout site have been made since 1978. Average stream width at the Lower Lookout Creek site is greater than that of the upstream sites.

In general, CWD pieces are clumped together and rarely occur alone. Typically, one or several relatively large pieces (length exceeding channel width) establish sites of CWD accumulation, thus forming large structures that may have a strong influence on stream morphology and sediment storage. These particularly large CWD pieces are referred to in this study as 'key-CWD'. Other pieces of CWD are piled up by the sieve-like effects of key-CWD, and these accumulations sometimes develop into stream obstructions called 'CWD-jams'. A CWD-jam is defined as a structure with at least five key-CWD pieces, and may exceed 3·0 m in height and measure 1·5–2 times bankfull channel width. Key-CWD was mapped with a tape measure and clinometer, and diameter, length and decay class were noted. Sediment storage volumes behind CWD were calculated by multiplying the vertical profile area of the step structure parallel to the channel by average channel width at that location. Although volumes of CWD in the five reaches were not measured in this study, some of the study site reaches overlap with those examined by Lienkaemper and Swanson (1987). Data from their study (Table I) suggest that the volume of CWD per unit area of streambed decreases as drainage area increases. This is probably because CWD is not produced in the streambed, and this effect becomes more significant as channel width increases. In addition, higher stream power and discharge in larger channels tend to transport CWD downstream.

Cross-sectional and/or longitudinal profiles of the streambed were measured at key-CWD and CWD-jams with a level and tape measure. Stream gradient was determined from measurements of 40 m long stream segments sampled at 20 m intervals throughout each of the approximately 500 m long sites. Channel width was measured at 20 m intervals along the channel. Annual maximum daily stream discharge, measured at the U.S. Geological Survey (USGS) gauging station located at the downstream end of the Lower Lookout Creek site, was used to express flood magnitude.

RESULTS AND DISCUSSION

Processes controlling CWD patterns

Tree-fall processes of CWD delivery to channels. Tree-fall from banks or hillslopes provides input of CWD and influences patterns of CWD distribution in stream channels. Tree-fall is initiated by mortality, windthrow, landslides originating from an upslope initiation site, streamside slides and bank erosion.

The ratio between average tree height and channel width influences the initial CWD–stream interaction. Tree size varies with site conditions and tree age; a typical old-growth Douglas-fir tree is 50–70 m in height (Franklin *et al.*, 1981). Most trees that fall into streams suffer breakage. Breakage of key-CWD pieces directly input from hillslopes or stream banks was investigated at all five study sites (Table I). However, most key-CWD in Watersheds 1 and 3 were fragmented pieces transported from adjacent hillslopes or upstream; which precluded analysis of breakage at these sites because breakage was sampled only on pieces for which the rooting site could be determined. Fallen trees in low-order (first–second) streams tend to be suspended over the channel or are pointing downslope and sticking into the valley floor, which limits interactions between CWD and streams, especially where bedrock constrains lateral movement of the stream channel.

Most fallen trees appear to suffer breakage prior to interacting with low-order stream channels. We hypothesize that breakage of key-CWD decreases with increase in stream order, because steep sideslopes bordering low-order channels and streambanks and steps between terrace levels commonly cause breakage upon impact. Therefore, sites with wider channels and valley floors should have longer pieces. Average tree height (approximately 60 m) divided by the average number of pieces produced by breakage is 18 m, 17 m and

22 m for Mack, Upper Lookout and Lower Lookout Creeks, respectively. These values are similar to channel width in each site (Table I).

Although CWD is delivered primarily by windthrow and landslides in steep, narrow, low-order streams, fluvial processes can play an important role in supplying CWD in medium-order (third–fourth) and large-order (fifth and larger) streams. Lateral migration of channels results in erosion of stream banks, and fall of large trees growing on valley floors or at the bases of hillslopes.

Debris flow. Debris flows redistribute CWD, especially in steep, low-order streams where debris flows are most common. The historical record in the Lookout Creek basin indicates that, in general, debris flows initiate in channel heads and steep, narrow streambeds, entrain CWD and sediment, flush materials downstream, and deposit piles of CWD along low-gradient channels and on alluvial fans formed at junctions with mainstem channels.

Two sites in this study provide examples of the influence of debris flow on CWD distribution. The forest in Watershed 1 was completely clear-cut without road construction between 1962 and 1966 (partially clear-cut at the time of the 1964 flood). In Watershed 3, roads were constructed over 6 per cent of the area in 1959, and 25 per cent was clear-cut in 1963. These two basins responded differently to the December 1964 flood. Landslides have occurred in Watershed 1 since clear-cutting, but did not develop into debris flows; in addition, sediment produced by landslides and other processes was trapped by CWD obstructions in first–second-order stream channels. In Watershed 3, debris flows that developed from landslides in road rights-of-way and in clear-cut and forested areas flushed all CWD from the debris-flow affected channels and deposited it at the mouth of the second-order channel and in the receiving fifth-order channel.

These differences in disturbance regime and sediment transport process are reflected in present channel form and CWD distribution (Figure 2). In both watersheds, relatively wide channels developed where key-CWD accumulated. In Watershed 1, many CWD pieces are distributed along the stream and widen the

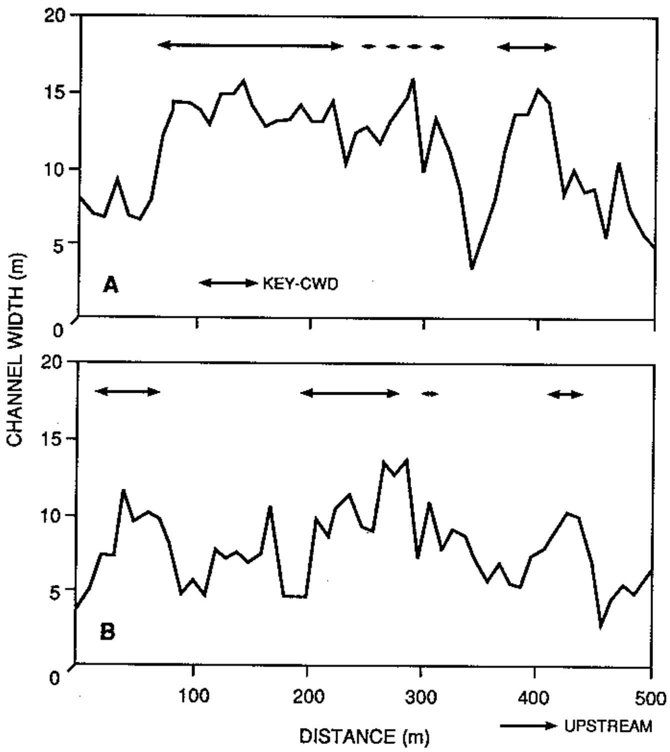

Figure 2. Distribution of key-CWD and variation of channel width. (A) Watershed 1 site; (B) Watershed 3 site

streambed locally by holding sediment. In contrast, relatively small amounts of CWD are found in Watershed 3, where debris flows scoured the basin and left a relatively narrow, bedrock streambed.

Flood. Redistribution of CWD by floods is a typical phenomenon in medium- and high-order streams. Lienkaemper and Swanson (1987) analysed the distance moved by CWD pieces during high flow, and concluded that most pieces that moved were shorter than bankfull width. In general, key-CWD pieces are anchored outside the stream channel, such as on banks or hillslopes, and are long enough to be stable during most flood flows. Key-CWD pieces trap shorter pieces transported from upstream and, in turn, may release captured pieces to downstream areas by pivoting movements or other processes. The spacing of key-CWD, therefore, is an important factor in understanding CWD redistribution and channel form.

Key-CWD in medium- and high-order streams is primarily supplied by tree-fall, but occasionally key-CWD pieces are supplied from upstream when CWD leaves a relatively wide, unconstrained reach and becomes trapped in a narrower, constrained reach. Alternatively, most CWD pieces that move from a constrained to a wider, unconstrained reach are left scattered over gravel bars and floodplains. The ratio between CWD length and channel width, which varies at the reach-to-reach scale, may influence variation in stability of CWD pieces along a stream network. Thus, CWD pieces may be stabilized in narrow reaches by anchoring effects outside the channel; in unconstrained reaches CWD pieces may be stabilized as a result of being bypassed when a channel moves laterally.

Geomorphic pattern and process

Channel widening and steepening associated with CWD. The effects of CWD on longitudinal and cross-sectional profiles of streambeds are pronounced in the medium-order streams. The Upper Lookout and Mack Creek sites were classified into four categories of reaches: (1) key-CWD dominant; (2) CWD-jam dominant; (3) no bedrock and no major CWD obstructions present; and (4) bedrock outcrop dominant. Channel width, stream gradient and CWD distribution among these categories were compared (Figure 3). Except in the portion of Mack Creek where bedrock outcrops limit channel change and sediment storage, channel widening and steepening associated with CWD were apparent in both sites. Three CWD-jams were found in both the Upper Lookout and the Mack Creek sites. The stream channel is widest and steepest at the largest CWD-jam in each site. Thus, width and gradient appear to be maximized at CWD-jam reaches.

Comparison of the mean channel widths and gradients for the four described categories (Figure 4) indicates that key-CWD locations in Upper Lookout and Mack Creeks were 25–42 per cent wider and CWD-jams 50–58 per cent wider than were no-CWD areas. Differences in channel gradient were less pronounced: CWD-jam locations were 17–36 per cent steeper than sites with no CWD.

In general, widths of areas upstream from key-CWD and CWD-jams are high and gradients are low relative to study site averages. Through CWD obstructions, channel widths reach a maximum and gradients sharply increase to adjust to the position of the original streambed. Streambed areas with no CWD pieces typically have relatively narrow, straight profiles and contain a step-pool structure created mainly by boulders. Variances in widths, therefore, increase in the order: bedrock outcrop, no major CWD, key-CWD, CWD-jam.

The bedrock outcrop reach in the Mack Creek site has, on average, the narrowest channel and the steepest gradient—14 m and 12·4 per cent, respectively—of the measured reaches. Although CWD pieces are present in this reach, they have little effect on channel morphology; most pieces are parallel with the stream axis and lie in the channel. This suggests that CWD may not have the capacity to change stream morphology where bedrock prevents lateral channel movement and the balance between sediment delivery and transport rates prevents significant deposition. Watershed 3, which has had a low average bedload discharge (20 m^3 km^{-2} yr^{-1}) since 1965 (Grant and Wolff, 1991), is a similar case of CWD having a trivial influence on channel form and sediment storage.

A certain rate of sediment delivery and retention is needed for CWD to affect stream width and gradient. In Upper Lookout Creek, for example, sediment delivery rate is relatively high because sediment is supplied not only from upstream, but also from the foot of an earthflow by uprooting trees and streamside landslides (Swanson and Swanston, 1977). Furthermore, landslide-delivered sediment typically contains large boulders

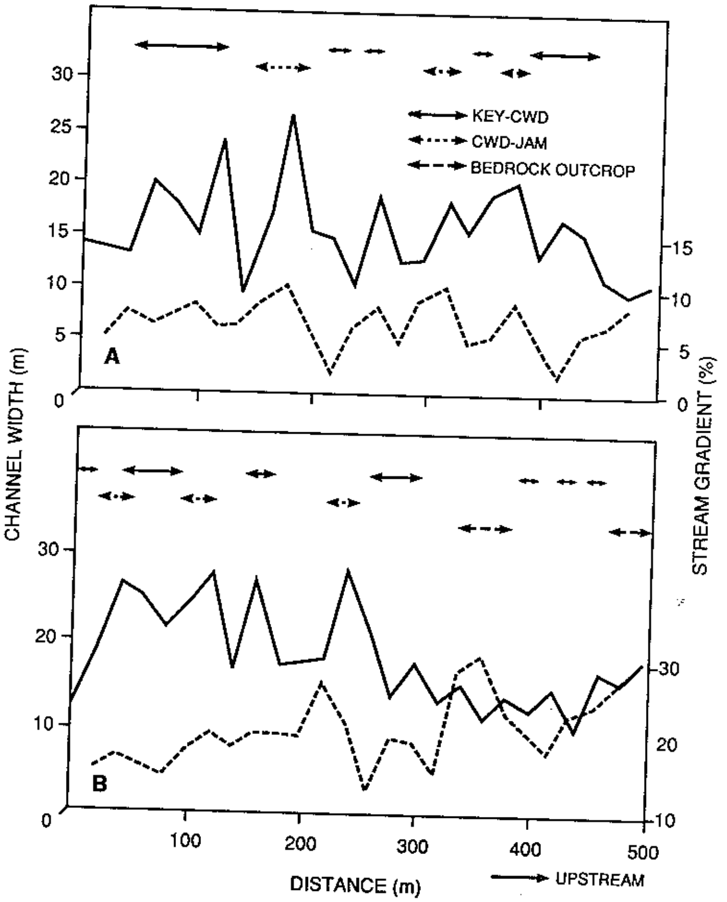

Figure 3. Variation of channel width and stream gradient in relation to key-CWD, CWD-jam and bedrock outcrop. Solid and broken lines indicate channel width and stream gradient, respectively. (A) Upper Lookout Creek site; (B) Mack Creek site

that are moved only rarely by fluvial processes. These structures create rough channel reaches that may impede sediment transport and facilitate entrapment by CWD pieces.

Observations of CWD structure suggest some alternative developmental sequences and associated geomorphic responses (Figure 5). Changes in stream morphology, especially changes in channel cross-section, begin when CWD is supplied from the sideslopes or banks. When trees fall from hillslopes or banks in response to windthrow, bank erosion and landslide, slope or bank surfaces may be disturbed by uprooting, which induces erosion and possibly additional failures (Figure 5A). If a fallen tree is long relative to channel width and strong enough to be suspended, it will be held by the sideslopes and initially have little direct effect on the channel (Figure 5B). Eventually these suspended CWD pieces will fall into the stream and break into several pieces. Some trees break when they hit the opposite hillslope and enter the stream immediately. In many cases, stream flow is diverted by the CWD obstruction. Diverted flows may scour the foot of a hillslope or stream banks, and this may result in additional tree fall and slope or bank failures (Figure 5C). Such hillslope failures were observed in the study sites. Some long, large-diameter CWD pieces become key-CWD which capture smaller pieces that have floated into place from upstream. These structures occasionally develop into CWD-jams, particularly where multiple tree-fall events occur at one location. The sediment delivered from upstream, produced by uprooting and hillslope and bank failures, is collected within and upstream of these CWD structures (Figure 5D). Consequently, the streambed widens in response to a combination of erosional processes triggered by diverted flows and deposition behind CWD obstructions.

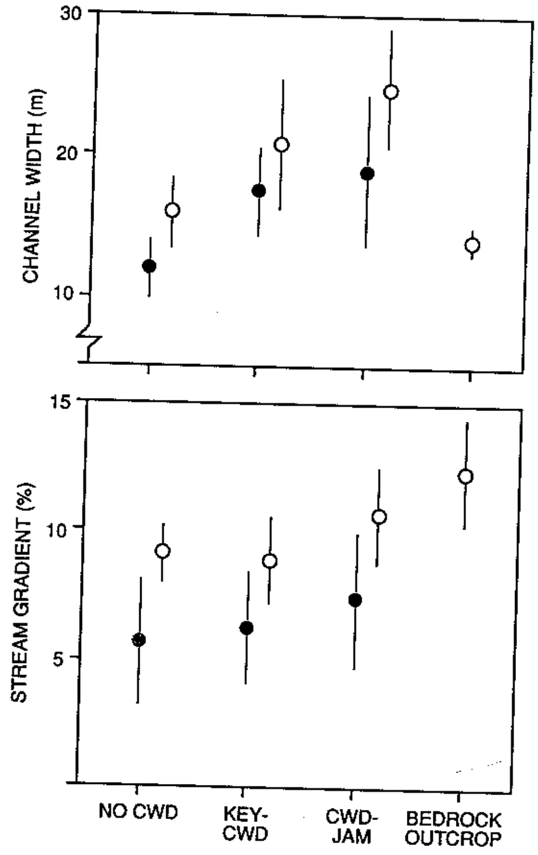

Figure 4. Mean value and standard deviation (error bar) of channel width and stream gradient with respect to no CWD, key-CWD, CWD-jam and bedrock outcrop reaches in Upper Lookout Creek (filled circles) and Mack Creek (open circles)

Spacing of channel widening and steepening. Fluctuations in channel width correlate approximately with stream gradient (Figure 3) because of CWD effects, and appear to occur at specific periodic intervals. Robison and Beschta (1990) discussed CWD and channel morphology interactions in Trap Creek, Alaska. They calculated autocorrelation coefficients for width and depth, and concluded that no periodicity existed along the stream. The watershed area of the Trap Creek study site is 11·4 km^2, similar to that of the Upper Lookout site.

Fluctuations of width and gradient in the Upper Lookout and Mack Creek sites (excluding the bedrock outcrop reach) were decomposed by spectral analysis (Figure 6). The peaks of the power spectra indicate the predominant wavelengths existing in the variation of width and gradient. The dominant wavelengths of the Upper Lookout site were 52 m and 70 m for width and gradient, respectively. Similarly for Mack Creek, width and gradient values were 80 m and 63 m, respectively. The mean width of Upper Lookout is 15·6 m and that of Mack Creek is 18·1 m; thus, the wavelengths of these periodic geomorphic features are three to four times mean channel width.

Studies of spacing of channel geomorphic elements with respect to CWD generally focus on pool and riffle sequences. Field observations in this study indicate that variation in channel width and gradient closely correspond to pool spacing, because many pools are formed downstream of key-CWD. Average intervals of pool spacing of the Upper Lookout and Mack Creek sites were 63 m and 75 m, respectively, which equal four channel widths. Therefore, we compared these dominant wavelengths with the pool spacing found in other studies. Lisle and Kelsey (1982) observed average pool spacing of 4·6 times average channel width in Jacoby Creek, northern California; however, in reaches with numerous large roughness elements, including CWD,

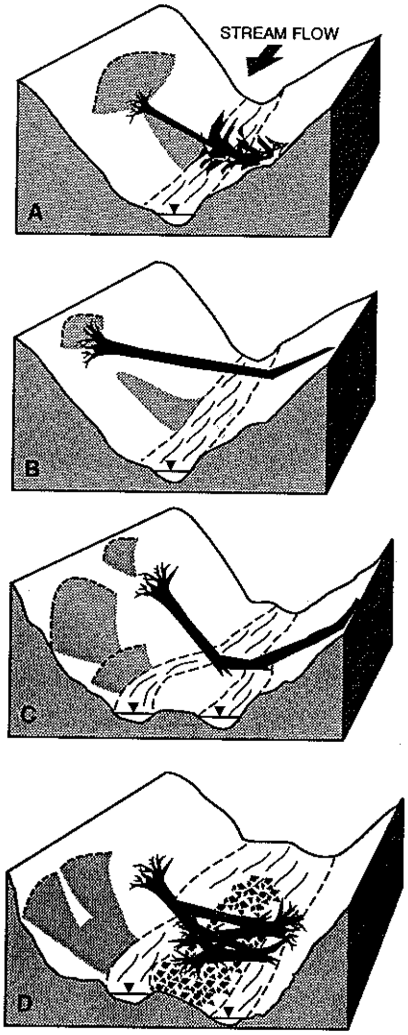

Figure 5. Channel widening associated with CWD input and aggregation of CWD pieces. (A) CWD input with uprooting; (B) CWD suspended by sideslopes; (C) CWD breakage and interaction with stream flow. Diverted flows scour the toeslope resulting in sideslope failures; (D) CWD pieces aggregate into CWD-jam and trap sediment

pool spacing averaged only three times the channel width. Keller *et al.* (in press) found that pool spacing was less than five times channel width in six of 10 CWD-influenced streams in the Redwood Creek drainage basin.

Spacing of key-CWD pieces in Upper Lookout and Mack Creeks is more frequent than suggested by peaks in the spectral analysis. Therefore, the spacing of key-CWD pieces alone does not directly control pool spacing and variation in channel width and gradient. Coarse woody debris may function as large roughness elements, as described by Lisle (1986), which can aid pool formation by creating zones of high turbulence. This process may shorten pool spacing from five to seven times the channel width in stream reaches free of large roughness elements, to perhaps three to four times average channel width. A lower limit probably exists for pool frequency influenced by CWD because hydraulic effects tend to merge at closely spaced CWD pieces, thus leading to the formation of a single pool and associated bars.

Both input and transport processes of CWD may be responsible for spacing of width and gradient changes. If inputs of large pieces, which have high potential to become key-CWD and CWD-jam features, by

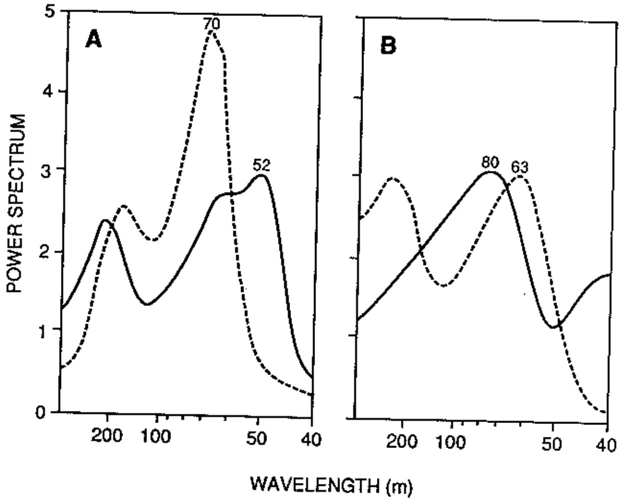

Figure 6. Spectral analysis of variation of channel width (solid lines) and stream gradient (broken lines). (A) Upper Lookout Creek site; (B) Mack Creek site, excluding bedrock outcrop reach

windthrow and bank erosion are primary factors in spacing, variation in width and gradient may exhibit periodicity by merging effects described above. If the present distribution of key-CWD is mainly controlled by flood events, hydraulic factors may be largely responsible for periodicity. Lienkaemper and Swanson (1987) found that pieces longer than bankfull width are strongly resistant to redistribution by flooding in Mack Creek. During a major flood, 12 of the 14 largest accumulations changed little, although a high percentage of small pieces moved. Field observations of locations of root pits and snags where key-CWD originated in Upper Lookout and Mack Creeks indicate that most key-CWD pieces are located where they originally fell, rather than having been floated into place. Both processes of initial placement and redistribution probably control the spacing of geomorphic variation; however, this and previous studies strongly support the prevailing effects of initial input processes on the distribution of key-CWD in fifth-order and smaller channels.

No predominant wavelength was found in a similar analysis of channel widths of Watersheds 1 and 3 (Figure 2). This may be explained by differences in transport processes of CWD or by logging history. The 1964 debris flows in Watershed 3 flushed most CWD from the channel, and channel morphology is controlled primarily by bedrock and boulders. In Watershed 1, logging influenced CWD distribution and the resulting variation in channel width. Studies of additional sites are needed to address whether or not the consistent periodicity existing in middle-sized streams of the Lookout drainage basin is typical, and to clarify the contributing factors.

Lateral migration of channel courses associated with CWD. Channel migration caused by CWD obstructions is common in streams of fourth order or higher, because constraints imposed by valley walls are less extensive than in smaller channels. Annual change of streambed and banks measured in the Lower Lookout Creek site provides a measure of channel dynamics in relation to CWD location and other processes. Fourteen survey lines were installed in this section in 1978 (Figure 7). A decade of surveying results indicates that changes in cross-sectional profiles have occurred primarily in the region between Transect 5 and Transect 11. This region is relatively wide and contains an abundance of CWD that entered the channel during the survey period (pieces noted by a star in Figure 7 and pieces at Transect 11) (Table II, Figure 7). Other transects (1–4, 12–14) generally indicate only minor changes. These findings suggest linkage between changes in stream channel morphology and CWD dynamics (Lisle, 1986). Cross-sectional variation of Transects 6 and 8 through time (Figure 8) indicates only minor change either in bank location, which is stabilized by tree roots and boulders, or in vertical direction (0·4–2·0 m); however, great change occurred in location of the low-flow channel within the active channel area.

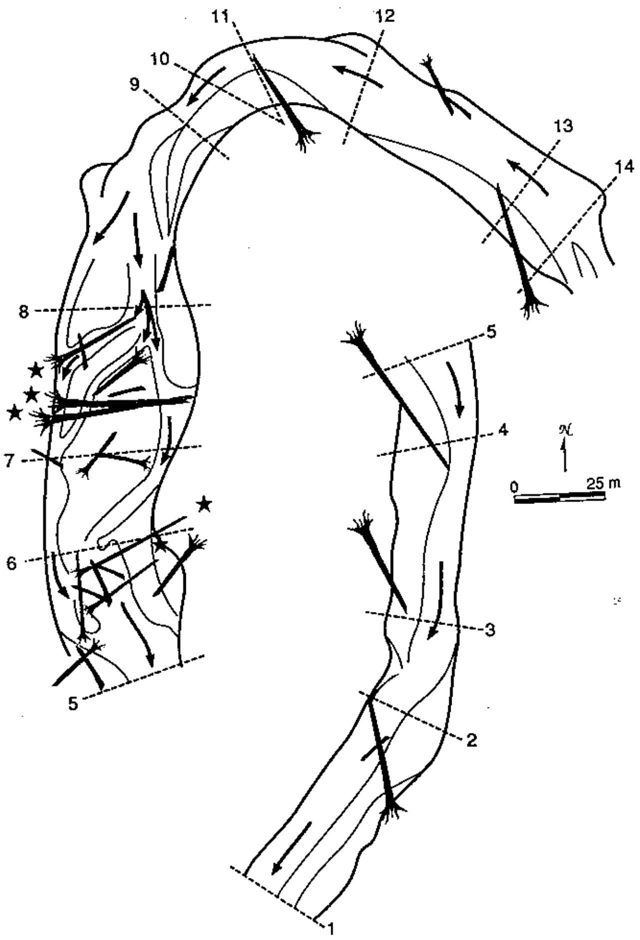

Figure 7. Channel morphology and CWD distribution in Lower Lookout Creek site as of July 1990. Numbered lines indicate locations of cross-sectional surveys, and CWD pieces marked with stars were input directly from terraces during the 1982 water year

These observations can be interpreted in relation to the annual maximum daily stream discharge measured by a USGS gauging station located at the lower end of the survey area (Figure 9). Seven transects were selected as representative of zones of major (Transects 5–9) and minor (Transects 2 and 12) change, and showed both deposition and scour areas throughout the measurement period (Figure 9). Great changes occurred in Transects 6–8, where four large old-growth trees fell into the channel in the winter of 1981–1982 in response to windthrow and bank erosion. Transect lines up- and downstream of this area show relatively small change. Each of these four CWD pieces is classified as key-CWD, which characteristically widens the channel and creates divergent channel patterns. Although stream discharge during the 1982 water year was not unusually high, major changes of the streambed were clearly accelerated. Obviously, CWD is responsible for these changes, and the effects were accentuated by high discharge during the 1986 water year. These effects are expected to continue for years or decades as bank erosion and changes in the configuration of CWD and associated sediment deposits proceed.

Sediment storage by CWD obstructions

Several types of interaction occur between CWD and stored sediment. Those interactions involving streams of different order can be grouped as follows: (1) steep, bedrock channels, where CWD may control the release of a limited volume of stored sediment (first and second order, Watersheds 1 and 3); (2) channels

Table II. Aggraded (A) and degraded (D) areas (m^2) measured along transects during the survey period. Bold print indicates cross-sectional area changes of 1·00 m^2 or more

Year	Area	Transect 1	2	3	4	5	6	7	8	9	10	11	12	13	14
78–80	A	0	0·28	0	0·58	0·90	0	**1·60**	**2·58**	0·34	0	**2·68**	0	**1·08**	0·72
	D	0	−0·18	0	0	0	0	**−1·96**	**−3·20**	−0·08	0	−0·10	−0·22	0	−0·32
80–81	A	0	0·26	0	0·54	0·18	**2·36**	0·80	**2·78**	0·85	0·39	0·71	0·51	0·77	**2·06**
	D	0	−0·57	−0·15	−0·81	−0·56	**−3·57**	−0·98	−0·88	−0·97	−0·89	−0·74	0	−0·77	**−1·06**
81–82	A	0·16	0·12	0·09	0·41	0·55	**5·07**	0·55	**1·79**	0·57	0·24	0·60	0·58	0·24	0·97
	D	**−1·03**	−0·13	−0·36	−0·22	0	**−1·69**	**−2·41**	**−3·41**	−0·29	−0·29	**−1·12**	−0·20	−0·93	**−1·06**
82–84	A	0·68	0	0	0·14	0	0	0·70	**1·32**	0	0·48	**1·00**	0	0·96	0
	D	0	0	0	−0·16	0	**−4·82**	**−1·70**	**−2·94**	**−2·26**	−0·46	−0·30	−0·48	−0·42	**−1·20**
84–85	A	0	0	0	0	0	0	0·73	0·72	0	0·44	0·12	0	0·51	0
	D	0	0	0	−0·53	0	**−2·41**	−0·75	−0·90	−0·61	−0·13	−0·10	0	−0·14	0
85–86	A	0·16	0·65	0	0·51	**1·21**	**12·36**	**2·23**	**7·73**	**2·77**	**4·14**	0	0·89	0·51	0
	D	−0·21	−0·06	0	−0·79	−0·41	**−5·28**	0	−0·21	0	−0·45	−0·17	0	−0·14	0
86–88	A	0	0·36	0	0·28	0	0·58	0	0·16	0·28	0·26	0·14	0	0·20	0·12
	D	0	−0·30	0	0	−0·36	**−2·50**	−0·96	0	−0·52	−0·48	−0·44	0	−0·26	−0·26
Net change		−0·24	0·43	−0·42	−0·05	**1·51**	0·10	**−2·15**	**5·54**	0·08	**3·25**	**2·28**	**1·08**	**1·61**	−0·03

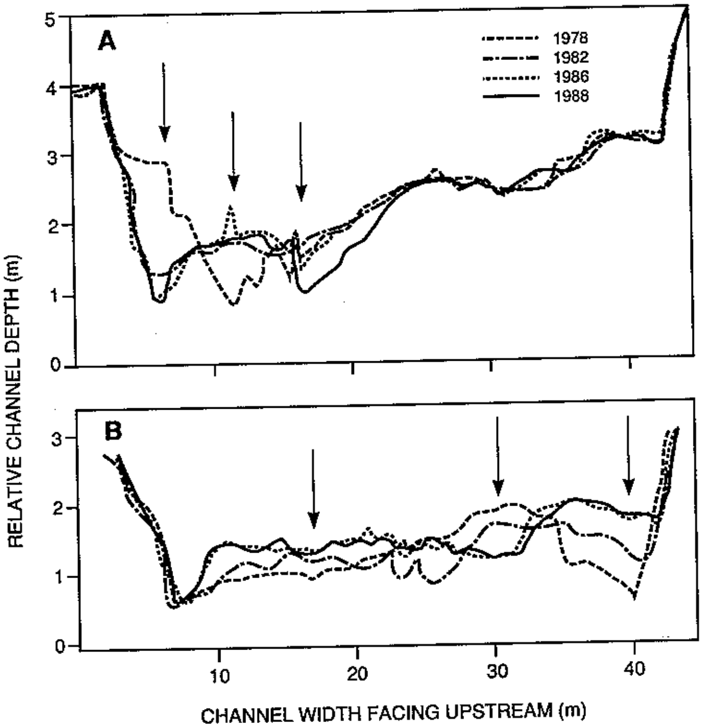

Figure 8. Temporal changes of cross-sectional channel morphology of the Lower Lookout Creek site. Arrows indicate location of predominant changes. (A) Transect 6; (B) Transect 8

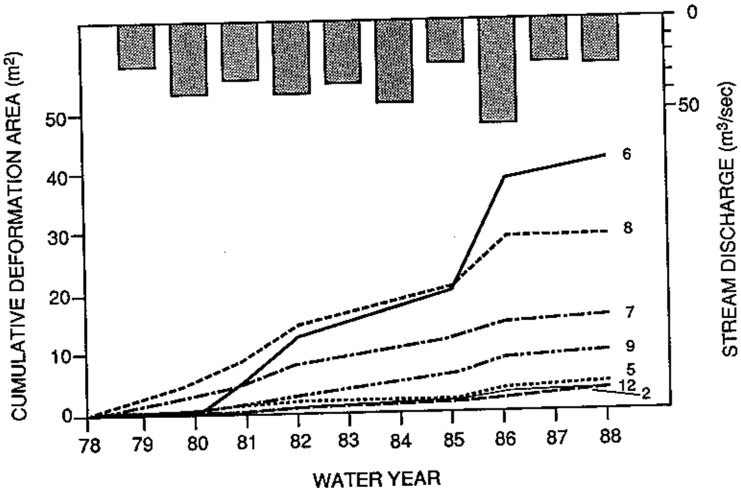

Figure 9. Relationship between channel bed change and stream discharge. Lines show the cumulative deformation areas (sum of cross-sectional areas of aggradation and degradation from one measurement date to the next), by transect (numbered on right) in the Lower Lookout Creek site. Bars show annual daily maximum stream discharges

constrained by sideslopes, where CWD occasionally forms accumulations (third and fourth order, Upper Lookout and Mack Creeks); and (3) relatively large, alluvial channels, where relations between CWD and stored sediment vary (fifth order, Lower Lookout Creek).

First- and second-order channels in the Lookout Creek Basin. Effects of debris flows on CWD and sediment yield in steep, bedrock-confined channels can be seen in a comparison of Watersheds 1 and 3, where sediment discharge has been measured since 1956. Continuous measurements of sediment discharge in Watershed 3 indicate that a large volume of sediment was delivered by multiple debris flows in 1964. Since 1965, bedload has declined to the same level as existed in the forested condition prior to road construction or clear-cutting, whereas suspended load remains relatively high (Grant and Wolff, 1991). Most of the coarse material stored in the Watershed 3 channel was flushed out in 1964, since when bedload discharge has been limited by sediment supply from hillslopes.

In Watershed 1, however, sediment produced by landslides and other processes was once stored on the streambed, particularly behind CWD during prelogging, logging (1962–1966) and slash-burning (1967) periods. Increased sediment discharge developed thereafter and bedload discharge has continued at a rate five times greater than that in Watershed 3, whereas suspended load remains approximately the same. Thus, bedload discharge is controlled in part by catch and release of sediment associated with CWD movement and decay. These processes were first reported by Swanson and Fredriksen (1982); however, the trend continues 10 years later, indicating that effects of CWD on sediment storage processes can last for decades following disturbance.

Third- and fourth-order channels in the Lookout Creek Basin. In third- and fourth-order streams, CWD creates relatively high steps (1–2 m in height) or natural dam structures (2–5 m in height) that capture transported sediment. In Upper Lookout and Mack Creeks the amount of storage created by key-CWD is small relative to that created by CWD-jams (Figure 10). The dominant volume of key-CWD storage was 50–200 m^3, whereas CWD-jam storage dominated size categories larger than 200 m^3.

The difference in stored sediment volume located in reaches upstream (bedrock outcrop) and downstream from the 300 m point along the Mack Creek study site provides an interesting contrast in sediment storage. Sediment storage in the upstream and downstream reaches is at 160 m^3/100 m and 500 m^3/100 m, respectively. Because average width and average slope of the channel in each unit constrain the amount of sediment trapped by CWD obstructions, the following relationship was developed and constants were determined by regression analysis:

$$V_s = \mathrm{a}(W)^{\mathrm{b}}(I)^{\mathrm{c}}$$

where V_s is the sediment volume per unit channel length (m^3/100 m), W is the average channel width (m), I is average channel gradient (per cent), and a, b and c are constants. Constants a, b and c for Upper Lookout Creek are 1·12, 0·69 and 2·22, respectively; for Mack Creek these respective constants are $1{\cdot}20 \times 10^{-5}$, 3·14 and 3·44. Measured and estimated values for both reaches are compared in Figure 11. These results suggest that the sediment volume stored by CWD obstructions may be determined by cross-sectional and longitudinal features of the channel. Consequently, the relationships between CWD and geomorphic factors, such as hardness of valley walls, stream gradient and sediment delivery rate, are important factors in estimating overall sediment storage.

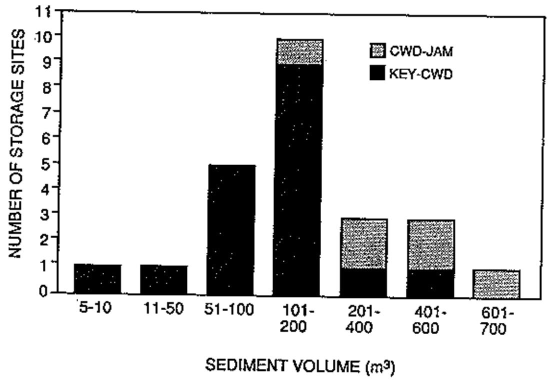

Figure 10. Volume of stored sediment storage in Upper Lookout and Mack Creeks. CWD-jams create large storage sites relative to key-CWD

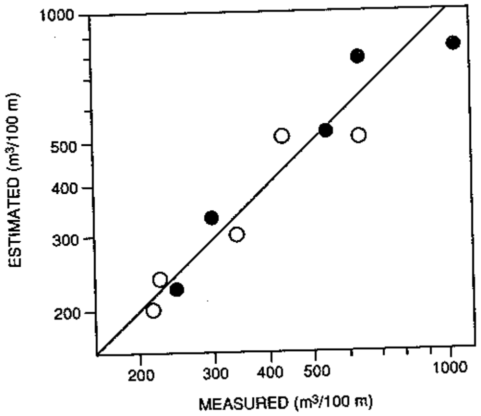

Figure 11. Measured and estimated sediment volumes per unit channel length for study reaches in Upper Lookout Creek (filled circles) and Mack Creek (open circles)

Fifth-order channels in the Lookout Creek Basin. Large CWD-jam structures are rare in relatively large, alluvial channels because of the channels' high capacity to float CWD before it aggregates. As shown previously, the predominant effect of CWD on sediment storage in fifth-order channels is deflection of the thalweg, which results in lateral scouring and deposition of sediment (Figure 8).

Bankfull channel cross-sectional area in Lower Lookout Creek is approximately 50–80 m^2 in the CWD-abundant reach (Transects 6–8) and 10–30 m^2 at other transects. Therefore, the magnitude of cross-sectional area change is about 5–20 per cent for both areas. Temporal variation in areas along Transects 6–8 (Figure 12) indicates relatively large aggradation and degradation for a decade in Lower Lookout Creek.

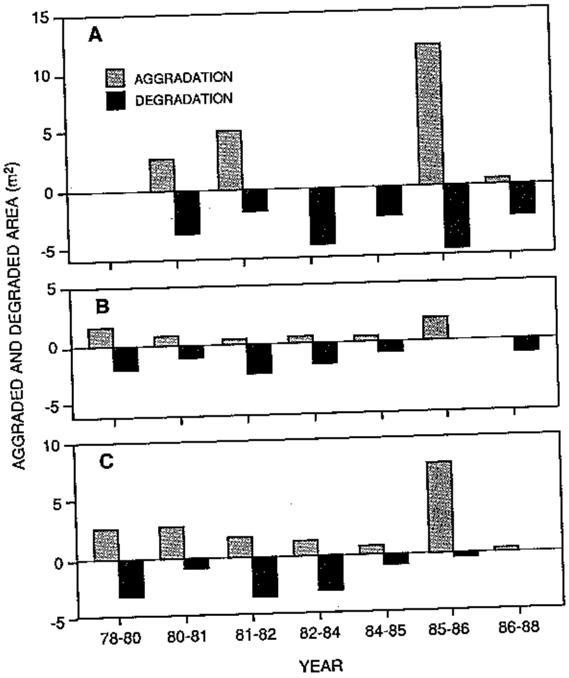

Figure 12. Temporal variation in cross-sectional areas of aggradation and degradation in the Lower Lookout Creek site. (A) Transect 6; (B) Transect 7; (C) Transect 8

Both aggradation and degradation occur in the same cross-sectional lines in most water years, and nearly average out over a decade.

These results indicate that the net change in cross-sectional area of the bankfull channel is relatively small in the fifth-order channel, regardless of CWD distribution. Furthermore, each year sediment can be trapped temporarily by CWD and scoured with or without shifting of CWD pieces.

Relationships between CWD and channel morphology with respect to drainage size

Comparison of average channel width at each site with respect to watershed area (Figure 13) reveals that widths of channels increase with increase in watershed area. This correlation suggests that channel morphology is controlled generally by basin hydrology. However, channels with key-CWD are about 1·5 times wider than channels without key-CWD (Figure 13).

The size of CWD that impacts channel morphology was found to vary with stream size. Figure 14 shows the cumulative percentage for length, diameter and decay class of key-CWD pieces located in each study site. Degree of decay is divided into four classes: 1, fresh, bark adheres tightly; 2, loose bark; 3, no bark; 4, punky. Cumulative curves indicate that thicker, longer and fresher CWD pieces act as key-CWD in larger streams, whereas more highly decayed pieces function as key-CWD in smaller streams.

No significant difference is believed to exist in initial height and diameter of CWD supplied from old-growth forest on sideslopes or banks at the various study sites in the Lookout Creek drainage basin. Although logging activity influenced the size and decay class distributions of CWD in Watershed 1, short pieces of CWD, fragmented and decayed as a result of breakage by falling, decomposition and transportation, can have a significant effect on stream morphology in low-order streams. Large pieces in these streams are usually suspended by hillslopes, and this limits initial interaction with the stream channel. On the other hand, many key-CWD in Lower Lookout Creek are predominantly fresh, long pieces, supplied directly by tipping in from bank, floodplain and terrace areas (Figure 7). In Upper Lookout and Mack Creeks, which are medium-sized channels, key-CWD is supplied both by direct input from sideslope and valley floor forests and by stream transported, fragmented pieces; these sources result in a wide range of decay classes of key-CWD.

CONCLUSION

Observations in the Lookout Creek drainage basin indicate that the effects of CWD on channel morphology and sediment storage of mountain streams vary with stream size (Table III). First- and second-order streams run through V-shaped, bedrock-confined valleys. Much of the CWD causing channel widening consists of decomposed, fragmented pieces, because large, solid pieces of CWD tend to be suspended by valley walls. However, the abundance and range of decay classes of CWD are influenced primarily by the history of

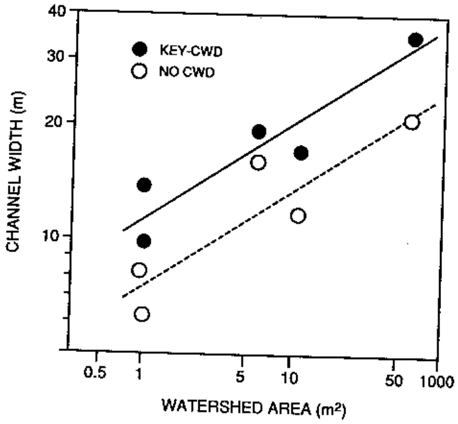

Figure 13. Regressions of average channel widths of reaches with no CWD (broken line) and key-CWD (solid line) in terms of watershed area

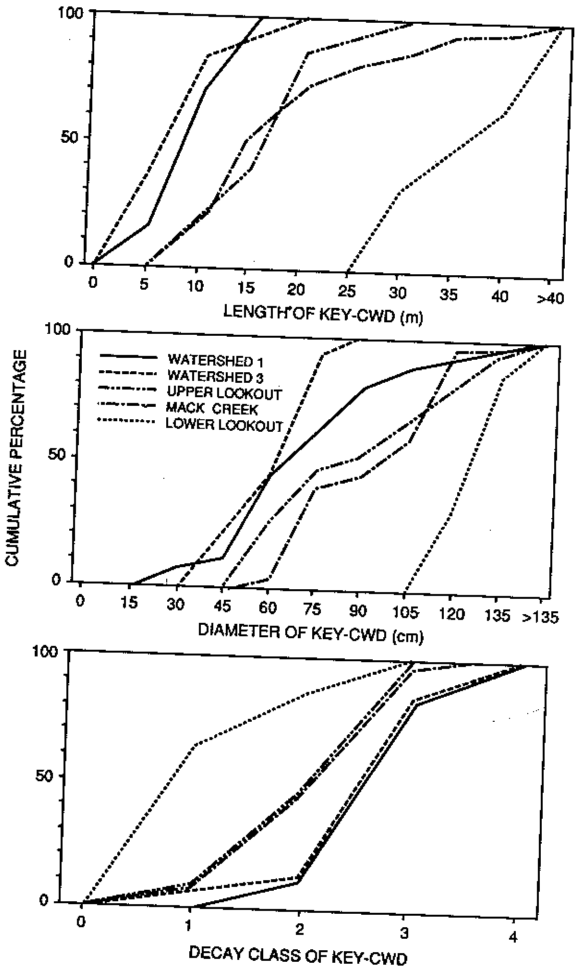

Figure 14. Cumulative percentage of length, diameter and decay class of key-CWD in investigated sites

watershed disturbances, such as windthrow, landslides, debris flows and logging. The step-forming and channel-widening effects of CWD are most pronounced in sediment-rich streams, but are limited in channels with narrow valley floors and steep gradients. Long-distance CWD transport in small streams is accomplished mainly by debris flow, because these streams are too small to redistribute most of their CWD by stream flow, even at peak flows. Variation in channel width associated with CWD shows no periodic spatial pattern.

In third- and fourth-order streams, the valley floor is wide, but still constrained locally by valley walls. Broken, medium-sized CWD pieces, delivered by blowdown or transported from upper reaches, become key-CWD which create vertical and horizontal variation in channel structure. The height of steps in the longitudinal profile ranges from small (1–2 m for individual pieces) to large (2–5 m for CWD-jams) structures. Streamflow diverted by CWD may erode the toes of hillslopes, resulting in soil movement. Channel widening and sediment storage effects are predominantly observed in medium-sized streams, especially in areas controlled by CWD-jams. CWD is transported and redistributed during high stream flow events, and occasionally by dam-break flood (Costa and Schuster, 1988). Spatially periodic variation in channel width and gradient are found to have dominant wavelengths three to four times mean channel width.

The studied fifth-order alluvial channel is relatively free to migrate laterally. CWD is supplied directly from floodplains and terraces by windthrow or bank erosion, and by debris flows from tributaries. In these

Table III. Summary of interactions between CWD and channel morphology in relation to stream order

Characteristic	Stream order		
	Low (1–2)	Medium (3–4)	High (5)
Valley morphology observed	Steep V-shape	U-shape, constrained by valley walls*	Gentle slope and unconstrained flat streambed*
Condition of key-CWD	Fragmented and decomposed small pieces; highly variable, depending upon disturbance history	Mixture of sizes, which occasionally develop into CWD-jams	Slightly fractured, large, fresh
CWD input processes	Windthrow Landslide	Windthrow Streamside slide Earthflow toe erosion	Windthrow Bank erosion Toeslope slide Debris flow from tributaries
CWD transport processes	Debris flow	Debris flow High stream flow (including dam-break flood)	High stream flow (flood)
Effects of CWD on channel morphology and sediment storage	Small step structure (key-CWD) Widening of valley floor with sediment accumulation Dominant storage control in sediment-rich streams	Small (key-CWD) to large (CWD-jam) step structure Widening of valley floor associated with sideslope failure and sediment accumulation Dominant storage control	Development and regulation of secondary channels Widening of valley floor associated with bank erosion Annual, temporary storage

* High reach-to-reach variation in degree of constraint.

channels, CWD contributes mainly to channel migration and development of secondary channels. Depending on the position of CWD, which is repositioned and redistributed by floods, sediment storage is temporary.

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