# Distribution of coarse woody debris in a mountain stream, western Cascade Range, Oregon[1]

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The distribution of coarse woody debris in a fifth-order Cascade Range (Oregon) stream system was examined from a geomorphic point of view. The number, volume, location, orientation, decay class, and pool formation roles of coarse woody debris were investigated. The processes of coarse woody debris production, transport, and storage, which vary with channel and valley floor geomorphology, are responsible for the pattern of coarse woody debris distribution on valley floors. Channel width and sinuosity are the main factors that control production, storage sites, and hydrologic effects of coarse woody debris. The amount of coarse woody debris and the number of pool-forming pieces are relatively high in wide, sinuous reaches, where a complex structure of floodplains and riparian forests develops in association with a braided channel pattern. These relations are transferable to other systems with similar relations of coarse woody debris piece length to channel width.

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La distribution des gros débris ligneux dans un réseau hydrographique de cinquième ordre situé dans la chaîne des Cascades, en Orégon, a été examinée d'un point de vue géomorphologique. Le nombre, le volume, la localisation, l'orientation, la classe de décomposition et le rôle des gros débris ligneux dans la formation des étangs ont été étudiés. Les processus de production, de transport et d'entreposage des gros débris ligneux, qui varient selon le lit du cours d'eau et la géomorphologie du fond de la vallée, sont responsables de la distribution des gros débris ligneux dans le fond des vallées. La sinuosité et la largeur du lit du cours d'eau sont les principaux facteurs qui contrôlent la production, les sites d'entreposage et les effets hydrologiques des gros débris ligneux. La quantité de gros débris ligneux et le nombre de pièces qui favorisent la formation des étangs sont relativement élevés dans les sections larges et sinueuses où se développe une structure complexe de plaines inondables et de forêts ripariennes en association avec une configuration entrelacée des lits du cours d'eau. Ces relations peuvent être appliquées à d'autres systèmes dont les relations entre la longueur des pièces de gros débris ligneux et la largeur du lit du cours d'eau sont semblables.

[Traduit par la Rédaction]

## Introduction

The input, movement, and spatial distribution of coarse woody debris (CWD) in streams are important components of the physical dynamics of stream systems (Keller and Swanson 1979; Bilby and Ward 1989; Nakamura and Swanson 1993), aquatic habitat (Sedell et al. 1988), and the disturbance and successional dynamics of riparian ecosystems (Harmon et al. 1986; Gregory et al. 1991). Several of these studies include general observations of effects of valley floor morphology on CWD dynamics.

In this study, we examined CWD distribution, production, and movement in stream reaches with different geomorphic structures (i.e., width and sinuosity). We undertook the study with two primary hypotheses: (*i*) wider reaches would have more CWD because lateral channel change can cause CWD input at high rates and (*ii*) straight reaches with single channels would have greater ability to transport CWD, and therefore, lower amounts of CWD. We define CWD as pieces that are greater than 1.0 m in length and 10 cm in diameter.

## Study site

We investigated the lower 4.5 km of Lookout Creek (drainage area 60 km$^2$), which is located at the eastern edge of the western Cascade Range in Oregon, United States (Fig. 1). The research section is a fifth-order stream, where a large, slow-moving landslide (earthflow type) and bedrock outcrops create variation in valley floor width, channel conditions, and stream sinuosity (Vest 1988). The landslide constrains the main channel, creating a narrow and sinuous channel along its margin (2.5- to 3.7-km area marked in Fig. 2) and a wide valley floor in upstream and downstream areas (Fig. 2). The ranges and mean values for channel width in the research section were 9 to 71 m and 23 m, respectively. Channel gradient range and mean were 1.9 to 2.8% and 2.2%, respectively. Channel gradient is maximum in the reach where the earthflow has deposited big boulders (Vest 1988). We did not include analysis of the influence of channel gradient on CWD distribution in this study because variation in channel gradient was quite small in comparison with variation in width and sinuosity, and because channel gradient controls the distribution of CWD on much larger spatial scales (e.g., from first through sixth stream order) than sampled in this study.

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Conifers, such as Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco), western hemlock (*Tsuga heterophylla* (Raf.) Sarg.), and western red cedar (*Thuja plicata* Donn ex D. Don), dominate on hillslopes and terraces. These conifers, which occupy the overstory of old-growth forests along the research section, are typically 50–70 m in height and 80–150 cm in diameter. Douglas-fir is the major source of conifer CWD in this stream. The deciduous species big-leaf maple (*Acer macrophyllum* Pursh), which reaches 20–30 m in height, is common on terraces and dominates the supply of deciduous CWD. Red alder (*Alnus rubra* Bong.), ranging from 5 to 20 m in height, predominates on gravel bars and floodplains, and willow (*Salix* spp.), 1 to 5 m in height, establishes on low gravel bars that are frequently submerged by winter floods.

Annual precipitation in the basin averages 2500 mm and is concentrated in the fall and winter, with little or no rain in the summer. Floods, especially those fed by rain-on-snow events within the transient snow zone (400 to 1200 m elevation) (Harr 1981), transport and redistribute CWD on the valley floor.

## Methods

We examined the geomorphology of the valley floor by mapping landforms within the research section. We used tape, compass, and clinometer to establish a base line along the center of the channel and transects spaced at 100-m intervals along the channel and extending from the channel to the base of the valley wall. In addition to detailed mapping, we divided the overall research site into sample units at intervals of 50 m along the channel and evaluated the mean channel width and the sinuosity of each sample unit.

The sinuous pattern of mountain rivers, such as Lookout Creek, shows fairly irregular form in comparison with the meandering pattern of alluvial channels because lateral channel shifts are limited by local constraints such as earthflows, bedrock outcrops, and alluvial fans. Therefore, sinuosity was calculated for the 50-m sample units following the approach in Fig. 3 and without consideration of the longer wave length of sinuous channel form (Fig. 3).

We classified each sample unit into four reach types according to channel width and sinuosity. Reaches with an average width >19.0 m and sinuosity ≥1.09 were grouped as the wide, sinuous type (WSi). Reaches with width ≥19.0 m and sinuosity <1.09 were grouped as the wide, straight type (Wst); units <19.0 and ≥1.09 were grouped as the narrow, sinuous type (NSi); units <19.0 and <1.09 were grouped as the narrow, straight type (NSt). We compared these four reach types with respect to CWD number, size, volume, location, orientation, and pool formation roles. The mean fluvially active, valley-floor width was calculated by dividing low-flow channel, gravel bar, and floodplain areas by the 50-m length of the sample unit.

A detailed geomorphological map generated in an earlier study was used in the field to record the location of CWD pieces; Fig. 2 is a highly generalized version of this map. Storage sites of CWD were classified as entrance of secondary channels, within secondary channels, outside of bend, behind or between large boulders, and other sites (Fig. 4).

We sampled CWD in the stream channel and on the gravel bars and floodplains. Pieces that lay only on terraces and hillslopes were omitted because floods do not inundate these areas; pieces extending from terraces or hillslopes into streams or onto floodplains were mapped and counted. On the basis of the presence of root throw pits, standing remnants of trees from which CWD pieces were derived, and other field criteria, CWD pieces were categorized as those supplied from adjacent forest (not fluvially transported) or as those fluvially transported.

Length, diameter, volume, location, orientation, roles in pool formation, and decay class were recorded for each piece of CWD. The diameters at each end were measured for logs longer than 5.0 m, except for pieces within large jams where we were unable to measure both ends. For jam pieces and pieces shorter than 5.0 m, we used the diameter measured at the center point.

The volume of a CWD piece was calculated by the formula

$$\text{volume} = \pi\,(\mathrm{D1}^2 + \mathrm{D2}^2)\left(\frac{L}{8}\right)$$

where D1 and D2 are the diameters at each end and $L$ is the length. For pieces whose diameters were measured only at the center, the center diameter was used for both D1 and D2 in the above formula.

The location of CWD pieces was classified by geomorphic surface as main channel, secondary channel, floodplain, hillslope, terrace, and boulder. Main channel, here, refers to the channel carrying most of the main-stem water. Both gravel bars and floodplains were included in the floodplain category. Hillslope and terrace categories were used only for the CWD pieces located on channel or floodplain areas. Pieces located on huge (diameter of 1–8 m) boulders were included in the boulder category.

Orientation was measured for the pieces longer than 5.0 m and classified in four direction classes (0–45°, 45–90°, 90–135°, 135–180°) relative to a line perpendicular to the channel axis (Fig. 5). Pieces that contributed to pool formation by obstructing streamflow and creating complex turbulence were noted. Damming, deflecting streamflow, and forming underflow are representative types of pool formation by CWD considered here (Robison and Beschta 1990).

Degree of decay was divided into four classes ((1) fresh, bark adheres tightly, (2) loose bark, (3) no bark, but hard, and (4) no bark and soft) following the approach of Lienkaemper and Swanson (1987).

Data on CWD distribution with respect to geomorphic features and decay class with respect to CWD size were analyzed with analysis of variance (ANOVA) followed by post-hoc tests of effects using Duncan's new multiple range test. Data on number and volume of CWD pieces were square-root transformed, tested for independence, equality of variance, and normality, and found to meet assumptions for ANOVA. Since more than a pairwise comparison was tested with Duncan's test, probabilities were conservatively adjusted to $\alpha/k$ using a Bonferroni procedure, where $\alpha$ is the desired level of significance (0.05) and $k$ is the number of comparisons (Neter et al. 1990; SYSTAT, Inc. 1992).

## Results and discussion

### *Channel width, sinuosity, and accumulation*

Channel width and sinuosity were the main factors that controlled CWD supply and the number of storage sites, and thereby the amount and distribution of CWD. Generally, terraces and floodplains develop in unconstrained reaches with a relatively wide valley floor; trees on these geomorphic surfaces frequently fall into streams because of windthrow, and other nongeomorphic causes of mortality, and bank erosion caused by the lateral shift of stream channels. Further, CWD pieces transported into unconstrained reaches are scattered over the valley floor because of the decrease in flow depth, as well as channel bifurcation.

Development of secondary channels in wide valley-floor areas may contribute to an abundance of CWD by trapping transported pieces (Figs. 4A, 4B). In constrained, sinuous reaches, especially on the outside of bends, streamside slides are commonly initiated by toe-slope erosion. These streamside slides and earthflow toes deposit large boulders and CWD pieces in streams, thus armoring the stream bed, creating hydraulic roughness and providing storage sites for CWD (Figs. 4C, 4D).

Channel width, number, and sinuosity were major factors influencing stream hydraulics (flow depth, velocity, channel

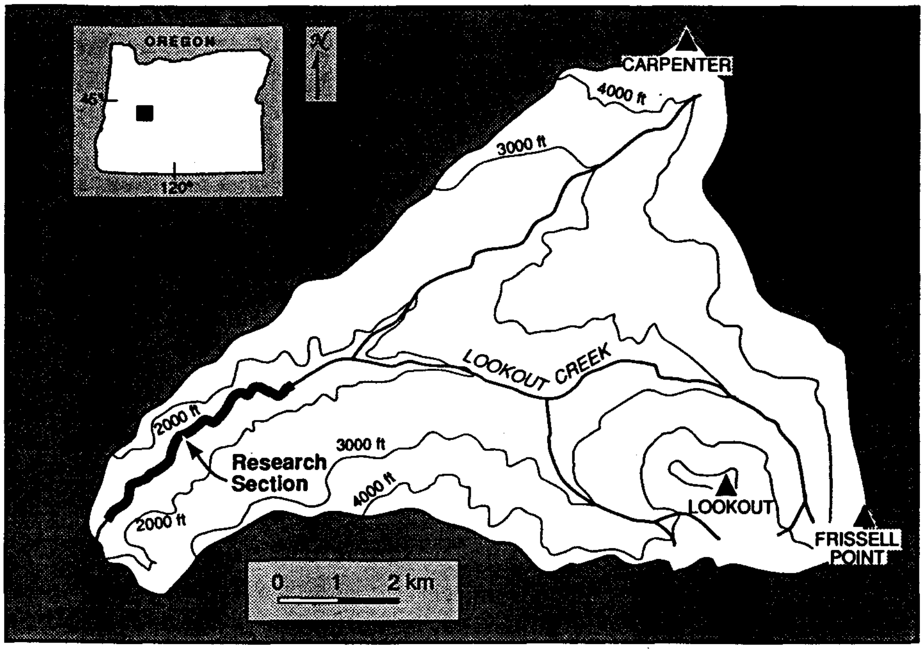

FIG. 1. Location of study site in the Lookout Creek basin, Oregon.

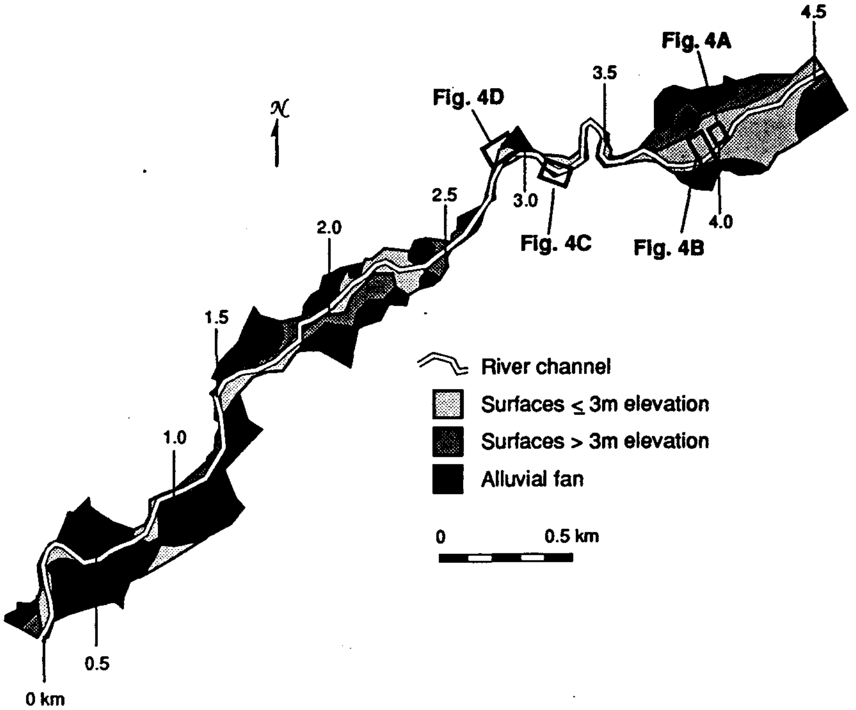

FIG. 2. Valley-floor geomorphology of the research section. Distances in 0.5-km increments along the channel shown in the figure are from the lower end of the research section. Maps of CWD patterns are noted and shown in Figs. 4A–4D.

roughness, and extent of overbank flows) and the types and numbers of CWD storage sites (such as mouths of secondary channels and outsides of channel bends) (Fig. 6). The number and volume of CWD pieces varied along the channel with respect to channel width, sinuosity, and occurrence of storage sites (Figs. 3 and 6). Peaks of CWD abundance approximately corresponded to areas with relatively high concentrations of storage sites, which were located generally in either wide and (or) sinuous reaches.

### *Number and volume of CWD pieces*

The range, mean, and standard deviation of the number and volume of CWD pieces were compared among the four reach types (Table 1). The average number and average volume of CWD decreased in the order WSi > WSt > NSi > NSt for both locally supplied and fluvially transported pieces. The two most geomorphically distinct types (WSi and NSt) exhibited the greatest (and statistically significant) differences in number and volume of CWD. The intermediate

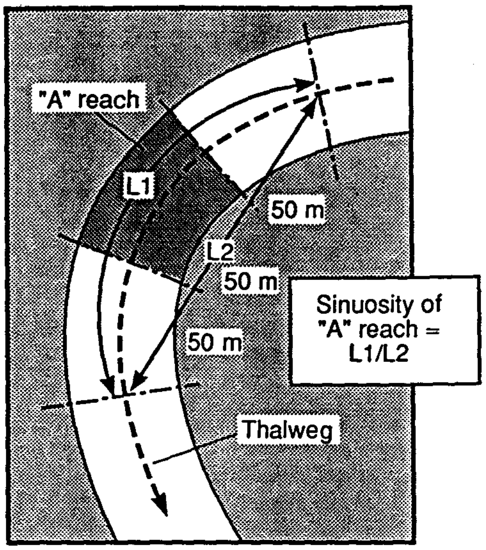

FIG. 3. The method for calculating channel sinuosity. Sinuosity of *A* was measured by the ratio of lengths of the straight line (L2) and center line at the channel (L1), both of which extend over three units centered on the *A* unit.

geomorphic types (WSt and NSi) were variable in the statistical significance of differences among the four reach types. The ranges of values for number and volume were greater for transported than for locally supplied pieces. Comparison among reach types in terms of CWD volume per hectare indicated that on average, WSi and NSi had high densities of CWD pieces, and NSt had low density.

We subdivided WSi and WSt types according to the presence of secondary channels (Table 1). Secondary channels are rare in narrow reaches (NSi and NSt types) and so were not tabulated for these reach types. The WSi reaches with secondary channels received three to five times more locally supplied CWD pieces and had greater retention of CWD than did WSi reaches with single channels. The comparisons between multiple- and single-channel parts of WSt reaches were not statistically significant, but in most cases were similar to trends in WSi reaches. The difference between multiple and single channels is consistent, but not statistically significant, in CWD volume per hectare. Stream reaches with secondary channels contained almost twice the CWD density of single-channel reaches.

These results (Table 1) can be attributed to (*i*) the extent of the CWD source area, (*ii*) the effect of hydrologic factors, and (*iii*) the distribution of trapping sites. First, a wide, unconstrained reach with multiple channels functions as a sediment storage area (Nakamura 1986*b*), which experiences frequent disturbance of the valley-floor forests by lateral channel shifts. Therefore, riparian forests established on such deposits are complex in age (Nakamura 1986*a*), structure, and species composition (Okamura and Nakamura 1989). The combination of geomorphic processes on valley floors and dynamics of forests on floodplains and terraces produces a greater supply of CWD pieces to streams compared with channels with fixed banks, where the CWD supply is determined predominantly by stand dynamics. In the sinuous reaches of this study area, large CWD pieces also enter the channel by lateral stream cutting and landslides where side slopes are formed of thick deposits of colluvium at the outside of bends. Landslides extend upslope from points where the stream progressively scours the toe slope. Some of the narrow reaches sampled are bordered by steep, rocky slopes where the forest cover is relatively sparce, thus limiting CWD supply.

Second, large CWD jams commonly dominate entrances of secondary channels (Fig. 4A) where channel divergence causes stream discharge and width to shrink abruptly (bottleneck effect). CWD is abundant in secondary channels because the discharge divided into multiple channels is not adequate to carry most CWD pieces (Fig. 4B).

Third, in the wide reaches, riparian trees impede the transport of large CWD pieces in flows entering floodplain forests, trapping fluvially transported pieces (sieve effect). Floodplains at the outsides of bends act as large "trash racks," trapping CWD from flood flows. In the earthflow-constrained, sinuous reaches, large boulders from earthflows also create a sieve effect.

### *Number, volume, size, and decay class of CWD with respect to geomorphic location*

Number, volume, length, and decay class were recorded for CWD pieces found in the six types of geomorphic surfaces (Table 2). A CWD piece spanning two or more locations was counted in each location. About 61% of the inventoried CWD pieces were found on floodplains, 17% in the main channel, and 16% in the secondary channels. In terms of volume, 46% was on floodplains, 26% in the main channels, and 10% in the secondary channels. In these locations, number and volume per unit area indicated that density of CWD in secondary channels and floodplains was greater than that in the main channel by factors of 1.5 and 4, respectively. The difference in percentage between number and volume reflects the difference in the size distribution among locations. The length and volume distributions of CWD pieces at each location show that CWD pieces smaller than 5.0 m accounted for 69% and 62% of CWD in secondary channels and on floodplains, respectively, whereas 54% of large (≥5.0 m) CWD pieces occurred in the main channel.

Many CWD pieces in the secondary channels, on floodplains, and on boulders were highly decayed, whereas fresh pieces were dominant on hillslopes and terraces, and were particularly abundant in the main channel. However, volume estimates of each decay class indicated that fresh CWD was dominant in main channels, secondary channels, hillslopes, and terraces, whereas highly decayed CWD dominated on floodplains and boulders.

This suggests that small- and moderate-sized CWD pieces in the main channel were easily transported by high discharges, leaving large, fresh pieces in place. Floods fragmented decomposed pieces in the main channel. In the secondary channels, however, the discharge was too low to carry most CWD pieces; thus, many small pieces remained. The stage of decay and age of living trees growing among them suggest that many of the abundant decayed pieces on floodplains and boulders were transported and left by the major floods in 1964–1965 (estimated recurrence interval = 100 years).

In general, mean length and mean volume of CWD pieces decreased in the classes of more advanced decay ($p \leq 0.01$, except for mean length between decay classes 2 and 3, which was significant at $p \leq 0.05$, Table 3).

As a whole, fluvially transported CWD pieces were substantially smaller than locally supplied (not fluvially

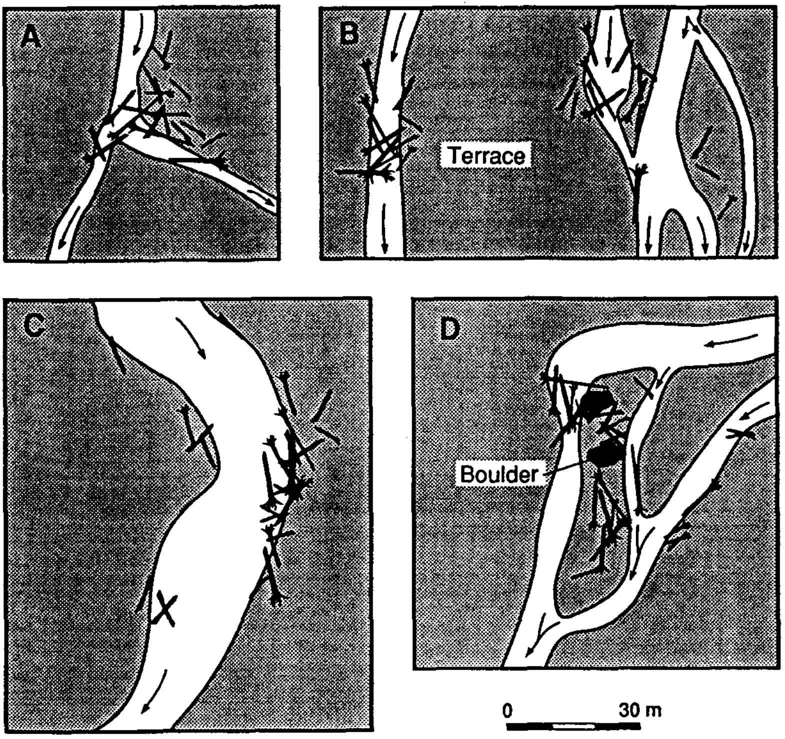

FIG. 4. Predominant types of storage sites of CWD observed in study site. (A) Entrance of secondary channels. (B) Within secondary channels. (C) Outside of bend. (D) Behind or between large boulders.

transported) pieces because large, sound pieces are transported only in extreme events and decomposed CWD pieces are fragmented during transport (Fig. 7). Virtually all transported pieces were shorter than mean bankfull width (23 m), but over 20% of untransported pieces were longer (Fig. 7). This corresponds with observations by others using different analysis approaches (Lienkaemper and Swanson 1987; Bilby and Ward 1989) that the relation of CWD piece length to channel width is a useful measure of CWD susceptibility to fluvial transport.

*Orientation*

Orientations of CWD pieces (Fig. 5) did not vary significantly ($\chi^2$, $p > 0.05$) among the six categories of reach types, including the distinction between reaches with and without secondary channels. CWD pieces longer than 5.0 m appeared to have equal probability of any orientation over all reaches. Orientations of CWD pieces longer than 5 m were significantly different ($\chi^2$ test for two samples: $p < 0.05$) for pieces that had been fluvially transported or were located where they had fallen. Transported pieces ($n = 591$) tended to be oriented parallel to the channel axis, but this was not statistically significant ($\chi^2$ test for one sample: $p > 0.05$). The nontransported pieces exhibited a significant preferred orientation perpendicular to the channel ($\chi^2$ test for one sample: $p < 0.05$).

*Pool formation*

The percentage of CWD pieces that influenced pool formation was compared among the six reach types (Fig. 8). About 17% of CWD pieces in WSi with secondary channels affected pool formation; this percentage is two to five times greater than for the other types. WSi units had the greatest lateral (wide valley floor) and vertical (relatively fine sediment) channel mobility and, therefore, the greatest opportunity for pool formation by CWD.

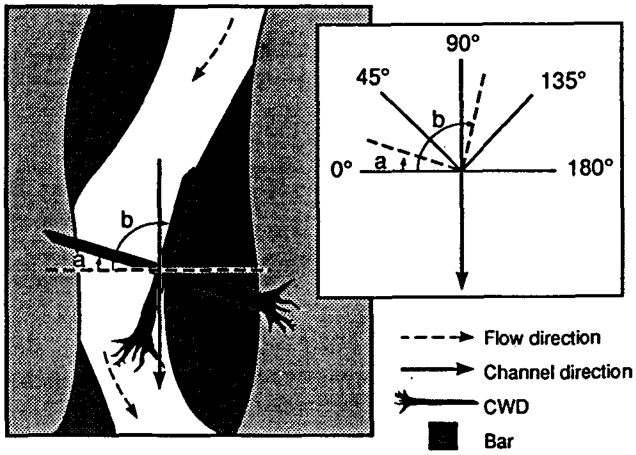

FIG. 5. Orientation of CWD pieces, based on angles between CWD pieces and main channel axis showing examples for logs *a* and *b*.

About 31% of CWD pieces located in the main channel were interpreted as influencing pool formation, as were 28% of the pieces in secondary channels. Between main and secondary channels, there was no significant difference in the number of pieces that affected pool formation. However, 65% of pieces in the main channel were longer than 5.0 m, whereas only 30% were that long in the secondary channels, indicating that small pieces have greater influence on pool formation in the smaller secondary channels. The contribution of small pieces to pool formation was distinctive in the WSi type with secondary channels, where 64% of pool-

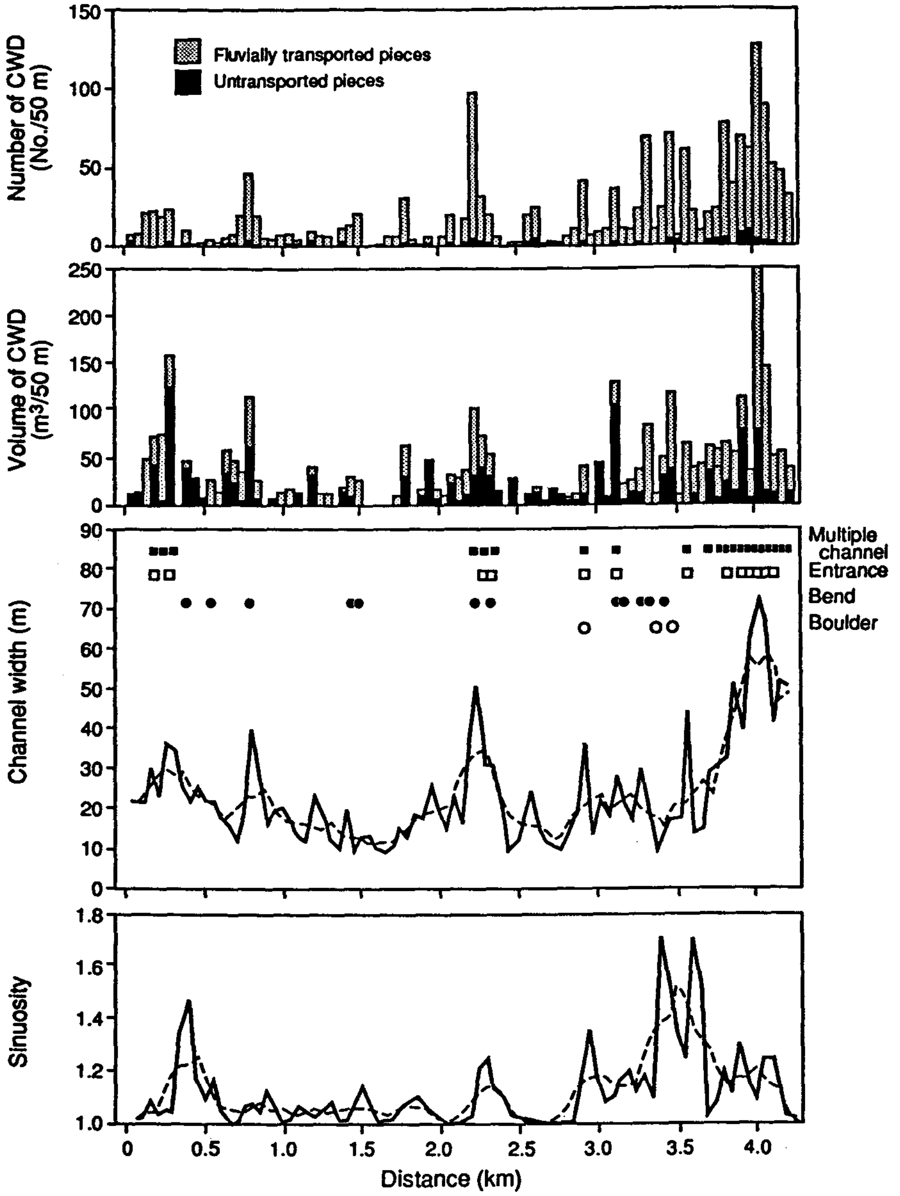

FIG. 6. Number and volume of CWD pieces in relation to storage sites, channel width, and channel sinuosity. The broken line represents 250 m running averages.

forming CWD pieces were ≤5.0 m in length. In other reach types, the percentage of pool-forming pieces ≤5.0 m ranged from 0 to 43%.

### *Relation of the number and volume of CWD to channel width and sinuosity*

Analysis of the valley reach types indicated that channel width and sinuosity influence CWD distribution through interactions with stream hydrology, the source area of CWD, and the density of CWD trapping sites. Channel width and sinuosity varied at different spatial scales. Spectral analysis of width variation along the channel showed weak peaks at 230- and 350-m wavelengths. Similarly, analysis of sinuosity variation indicated relatively strong peaks around 230 and 560 m. We concluded that to analyze the amount of CWD appropriately, the minimum reach length should be about 250 m for both channel width and sinuosity. Consequently, the number and volume of CWD pieces were summed as dependent variables, and the channel width and sinuosity were averaged at an interval of 250 m as independent variables. The spatial distribution of CWD was analyzed at scales ranging from 50 to 250 m, which corresponded to the reach or segment scale in the stream hierarchy proposed by Frissell et al. (1986).

Regression analyses yielded the estimated functions:

$$N = a1 + b1(W) + c1(S)$$

$$V = a2 + b2(W) + c2(S)$$

where $N$ and $V$ are the number and volume of CWD pieces per 250-m units of channel length; $W$ and $S$ are channel width and sinuosity; and a1, a2, b1, b2, c1, and c2 are constants. These constants are −309.7, −463.3, 6.83, 9.35, 222.7, and 375.3, respectively, for the overall research site. Null hypotheses, $H_0$, that b1 = 0, b2 = 0, and c2 = 0 were all rejected at the 1% level; $H_0$ that c1 = 0 was rejected at the 5% level. Multiple

TABLE 1. Number and volume of CWD classified by reach type and channel number (single or multiple) for two reach types expressed in terms of mean ± standard deviation and range

| Reach type and channel number | Width (m) | Sinuosity | Number of CWD pieces | | Volume of CWD ($m^3$/50-m sample unit) | | Total ($m^3$/ha) |
|---|---|---|---|---|---|---|---|
| | | | Supplied | Transported | Supplied | Transported | |
| **Classified by reach type** | | | | | | | |
| Wide, sinuous reaches | 35.7±14.9 | 1.22±0.14 | 2.5±2.5*a* | 38.5±32.8*a* | 22.5±27.7*a* | 39.9±41.1*a* | 337±236*a* |
| (23 sample units) | 19.7–70.9 | 1.10–1.70 | 0.0–10.0 | 0.0–122.0 | 0.0–103.8 | 0.0–173.2 | 0–946 |
| Wide, straight reaches | 28.3±9.5 | 1.04±0.03 | 1.9±1.4*ab* | 16.6±11.5*b* | 20.7±28.2*ab* | 21.6±20.2*a* | 284±207*ab* |
| (21 sample units) | 19.0–51.3 | 0.99–1.09 | 0.0–4.0 | 3.0–47.0 | 0.0–122.9 | 0.7–71.6 | 30–903 |
| Narrow, sinuous reaches | 15.2±2.9 | 1.27±0.20 | 1.2±1.3*ab* | 16.5±16.0*ab* | 8.3±11.8*ab* | 17.4±21.7*ab* | 352±401*ab* |
| (13 sample units) | 9.5–18.9 | 1.09–1.71 | 0.0–4.0 | 3.0–66.0 | 0.0–33.7 | 0.3–82.8 | 21–1352 |
| Narrow, straight reaches | 13.5±3.0 | 1.03±0.03 | 0.8±1.1*b* | 3.9±4.2*c* | 5.7±9.6*b* | 6.3±7.7*b* | 177±208*b* |
| (28 sample units) | 9.3–18.8 | 1.00–1.09 | 0.0–5.0 | 0.0–19.0 | 0.0–35.2 | 0.0–25.5 | 0–711 |
| Total | 23.4±13.3 | 1.12±0.15 | 1.6±1.8 | 18.3±23.4 | 14.3±22.7 | 20.9±28.6 | 274±264 |
| (85 sample units) | 9.3–70.9 | 0.99–1.71 | 0.0–10.0 | 0.0–122.0 | 0.0–122.9 | 0.0–173.2 | 0–1352 |
| **Classified by channel number** | | | | | | | |
| Wide, sinuous reaches | | | | | | | |
| Multiple | 43.7±13.9 | 1.23±0.15 | 3.7±2.5*a* | 54.6±28.8*a* | 31.5±30.8*a* | 53.9±43.5*a* | 400±214*a* |
| (14 sample units) | 27.2–70.9 | 1.10–1.70 | 1.0–10.0 | 17.0–122.0 | 0.2–103.8 | 19.6–173.2 | 103–946 |
| Single | 23.2±2.9 | 1.20±0.12 | 0.7±0.8*b* | 13.3±20.3*b* | 8.4±12.7*a* | 18.0±24.3*b* | 239±234*a* |
| (9 sample units) | 19.7–29.6 | 1.10–1.46 | 0.0–2.0 | 0.0–68.0 | 0.0–36.8 | 0.0–81.3 | 0–825 |
| Wide, straight reaches | | | | | | | |
| Multiple | 37.4±10.3 | 1.04±0.02 | 1.5±1.3*a* | 25.8±10.2*a* | 33.6±42.5*a* | 40.3±16.4*a* | 442±255*a* |
| (6 sample units) | 23.3–51.3 | 1.01–1.07 | 0.0–3.0 | 17.0–47.0 | 0.0–122.9 | 25.7–71.6 | 140–903 |
| Single | 24.7±6.1 | 1.04±0.03 | 2.1±1.5*a* | 12.9±9.8*a* | 15.5±17.3*a* | 14.2±16.4*a* | 221±141*a* |
| (15 sample units) | 19.0–40.0 | 0.99–1.09 | 0.0–4.0 | 3.0–42.0 | 0.0–58.6 | 0.7–52.6 | 30–557 |

NOTE: Sample units were 50 m of channel length. Within a classification, means followed by the same letter in a column are not significantly different from each other using Duncan's new multiple range test ($p < 0.05$), conservatively adjusted with a Bonferroni procedure (see Methods).

correlation coefficients were 0.91 for number and 0.94 for volume of pieces. In terms of the number of CWD pieces, partial correlation coefficients of channel width and sinuosity were, respectively, 0.89 and 0.52, and coefficients for volume were 0.92 and 0.66. Thus, the amount of CWD was controlled more strongly by channel width than by sinuosity.

## Conclusion

Geomorphic features at a series of spatial scales regulate CWD input, spatial arrangements, and, therefore, function in stream systems. Unconstrained valley-floor areas are subject to CWD input by lateral channel change and have relatively high densities of CWD trapping sites, such as mouths of secondary channels, heads of islands, and secondary channels themselves. These factors lead to relatively high abundances of CWD in wide, sinuous valley-floor areas. At the opposite extreme of valley-floor geomorphic settings, narrow, straight valley floors have more limited supplies of CWD, although some streamside sliding in response to stream cutting of toe slopes may augment input by windthrow and biotic processes. Narrow, straight valley-floor environments lack secondary channels, but may have other trapping sites, such as very large, landslide-derived boulders. Thus, individual CWD trapping sites differ in type and overall density among valley-floor environments distinguished on the bases of landform origin and width or sinuosity characteristics.

These contrasting CWD characteristics have different implications for management. In the case of CWD-related

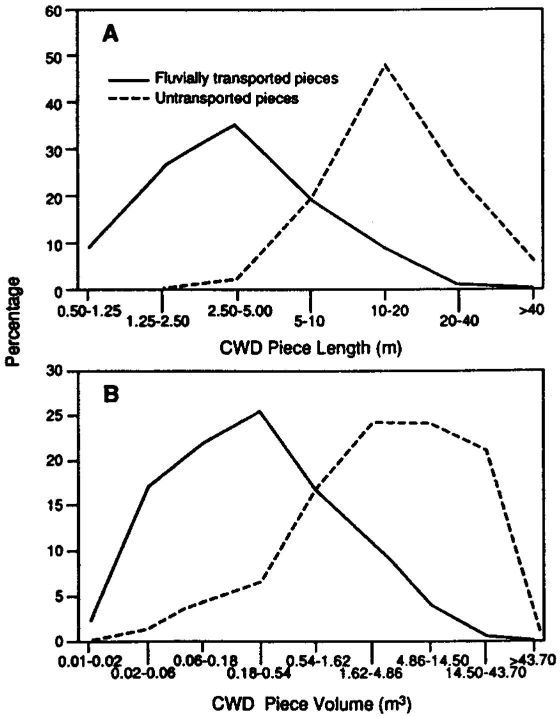

FIG. 7. Distributions of length (A) and volume (B) of locally supplied (untransported) and fluvially transported CWD pieces.

TABLE 2. Number, volume, size, and decay class of CWD distributed on different geomorphic surfaces

| | Main channel | Secondary channel | Flood-plain | Hillslope | Terrace | Boulder | Total |
|---|---|---|---|---|---|---|---|
| No. of pieces | | | | | | | |
| % | 17.1 | 15.9 | 60.8 | 2.9 | 1.7 | 1.7 | 100.0 |
| No./ha | 77 | 301 | 254 | | | | |
| Volume | | | | | | | |
| % | 26.0 | 10.2 | 45.9 | 9.1 | 6.4 | 2.3 | 100.0 |
| $m^3$/ha | 198 | 301 | 380 | | | | |
| Length (%) | | | | | | | |
| 1.0–2.5 m | 16.9 | 34.9 | 30.8 | 0.0 | 12.5 | 36.4 | 27.9 |
| 2.5–5.0 m | 29.3 | 34.5 | 31.4 | 3.6 | 0.0 | 18.2 | 30.0 |
| 5.0–10.0 m | 23.9 | 14.7 | 20.5 | 19.6 | 31.3 | 15.2 | 20.2 |
| 10.0–20.0 m | 18.4 | 11.1 | 13.4 | 46.4 | 21.9 | 24.2 | 15.2 |
| >20.0 m | 11.5 | 4.9 | 4.0 | 30.4 | 34.4 | 6.1 | 6.7 |
| Volume (%) | | | | | | | |
| 0.01–0.05 $m^3$ | 16.6 | 20.2 | 12.8 | 0.0 | 0.0 | 21.2 | 14.2 |
| 0.05–0.25 $m^3$ | 13.0 | 29.6 | 29.7 | 0.0 | 12.5 | 21.2 | 25.6 |
| 0.25–1.25 $m^3$ | 29.3 | 30.9 | 30.7 | 8.9 | 9.4 | 21.2 | 29.3 |
| 1.25–6.25 $m^3$ | 24.2 | 14.3 | 19.1 | 48.2 | 34.4 | 18.2 | 20.3 |
| >6.25 $m^3$ | 16.9 | 4.9 | 7.6 | 42.9 | 43.8 | 18.2 | 10.6 |
| Decay class (no., %) | | | | | | | |
| 1 | 13.9 | 6.5 | 7.6 | 37.5 | 28.1 | 3.0 | 9.7 |
| 2 | 8.5 | 3.9 | 6.7 | 8.9 | 9.4 | 0.0 | 6.6 |
| 3 | 36.0 | 45.3 | 26.7 | 28.6 | 34.4 | 21.2 | 31.3 |
| 4 | 41.7 | 44.3 | 59.0 | 25.0 | 28.1 | 75.8 | 52.5 |
| Decay class (vol., %) | | | | | | | |
| 1 | 46.7 | 45.1 | 27.1 | 40.6 | 72.3 | 0.2 | 37.6 |
| 2 | 14.1 | 9.0 | 10.5 | 17.7 | 4.0 | 0.0 | 11.3 |
| 3 | 24.3 | 26.8 | 28.7 | 26.0 | 17.7 | 64.4 | 27.3 |
| 4 | 14.9 | 19.1 | 33.7 | 15.7 | 5.9 | 35.3 | 23.9 |

TABLE 3. Decay class and size of CWD pieces expressed in terms of mean ± SD and range

| Decay class | Debris pieces (no.) | Length (m) | Volume ($m^3$) |
|---|---|---|---|
| 1 | 125 | 14.0±11.9*a*<br>1.5–50.0 | 6.58±11.72*a*<br>0.03–56.57 |
| 2 | 103 | 7.9±8.3*b*<br>1.0–39.0 | 3.24±6.88*b*<br>0.03–42.42 |
| 3 | 522 | 6.5±5.8*b*<br>0.8–48.0 | 1.68±4.10*c*<br>0.02–38.08 |
| 4 | 942 | 4.5±4.1*c*<br>0.8–32.6 | 1.02±2.14*d*<br>0.01–26.64 |

NOTE: Means within columns followed by the same letter are not significantly different from each other according to Duncan's new multiple range test ($p < 0.05$), conservatively adjusted with a Bonferroni procedure (see Methods).

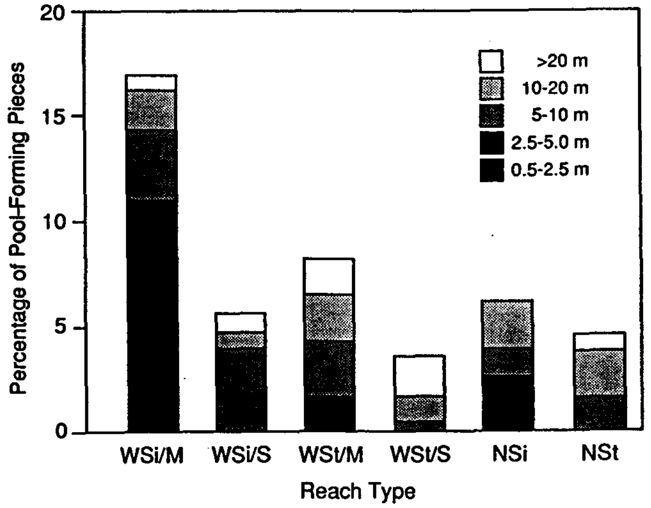

FIG. 8. Pool formation associated with CWD. Percentage and length class of pool-forming pieces are compared among unit types.

flood damage, for example, narrow, straight reaches can be source areas of CWD-laden flood surges that can damage habitat, roads, and dwellings in downstream areas. Wide valley floors can be trapping sites for CWD, although they are subject to channel change. In either environment CWD pieces significantly longer than channel width are likely to be relatively stable (Lienkaemper and Swanson 1987; Bilby and Ward 1989). Maintenance of a significant density of long pieces of CWD combined with information on the density and distribution of CWD trapping sites can be used to retain CWD functions that benefit fish habitat while providing for a balance between valley-floor change and hazard management.

We have sampled only one 4.5-km length of a stream system, but this sampling provides lessons transferable to other sites with similar relations of CWD piece length to channel width. This and several other studies have observed that CWD interactions with streams are a function of the relation of CWD piece length to channel width (Keller and Swanson 1979; Bilby and Ward 1989; Abbe et al. 1993). This relationship provides a useful scaling index for placing the Lookout Creek study in the context of a wide range of channel sizes and for characterizing CWD effects in channels. In the Lookout Creek study site, for example, virtually all transported pieces are shorter than bankfull width, but over 20% of untransported pieces are longer (Fig. 7). In this setting, therefore, individual, very large CWD pieces are significant as CWD trapping sites, but geomorphic types of trapping sites are important as well. Geomorphic trapping sites dominate in larger rivers where all CWD is shorter than channel width. CWD types of trapping sites dominate in small streams where most pieces are longer than channel width. These relationships have important manifestations in CWD arrangement and function.

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