Function and dynamics of woody debris in stream reaches in the central Sierra Nevada, California

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Abstract: In 1993, we located, measured, and tagged almost 1700 woody debris pieces on six streams in California's central Sierra Nevada. The stability, geomorphic function, and use by fish for cover of each piece were recorded. In 1994 and 1995, piece movement was quantified and new debris pieces were measured. In the 60 study reaches, debris was not influential in shaping channel morphology and fish cover. Although woody debris was often associated with habitat units, few pieces deflected flow or contributed to the formation of pools or steps. Fish used deep water as cover more often than debris or any other cover type. Medium-sized debris was, however, used in a greater proportion than its availability to fish. Little sediment was stored by debris, and five large pieces stored 85% of the sediment volume measured. Debris frequency and volume did not differ significantly by channel type. After a low stream flow year (1993–1994), few pieces had moved and few new pieces were identified. After a high-flow season (1994–1995), 31% of the pieces had either moved or were not found and new pieces represented over 5% of the originally surveyed volume of wood.

Résumé : En 1993, nous avons repéré, mesuré et marqué près de 1 700 pièces de débris ligneux dans six cours d'eau du centre de la Sierra Nevada, en Californie. Nous avons pris des données sur la stabilité et la fonction géomorphologique de chaque pièce, ainsi que sur l'utilisation qu'en faisaient les poissons pour s'abriter. En 1994 et 1995, nous avons quantifié les déplacements des pièces et avons mesuré de nouvelles pièces. Dans les 60 tronçons de l'étude, les débris n'influaient pas sur la morphologie du chenal et sur le couvert utilisé par les poissons. Alors que les débris ligneux étaient souvent associés à des unités d'habitat, peu de pièces détournaient le courant ou contribuaient à la formation de fosses ou de seuils. Les poissons fréquentaient plus souvent les eaux profondes que les zones à débris ou toute autre type de couvert. Cependant, les débris de taille moyenne étaient surutilisés en regard de leur disponibilité. Les débris accumulaient peu de sédiments, et cinq grandes pièces ont accumulé 85% du volume de sédiments mesuré. La fréquence et le volume des débris ne différaient pas de façon significative d'un type de chenal à l'autre. Après une année de faible débit (1993–1994), peu de pièces se sont déplacées et peu de nouvelles pièces ont été repérées. Après une année de fort débit (1994–1995), 31% des pièces se sont déplacées ou n'ont pu être retrouvées, et les nouvelles pièces représentaient plus de 5% du volume de bois mesuré à l'origine.

[Traduit par la Rédaction]

Introduction

Woody debris functions in many ways in mountain streams. Woody debris is instrumental in storing sediment (Megahan 1982; Nakamura and Swanson 1993) and fine organic matter (Bilby and Ward 1991). It influences channel morphology (Robison and Beschta 1990; Nakamura and Swanson 1993), the composition of riparian vegetation (Malanson and Butler 1990), nutrient dynamics (Aumen et al. 1990), and fish habitat (Carlson et al. 1990). Because of the potential importance of wood in streams, effects of stream-side management on woody debris have been extensively investigated (Carlson et al. 1990; Bilby and Ward 1991). Earlier research on these and related topics is well summarized in Harmon et al. (1986), Bisson et al. (1987), and Sedell et al. (1988).

Although woody debris dynamics in the Pacific Northwest and the redwood – Douglas fir zone of northern California have been investigated (Lisle and Kelsey 1982; O'Conner and Ziemer 1989; Knopp 1993), little is documented about the role of debris in streams in California's Sierra Nevada (S. Gregory, Oregon State University, unpublished data; Ruediger and Ward 1996). General statements about the effects of woody debris on system processes can be misleading because they vary with the scale at which woody debris effects are considered, with characteristics of the channel, and with the size, density, and orientation of debris (Lisle 1995). Regional differences in causative factors in woody debris dynamics (e.g., riparian zone disturbance history, climate, fluvial geomorphology, and type, size, and density of riparian sources of debris (Evans et al. 1993)) also make ex-

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Table 1. Characteristics of the study streams.

Stream[a]	Basin elevation range (m)	Bankfull width (m)[b]	Bankfull depth (m)[b]	Stream order	Gadient (%)	Channel length (km)[c]	Management history
East Fork	1220–2010					13.2	Harvest since 1975 on 40 ha
Upper[d]		7.0*	0.83	2	4.3		No known pre-1975 harvest
Lower[d]		12.8	1.16	2	2.5		Fire history shows no fires
Empire	1055–1840					9.0	Parts of basin harvested 1952–1955
Upper		5.5*	0.88	2	6.9		No post-1955 harvest
Lower		8.7	0.85	3	3.3		Fire history shows no fires
Lavezolla	915–1960					20.0	No known harvest or fires
Upper		7.5*	1.09	2	7.8*		
Lower		12.7	1.29	4	2.5		
Badenaugh	1645–2390					9.0	Harvest since 1975 on at least 250 ha
Upper		2.5*	0.48*	2	6.6*		Entire basin railroad logged 1906–1918
Lower		4.0	0.65	3	2.6		Entire basin burned between 1950 and 1959
Sagehen	1785–2535					16.1	Harvest since 1975 on 375 ha
Upper		2.1	0.47	2	5.9*		Entire basin logged between 1900 and1912
Lower		5.0	0.61	3	2.1		250-ha headwaters fire between 1920 and 1929
Pauley	790–2010					21.9	No known harvest or fires
Upper		6.6*	0.72*	2	7.0		
Lower		12.2	1.20	4	3.2		

Note: *Significant differences between upper and lower sections at $\alpha = 0.95$ (e.g., East Fork upper section bankfull width (7.0 m) differs significantly from the lower section width (12.8 m)).

[a]East Fork, Empire, Lavezolla, and Pauley creeks are on the west side of the Sierra Nevada crest; Sagehen and Badenaugh are on the east side.

[b]Bankfull width and depth and gradient values are means of measurements made at two or three locations in each of the five 100-m study reaches.

[c]Channel length is the distance from the downstream end of the lowest study reach to the upstream end of the channel as designated by the end of the solid blue line on the relevant 1 : 24 000 U.S. Geological Survey topographic map.

[d]Upper and lower each refer to five 100-m reaches. The lower five reaches begin at the location on each channel where the upstream basin area is about 2500 ha. The upper five reaches begin where the upstream basin area is about 830 h.

trapolation of results from elsewhere to the Sierra Nevada problematic. For instance, the Sierra Nevada has a drier, warmer climate and smaller mature, stream-side trees (the source of woody debris) than the Pacific Northwest. Sierra Nevadan streams are probably less prone to debris torrents or other mass movement sources of woody debris than streams in the Pacific Northwest. Many published studies also confine their results to debris pieces at least 10–20 cm in diameter and typically 1.5–2 m in length. One of the few exceptions is Richmond and Fausch's (1995) investigation of debris dynamics in headwater reaches in northern Colorado.

We investigated several aspects of woody debris dynamics on six headwater streams in the central Sierra Nevada. Two size classes of debris are considered: medium (MW), at least 0.08 m in diameter and 1 m in length, and large (LW), at least 0.3 m in diameter and 3 m in length. In relation to the water depth and channel width of the study stream reaches, pieces in the LW class should have a more lasting impact on sediment and channel dynamics and in the Pacific Northwest have been found to remain in streams over 200 years (Murphy and Koski 1989). Specific objectives include evaluation of baseline conditions of woody debris frequency and volume, differences in debris frequency and volume by stream type, influences of woody debris on fish habitat, fish use of woody debris as cover, geomorphic function of woody debris, woody debris movement and recruitment, and inorganic sediment storage by woody debris. Although results from this study are applicable strictly to the field locations investigated, they offer a framework for comparing with woody debris dynamics elsewhere.

Methods

Field measurements of woody debris location, size, and abundance, geomorphic function, stability, associated inorganic material, and fish habitat and cover dynamics were the basis of the study. Measurements were made in the summers of 1993, 1994, and 1995.

Study sites

Observations were made on reaches of six streams located northwest of Lake Tahoe in the central Sierra Nevada (Table 1; Fig. 1). The climate of this area is influenced by the general maritime climate of California. Summer and winter air temperatures are mild, and summers are dry with no precipitation except occasional thunderstorms. The hydrologic regime is dominated by snowmelt flows, with the highest flow volumes occurring between May and July. Flows likely to move woody debris can occur, however, in winter floods caused by rain-on-snow events. Baseflow dominates late-summer stream conditions, and there is the potential for dewatering of channels (except for major rivers) after sustained drought periods. Mass wasting, as a source of in-channel debris, is not regarded as a major erosive agent in most of the Sierra Nevada, and there seems to be relatively little interaction between high flows and initiation of landslides within the inner gorges of Sierra Nevada streams (Seidelman et al. 1986).

In 1993, six streams (Lavezolla, East Fork, Sagehen, Empire, Badenaugh, and Pauley creeks) were selected to represent small headwater streams having a range of land disturbance histories and locations on the western and eastern slopes of the central Sierra Nevada (Table 1). Major portions of the Sagehen and Badenaugh Creek basins were harvested between 1900 and 1918 and again since 1975. Both of these basins also burned during the past 75 years. There is no evidence of fire on any of the other four basins, and harvest intensity on the other four basins is relatively low. Analysis of orthophotographs of the basins upstream from the study reaches revealed no evidence of mass wasting that could have caused catastrophic inputs of debris into the stream channels, and no evidence of mass wasting was observed during the field surveys. Although basin disturbance history differed among the streams, there was no evidence of tree removal in the riparian zone on any of the streams, and mature conifers typically lined the stream banks. There was also no evidence of removal of debris from the channel.

The streams were assumed to be representative of woody debris dynamics in the area, although they were not selected at random; stream size and magnitude of land disturbance in the watersheds influenced selection. Stream bottom substrata consist primarily of a mix of cobbles and boulders with finer sediment or bedrock in some places. The streams are characteristically high-gradient (Table 1) step–pool systems. They are bordered by mixed conifer and red fir forest types on the western slope of the Sierra Nevada and the east-side pine forest type on the eastern slope (Burns and Honkala 1990). Trees in these forest types often grow to be over 1 m in diameter at breast height and 45–65 m in height. Riparian tree spacing is closer, and tree growth rates are generally greater on the western slope than on the eastern slope of the range. All streams have fish populations and flows unimpeded by dams or reduced by diversions.

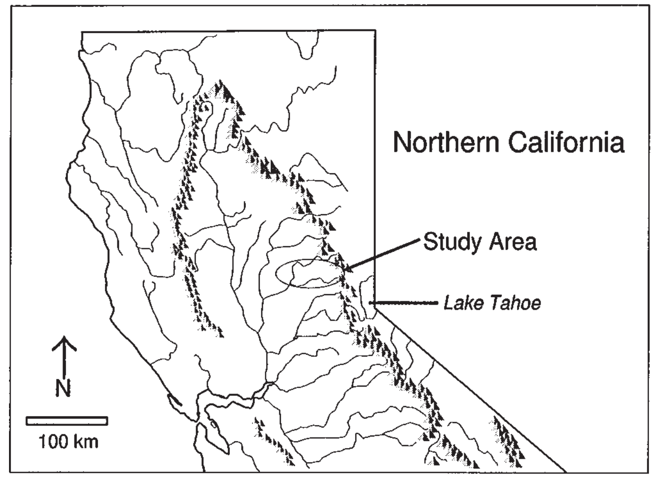
To assess the effect of basin area and channel gradient on woody debris characteristics, ten 100-m reaches were identified on each stream, five in a lower and five in an upper section of each channel. Location of the lowest study reach in the section was determined by upstream basin drainage area. The lowest of the lower five reaches began where the basin drained about 2500 ha. The lower end of the upper five reaches began where the upstream drainage area was about 830 ha. To reduce geomorphological sources of variation and to determine whether channel type affected woody debris dynamics, each study reach was limited to one channel type as described by Rosgen (1994). Rosgen stream channel typing classifies channel segments with regard to gradient, substrata, and entrenchment. Rosgen typing is commonly used as a stratifying variable in stream studies. Study reaches could be adjacent if sequential 100-m channel segments were a single channel type. Otherwise, there were gaps of varying lengths between study reaches.

Measurement variables and procedures

Hydrologic variables quantified for each 100-m reach included bankfull width and depth, low-flow wetted width, Rosgen channel type, and surface water gradient. Two or three measurements of these variables were made per reach, except channel type. Stream habitat was classified using the USDA Forest Service Pacific Southwest Region system (USDA Forest Service 1992) and then condensed into habitat types associated (or not associated) with large woody debris or rootwads. To put stream flows during the study period into a longer term perspective, we used discharge data from the only two U.S. Geological Survey gaging stations within the study area having flows unaltered by dams or diversions.

Wood-related variables quantified for each 100-m reach included longitudinal distance of all debris pieces from a benchmark located at the downstream end of each reach and length and representative diameter of each piece. Piece volume was calculated as the volume of a cylinder. If a piece or aggregate of pieces functioned as a trap for sediment, the dimensions (length, width, height) of the measurable sediment accumulation were recorded.

Fig. 1. Location of the study area in northern California.



All pieces (including rootwads) within the bankfull channel ≥0.08 m in diameter and 1 m in length were tagged in three places with numbered metal disks that uniquely identified each piece. In 1994, we quantified the addition of new debris in all 60 study reaches by tagging, locating, and measuring new pieces meeting the size criteria. We also measured downstream movement (defined as a change of debris position of at least 5 m) of each previously tagged piece. In 1995, we quantified recruitment and movement of tagged pieces in 34 reaches.

To better understand how woody debris stability relates to woody debris dimensions, we classified pieces from the 1993 survey into five possible stability categories: greater in length than bankfull channel width, greater in length than one-half bankfull channel width, anchored or buried in the streambed, braced downstream by other wood pieces or other objects, and loose in the channel. These classes characterize stability of each piece in the channel, with pieces anchored or buried in the streambed presumed to be more stable than pieces loose in the channel. Fewer than 5% of the debris pieces occupied more than one class. If a debris piece was classified in more than one of these categories, we selected the dominant category for analysis. We assessed this classification scheme by comparing the percentage of pieces that moved in the second and third years of the study among the stability classes.

We also classified woody debris in sections surveyed in 1995 as either stable or nonstable on the basis of whether they moved over the 1994–1995 winter (a period with high stream flows). The nonstable category included pieces that were not found in the sections in 1995. We hypothesized that piece length would be the single descriptor most likely to relate to stability, with diameter of secondary importance. We used probit analysis (McCullagh and Nelder 1983), with stable and nonstable as a Bernoulli response variable, to relate piece dimensions to stability. We realized that the individual pieces in any one 100-m reach are not independent, an assumption of the probit analysis. To minimize the possible effects of the lack of independence, we decided to collapse data from the four streams (34 reaches) surveyed in 1995 into a single probit analysis.

Within each 100-m study reach, debris pieces were classified into one or several of the following geomorphic function classes: no function, dams water, causes plunge pool downstream, contributes to or causes some other type of pool, forms step, significantly deflects flow, armors bank, and stores sediment. These classes characterize potential effects of woody debris on fluvial processes. They are not ordered by importance. Several of the classes (e.g., dams water and contributes to pool formation) directly influence

Table 2. Volume and frequency of MW and LW debris per 100 m channel distance on reaches of six streams in the central Sierra Nevada in 1993.

	Volume (m^3)				Frequency			
	MW		LW		MW		LW	
Stream[a]	Mean	SE	Mean	SE	Mean	SE	Mean	SE
East Fork	2.49	0.60	18.5	6.4	25.7	5.9	6.6	1.6
Upper[b]	1.77	0.60	8.3	3.9	18.8	7.4	4.0	0.8
Lower[b]	3.13	1.02	28.6	10.9	32.6	8.8	9.2	2.8
Empire	3.92	0.95	13.9	2.8	33.5	5.4	6.5	2.1
Upper	4.92	1.63	16.1	5.2	37.4	10.1	8.8	3.8
Lower	2.93	0.94	11.8	2.6	29.6	4.9	4.2	1.4
Lavezolla	1.59	0.46	4.6	2.5	17.6	3.4	2.0	0.9
Upper	2.52	0.71	7.9	4.7	24.0	5.0	3.6	0.2
Lower	0.66	0.18	1.3	1.3	11.2	2.6	0.4	0.0
Badenaugh	3.03	0.63	1.7	1.0	30.7	3.1	0.7	0.3
Upper	4.07	1.00	1.4	1.0	35.6	3.5	1.0	0.6
Lower	1.99	0.51	1.9	1.8	25.8	4.5	0.4	0.2
Sagehen	2.39	0.39	3.7	1.5	17.1	2.8	2.2	0.6
Upper	1.85	0.58	1.7	0.6	14.4	3.3	1.6	0.7
Lower	2.93	0.46	5.8	2.8	19.8	4.5	2.8	1.0
Pauley	0.82	0.37	8.7	5.3	9.3	2.3	2.5	1.2
Upper	0.19	0.06	0.6	0.5	5.2	0.6	0.4	0.2
Lower	1.45	0.64	16.8	9.6	13.4	4.0	4.6	1.9

[a]Statistics in the top line for each stream are for all ten 100-m study reaches combined.
[b]Upper and lower each refer to five 100-m reaches. The lower five begin at the location on each channel where the upstream basin area is about 2500 ha. The upper five begin where the upstream basin area is about 830 h.

habitat of aquatic biota. Function under high flows likely to be important for habitat formation was considered.

Within each 100-m reach, up to five distinct deep- or slow-water habitat units (pools, runs, glides) were snorkeled after completion of the wood surveys. If more than five units were available, five were randomly selected for snorkeling. If fewer than five units were available, all available units were snorkeled. Unit selection was independent of presence or abundance of woody debris. Fish species, number, and 50-mm size class and the abundance and use by fish of 11 cover elements in each habitat unit were quantified. All snorkeling was conducted in summer, low-flow conditions. Visibility was excellent during the snorkel counts. We counted fish while slowly moving upstream in the selected habitat unit along the substrata and systematically searching for fish at all obstructions and undercut banks. Because snorkelers approached fish from downstream, the divers observed fish in the habitat unit without disturbing them. Fish were not "pushed" into the selected habitat unit by snorkelers nor were they disturbed or pushed into adjacent units.

Cover complexity elements were identified at water level by the snorkelers and were categorized in each unit by percent water surface coverage classes: none, 1–25, 26–50, and 50+. Cover complexity elements were none, undercut bank, MW, LW, boulders >0.30 m in diameter, bedrock ledges, water deeper than 0.30 m, deepest portion of the unit, white water (surface turbulence), aquatic vegetation, and terrestrial vegetation overhanging the water surface by 1 m or less.

We used the modified Tukey method for multiple pairwise comparisons (Kaselman and Rogan 1978) or *t*-tests (two-sample, nonpaired) to assess differences in woody debris frequency and volume among the study streams, between the upper and lower sections of individual streams, and among channel types. We used correlation techniques and a chi-square goodness-of-fit test to evaluate fish use of available cover elements. Descriptive statistics were used to quantify debris-associated habitat units, the geomorphic function of woody debris, and aspects of fish use of cover. We used *Z*-tests (Fleiss 1981), with Bonferroni's adjustment to the α level, to identify differences in proportions of new and mobile debris pieces among the six streams. We also used Kruskal–Wallace one-way nonparametric ANOVA (Mosteller and Rourke 1973) to compare the mean distances that debris pieces moved among the six streams between measurements in 1993 and 1994 and in 1994 and 1995.

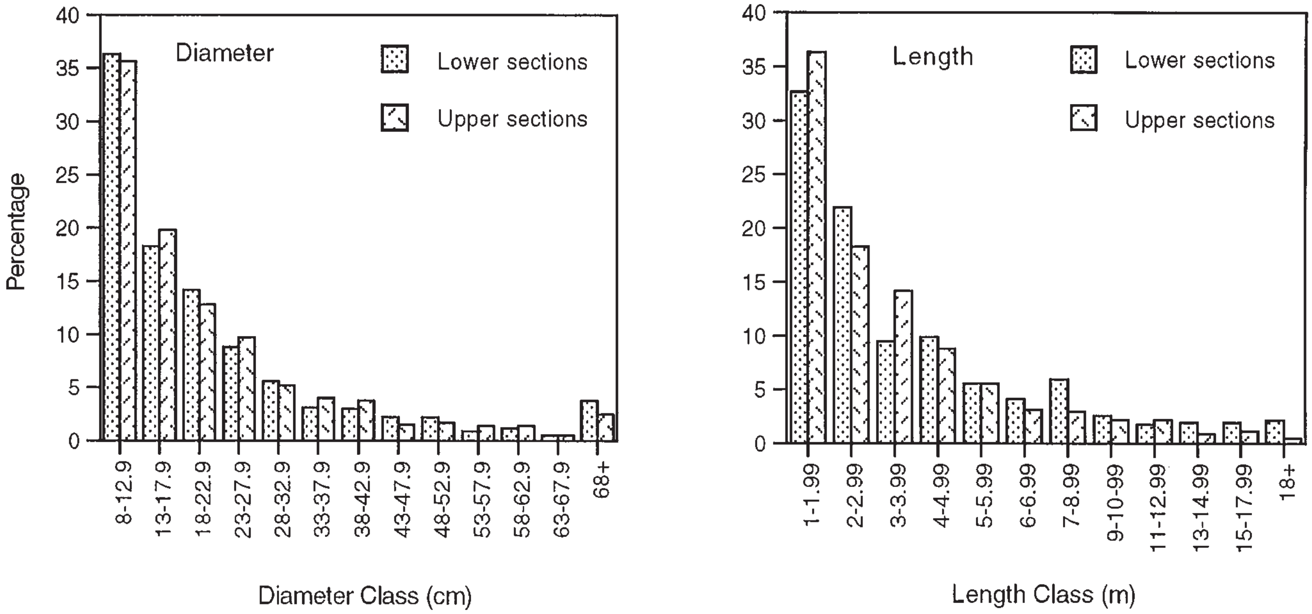
Results and discussion

Baseline conditions of woody debris frequency and volume

Over 1670 debris pieces were measured on the 6000 m of channel surveyed in 1993. The vast majority of all pieces appeared to result from natural recruitment; they were broken branches or logs without needles or bark. Fewer than 10 of the pieces had cut marks, and there was no evidence of accumulation of logging debris.

We anticipated differences in woody debris frequency and volume (*i*) between the upper and lower sections of individual streams and (*ii*) among stream reaches of different Rosgen channel type. We did not expect differences in woody debris amounts due to differences in land disturbance history because the existence of mature conifers lining the banks of the study reaches would buffer effects of logging (McGreer 1975). To assess these potential differences, we compared frequencies and volumes both among individual streams (all 10 reaches combined) and among streams grouped by Rosgen channel type and by position within each stream (upper versus lower sections).

Fig. 2. Frequency distributions of woody debris diameter and length, 1993 survey, upper and lower sections.



In 1993, the mean frequency of MW varied from 9.3 to 33.5 pieces/100 m among the study streams (Table 2). Variation in frequency within the streams was large enough so that few paired comparisons of frequency among individual streams were significant (two-tailed *t*-test with unequal variances, $\alpha = 0.05$). Of the 15 possible comparisons, three differed significantly. One of these was between two west-side streams (Pauley and Empire), one was between the two east-side streams (Badenaugh and Sagehen), and one was between Badenaugh (east side) and Pauley (west side). Although these differences may be due to location on the east versus west side of the range, an inadequate number of streams were surveyed to verify this hypothesis.

In 1993, the range in mean frequencies of LW among the study streams (0.7–6.6 pieces/100 m) was much less than the range of MW frequencies (Table 2). Similar to MW, few LW frequencies differed among individual streams ($\alpha = 0.05$). Of the two that did, both were between streams on the east and west slopes (Badenaugh and Empire and Badenaugh and East Fork). We postulate that the west slope basins are better stocked with larger trees than the east slope basins, and this is the cause of the difference in frequency.

Mean volumes of MW varied from 0.82 to 3.92 m^3/100 m channel distance (Table 2). The volumes did not differ significantly for any of the 15 pairwise comparisons among streams, again probably because of relatively large intra-stream variation. Volume of LW was much greater than volume of MW (Table 2), and the range in volumes was greater in both percentage and absolute magnitude for LW versus MW. Only one of the 15 possible comparisons (Badenaugh with Empire) of LW volumes among individual streams was significant ($\alpha = 0.003$).

Significant differences in LW volume and frequency among study reaches on Badenaugh and several of the other creeks may be due to the burning of the entire Badenaugh basin 35–40 years prior to the 1993 woody debris survey. Large logs may not have been available since the burn. Sagehen, the only other basin with known fire occurrence during the past 100 years, also has relatively low LW frequency and volume. A complicating factor in this linkage between fire and debris frequency and volume is the role of climate. The east-slope basins, Sagehen and Badenaugh, are located in the rain shadow of the Sierra Nevada and receive less precipitation than west-slope sites at similar elevations. Tree densities are lower on the eastern slope than on the west slope, and consequently the frequency of woody debris in stream channels on the east slope may be less than frequencies on the western slope.

Upper and lower sections

As anticipated, the upper sections of the study streams were significantly narrower and one half of the upper sections had significantly greater channel gradients than the lower sections (Table 1). Neither MW nor LW frequency or volume differed ($\alpha = 0.05$) between the upper and lower sections of any stream (Table 2). And frequency distributions of debris length and diameter were similar in the upper and lower sections (Fig. 2). These findings parallel those of Bisson et al. (1987) and Robison and Beschta (1990) who found debris to be randomly distributed in first- to third-order streams. There are several potential reasons for the lack of frequency and volume differences between upper and lower sections of each stream. It was not possible to differentiate between woody debris sources, and transport may not have been the dominant cause of debris distribution; many of the pieces may have originated from nearby banks. The lower sections may still be too small to redistribute LW, and the LW was therefore randomly located where it entered the channel. This is the case in some first- and second-order streams in the Pacific Northwest (Keller and Swanson 1979). The upper sections may have been large or steep enough to transport MW in a manner similar to the lower sections, so that differences in volume or frequency would not be apparent. Differences in the frequency and size of stream-side source tree stems could differ between the upper and lower sections. These differences could “cancel” the effects of channel size and carrying capacity that would otherwise result in differences in volume and frequency of woody debris between the upper and lower sections. Alternatively, the inherent variability in woody debris frequency and volume on the basin scale in the study streams could be greater than differences imposed by channel size.

Woody debris frequency and volume differences by stream type

Because the Rosgen stream channel classification is based largely on channel entrenchment, gradient, and bankfull width-to-depth ratio, elements potentially controlling debris dynamics, we anticipated differences in debris frequency and volume by Rosgen stream channel type.

Many headwater streams in the Sierra Nevada have steep, bedrock-controlled channels that are typically Rosgen type A or B, or C in their less-steep sections. Type A have slopes between 4 and 9.9% and bankfull width/depth ratios <12. Their channels are entrenched, and they are characterized as cascading, step–pool streams with high energy/debris transport. Type B are gentler in slope (2–3.9%) and have width/depth ratios >12 and entrenchment ratios between 1.4 and 2.2. They are described as moderately entrenched, with riffle-dominated channels and infrequently spaced pools. Type C are low gradient (<2% slope) with width/depth ratios >12 and entrenchment ratios >2.2. They are typically alluvial channels with well-defined flood plains and riffle–pool bed morphology (Rosgen 1994).

The primary (A, B, C) stream types are subdivided by dominant bed material in a six-class, second-level categorization ranging from bedrock (A1, B1 or C1) through boulder, cobble, gravel, sand, and silt–clay (A6, B6, or C6). Several factors complicate differential loading of debris by Rosgen stream type. Narrow channels, most commonly found in type A streams, could wedge long pieces of debris, and larger substrates could catch and stabilize larger pieces. Frequency and volume of debris are also a function of rate of recruitment from the stream bank, which itself depends on the balance of inputs from catastrophic events like mass movements, debris torrents, and blowdowns and potentially steadier inputs like bank collapse and riparian tree mortality. Stream type may have little effect on these recruitment factors.

We looked for differences in woody debris volume and frequency by comparing among individual level II stream types (e.g., A1, B4) and aggregated level I types (e.g., A, B, C). Of the 60 study reaches, 25 were type A, 33 were type B, and two were type C. One reach was classified as B6; the others had coarser bed material and were classified as A1–A4, B1–B4, or C1–C4. Because of the small number of type C reaches, these reaches were not included in the statistical analyses.

Of the four possible level I comparisons (volume and frequency of MW and LW), none differed (two-tailed *t*-test, unequal variance, $\alpha = 0.05$) between types A and B. Similarly, none of the 28 possible level II paired stream type comparisons differed significantly for either volume or frequency of LW. Two comparisons (between types B3 and B2 and between types B3 and A1) were significant for frequency of MW. Three comparisons (also between types B3 and B2 and between types B3 and A1 and between types B3 and B1) were significant for volume of MW. Although these results suggest that in the moderate gradient B stream types, bed material differences in the boulder to gravel size ranges may influence the volume and frequency of MW; overall, Rosgen channel type does not appear to be a primary controlling factor in woody debris volume or frequency in the study streams.

Influences of woody debris on fish habitat and fish use of woody debris as cover

A measure of the role of woody debris in aquatic habitats is the relative frequency of wood-associated habitat units. Of the 23 habitat types in the USDA Forest Service's standard stream survey procedure for the Pacific Southwest Region (USDA Forest Service 1992), four types refer specifically to large woody debris or rootwads: (*i*) backwater pool associated with rootwad, (*ii*) backwater pool associated with large woody debris, (*iii*) lateral scour pool associated with large woody debris, and (*iv*) lateral scour pool associated with rootwad. These are not the only habitats associated with debris. Dammed pools and plunge pools, two habitat types often dominant pool types in headwater mountain streams, are addressed in the section on geomorphic functions.

Of the 6000 m surveyed, 20% was classified in these four wood-associated habitat types. Two of the west-slope streams (Lavezolla and Pauley) had almost 35% of the lineal distance in the study reaches in these wood-associated habitats in contrast with <3% for the east-slope study reaches (Sagehen and Badenaugh). These major differences may be due to the east-side pine forest type that results in lower volumes of LW in the two east-side streams (Table 2) and to differences in clast size and channel morphology. The percentages are conservative in that plunge and dammed pools formed by woody debris were not quantified.

Wood debris in forested streams is one of the most important components of fish habitat (MacDonald et al. 1991; Meehan 1991; Reeves et al. 1993). Fish use their environment as a three-dimensional space; therefore, we expected that the arrangement and abundance of wood would affect the potential use of the habitat. Early investigations of fish habitat in streams identified wood debris as a major source of cover (Boussu 1954; Hunt 1971; Triska and Cromack 1980). Angermier and Karr (1984) found fish and benthic invertebrates to be more abundant in experimental stream reaches with wood debris than in cleared reaches. At two sites in the Oregon Coast Range, Baker (1979) found that fish biomass was significantly higher behind debris dams than in either upstream or downstream areas without debris dams. Although structurally, wood may stay the same in a stream throughout a given year, its function as fish habitat changes from season to season as stream flows and stream dynamics change. In addition, the role that wood plays in relation to a fish changes as the life stage of the fish evolves. For example, a young fish might use slower flows behind wood-formed habitat to conserve energy. Abundance of juvenile salmonids in a stream has been directly correlated with the amount of large wood debris (Murphy et al. 1986; Bisson et al. 1987). Adult salmonids use the large pools often formed by large wood debris for resting cover and the gravel retained by wood for spawning (Bisson et al. 1987; Murphy and Koski 1989).

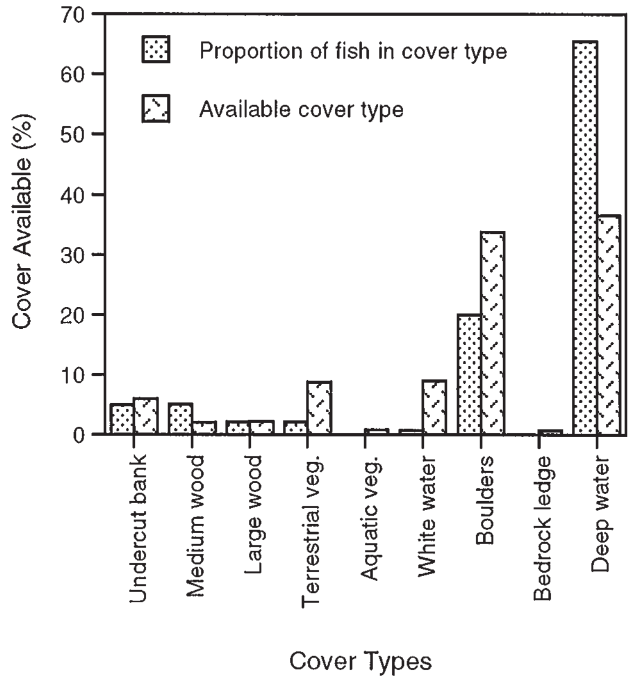
We expected wood-related habitats to be of higher quality to fish than non-wood-related habitat because of cover and habitat complexity provided by wood. Therefore, we expected a greater number of fish to use wood-related habitats. Because wood-associated habitat types were relatively common, we expected fish to use woody debris routinely. A total of 235 deep- or slow-water habitat units (pool, run, or glide) were sampled in the study reaches in 1994. Over 1760 trout were observed (1428 rainbow (*Oncorhynchus mykiss*), 151 brown (*Salmo trutta*), and 187 brook (*Salvelinus fontinalis*)). Although rainbow, brown, and brook trout compete with each other (Fausch and White 1981; Cunjak and Green 1984) and may use different habitats and food resources during their life cycles (Moyle 1976), we hypothesized that all trout would prefer habitats with woody debris. Woody debris provides cover from predators which is a habitat condition favored by all of these species of trout (Butler and Hawthorne 1968; Lewis 1969). Other habitat factors such as food abundance (Wilzbach 1985) and water depth (Gibson and Power 1975) can also influence habitat use by trout. For this study, we chose to pool trout species for analysis of habitat selection in relation to presence of woody debris. We assessed habitat selection by trout in 1994 by (*i*) correlating trout frequency with habitat unit depth, volume, and cover type and (*ii*) determining if trout used wood-related cover types in a greater proportion than those types existed in the units.

We anticipated that large, deep units with complex cover would be preferred by trout. Habitat unit volume and maximum unit depth correlated positively with number of trout, with 0.55 and 0.36 coefficient values. Although these correlation coefficients are not particularly high, they support our initial expectation. To further explore these relationships, a chi-square test was used to determine if trout used habitat cover in the same proportion as it existed or if trout showed a preference for one or more cover types. The test rejected the null hypothesis that fish were observed in cover types at the same frequency at which the types existed. Large portions of the chi-square value were attributed to the deep-water (>0.3 m) cover type. Boulder cover also added a large portion to the overall chi-square value. Deep water was the most commonly available cover type (Fig. 3), and trout used deep water much more than any other type available. From this analysis, it appears that trout tended to locate by habitat volume and (or) depth and that presence or absence of woody debris was not a primary factor in habitat selection.

Mean volumes of the snorkeled units were greater in the lower study sections. Greater numbers of trout in all size classes were observed in lower stream sections (1344 fish) than in upper sections (422 fish), and the frequency of fish in the units was positively correlated (0.71) with unit volume. These findings support the expectation that larger, deeper habitats occur in the lower stream sections that would be associated with greater numbers of trout.

Of the cover types identified (undercut bank, MW, LW, terrestrial vegetation, aquatic vegetation, white water, boulders, bedrock ledges, deep water), boulders and deep water were the most frequently observed; these two cover types accounted for almost 80% of the available cover (Fig. 3). MW and LW were not prevalent cover types in the stream reaches studied. However, when fish were observed in slow-water habitats with cover, the percentage of trout that used MW (5%) was over twice the percentage of MW cover available (2%) (Fig. 3). This was the greatest use-to-availability ratio of any cover type. Except for deep water, all other cover types were used less than their relative availability, suggesting that when available, MW was an important source of cover for trout. Relative to MW, LW was not a favored cover type; 68 trout used habitats with MW whereas 29 trout used habitats with LW. Relative use by trout of MW versus LW as cover may be due to the higher cover complexity often associated with MW versus LW or the position and quality of the cover.

Fig. 3. Fish use and available cover on reaches of six streams in the central Sierra Nevada, 1994.

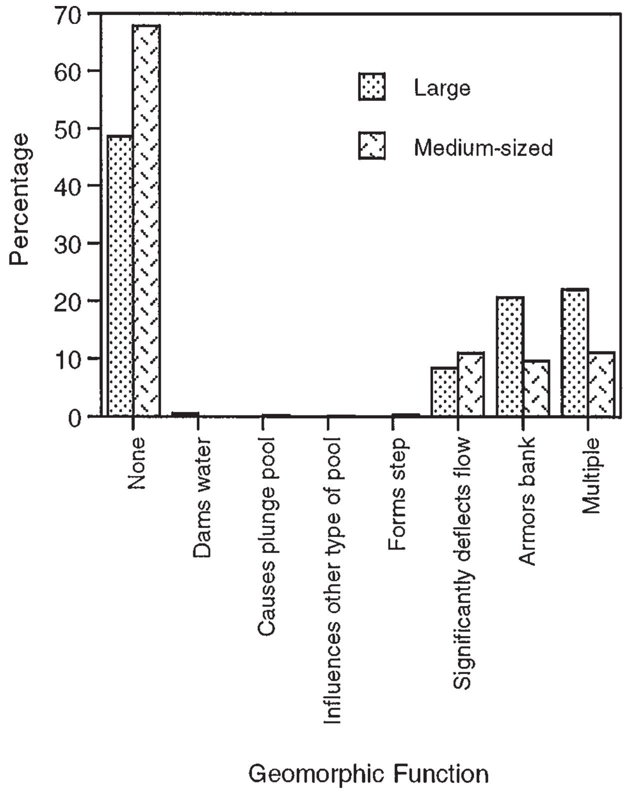


We expected woody debris to be a significant cover source for trout because the structural diversity associated with debris offers habitat complexity typically seen as beneficial to fish (Bisson et al. 1982; McMahon and Hartman 1989). Debris jams often create slower water which allows for diversity in feeding behaviors (McGreer and Andrus 1992). Because trout are visual feeders and often seek habitats with cover for resting and predator avoidance near feed sites in swift water, we expected that trout would select habitats with debris because debris adds to habitat complexity, cover from predators, and potential wood-related food resources such as aquatic insects. If we believe that high relative use indicates the importance of MW functions, then in the study reaches, MW was an important functional component for trout.

Geomorphic function

Contrary to findings from headwater streams in northern Colorado (Richmond and Fausch 1995), almost none of the debris pieces dammed flow, formed steps, or affected pool formation (Fig. 4). These results suggest that woody debris in the study reaches does not perform some of the functions

Fig. 4. Geomorphic function of LW and MW debris on reaches of six streams in the central Sierra Nevada, 1994.



of woody debris common elsewhere, like dissipating energy between wood-formed steps, which can reduce energy available for erosion of banks and the substrate (Heede 1972, 1985). Steps in the high-gradient Sierra Nevada headwater reaches are more likely controlled by boulders and geologic factors.

Over one-half of the MW and LW pieces in the study reaches were classified as having no geomorphic function. More of the MW pieces were in this category than the LW pieces (Fig. 4). Over 20% of the LW nevertheless was classified as armoring channel banks. These pieces may hold gravels, soil, and fine sediment in place on the bank and thereby reduce bank erosion. In combination with the observance that wood-associated habitat units formed up to 35% of all units on some streams, these findings suggest that woody debris plays a relatively small but potentially important role in the fluvial geomorphology of some of the stream reaches studied, and match similar results from a study of other streams on the west slope of the central Sierra Nevada (Ruediger and Ward 1996). Also, because sediment budget information is not available for the study basins, the magnitude of non-wood-associated geomorphic activity is unknown, and therefore the relative geomorphic importance of debris cannot be quantified. The little available information suggests that because of relatively low natural surface erosion rates in the Sierra Nevada, the channel itself is an obvious candidate as a source of most in-channel sediment (King 1993).

The limited role of woody debris in pool formation in the study reaches may also relate to geologic factors as the primary controllers of pool formation in the study reaches. Elsewhere (e.g., New Zealand (Evans et al. 1993), Oregon (Long 1987)), woody debris size has been related to pool formation, but at differing magnitudes depending on substrate size and channel gradient. Pools in lower gradient channel reaches, uncommon in our study, had greater volumes for a given level of woody debris than higher gradient reaches in northeastern Oregon streams (Carlson et al. 1990). Some New Zealand streams, however, are similar to the Sierra Nevada study reaches, with geomorphic factors overriding the control of pool formation by woody debris (Evans et al. 1993).

Woody debris movement

Few pieces of either MW or LW moved between the 1993 and 1994 surveys. Eleven of 1348 MW pieces (0.8%) moved on the six streams. The volume of these pieces, 1 m^3, was 0.2% of the total wood volume. On two of the six streams, no movement was observed, and one or two pieces moved on two other streams (Table 3). None of 206 LW pieces moved. We knew of no reasons to expect different mobility rates among the study reaches on the six streams, and no significant differences in the proportion of mobile pieces among the six streams were identified (*Z*-test (Fleiss 1981), $\alpha = 0.003$). These calculations do not include four pieces (0.2 m^3 in total volume) tagged in 1993 but not found in 1994. Those pieces could have been missed in the 1994 survey, or they may have moved downstream beyond the survey areas.

Movement was much greater over the 1994–1995 winter; about 10% of the pieces moved and were relocated in 1995. These pieces constituted 8% of the original 1993 volume (Table 3). Eleven LW pieces moved on the 3400 m surveyed in 1995; these pieces accounted for the majority of the volume of wood that moved between the 1994 and 1995 surveys. Another 297 pieces were not found in 1995. Assuming that these pieces had moved out of the study area, 31% of the pieces tagged in 1994 had moved on the sections surveyed in 1995.

Mean distance moved by debris pieces between surveys in 1993 and 1994 varied from 0 m (on the two east-side streams) to 104 m on Lavezolla Creek (Table 3). There were no differences (Kruskal–Wallace ANOVA, $\alpha = 0.008$) in the mean distances moved among the four west-side streams. Movement distances were significantly greater over the 1994–1995 winter than over the previous winter and ranged from 70 to 361 m as the mean for the reaches surveyed in 1995 (Table 3). Differences in mean distance moved were not significant among the west-side stream reaches (Empire and East Fork), but these two had significantly greater mean distance of movement than Sagehen.

Movement rates calculated for 1994–1995 approximate rates from other studies. In a comparison of woody debris dynamics between burned and unburned channels in Wyoming, 18% of tagged pieces moved over one year in the unburned channel (compared with 58% in the burned channel) (Young 1994). In lower gradient (0.5–2%) channels in smaller (340–1240 ha) basins in northwest Washington, the mean annual mobility rate was 18% (Grette 1985). In an even lower gradient (0.02%) stream system in the southeastern United States, 17% of the debris pieces were mobile

Table 3. Volume, number, and percentage of MW and LW debris pieces that moved between surveys in 1993, 1994, and 1995.

Stream	Volume (m^3/100 m)		Number/100 m		% of 1993 total number		% of total volume		Mean distance moved (m)	
	1993–1994	1994–1995	1993–1994	1994–1995	1993–1994	1994–1995	1993–1994	1994–1995	1993–1994	1994–1995
East Fork[a]	0.08	0.432	0.60	3.30	1.86	11.79	0.38	3.06	55	179
Empire	0.006	0.518	0.10	4.00	0.25	10.05	0.03	2.90	16	213
Lavezolla	0.012	—[b]	0.30	—	1.53	—	0.06	—	60	—
Badenaugh	0	—	0.00	—	0.00	—	0.00	—	0	—
Sagehen	0	0.503	0.00	2.40	0.00	11.82	0.00	8.07	0	70
Pauley[c]	0.007	0.058	0.10	0.30	0.85	3.37	0.07	0.64	104	361

Note: Ten 100-m reaches were surveyed each year on each stream except as noted below.
[a]Ten 100-m reaches surveyed in 1993 and 1994 and nine in 1995.
[b]Not surveyed in 1995.
[c]Ten 100-m reaches surveyed in 1993 and 1994 and five in 1995.

(Benke and Wallace 1990). During a 7- to 9-year period, woody debris movement varied from 10 to >50% annually in five streams in the Pacific Northwest (Lienkaemper and Swanson 1987). Although these comparisons provide valuable order-of-magnitude information, they are not strictly comparable because the minimum size of the pieces tagged varies between the studies and stream-flow magnitudes affecting the woody debris are not standardized.

Because only 2 years of movement data are available, the representativeness of the rates of movement for our study reaches is incompletely known. Nevertheless, the movement rates can be addressed in reference to factors affecting movement, including fragmentation, biological breakdown (Evans et al. 1993), the spacing of channel roughness elements (e.g., boulders, large log jams), and stream-flow magnitude (Young 1994). Stream flow is probably the single best proxy for movement. Factors securing woody debris to the channel (e.g., woody debris embeddedness) and factors increasing the number of debris pieces (e.g., breakage of in-channel woody debris) are important, but secondary.

The 1993–1994 movement rates may be lower than average because of low stream discharge during the winter–spring of 1993–1994. Two stream gaging stations, on Sagehen Creek and the South Yuba River near Cisco, have long-term records and are close to the study reaches (no other records of long-term flows unimpeded by dams or unaffected by diversions exist for the study area). At the gaging locations, Sagehen Creek drains a 2718-ha basin and the South Yuba River a larger area (13 416 ha). Instantaneous maximum and daily maximum flows are the best available flow indices relevant to woody debris movement. At both stations, flows in water year 1994 (1 October 1993 to 30 September 1994) were much lower than the long-term means (50-year record on South Yuba and 41-year record on Sagehen). The daily maximum and instantaneous maximum flows were in the second and 10th percentiles of all flows of record at Sagehen and South Yuba gaging stations (e.g., 40 of the 41 years of record at the Sagehen gage had *greater* flows than the 1994 daily or instantaneous maximum flows). Flows during 1993 were above average and may have moved pieces that might otherwise have moved in 1994. In this sense, the 1993 flows could have “reset the clock” for moveable wood.

Flows throughout the Sierra Nevada were high in spring 1995. Unfortunately, flow gaging was terminated at the South Yuba River site in 1994, and data are not available from this station for winter 1994–1995 woody debris movement. Both the daily maximum and instantaneous maximum flows at the Sagehen gage in 1994–1995 were over 10-fold greater than the analogous 1993–1994 flows, and the 1994–1995 flows were in the 85th and 71st percentiles of all daily and instantaneous maximum flows recorded at Sagehen. The 1993–1994 and 1994–1995 flows represent near-extremes in flow on Sagehen Creek, and as such, movement rates may also represent near-extremes to the extent that stream discharge is a significant control of woody debris movement.

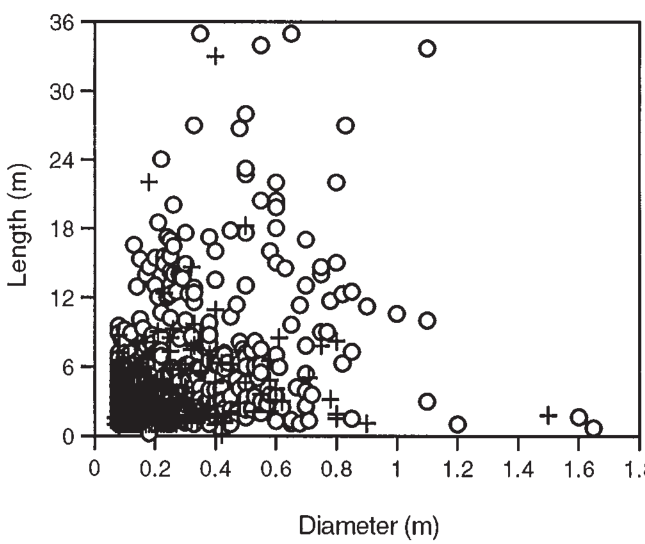
Stability

The stability class with the greatest frequency of woody debris in 1993 was “anchored or buried in streambed” (Table 4). Over 75% of the 200 LW pieces categorized were in

Table 4. Stability of LW and MW debris on ten 100-m reaches in six streams in the central Sierra Nevada, 1994, and percentage of pieces moved or missing between summer 1994 and 1995 woody debris surveys.

	Anchored or buried	Longer than bankfull width	Greater than one-half bankfull width and less than or equal to bankfull width	Braced downstream	Loose in channel	Multiple	Total
LW debris							
East Fork	45	8	10	2	0	0	65
Sagehen	20	2	0	0	0	0	22
Badenaugh	7	2	0	0	0	0	9
Empire	56	4	2	1	0	2	65
Pauley	11	6	3	0	0	0	20
Lavezolla	12	2	4	1	0	0	19
Total	151	24	9	4	0	2	200
%	75.5	12	9.5	2	0	1	100
MW debris							
East Fork	39	12	75	80	75	0	262
Sagehen	95	17	31	19	51	12	186
Badenaugh	137	126	42	4	6	1	311
Empire	60	36	75	89	1	18	351
Pauley	15	3	16	46	10	6	96
Lavezolla	21	8	31	50	53	16	179
Total	367	231	270	288	194	53	1385
%	26.5	15.4	19.5	20.8	14.0	3.8	100
% LW and MW moved or missing							
1994–1995	19	36	49	52	72		

Fig. 5. Scatterplot of lengths and diameters of debris pieces that were stationary (○) or moved (or were not found) (+) between surveys in 1994 and 1995.



this class, as were 26% of the 1385 MW pieces classified. Less than 5% of the LW was classified in the less stable categories ("piece braced downstream by other pieces or other causes" and "piece loose in channel"), although over 35% of the MW was in these classes. As expected, these results suggest that LW, because of its greater length, was more stable than MW, and greater year-to-year movement of MW would be anticipated.

"Stability" of woody debris is related to several variables, with stream-flow magnitude probably a major determinant of stability; as flow magnitudes increase, fewer pieces remain in place. Pieces may remain stationary for years under low-flow conditions, but become mobilized under less-frequent, high-magnitude flow events. Stream flow during the 1993–1994 winter and spring seasons was very low, and most debris pieces did not move. Stream flow during the 1994–1995 season, however, was much higher, and the percentage of pieces that moved increased progressively as the stability class changed from most stable (anchored/buried) to least stable (loose in channel) (Table 4). Although some of the anchored or buried pieces moved under the high, infrequent flows of the 1994–1995 winter, the stability classification appears to provide a useful relative assessment of woody debris stability in the study reaches.

In the 1995 survey, 389 debris pieces moved (or were not found). The pieces that did not move were usually larger than those that moved or were not found (Fig. 5). Ninety percent of these "mobile" pieces had diameters ≤ 0.32 m and lengths ≤ 4.9 m, compared with diameters ≤ 0.55 m and lengths ≤ 12.5 for 90% of the pieces that had not moved.

Pieces that had moved (or were not found) between the 1994 and 1995 surveys were considered nonstable; all other pieces were stable. Initial probit analysis calculations to relate piece length and diameter to stability revealed a large number of outlying points that might bias the analysis. We applied a logarithmic transformation to stabilize the variance and deleted 12 points that were still outliers. These were all very large pieces of wood that would obviously be stable in our systems. A probit model with coefficients for intercept,

Fig. 6. Probability of debris stability as a function of piece length for two diameters.

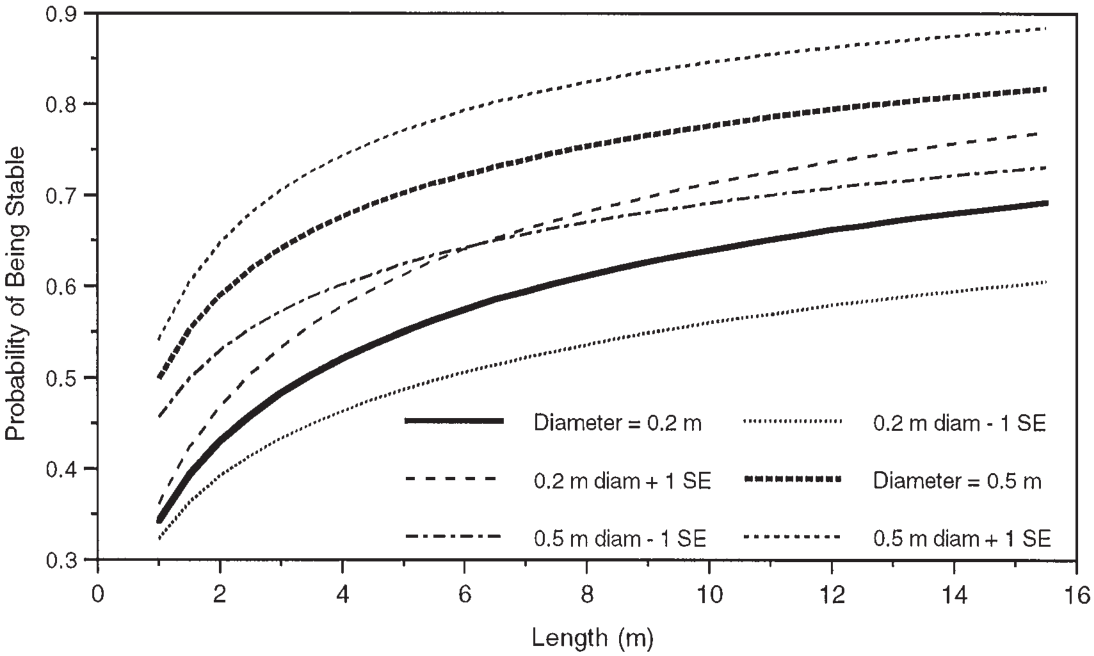


Table 5. Volume, number, and percentage of MW and LW debris pieces that were new in 1994 and 1995.

	Volume (m^3/100 m)		Number/100 m		% of 1993 total number		% of 1993 total volume	
Stream	1994	1995	1994	1995	1994	1995	1994	1995
East Fork[a]	0.05	1.04	0.60	7.22	1.86	23.21	0.21	6.62
Empire	0.28	0.37	1.90	2.90	4.77	7.29	1.54	2.08
Lavezolla	0.07	—[b]	0.20	—	1.02	—	1.13	—
Badenaugh	0.02	—	0.10	—	0.32	—	0.43	—
Sagehen	0.34	1.19	0.50	6.50	2.46	32.02	5.50	19.03
Pauley[c]	0.00	0.11	0.20	3.00	1.69	16.85	0.03	1.20

Note: Ten 100-m reaches were surveyed in 1993, 1994, and 1995 except as noted below.
[a]Ten 100-m reaches surveyed in 1993 and 1994 and nine in 1995.
[b]Not surveyed in 1995.
[c]Ten 100-m reaches surveyed in 1993 and 1994 and five in 1995.

log of length, and log of volume passed both lack-of-fit tests (Pearson and log-likelihood ratio chi-square tests, SAS Institute Inc. 1989). The error estimates in Fig. 6 are conservative approximations in that they incorporate ±1 SE for each parameter in the probit model. For example, debris pieces 0.2 m in diameter would need to be at least 9 m long to have a 70% likelihood of being stable. Similarly, pieces 0.5 m in diameter would need to be at least 1.5 m long to have a 60% chance of being stable.

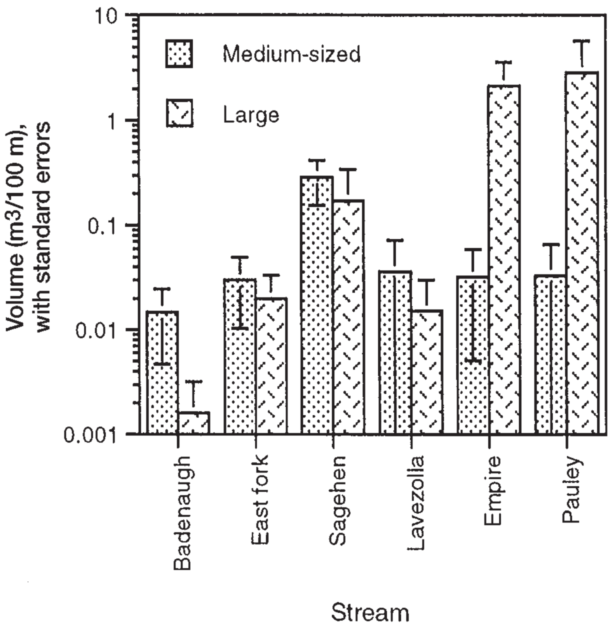
New woody debris

Three sources of "new" woody debris in a channel reach are (*i*) movement of debris into the reach from upstream, (*ii*) stems or branches entering from the banks or hillslope within the reach (and not moving out of the reach), and (*iii*) breakage of pieces previously within the reach. Except for episodic events like mass movement, fire, and blowdowns, which could deposit numerous pieces of debris into a channel, stream discharge is probably the single best predictor of new woody debris. Higher discharges will move pieces into the study reach and may also degrade or undercut banks to hasten inputs of woody material from the banks.

Thirty-four pieces of debris, representing 2.2% of the 1993 tagged total, that had not been tagged in 1993 were found on the study reaches in 1994. These new pieces had a total volume of 4.5 m^3, or 0.7% of the total from 1993 (Table 5). None of these pieces were LW. Over one half of these pieces were on Empire Creek. We knew of no reasons to expect different rates of recruitment of new pieces among the study reaches on the six streams, and no significant differences in the proportion of new pieces among the six streams were identified (*Z*-test (Fleiss 1981), $\alpha = 0.003$).

As with woody debris movement, many more new pieces were identified during the 1995 surveys than during the prior year (Table 5). Almost 190 new pieces were tagged and measured in 1995 on the 3400 m of stream surveyed (versus 34 pieces on the 6000 m surveyed in 1994). New pieces were found on all streams surveyed, with a range of frequency between 2.9 and 7.2 pieces/100 m channel distance (Table 5). The volume of new pieces was over 10

Fig. 7. Volume of sediment trapped by woody debris on sixty 100-m reaches of six streams in the central Sierra Nevada, 1994.



times greater on Sagehen and East Fork creeks in 1995 than in 1994. Contrary to 1994, new pieces were least frequent on Empire Creek. Large woody debris accounted for 8% of the number of the 1995 new pieces, but over 40% of the volume of the new pieces.

Again, without comparative data from other years or localities, the representativeness of these values or of the lack of differences among streams is not known. Stream flow may be less relevant to the generation of new woody debris than to debris movement. High flows could increase breakage of wood already in the channel and potentially entrain pieces that are located slightly above the bankfull position, but in an area like the central Sierra Nevada with little evidence for extensive mass movements directly into the channel, terrestrial processes like blowdowns and mortality resulting from pest infestation or disease may be the major causes of recruitment of wood into the channels.

Storage of inorganic sediment by woody debris

Woody debris did not store appreciable amounts of inorganic sediment in the study reaches in 1994. In total, 46 debris pieces "trapped" measurable inorganic material occupying 56 m^3 in the 6000 m surveyed. Eighty-eight percent of the debris-associated sediment volume accumulated behind five pieces of LW on two streams, suggesting that MW specifically was not an effective trapping agent of inorganic material on the study reaches. The 46 pieces were a small percentage (2.7) of the pieces surveyed. Accumulation of inorganic material associated with MW was relatively low and varied over one order of magnitude (0.02–0.3 m^3/100 m channel length) among study reaches (Fig. 7). Sediment associated with LW was more variable, but still low compared with third- and fourth-order streams studied in Oregon (20.1 m^3 stored in one 100-m reach on the H.J. Andrews Experimental Forest (Swanson and Lienkaemper 1978) and >500 m^3/100 m in the Willamette National Forest (Nakamura and Swanson 1993)) and Idaho where woody debris associated sediment accumulation is a major component of in-channel sediment storage (Megahan 1982). The low accumulation in our study reaches may be due to the relatively high channel gradients and the consequent inefficiency of woody debris in the study reaches to slow water velocity enough for inorganic material to be deposited. Alternatively, the study streams could be "sediment limited" and have minimal inorganic material available for movement and deposition. To better understand the role of woody debris in sediment storage in the study streams, data on other sediment storage components are required, along with information on rates of sediment movement through the channels.

This study provides information on woody debris dynamics from locations in the central Sierra Nevada, a major region for which little published data on debris processes are otherwise available. Contrary to many other studies on woody debris elsewhere, we found that debris plays a relatively minor role in providing cover for trout, in pool formation, or in storing sediment in the headwaters stream systems we investigated.

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