Colorado

THESIS

CHARACTERISTICS AND FUNCTION OF LARGE WOODY DEBRIS IN MOUNTAIN STREAMS OF NORTHERN COLORADO

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ABSTRACT OF THESIS

CHARACTERISTICS AND FUNCTION OF LARGE WOODY DEBRIS IN MOUNTAIN STREAMS OF NORTHERN COLORADO

Large woody debris (LWD) has been well studied in the Pacific Northwest, but little is known of its role in Rocky Mountain streams. Large woody debris was measured in 11 north central Colorado streams associated with old-growth Engelmann spruce (Picea engelmannii)-subalpine fir (Abies lasiocarpa) forests to assess natural LWD abundance, characteristics, and function in undisturbed systems. Woody debris pieces were smaller in Colorado streams than in the Pacific Northwest and bankfull biomass was substantially lower, but debris abundance was similar. Eighty-one percent of the pools were formed by LWD, although only 4-20% of the woody debris present in the 11 stream reaches functioned to create pools. Pool frequency increased with increasing LWD abundance across streams. Of the pools measured, plunge pools were most prevalent (59%), followed by dammed pools (23%), scour pools (16%), and trench pools (3%). Pool-forming LWD pieces were, on average, significantly larger than other pieces, and most lay perpendicular to flow and spanned the bankfull channel. Pool surface area and residual depth were related more to stream size than to size of the LWD piece forming the pool. Most LWD pieces were old and decayed. However, pieces that formed pools represented all decay classes, indicating that younger pieces also formed pools.

Characteristics and function of large woody debris were related to stream size and gradient. Woody debris piece abundance increased with increasing stream size, although proportionately fewer of these pieces formed pools. The percentage of pieces that spanned the channel decreased in larger streams, as did the percentage of pieces that lay perpendicular to stream flow. Smaller streams, and those with lower gradients, had a higher *percentage* of pieces functioning as overhead cover for fish than larger and higher-gradient streams. Despite this, large woody debris provided a higher total *amount* of overhead cover in larger low-gradient streams that had more LWD. In larger streams more LWD was located at the margins of the bankfull channel, above the wetted channel, than in small streams. Moreover, clumps of LWD were always more frequent and larger than expected by chance in larger streams. These patterns indicated that flows in larger streams were capable of redistributing wood along the channel. The four disturbed streams used for comparison had less LWD and significantly smaller LWD than the old-growth streams, but had a similar frequency of pools. Information gained from this research can be used by fishery managers in the Rocky Mountain region to simulate LWD abundance, position, and orientation when rehabilitating or enhancing stream habitat, and to concentrate their efforts in streams where success is most likely.

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Table of Contents

	Page
List of Tables	viii
List of Figures	x
Introduction	1
Study Area	2
Methods	4
Characteristics of Valleys and Stream Channels	4
Salmonid Habitat	5
Large Woody Debris	6
Statistical Analysis	9
Results	11
Large Woody Debris	10
Large Woody Debris Pieces that Formed Pools	13
Agents Forming Pools	14
Relationships Across Streams and Among Pools	15
Large Woody Debris	15
Characteristics of Pools and Channels	16
Cover	18
Distribution of Large Woody Debris	19

Discussion 21

Large Woody Debris 21

Characteristics of LWD Across Streams 24

Large Woody Debris and Fish Habitat 26

Disturbed Streams 31

Literature Cited 33

Management Applications 53

Introduction 53

Implications for Rehabilitating and Enhancing Stream Habitat 53

Predictive Regressions 59

Recruitment from the Riparian Forest 62

Important LWD Characteristics to Measure in Stream Inventories 64

List of Tables

Page

Table 1. Characteristics of study reaches and pool habitat in 11 old-growth and 4 disturbed streams in north central Colorado where large woody debris was measured. 39

Table 2. Characteristics of large woody debris measured in study reaches of 11 old-growth and 4 disturbed streams in north central Colorado. 40

Appendix Table 1. Characteristics of study reaches in 11 old-growth and 4 disturbed streams in north central Colorado where large woody debris was measured. 70

Appendix Table 2. Primary and ancillary old-growth characteristics developed by the U. S. Forest Service for Arapaho and Roosevelt National Forests (Lowry 1992). 71

Appendix Table 3. Modified Wentworth substrate size classification (after Orth 1983). 72

Appendix Table 4. Influence zones for large woody debris (from Robison and Beschta 1990a). 73

Appendix Table 5. Decay classes for large woody debris. 74

Appendix Table 6. Stream and habitat characteristics measured in 11 old-growth and 4 disturbed streams in north central Colorado. 75

Appendix Table 7. Characteristics of large woody debris measured in study reaches of 11 old-growth and 4 disturbed streams in north central Colorado. 76

Appendix Table 8. Position, function, and relative age by percentage of large woody debris pieces in study reaches of 11 old-growth and 4 disturbed streams in north central Colorado. 77

Appendix Table 9. Ranges in characteristics of 11 old-growth streams measured. 78

Appendix Table 10. Parameters for models that predict stream and LWD characteristics. 79

List of Figures

Page

Figure 1. Locations of 11 old-growth and 4 disturbed streams measured. 42

Figure 2. Distribution of diameter and length of large woody debris pieces in Bowen Gulch and Baker Gulch, which are representative of the 11 old-growth streams measured. 44

Figure 3. Comparison of large woody debris abundance (pieces per 100 m) and volume (m^3/100 m) for the 11 old-growth streams in Colorado, a relatively undisturbed stream section in British Columbia, and 5 undisturbed streams in Alaska. 46

Figure 4. Distribution of pool-forming large woody debris and all other large woody debris pieces by position and orientation for 11 old-growth streams. 48

Figure 5. Percentages of pools formed by large woody debris or other agents (i.e., boulder, meander bend), and of pools by types in 11 old-growth streams and 4 disturbed streams in Colorado. 50

Figure 6. Distribution of distances of large woody debris pieces along study reaches in the tributary of North Fork Joe Wright Creek, which is representative of small streams, and Arapaho Creek, where large woody debris is clumped, which is representative of the four larger streams measured in north central Colorado. 52

Appendix Figure 1. Orientation classes, in degrees, used to describe large woody debris in 11 old-growth and 4 disturbed streams. 82

Appendix Figure 2. Large woody debris piece diameter as a function of piece length for 150 debris pieces forming pools in 11 old-growth reaches measured in northern Colorado. 84

Appendix Figure 3. Predicted mean residual pool depths, with 95% prediction intervals, across a range of drainage basin areas. 86

Appendix Figure 4. Predicted proportion of stream area made up by pools, with 95% prediction intervals, for streams 13 ft. (4 m) bankfull width across a range of large woody debris piece abundance. 88

Large woody debris (LWD) plays important roles in the structure and function of stream ecosystems. Research in the Pacific Northwest indicates that LWD shapes channel morphology (Bisson et al. 1987), contributes to the abundance and geometry of pools (Murphy and Hall 1981; Beschta and Platts 1986; Fausch and Northcote 1992), and stores organic and inorganic sediment (Harmon et al. 1986; Bilby and Ward 1989; Nakamura and Swanson 1993). Natural log dams create a stepped channel profile (Bilby and Likens 1980), allowing dissipation of energy at each step and reducing energy available for sediment transport (Heede 1972, 1985). Woody debris contributes to substrate diversity and aids in creating habitat complexity on a variety of scales (Keller and Swanson 1979), which together are thought to provide critical winter habitat for juvenile salmonids (Tschaplinski and Hartman 1983; Johnson et al. 1986; Murphy et al. 1986). Woody debris also creates lateral habitats and backwaters which serve as refuges and rearing areas for fish (Bryant 1985), and provides habitat and food for aquatic invertebrates on which fish feed (Angermeier and Karr 1984; Benke et al. 1985).

Although it is now evident that LWD plays a complex role in streams of the Pacific Northwest, few data are available on characteristics and function of LWD in streams of the Rocky Mountains (cf. Harmon et al. 1986). Many of the mountain streams and associated riparian zones in the region were extensively altered by mining, logging, and railroad tie drives from about 1850 to 1900 (Wroten 1956; Young et al. 1990), and human activities continue to affect riparian forests. As a result, relatively few undisturbed lotic systems associated with old-growth forests remain, and little is known about the importance of wood in streams of this region.

The purpose of this study was to describe the characteristics and functions of LWD in undisturbed streams associated with Engelmann spruce (Picea engelmannii)-subalpine fir (Abies lasiocarpa) old-growth forests in the mountains of northern Colorado. The main objective was to determine the role of LWD in forming pools and creating overhead cover for salmonids in these lotic systems. For comparison, LWD and salmonid habitat was also measured in four altered streams that generally lacked LWD.

Study Area

Reach Locations and General Characteristics

Eleven stream reaches associated with old-growth forest were selected for study during the summers of 1992 and 1993 (Table 1; Appendix Table 1). All are located in the Arapaho and Roosevelt National Forests in the mountains of north central Colorado (Fig. 1). The reaches are at elevations of 2719 m to 3204 m, and flow through glaciated valleys with shallow soils overlying glacial till. These mountains are composed primarily of pre-Cambrian granite, schist, and gneiss (Chronic 1980). Riparian forests were Engelmann spruce and subalpine fir with grasses, sedges, and forbs such as Vaccinium, Senecio, Mertensia, and Arnica, in the understory. Salix and Ribes were also present at some sites. Engelmann spruce-subalpine fir forests are usually found at elevations above 2750 m, although this forest type can occur as low as 2440 m in northern Colorado (Hess and Alexander 1986). Annual precipitation in the spruce-fir zone ranges from 64 to 76 cm at 3050 m elevation (Hess and Alexander 1986).

The reaches selected for study were associated with old-growth forests, which for this region and vegetation type are generally >250 yr old. Old-growth forest stands were identified using six structural characteristics defined by Lowry (1992; Appendix Table 2) for this region. Although not all characteristics needed to be present, the minimum requirements for selecting old growth were: (1) large live trees (≥35 cm diameter at breast height; dbh), including 15 or more trees ≥30 cm dbh per 0.4 ha; (2) either snags or fallen trees ≥35 cm dbh, with at least two snags or three fallen trees ≥30 cm dbh per 0.4 ha; (3) a multistoried tree canopy; and (4) more than 20% overhead canopy closure (Lowry 1992).

Stream reaches were selected to meet four additional criteria: (1) old-growth spruce-fir forest on both sides of the stream reach; (2) no major disturbance (i.e., clear-cut logging, fire) upstream of the study reach; (3) no evidence of beaver (Castor canadensis) upstream or in the reach; and (4) minimum bankfull width of 2.0 m. In addition to these criteria, reaches with significant gradient changes and those that received tributaries in mid-reach were also avoided, because either could affect LWD abundance and characteristics. Reaches selected were B channels based on Rosgen's channel classification system (Rosgen 1985). Streams of this channel type are common in spruce-fir old growth of this region, and provide a large share of habitat volume for resident trout. Only 13 stream reaches that met these criteria were found in the Arapaho and Roosevelt National Forests, 11 of which were studied.

All reaches were judged to provide habitat for salmonids at flows during middle to late summer, when LWD and habitat was measured. Fish were observed in all study reaches except three: the tributary of Joe Wright Creek, and Beaver and Hourglass creeks. The headwaters of Little South Fork Cache la Poudre River (hereafter Little South Fork Poudre), where the reach was located, has an endemic population of greenback cutthroat trout (Oncorhynchus clarki stomias; Behnke 1992).

Four stream reaches associated with riparian forests that had been altered by either anthropogenic or natural disturbances were measured for comparison to old-growth streams. The disturbances at all four sites likely occurred before 1900, because riparian forests have recovered; at two sites the riparian forest had been cut. One stream is in the Roosevelt National Forest, and the other three are in the adjacent Routt National Forest to the west (Fig. 1). The disturbed streams were all associated with spruce-fir forests in glacial valleys, and were similar to the old-growth stream reaches in elevation, width, gradient, sinuosity, and channel type (Table 1). The four 245 to 250-m reaches were selected in 1987 as control sections for a long-term study of trout population response to habitat enhancement using log drop structures (Riley and Fausch MS) because they generally lacked LWD.

Methods

Characteristics of Valleys and Stream Channels

Characteristics of the stream and its valley were measured either in the field or from U. S. Geological Survey 1:24,000 topographic maps. Valley type was classified based on cross-sectional shape as glacial (U-shaped) or alluvial (V-shaped). Valley floor widths and slope of the valley walls were estimated from topographic maps. Reach sinuosity was estimated as the thalweg distance divided by the straight-line down valley distance, measured by tape or range finder. Gradient was determined by using a level and leveling rod in 50-m sections. Both sinuosity and gradient were measured at the top, middle, and bottom of each reach, and averaged.

Salmonid Habitat

Habitat types were classified as pools, riffles, and glides based on criteria of Bisson et al. (1982). Pools were classified after Bisson et al. (1982) as plunge, dammed, lateral scour, and trench pools. In addition, pools created by scour of the stream bed around large woody debris at moderate to high discharges were considered separately.

Within each habitat type, wetted and bankfull widths were measured at transects perpendicular to flow at 1-m intervals for pools in all reaches and 2- to 5-m intervals for riffles and glides. Transect spacing in riffles and glides was longer in larger streams. The initial transect in each habitat unit was placed at half the transect interval from the downstream end. Diameter of dominant and codominant substrates (Appendix Table 3) was visually estimated at five equidistant points along each transect (at each bank, and 1/4, 1/2, and 3/4 of stream width) in all habitat types in seven streams measured in 1992, and in riffles and glides only in four streams measured in 1993 (the tributary of North Fork Joe Wright Creek, Baker Gulch, Bowen Gulch, and Arapaho Creek). Substrate was estimated at seven equidistant points in pools for the four streams in 1993.

In pools, depths were measured at the same points where substrate was recorded to allow estimating pool volume.

Maximum depth, and depth of the downstream hydraulic control, were measured for each pool; the difference between them is the residual pool depth (Lisle 1987), an index of pool volume that is relatively independent of discharge. At each transect, bank stability was assessed using the streambank stability rating of Platts et al. (1987). Length of overhead cover that could conceal a salmonid 15 cm long from overhead view was also measured. For this study, overhead cover was defined as logs or undercut banks that were at least 15 cm wide, had water at least 15 cm deep beneath them, and were no more than 15 cm above the water surface (cf. Fausch and Northcote 1992).

Percent habitat area, wetted width, total pool volume, overhead log and bank cover, and substrate percentages for the four disturbed stream reaches were obtained from Riley and Fausch (1990; MS). Sinuosity, gradient, pool types, pool bankfull width, and maximum and hydraulic control depths in each pool of disturbed streams were measured during August 1993.

Large Woody Debris

Large woody debris was defined as logs ≥10 cm diameter and ≥1 m long. Pieces that met these criteria were measured if any part occurred within or was suspended above the bankfull stream channel. The total length and diameter at each end of each LWD piece was measured using a tape measure and tree caliper. The volume of each piece was estimated from the equation given by Lienkaemper and Swanson (1987):

$$\text{Volume} = \frac{\pi(D_1^2 + D_2^2)L}{8}$$

where D_1 and D_2 are the end diameters (m) and L is the length (m). Total biomass of LWD within the bankfull channel was estimated by multiplying the volume of each LWD piece that lay within or above the bankfull channel by a wood density of $0.4\ Mg \cdot m^{-3}$ (cf. Fausch and Northcote 1992). Harmon et al. (1986) reported that an average density for undecayed conifer wood of $0.5\ Mg \cdot m^{-3}$ had often been applied, but that this value probably overestimated decayed coniferous wood by as much as 20-40%.

The relation of each LWD piece to the channel was classified in four influence zones (Robison and Beschta 1990a; Appendix Table 4), and the length of each piece in each zone and end diameters at the bankfull channel margins were measured. Since many LWD pieces occupied more than one influence zone, four categories were defined: (A) completely within the wetted channel (influence zone 1 only), (B) partially within the wetted channel (partly in zone 1), (C) between the wetted and bankfull channel (not in zone 1, wholly or partly in zone 2), and (D) above the bankfull channel (not in zones 1 or 2, wholly or partly in zone 3). Woody debris pieces that were wholly above the bankfull channel have no effect on channel morphology or stream flows below bankfull stage, but may be affected at flood flows and with time will enter the channel when decay causes breakage. Therefore, LWD above the bankfull channel represents a future source of debris.

Orientation in relation to stream flow and position within the channel were also recorded for each LWD piece. Orientation affects stream flow characteristics and channel morphology and both characteristics affect piece stability (Hogan 1984). Piece orientation was determined by the angle relative to direction of stream flow. Eight orientation classes were used, each representing 45° (Appendix Fig. 1). However, because most LWD pieces lacked attached rootwads or were broken, their tips often could not be distinguished, so the eight classes were combined into four (0° (parallel to flow), 90° (perpendicular), and 45° and 135° (diagonal)). Four categories were used to describe LWD position: touching the left or right banks only, touching neither bank (midchannel), and touching both banks (spanning).

The apparent functions of each LWD piece were also recorded. Large woody debris was classified as forming pools, storing sediment, providing overhead cover for salmonids, having other functions (i.e., bank stability, catching other organic debris), or having no apparent function. Because LWD may serve one or more functions, only the last category was mutually exclusive of the rest.

Decay classes were used to assess relative age of LWD pieces. Classes developed by Grette (1985; Appendix Table 5) were used when measuring LWD in two reaches, North Fork Cache la Poudre River (hereafter North Fork Poudre) and the tributary of Joe Wright Creek. However, this classification was developed for tree species and decay processes in the Pacific Northwest and did not reflect patterns observed in Colorado. Thereafter, the decay classes were modified and combined into five for use here: (1) bark intact, limbs present; (2) bark loose or absent, limbs present; (3) bark and limbs absent, surface solid to slightly rotted; (4) log surface extensively to completely rotted; (5) log breaking apart or broken.

Statistical Analysis

Relationships among LWD and stream channels were analyzed at three scales: individual LWD pieces, pools, and stream reaches. Relationships among characteristics of habitat and LWD in stream reaches, such as percent pool area or the length of overhead log cover, and three types of independent variables, stream width or drainage area, gradient, and LWD variables (abundance per 100 m, total volume, or bankfull biomass), were analyzed using simple and multiple linear regression. Dependent variables that were percentages (e.g., percentage pool area) were subjected to a logit transformation ($p/(1-p)$, where p is the proportion) to stabilize variance and improve normality if percentages were outside the range 20-80%. This occurred for all variables except the percentage of LWD pieces in various influence categories.

Relationships among the area and residual depth of 72 individual pools created by single LWD pieces versus stream width, gradient, LWD variables (diameter, length, bankfull volume), and interactions between LWD variables and width or gradient, were analyzed using a split-plot analysis of variance (ANOVA) via the General Linear Models (GLM) algorithm in SAS (SAS 1992). This analysis was needed because pools were not randomly chosen from a homogeneous population, and allowed comparing the effect of "within-plot" LWD variables on individual pool area after accounting for the "whole-plot" effects of width, gradient, and individual streams.

The distribution of LWD along the reaches was compared to a random distribution using randomization tests (Manly 1991). For each of the 11 old-growth streams, Monte Carlo simulation was used to assign the number of pieces actually found in a reach to 3-m intervals at random, and repeated 1000 times. The maximum number of pieces actually found in any 3-m interval in the reach, and the number of intervals that held at least four times the expected number of LWD pieces based on a uniform distribution, were compared to the distributions of these test statistics generated by the simulations to judge significance.

Results

All study reaches were 1st- to 3rd-order streams (Strahler 1957) with mean bankfull widths of 3.7 m to 10.2 m, moderate gradient (0.4-6%), and low sinuosity (<1.35; Table 1). Reach lengths ranged from 221 m to 575 m, although lengths ranged from 260 m to 345 m for nine of the reaches. Riffles predominated in reaches with gradients >2% (40-87% of wetted area; Appendix Table 6), except for the tributary of the North Fork Joe Wright Creek (6.4% gradient) where glides predominated (44%). In the two reaches with gradients <1%, Beaver and Hourglass creeks, glides constituted the majority of stream area (57 and 60%). Gravel and cobble (2.0-256 mm diameter) were the dominant substrates in all streams (i.e., visually estimated as dominant substrate at 49-89% of points measured, $\underline{n}$=403-1312; Table 1; Appendix Table 6), although in four streams boulder was also prevalent (i.e., visually estimated as dominant substrate at 23-33% of points measured). Stream banks for all study reaches were nearly always highly stable.

Large Woody Debris

Distributions of large woody debris diameters and lengths were skewed toward smaller pieces, with the highest percentages in the smallest size classes (Fig. 2), so medians were used for comparison among streams. Median LWD diameters were similar for all old-growth reaches studied, ranging from 16 cm in Baker Gulch to 22 cm in the tributary of Joe Wright Creek and Hourglass Creek (Table 2; Appendix Table 7). Very few pieces in any stream were larger than 50 cm. Median LWD piece length for 10 of 11 reaches ranged from 2.1 m for Bowen Gulch to 3.7 m for Fall Creek; median piece length for the tributary of Joe Wright Creek was 7.7 m. Only about 1% of the 1412 pieces measured were longer than 20 m. Median LWD piece volume reflected the variability in piece length, ranging from 0.058 m^3 for Bowen Gulch to 0.407 m^3 for the tributary of Joe Wright Creek.

Large woody debris volume, biomass (Mg/ha), and abundance also varied among the 11 old-growth reaches (Table 2; Appendix Table 7). Total LWD volume per 100 m of stream averaged 13.3 m^3 (Fig. 3), ranging from 6.6 m^3 for North Fork Joe Wright Creek to 27.1 m^3 for Arapaho Creek. Total LWD volume estimates include portions of debris pieces extending beyond the bankfull channel and thus not currently affecting fish habitat or channel morphology except at the highest flows. The proportion of woody debris volume comprising the terrestrial component ranged from 23% for North Fork Joe Wright Creek to 64% for the tributary of Joe Wright Creek. Biomass of LWD within the bankfull channel averaged 55.8 Mg/ha for the 11 stream reaches. The tributary of the North Fork Joe Wright Creek had the highest bankfull biomass with

101.7 Mg/ha, which was almost 100% more than the average for the other 10 reaches, where biomass ranged from 36.6 to 74.6 Mg/ha. Large woody debris abundance averaged 43 pieces per 100 m of stream, but was highly variable, ranging from 18 pieces per 100 m for the tributary of Joe Wright Creek to 64 pieces per 100 m for Arapaho Creek. Five of 11 stream reaches had ≥50 LWD pieces/100 m.

Much of the LWD occurring in the 11 old-growth reaches was apparently old, because the percentage of pieces that were classified as extensively rotted or breaking apart ranged from 56 to 78% (Table 2; Appendix Table 8). Distribution of LWD among the younger decay classes varied. Four of the reaches had only 1% or less of woody debris with bark and limbs intact, whereas five reaches had between 10% and 18% of debris in this class. Fall Creek and the Little South Fork Poudre had the highest percentages of LWD in the youngest decay class. Rootwads increase stability of LWD (Bisson et al. 1987) and increase habitat complexity if they lie within the stream channel. Only 15% of LWD pieces, on average, had rootwads attached (range: 10-21% among streams) and few of these occurred within the bankfull channel. When analyzed by decay class, there was a progressive decline in the percentage of pieces with rootwads as relative debris age increased. Forty-one percent of debris pieces in the youngest decay class had rootwads, compared to only 8% in the oldest.

Large woody debris in the four disturbed stream reaches was less abundant and smaller than in the old-growth reaches (Table 2). Abundance ranged from 2 to 26 pieces per 100 m in disturbed reaches, which was significantly less than in old-growth streams ($\underline{P}=0.02$, by Wilcoxon Rank Sums test). Length and volume of LWD pieces were significantly smaller in disturbed streams than old-growth streams ($\underline{P}<0.04$ for both), and the difference in average LWD diameter was marginally significant ($\underline{P}=0.058$). Total woody debris volume per 100 m was also significantly less in disturbed than in old-growth streams ($\underline{P}=0.006$).

Large Woody Debris Pieces that Formed Pools

Large woody debris pieces that formed pools in old-growth reaches were, on average, larger than debris pieces that did not form pools. The median diameter of pool-forming pieces was 22 cm (based on average piece diameter), compared to 19 cm for all other pieces. Median length of pool-forming pieces was 4.4 m compared to 2.6 m for all other pieces, and median piece volume was 0.186 m^3 for pool-forming pieces versus 0.079 m^3 for all other pieces. All of these differences were significant ($\underline{P}=0.0001$ by Wilcoxon Rank Sums test).

Position within the bankfull channel and orientation in relation to stream flow also differed between pool-forming and all other LWD pieces. The majority of pool-forming pieces (53%) spanned the channel, touching both left and right channel banks, whereas only 12% of all other woody debris pieces were spanning. Similarly, 57% of pool-forming debris pieces were oriented nearly perpendicular to stream flow compared to 23% of all other wood pieces (Fig. 4). These distributions of pool-forming pieces among position and orientation classes were significantly different than distributions for all other pieces ($\underline{P}<0.001$ for both by $\underline{G}$-test). Distribution of pool-forming debris pieces among the five decay classes was not significantly different than distribution of all other pieces ($\underline{P}$=0.36 by $\underline{G}$-test).

Agents Forming Pools

A total of 144 pools were measured in the 11 old-growth reaches, of which 81% ($\underline{n}$=116) were formed by LWD (Fig. 5; Table 1). Of these LWD pools, plunge pools were most prevalent (59%), followed by dammed pools (23%), scour pools (16%), and trench pools (3%). No lateral scour pools formed by LWD occurred within the stream reaches, although woody debris enhanced at least one lateral scour pool by damming the lower end. Trench pools and lateral scour pools created at meander bends dominated the 19% of pools not formed by LWD. Of these 28 pools, lateral scour and trench pools each made up 36%, and 25% were plunge pools formed by boulders. Pool abundance, standardized per 10 channel widths, ranged from 1.09 for Fall Creek to 3.57 for Baker Gulch (Table 1; Appendix Table 6).

Pool abundance per 10 channel widths in disturbed streams was not significantly different than in old-growth streams ($\underline{P}$=0.48 by Wilcoxon Rank Sums test; Table 1). However, of the 38 pools measured in the four disturbed streams, only 32% were formed by LWD (Fig. 5). Seventy-five percent of the 12 pools formed by woody debris were plunge pools, 17% were dammed pools, and 8% were scour pools. Thirty-eight percent of the 26 pools formed by other agents (i.e., boulders, meander bends) were trench pools, 23% were scour pools, 19% were lateral scour pools, and 20% were dammed or plunge pools. Percentage of area as pools in three of the four disturbed streams (3-9%)

was substantially less than in old-growth streams (median 17%, range: 11-30%). The fourth disturbed stream, Colorado Creek, had 20% of stream area as pools, but also had more LWD (26 pieces/100 m) than the other disturbed streams (Table 2).

Relationships Across Streams and Among Pools

Large Woody Debris

Characteristics of LWD pieces were also related to larger-scale stream characteristics, such as gradient and stream size. For example, the percentage of pieces spanning the channel decreased in larger streams that had larger drainage area or bankfull width (Table 2; $\underline{r}^2=0.49$, $\underline{P}=0.02$ by linear regression for both after logit transformation). Relatively little wood was in midchannel (Appendix Table 8), except in the Little South Fork Poudre, Beaver Creek, and Arapaho Creek, probably due to debris jams with large numbers of pieces. The percentage of pieces laying perpendicular to the channel was also significantly related to drainage area ($\underline{r}^2=0.45$, $\underline{P}=0.02$) and bankfull width ($\underline{r}^2=0.47$, $\underline{P}=0.02$), with fewer perpendicular pieces in larger channels. When LWD was pooled across streams, orientation was relatively evenly distributed among the four classes, ranging from 23% laying parallel to stream flow to 29% laying perpendicular (Fig. 4).

The percentage of pieces functioning to form pools and create overhead cover for fish was related to stream size or gradient. Although only 10% (range: 4-20%) of the 1412 LWD pieces measured functioned to form pools, the percentage of pieces creating pools declined significantly with drainage area ($\underline{r}^2$=0.64, $\underline{P}$=0.003) and bankfull width ($\underline{r}^2$=0.50, $\underline{P}$=0.01), indicating that more of the LWD in smaller streams formed pools (Table 2). Similarly, although only 14% of LWD pieces functioned as cover (range: 6-35%), multiple regression analysis indicated that smaller streams, and those with lower gradients, had a higher percentage of pieces functioning as overhead cover than larger and higher-gradient streams. The interaction term, bankfull width times gradient, was the single variable most closely related to the percentage of pieces forming cover ($\underline{r}^2$=0.75, $\underline{P}$=0.0006), although a regression with both bankfull width and gradient as predictors was also significant ($\underline{R}^2$=0.78, $\underline{P}$=0.002). Coefficients of all these variables were negative. Much of the large woody debris (33-68%) in the stream reaches served no apparent function near base flow (Appendix Table 8).

Characteristics of Pools and Channels

The percentage of stream area as pools (Table 1) increased with decreasing stream size and increasing LWD abundance. A two-variable model with LWD abundance per 100 m and the interaction term, LWD abundance times bankfull width, best predicted the percentage of pool area ($\underline{R}^2$=0.57, $\underline{P}$=0.035). The percentage of pool area was not a significant function ($P>0.05$) of either LWD volume or bankfull biomass, or combinations of these variables with gradient and width or drainage area.

Several other characteristics of pools were also related to LWD, stream size, and gradient. For example, streams with higher LWD abundance had significantly more pools per 10 channel widths ($\underline{r}^2$=0.36, $\underline{P}$=0.05), although the relationship was not precise. However, pool frequency was not significantly related to LWD volume or bankfull biomass, or combinations of these variables with gradient and width or drainage area ($\underline{P}>0.05$). Residual pool depth averaged 33 cm (Table 1) and increased with bankfull width or drainage area ($\underline{r}^2=0.74$, $\underline{P}=0.0007$ for both). The percentage of pools that were plunge pools was significantly related to stream gradient ($\underline{r}^2=0.36$, $\underline{P}=0.05$), indicating that higher-gradient streams had more plunge pools. The percentage of plunge pools in relation to all pools among streams ranged from 17% for Hourglass (0.6% gradient) and Arapaho (2.2%) creeks to 75% for the tributary of North Fork Joe Wright Creek (6.4%) and Baker Gulch (3.3%).

Relationships were also analyzed among area and residual depth of 72 individual pools versus stream width and gradient, and LWD diameter, length, or bankfull volume, using a split-plot ANOVA. After accounting for the effects of width, gradient, and individual stream, neither pool surface area nor residual depth were significantly related ($\underline{P}>0.13$) to the diameter, length, or bankfull volume of single LWD pieces functioning to form the pools. Mean diameter of single pool-forming pieces was not significantly different among streams ($\underline{P}=0.45$ by oneway ANOVA), but length of these pieces was significantly longer in Arapaho Creek, the largest stream, than in 5 of 10 smaller ones (North Fork Joe Wright Creek, Beaver Creek, Little South Fork Poudre, the tributary of North Fork Joe Wright Creek, and Baker Gulch; $\underline{P}=0.0005$ by ANOVA, overall; $\underline{P}<0.05$ by Tukey's HSD multiple comparisons). Pieces forming pools in the tributary of Joe Wright Creek also were significantly longer than in North Fork Joe Wright Creek. Bankfull volume of pool-forming pieces was different among streams ($\underline{P}=0.0001$) but only in Arapaho Creek, the largest stream, were pool-forming pieces of significantly greater volume than all other streams except Fall Creek ($\underline{P}<0.05$ by multiple comparisons). In turn, volume of pool-forming pieces in Fall Creek, in which two of nine pool-forming pieces had $>1.5 m^3$ bankfull volume, were significantly greater than those in North Fork Joe Wright Creek and Beaver Creek, the two streams where all pool-forming pieces were $<0.85 m^3$ bankfull volume.

Of the 114 pools formed by woody debris in the 11 old-growth streams, 105 could be attributed to specific LWD pieces. Seventy-four pools (70%) were formed by single debris pieces, 21 pools (20%) were formed by two pieces, and 10 pools (10%) were formed by three or more debris pieces. The remaining nine pools were formed by small woody debris. There was a significantly higher percentage of pools formed by single versus multiple LWD pieces in smaller streams (<5.0m bankfull width) than in larger streams ($\underline{P}=0.026$ by oneway ANOVA). Seventy-five percent of the pools formed by LWD in smaller streams were formed by single pieces, compared to 47% in the larger streams.

Cover

Large woody debris provided a larger amount of overhead cover for trout in low-gradient streams of greater bankfull width and drainage area, that had more LWD. A multiple regression of length of log cover against drainage area, and the interaction of area times gradient (both negative coefficients), and LWD abundance (positive coefficient) was significant ($\underline{P}=0.003$), and accounted for 84% of the variation in amount of overhead log cover. Two other two-variable models that incorporated stream size, gradient, and LWD abundance or bankfull biomass were also significant and relatively precise ($\underline{R}^2$=0.60-0.63; $\underline{P}$<0.03) and had coefficients of the same sign (i.e., positively related to LWD, negatively related to stream size and gradient).

Overhead cover provided by undercut stream banks was more plentiful in narrow low-gradient streams, or streams with intermediate width and gradient, that had more LWD. A three-variable regression model with bankfull width and stream gradient (both coefficients negative), and LWD abundance (positive coefficient) as predictors accounted for 85% of the variation in length of bank cover (P=0.003). A two-variable model with LWD abundance (positive coefficient) and the interaction term bankfull width times gradient (negative coefficient) was also significant ($\underline{R}^2$=0.81, $\underline{P}$=0.001), as was a one-variable model with bankfull width times gradient ($\underline{r}^2$=0.62, $\underline{P}$=0.004, negative slope).

Distribution of Large Woody Debris

The location of LWD within the bankfull channel, and the distribution of clumps of debris along the reaches, were also related to stream size. The percentage of debris pieces at least partially within the wetted channel decreased significantly with increasing drainage area ($\underline{r}^2$=0.62, $\underline{P}$=0.004 by linear regression). The analogous relationship based on stream bankfull width was also significant, but less precise ($\underline{r}^2$=0.35, $\underline{P}$=0.05). The percentage of debris pieces above the wetted channel but still within the bankfull channel increased significantly with both drainage area ($\underline{r}^2$=0.61, $\underline{P}$=0.004) and bankfull width ($\underline{r}^2$=0.67, $\underline{P}$=0.002), indicating that in larger streams less of the LWD influenced fish habitat at low flow. There was less wood suspended above the bankfull channel in the three streams ≥7.0 m bankfull width (3-7%; Baker Gulch, Bowen Gulch, and Arapaho Creek) than in six of the smaller streams (10-34%), although North Fork Joe Wright Creek and its tributary had only 4-5% of debris pieces above the bankfull channel (Appendix Table 8).

In streams <5.0 m bankfull width LWD was often distributed relatively evenly along the reach, whereas in the four larger streams the distribution of debris was usually clumped (Fig. 6). In two of seven small streams the maximum frequency of LWD pieces in 3-m intervals was no different than expected by chance ($\underline{P}>0.05$ by randomization test based on 1000 simulations), and the frequency of clumps that were at least four times the average number of LWD pieces was no different than expected in four of seven streams (Table 2). In contrast, the maximum frequency of LWD pieces in 3-m intervals was much different than expected by chance in all four larger streams ($\underline{P}<0.01$ for all), as was the frequency of clumps that were at least four times the average ($\underline{P}\leq0.02$ for all). Arapaho Creek, the largest stream measured, also had two very large debris accumulations within the reach, so large that it was not possible to count individual pieces because most were buried. These debris jams measured 16 m wide, 11.5 m long, and 2.5 m high (460 m^3) and 32 m wide, 14 m long, and 1.5 m high (672 m^3) and were spaced approximately 120 m apart. Five additional large accumulations of LWD, and four smaller debris accumulations, were located within a 3.2-km section bordered by old-growth that extended both upstream and downstream of the reach.

DISCUSSION

Large Woody Debris

Large woody debris measured in the 11 stream reaches associated with old-growth spruce-fir forest was, on average, smaller than that found in riparian forests of the Pacific Northwest, Alaska, and British Columbia (cf. Harmon et al. 1986; Fig. 2). On average, median LWD diameter was 19 cm and median length was 3.3 m, compared to 53 cm average diameter and 7.4 m average length in five undisturbed Alaska streams (Robison and Beschta 1990a). Similarly, large woody debris in undisturbed reaches of a British Columbia stream had geometric mean diameter of 26 cm and geometric mean length of 7.4 m (Fausch and Northcote 1992). Median LWD piece volume averaged 0.131 m^3 in the Colorado streams compared to 1.7 m^3 in the five Alaska streams (Robison and Beschta 1990a). Large woody debris volume per 100 m of stream averaged 58 m^3 in the five Alaska streams (Fig. 3) and 43.2 m^3 in the British Columbia stream, compared to 13.3 m^3 for the 11 reaches in Colorado. Similarly, Fausch and Northcote (1992) estimated mean bankfull biomass of 234.5 Mg/ha for undisturbed reaches in the British Columbia stream, whereas estimated mean bankfull biomass was only 55.8 Mg/ha in the Colorado stream reaches. Although LWD pieces were smaller in the Colorado streams, abundance of woody debris pieces (average 43 per 100 m; Fig. 3) was comparable to that found in Alaska (33/100 m) and British Columbia (42/100 m). Robison and Beschta (1990a) defined LWD as having greater diameter and length (>20 cm diameter, >1.5 m long) than for this study, which could account for the lower woody debris abundance in the Alaska streams.

Although LWD in the 11 Colorado old-growth streams was small compared to the Pacific Northwest, it was comparable in diameter to trees in riparian Engelmann spruce-subalpine fir forests in southeastern Wyoming (Young et al. 1990). Standing conifers in the riparian zone of an undisturbed Wyoming stream seldom exceeded 50 cm diameter and had a similar size distribution to LWD in Colorado.

Among the Colorado streams, larger streams had more LWD per 100 m than smaller streams. However, Bilby and Ward (1989, 1991) found that LWD abundance decreased with increasing stream size for 2nd- to 5th-order streams in southwestern Washington. Lienkaemper and Swanson (1987) also reported decreasing LWD abundance with increasing stream size for five relatively undisturbed streams in Oregon. The reason for this difference between streams in Colorado and the Pacific Northwest is unclear, but may reflect differences in drainage densities, flow regimes, geomorphic characteristics, or forest types in the two regions.

Large woody debris in the four disturbed stream reaches was less abundant and smaller than in the old-growth reaches. Young et al. (1990) also reported lower debris abundance in a section where logs for railroad ties had been cut and driven downstream than in an undisturbed section of a southeastern Wyoming stream. Large woody debris pieces were significantly larger in old-growth than second-growth sites for streams 7-10 m wide in southwestern Washington, but no differences were seen for smaller streams (Bilby and Ward 1991).

The rates and processes of wood decay may vary depending on specific characteristics of the LWD piece, stream, and region in which it occurs (Harmon et al. 1986), making it difficult to accurately estimate debris age in streams. The age of LWD pieces and their residence time in Colorado streams are unknown, although decay classes allow ranking LWD age relative to other pieces in the same stream. Most of the LWD in the 11 old-growth reaches was extensively rotted or broken, suggesting that it was very old. Large woody debris may remain in Pacific Northwest stream systems more than 200 years (Murphy and Koski 1989), as estimated by dendrochronology, but these ages may not apply to other regions.

Distributions of LWD within the five decay classes suggest episodic recruitment events in some streams. For example, Fall Creek and the Little South Fork Poudre had a high percentage of LWD with intact bark. Severe storms occurred near the reaches in 1987, including a tornado that touched down, which may have felled many riparian trees into both streams. Episodic recruitment processes are, by definition, uncommon and unpredictable, and so may not have occurred recently in the four reaches with relatively little LWD in younger decay classes (Table 2). More knowledge of wood decay rates in the region and estimates of debris ages are needed before LWD recruitment rates can be understood.

Only a small proportion (15%) of LWD pieces in old-growth streams had rootwads attached and few of these occurred within the bankfull channel. Trees recruited by bank undercutting or erosion would likely have attached rootwads, which would be incorporated into larger stream channels as stream flow was diverted around them (Robison and Beschta 1990a). The general lack of attached rootwads within bankfull channels of the Colorado streams suggests, in general, that little lateral stream movement is occurring. This may be due to large clasts composing the glacial till within the valleys, which present stream flows are unable to move.

Characteristics of LWD Across Streams

Large woody debris position and orientation within the channel was related to larger-scale stream characteristics. The percentage of debris pieces spanning the channel decreased in larger streams with larger drainage area or bankfull width. This could be because channel width exceeded most piece lengths in larger streams (Lienkaemper and Swanson 1987), which prohibits pieces from anchoring at both stream banks, or because increased stream power more readily moved LWD into more stable positions. Robison and Beschta (1990b) also found that LWD was less apt to span channels in larger Alaskan streams than smaller ones.

Fewer LWD pieces lay perpendicular to stream flow in the larger Colorado streams. This, too, may relate to piece size in relation to channel width and the susceptibility of LWD to movement at high flows in larger streams. Bilby and Ward (1989) reported that LWD was oriented perpendicular to stream flow more often than expected in Washington streams <7 m wide, and oriented diagonally downstream more often than expected in streams >10 m wide. Robison and Beschta (1990a) also found fewer pieces oriented perpendicular to flow as stream size increased in five Alaska streams.

The location of LWD within the bankfull channel in relation to influence categories, and its distribution along the stream reach were also related to stream size and the ability of stream flow to redistribute wood. A lower proportion of wood occurred at least partially within the wetted channel and more wood occurred above the wetted stream margin but within the bankfull channel in larger streams. Much of this wood had apparently been transported at higher flows and deposited along channel margins as flows receded, where it had little or no influence on fish habitat near baseflow. The proportion of pieces wholly above the bankfull channel also decreased in the larger old-growth streams. Robison and Beschta (1990a) reported similar changes in distribution of LWD among influence zones with stream size. Direct comparisons are difficult because categories were combined in the Colorado study, but the percentage of pieces wholly within the bankfull channel (i.e., within influence zones 1 and 2) increased in the larger Alaska streams whereas percentage of pieces wholly above the bankfull channel (i.e., in influence zones 3 and 4) decreased (Robison and Beschta 1990a).

Distribution of LWD pieces along the old-growth reaches also changed with stream size. Large woody debris in smaller streams (<5.0 m bankfull width) was often relatively evenly distributed, whereas clumps that were larger and more frequent than expected by chance occurred in all larger streams (Fig. 6). This concurs with other studies (Bisson et al. 1987; Robison and Beschta 1990a) which found a relatively even distribution of wood in 1st-, 2nd-, and small 3rd-order streams, where logs tended to lay where they fell because flows were generally inadequate to move most of them. In this study, however, some clumping was apparent in four of seven smaller streams (Table 2), suggesting nonrandom entry of LWD from the riparian forest, such as would occur if one tree felled by wind also toppled several other trees. Therefore, clumping of LWD in small streams may result from events occurring in the riparian forest (Swanson et al. 1976).

In contrast, flows in larger streams are able to redistribute more of the LWD, causing clumping of wood. Arapaho Creek, the largest stream, had two very large debris accumulations (460 m^3 and 672 m^3) for which most individual LWD pieces could not be measured. These jams were composed mainly of debris pieces >20 cm diameter and >2 m long. One large debris accumulation within the study reach formed a large dammed pool of 52 m^2 surface area. The other was not associated with pool habitat at base flow, although a backwater pool had formed immediately upstream that was largely isolated from the active channel. Although some of the large debris accumulations observed along the 3.2-km section of Arapaho Creek stored large amounts of sediment, many were not associated with pools during baseflow. These debris jams may serve more important functions during high flows, when they may form pools or areas of lower velocity for fish, or function to dissipate stream energy that would otherwise erode the stream channel.

Large Woody Debris and Fish Habitat

Although only 10% of the 1412 LWD pieces measured functioned to form pools, 81% of the pools in the study reaches were formed by LWD. Young et al. (1990) also found that LWD formed the majority of pools (70%) in an undisturbed stream section in southeastern Wyoming, and other researchers have found LWD to be of primary importance in pool formation in other regions (Heifetz et al. 1986; Murphy et al. 1986; Andrus et al. 1988; Fausch and Northcote 1992). I also found that the number of pools per 10 channel widths generally increased with increasing LWD abundance in old-growth streams. Similarly, Grette (1985) reported a significant relationship between LWD and abundance of pools $>10\ m^2$ surface area in small low-gradient streams of western Washington. In contrast to relationships with LWD abundance, I found that pool frequency was not significantly related to LWD volume or bankfull biomass, which suggests that position of individual debris pieces within the bankfull channel and their effect on stream flow influence pool formation more than overall volume. Fausch and Northcote (1992) reported that a relatively few stable influential debris pieces accounted for most of the pool volume in a British Columbia stream, and also suggested that LWD volume was less important in pool formation.

Of the 116 pools formed by LWD, plunge and dammed pools were most prevalent (59% and 23%, respectively). Bilby and Ward (1989) also found that plunge pools were the most common type in streams <7 m wide, and that plunge pools were most often formed by LWD laying perpendicular to flow in streams <7 m and >10 m wide in southwestern Washington. In my study, linear regressions indicated that higher gradient streams had more plunge pools. Plunge pools formed at log steps act to dissipate stream energy (Heede 1972), so higher-gradient streams have shorter distances between steps. Bilby and Ward (1991) found that plunge pools decreased and scour pools increased in abundance with increasing stream sizes in Washington. Robison and Beschta (1990b) suggested that the changing relationship between LWD and stream flow with changing stream size could influence occurrence of various pool types. In my study, small samples of pool types other than plunge pools precluded statistical analysis, and no clear pattern was evident.

Large woody debris that formed pools had different attributes than other pieces. The LWD forming pools was significantly longer (4.4 vs. 2.6 m) and larger diameter (22 vs. 19 cm) than other pieces, and most spanned the channel nearly perpendicular to stream flow (Fig. 4). Longer debris pieces may be more stable in streams because they more often span the stream or are anchored on stream banks. Stable woody debris can have more effect on channel morphology than unstable pieces (Bryant 1983), which tend to move during the moderate to high flows that shape stream channels. Moreover, LWD pieces that are also oriented nearly perpendicular to flow may offer greater resistance to stream flow than pieces oriented in other directions or laying only partially within the channel, which causes the localized erosion and deposition that forms pools (Sullivan et al. 1987).

Pool surface area and residual depth were related more to stream size than to LWD size. When analyzed among streams, mean residual pool depth increased significantly with stream size. However, after accounting for width, gradient, and individual stream, there was no additional significant effect of LWD diameter, length, or volume on area or residual depth of 72 individual pools. These results suggest that geomorphic and fluvial characteristics of streams exert primary control on individual pool characteristics and type. For example, stream power, which is related to stream depth and gradient, and resistance of stream bed and bank materials to erosion are important determinants of pool size. Flows around LWD in larger streams are capable of scouring deeper pools than flows around equivalent debris pieces in smaller streams. Similarly, within a stream, woody debris pieces that attain stability at sites where cobble and boulder substrates predominate will scour small or shallow pools as compared to stable pieces at sites where smaller substrate sizes predominate. Other researchers have also suggested that larger-scale stream and valley characteristics such as gradient, bedload composition, or geomorphic factors may, beyond some threshold, override the influence of large woody debris in pool formation (Andrus et al. 1988; Evans et al. 1993). In contrast, Bilby and Ward (1989) found that LWD piece volumes were significantly related to surface area of scour pools formed by those pieces, although they did report that piece influence changed with stream size.

The percentage of stream area as pools increased in smaller streams that had more LWD. However, the percentage of pool area was not significantly related to either LWD volume or bankfull biomass, or combinations of these with other variables. As for pool frequency, this suggests that individual influential pieces are more important than total debris volume or biomass in forming pools in Colorado old-growth streams. In contrast, other investigators found no relationship between percentage pool area and LWD abundance (Carlson et al. 1990) or volume (Grette 1985) in Pacific Northwest streams, although Grette (1985) did find a significant negative correlation with gradient.

The percentage of LWD pieces forming pools and providing overhead cover for fish was also related to larger-scale stream variables. Smaller streams had proportionately more woody debris pieces forming pools than larger streams, probably because even small pieces can affect flow and cause scour in smaller streams. Although the percentage of pools formed by LWD was similar among the 11 old-growth streams, a higher proportion of pools were associated with multiple LWD pieces ($\geq$2 pieces) in larger streams. This could be because fewer single debris pieces can attain stability and anchor pools in larger streams, or because the flows in larger streams redistribute wood into accumulations that form around large stable pieces. Smaller streams and those with lower gradients also had a higher percentage of pieces functioning as overhead cover for fish than larger and higher-gradient streams. In larger streams, most wood was located outside the wetted channel and provided no overhead cover at or near baseflow.

In contrast, the total amount of overhead cover provided by LWD was greater in larger, low-gradient streams that had more LWD. This was probably because the larger streams sampled were of moderate gradient and tended to have more LWD available to provide overhead cover for fish. Overhead cover for fish provided by undercut banks was more plentiful in narrow low-gradient streams, or streams with intermediate width and gradient, that also had higher LWD abundance. Bank materials in lower-gradient streams are likely to be less resistant to erosion, and thus more prone to undercutting. Large woody debris can divert flow towards stream banks and increase bank erosion (Robison and Beschta 1990b) and undercutting, and may also stabilize upper portions of stream banks and allow undercutting below. It is unclear why the larger streams had less overhead bank cover.

Disturbed Streams

Comparisons between the 4 disturbed streams and 11 old-growth streams suggested that pool formation was not dependent on LWD. There was no significant difference between pool frequency in disturbed and old-growth streams, even though disturbed streams had significantly less LWD. Grette (1985) also found abundant pool habitat in Washington streams that had little LWD. However, in my study, the percentage of pool area was substantially less in three of four disturbed streams with low LWD abundance than in old-growth streams, suggesting that pools formed in disturbed streams were smaller. This may be a function of prevalent pool types in disturbed streams, or differences in flow regimes. Overall, most pools in disturbed streams were formed by agents other than LWD (boulders, meander bends), of which trench and scour pools predominated (Fig. 5). Of the 32% of pools formed by LWD, plunge pools were most common, as in old-growth streams.

Overall, the results of my study indicate that large woody debris in the 11 old-growth reaches was smaller and had less volume than in streams of the Pacific Northwest, but abundance was similar. The majority of pools in these old-growth streams were plunge pools, and most pools were formed by LWD pieces that spanned the bankfull channel and were oriented nearly perpendicular to stream flow. The area and residual depth of pools were related more to stream size and gradient than to LWD size. Individual debris pieces were effective in forming most pools in smaller streams, but not larger ones. A higher proportion of LWD formed pools and provided overhead cover in smaller streams, whereas larger streams were capable of redistributing LWD into discrete clumps or to the stream margins.

Information gained from this research can be used by fishery managers to simulate LWD abundance, position, and orientation when rehabilitating altered streams. My results also indicate that the role of LWD in providing fish habitat changes markedly with stream size and gradient. Knowledge of these relationships will allow managers interested in using LWD to increase pool habitat or overhead cover for fish to concentrate their efforts in streams or stream reaches where success is most likely.

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Table 1. Characteristics of study reaches and pool habitat in 11 old-growth and 4 disturbed streams in north central Colorado where large woody debris (LWD) was measured. Stream order was determined from U. S. Geological Survey 1:24,000 topographic maps, based on perrenial streams only. Substrates are gravel and cobble (2-256 mm diameter) and boulder (>256 mm).

Stream	Location	Elevation	Stream order	Reach length (m)	Mean bank full width (m; SE)	Gradient	Drainage area (km^2)	Sinuosity	Dominant substrate percent 2-256	Dominant substrate percent >256	Percent pool area	Pools per 10 channel widths	Percent pools by LWD	Mean residual pool depth (cm; SE)
Old-growth Streams														
Trib. Joe Wright Cr.	7N 75W 19	3204	1	268	3.7 (0.14)	0.027	3.4	1.04	89	3	12	1.79	85	22 (3.14)
Trib. N. Fk. Joe Wright Cr.	7N 76W 14	3085	1	285	3.8 (0.12)	0.064	2.4	1.08	73	19	17	2.67	90	28 (2.61)
N. Fk. Joe Wright Cr.	7N 76W 23	3036	2	577	3.9 (0.07)	0.034	3.9	1.20	80	13	18	2.03	90	23 (1.85)
Hourglass Cr.	7N 74W 14	3109	1	221	4.1 (0.14)	0.006	5.1	1.14	89	2	16	1.11	67	36 (4.89)
Fall Cr.	7N 73W 19	2914	3	263	4.1 (0.13)	0.030	9.9	1.20	61	23	18	1.09	71	28 (4.45)
Beaver Cr.	7N 74W 10	3011	2	260	4.2 (0.11)	0.004	8.9	1.34	78	3	30	2.75	88	33 (4.10)
N. Fk. Poudre R.	10N 74W 3	2902	1	277	4.5 (0.12)	0.020	11.0	1.13	49	33	17	1.46	78	26 (3.04)
Little S. Fk. Poudre R.	7N 73W 30	2847	3	344	5.6 (0.12)	0.027	21.7	1.32	80	8	15	1.47	78	39 (4.36)
Baker Gulch	4N 76W 29	2743	2	314	7.0 (0.26)	0.033	17.4	1.04	85	7	22	3.57	81	36 (4.50)
Bowen Gulch	4N 76W 3	2829	2	260	8.0 (0.21)	0.034	24.5	1.13	64	23	20	3.08	30	40 (4.28)
Arapaho Cr.	1N 74W 5	2719	3	300	10.2 (0.51)	0.022	29.1	1.20	64	27	11	2.04	83	48 (4.28)
Disturbed Streams														
N. Fk. Poudre R.	10N 74W 21	2730	2	250	4.0[a]	0.010	----	1.22	72	6	7	0.96	17	30 (4.92)
Colorado Cr.	6N 82W 29	2775	2	245	4.5	0.025	----	1.20	61	17	20	2.94	44	25 (2.72)
Jack Cr.	5N 77W 13	2925	2	245	4.8	0.007	----	1.25	94	4	9	1.37	43	22 (4.46)
Walton Cr.	5N 83W 15,16	2775	2	245	5.1	0.012	----	1.10	63	35	3	1.87	11	25 (3.36)

[a] Bankfull widths based on only one transect at each pool (n=6-16)

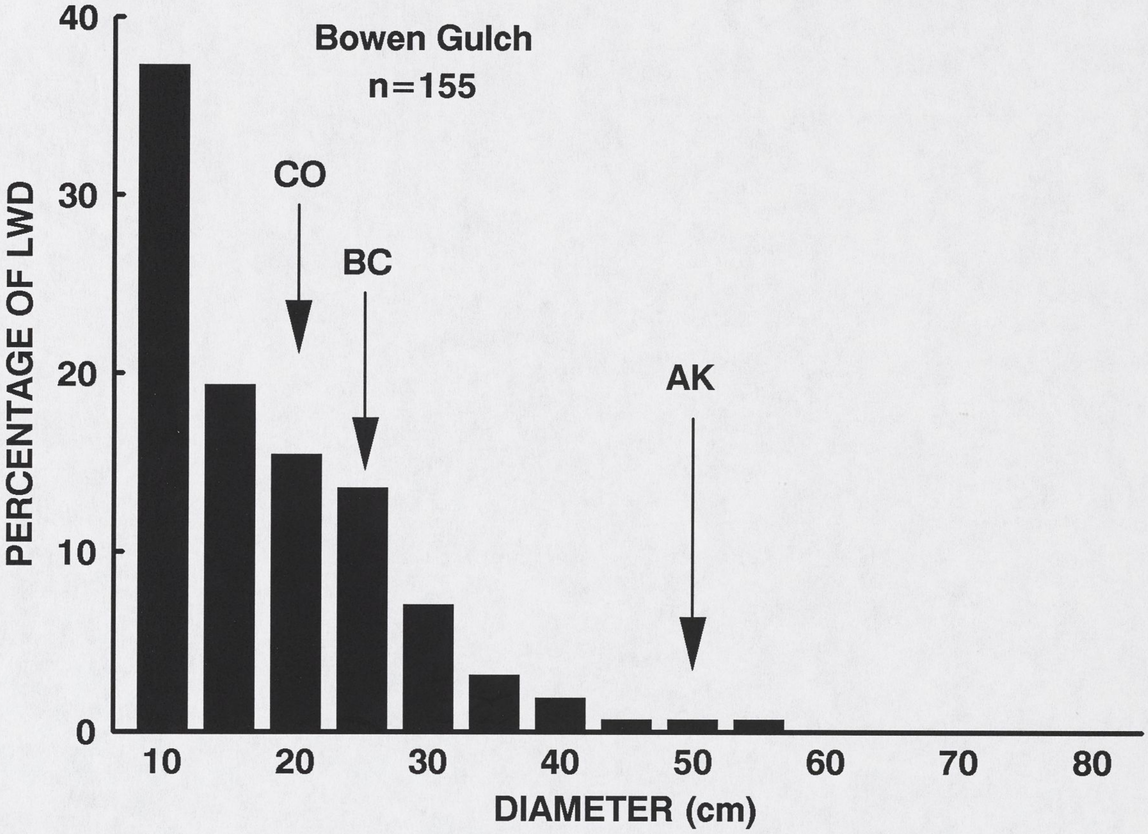
Table 2. Characteristics of large woody debris (LWD) measured in study reaches of 11 old-growth and 4 disturbed streams in north central Colorado. Streams are arranged in order by width, as in Table 1. The probability (P) of finding a given number of clumps (No.) that had at least four times the average number of pieces expected, and the probability of finding a clump of the maximum number of pieces found, are shown (see text). Decay: B=bark intact; ER+O=extensively rotted and broken classes combined. Orientation: Perp.=perpendicular; diag.=diagonal.

	Median			Total volume	Bankfull	Pieces per 100 m	Percent decay		Per-cent span-ning	Percent LWD by orientation		Percent LWD by function		LWD clumps 4X average		LWD clumps Maximum	
Stream	Length (m)	Diameter (m)	Volume (m^3)	(m^3/ 100 m)	biomass (Mg/ha)	(total number)	B	ER+O	LWD	Perp.	Diag.	pool	cover	P	No.	P	No.
						Old-growth Streams											
Trib. Joe Wright Cr.	7.7	0.22	0.407	9.3	36.6	18 (47)	13	67	60	51	20	15	15	0.660	3	0.001	7
Trib. N. Fk. Joe Wright Cr.	3.1	0.21	0.119	20.7	101.7	50 (152)	<1	63	24	29	46	12	6	1.000	7	0.970	6
N. Fk. Joe Wright Cr.	3.1	0.20	0.115	6.6	37.3	24 (138)	6	77	22	38	41	20	8	<0.002	4	0.040	7
Hourglass Cr.	2.9	0.22	0.107	12.8	53.9	33 (72)	10	68	6	18	59	10	18	0.320	5	0.060	7
Fall Cr.	3.7	0.19	0.108	14.3	74.6	46 (117)	16	59	26	34	49	6	15	0.350	6	0.300	7
Beaver Cr.	2.3	0.18	0.069	9.1	66.3	54 (140)	6	70	19	33	41	7	35	0.010	7	<<0.002	15
N. Fk.Poudre R.	2.8	0.20	0.239	12.6	49.2	37 (102)	11	72	25	32	55	16	22	0.030	5	0.040	8
Little S. Fk. Poudre R.	3.3	0.18	0.075	11.8	45.1	32 (111)	18	59	11	24	66	6	14	0.002	5	<<0.005	14
Baker Gulch	2.8	0.16	0.062	11.7	42.5	59 (186)	<1	75	14	27	49	9	6	0.020	8	<<0.006	15
Bowen Gulch	2.1	0.18	0.058	10.5	37.8	60 (155)	<1	78	3	17	53	4	8	0.010	8	<0.002	14
Arapaho Cr.[a]	2.6	0.20	0.085	27.1	68.5	64 (192)	1	56	5	17	51	4	10	<<0.004	9	<0.001	14
						Disturbed Streams											
N. Fk. Poudre R.	2.7	0.16	0.057	3.1	----	22 (55)	2	68	13	27	40	5	23	----	-	----	--
Colorado Cr.	2.8	0.20	0.095	6.6	----	26 (64)	0	63	21	34	43	13	9	----	-	----	--
Jack Cr.	1.7	0.15	0.036	1.3	----	16 (38)	5	58	3	46	33	10	14	----	-	----	--
Walton Cr.	5.8	0.24	0.223	0.6	----	2 (5)	0	60	20	60	40	17	17	----	-	----	--

[a] Excluding LWD pieces in two large accumulations (see text)

Fig. 1. Locations of 11 old-growth and 4 disturbed streams measured in northern Colorado. Old-growth streams are: 1 = North Fork Cache la Poudre River; 2 = tributary of Joe Wright Creek; 3 = North Fork Joe Wright Creek; 4 = Beaver Creek; 5 = Hourglass Creek (tributary of Hourglass Reservoir); 6 = Fall Creek; 7 = Little South Fork Cache la Poudre River; 8 = tributary of North Fork Joe Wright Creek; 9 = Baker Gulch; 10 = Bowen Gulch; 11 = Arapaho Creek. Disturbed streams are: D1 = North Fork Cache la Poudre River; D2 = Jack Creek; D3 = Colorado Creek; D4 = Walton Creek.

Fig. 2. Distribution of diameter (top) and length (bottom) of large woody debris pieces (e.g., 10-15.9 cm or 1-1.4 m, etc.) in Bowen Gulch and Baker Gulch, which are representative of the 11 old-growth streams measured. For comparison, mean diameter and length of large woody debris pieces in the 11 Colorado streams (CO), in a relatively undisturbed stream section in British Columbia (BC), and in 5 undisturbed streams in Alaska (AK) are shown (see text).


Bowen Gulch
n=155
CO
BC
AK
PERCENTAGE OF LWD
0
10
20
30
40
10
20
30
40
50
60
70
80
DIAMETER (cm)

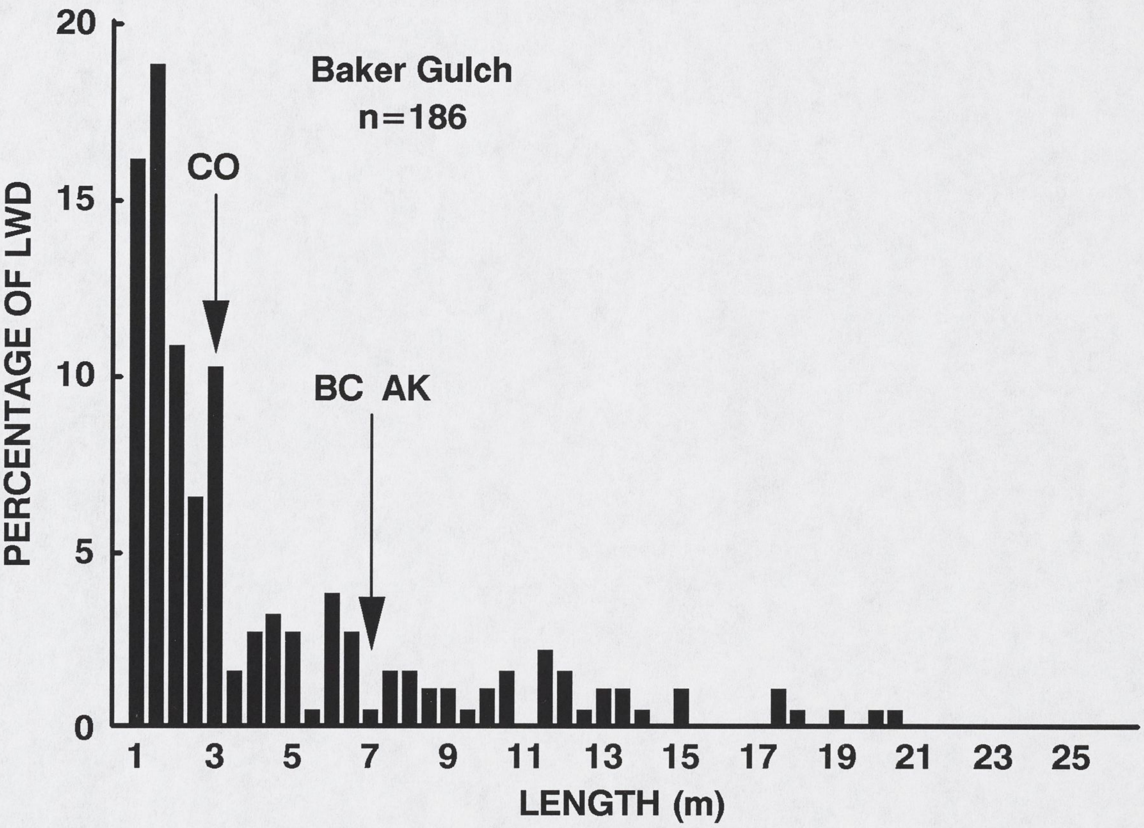

Baker Gulch
n=186
CO
BC AK
PERCENTAGE OF LWD
0
5
10
15
20
1
3
5
7
9
11
13
15
17
19
21
23
25
LENGTH (m)

Fig. 3. Comparison of large woody debris abundance (pieces per 100 m) and volume (m^3/100 m) for the 11 old-growth streams in Colorado, a relatively undisturbed stream section in British Columbia, and five undisturbed streams in Alaska (see text).

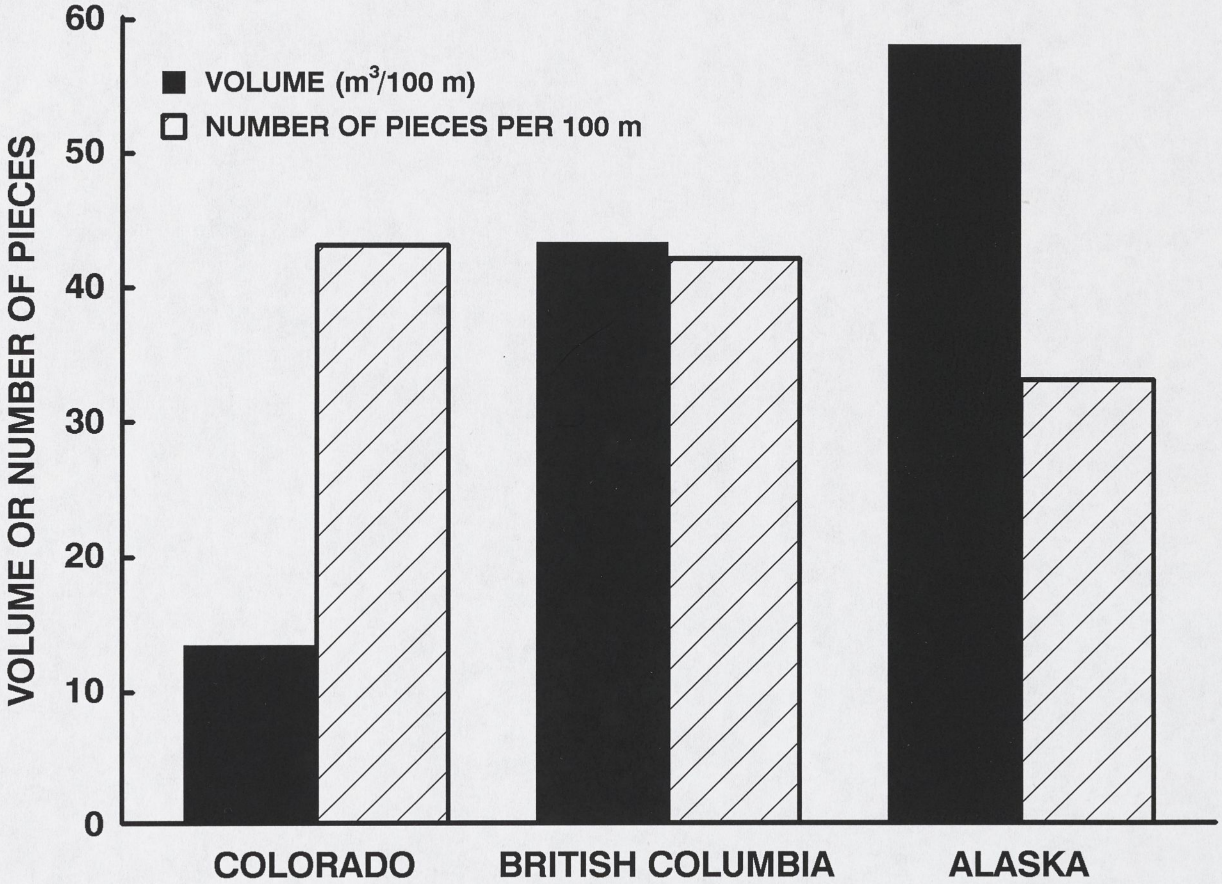
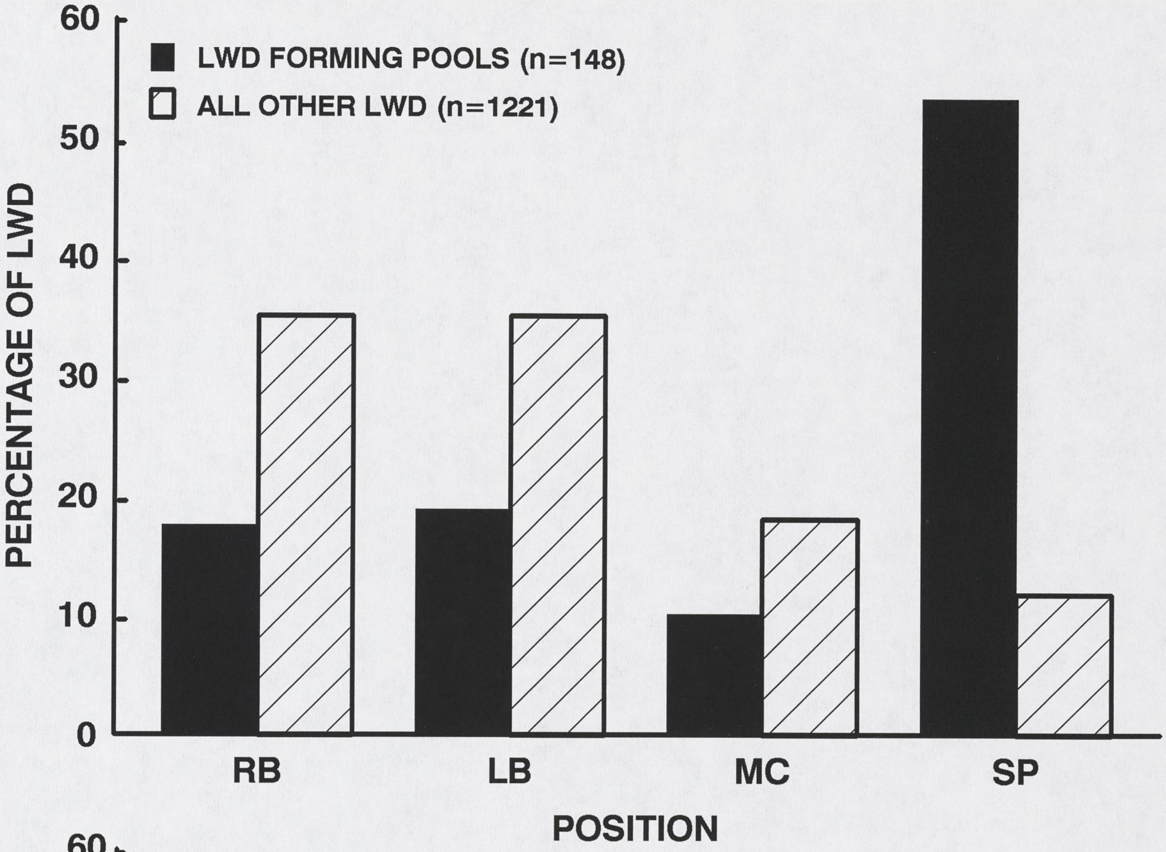

60
50
40
30
20
10
0
VOLUME OR NUMBER OF PIECES
VOLUME (m³/100 m)
NUMBER OF PIECES PER 100 m
COLORADO
BRITISH COLUMBIA
ALASKA

Fig. 4. Distribution of pool-forming large woody debris and all other large woody debris pieces by position (top) and orientation (bottom) for 11 old-growth streams. Position codes are: RB = touching right bank only; LB = touching left bank only; MC = touching neither bank (midchannel); and SP = touching both banks (spanning). Orientation is in degrees: 0° is parallel to stream flow, 90° is perpendicular to stream flow (see text).


60
50
40
30
20
10
0
PERCENTAGE OF LWD
LWD FORMING POOLS (n=148)
ALL OTHER LWD (n=1221)
RB
LB
MC
SP
POSITION

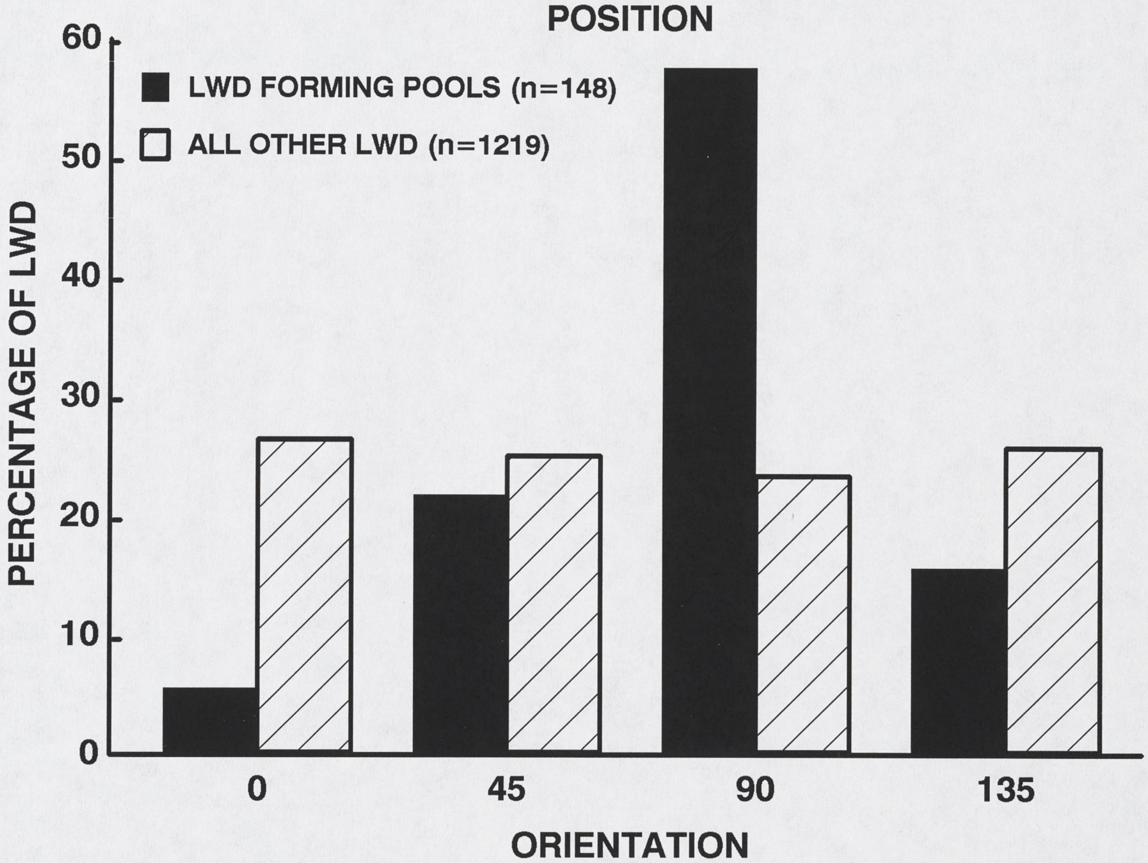
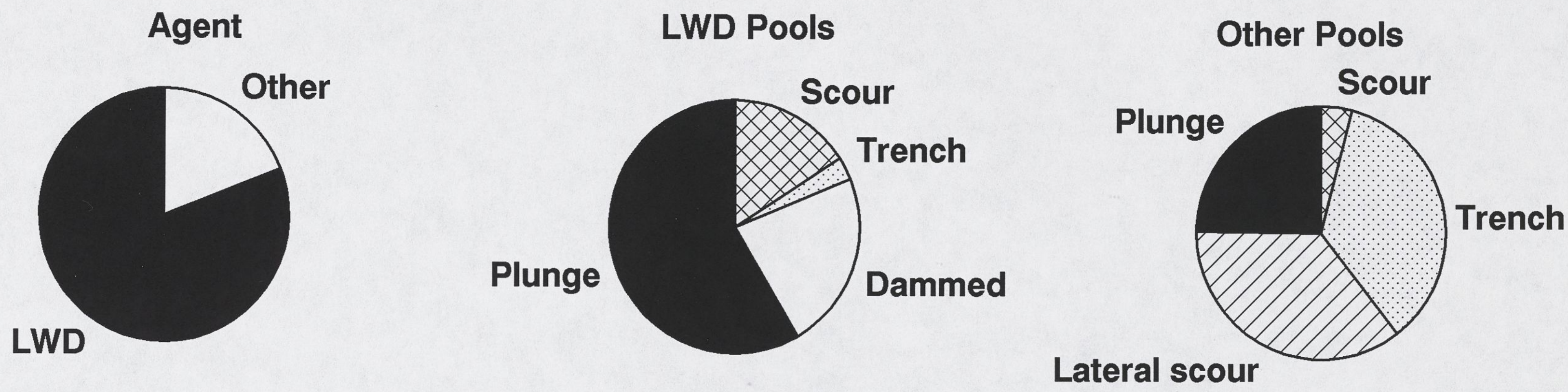

60
50
40
30
20
10
0
PERCENTAGE OF LWD
LWD FORMING POOLS (n=148)
ALL OTHER LWD (n=1219)
0
45
90
135
ORIENTATION

Fig. 5. Percentages of pools formed by large woody debris or other agents (i.e., boulder, meander bend), and of pools by types in 11 old-growth streams and four disturbed streams in Colorado. Sample size was 144 pools in the old-growth streams, and 38 pools in the disturbed streams.

Old-growth Streams



Disturbed Streams

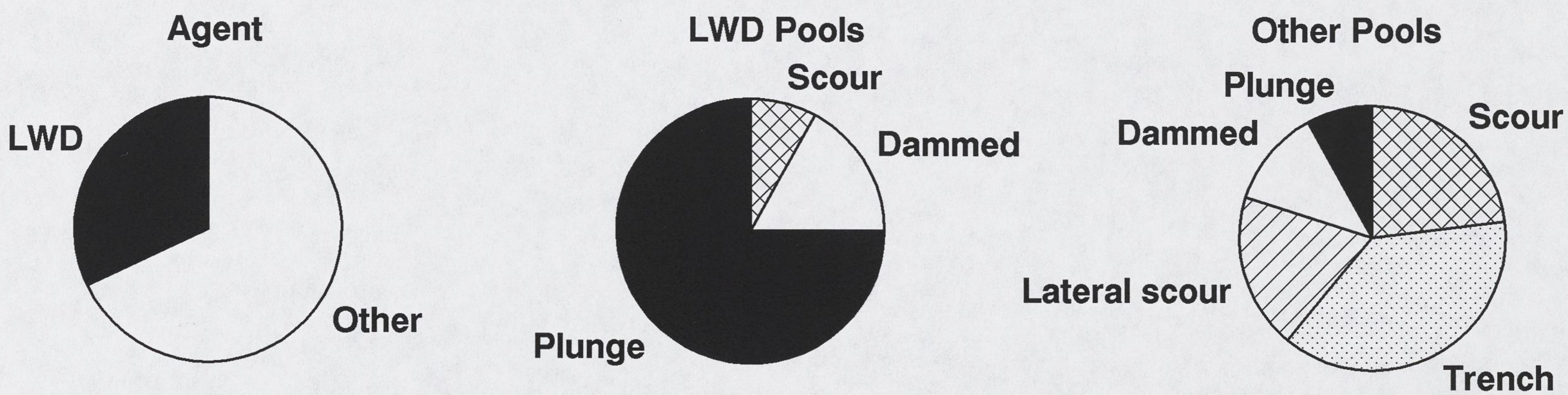
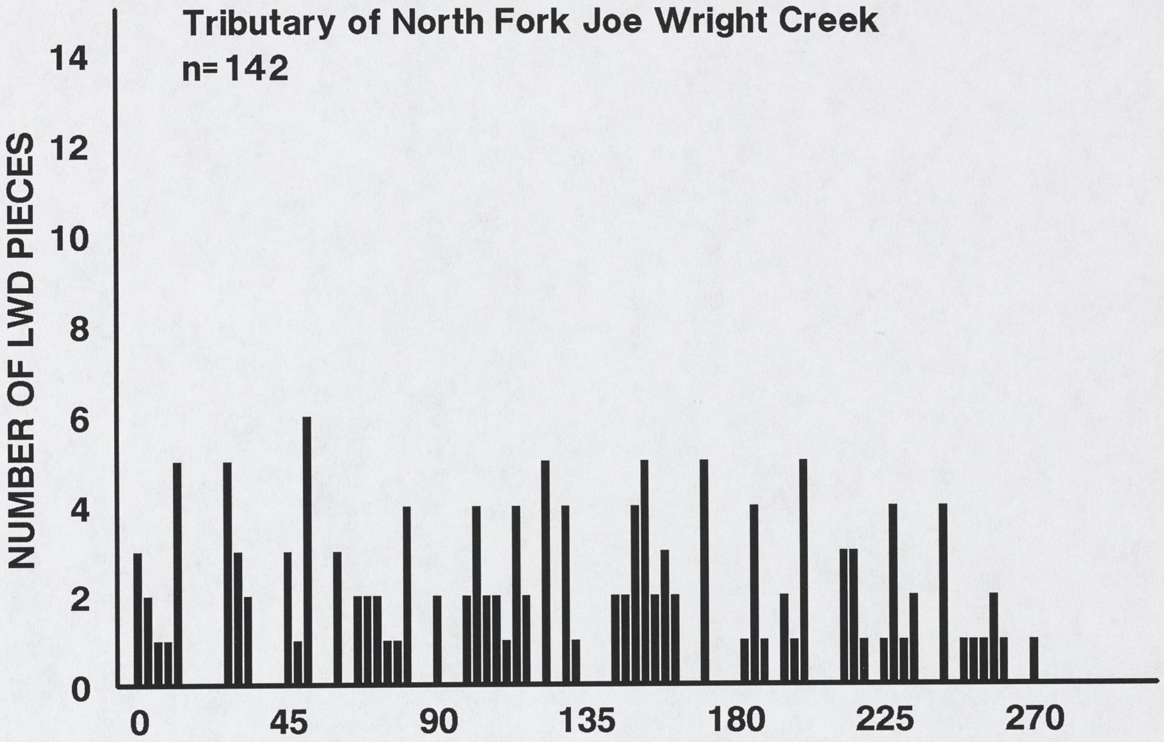
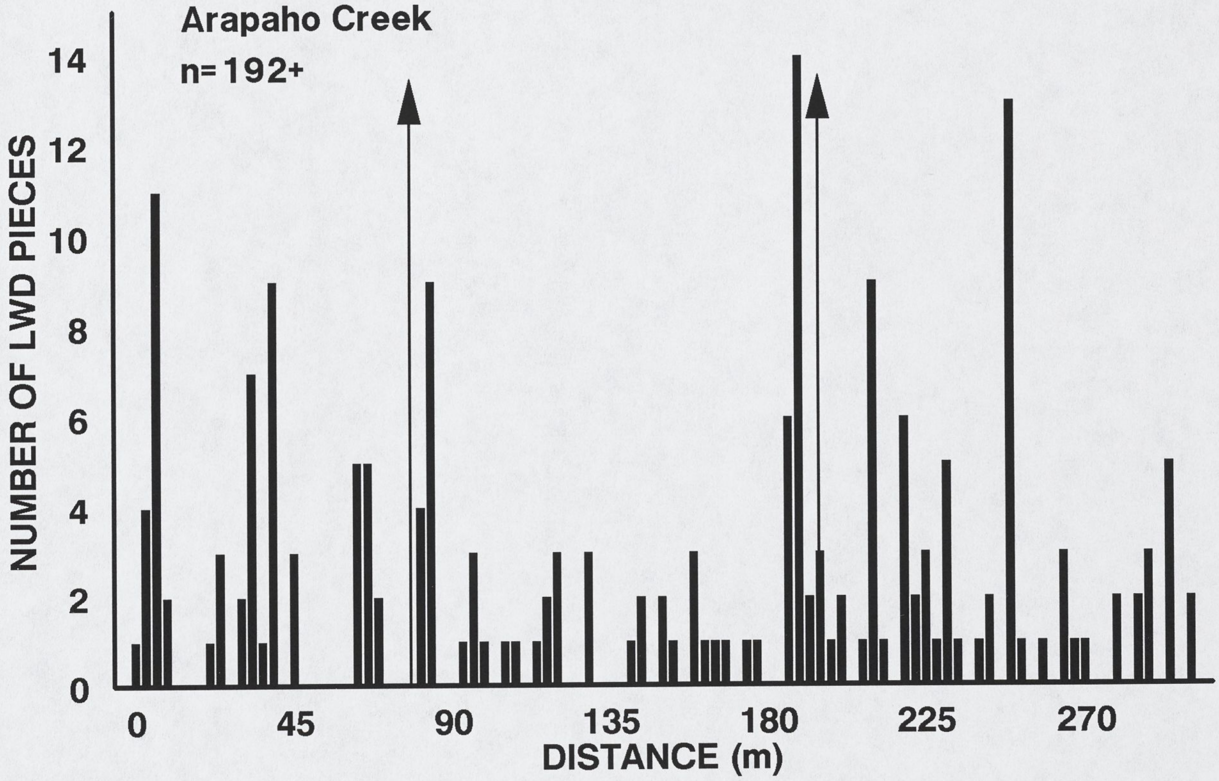


Fig. 6. Distribution of distances of large woody debris pieces along study reaches in the tributary of North Fork Joe Wright Creek (top), which is representative of small streams (<5.0 m bankfull width), and Arapaho Creek (bottom), where large woody debris is clumped, which is representative of the four larger streams measured in north central Colorado. Arrows indicate locations of two very large debris accumulations in Arapaho Creek.


Tributary of North Fork Joe Wright Creek
n=142
NUMBER OF LWD PIECES
0
2
4
6
8
10
12
14
0
45
90
135
180
225
270


Arapaho Creek
n=192+
NUMBER OF LWD PIECES
0
2
4
6
8
10
12
14
0
45
90
135
180
225
270
DISTANCE (m)

MANAGEMENT APPLICATIONS

Introduction

The objectives of this research were to measure LWD abundance and characteristics in streams associated with spruce-fir old-growth forests in the Arapaho and Roosevelt National Forests, and to assess how it shapes channel morphology and forms fish habitat. Published data on LWD in the central Rocky Mountain region are largely lacking, except for one paper on a stream in southeastern Wyoming (Young et al. 1990). One goal of this study was to provide managers with information on LWD that will be useful in their efforts to rehabilitate and enhance stream habitat, manage riparian zones for long-term recruitment of LWD, and measure relevant LWD characteristics during stream inventories. In this section we synthesize information from the research described above to address these management applications.

Implications for Rehabilitating and Enhancing Stream Habitat

Here we present the 10 major findings from our research that we believe will be most useful to managers attempting to rehabilitate and enhance stream habitat in spruce-fir forests of the central Rocky Mountains. These statements are based on analyses described in the previous section, and apply only to relatively small, moderate gradient streams with B-channels (Rosgen 1985) that have characteristics in the ranges shown in Appendix Table 9. Results are not likely to apply as well in other channel types, forest types, or in other regions. Each major finding presented is followed by supporting data or explanation. Attributes that can be estimated from predictive regression equations are noted (see below).

1. Overall, natural LWD abundance in old-growth streams was 43 pieces per 100 m.

• Woody debris piece abundance is based on data from 11 old-growth streams in the Arapaho-Roosevelt National Forests of northern Colorado.

• Abundance of LWD (>4 inches diameter, >3 feet long) varied from 18 to 64 pieces per 328 ft. (100 m), and was greater in larger streams.

• We suspect that debris abundance may be even higher in streams subjected to natural disturbance (e.g., fire, blowdown) within the past 250 years, which would no longer have old-growth riparian forests.

2. Most pools in old-growth streams were formed by LWD, and most were plunge and dammed pools.

• Fifty-nine percent of the pools formed by LWD were plunge pools and 23% were dammed pools.

• Plunge pools occurred more frequently in higher-gradient streams. [Regression available to estimate proportion of plunge pools from stream gradient (see below)]

• Streams with higher LWD abundance had significantly more pools per 10 channel widths than did streams with less LWD. [Regression available to estimate pool abundance from LWD abundance]

3. Only 10% of all LWD pieces measured formed pools. On average, these pieces were larger than all other pieces.

• The percentage of LWD pieces forming pools ranged from 4-20% among streams.

• Smaller streams had proportionately more LWD pieces forming pools than larger streams. [Regressions available to predict percentage of LWD pieces forming pools from stream size]

• On average, pool-forming LWD was 8.5 in. (22 cm) in diameter, compared to 7.5 in. (19 cm) for all other pieces, and 14.4 ft. (4.4 m) in length, compared to 8.5 ft. (2.6 m) for all other pieces.

• Longer pieces of LWD are more likely to achieve stability in streams, and thus more likely to form pools.

• Even small pieces (4 in. diameter, 3 ft. long) can form pools in small streams (Appendix Fig. 2).

4. Most pieces of LWD that formed pools lay perpendicular to flow and spanned the bankfull channel.

• Single debris pieces formed the majority of pools (70%).

• Smaller streams had a higher proportion of LWD pieces spanning the channel and nearly perpendicular to stream flow than did larger streams. [Regressions available to estimate proportion of pieces spanning or perpendicular from stream size]

• In larger streams, wood was less likely to span the channel and tended to be oriented diagonal to stream flow.

5. Woody debris pieces which formed the framework of debris accumulations were larger, on average, than all other debris pieces.

- Twenty-four debris pieces were identified as providing the framework, or backbone, of debris accumulations in the 11 old-growth streams.
- Mean diameter of backbone pieces was 9 in. (23 cm) and mean piece length was 31.5 ft. (9.6 m).
- The majority of backbone pieces (79%) spanned the channel.
- Fifty-eight percent of the backbone pieces were oriented diagonally to stream flow and 25% were oriented perpendicular to stream flow.

6. Most LWD pieces were old and decayed. However, the 10% of pieces that formed pools were of all decay classes, indicating that younger pieces also formed pools.

- Among streams, 56-78% of all LWD pieces were either extensively rotted or breaking apart.
- Higher proportions of pieces with limbs or bark in four streams suggested that an episodic event (e.g., storms causing blowdown) had occurred recently.

7. Disturbed streams had less LWD and significantly smaller LWD than old-growth streams, but a similar number of pools.

• Woody debris abundance ranged from 2 to 26 pieces per 100 m in four stream reaches that generally lacked LWD due to past activities in the riparian zone. Pieces of LWD in disturbed streams were significantly shorter and of less volume than in old-growth streams.

• Most pools (68%) in disturbed streams were formed by agents other than LWD, such as boulders and meander bends.

• Of the 32% of pools formed by LWD, plunge pools were the most common type.

• Although pool abundance in disturbed streams was similar to old-growth streams, the percentage of stream area as pools was less, suggesting that agents other than LWD formed smaller pools.

8. Streams with higher LWD abundance had more overhead log cover and bank cover for fish.

• Overhead cover provided by LWD was greatest in larger, low-gradient streams with more LWD. It may be that in smaller, high-gradient streams with low width-to-depth ratios, LWD is less likely to lay in the channel in positions that form overhead cover, whereas in larger, low-gradient streams LWD is more likely to lay in ways that provide overhead cover. [Regressions available to predict log cover from stream size, gradient, and LWD abundance]

• Cover provided by undercut banks was greater in streams of moderate or low gradient with more LWD. Wood in these systems may stabilize banks, allowing undercutting to occur, or it may direct flow against banks, which may be less resistant. [Regression available to predict bank cover from width, gradient, and LWD abundance]

9. Larger streams are wider and have enough power to move LWD into clumps or to the channel margins, so individual LWD pieces are less likely to become stable and form pools in streams wider than 25-35 ft. (8-10 m).

• Large woody debris pieces in Colorado streams are generally short and of small diameter, so single pieces are less likely to assume stable positions that span the channel perpendicular to flow in larger streams.

• Large woody debris in Colorado streams is generally too small to affect channel morphology and form pools in large streams (≥35 ft. bankfull width), even if it does become stable.

• In large streams, accumulations of LWD were always larger and more frequent than expected by chance, most likely due to being moved by flow. In smaller streams (<16 ft. (5.0 m)), accumulations often were also more frequent than expected, but this was probably due to several trees being toppled as a larger tree falls, or other factors.

10. Surface area and residual depth of pools formed by single LWD pieces was influenced most by stream size, rather than LWD size.

• Residual pool depth was greater in larger streams. [Regression available to estimate residual pool depth from stream size]

• Statistical analysis showed that after accounting for the effects of stream width or drainage area, gradient, and individual streams, LWD variables had no significant effect on surface area or depth of individual pools. This indicates that geomorphic and fluvial characteristics of streams exert primary control on individual pool size and type.

• These results suggest that once a LWD piece becomes stable in a stream, it may then form a pool whose depth and surface area are a function of stream power and the underlying geology and geomorphology of the system.

Predictive Regressions

Several regression equations that can be used to predict characteristics of stream habitat from LWD variables or stream characteristics were described in the previous section. This section explains how such models may be used, and refers the reader to Appendix Table 10, which shows the parameters for all models that were fitted. All models are based on data from 11 old-growth streams of B channel-type in spruce-fir forests of the Arapaho and Roosevelt National Forests in northern Colorado, and so are not expected to be useful in other channel types or other biomes or regions. Here we present two examples of regression equations that may be useful for managers.

Predicting Average Residual Pool Depth from Stream Size

Several simple linear regressions that we developed predict average residual pool depth for a stream reach from drainage basin area or stream width. The model for the first is highly significant (P=0.0007) and relatively precise (r^2=0.74):

$$\text{Average residual pool depth (cm)} = 23.228 + 0.761 \cdot \text{Drainage area (km}^2\text{)}$$

Thus, for a stream of 20 km^2 (7.7 mi^2) drainage area, average residual pool depth is predicted to be:

$$\text{Average residual pool depth} = 23.228 + 0.761 \cdot (20) = 38 \text{ cm (15 in.)}$$

Ninety-five percent prediction intervals indicate the range in which the next observation will lie, with 95% expected to lie within the interval. In other words, of the next 100 streams for which predictions are made, actual values for 95 are expected to lie within the 95% prediction interval. Predicted average residual pool depth, and its 95% prediction intervals, are presented in Appendix Fig. 3. The prediction intervals are quite wide, primarily due to the small sample size used to fit the model (n=11 streams). Despite this, the models are useful as tools to understand the relative importance of LWD and other factors in influencing stream habitat across stream sizes.

Predicting Proportion of Pool Area from Stream Width and LWD Abundance

Many regressions we fit were of proportions, and required a logit transformation to meet statistical assumptions, which makes prediction more challenging. One such equation predicts the logit of proportion of pool area from two variables, LWD abundance and the interaction term LWD abundance times stream width. The model is significant (P=0.035) and moderately precise (R^2=0.57):

$$\propto = \ln (P/1\text{-}P) = -2.305 + 0.0311 \cdot (LWD) - 0.00239 \cdot (LWD \cdot width)$$

Where: P = proportion of stream area as pools

LWD = LWD pieces per 100 m (328 ft)

width = bankfull stream width (m)

Once the equation is solved for alpha, the actual proportion of pool area can be determined by the back transformation: $P = 1/(1 + e^{-\propto})$. Thus, if a manager wanted to predict the proportion of pool area eventually to be expected in a 4-m wide (13 ft.) stream after supplying it with 40 pieces of LWD per 328 ft. (100 m), the calculations would be:

$$\propto = -2.305 + 0.0311 \cdot (40) - 0.00239 \cdot (40)(4)$$

$$= -1.4434$$

Back transformation:

$$P = 1/(1+e^{-\propto}) = 1/(1+e^{-(-1.4434)})$$

$$P = 1/(1+4.24)$$

$$P = 0.19, \text{ or } 19\% \text{ pool area}$$

Predicted proportion of pool area, and 95% prediction intervals, for streams of 4 m (13 ft.) wide at different levels of LWD abundance are shown in Appendix Fig. 4.

It is hoped these models will be useful to managers for predicting how characteristics of LWD and pools in altered streams can be expected to change when LWD is added to achieve debris levels present in old-growth streams. An understanding of such stream responses to LWD will also be useful to managers when developing stream habitat management strategies in this region. For example, if funds are available for only two or three stream habitat improvement projects, a manager may be able to use these predictive models to aid in selecting stream reaches where success is most likely.

Recruitment from the Riparian Forest

Riparian forests should be managed to ensure that sufficient amounts of LWD of adequate size are available for future recruitment to streams. When pooled across streams, even LWD of small sizes formed pools (Appendix Fig. 2), although small pieces were effective primarily in smaller streams. In contrast, in Arapaho Creek, the largest stream sampled (33 ft. (10.2 m) bankfull width), LWD that formed pools was significantly larger and of greater volume than in most of the other streams.

Different methods have been developed to estimate recruitment rates, source distance, and number of riparian trees needed to replace LWD in streams of the Pacific Northwest (McDade et al. 1990; Robison and Beschta 1990; Van Sickle and Gregory 1990). However, Robison and Beschta (1990) and Van Sickle and Gregory (1990) make broad, simplifying assumptions, such as that trees will fall in random directions and at relatively uniform rates through time. We suspect that these assumptions are generally unrealistic for the central Rocky Mountains, and probably other regions as well. It is likely that a greater understanding of riparian spruce-fir stand dynamics will be necessary to determine the number and sizes of trees needed for adequate LWD recruitment in the central Rocky Mountain region. As a result, it will be important for fishery biologists to work closely with forest biologists to successfully manage riparian forests for LWD recruitment.

Despite the complexity of LWD recruitment, we suggest two basic approaches that future researchers and managers might use to estimate the number of trees needed in riparian forests for adequate future LWD recruitment:

1. Maintain Large Woody Debris Abundance - Ensure that enough riparian trees are present to maintain a supply of about 43 debris pieces per 330 ft. (100 m) of stream in a range of diameters >4 in. (10 cm) and lengths >3 ft. (1 m). More LWD, and more pieces of larger size, would be needed in larger streams; less LWD would be needed in smaller streams (see Appendix Table 7).

2. Supply Pool-forming Pieces - Use pool frequency per 330 ft. (100 m) of stream as an indicator of the number and size of LWD pieces needed for recruitment from riparian forests. In this study, we found a maximum of 3-4 pools per 10 channel widths, and pools were formed by debris pieces which averaged 8.5 in. (22 cm) in diameter and 14.4 ft. (4.4 m) long. However, only 10% of the total LWD pieces formed pools at any one time, and not all large stable debris pieces were associated with pools. We suggest that these data could be combined to estimate the numbers of LWD pieces of certain sizes needed to maximize pool habitat. Thus, riparian forests could be managed to ensure that an adequate number of logs of the required size are recruited to streams to maintain a desired pool frequency.

Important LWD Characteristics to Measure in Stream Inventories

Fishery managers must conduct stream habitat inventories to assess current stream conditions and identify fish habitat types that may be in short supply. Therefore it is important for managers to know the most important characteristics of streams and LWD to measure for a variety of applications.

Current Arapaho-Roosevelt National Forests stream habitat inventory (level III) procedures assess woody debris as follows:

- Record woody debris pieces that lie within the flood-prone channel.

- Record the number of debris pieces in three size categories: fine (≤4 in. diameter, <3 ft. long); small (4-8 in. diameter, ≤15 ft long); and large (8-15 in. diameter, ≤25 ft. long).

- Estimate the percentage of debris pieces in seven decay classes, based on Grette (1985; see Appendix Table 5).

- Estimate square feet of resting and escape cover provided by LWD and undercut banks.

Additional measures of LWD characteristics may be beneficial to fishery managers when assessing current and future fish habitat in streams. In making the following recommendations, we strove for maximum information with minimum time and effort. These recommendations pertain mainly to streams 10-26 ft. (3-8 m) in bankfull width. We emphasize that characteristics measured and categories chosen will depend, in part, on stream size and the objectives of the inventory.

1. Size - Large woody debris piece size is an important factor influencing its stability within the stream, its role in providing fish habitat, and its longevity in the system.

a. Diameter - Woody debris pieces <4 in. (10 cm) diameter play a less important role than larger pieces, except possibly in systems where only small woody debris is available for recruitment. **We recommend that average piece diameters be classified in four 4-in. (10-cm) intervals: 4-8, 8-12, 12-16, ≥16 in. (10-20, 20-30, 30-40, ≥40 cm).**

b. Length - Woody debris piece length is probably more important than diameter in influencing piece stability. Minimum piece lengths of 3-10 ft. (1-3 m) have been used to define LWD in various studies, but minimum length used for management purposes should be determined by stream size. **We recommend classifying piece length in the following categories: 3-6, 6-13, 13-26, ≥26 ft. (1-2, 2-4, 4-8, ≥8 m).**

2. Influence categories - Location of large woody debris in relation to the channel influences its role in forming fish habitat. **We propose the following four influence categories to record piece location:**

a. Completely within the wetted channel

b. Partially within the wetted channel

c. Between the wetted and bankfull channel

d. Above the bankfull channel

3. Position - Large woody debris position within the channel can affect its stability, and its role in forming pools, and fish habitat. Woody debris pieces that span the channel are most stable and form most pools, whereas pieces in midchannel are least stable. **We recommend three position categories: touching one bank, spanning, and midchannel.**

4. Orientation - Large woody debris orientation in relation to stream flow plays an important role in determining whether a piece will form a pool. It is also an indicator of the ability of stream flow to redistribute LWD. **We recommend three orientation categories: parallel to flow (0°), perpendicular to flow (90°), and diagonal to flow (45° and 135°).**

5. Function - Six functions were attributed to LWD in this study: pool formation, sediment storage, overhead cover, bank stability, catching other debris, and no apparent function. Which, if any, functions are recorded depends on objectives of the investigator.

For example, if adequate salmonid spawning habitat is of interest, it may be useful to record pieces storing sediment. If spawning habitat is not a concern, but overwintering habitat is, the investigator may choose to record function for those pieces associated with pools, but not for those pieces storing sediment.

6. Decay classes - The usefulness of decay classes depends on the type of information needed. For example, we found that LWD of all decay classes functioned to form pools. Therefore, if a biologist is interested in how much LWD is available to form pools over the next 20 years, it may be most important to know what proportion is in the oldest decay classes and likely to break apart and wash away in the near future, while also knowing the amount in younger decay classes that is available to enter the stream and form pools over the next 100-200 years. Early in the research we discovered that wood in this region does not break and decay as Grette (1985) proposed, based on research in the Pacific Northwest, so his eight classes were modified (Appendix Table 5), and combined into five that we judged most informative. **We propose using these five decay classes:**

a. Bark intact, limbs and twigs present

b. Bark loose or absent, limbs present

c. Bark and limbs absent, surface solid to slightly rotted

d. Log surface extensive to completely rotted

e. Log breaking apart or broken

7. Very large debris accumulations - Very large debris accumulations were prevalent in the larger streams (>33 ft. (10 m) bankfull width), although their function and importance is unclear. They may provide important fish habitat at high flows when velocity refuges are likely to be critical. They may also be important to channel stability and energy dissipation at high flows. Without these steps in gradient to dissipate energy, greater channel erosion and sediment transport would likely occur. **It is important to record the occurrence of such large accumulations, and we suggest the following protocol:**

a. Measure the dimensions (width, length, height)

b. Categorize the diameter and length of backbone pieces when possible (see categories above)

c. Estimate the proportion of pieces larger than 8 in. (20 cm) diameter and longer than 6-13 ft. (2-4 m), ***or***

d. Estimate the proportions of debris comprising the majority of the accumulation that fall in various diameter and length categories (see above)

Recording common debris piece sizes in a large accumulation can provide an indication of accumulation stability (i.e., whether the stream is likely to break through at higher flows), and can give an indication of the size and amount of LWD available in the system. Large accumulations are also a source of LWD for downstream reaches.

8. Stream size - This research has shown that the role large wood debris plays in streams depends on larger-scale stream characteristics of bankfull width (or drainage area) and gradient. Stream response to LWD will depend on stream size and gradient, so these characteristics should always be measured. Stream bankfull width and drainage area were highly correlated, and results from this research suggest that either measure of stream size can be used in predictive models. Bankfull width can be accurately measured during stream inventories, based on about 10 measurements evenly spaced along a reach. Drainage area and stream gradient can be obtained from topographic maps and, when coupled with the relationships developed from this study, can provide investigators with information on how streams that fall within the constraints of these data may respond to LWD. However, care must be taken when using drainage area to ensure that climatic and geologic characteristics are similar among comparisons.

Appendix Table 1. Characteristics of study reaches in 11 old-growth and 4 disturbed streams in north central Colorado where large woody debris was measured. Stream order was determined from U. S. Geological Survey 1:24,000 topographic maps, based on perrenial streams only.

Stream	Location (T R S)	Elevation (m)	Stream order	Reach length (m)	Drainage area (km^2)	Sinuosity	Gradient	Valley type	Valley floor width (m)	Side-slope (%)	Discharge (m^3/s)
					OLD-GROWTH STREAMS						
Trib. Joe Wright Cr.	7N 75W 19	3204	1	268	3.4	1.04	0.027	glacial	119	22	----
Trib. N. Fk. Joe Wright	7N 76W 14	3085	1	285	2.4	1.08	0.064	glacial	180	19	0.100
N. Fork Joe Wright Cr.	7N 76W 23	3036	2	577	3.9	1.20	0.034	glacial	128	25	----
Hourglass Creek[a]	7N 74W 14	3109	1	221	5.1	1.14	0.006	glacial	190	23	----
Fall Creek	7N 73W 19	2914	3	263	9.9	1.20	0.030	glacial	278	18	----
Beaver Creek	7N 74W 10	3011	2	260	8.9	1.34	0.004	glacial	303	21	----
N. Fork Poudre R.	10N 74W 3	2902	1	277	11.0	1.13	0.020	glacial	150	13	----
Little S. Fk. Poudre R.	7N 73W 30	2847	3	344	21.7	1.32	0.027	glacial	267	27	----
Baker Gulch	4N 76W 29	2743	2	314	17.4	1.04	0.033	glacial	96	30	0.214
Bowen Gulch	4N 76W 3	2829	2	260	24.5	1.13	0.034	glacial	200	32	0.323
Arapaho Creek	1N 74W 5	2719	3	300	29.1	1.20	0.022	glacial	162	45	0.359
					DISTURBED STREAMS						
N. Fork Poudre R.	10N 74W 21	2730	2	250	----	1.22	0.010	glacial	---	--	0.398
Colorado Creek	6N 82W 29	2775	2	245	----	1.20	0.025	glacial	---	--	0.047
Jack Creek	5N 77W 13	2925	2	245	----	1.25	0.007	glacial	---	--	0.584
Walton Creek	5N 83W 15,16	2775	2	245	----	1.10	0.012	glacial	---	--	0.131

[a] Tributary of Hourglass Reservoir

Appendix Table 2. Primary (top) and ancillary (bottom) old-growth characteristics developed by the U. S. Forest Service for Arapaho and Roosevelt National Forests (Lowry 1992). All characteristics need not be present in old-growth stands.

Primary Old-growth Characteristics

1. Presence of large live trees (≥35 cm dbh), including 15 or more trees per acre[a] ≥30 cm dbh.

2. Presence of large snags (≥35 cm dbh), including 2 or more snags per acre[a] ≥30 cm diameter.

3. Presence of large fallen trees (≥35 cm dbh), including 3 or more per acre[a] ≥30 cm diameter.

4. Presence of multi-storied canopy.

5. Overhead canopy closure >20%.

6. Presence of large, old, senescing live trees.

[a] 1 acre = 0.4 ha

Ancillary Old-Growth Characteristics

1. Presence of more than one tree species.

2. Presence of small openings with grasses, forbs, or shrubs.

3. Presence of seedlings, saplings, or poles.

4. Little or no evidence of logging.

5. Little or no evidence of fire, insect, or wind disturbance.

Appendix Table 3. Modified Wentworth substrate size classification (after Orth 1983).

Substrate type	Diameter (mm)
Silt, Clay	<0.062
Sand	0.062-2.0
Gravel	2.0-64.0
Cobble	64.0-256.0
Boulder	>256.0

Appendix Table 4. Influence zones for large woody debris (from Robison and Beschta 1990a).

Zone	Characteristics
1	Within the wetted channel during low flow
2	Between baseflow and bankfull flow
3	Directly above the active channel
4	The portion of any wood in zones 1, 2, or 3 that is resting on the stream bank

Appendix Table 5. Decay classes for large woody debris. Modified classification from Grette (1985), left; Grette's decay classification, right.

Class	Modified decay classes	Class	Grette's decay class
1	Bark intact, limbs and twigs present	1	Bark intact, limbs and twigs present
2	Bark loose or absent, limbs present	2	Bark intact, limbs absent
		3	Bark loose or absent
3	Bark and limbs absent, surface solid		
4	Bark and limbs absent, surface slightly soft or rotted	4	Bark absent, surface slightly rotted
5	Surface extensively soft or rotted	5	Surface extensively rotted
6	Surface completely soft or rotted, log intact	6	Surface completely rotted, center solid
7	Surface completely soft or rotted, log splitting or breaking apart	7	Surface and center completely rotted
8	Outer surface absent and/or inner core breaking apart		

Appendix Table 6. Stream and habitat characteristics measured in 11 old-growth and 4 disturbed streams in north central Colorado. Habitat codes are: po = pool; ri = riffle; gl = glide. Pool codes are: S = scour; P = plunge; D = dammed; L = lateral scour; T = trench. Substrate codes are: G = gravel; C = cobble; B = boulder.

Stream	Total area (m^2)	Percent habitat area			Mean bankfull width (m; SE)	Total pool volume (m^3)	Number of pools					Percent pools by LWD	Pools per 10 channel widths	Mean maximum pool depth (SE, range; cm)	Mean residual pool depth (SE; cm)	Dominant substrate percentages		
		po	ri	gl			S	P	D	L	T					G	C	B
OLD-GROWTH STREAMS																		
Trib. Joe Wright Creek	990	12	87	3	3.7 (0.14)	15.4	3	7	1	1	1	85	1.79	38 (3.06) (25-60)	22 (3.14)	43	46	3
Trib. N. Fork Joe Wright Creek	1063	17	39	44	3.8 (0.12)	24.8	0	15	5	0	0	90	2.67	46 (0.02) (34-66)	28 (2.61)	57	16	19
N. Fork Joe Wright Creek	2270	18	66	14	3.9 (0.07)	50.1	2	22	2	1	3	90	2.03	39 (1.55) (26-60)	23 (1.85)	45	35	13
Hourglass Creek[a]	910	16	25	60	4.1 (0.14)	21.5	2	1	0	1	2	67	1.11	51 (4.00) (41-68)	36 (4.89)	76	13	2
Fall Creek	1081	18	58	24	4.1 (0.13)	34.0	2	3	3	0	0	71	1.09	56 (3.08) (47-70)	28 (4.45)	17	44	23
Beaver Creek	1092	30	13	57	4.2 (0.11)	65.7	3	8	3	3	0	88	2.75	51 (3.87) (30-98)	33 (4.10)	68	10	3
N. Fork Poudre R.	1369	17	71	13	4.5 (0.12)	34.7	0	2	4	1	2	78	1.46	47 (2.71) (33-59)	26 (3.04)	25	24	33
Little S. Fork Poudre R.	1912	15	45	40	5.6 (0.12)	49.8	4	2	1	1	1	78	1.47	61 (3.82) (45-85)	39 (4.36)	37	43	8
Baker Gulch	2192	22	40	38	7.0 (0.26)	72.5	0	12	1	2	1	81	3.57	58 (0.04) (35-91)	36 (4.50)	50	35	7
Bowen Gulch	2082	20	73	8	8.0 (0.21)	60.1	1	3	1	1	4	30	3.08	65 (0.04) (51-85)	40 (4.28)	33	31	23
Arapaho Creek	3067	11	78	11	10.2 (0.51)	79.3	1	1	4	0	0	83	2.04	83 (0.02) (74-89)	48 (4.28)	30	34	27
DISTURBED STREAMS																		
N. Fork Poudre R.	----	7	81	12	4.0[b]	17.0	0	1	0	2	3	17	0.96	61 (0.04) (45-69)	30 (4.92)	24	48	6
Colorado Creek	----	20	58	22	4.5	32.0	2	7	2	2	3	44	2.94	44 (0.02) (31-65)	25 (2.72)	29	32	17
Jack Creek	----	9	74	17	4.8	19.0	0	3	0	1	3	43	1.37	57 (0.05) (44-72)	22 (4.46)	10	84	4
Walton Creek	----	3	--	--	5.1	10.0	5	0	3	0	1	11	1.87	48 (0.03) (40-65)	25 (3.36)	20	43	35

[a] Tributary of Hourglass Reservoir

[b] Bankfull widths based on only one transect at each pool (n=6-16)

Appendix Table 7. Characteristics of large woody debris measured in study reaches of 11 old-growth and 4 disturbed streams in north central Colorado.

Stream	Pieces per 100 m	Median length (m)	Median diameter (m)	Median volume (m^3)	Total volume per 100 m (m^3)	Bankfull biomass (Mg/ha)	Overhead log cover (m/100 m)	Overhead bank cover (m/100 m)
OLD-GROWTH STREAMS								
Trib. Joe Wright Creek	18	7.7	0.22	0.407	9.3	36.6	9.5	4.0
Trib. N. Fk. Joe Wright Cr.	50	3.1	0.21	0.119	20.7	101.7	6.9	1.9
N. Fork Joe Wright Creek	24	3.1	0.20	0.115	6.6	37.3	6.3	2.6
Hourglass Creek[a]	33	2.9	0.22	0.107	12.8	53.9	7.9	9.9
Fall Creek	46	3.7	0.19	0.108	14.3	74.6	11.4	7.5
Beaver Creek	54	2.3	0.18	0.069	9.1	66.3	24.5	21.8
N. Fork Poudre R.	37	2.8	0.20	0.239	12.6	49.2	13.6	15.6
Little S. Fork Poudre R.	32	3.3	0.18	0.075	11.8	45.1	9.8	3.2
Baker Gulch	59	2.8	0.16	0.062	11.7	42.5	11.0	1.6
Bowen Gulch	60	2.1	0.18	0.058	10.5	37.8	7.0	1.8
Arapaho Creek[b]	64	2.6	0.20	0.085	27.1	68.5	21.2	0.4
DISTURBED STREAMS								
N. Fork Poudre R.	22	2.7	0.16	0.057	3.1	----	9.7	13.5
Colorado Creek	26	2.8	0.20	0.095	6.6	----	24.9	25.5
Jack Creek	16	1.7	0.15	0.036	1.3	----	13.5	15.5
Walton Creek	2	5.8	0.24	0.223	0.6	----	2.6	9.8

[a] Tributary of Hourglass Reservoir
[b] Excluding LWD pieces in two large debris accumulations

Appendix Table 8. Position, function, and relative age by percentage of large woody debris pieces in study reaches of 11 old-growth and 4 disturbed streams in north central Colorado. Influence zone codes are: A = completely within wetted channel; B = partially within wetted channel; C = between wetted and bankfull channel; D = above active channel. Orientation is in degrees in relation to direction of stream flow (0 = parallel to flow; 90 = perpendicular to flow). Decay codes are: B = bark present; L = bark absent but limbs present; SR = bark and limbs absent, solid to slightly rotted; ER = extensively to completely rotted, log intact; O = log beginning to break apart or broken (see text). The number of pieces measured in each stream (N) is shown.

Stream	Influence zone				Position				Orientation				Function					Decay					N
	A	B	C	D	R	L	M	S	0	45	90	135	pool	sed.	cover	other	none	B	L	SR	ER	O	
OLD-GROWTH STREAMS																							
Trib. Joe Wright Creek	38	19	15	28	23	11	6	60	29	13	51	7	15	32	15	2	37	13	13[b]	7[b]	13	54	47
Trib. N. Fk. Joe Wright	26	31	38	5	35	31	10	24	25	23	29	23	12	23	6	24	36	<1	8	27	16	47	152
N. Fork Joe Wright Creek	22	33	41	4	30	44	4	22	21	18	38	23	20	13	8	7	51	6	1	16	24	53	138
Hourglass Creek[a]	40	24	26	10	43	42	10	6	24	24	18	35	10	3	18	3	68	10	6	17	21	47	72
Fall Creek	12	27	35	27	34	27	13	26	18	22	34	27	6	3	15	12	64	16	1	25	28	31	117
Beaver Creek	33	34	23	11	33	21	27	19	26	24	33	17	7	12	35	3	44	6	1	23	33	37	140
N. Fork Poudre R.	34	14	31	20	27	41	7	25	13	31	32	24	16	13	22	14	35	11	11[b]	6[b]	11	61	102
Little S. Fork Poudre R.	7	16	42	34	29	34	26	11	10	37	24	29	6	1	14	19	60	18	5	17	17	42	111
Baker Gulch	24	22	48	6	40	35	11	14	24	27	27	22	9	14	6	15	55	<1	12	13	31	44	186
Bowen Gulch	18	16	63	3	34	47	16	3	29	26	17	27	4	5	8	23	58	<1	7	12	13	65	155
Arapaho Creek	21	15	57	7	29	27	39	5	32	22	17	29	4	2	10	16	68	1	16	28	16	40	192
DISTURBED STREAMS																							
N. Fork Poudre R.	40	25	25	9	38	35	15	13	33	24	27	16	5	3	23	31	38	2	5	25	15	53	55
Colorado Creek	27	9	55	9	41	25	13	21	22	34	34	9	13	23	9	25	66	0	17	20	22	41	64
Jack Creek	39	11	47	3	16	39	42	3	22	22	46	11	10	16	14	22	38	5	8	29	13	45	38
Walton Creek	0	60	40	0	60	20	0	20	0	0	60	40	17	17	17	17	33	0	0	40	0	60	5

[a] Tributary of Hourglass Reservoir

[b] These classifications, using Grette's decay classes, might have been classified differently using the modified version of Grette's classification, and thus cannot be compared to similarly classified LWD in the other reaches.

Appendix Table 9. Ranges in characteristics of 11 old-growth streams measured.

Forest type	Engelmann spruce-subalpine fir
Elevation (m)	2719-3294
Valley type	glacial
Valley floor width (m)	96-303
Sideslope (%)	13-45
Stream order	1st-3rd
Channel type[a]	B
Drainage area (km^2)	5.1-29.1
Gradient (%)	0.4-6.4
Sinuosity	1.04-1.34
Bankfull width (m)	3.7-10.2

[a] After Rosgen (1985)

Appendix Table 10. Parameters for linear regression models that predict stream and LWD characteristics. Predicted variables that are transformed using logit can be back-transformed using $p=1/(1+e^{-\propto})$, where ∝ is the predicted value, and p is the percentage sought. Width = bankfull width (m); area = drainage area (km^2); gradient = proportion (0.06, not 6%); LWD abundance = pieces per 100 m (328 ft.); biomass = LWD biomass (Mg/ha; see text). Influence categories: A = LWD pieces wholly within the wetted channel; B = LWD pieces at least partially within the wetted channel; C = LWD pieces above wetted, but within bankfull channel. See text for example of equation use.

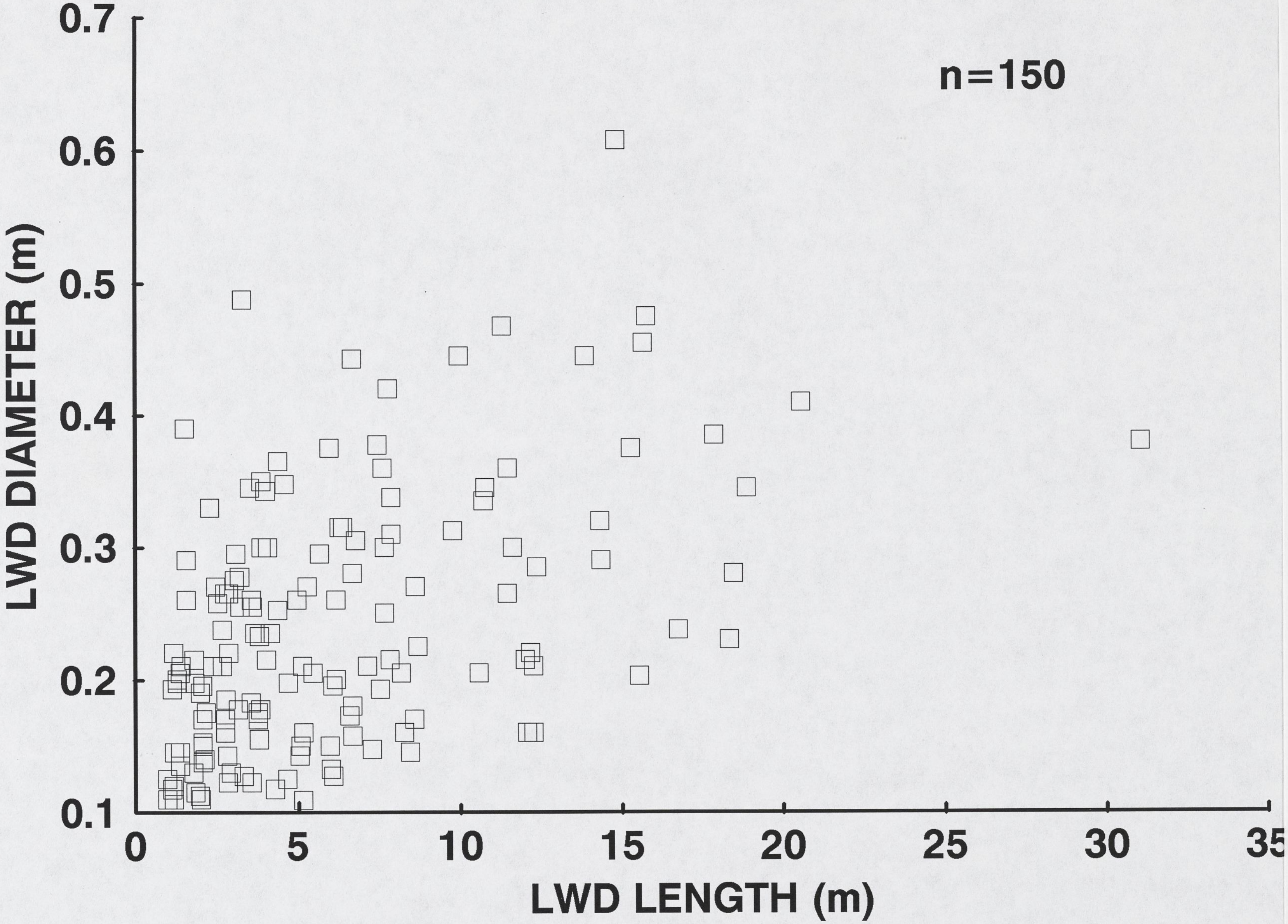
Predicted variable	Predictors	Coefficients (*b*)	SE(*b*)	*P*	r^2 or R^2	*N*
Logit(percent pieces spanning)	intercept	0.215	0.6909	0.016	0.49	11
	width	-0.356	0.1202			
Logit(percent pieces spanning)	intercept	-0.683	0.4263	0.017	0.49	11
	area	-0.0813	0.02785			
Logit(percent pieces perpendicular)	intercept	-0.0701	0.3297	0.020	0.47	11
	width	-0.161	0.0574			
Logit(percent pieces perpendicular)	intercept	-0.482	0.2051	0.024	0.45	11
	area	-0.0365	0.01340			
Percent pieces in influence categories A and B	intercept	68.306	9.8653	0.053	0.35	11
	width	-3.813	1.7167			
Percent pieces in influence categories A and B	intercept	62.319	4.6323	0.004	0.62	11
	area	-1.162	0.3026			
Percent pieces in influence category C	intercept	8.546	7.4105	0.002	0.67	11
	width	5.499	1.2896			
Percent pieces in influence category C	intercept	22.977	4.9125	0.004	0.61	11
	area	1.211	0.3209			
Logit(percent pieces forming cover)	intercept	-0.977	0.2140	0.0006	0.75	11
	width*gradient	-6.542	1.2720			
Logit(percent pieces forming cover)	intercept	-0.388	0.3534	0.002	0.78	11
	width	-0.118	0.0513			
	gradient	-33.295	6.8678			

Appendix Table 10. Continued.

Predicted variable	Predictors	Coefficients (b)	SE(b)	P	r^2 or R^2	N
Logit(percent pieces forming pools)	intercept	-1.255	0.3828	0.014	0.50	11
	width	-0.202	0.0666			
Logit(percent pieces forming pools)	intercept	-1.689	0.2014	0.003	0.64	11
	area	-0.052	0.0132			
Logit(percent pool area)	intercept	-2.305	0.2742	0.035	0.57	11
	LWD abundance	0.0311	0.00962			
	LWD abund.*width	-0.00239	0.000818			
Logit(percent plunge pools)	intercept	-1.423	0.5589	0.052	0.36	11
	gradient	39.994	17.8452			
Pools per 10 channel widths	intercept	0.713	0.6778	0.050	0.36	11
	LWD abundance	0.0319	0.01414			
Residual pool depth	intercept	14.923	3.7589	0.0007	0.74	11
	width	3.314	0.6541			
Residual pool depth	intercept	23.228	2.3157	0.0007	0.74	11
	area	0.761	0.1513			
LWD cover	intercept	3.147	2.6752	0.003	0.84	11
	area	1.186	0.2472			
	area*gradient	-41.904	7.8599			
	LWD abundance	0.172	0.0729			
LWD cover	intercept	4.980	3.9417	0.025	0.60	11
	width*gradient	-50.844	18.0548			
	LWD abundance	0.327	0.1015			
LWD cover	intercept	11.497	3.3657	0.019	0.63	11
	gradient	-232.147	80.7891			
	biomass*width	0.0223	0.00847			
Bank cover	intercept	15.431	2.6911	0.004	0.62	11
	width*gradient	-16.816	15.9949			
Bank cover	intercept	8.834	3.1250	0.001	0.81	11
	width*gradient	-83.108	14.3139			
	LWD abundance	0.224	0.0805			
Bank cover	intercept	18.342	3.4712	0.003	0.85	11
	width	-2.891	0.6602			
	gradient	-315.406	64.0551			
	LWD abundance	0.282	0.0914			

Appendix Fig. 1. Orientation classes, in degrees, used to describe large woody debris in 11 old-growth and 4 disturbed streams.

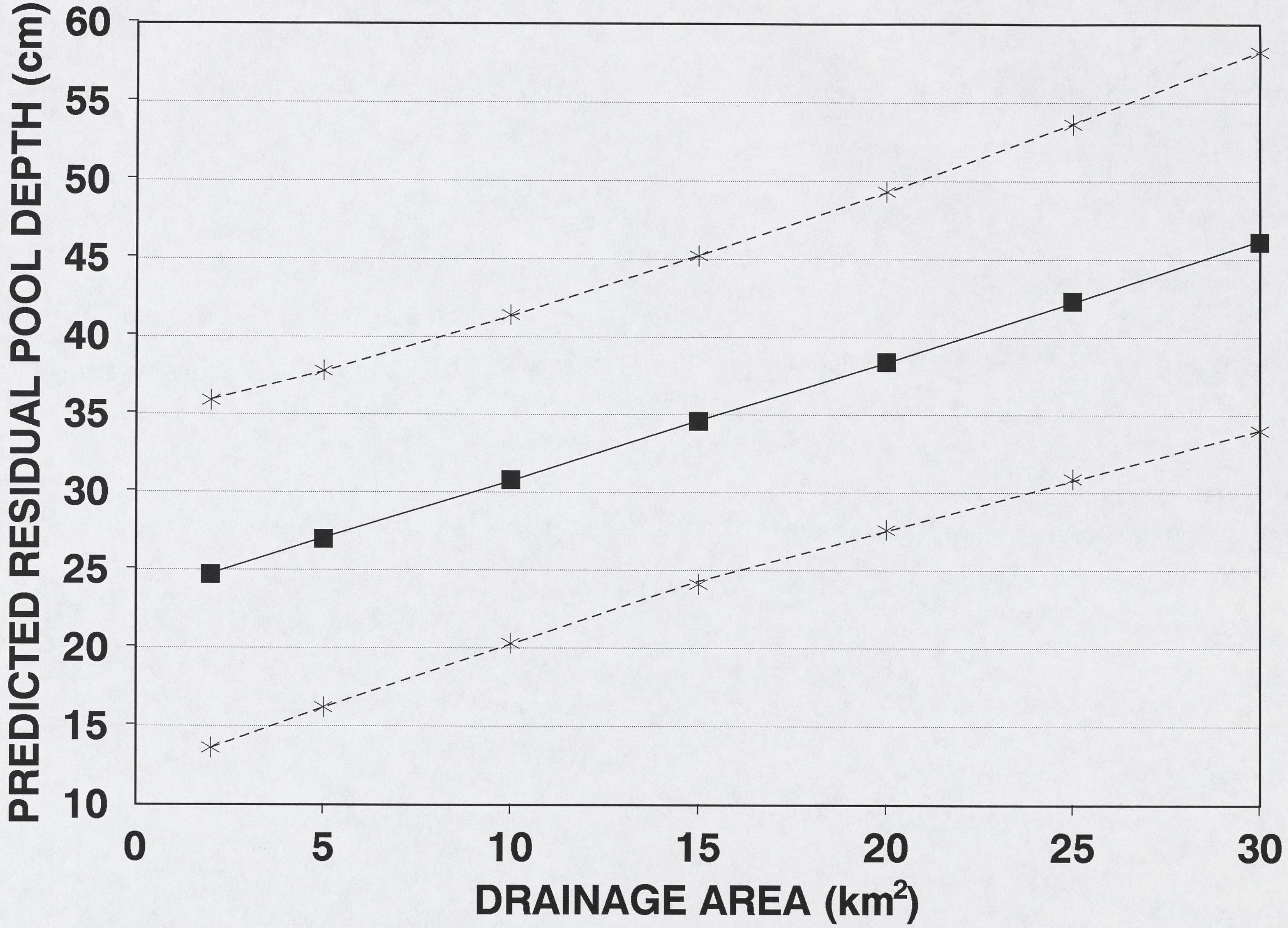
Appendix Fig. 2. Large woody debris piece diameter as a function of piece length for 150 debris pieces forming pools in 11 old-growth reaches measured in northern Colorado.



n=150
LWD DIAMETER (m)
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
5
10
15
20
25
30
35
LWD LENGTH (m)

84 90

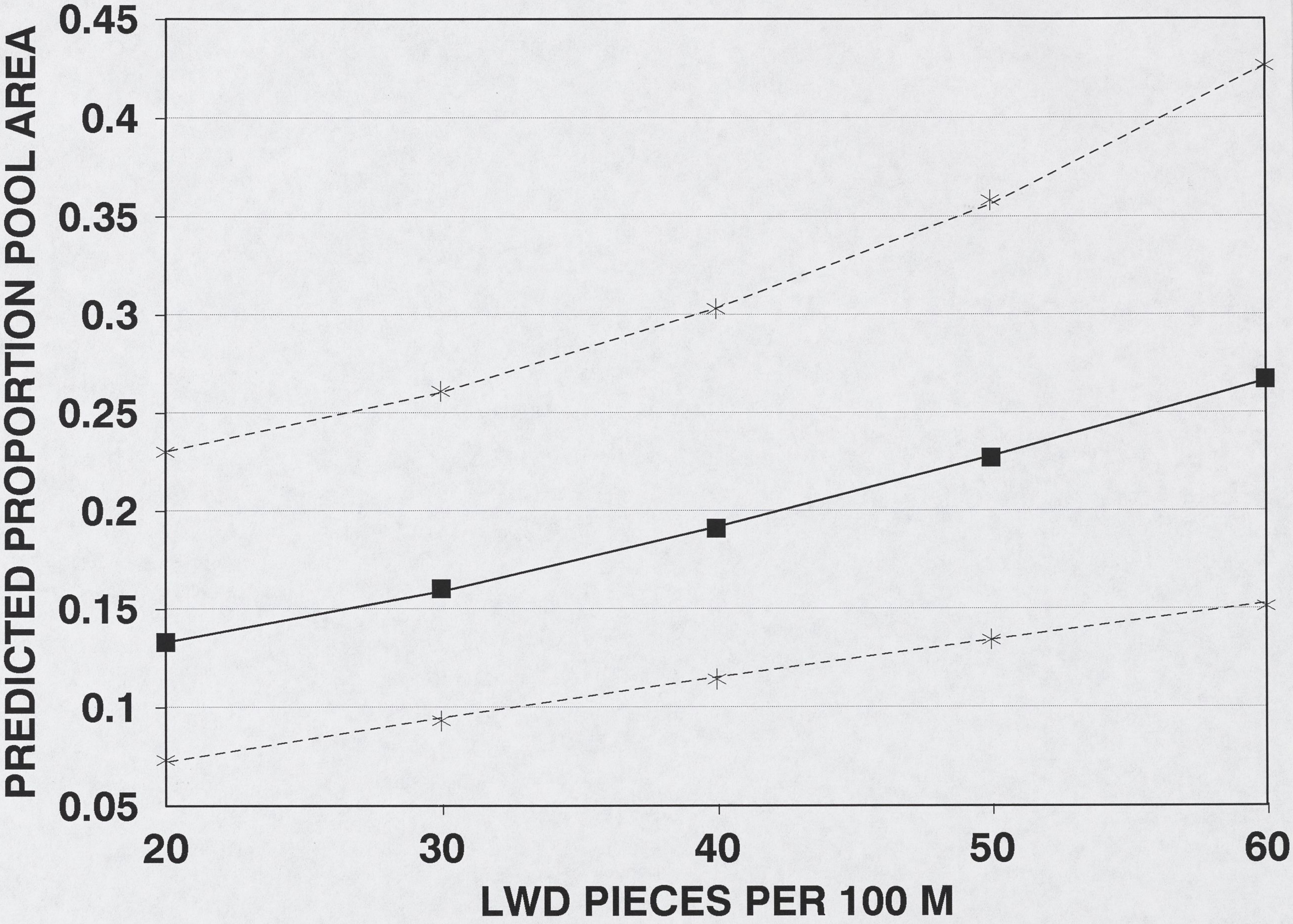
Appendix Fig. 3. Predicted mean residual pool depths, with 95% prediction intervals, across a range of drainage basin areas. Predictions are based on a regression equation for 11 old-growth streams in northern Colorado (see text).



PREDICTED RESIDUAL POOL DEPTH (cm)
60
55
50
45
40
35
30
25
20
15
10
0
5
10
15
20
25
30
DRAINAGE AREA (km2)

98 92

Appendix Fig. 4. Predicted proportion of stream area made up by pools, with 95% prediction intervals, for streams 13 ft. (4 m) bankfull width across a range of large woody debris piece abundance. Predictions are based on a regression equation for 11 old-growth streams in northern Colorado (see text).


PREDICTED PROPORTION POOL AREA
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
20
30
40
50
60
LWD PIECES PER 100 M