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[Article]

A Regional and Geomorphic Reference for Quantities and Volumes of Instream Wood in Unmanaged Forested Basins of Washington State

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Abstract.—We collected field data on instream wood quantities and volumes from 150 stream segments draining unmanaged basins within Washington State to develop reference conditions for restoration and management. The wood loads in these streams provide a reference for management since it is assumed that they incorporate the range of conditions to which salmonids and other species have adapted. We also used these data to evaluate existing standards for large wood in streams. Large wood is an important component of salmonid habitat, and stream channel assessments and restoration and enhancement efforts often associate habitat quality for salmon *Oncorhynchus* spp. with the quantity and volume of woody debris; however, the wood targets currently used to assist resource managers typically do not account for variations in quantity or volume owing to differences in geomorphology, forest zones, or disturbance regimes. For restoring the appropriate range of conditions in salmon habitat, we offer a percentile wood distribution of natural and unmanaged wood-loading ranges based on regional and geomorphic variation for the purpose of reestablishing central tendencies. We recommend that streams in a degraded state (e.g., below the 25th percentile) be managed for an interim target at or above the 75th percentile until the basin-scale wood loads achieve these central tendencies. Based on the sample distribution, these reference conditions are applicable to streams with bank-full widths between 1 and 100 m, gradients between 0.1% and 47%, elevations between 91 and 1,906 m, drainage areas between 0.4 and 325 km^2, glacial and rain- or snow-dominated origins, forest types common to the Pacific Northwest, and several other distinguishing physical and regional classifications.

Because large woody debris (LWD) is an important indicator of salmonid habitat, resource managers often rely on standards for the number and size of large pieces of wood to evaluate and restore wood to streams. Typically, these standards are not applicable to all channel types and regions owing to multiple factors that influence variability. Wood loads in natural and unmanaged streams are often assumed to provide a reasonable reference for management since they incorporate the range of conditions to which salmonids and other species have adapted.

This paper examines data on the number and volume of wood from unmanaged streams to (1) develop reference ranges as a resource management tool to assess, protect, restore, and enhance salmonid habitat in streams as it relates to wood and (2) evaluate existing management targets for geomorphic and regional compatibility. The objective of this study is to develop references for instream wood quantities based on natural geomorphic and regional characteristics for streams both east and west of the Cascade Mountains of Washington State. These references will be compared with instream wood standards currently applied to streams in the Pacific Northwest.

The role of LWD in Pacific Northwest streams is linked to channel processes that benefit salmonids. Woody debris plays an important role in controlling channel morphology, the storage and routing of sediment and organic matter, and the creation of fish habitat (Bisson et al. 1987; Bjornn and Reiser 1991). Large wood creates habitat heterogeneity by forming pools, back eddies, and side channels, and by increasing channel sinuosity and hydraulic complexity (Spence et al. 1996). Pools are, perhaps, one of the most important habitat features for salmon *Oncorhynchus* spp. formed by LWD (Keller and Swanson 1979). In high-energy channels, LWD functions to retain spawning gravel and can also provide thermal and physical cover for salmonids (Schuett-Hames et al. 1994). Wood indirectly serves as an important food source for salmonids by providing nutrients and insects to the stream (Naiman and Sedell 1979; Spence et al. 1996) or by retaining salmon carcasses (Cederholm et al. 1989; Bilby et al. 1996). Wood serves as cover for

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juvenile salmonids, which are particularly vulnerable to predators when migrating (Larsson 1985). The geomorphic potential of the channel to process wood into features that benefit salmonids is often limited by the quantity and size of wood (Abbe and Montgomery 1996).

Channel responses to wood vary with the geomorphic characteristics of the stream (Murphy and Koski 1989; Robison and Beschta 1990; Montgomery et al. 2003). In high-energy channels, LWD functions to retain spawning gravel and can also provide thermal and physical cover for salmonids (Schuett-Hames et al. 1994). Logjams can create sections of low gradients with alluvial substrates in bedrock channels by storing sediment upstream of the jam (Montgomery et al. 1996; Massong and Montgomery 2000), which can provide localized low-gradient habitats in steep valley segments where none would otherwise have existed.

Restoration activities in the Pacific Northwest often involve long-term recovery of riparian and channel processes and are frequently combined with short-term "fixes" by the placement of habitat structures. Often, to expedite habitat recovery while riparian areas convalesce, wood is placed in streams to provide habitat for salmonid use (Reich et al. 2003; Roni et al. 2003). We assume that, to maximize the success of improving habitat, the amount of wood placed in a channel or intended to be recruited from riparian management areas is representative of the wood quantities and volumes to which salmonids have adapted. A one-size-fits-all wood target approach may diminish habitat heterogeneity by reducing the natural range of wood conditions. Therefore, knowledge of the natural variation of instream wood loads among different stream types and regions should improve restoration activities as well as the scientific defensibility of regulatory thresholds.

The number and volume of instream wood are highly variable owing to several types of processes that influence the mass balance of wood in a system (Benda et al. 2003). Geomorphological features, such as channel size, channel type, and confinement, can influence wood loads and distribution (Bilby and Ward 1989; Montgomery and Buffington 1997; Rot et al. 2000; Martin and Benda 2001). Anthropological disturbances, such as riparian vegetation modifications, forest practices (Bilby and Ward 1991; Ralph et al. 1991), flow regulation (Nakamura and Swanson 2003), urban development, and agricultural practices, can also alter the amount of wood in channels. Natural disturbances, such as fire (Rot et al. 2000; Fox 2001), floods (Braudrick and Grant 2000), debris flows (Ikeya 1981; Costa 1984), and snow avalanches (Keller and Swanson 1979), are other factors having an impact on variability in wood loading over space and time. Regional considerations due to climate influences often dictate riparian characteristics that ultimately are reflected in instream wood loads (Tappeiner et al. 1997; McHenry et al. 1998; Rot et al. 2000).

Stream channel assessments often associate the size, distribution, and abundance of woody debris with salmon habitat quality. As a result, wood targets have been developed by state and federal agencies to evaluate the adequacy of instream wood quantities in the Pacific Northwest (Table 1). Efforts to restore riparian areas with the aid of various recruitment models tied to riparian characteristics and to enhance stream habitat through the artificial placement of wood often use objectives derived from these management targets.

The LWD piece quantity targets now frequently used as management and restoration standards were developed with the most complete data available for relating wood frequency to channel width in Pacific Northwest streams (Peterson et al. 1992). However, Spence et al. (1996) note that those targets do not fully consider potential sources of variation found throughout their application range and that they should only be applied to the types of streams for which they were derived. Because the current targets do not fully account for this variation and are applied generically, they may be inappropriate for some channel types and regions outside the area where the targets were developed. For example, a stream enhancement project may place wood in a stream channel based on the quantities recommended by target references, but these efforts may not provide the quantities or volumes of wood representative of local conditions to which salmonids have adapted. Because of the reliance upon wood targets by resource managers for critical decision making, a need exists to reevaluate existing wood targets and refine these values where appropriate.

Methods

To better characterize the natural quantities and volumes of instream wood within Washington State, survey sites were chosen within stream basins that are relatively unaffected by anthropogenic disturbance. Selected basins are characterized by forests that are loosely termed as "natural and unmanaged" and meet the following criteria: (1) no part of the basin upstream of the survey site was ever logged using forest practices common after European settlement and (2) the basin upstream of the survey site contains no roads or human modifications to the landscape that could affect the hydrology, slope stability, or other natural processes of wood recruitment and transport in streams. These basins will hereafter be referred to simply as "natural

TABLE 1.—Various state and federal management targets for large woody debris (LWD) used to define adequate salmonid habitat in Pacific Northwest streams.

Agency	Applicable region	Wood metric
National Marine Fisheries Service[a]	Coastal Washington	Number of LWD pieces
	Eastern Washington	Number of LWD pieces
U.S.Forest Service and Bureau of Land Management[b]	Anadromous fish-producing watersheds in western Oregon, Washington, Idaho, and portions of California	Number of LWD pieces
	Anadromous fish-producing watersheds in eastern Oregon, Washington, Idaho, and portions of California	Number of LWD pieces
Washington Forest Practices Board[c]	All forested streams of Washington, channels <20 m bank-full width	Number of LWD pieces
	Western Washington, channels <20 m in bank-full width (BFW)	Number of key pieces
Oregon Watershed Enhancement Board[d]	Western Oregon	Number of LWD pieces
		Volume of LWD pieces
		Number of key pieces

[a] Matrix of pathways and indicators (NMFS 1996) to address Endangered Species Act listed aquatic species in the Pacific Coast Salmon Plan (NMFS 1998).
[b] USFS and BLM (1995).
[c] WFPB (1997).
[d] Watershed Professionals Network (1998).

and unmanaged basins," although it is acknowledged that some basins are managed to remain pristine and that management may include fire suppression. The purpose of choosing sites in natural, unmanaged forested basins is based on the assumption that natural wood characteristics that have been influenced by natural disturbance cycles as found in these basins are those to which salmonids and other aquatic species have adapted and, hence, should provide a reasonable reference condition to the quantities and volumes of wood for management purposes.

Sites were stratified to represent a broad array of forest types, channel morphologies, and hydrological origins in Washington State. The strata served to characterize the channel in relation to the processes that drive fluvial geomorphology and represent a wide range of climates and vegetation types occurring in the Pacific Northwest (Table 2) that are also potential influences on the quantity and quality of instream wood. Comparisons with other Pacific Northwest management standards where similar forest types exist will offer valuable insight for managers, although the data were collected entirely in Washington State. Regional climatic variations that were presumed to control the characteristics of forest vegetation common to Pacific Northwest streams were grouped into forest zones using the classifications of Franklin and Dyrness (1973), Henderson et al. (1992), and Agee (1993; Table 2; Figure 1). Although riparian forests have some structural difference from their upland counterparts owing to soil heterogeneity, moisture, and other factors that may influence stand attributes, these regional climatic influences that classify forest zones provide information on the general characteristics of riparian areas of streams flowing through these forests.

All wood pieces greater than 10 cm in midpoint diameter and 2 m in length were counted and measured with tape and calipers within each survey reach. Stream survey methods used many components of the Timber–Fish–Wildlife (TFW) Monitoring Program method manuals (Pleus and Schuett-Hames 1998; Schuett-Hames et al. 1999), and riparian inventories were conducted following the methods of Cottam and Curtis (1956). Randomly selected stream segments were divided into three partitions before sampling to avoid clumping of survey reaches. Each survey reach was 100 m in length for channels up to 20 m in bank-full width (BFW) and 200–300 m in length for channels more than 20 m BFW. Minimum total sample length was 20 channel widths to fully represent repetitive patterns of the stream (Leopold et al. 1964; MacDonald et al. 1991; Montgomery and Buffington 1997); however, in channels approaching 100 m in width, surveys ceased at cumulative distances of approximately 1 km owing to time and personnel constraints.

Sites were evaluated in the field for disturbances caused by fires (date of stand origin) from the Cascade crest westward, floods (exceedance probability of 0.04 [25-year flood] recurrence within 10 years from preceding surveys), debris flows (15 years from preceding surveys), and snow avalanches (15 years from preceding surveys). Other forms of disturbances, such as catastrophic wind throw, insect and disease mortality, or other causes of tree mortality, are acknowledged as significant sources of wood recruitment to streams; however, these other disturbances were seldom observed in the surveys. Field crews had

TABLE 1.—Extended.

Agency	LWD minimum size criteria	Necessary quantity for adequate fish habitat
National Marine Fisheries Service[a]	15.2 m in length × 0.6 in diameter	>80 pieces/mile
	10.7 m in length × 0.35 in diameter	>20 pieces/mile
U.S.Forest Service and Bureau of Land Management[b]	15.2 m in length × 0.6 in diameter	>80 pieces/mile
	10.7 m in length × 0.35 in diameter	>20 pieces/mile
Washington Forest Practices Board[c]	2 m in length × 0.10 in diameter	>2 pieces/channel width
	1 m^3 (channels 0–5 m BFW); 2.5 m^3 (channels. >5–10 m BFW); 6 m^3 (channels. >10–15 m BFW); 9 m^3 (channels. >15–20 m BFW)	>0.3 pieces/channel width for streams <10 m BFW, and >0.5 pieces/channel width for streams 10–20 m BFW
Oregon Watershed Enhancement Board[d]	3 m in length × 0.15 in diameter	>20 pieces/100 m of stream
		>30 m^3/100 m of stream
	10 m in length × 0.60 in diameter	>3 pieces/100 m of stream

received formal training in TFW field methods through the stream monitoring programs at the Northwest Indian Fisheries Commission, and quality assurance–quality control (QA–QC) surveys were conducted on each crew member to ensure data replicability and accuracy. Based on the positive results of the QA–QC surveys (within 10%), confidence in the quality and accuracy of the data are high.

Data were analyzed by means of a three-pronged approach. First, descriptive statistics were calculated to establish correlations, check for normality, and evaluate correlation coefficients to eliminate variables that had less mechanistic value toward influencing wood loads based on field observations. Second, hypotheses relating to the variability of both (1) wood volume and (2) number of pieces as influenced by the above-referenced variables were evaluated with the Akaike information criterion (AIC). Based on our understanding of the processes that lead to wood in streams, we used AIC as a measure of fit for specific variables to an ordinary-least-squares (OLS) regression. Variables were chosen in a forward-model-selection, backward-elimination procedure based on the lowest AIC score (Burnham and Anderson 2002) to explain the full range of variability in the model. Third, we chose the best-fitting variables from the AIC subset based on the lowest P-values ($\alpha = 0.05$) and further tested these variables by comparing means of categorical groupings rather than individually using analysis of variance (ANOVA), post hoc tests of Tukey's least significant difference, and Fisher F-tests for testing variances (Zar 1999). Categorical groupings were combined, when warranted, based on homogenous means, which also increased statistical power of tests. Determining the strongest predictors for instream wood was done to enable practical graphical relationships to illustrate the range of the data and to make comparisons with other wood standards. Instream wood was scaled by a unit length (per 100 m) because of statistical advantages when grouping classes of different BFWs based on an independent analysis by Fox (2001). Data were $\log_{10}$ transformed to meet the assumptions of the general linear model and to test hypotheses from normally distributed populations (Zar 1999). Regressions were conducted with continuous and categorical data for the independent variables. All possible combinations of BFW classes (starting at 3- to 5-m bins) were initially based on visual fine groupings (histograms, scatterplots, and box plots), then tested and further grouped in this manner where warranted. Forest zones were grouped if they exhibited similar instream wood loads and riparian basal areas. Box-and-whisker plots are used to present the range of nonnormal data distributions, and the median and 75th and 25th percentiles are offered as reference points for management purposes.

Creating minimum-size definitions of qualifying "key pieces" was first needed to more widely assess key-piece quantities since the Washington Forest Practices Board (WFPB) has no standards for minimum key-piece volume for eastern Washington streams and none for western Washington streams greater than 20 m BFW (WFPB 1997). A "functional" piece of wood is likely to vary in size with stream size owing to the variation in physical forces that move wood in relation to stream size (WFPB 1997; Braudrick and Grant 2000); therefore, establishing minimum piece sizes according to channel size is justifiable. This rationale is also applicable to Oregon targets, where the minimum-size definition for key pieces as defined by the Oregon watershed assessment manual (Watershed Professionals Network 1998; Table 1) is applicable to all western Oregon channels rather than according to channel size. To accomplish this objective, minimum key-piece volumes for western Washington channels (>20 m BFW) were based on the geomorphic definition for "stability and function" given in WFPB (1997), namely,

> a log and/or rootwad that is (1) independently stable in the stream bank-full width (not functionally held by another factor, i.e., pinned by another log, buried, trapped against a

TABLE 2.—Forest zone, gradient, drainage area, confinement, bedform, channel type, and origin classes used to stratify surveyed stream reaches in Washington, 1999–2000.

Forest zone (abbreviation)[a]	Gradient (%)	Drainage area (km^2)[b]	Confinement[b]	Bedform[c]	Channel type	Origin
Sitka spruce *Picea sitchensis* (SS)	1	0–2	Confined	Plane bed	Alluvial	Snow melt or rain
Western hemlock *Tsuga heterophylla* (WH)	>1–2	>2–4	Moderately confined	Pool or riffle	Bedrock	Glacial melt
Silver fir *Abies amabilis* (SF)	>2–4	>4–8	Unconfined	Step pool		
Mountain hemlock *T. mertensiana* (MH)	>4–8	>8–20		Cascade		
Subalpine fir *A. lasiocarpa* (SF)	>8–20	>20–100				
Grand fir *A. grandis* (GF)[d]	20	>100				
Douglas-fir *Pseudotsuga menziesii*–ponderosa pine *Pinus ponderosa* (DF–PP)[d]						

[a] As described in Franklin and Dyrness (1973), Agee (1993), and Henderson et al. (1992).
[b] As defined in Pleus and Schuett-Hames (1998).
[c] As described in Montgomery and Buffington (1997).
[d] Predominantly found east of the Cascade crest.

rock or bed form) and (2) retaining (or [having] the potential to retain) other pieces of organic debris.

The length and diameter of key pieces are factors influencing buoyancy and mobility. Although some dimensional combinations (independent of rootwads) may influence piece stability more than others as they interact with channel shape, we assume that piece volume provides a reasonable representation of both length and diameter proportions factored into stability determinations. The presence of rootwads was also assessed in combination with key-piece size to determine their influence on stability.

Results

During the summer and fall of 1999 and 2000, 150 sites were surveyed that totaled nearly 38 km of stream length. Sampled stream gradients ranged between 0.04% and 49% and 139 of the sites (93%) met the WFPB (2001) physical criteria for fish presence. Although every possible combination of strata (Table 2) could not be sampled because of their unavailability

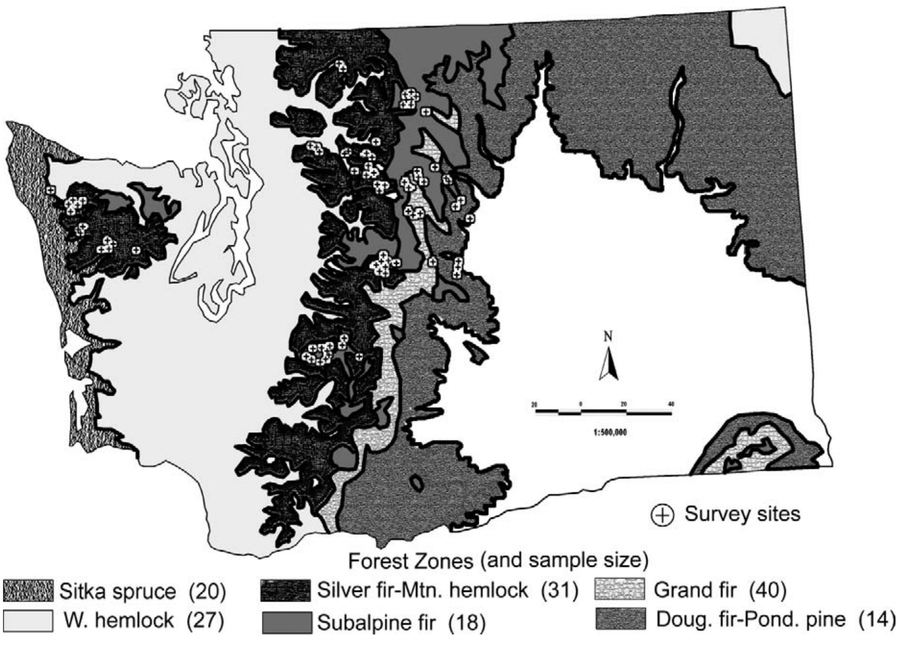

FIGURE 1.—Survey site distribution according to forest zones across Washington State, 1999 and 2000. Each point represents one or more streams ($n = 150$). The shadings represent forest zones and a vegetation classification system largely based on (1) natural fire succession and potential climax tree species, (2) elevation, and (3) climate. The forest zone boundaries depicted here are greatly simplified, and multiple plant associations can be found within these areas owing to microclimatic differences (after Franklin and Dyrness 1984; Henderson et al. 1992; Agee 1993).

TABLE 3.—Best-fitting regressions for the $\log_{10}$ transformed number of pieces and volume (m^3) of large woody debris (LWD) per 100 m of stream, as determined by Akaike information criterion values. Abbreviations are as follows: BFW = bank-full width; GF, SAF, SF–MH, and SS–WH =← grand fir, subalpine fire, silver fire–mountain hemlock, and Sitka spruce–western hemlock forest types; BR = bedrock bedform; MC and U = moderately confined and unconfined classes; slope =←channel reach slope. Times signs denote interaction terms.

Variable	Coefficient	SE	*t*-value	*P*-value
Pieces of LWD[a]				
Intercept	1.1326	0.2998	3.778	0.0002
$\log_{10}$(BFW)	0.2385	0.2272	1.0499	0.2958
GF	0.5357	0.3219	1.6642	0.0986
SAF	0.568	0.4116	1.3797	0.1701
SF–MH	0.6053	0.3607	1.6781	0.0958
SS–WH	0.4535	0.3155	1.4372	0.1532
BR	1.4232	0.4669	3.0482	0.0028
MC	0.0922	0.1497	0.6159	0.5391
U	0.0033	0.164	0.0202	0.9839
$\log_{10}$(slope)	0.0508	0.2387	0.213	0.8317
$\log_{10}$(BFW) × GF	0.2776	0.2481	1.1187	0.2654
$\log_{10}$(BFW) × SAF	1.591	0.4367	3.6431	0.0004
$\log_{10}$(BFW) × SF–MH	0.117	0.3097	0.3778	0.7062
$\log_{10}$(BFW) × SS–WH	0.5249	0.2377	2.2084	0.029
$\log_{10}$(BFW) × BR	0.634	0.2456	2.5815	0.011
$\log_{10}$(BFW) × MC	0.1193	0.1501	0.7952	0.428
$\log_{10}$(BFW) × U	0.2853	0.1536	1.857	0.0657
GF × BR	0.9373	0.3627	2.5846	0.0109
SAF × BR	1.0202	0.4522	2.2563	0.0258
SF–MH × BR	1.3031	0.3707	3.5149	0.0006
SS–WH × BR	1.0778	0.3657	2.9476	0.0038
GF × $\log_{10}$(slope)	0.2608	0.2567	1.0158	0.3117
SAF × $\log_{10}$(slope)	0.0588	0.3064	0.1917	0.8483
SF–MH × $\log_{10}$(slope)	0.1878	0.2923	0.6425	0.5217
SS–WH × $\log_{10}$(slope)	0.2865	0.2521	1.1363	0.258
Volume of LWD[b]				
Intercept	0.1823	0.2361	0.7721	0.4414
$\log_{10}$(BFW)	1.1338	0.2527	4.4876	0
GF	0.684	0.2511	2.7237	0.0073
SAF	0.2482	0.3741	0.6635	0.5082
SF–MH	1.9225	0.3355	5.7299	0
SS–WH	1.4871	0.2315	6.423	0
BR	0.194	0.2731	0.7104	0.4787
MC	0.5146	0.2256	2.2808	0.0242
U	0.0952	0.3435	0.2772	0.782
$\log_{10}$(slope)	0.1459	0.1112	1.3122	0.1917
$\log_{10}$(BFW) × GF	0.6076	0.2971	2.0451	0.0428
$\log_{10}$(BFW) × SAF	0.4256	0.5091	0.836	0.4047
$\log_{10}$(BFW) × SF–MH	1.3385	0.3573	3.7465	0.0003
$\log_{10}$(BFW) × SS–WH	0.8448	0.2732	3.0925	0.0024
$\log_{10}$(BFW) × BR	0.4857	0.2759	1.7607	0.0806
MC × $\log_{10}$(slope)	0.4001	0.1718	2.3291	0.0214
U × $\log_{10}$(slope)	0.1219	0.2196	0.5553	0.5796

[a] Standard error = 0.2731, df = 125, $R^2 = 0.5966$, $F_{24,;t3125} = 7.703$, $P = 3.442 \times 10\ ^{15}$.

[b] Standard error = 0.3737, df = 133, $R^2 = 0.6168$, $F_{16,;t3133} = 13.38$, $P = 0$.

in nature, the time constraints of the study, or both, sites nevertheless represented a diverse array of channel types, confinement classes, bedforms, dominant water origins, disturbance histories (fire, debris flows, snow avalanches, and floods), and forest types common in the Pacific Northwest. Basin drainages ranged between 0.4 km^2 and 325 km^2. Site elevations ranged between 91 m and 1,906 m (above mean sea level). A total of 21,671 LWD pieces were counted and measured. The general distribution of sites within each forest zone of Washington State is illustrated in Figure 1. Detailed sampling stratifications and site maps can be found in Fox (2001).

Modeling and Exploratory Analyses

We found that a $\log_{10}$ transformation provided normal distributions in the continuous data. Using these transformed data, we found that the AIC approach produced the best fit for predicting the number of LWD pieces and volume per 100 m of stream reach by including covariates of BFW, forest type, bedform, gradient, and confinement in the OLS regression along with several combinations of interactions (Table 3). Interactions predicting LWD number of pieces per 100 m are between BFW and forest type, BFW and bedrock bedform, BFW and confinement class, bedrock bedform and forest region, and channel reach slope and forest region. Interactions predicting LWD volume per 100 m are between BFW and forest type, BFW and bedrock bedform, and confinement class and channel reach slope.

In the exploratory analysis of these variables, we found that BFW and forest zone were also correlated with wood volume, but the covariates of bedform, gradient, and confinement were insignificantly correlated despite being included in the AIC selection process. This disparity between the two analyses is probably due to the difference in selection criteria and the low test power for regressions, ANOVA (among groupings), and other tests involving multiple strata, which often resulted in small samples. The descriptive analysis also suggests that wood loads have a high variance; however, there are differences in the distributions by discrete channel size-classes among regions. The following sections describe these differences as well as correlations in further detail.

Regional and Geomorphological Processes Affecting Instream Wood

Watershed and valley morphology play complex roles in the number and volume of instream wood. The number and volume of instream wood per 100 m of channel length generally increase as drainage area increases (linear regression: $P < 0.001$) and as streams become less confined, particularly in watersheds greater than about 10 km^2 in drainage area. We found that BFW is a significantly better predictor of wood parameters than basin size (paired-sample *t*-test: $P =$← 0.05), which stems from the fact that similar BFWs can

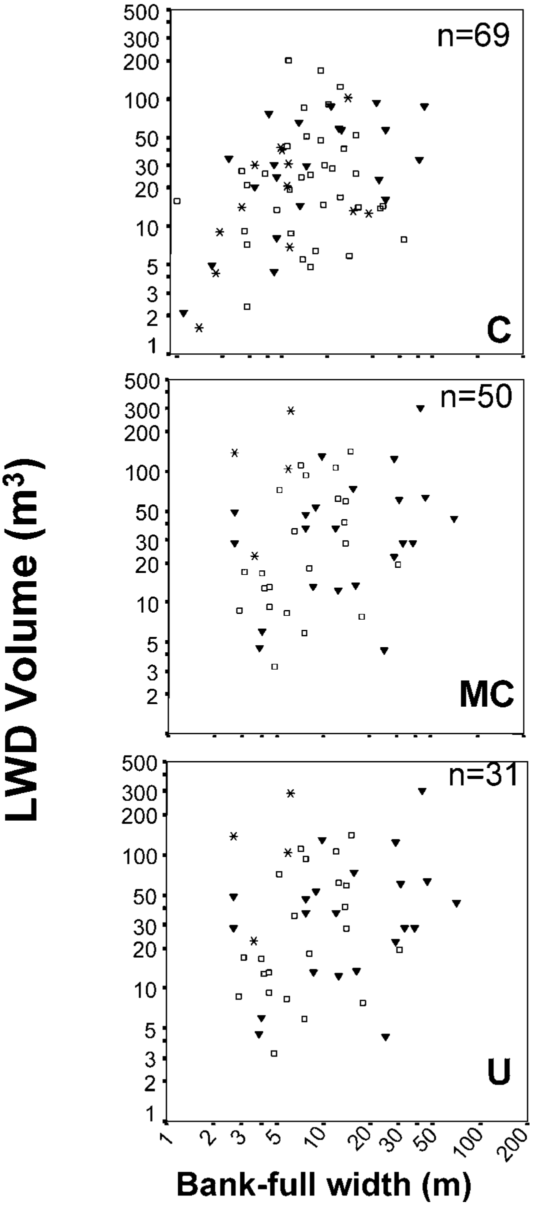

FIGURE 2.—The combined effect of gradient (triangles = 0–4%, squares = 4–20%, and asterisks = 20% or more) and confinement (confined [C], moderately confined [MC], and unconfined [U]) on the volume of instream wood (LWD) per 100 m of channel length by bank-full width for surveyed streams in Washington, 1999–2000.

be produced by different basin sizes owing to regional disparities in precipitation (e.g., western versus eastern Washington); however, because of the high error among all comparisons ($R^2 < 0.37$), there is probably little difference in predictive qualities between the two variables when wood is scaled per 100 m of channel length. The relationship of channel cross-sectional area to BFW is also strongly correlated ($R^2 = 0.93$) and highly significant ($P < 0.001$), suggesting that the cross-sectional area of high flow can be predicted by a BFW measurement. The isolated influences of gradient and confinement upon wood volumes are largely inconsistent (Figure 2) as well as for number of wood pieces, suggesting that there may be other controlling factors governing wood quantities; however, the small sample sizes per gradient and confinement stratification could not support statistical inferences.

In all basin sizes, more wood volume is generally observed in alluvial channels than in bedrock channels (Figure 3A), but the relatively small sample of bedrock channels does not allow statistical conclusions. This phenomenon, whether a cause or effect of the channel condition–wood relationship, holds true even when isolating the influence of gradient and confinement (Figure 3B). It should be noted that over 90% of the bedrock channels surveyed were in confined valleys.

In basin drainages of 70 km^2 or more, streams predominantly originating from glacial sources (e.g., Mount Rainier, Glacier Peak, and Mount Olympus) had significantly more wood volume per 100 m than streams fed predominantly with snowmelt and rain. This may be related to the larger number of side channels in streams originating from glacial sources, which averaged 3 per 100-m stream reach ($n = 7$) compared with only 1.8 in snow- or rain-dominated channels ($n = 47$). Although this phenomenon is noteworthy, the sample size of glacial-origin streams was too small to create a separate classification.

Although there is no significant relationship between channel morphology and the volume of wood, pool–riffle channels (where lateral migration is typical) commonly exhibited greater volume per 100 m than plane-bed, step-pool, or cascade morphologies.

Influences on Instream Wood by Channel Disturbance

Fire, as it affects riparian trees, was found to influence instream wood quantities and volumes in streams from the Cascade crest westward. Regression analysis suggests that instream wood volumes increase with adjacent riparian timber age, as dictated by the last stand replacement fire ($P = 0.013$). Riparian characteristics, such as mean tree diameter at breast height and basal area (m^2/ha), are influenced by timber age, increasing as stands grow older (both with $P < 0.001$).

Debris flows and snow avalanches probably have an effect on instream wood, although because of the paucity of sites that exhibited these forms of disturbance, statistical verification was not possible (power of test <20% in most cases). Trend analyses suggest

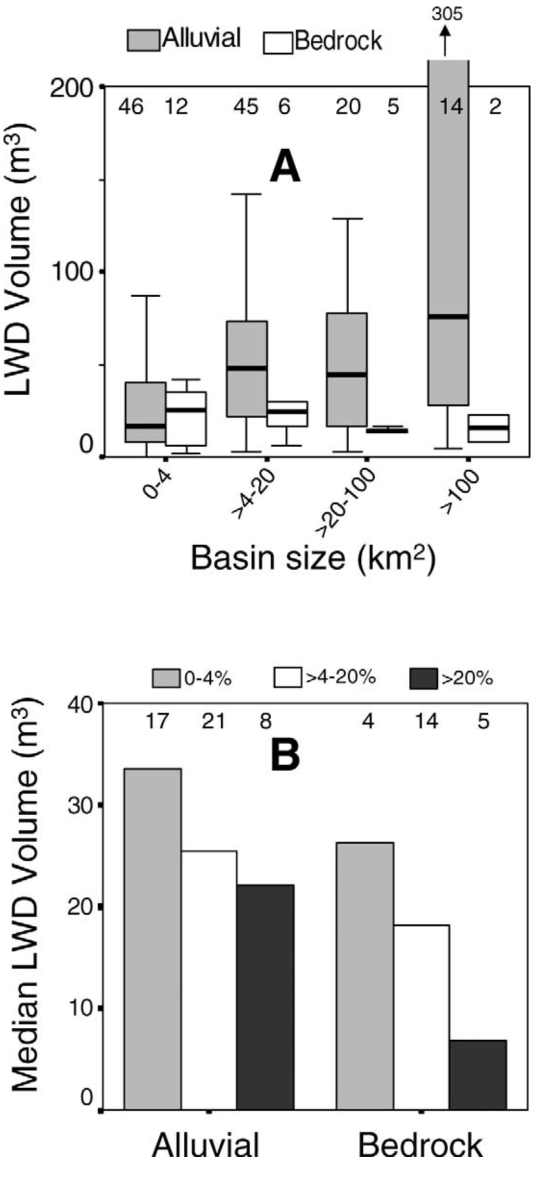

FIGURE 3.—Comparisons of instream wood volume (LWD [m^3 per 100 m]) in surveyed stream channels in Washington, 1999–2000, by **(A)** channel type (alluvial or bedrock) and basin size (km^2) and **(B)** channel type and gradient class (confined channels only). The number above each bar is the number (sample size) of stream reaches in that category (channel type–basin size or channel type–gradient). In the box-and-whisker diagrams, the horizontal lines within the boxes represent the medians, the upper and lower edges of the boxes the central 50% of the distribution, and the whiskers the highest and lowest values, including "outliers" (circles) and "extreme values" (asterisks). Outliers are defined as values between 1.5 and 3 box lengths from the upper and lower edges of the boxes and extreme values as values more than 3 box lengths from the upper and lower edges of the boxes.

that debris flows and snow avalanches reduce the number and volume of LWD per 100 m of channel length in channels exceeding 10% in gradient compared with similar-gradient channels without recent disturbance. Notably, channels less than 6% in gradient with and without debris flows and snow avalanches have nearly the same number of wood pieces per 100 m of channel; however, wood volumes (m^3/100 m) are greater in channels of this gradient with recent debris flows but less with recent snow avalanches than in channels of this gradient without recent disturbance.

Recent floods did not appear to have a significant effect on instream wood in the streams surveyed. The comparison of regressions between channels with and without recent floods (within 10 years of survey and having a magnitude 25-year flood recurrence) suggests that floods do not significantly decrease the quantity and volume of instream wood per 100 m with increasing channel width ($P > 0.6$ for both regression slopes and intercepts). Although this phenomenon is implied by these data, the effects of floods depicted in these relationships are, perhaps, poorly defined owing to the lack of equal replication of sites containing similar morphologies and regional characteristics. Without controlling for these variables, relationships are probably biased by one or multiple regional and geomorphic influences.

Reference Conditions for Instream Wood Quantity and Size

Minimum key piece volumes for channels greater than 20 m BFW.—The length and diameter of key pieces are factors influencing buoyancy and mobility. Although some dimensional combinations (independent of rootwads) may influence piece stability more than others as they interact with channel shape, we assume that piece volume provides a reasonable representation of both length and diameter proportions factored into stability determinations.

The range of volumes for wood pieces meeting the geomorphic definition for stability and function (WFPB 1997) is presented in the form of percentile distribution plots (box plots) for channel classes greater than 20 m BFW, as distinguished by differences in variances (Fisher F-tests: $P < 0.01$; Figure 4). From this distribution, the recommended minimum volumes, as we define by the 25th percentiles, are approximately 9.7 m^3 for the 20- to 30-m BFW class, 10.5 m^3 for the 30- to 50-m^3 BFW class, and 10.7 m^3 for channels greater than 50 m BFW. A plot of these minimum volumes, including those currently defined by WFPB (1997), is presented in Figure 5.

The influence of rootwads on key pieces.—Of the pieces composing the volume percentile distributions (>25th percentile) presented in Figure 4 and the

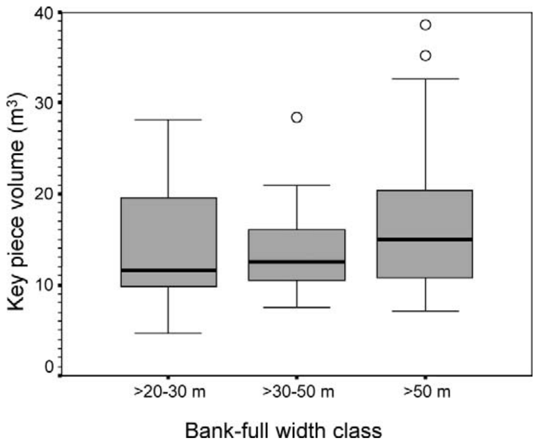

FIGURE 4.—Distributions of instream wood volumes for individual pieces meeting the definition of "key pieces" (i.e., pieces with independent stability; WFPB 1997) for surveyed channels with bank-full widths greater than 20 m in Washington, 1999–2000. According to our methods, the minimum volume for key pieces in channels greater than 20 m is defined as the 25th percentile. The box-and-whisker diagrams are as described in Figure 3.

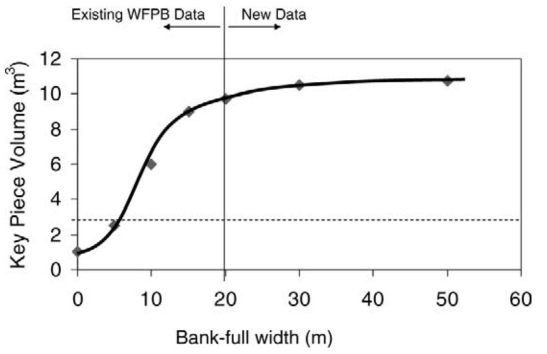

FIGURE 5.—Plot of the minimum wood volumes in surveyed channels used to define key pieces in both western and eastern Washington, 1999–2000. The points to the right of the vertical line represent the new minimum volumes defined in this analysis, the points to the left the values currently used in Washington's "Watershed Analysis for Western Washington" (WFPB 1997), and the dashed line the minimum key-piece volume (2.83 m^3) interpreted from the Oregon Watershed Enhancement Board (based on minimum length and diameter criteria; Watershed Professionals Network 1998).

corresponding curve in Figure 5, it would appear that the recommended minimum volumes defining key pieces are very similar in all channels with BFWs greater than 20 m (and they are not, in fact, significantly different). As channels become larger, one would also expect the wood mobility to increase owing to wood buoyancy and higher-unit stream power. The reason that this is not reflected by an increase in the minimum key-piece volumes as channels become larger probably lies in the presence of rootwads, which compensate for stability in lieu of volume increases. Indeed, 96% of the wood pieces meeting the WFPB definition for key pieces in channels greater than 50 m BFW had rootwads attached to them. In channels with BFWs between 30 m and 50 m, 91% of the pieces had rootwads, and in channels with BFWs between 20 m and 30 m, 71% had rootwads attached. Notably, when selecting for wood functioning as key pieces without rootwads attached, the 25th percentile of individual piece volumes in channels 50–100 m is over 26 m^3, suggesting a linear trajectory with the sizes defined for channels less than 20 m. However, because of the small sample size ($n =$ 13) for key pieces without rootwads in channels between 20 m and 100 m, this observed trend could not be supported with statistical inference.

The application of key-piece minimum volumes to eastern Washington.—As described previously, the minimum volume required for a piece of wood to achieve independent stability as defined by WFPB (1997) currently applies only to western Washington streams less than 20 m BFW. Based on the minimum key-piece volume definitions provided by WFPB for channels less than 20 m BFW and the results of this study presented above for channels greater than 20 m BFW, the percent of LWD qualifying as a key piece per 100-m reach is not significantly different among forest zones (ANOVA: $P = 0.073$). This suggests that the minimum key-piece volumes established on the basis of fluvial forces rather than region are reasonable criteria for evaluating key-piece frequencies in both eastern and western Washington.

Volumes, LWD numbers, and key-piece quantities.—Overall, both the number and volume of LWD per 100 m of channel length increased with increasing BFW; however, the variance is not well explained by regressions ($R^2 = 0.14$ and 0.23, respectively). Therefore, a classification approach of BFW is more practical as a management tool than a regression or general linear model, since a range of conditions is provided rather than a single point estimate predicted by an equation.

Based on the similarities in LWD volume and riparian basal area, the Sitka spruce, western hemlock, silver fir, and mountain hemlock forest zones are grouped to form the "Western Washington Region," and the subalpine fir and the grand fir forest zones are grouped to form the "Alpine Region" (Figure 6). The Douglas-fir and ponderosa pine (DF–PP) forest zone

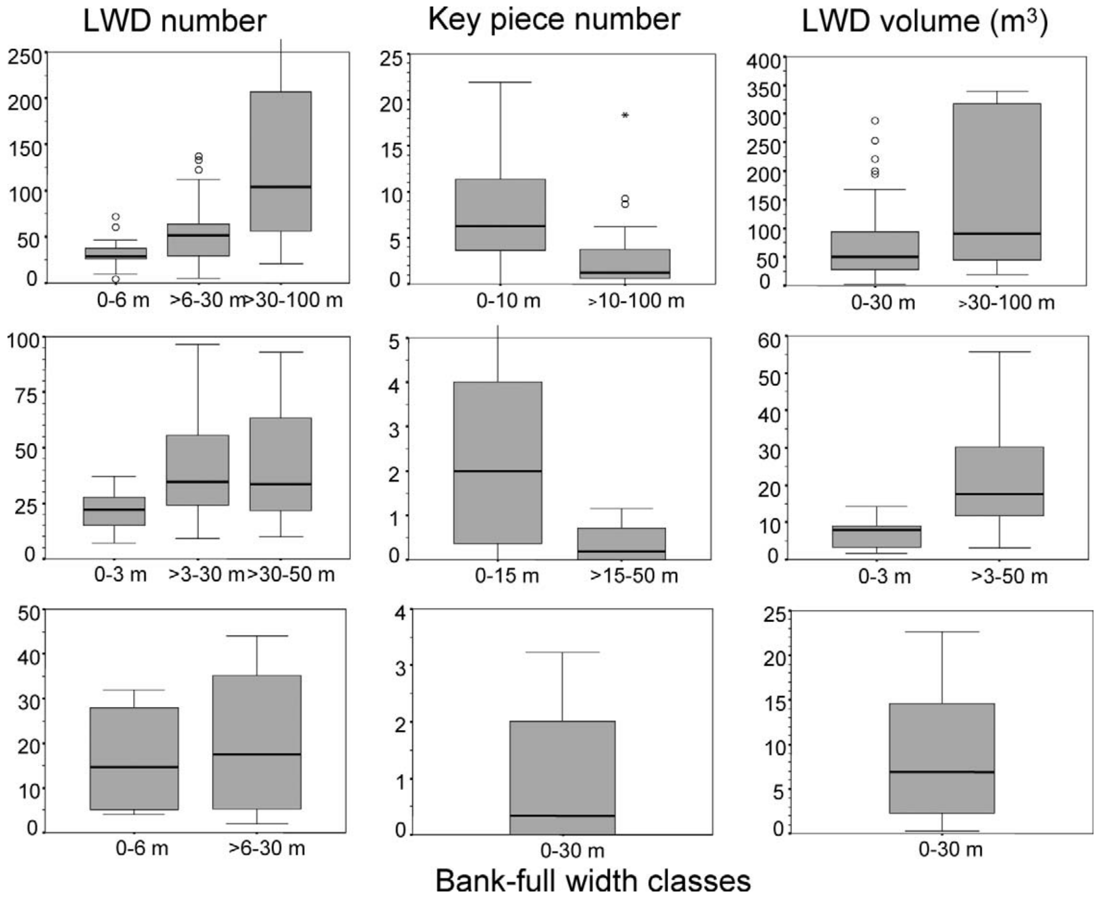

FIGURE 6.—Distributions of the number of wood pieces (LWD) per 100 m, the number of key pieces per 100 m, and the volume of LWD (m^3) per 100 m in channel reaches in the Western Washington Region (first row; $n = 78$), the Alpine Region (second row; $n = 58$), and the Douglas-fir–ponderosa pine forest zone (third row; $n = 14$), 1999–2000. Note that the scales of the *y*-axes differ and that the bank-full width classes are specific to each region based on discrete homogeneous groupings. See Figure 3 for an explanation of the box-and-whisker diagrams.

did not have significant similarities to any of the other forest zones; therefore, it remains simply the "DF–PP" forest zone.

The percentile distribution of these data, as distinguished by BFW classifications, provides reference conditions for wood quantity, key-piece quantity, and wood volume for Washington State and potentially synonymous forested regions of the Pacific Northwest based on these regional groupings. Based on significant differences in lognormal means and variances, distinct BFW classes were identified to report the natural ranges of LWD numbers, numbers of key pieces, and LWD volume per 100 m of stream for each region (Figure 6). Numeric summaries for these distributions and minimum volume-defining key pieces (Figures 4, 5) are presented in Tables 4 and 5.

Discussion

Choice of Predictor Variables

Geomorphological influence.—Channel bedform, origin, gradient, and confinement are predictive of geomorphological influence on instream wood quantities and volumes to some degree, based on the AIC analysis; however, the significance of these correlations (*P*-value) appears to be inconsistent among categories or interactions. This is also reflected in the exploratory analysis, which suggests the small sample stratification in each geomorphic category cannot consistently isolate the effects of these factors for making statistical inferences. Greater certainty regarding these influences would require additional sampling of these morphologies.

Bank-full width is supported as the most significant geomorphic indicator for predicting instream wood

TABLE 4.—Distributions of large woody debris (number of pieces, volume [m^3], and number of key pieces, all per 100 m of channel) by region and bank-full width (BFW) class. Large wood debris is defined as a pieces exceeding 10 cm in diameter and 2 m in length. Data are portrayed visually in Figure 6.

Region	BFW class	75th percentile	Median	25th percentile
		Number of pieces		
Western Washington	0–6 m	>38	29	<26
	>6–30 m	>63	52	<29
	>30–100 m	>208	106	<57
Alpine	>0–3 m	>28	22	<15
	>3–30 m	>56	35	<25
	>30–50 m	>63	34	<22
DF–PP forest zone	0–6 m	>29	15	<5
	>6–30 m	>35	17	<5
		Volume		
Western Washington	0–30 m	>99	51	<28
	>30–100 m	>317	93	<44
Alpine	>0–3 m	>10	8	<3
	>3–50 m	>30	18	<11
DF–PP forest zone	0–30 m	>15	7	<2
		Number of key pieces		
Western Washington	0–10 m	>11	6	<4
	>10–100 m	>4	1.3	<1
Alpine	>0–15 m	>4	2	<0.5
	>15–50 m	>1	0.3	<0.5
DF–PP forest zone	0–30 m	>2	0.4	<0.5

volumes and number of pieces. This is based on (1) the results of the trend analysis with wood volumes with increasing basin size, (2) the correlation of BFW to basin size and cross-sectional area, (3) the demonstration that BFW has better predictive qualities than basin size for instream wood, and (4) the interaction and correlation this variable has with the previously discussed reach geomorphology influences. For example, streams with large BFWs are often less confined and of lower gradient than streams with small BFWs; thus, BFW may effectively be representative of multiple reach geomorphological influences. Due to the development of these BFW relationships with basin area in unmanaged streams, caution is needed if applied to streams in managed basins, human-modified channels, or recently disturbed channels. Bank-full width and cross-sectional area of flow are probably more representative of the hydraulic forces that influence the distribution and retention of wood than basin size, further favoring the use of BFW rather than basin size as a predictor of instream wood numbers and volumes.

Influence of disturbance.—The AIC analysis supports a better fit using the five forest zones for predicting wood numbers and volumes compared with using the three state regions in the OLS model; however, we chose to simplify these categories by

TABLE 5.—Minimum volume required for key pieces of large woody debris, by bank-full width (BFW) class.

BFW class	Minimum volume (m^3)
0–5 m	1.00[a]
5–10 m	2.50[a]
10–15 m	6.00[a]
15–20 m	9.00[a]
20–30 m	9.75
30–50 m	10.50[b]
50–100 m	10.75[b]

[a] Current WFPB (1997) definition.
[b] Piece must have an attached rootwad.

grouping them into the state regions based on the descriptive analysis. Through the descriptive analysis, the forest zones grouping did not substantially increase the variability; thus, we believe little was lost while gaining utility in simplification. Therefore, we chose state regions as the best single regional indicator for predicting instream wood loads in relation to various forms of climate-induced disturbance. Tree age, as influenced by natural fire history, increases with wetter climates. Because the adjacent riparian trees influence instream wood loads, the characteristics of riparian trees, as influenced by fire recurrence, vary by forest zones.

We could not isolate any other form of disturbance as a significant predictor of instream wood loads; however, the wide range of wood loads found within any one grouping probably reflects some level of natural disturbance that creates typical patchy stream habitat. From our data, floods do not appear to have a significant influence on long-term wood abundance and therefore are inconsequential to variable selection. Observationally, debris flows and snow avalanches, perhaps, have some local influence on instream wood loads; however, this influence could not be verified with statistical rigor because of the small number of disturbed sites relative to nondisturbed sites.

Setting Management Targets

The percentile (box plot) distributions for LWD quantity, volume, and key-piece quantity (Figure 6) represent the range of conditions found in streams draining unmanaged forests that are subject to a natural rate of disturbance (except fire suppression). Assuming these data include both favorable and unfavorable salmonid habitat conditions as they relate to instream wood, this range can be used to set management targets for riparian recruitment objectives, regulation, habitat restoration, enhancement, and evaluation. For restoration and enhancement of instream wood loads, we recommend that streams be managed to meet this natural distribution at a basin scale, where restoring the

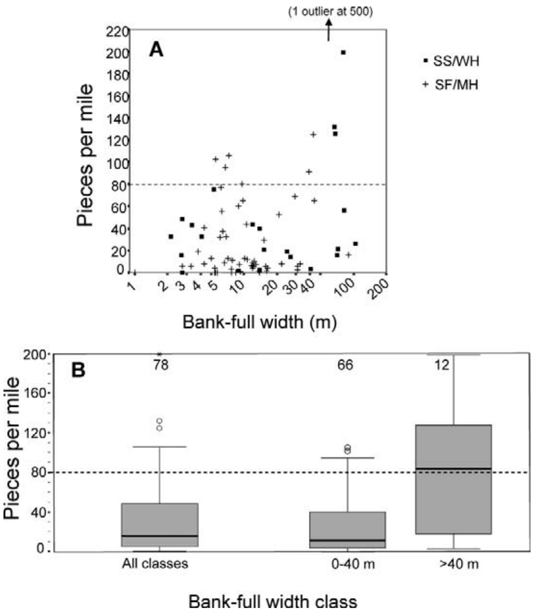

FIGURE 7.—Distribution of surveyed channel sites in western Washington, indicating the number of instream wood pieces that meet the National Marine Fisheries Service criteria for "properly functioning condition" (PFC) and the identical "resource management objective" (RMO) of the U.S. Forest Service and Bureau of Land Management for coastal Oregon and Washington. To illustrate disparities among bank-full widths, panel **(A)** presents a scatterplot of the data by forest zone (squares = the Sitka spruce–western hemlock zone [SS/WH], plus signs = the silver fir–mountain hemlock zone [SF/MH]), while panel **(B)** shows percentile distributions for all bank-full width classes and for two classes separately. The horizontal dashed line represents the lower threshold for streams meeting the PFC–RMO criteria. The number of channel reaches appears above the bars in (B); in (A), the number of channel reaches is 78. See Figure 3 for an explanation of the box-and-whisker diagrams.

natural heterogeneity of wood loads is the primary objective. Streams in a degraded state (e.g., below the median) should be managed for wood inputs exceeding the median of this range. We recommend that the top of these distributions, the 75th percentile and above, be used as an interim management "target" until the basin-scale wood loads achieve the central tendencies of natural and unmanaged wood-loading ranges.

The precise quantities and volumes of wood needed by salmonids for successful production are not well understood. Statistically sound studies to link instream wood loads to salmonid production would be expensive and have high levels of uncertainty owing to the multiple variables influencing salmon production (Roni et al. 2003). However, we do know that historic salmon populations were much higher than those found today and, as noted earlier, we assume that unmanaged forests offer the best source of information on wood loads as one component of habitat to which salmonids have adapted. In degraded streams, where management is needed to restore favorable conditions, wood loads are often no longer found in the upper distribution of these ranges, or the distribution is centered around a lower mean. In these cases, merely managing for the mean or median will not restore the natural ranges of heterogeneity. Thus, for management purposes intending to restore natural wood-loading conditions, establishing instream wood targets based on the upper portion of the distribution observed in natural systems (i.e., the 75th percentile) rather than the lower portion of the distribution are reasonable as well as prudent to restore natural ranges.

Comparison of Data with Existing Management Standards

National Marine Fisheries Service (NMFS) and U.S. Forest Service (USFS)–Bureau of Land Management (BLM): number of LWD pieces.—Streams achieving a "properly functioning condition" or the "resource management objective," as defined by NMFS and USFS–BLM, respectively (Table 1), for Pacific Northwest streams were assessed. Of the 78 natural and unmanaged streams sampled in western Washington, only 11 met the requirements of 80 pieces per mile (1 mile = 1.61 km) put forth by these federal agencies (Figure 7A); however, of the 54 streams sampled in eastern Washington, 30 met the federal standard of 20 pieces per mile (Figure 8A). Percentile distributions and one-sample t-tests with normalized data suggest that the sample mean of qualifying wood pieces per mile is significantly lower than the federal target for western (coastal) Pacific Northwest streams ($P < 0.001$), but significantly higher than the federal target for eastern Pacific Northwest streams ($P = 0.02$). The data in western Washington also suggest that the mean is similar to the federal standard only in channels greater than 40 m BFW (Figure 7B). The 75th percentile of data from streams equal to or less than 5 m BFW sampled in eastern Washington is near the federal target of 20 pieces per mile for eastern Washington streams, but only near the 25th percentile in streams 5–50 m BFW (Figure 8B).

In comparisons of natural and unmanaged wood-loading ranges with the federal management targets for coastal areas of the Pacific Northwest, we found that the 75th percentile derived from our data meets the federal target only in streams greater than 40 m BFW, suggesting that 80 pieces per mile seems to be a reasonable target only for the larger streams (Figure 7B). For interior Pacific Northwest streams, the federal

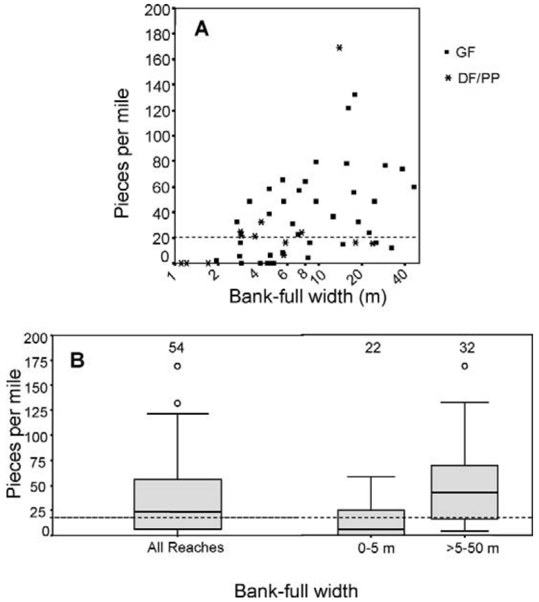

FIGURE 8.—Distribution of surveyed channel sites in eastern Washington, indicating the number of instream wood pieces that meet the National Marine Fisheries Service criteria for "properly functioning condition" and the identical "resource management objective" of the U.S. Forest Service and Bureau of Land Management for eastern Oregon and Washington. To illustrate disparities among bank-full widths, panel **(A)** ($n = 53$) presents a scatterplot of the data by forest zone (squares = the grand fir zone [GF] and asterisks = the Douglas-fir–ponderosa pine zone [DF/PP]), while panel **(B)** shows percentile distributions for all bank-full width classes and for two classes separately. See Figure 7 for additional details.

target is near the 75th percentile for Washington streams 0–5 m BFW in this study, but only near the 25th percentile for streams 5–50 m BFW (Figure 8B), suggesting that the federal target may be set too low for these streams. As applied, however, the NMFS and USFS–BLM targets do not differentiate between BFW classes and are applied to all streams (i.e., those with potential to provide habitat for salmonid species).

Washington Forest Practices Board: number of LWD and key pieces.—Comparing the data mean from this study for instream LWD quantities in Washington streams (channels < 20 m BFW) with the WFPB target of two pieces per channel width, there was no significant difference (one-sample t-test: $P = 0.969$; $n = 121$). The distribution of data (Figure 9a) suggests that this target is not applicable for all channel widths less than 20 m because of the significantly positive regression slope ($P < 0.001$) described by the equation

$$Y = 0.22x^{1.26}, \quad (1)$$

where Y is the predicted number of LWD pieces per channel width and x is the BFW in meters. Based on data partitioning of LWD quantity to define three distinct BFW classes (Figure 9b), one-sample t-tests suggest that the WFPB target is higher than the mean of the data distributions for channels less than 3 m BFW ($P < 0.001$), not different in channels greater than 3–12 m BFW ($P < 0.194$), and lower in channels greater than 12–20 m BFW ($P < 0.001$).

One-sample t-tests suggest that the lognormal mean of these data is not significantly different from the WFPB target of 0.3 key pieces per channel width for channels 0–10 m BFW in western Washington ($P = 0.897$); however, the mean for key pieces per channel width in channels 10–20 m BFW is significantly different from the WFPB target of 0.5 pieces per channel width ($P = 0.001$). The percentile distribution (Figure 9c) suggests the data mean in channels 10–20 m BFW is *less* than the WFPB target. The relationship of the number of key pieces per channel width to BFW is not significant ($P = 0.625$).

Oregon Watershed Enhancement Board (OWEB) targets.—There was a significant difference when comparing the data mean from this study with the OWEB "desirable" habitat quality rating (Table 1) for numbers ($P < 0.001$) and volumes ($P < 0.001$), but not for key pieces ($P = 0.061$; each with one-sample t-tests, $n = 78$) of instream LWD per 100 m of stream (Watershed Professionals Network 1998). Figure 10a suggests that the OWEB standard for numbers of LWD per 100 m of stream is lower than expected in natural and unmanaged streams of similar forest types in Washington. Furthermore, regression analysis suggests that the OWEB target is not applicable for all channel widths, where the number of pieces per 100 m of this study increases with increasing channel widths ($P = 0.004$). Figure 10b suggests that the OWEB standard for LWD volume is lower than expected in natural and unmanaged streams. As with the number of LWD, regression analysis of these data also suggests a positive relationship with LWD volume as channel width increases. Figure 10c suggests no significant difference between the OWEB standard and the data of this study. Regression analysis ($P = 0.197$) suggests no significant increase or decrease in the number of key pieces per 100 m, as defined by the OWEB key-piece size criteria with BFW.

The appropriateness of Washington and Oregon state LWD standards may be reasonable only for a select channel size. Figure 9b illustrates that the WFPB target is only near the median for streams between 3 m and 12 m BFW (yet below the 75th percentile) and quite different from the distributions found in smaller and larger natural and unmanaged streams. Regressions using the WFPB LWD metrics (Figure 9a) and the OWEB metrics further suggest that numbers of LWD pieces vary by channel size, and a single target may not serve well for all stream sizes. This relationship is similar for LWD volume, suggesting a similar discrepancy with the OWEB volume targets. However, the state targets for LWD numbers and volume do not differentiate between channel sizes and are, overall, lower than the 75th percentiles of distributions found in natural and unmanaged streams, which, therefore, suggests that the state targets may be set too low.

The state LWD targets may also not be appropriate for all forest types. Figure 9a illustrates that there is regional variation with numbers of wood pieces, suggesting that applications of a fixed management target may not be judicious across different forest zones of Washington and Oregon. As applied, however, the Washington targets for piece numbers are applied to all forest types across the state, and the Oregon targets are applied to all forest types in western Oregon.

The key-piece standards of Washington and Oregon are quite different in size definition and hence are difficult to compare. The WFPB key-piece size definition increases by channel size, where the OWEB key-piece size definition is constant for all channels. Based on the functional definition for independent stability (WFPB 1997) and what we know about increasing fluvial forces acting upon wood as stream size increases (Braudrick and Grant 2000), it would seem that the minimum size of an independently stable piece of LWD must increase with channel size. Certainly, the size definitions of the WFPB (1997), which are based on data collected under this definition

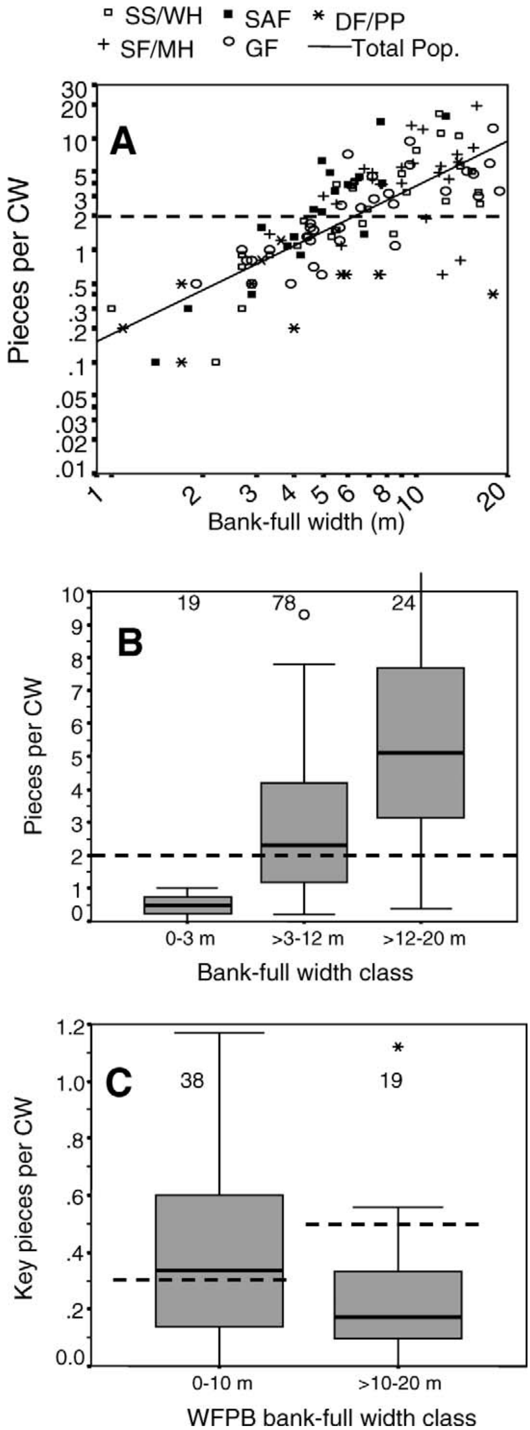

FIGURE 9.—Number of pieces and key pieces of wood (LWD) per channel width (CW) by bank-full width for surveyed channels in Washington with bank-full widths less than 20 m for comparison with the Washington Forest Practices Board (WFPB) targets. Panel **(A)** presents a ←

scatterplot in which the points represent the mean quantities per sample by discrete forest region (open rectangles = the Sitka spruce–western hemlock zone [SS/WH], filled rectangles = the subalpine fir zone [SAF], asterisks = the Douglas-fir–ponderosa pine zone [DF/PP], plus signs = the silver fir–mountain hemlock zone [SF/MH], and circles = the grand fir zone [GF]). The sloping line is the fitted regression line $y =$← $0.191x^{1.29}$, where y represents pieces per channel width and x bank-full width. Panel **(B)** presents box plots illustrating the range of data among discrete bank-full width classes and panel **(C)** box plots illustrating the data distribution as compared with the WFPB targets for key-piece quantities per CW (applicable to western Washington only). The horizontal dashed lines represent the WFPB targets that indicate "good" habitat quality (WFPB 1997). The number of channel reaches appears above the bars in (B) and (C); in (A), the number of channel reaches is 121. See Figure 3 for an explanation of the box-and-whisker diagrams.

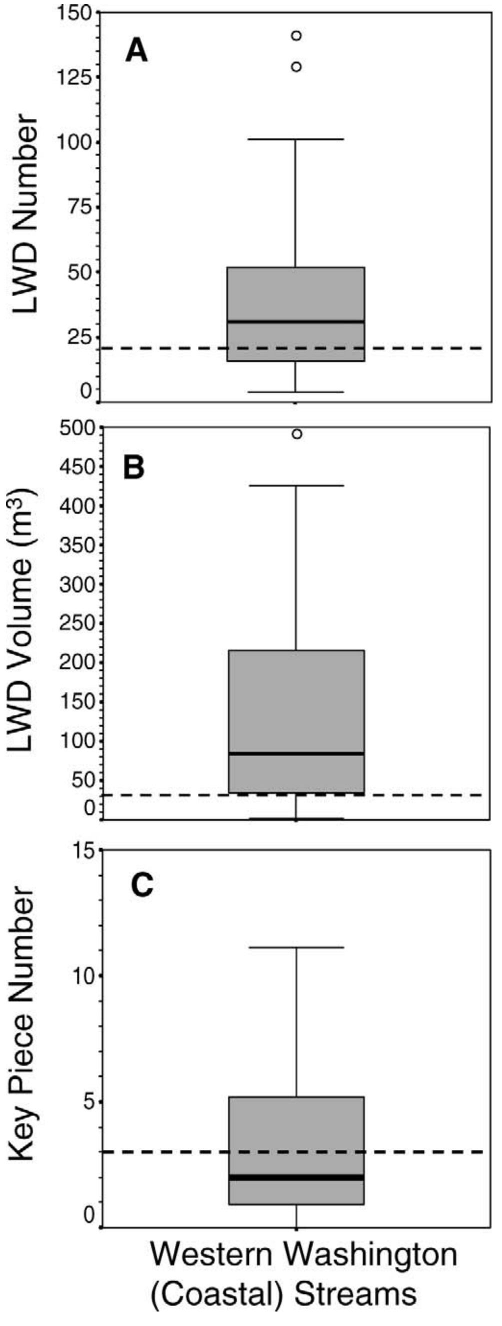

FIGURE 10.—Distributions of **(A)** the number of pieces of wood (LWD), **(B)** the volume of LWD, and **(C)** the number of key pieces of LWD per 100 m of stream in surveyed channels in Washington that meet the Oregon Watershed Enhancement Board's qualifying criteria (Table 1). The dashed horizontal lines indicate the board's "desirable" condition (Watershed Professionals Network 1998) for each wood habitat metric. For each plot, $n = 78$. See Figure 3 for an explanation of the box-and-whisker diagrams.

(M. J. Fox, 1994 memorandum to the Cumulative Effects Steering Committee from the Muckleshoot Tribe on LWD key piece size and distribution data set for several late-successional Douglas-fir forests of western Washington), reflect this increase. Thus, the Oregon single size definition for key pieces is likely to overestimate independently stable LWD pieces (i.e., key pieces) in smaller streams, but qualify pieces that are, perhaps, not functioning as true key pieces in larger streams. Although the OWEB key-piece target is not significantly different than the data mean quantity from natural and unmanaged streams, it may not reflect true key-piece quality and the intended geomorphic role of those pieces. Therefore, the OWEB target for key pieces may better serve as a reference to the quantity of "large" pieces of LWD rather than true "key pieces" expected in coastal streams, yet may fall short as a management target since it is lower than the 75th percentile of pieces meeting that size definition in natural and unmanaged streams. The WFPB targets for key pieces are also different from the 75th percentile (Figure 9c), and adjusting the target to meet the quantities expected in natural and unmanaged streams may more prudently facilitate some management objectives.

Defining New Key-Piece Minimum Volumes for Channels Greater Than 20 m BFW

The minimum volumes established in Figure 4 illustrate that the size of the pieces in channels greater than 20 m BFW do not increase at the same rate as the minimum defined volumes in channels between 0 and 20 m BFW (WFPB 1997). The change in rate is illustrated in Figure 5 as channels reach 15–20 m BFW (i.e., 9 m^3) and suggests that the relationship between BFW (as representative of potential fluvial forces such as buoyancy) and wood volume (as a function of stability) is not linear. Certainly, one would expect that wood must be larger to counter the tendency to mobilize as channels become larger. This is not the case and is probably attributed to the presence of rootwads to help anchor logs. Clearly, this often compensates for the need of increased volume for stability. This is illustrated by the increased prevalence of rootwads attached to key pieces as BFW increased, although the minimum volumes did not increase proportionately. The data suggest that without rootwads attached, the minimum volume required to meet the definitions for key pieces may indeed follow the near-linear relationship with BFW established by the WFPB in channels 0–20 m BFW. However, this relationship may not be fully realized because samples for pieces this large without rootwads were rare ($n = 3$).

Application of Key-Piece Size Definitions to Eastern Washington Streams

The application of the minimum key-piece volumes established for western Washington (WFPB 1997) to eastern Washington is demonstrable. First, there was no significant difference in the total percent of wood qualifying as key pieces between eastern and western Washington forest zones. Second, fluvial forces for a given channel size are likely to be the same and, thus, the mobilization of wood is likely to be the same. Indeed, Fox (2001) found that the physical dry densities of wood species commonly distributed in the riparian areas are not significantly different between forest zones. Although the quantities of key pieces vary among regions (Figure 6), the physical criteria used to define a key piece (using the WFPB definition) should be similar. Therefore, the application of minimum key-piece volumes established for western Washington streams to eastern Washington streams is appropriate and, thus, applicable among these forest types.

Restoration and Management Recommendations

Instream wood is merely one indicator of stream and salmonid habitat conditions; however, it is one of the few tangible stream features that can be manipulated by the management of riparian areas or used in wood restoration intended to "jump-start" habitat recovery until natural processes recover. Management objectives are most valid if they are based on reference conditions to which salmonids have adapted. The percentile (box plot) distributions for LWD quantity, volume, and key-piece quantity (Figure 6) provide this range of reference conditions for discrete regions and channel sizes and can be used in habitat restoration, enhancement, evaluation, regulation and, perhaps, to develop riparian recruitment objectives. Because these data represent a wide range of conditions found in streams draining unmanaged forests that are subject to a natural rate of disturbance (except fire suppression), the recommendations provided herein are relevant to basin-scale objectives intended to restore the natural heterogeneity of wood distributions found in unmanaged systems. In many cases, conditions in impacted streams often reside in a reduced range of historic heterogeneity or are grouped around a different mean. As such, reestablishing values within the historic range that "pull" the mean closer to the historic mean will probably better serve the restoration of habitat conditions. Due to the effect of past management practices on instream wood, impacted streams commonly contain conditions lower than the historic range. Thus, merely managing for the mean or median will not likely restore the natural ranges of heterogeneity, and achieving this range in degraded systems may initially require setting objectives above the mean or median of this range (e.g., the 75th percentile) to expedite recovery and resemble the central tendencies of natural and unmanaged wood-loading ranges.

Current management targets often do not consider the regional or geomorphic variation in wood loads, and hence caution should be exercised in applying these standards broadly. The data in this study illustrate these significant variations by forest type and channel size and offer improved references in which to base management objectives.

The minimum piece volumes used to define a key piece should also consider the role rootwads play in achieving stability. In channels greater than 30 m BFW, more than 91% of all key pieces had rootwads attached. Therefore, in order to meet the objective of defining a key piece, not only do the prescribed minimum volumes need to be met but also rootwads must be considered in this definition. Without rootwads to stabilize key pieces, the minimum volume needed for stability in large channels would be extremely large. Logs of this size are rare and probably impossible to obtain for stream habitat enhancement projects, let alone transporting and positioning them into a channel. Therefore, we recommend that for channels greater than 30 m, a log must have a rootwad attached to be defined as a key piece and meet the minimum-volume requirements defined in Figure 4. Although having a rootwad attached to a log placed in a stream channel as part of a restoration or enhancement effort adds stability and longevity (Braudrick and Grant 2000), the data do not justify a requirement that all key pieces meeting the minimum-volume requirement have an attached rootwad for BFW classes smaller than 30 m.

Table 4 summarizes the central percentile distributions for instream wood loadings based on Figure 6. These values offer typical ranges of conditions for the quantities and volumes of wood found within the historical variability of watershed conditions, given the natural disturbance regime in forest zones of Washington State. These ranges can be used to (1) assess current instream wood condition and ratings for the evaluation of stream habitat; (2) identify target wood load levels for restoration, enhancement, and mitigation projects; and (3) develop land-use regulations, ordinances, and laws to protect and manage salmon habitat.

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