Sandy Guinn

From: Dave Kuhl
Sent: Thursday, January 22, 2015 1:38 PM
To: Sandy Guinn
Cc: Comp Plan

From: Karen Walter [mailto:KWalter@muckleshoot.nsn.us]
Sent: Friday, January 09, 2015 2:47 PM
To: Dave Kuhl

Dave,
We have reviewed Woodinville’s Draft EIS; 2015 Comp Plan and Code update and associated documents available on the City’s website. Please note that we did comment on the DS and could not find a response to these issues either directly back to us or in any of the documents we reviewed. In addition to our previous scoping comments, we offer the following comments on the various documents:

Draft Comprehensive Plan

1. With respect to the proposed Comprehensive Plan, there needs to be language added to the transportation, utilities and natural environment elements that identify the avoidance of new fish passage barriers and the replacement of existing fish passage barriers to provide passage. From this language, additional language should be added in the “tools” section for each of these elements that include a fish passage barrier assessment plan and the incorporation of projects into the 6-year CIP lists.

2. The Natural Environment element should include previous and current restoration program information and discuss potential expansion efforts particularly for the Sammamish Re-Leaf project which was an implementation measure identified in the Bear-Evans Creek TMDL (www.ecy.wa.gov/biblio/1110024.html). There should also be more explicit policies and goals specific to the Shoreline Master Program and its restoration Plan. Finally there should be more explicit policies and goals related to the implementation of the WRIA 8 salmon recovery plan where it applies specifically to the City to just a citation of the plan.

3. The land use classifications and zoning should be re-analyzed using the information provided in the Best Available Science Review and other consultant work products associated with this project. For example, there are floodplain, erosion and landslide hazard areas that should be avoided; however, some of these areas overlap with proposed increased land uses and housing densities. This can lead to false expectations about development opportunities and force variances and reductions on protections for these critical areas that could lead to further degradation of fish habitat.

4. The comments below regarding the development regulations may further affect the proposed alternative land use designations and zoning alternatives.

Draft Development Regulations

5. The City should modify the existing regulations by incorporating the elements, issues, language, etc identified in the Critical Areas Gap Analysis completed by the Watershed Company which are extensive and cover all of the critical areas. The City’s current regulations are out of date and do not sufficiently protect streams, wetlands, riparian areas and floodplains. In addition to the recommendations from this report, the City needs to include provisions for presumed fish habitat which should be based on the language found in WAC 222-16-031. Please note that the Critical Areas Gap Analysis incorrectly identifies the water typing WAC as 222-16-030 which has not been fully implemented as the WA Forest Practices Board has not adopted water typing maps. Therefore, the interim rule is still in effect which includes the provisions regarding potential fish use.
6. The development regulations need to clearly describe how they meet the FEMA Floodplain insurance Biological Opinion requirements.

7. Similarly, the regulations for riparian areas along the Sammamish River are potentially inadequate to provide sufficient shade necessary to meet State Water Quality standards and improve the existing lethal and sublethal water temperatures that can occur to the detriment of salmon. For example, the implementation plan for the Bear Evans Creek Total Maximum Daily Load indicated that a minimum mature vegetation buffer of 150 feet should be pursued on both sides of these streams outside of wetland areas.

It should be noted that stormwater regulations and manual consistent with WA Dept of Ecology’s stormwater manual do not fully mitigate for all impacts. We identified this concern for several projects in the City and will reiterate them here. The 2009 King County Surface Water Design Manual states on page 1-20:

1.1.4 DRAINAGE DESIGN BEYOND MINIMUM COMPLIANCE
This manual presents King County’s minimum standards for engineering and design of drainage facilities. While the County believes these standards are appropriate for a wide range of development proposals, compliance solely with these requirements does not relieve the professional engineer submitting designs of his or her responsibility to ensure drainage facilities are engineered to provide adequate protection for natural resources and public and private property.

Compliance with the standards in this manual does not necessarily mitigate all probable and significant environmental impacts to aquatic biota. Fishery resources and other living components of aquatic systems are affected by a complex set of factors. While employing a specific flow control standard may prevent stream channel erosion or instability, other factors affecting fish and other biotic resources (e.g., increases in stream flow velocities) are not directly addressed by this manual. [emphasis added]

Likewise, some wetlands, including bogs, are adapted to a very constant hydrologic regime. Even the most stringent flow control standard employed by this manual does not prevent increases in runoff volume, which can adversely affect wetland plant communities by increasing the duration and magnitude of water level fluctuations. Thus, compliance with this manual should not be construed as mitigating all probable and significant stormwater impacts to aquatic biota in streams and wetlands; additional mitigation may be required.

As we suggested previously, the 2009 KC Storm Water Manual language indicates that even with detention, it is unlikely that all impacts to fish and aquatic biota are fully mitigated. As we have discussed with the applicant’s consultant, there are potential impacts from increase stormwater discharges to juvenile salmon using the margins along the Sammamish River where flows are slower than the thalweg. In areas where the margin habitat is simplified, i.e. lacking off-channel areas, wood, connected wetlands, etc. as is much the case for the Sammamish River and other streams in the City, increases in water velocities along these margins can displace juvenile salmon, force them to expend more energy staying in place leaving them susceptible to disease and predation, or reduced feeding opportunities that also leads to reduced growth and predation avoidance.

8. Sockeye salmon should be added to the Sockeye should be added to list of locally important salmon species to Table 146 in the Critical Areas Gap Analysis. They are an important salmon species to the Tribe and found in the City’s waterbodies.

9. Another consideration for modifying the Critical Areas Regulations is based a further consideration of the importance of wood to providing habitat for fish. The Best Available Science Review failed to note that McDade et al (1990) found a significant contribution of wood came from upstream sources. Further this review did not
include Fox and Bolton (2007) which identifies the amount, sizes and volumes of wood that should be in streams of various sizes based on an extensive study of reference watersheds in Washington State (see attached).

Draft Environmental Impact Statement
For the assessment in the Environmental Impact statement to be correct regarding impacts and mitigation measures under the two action alternatives, the issues identified above need to be addressed.

We appreciate the opportunity to review this proposal. Given the nature and extent of these comments, it would be useful for us to meet with you and your staff to discuss these comments further. Please contact me to set up such a meeting.

Thank you,
Karen Walter
Watersheds and Land Use Team Leader
Muckleshoot Indian Tribe Fisheries Division
Habitat Program
39015 172nd Ave SE
Auburn, WA 98092
253-876-3116

From: Karen Walter
Sent: Thursday, February 06, 2014 4:45 PM
To: 'Dave Kuhl'
Subject: Woodinville Comprehensive Plan and Municipal Code update, Determination of Significance

Dave,
We have reviewed the Determination of Significance and Request for Comments on the Scope of EIS for Woodinville’s Comprehensive Plan and Municipal Code Update. Per the map available on the City’s website, there are areas contemplated to become part of Woodinville or considered with the Comp Plan update that are in unincorporated Snohomish and King Counties. Some of these areas include the Sammamish River, streams, and wetlands. The EIS should analyze the differences in code regulations for the Sammamish River, streams and wetlands between the three jurisdictions as regulated in Critical Areas Ordinances and the relevant Shoreline Master Program and how Woodinville intends to address any differences to ensure that these critical areas are protected to the fullest extent.

Further, the DEIS should discuss Woodinville’s plans to inventory and fix fish passage barriers within the existing and expanded City planning area. Since the plan is contemplating transportation and capital facilities programs and projects over an extended period (i.e. 20 years or more), now would be a good time to put an inventory and repair program in place to ensure culverts in the City’s jurisdiction are fish passable.

We appreciate the opportunity to review this proposal and look forward to reviewing a Draft EIS that addresses these comments.

Thank you,
Karen Walter
Watersheds and Land Use Team Leader
Muckleshoot Indian Tribe Fisheries Division
39015 172nd Ave SE
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253-876-3116
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 salmonid species 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 km², 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 salmonid species (Palmisano 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 salmonid species (Palmisano et al. 1987; Bjornn and Reiser 1991).
juveniles, 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 Koekl 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; Masseng 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 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 (Keya 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
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 Dymess (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
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, scatter-plots, 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 rootwat 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.

<table>
<thead>
<tr>
<th>Forest zone (abbreviation)</th>
<th>Gradient (%)</th>
<th>Drainage area (km²)²</th>
<th>Confinement¹</th>
<th>Bedform¹</th>
<th>Channel type</th>
<th>Origin</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sitka spruce <em>Picea sitchensis</em> (SS)</td>
<td>≤1</td>
<td>0–2</td>
<td>Confined</td>
<td>Plane bed</td>
<td>Alluvial</td>
<td>Snow melt or rain</td>
</tr>
<tr>
<td>Western hemlock <em>Tsuga heterophylla</em> (WH)</td>
<td>&gt;1–2</td>
<td>&gt;2–4</td>
<td>Moderately confined</td>
<td>Pool or riffle</td>
<td>Bedrock</td>
<td>Glacial melt</td>
</tr>
<tr>
<td>Silver fir <em>Abies amabilis</em> (SF)</td>
<td>&gt;2–4</td>
<td>&gt;4–8</td>
<td>Unconfined</td>
<td>Unconfined</td>
<td>Bedrock</td>
<td>Glacial melt</td>
</tr>
<tr>
<td>Mountain hemlock <em>T. mertensiana</em> (MH)</td>
<td>&gt;4–8</td>
<td>&gt;8–20</td>
<td>Cascade</td>
<td>Cascade</td>
<td>Bedrock</td>
<td>Glacial melt</td>
</tr>
<tr>
<td>Subalpine fir <em>A. lasiocarpa</em> (SF)</td>
<td>&gt;8–20</td>
<td>&gt;20–100</td>
<td>Cascade</td>
<td>Cascade</td>
<td>Bedrock</td>
<td>Glacial melt</td>
</tr>
<tr>
<td>Grand fir <em>A. grandis</em> (GF)</td>
<td>20</td>
<td>&gt;100</td>
<td>Cascade</td>
<td>Cascade</td>
<td>Bedrock</td>
<td>Glacial melt</td>
</tr>
<tr>
<td>Douglas-fir <em>Pseudotsuga menziesii</em>—ponderosa pine <em>P. ponderosa</em> (DR–PP)</td>
<td>²D</td>
<td>&gt;20–100</td>
<td>Cascade</td>
<td>Cascade</td>
<td>Bedrock</td>
<td>Glacial melt</td>
</tr>
</tbody>
</table>

¹ As described in Franklin and Dymess (1973), Agee (1993), and Henderson et al. (1992).
² As defined in Pleus and Schuett-Hames (1998).
³ As described in Montgomery and Buffington (1997).
⁴ Predominantly found east of the Cascade crest.

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...
TABLE 3.—Best-fitting regressions for the log_{10} transformed number of pieces and volume (m³) 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, SI-MH, and SS-WH = grand fir, subalpine fir, silver fir–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.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Coefficient</th>
<th>SE</th>
<th>t-value</th>
<th>P-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pieces of LWD⁴</td>
<td>Intercept</td>
<td>1.1326</td>
<td>0.2993</td>
<td>3.778</td>
</tr>
<tr>
<td>Log_{10}(BFW)</td>
<td>-0.2385</td>
<td>0.2272</td>
<td>-1.0499</td>
<td>0.2938</td>
</tr>
<tr>
<td>GF</td>
<td>0.5353</td>
<td>0.3219</td>
<td>1.6642</td>
<td>0.0986</td>
</tr>
<tr>
<td>SAF</td>
<td>-0.3581</td>
<td>0.4116</td>
<td>-0.8797</td>
<td>0.3801</td>
</tr>
<tr>
<td>SI-MH</td>
<td>0.0523</td>
<td>0.3057</td>
<td>0.1718</td>
<td>0.8671</td>
</tr>
<tr>
<td>SS-WH</td>
<td>0.4355</td>
<td>0.3155</td>
<td>1.4372</td>
<td>0.1532</td>
</tr>
<tr>
<td>BR</td>
<td>1.4232</td>
<td>0.4669</td>
<td>3.0482</td>
<td>0.0023</td>
</tr>
<tr>
<td>MC</td>
<td>-0.0922</td>
<td>0.1497</td>
<td>-0.6159</td>
<td>0.5391</td>
</tr>
<tr>
<td>U</td>
<td>-0.0353</td>
<td>0.1640</td>
<td>-0.2020</td>
<td>0.8399</td>
</tr>
<tr>
<td>Log_{10}(slope)</td>
<td>-0.0358</td>
<td>0.2387</td>
<td>-0.133</td>
<td>0.8917</td>
</tr>
<tr>
<td>Log_{10}(BFW) × GF</td>
<td>0.2776</td>
<td>0.2481</td>
<td>1.1187</td>
<td>0.2654</td>
</tr>
<tr>
<td>Log_{10}(BFW) × SAF</td>
<td>1.591</td>
<td>0.4367</td>
<td>3.6431</td>
<td>0.0004</td>
</tr>
<tr>
<td>Log_{10}(BFW) × SI-MH</td>
<td>-0.117</td>
<td>0.3097</td>
<td>-0.3778</td>
<td>0.7062</td>
</tr>
<tr>
<td>Log_{10}(BFW) × SS-WH</td>
<td>0.5249</td>
<td>0.2377</td>
<td>2.2084</td>
<td>0.029</td>
</tr>
<tr>
<td>Log_{10}(BFW) × BR</td>
<td>-0.634</td>
<td>0.2456</td>
<td>-2.5815</td>
<td>0.011</td>
</tr>
<tr>
<td>Log_{10}(BFW) × MC</td>
<td>0.1193</td>
<td>0.1501</td>
<td>0.7952</td>
<td>0.428</td>
</tr>
<tr>
<td>Log_{10}(BFW) × U</td>
<td>0.2853</td>
<td>0.1536</td>
<td>1.857</td>
<td>0.0657</td>
</tr>
<tr>
<td>GF × BR</td>
<td>-0.9537</td>
<td>0.3627</td>
<td>-2.6546</td>
<td>0.0019</td>
</tr>
<tr>
<td>SAF × BR</td>
<td>-1.0202</td>
<td>0.4522</td>
<td>-2.2563</td>
<td>0.0238</td>
</tr>
<tr>
<td>SI-MH × BR</td>
<td>-1.3031</td>
<td>0.3707</td>
<td>-3.5149</td>
<td>0.0006</td>
</tr>
<tr>
<td>SS-WH × BR</td>
<td>-1.0778</td>
<td>0.3057</td>
<td>-3.4976</td>
<td>0.0038</td>
</tr>
<tr>
<td>GF × log_{10}(slope)</td>
<td>0.2608</td>
<td>0.2567</td>
<td>1.0158</td>
<td>0.3147</td>
</tr>
<tr>
<td>SAF × log_{10}(slope)</td>
<td>-0.0588</td>
<td>0.3064</td>
<td>-0.1917</td>
<td>0.8493</td>
</tr>
<tr>
<td>SI-MH × log_{10}(slope)</td>
<td>-1.1878</td>
<td>0.2923</td>
<td>-4.0425</td>
<td>0.0217</td>
</tr>
<tr>
<td>SS-WH × log_{10}(slope)</td>
<td>0.2853</td>
<td>0.2521</td>
<td>1.1363</td>
<td>0.258</td>
</tr>
</tbody>
</table>

| Volume of LWD⁵ | Intercept | -0.1823 | 0.2361 | -0.7721 | 0.4414 |
| Log_{10}(BFW) | 1.1338 | 0.2537 | 4.4876 | 0 |
| GF | 0.684 | 0.2511 | 2.7237 | 0.0073 |
| SAF | 0.2482 | 0.3741 | 0.6635 | 0.5082 |
| SI-MH | 1.9225 | 0.3355 | 5.7299 | 0 |
| SS-WH | 1.4571 | 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 | -1.3212 | 0.1917 |
| Log_{10}(BFW) × GF | -0.6076 | 0.2971 | -2.0451 | 0.0428 |
| Log_{10}(BFW) × SAF | 0.2556 | 0.2921 | 0.836 | 0.4047 |
| Log_{10}(BFW) × SI-MH | -1.3385 | 0.3373 | -3.9465 | 0.0003 |
| Log_{10}(BFW) × SS-WH | -0.8448 | 0.2732 | -3.0925 | 0.0024 |
| Log_{10}(BFW) × BR | -0.4587 | 0.2759 | -1.6707 | 0.0986 |
| 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, R² = 0.5966, F_{16,131} = 7.033, P = 0.442 × 10⁻¹³.  
B Standard error = 0.3737, df = 133, R² = 0.6168, F_{16,131} = 13.38, P = 0.

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 Geomorphic 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 km² 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}

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 km² and 325 km². 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).
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 drainage areas of 70 km² 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 ($n = 17$). 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 (m²/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...
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 $\geq$ 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 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
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 m³, 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 (R² = 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
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
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 more 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 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
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 (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
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

\[
Y = 0.22x^{1.26},
\]  

- **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) (\( n = 33 \)) 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.

- **Figure 9**—(A) Distribution of number of instream LWD and key pieces per channel width 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

- **Figure 10**—Distribution of number of instream LWD and key pieces per channel width 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).
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 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 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 must 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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References


Montgomery, D. R., B. D. Collins, J. M. Buffington, and T. B.


