Spatial Organization, Position, and Source Characteristics of Large Woody Debris In Natural Systems

Martin J. Fox

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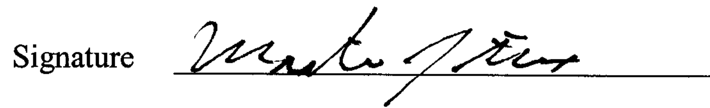
Signature 

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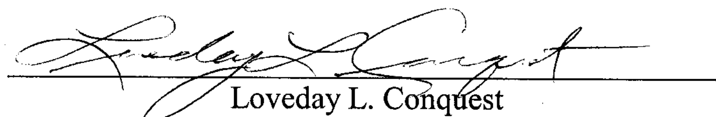

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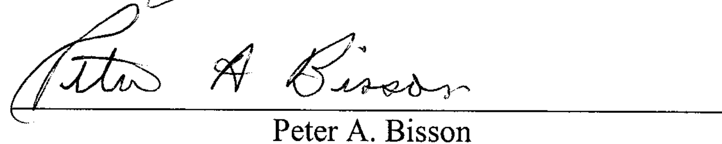

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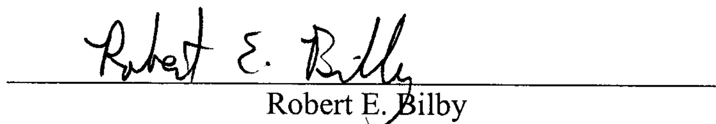

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Abstract

Spatial Organization, Position, and Source Characteristics of Large Woody Debris In Natural Systems

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Field data were collected from 150 stream sites with a diverse array of channel types and disturbance patterns within basins relatively unaffected by anthropogenic disturbance to assess the characteristics of natural large woody debris (LWD) organization, size, and riparian areas across forested regions of Washington State. Bankfull channel width was found to be the dominant factor influencing the grouping of LWD pieces. LWD group size as well as stability increased with channel size. Jams (groups $\geq$10 pieces) contained proportionately similar diameter distributions regardless of size. As bankfull channel width increased the percent of LWD volume decreased in the low-flow channel but increased in the high-flow channel. Both the median LWD lengths and diameters increased with bankfull width and proximity to the low-flow channel, as well as with increasing LWD group size. As channel width increased, the proportion of pieces oriented parallel to the high-flow channel increased while the frequency of perpendicular pieces decreased, especially if rootwads were attached.

Forest zones, as defined by climatic influence and fire history, are the best regional predictors of riparian stand attributes such as tree height, basal area, stem diameter and density. Observed riparian stand composition ranged from 8 to 17 tree species within each of six forest zones. Species richness was greater in milder climates and lower in more extreme climates. The greatest observed tree species diversity was within 35 m of the stream channel; however, stream influences on riparian characteristics were observed out to 65 m, the extent of the sample transect. Large streams with active flood plains had a significantly greater deciduous riparian component than channels less

prone to fluvial disturbances. LWD volumes did not peak or plateau until adjacent riparian stands reached 550 years in age; however, LWD quantities were also high during the first 150 years of stand origin. The percent of instream wood quantities that could be attributed to an adjacent riparian source decreased with increasing channel size. Where restoration of instream wood and/or riparian areas are warranted, these characteristics offer guidance to the range of conditions found in natural systems to which aquatic and riparian species have adapted.

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Chapter 1:

Spatial Organization and Channel Position

1. INTRODUCTION

1.1. The Importance of Instream Wood to Salmonid Habitat

Wood in Pacific Northwest streams is implicitly linked to channel processes that benefit salmonids. Instream wood influences stream morphology and channel form (Lisle and Kelsey 1982; Bilby and Ward 1991; Abbe and Montgomery 1996; Beechie and Sibley 1997), that creates structural heterogeneity to provide favorable fish habitat (Larsson 1985; Bisson et al. 1987; Bjornn and Reiser 1991; Schuett-Hames et al. 1994; Reeves et al. 1995). Wood also provides nutrients (Naiman and Sedell 1979; Wei and Kimmins 1998), cover (Hartman 1965, Bustard and Narver 1975; Murphy et al. 1984, Bisson et al. 1987), and can retain salmon carcasses for nutrient loading (Cederholm et al. 1989; Bilby et al. 1996). Wood slows water velocities to aid with metabolic conservation (Bustard and Narver 1975), and increases survival by reducing the effects of predation (Bilby 1984; Everett and Ruiz 1993; Nielsen et al. 1994). Certainly, wood is an important component of channel morphology and salmonid habitat.

1.2. Regional and Geomorphic Influences on Instream Wood Characteristics

Various aspects of channel form and the landscape influence instream wood characteristics. The composition and character of riparian vegetation can dictate large woody debris (LWD[1]) quantity, size, and volumes recruited to the channel (Bisson et al. 1987; Bilby and Wasserman 1989; Bilby and Ward 1991; Ralph et al. 1994; Bilby and Bisson 1998; Fox 2001) and lateral and vertical distribution within the channel (Ralph et al. 1994). Stream width can influence wood orientation (Bilby and Ward 1989; Braudrick et al. 1997) as well as jam size (Abbe and Montgomery 1996).

The size of wood pieces can have different influences channel morphology. Montgomery et al. (1996) found that very large wood pieces (i.e. key pieces) can catalyze log jams and create

[1] LWD is often defined by a length of $\geq$2 m and diameter $\geq$10 cm (Bilby and Ward 1989; Schuett-Hames et al. 1999; Beechie and Wyman 1992)

alluvial channels that are more hospitable to aquatic life than in what would otherwise be bedrock reaches. Bilby and Ward (1991) reported that larger pieces of wood had a greater frequency of forming plunge pools than smaller wood pieces in small channels, and Bisson et al. (1981) reported that the greatest coho (*Oncorhynchus kisutch*) densities of four western Washington streams were found in plunge pools. Small wood pieces function in concert with larger pieces by filling interstitial spaces in clusters of wood (Wallace et al. 2001), which in addition to providing cover, is likely to facilitate more pronounced pool formation and greater sediment storage.

Various theories on instream wood characteristics based on observation and science exist in the literature and provide useful insight to channel processes of LWD. In terms of distribution, Bilby and Bisson (1998), Bisson et al. (1997), Swanson et al. (1982), and Keller and Swanson (1979) have observed that wood is more 'clumped' as streams become larger. In terms of orientation, Bilby and Ward (1989) found greater-than-expected frequencies of wood oriented perpendicular to the flow in channels less than 7 m BFW, but not in two larger channel size classes of >7-10 m and >10 m BFW. They also found significantly greater-than-expected frequencies of wood oriented in a downstream direction in the two classes >7 m, and pieces oriented parallel to flow were approximately equal in occurrence among these channel width classes. Ralph et al. found approximately 38% of wood pieces were wholly in, and approximately 42% were partially in the wetted low-flow channel of wood protruding into at least the high-flow channel in old-growth streams of western Washington.

1.3. The Management of Instream Wood

Between the 1950s and 1970s, the removal of wood from streams (also known as "stream cleaning") was common practice in the Pacific Northwest (Bisson et al. 1987). To "improve" upstream fish passage, navigation, and the protection of bridges and features beyond the channel banks, state and local programs were successful at eradicating wood from many streams (Reeves et al. 1991). Repercussions to fish habitat still exist as a result of these practices (Bisson et al. 1987), and have contributed to declines in salmonid abundance (Dolloff 1986; Bisson et al. 1987, Fausch and Northcote 1992).

Over the last 30 years, many researchers have advocated the maintenance of wood loads by restoring natural riparian processes (Sedell and Luchessa 1981; Elmore and Beschta 1988; Cederholm et al. 1997; Roni and Quinn 2001). Unfortunately, restoration of riparian areas and

watersheds to facilitate these processes takes much time. Therefore, because of the correlations wood has to channel morphology, aquatic habitat, and salmonid production, and due to the paucity of instream wood stemming from past land-use practices, wood placement projects have become a common method for restoring or enhancing salmonid habitat (Kauffman et al. 1997). Indeed, resource managers have been successful at inducing salmonid response by placing wood in streams (House and Boehne 1986; Cederholm et al. 1988; Nickelson et al. 1992; Murphy 1995; Riley and Fausch 1995; Solazzi et al. 2000; Roni and Quinn 2001).

1.4. Factors Potentially Leading to Failure of Instream Wood Habitat Structures

Despite some reported success, wood placement structures often fail to increase salmonid populations due to both physical and biological factors. Physically, structures often succumb to hydrological forces (Hartman and Miles 1995; Cederholm et al. 1997; Schult et al. in review), perhaps exacerbated by upstream anthropological disturbance, landuse (Roper et al. 1998), and modification to basin hydrology (Frizzel and Nawa 1992). As a result of physical failure of placed wood, biological response is often precluded. Biologically, structures often do not produce the desired habitat for life-history requirements that are factors limiting production. Some logs or structures are not of sufficient size to form deep pools for summer and winter rearing, store gravel for spawning, etc. for a given size channel, and therefore do not provide adequate habitat to facilitate salmonid production. Also, some structures are constructed in channel locations that do not provide habitat for a particular life history that limits smolt output (i.e. a "bottleneck")(Reeves et al. 1991). Wood structures also tend to "lock a stream channel in place" and do not allow for dynamic processes and redistribution dictated by natural stream morphology. Additionally, the repeated placement of limited wood structure designs may reduce the heterogeneity of natural systems. Because wood placement project are often not adequately sized to withstand physical stream forces, or not designed to create or enhance habitats potentially limiting production, they can fail to restore salmonid populations.

1.5. Restoration Goals using Wood Placement

The issue of habitat suitability, fish preference, and optimal conditions are often hypothesized, but at best, restoration designs are often merely supposition of the needs of fish and therefore lack certainty. Perhaps those conditions we know were successful in producing salmonids are those to

which salmonids have adapted. Heterogeneity in habitat structure, the dynamic continuum of stream and riparian processes, a natural rate of disturbance, all of which has provided conditions at multiple spatial and temporal scales to influence salmonid evolution. Wood structures that mimic natural characteristics may be more effective than unnatural "engineered" designs, and may provide the best template for restoration. Sedell and Luchessa (1981) write:

> "Until we understand the structure of undisturbed habitats that wild stocks have developed within, and the sequence of changes that have occurred in those habitats, our present protection and enhancement efforts will lack both a rational context and effective direction."

Structures that mimic natural channels in terms of size, spatial distribution, orientation, and shape may provide conditions that wild salmonids have adapted and to some extent evolved. Careful considerations of what the limiting factors are, why they exist, what is needed to ameliorate these conditions, and how to return natural structure and process is seemingly a prudent approach. With the knowledge of these conditions, restoration projects may begin to resemble the natural structure of wood and consequential habitat to which salmonids have adapted, and therefore increase certainty for success until natural watershed processes can resume these functions.

1.6. Objectives:

This study evaluates the spatial distribution, organization, size distribution, orientation, channel position, and other characteristics of instream wood in natural streams draining unmanaged basins, and how it may vary by channel geomorphology and forested landscapes found across the State of Washington. Recommendations for restoration projects involving instream wood placement that promote the conditions of natural streams are provided.

2. METHODS

2.1. Site Selection

To best characterize spatial distributions, organization, orientation, channel position, and other characteristics of instream wood across regions of Washington State, survey sites are chosen within stream basins relatively unaffected by anthropogenic disturbance. These basins are

characterized by forests that are loosely termed as "old-growth", which also meet the following criteria: 1) no part of the basin upstream of the survey site was ever logged using forest practices commonly employed since European settlement, 2) the basin upstream of the survey site contains no roads or human-made modifications to the landscape that potentially could affect the hydrology, slope stability, or other factors potentially affecting the natural processes of wood recruitment and transport in streams. These basins will hereafter be referred to simply as natural or "unmanaged basins", although it can be acknowledged that some basins are "managed" to remain pristine, and may also include fire suppression. Fish presence in the surveyed stream was not necessarily a criteria; however, most sites contained physical conditions that are known to support them based on the definitions provided by the WFPB (2001).

Assumptions

The purpose of choosing sites in natural unmanaged forested basins is that we are making the assumption that natural wood characteristics as 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 for management purposes.

To isolate variability of instream wood distributions, sites were randomly chosen within discrete geomorphic and regional stratifications. Channel sizes were found to correlate with other geomorphic influences such as gradient, confinement, and drainage area (Fox 2001), therefore, channel size as represented by bankfull width was used as a rudimentary stratification to represent geomorphic influences. Regional stratifications were accomplished using three state regions (Western Washington, Alpine, and the Douglas-fir/Ponderosa Pine [DF/PP]) consisting of eight forest zones, grouped on the basis of similar riparian basal area and instream wood loads (Fox 2001).

2.2. Field Methods

2.2.1. The TFW Monitoring Program Method Manual

Survey methods use many components of the TFW Monitoring Program Method Manuals (MPMM) (Pleus and Schuett-Hames 1998; Schuett-Hames et al. 1999). All wood meeting the minimum size definition of 10 cm in diameter and 2 m in length were counted and measured if at least 0.1 m protruded into Zone 2 (the bankfull channel). Lateral channel distribution of LWD is obtained by assessing wood to four "zones:" Zone 1 is the portion of the log protruding into the

wetted low-flow channel, Zone 2 is above the wetted low-flow channel but below the estimated bankfull flow water surface, Zone 3 is above the bankfull flow, but within the vertical boundaries of the bankfull width, and Zone 4 is beyond the vertical confines of bankfull width. Wood pieces were classified as key pieces based on the definitions set forth by WFPB (1997) for BFWs of 0-20 m, but also used those defined by Fox (2001) for channels >20-100 m BFW. Stable LWD pieces are those that are either pinned, buried, or have an attached rootwad, while those pieces that do not have these features are considered "unstable." Each wood piece was classified whether or not it is storing sediment ($\geq$1 m^2 surface area of material). Wood piece orientation was determined by the methods of Bilby and Ward (1989) as described in Schuett-Hames et al. (1999), but pieces were denoted as to which end was most influencing the high-flow channel (i.e. large end, small end, or both) based on natural log taper. Thus, 11 possible orientation classes exist by this method; however, to facilitate some simpler analyses as well as provide compatibility with the work of others, some lumping occurred. Log orientation was only applied to non-jam pieces (groups <10) due to the difficulty in measuring pieces obscured by other wood within jams.

Additions to the TFW-MPMM were developed to evaluate spatial organization of wood and provide more detail on jam pieces. Each piece of wood was identified to a group association. For convention, I will often use the term "group" to refer to the size of the cluster of touching wood pieces beginning with groups as small as one piece, since the use of the term "jam" does not apply to groups smaller than 10 pieces according to the TFW-MPMM Large Woody Debris Survey definition. A >70cm diameter class was added to the jam surveys in order to refine the classification of large pieces, and a stratified random sample of lengths from each of the four diameter classes were measured (see Fox 2001 for further detail). Field crews received prior formal training in the TFW field methods through the Stream Monitoring Programs at the Northwest Indian Fisheries Commission (NWIFC), and "QA/QC" surveys were conducted on each crew to ensure data replicability and accuracy. QA/QC methods are conducted by the authors of the TFW-MPMM and are based on consistency with evaluator's survey. Based on the positive results of the QA/QC surveys, confidence in the quality and accuracy of the data are high.

2.3. Methods of Analysis

An array of statistical tests (Zar 1999) and descriptive comparisons are employed where appropriate. Data were normalized when appropriate to gain statistical benefits for testing hypotheses from normally distributed populations (Zar 1999). Regressions were conducted using continuous data for the independent variables, although some related figures are represented using categorical groupings. The grouping or "lumping" of variables was conducted when warranted, in order to increase statistical power of tests. To enable group comparisons, wood groups were organized into classes based on differences in means or variances (heteroscedasticity) between mean percent distribution per group within channel size classes. Similar methods for grouping channel size classes (BFW) were conducted with the dependent variables of wood quantities and volumes (Fox 2001), and these classifications are adopted herein. Piece orientations classes were lumped into five categories for some aspects of the analysis: **1**- parallel to the high-flow channel with the large end upstream, **2**- parallel to the high-flow channel with the large end downstream, **3**- perpendicular to the high flow channel, **4**- angled downstream to the high-flow channel, and **5**- angled upstream to the high-flow channel. To be compatible with existing piece orientation theory (Bilby and Ward 1989), comparative analyses were also conducted with the above categories, but with both Category 1 and 2 orientations combined into a single class.

3. RESULTS

One hundred fifty sites were surveyed, totaling nearly 38 km of stream length. Sampled stream gradients ranged between 0.04% and 66%, with 139 of the sites (93%) meeting the WFPB (2001) physical criteria for fish presence. 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). Sites consisted of a diverse array of channel types, confinement classes, bedforms, dominant water origins, and disturbance histories (fire, debris flows, snow avalanches, and floods). 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. Site summary tables and maps can be found in Appendix A and B, respectively. Further detail on sampling stratifications can be found in Fox (2001).

3.1. LWD Group Size Distribution

3.1.1. Regional Influence

Forest regions did not have a pronounced effect upon the grouping or clustering of LWD pieces. 'Within-region' comparisons of based on insignificant differences in both means and variances of LWD groups sizes suggested groupings of: 1-3, 4-9, 10-20, 21-50, 51-200, and >200 pieces per group were possible, enabling increased statistical power of tests. Comparisons of LWD group sizes stratified by five stream channel width classes indicate that there are no significant differences in mean reach percentages of wood pieces and volume distributed to this array of LWD group size classes (P>0.18, ANOVA, all groups) between State regions. However, it is understood that the numeric quantity and volume of wood among LWD size groups is known to differ (Fox 2001). Thus, the similarities in proportions allocated to each LWD group size class between regions enabled the use of combined regional data.

3.1.2. Geomorphic Influence

Channel size (as represented by bankfull width) is a significant geomorphic influence on group size distribution. Figure 2 illustrates that the percent of wood allocated to larger group sizes increases with channel size. With each greater channel size class, the percent distribution of LWD shifts to larger group size classes, as depicted by the shift in the median in Figure 2. The percentages in wood volumes are also similar in terms of allocations to each group; subsequently, we have refrained from the redundancy of an additional figure illustrating volume proportions. In small channels (BFW≤5 m), 70% of wood pieces were distributed into groups of 9 or less, with the most frequent distribution of pieces occurring in groups of one (32%); however, in channels >50-100 m BFW, only 19% of wood pieces were distributed into groups of 9 or less, with 81% distributed in groups of 10 or more. In channels >50-100 m BFW, the most frequent distribution of LWD pieces occurred in groups of 200 or more (24%). Most notably, the median shift in LWD distribution from small groups (<10 pieces) to large groups (≥10 pieces) occurs when channels reach merely 5 m BFW and greater, (Figure 2) (P<0.001, ANOVA) [Aside, the mean bankfull depth (BFD) in channels 0-5m BFW was 0.32 m while channels >5-10 m BFW was 0.40 m]. These data support the theories and hypotheses Bilby and Bisson (1998); Bisson et al. (1997); Swanson et al. (1982); and Keller and Swanson (1979) that wood becomes more clumped (i.e. organized into larger jams) with increasing channel size.

Factors of confinement, bedform (alluvial vs. bedrock), gradient, and channel type (Montgomery and Buffington 1997) were assessed upon influencing spatial distribution of wood. Due to the inconsistent influence upon all channel sizes, the presence of geomorphological irregularities and interactions confounding the effects, and lack of statistical significance, the analyses suggests that none of these geomorphic variables are a consistent predictor of wood group size distributions. Although some patterns were observed by trend analyses (albeit insignificant), a greater sample size or a study design that isolates these geomorphic variables would be needed in order to reveal that these are in fact influential on wood group size distribution. Therefore, these factors were not used further in the analyses.

Due to the strong relationship of channel size upon LWD group size distribution, and the inconsistencies with confinement, gradient, bedform, channel type, and regional influences, channel size as expressed by bankfull width is a strong predictor in the spatial organization of wood.

3.1.3. Group Stability

The stability of wood in small groups (<10 pieces per group) increased with group size ($P<0.001$). Also, comparison of these variables as separated by BFW classes indicate significant differences ($P<0.05$) of y-intercepts and regression slopes, suggesting that LWD groups of the same size are more stable in smaller channels than they are in larger channels (Figure 3).

3.2. Relationship of Key Pieces to Racked Member LWD

In general, the quantity of "racked member" LWD increased with the number of key pieces per group ($P<0.0001$, regression). A three-fold increase in racked member LWD for each key piece was exhibited in channels 0-5 m BFW, whereas a 25-fold increase in racked member LWD per key piece was observed in channels 50-100 m BFW. Notably, the range of racked member LWD per key piece varied greatly. Figure 4 illustrates the ranges between key pieces and racked member LWD by five bankfull width classes in terms of percentile distributions (i.e. box plots), along with a table of regression statistics expressing this relationship.

3.3. Lateral Channel Position

The magnitude of fluvial forces, as indicated by channel size, influences the lateral distribution of LWD in the channel. The percent of LWD volume in the low-flow channel (Zone 1) decreased

with increasing bankfull width (P=0.004, regression), while the percent of LWD volume in the high-flow channel (Zone 2) increased with bankfull width (P<0.001, regression). Furthermore, the proportion of wood that extends into Zone 4 decreased with increasing bankfull width (P=0.002, regression). LWD groups equal or greater than 10 pieces had a greater percent of wood volume suspended above the bankfull channel (i.e. Zone 3) than LWD groups less than 10 pieces; however, the percent LWD volume that extends beyond the bankfull channel (Zone 4) was greater in small LWD groups than in large LWD groups (both at P<0.001, t-test). Small LWD groups in small channels (<10 m BFW) had significantly less LWD volume in Zones 1 than larger channels (P<0.001, t-test), and large and small LWD groups had relatively similar Zone 2 distributions in all channel sizes. The comparisons of LWD volumes among four channel zones according to bankfull width are presented in Figure 5 for both small (A) and large (B) LWD groups.

3.3.1. Piece Distribution

Individual LWD pieces often span more than one zone, and their distribution is influenced by channel size. The percent of LWD pieces (groups <10)[2] wholly within Zone 1, and partially in Zone 2 (i.e. protruding *into* from Zone 3 and/or 4) did not change significantly (P=0.271 and 0.462, respectively, ANOVA) with BFW class; the mean percent was approximately 13% and 18%, respectively, for all combined BFW classes (Figure 6). In contrast, the mean percent of pieces partially in Zone 1 decreased with increasing BFW, and the mean percent of pieces wholly within zone 2 increased with increasing BFW (both at P<0.001, regression). There were no significant differences in these relationships between state regions; the proportions were remarkably similar (P=0.997) although the quantities and volumes per zone differed as described in Fox (2001).

3.3.2. Sediment Storage By Zone

The frequency that LWD in small groups (<10 pieces per group) stores sediment is related to channel zone. The percent of pieces that store sediment increased with proximity to the low-flow channel (P<0.001, ANOVA, post-hoc Tukey's HSD) in all channel width classes. Notably, this may relate to wood stability, where wood wholly or partially in Zone 1 had a greater probability

[2] Due to the methods and practical limitations, the evaluation of zone distribution for individual pieces was not conducted for LWD in large groups (≥10 pieces).

of having a stability factor than wood wholly or partially in Zone 2 ($P<0.001$, t-test). There was no significant relationship of LWD-associated sediment storage to channel width; however, the percent sediment storage by pieces wholly in Zone 2 and below (towards the low-flow channel) appeared to decrease to approximately 20 m BFW, and then increase as BFW became larger. Percentile distributions of the percent LWD (in groups <10) that store sediment by channel position, as grouped according to five bankfull width classes are presented in Figure 7.

3.3.3. Piece Diameter and Length by Lateral Position

The distribution of wood to zones begs the question, "do the sizes of logs differ among zones?" Markedly, both the mean lengths and diameters of LWD pieces of small groups (<10 LWD pieces) increased with bankfull width ($P<0.05$, regressions); however, there were also significant differences in diameter, and more prominently, lengths, by channel zone. As expected, both the mean diameters and lengths were greater for LWD pieces that were partially in (i.e. protruding *into*) a zone than LWD pieces that were wholly within a zone (both at $P<0.001$, paired t-tests) since pieces that extend across zone boundaries are presumable longer. These relationships are presented as box plots for five bankfull width classes in Figure 8.

The stability of logs also varies by lateral channel position. Logs spanning more than one zone had a greater probability of having a stability factor than logs wholly within a zone ($P=0.015$, t-test). Additionally, the large size of logs as described in the preceding paragraph adds to the stability of pieces, which is not reflected as a factor of stability according to the methods.

The proportion of wood wholly within and partially within the low-flow channel is compared to the findings of Ralph et al. (1994). When isolating the data of this study to drainage areas similar to those surveyed by Ralph et al. (1994), the combined proportions of wood interacting with the low-flow channel (Zone 1) are not dissimilar between studies ($P=0.102$, t-test). However, separate proportions of wood that were 1) wholly within the low-flow channel and 2) partially in the low-flow channel are both significantly different from Ralph et al. (1994) ($P<0.01$, t-test), where they found proportionately more wood wholly within the low-flow channel and less wood partially in (protruding into) the low flow channel than this study.

3.4. Jam Composition

The percent distribution of LWD by diameter class varies significantly within jams (≥10 pieces per group) (P<0.001, ANOVA), and little difference in this percentage were found between jams regardless of size. LWD pieces >70 cm diameter averaged approximately 4% per jam, which did not differ significantly between jams of six LWD group size classes (P=0.65, ANOVA). Pieces 50-70 cm diameter averaged approximately 10% per jam (P=0.26 between jams-ANOVA), pieces 20-50 cm diameter averaged approximately 41% (P=0.279 between jams), pieces 10-20 cm diameter averaged approximately 45% (P=0.053 between jams), and rootwads (with boles <2m in L) averaged less than 0.5% per jam (P=0.394 between jams). The mean percentage of LWD by diameter class for six jam size classes, along with standard deviations is presented in Figure 9.

3.5. LWD Length Distributions

LWD lengths per diameter class varied within as well as between LWD group sizes. With greater diameter class, LWD had greater median lengths in all LWD group size classes. Regression analyses suggest that as group size increases, piece lengths within each diameter class also increased (P<0.022) except for the >70 cm diameter class pieces, where length differences between groups was not significantly different (P=0.540, ANOVA, P=0.65, regression). Box plots representing the percentile distribution of LWD lengths for six jam size classes (≥10 pieces per group) as well as small groups (1-9 pieces) according to four diameter classes are presented in Figure 10.

3.6. LWD Piece Orientation

Analyses on the distribution of wood (LWD groups <10 pieces) suggest that LWD piece orientations are influenced by channel size and the presence of an attached rootwad. The analysis suggests that with increasing channel size, the proportion of pieces oriented to Category 1 increase while the pieces in Category 3 decrease (P<0.001, regression). As channel size increased, LWD pieces with rootwads had a significantly greater probability to orient parallel to the flow with the large end upstream (Category 1) than pieces without rootwads (P=0.039, ANCOVA); however, in the small channels (BFW< 10m), pieces with rootwads were more frequently oriented perpendicularly to the channel (Category 3) compared to pieces without rootwads as indicated by differences in y-intercepts (P<0.001, ANCOVA). The comparison of orientations for pieces with and without rootwads is presented in Figure 11.

The size, shape, and stability of LWD influence piece orientation and sediment storage. Regression analyses suggest that the mean length, diameter, and volume of LWD pieces oriented to Categories 1 and 4 increases with channel width ($P<0.05$, regression). Of pieces oriented to Categories 3 and 4, there was a greater probability for pieces to have the smaller end of the log protruding toward the center of the channel rather than the larger end ($P=0.025$ and $P<0.001$, respectively, paired t-tests). In large channels (BFW >50-100 m), significantly fewer pieces oriented to Categories 2 and 5 included a factor of stability ($P<0.05$, ANOVA) than pieces in other orientations categories. Pieces oriented to Category 3 had the highest mean percent frequency of occurrence of a stability factor than other orientation categories (70%). Among all possible orientation scenarios, the observed frequency that pieces store sediment was roughly inversely proportional to their observed orientation frequency of occurrence (Figure 12). Pieces with the large ends influencing the high-flow channel were more frequently observed storing sediment than pieces with the small ends influencing the high-flow channel ($P<0.05$, paired t-tests), and perpendicular pieces had a greater propensity to store sediment than parallel pieces. The frequency that LWD pieces are observed storing sediment in all 11 evaluated orientation scenarios in the order of highest to lowest frequency of observed sediment storage is presented in Figure 12, along with relative statistics.

4. DISCUSSION

4.1. Group Distribution

4.1.1. Regional Influence

The lack of significant differences in percent wood allocated to mutual group sizes among the three state regions suggests that riparian species composition, stem density, and other factors attributed to climate conditions do not significantly influence how wood is grouped. This illustrates that the physical response of wood to stream forces is similar in all regions, and the vegetative conditions are not a significant influence to proportional wood distributions. Indeed, comparison of dry wood densities for riparian tree species observed in all three regions had no significant differences in a comparison by Fox (2001), suggesting that buoyant forces of wood and subsequent entrainment thresholds do not differ significantly among regions. Regional differences and riparian composition are reported to account for the disparate quantities and volumes of LWD allocated to common group size classes among regions (Fox 2001); however,

the lack of differences in percentage distributions to common group classes suggests that the factors catalyzing group formation (e.g. the presence of key pieces, fluvial forces, and similarities in channel morphology) are available in each region.

4.1.2. Geomorphic Influence

The shift in the percent of wood allocated to larger group sizes (Figure 2) suggests that pieces become more dependent upon one another for stability in channels greater than 5 m. Wood is more readily mobilized with increasing channel sizes, due to the potential for greater buoyant forces with water depth (Braudrick and Grant 2000). Evidently, the increase in the mean bankfull depth (BFD) from 0.32 m to 0.40 m between channels classes of 0-5 and >5-10 m BFW, respectively, is (or contributes to) the threshold at which the majority of wood recruited to these channels becomes organized by fluvial processes.

The fact that even small channels (0-5m BFW) contain large groups (up to 51-100 pieces) may be indicative of local disturbance rather than fluvial processes. Seemingly, these channels normally lack the fluvial forces to move and organize wood into large groups even during large floods; however, local episodic disturbances such as debris flows, snow avalanches, mass wasting, wind throw, and perhaps other forms could recruit large quantities of wood locally into a small channel reach. These influences were not significant enough to change the median distribution among LWD group sizes by bankfull width classes (Figure 2) suggesting these events are infrequent; however, these processes are known to occur and likely contribute to the distribution of group sizes in small channels.

Although gradient, confinement, bedform, and channel type were not found to be reliable predictors in spatial distribution of wood, some geomorphic factors are intrinsically linked to channel size. For example, large channels are often unconfined and at low gradients, while small channels are frequently confined and often at higher gradients (unless in the flood plains of larger streams). Therefore, channel size often reflects a combination of inter-related geomorphic features that contribute to instream wood organization.

4.2. Group Stability

Factors inducing wood stability are seemingly due to the interaction of pieces within groups, and how groups are assembled during fluvial processes. The fact that the stability of wood in small groups (<10 pieces per group) increases with group size suggests that larger jams are more stable

than smaller jams due to a larger matrix of pinned logs. However, the fact that groups decreased in the percent of stable logs as channel size increased may be the result of how small groups are formed. Although LWD in these small groups may be touching (by our definition of a group), the fact that there are fewer stable pieces indicates that the degree to which these pieces were interlocked and pinned against one another is less. This suggests that larger streams may loosely assemble small groups on gravel bars, such as when flows subside following floods. Indeed, small loosely organized LWD groups were frequently observed on gravel bars of large streams, apparently stranded during high flow recession. These bars were frequently observed at river bends and island points, and favorably positioned to intercept entrained wood. Conversely, gravel bars and highly sinuous channels were less commonly observed in small streams, thus accumulations of wood along the banks and channel margins may require greater proactive fluvial force to impinge wood since there are fewer collection points for wood during flow recession.

4.3. Key Pieces to Racked Members

As channels increased in size, the greater quantity of racked-member LWD associated per key piece is explained by the increased mobility of wood. As channels become larger, wood is more readily entrained by fluvial forces and has a proclivity to form accumulations (Figure 2). Since key pieces often serve as a catalyst to jam formation, and jams/groups increase in size with channel size, it bears logic to conclude that key pieces will be associated with greater quantities of racked-member LWD as channel size increases.

4.4. Lateral Distribution

4.4.1. Volume distribution

Channel size is perhaps the most dominant influence on lateral channel location of LWD. The fact that the LWD volume in the low-flow channel (Zone 1) and LWD volume in the high-flow channel (Zone 2) increased as channels width increased suggests that the difference can be attributed to buoyant forces; larger streams typically have greater buoyant forces than in small streams. Wood in Zone 1 is more likely to resist entrainment in smaller streams compared to larger streams for a give piece size. Thus fewer pieces, albeit larger on the average, will remain in low-flow channel of larger streams than smaller streams. Also, during high flows, mobilized wood is often deposited on bars and channel margins as flow recede. Typically, larger channels

will have a greater surface area between the outer bounds of the low-flow channel to the outer bounds of the high-flow channel (i.e. Zone 2) than smaller channels. While this may be proportionate to the stream size, wood is usually of a "fixed size" relative to the riparian trees that do not adjust with stream size. As a result, the greater Zone 2 area in large channels can contain more wood pieces than in smaller channels, as observed in the low-flow survey. The observation that more wood extends into Zone 4 as channels decrease in width is also likely due to physical forces of the stream. Wood is more likely to be recruited into large streams by fluvial processes, where adjacent riparian trees are often drawn entirely into the stream. Wood recruitment to small streams is mostly due to tree fall and bole breakage from the adjacent riparian area. The large streams may also possess the force to pull partially recruited trees fully into the channel, while small streams do not. Due to both of these factors, a greater proportion of a recruited tree may subsequently remain on the banks of smaller streams than with larger streams. This process of recruitment also may explain why large groups of LWD (≥10 pieces) have more wood in Zone 1 and less in Zone 4 than small groups of LWD (<10 pieces)(Figure 5). Large groups are typically more stable than small groups (Figure 3) and are therefore less likely to be moved outward from the low-flow channel, providing the proportionately higher quantities in Zone 1. Also, large groups are typically formed by fluvial processes and therefore are usually residing in the channel, whereas small groups, particularly individual logs, may reside "as they fell" (e.g. non-fluvial tree mortality and local disturbances) and often have a greater proportion outside the banks (Zone 4).

4.4.2. Piece Distribution

Channel size, as it relates to fluvial forces and cross-sectional area may drive LWD distributions across channel zones. Notably, the proportion of small group LWD (<10 pieces) partially in the low-flow channel (Zone 1) decreased nearly proportionately to increases in LWD wholly within the high-flow channel (Zone 2); however, the proportion of wood pieces wholly in Zone 1 and pieces partially in Zone 2 remained constant (Figure 6). This may arise from two factors: 1) larger channels typically will have greater forces of buoyancy that can move wood laterally outward from the low-flow channel during high flows. Secondly, there is often a greater Zone 2 area in larger channels that can contain whole pieces of wood after they are moved outward, whereas in smaller channels, this Zone 2 area may not be sufficiently large to contain whole pieces. Because recruited tree sizes are independent of stream size and thus the zones are proportionately larger in larger channels, and because of the stream forces to move pieces laterally increases with channel size, wood wholly in Zone 2 increases with channel size.

4.4.3. Sediment Storage by Zone

The geomorphic function of wood appears to be linked with lateral channel position, and is independent of channel size. The increase in percent that LWD stores sediment with increased proximity to the low-flow channel is likely a combination of stability and the frequency with which it interacts with channel flow. As noted in Section 3.3.2, pieces wholly in the low-flow more frequently are associated with a stability factor than pieces wholly or partially in Zone 2. Stable pieces will likely retain more sediment than mobile pieces due to the greater longevity in a static position, and pieces that more frequently interact with flow will have a greater likelihood of trapping alluvium. This explanation is apparently valid for all channel sizes.

4.4.4. Piece Diameter and Length by Lateral Position

The mean lengths and diameters of LWD pieces from small groups logically increased with channel width, since there would likely be a propensity for smaller pieces to be entrained with the greater buoyant forces of larger channels, thus elevating the mean size. The difference in both diameter and length between pieces wholly within a channel zone vs. pieces that protruded into these zones (i.e. span more than one Zone) is not surprising: 1) longer pieces are more likely to span multiple lateral channel zones than smaller pieces, which are more likely to fit within a zone, and 2) longer pieces are often larger in diameter (but not overwhelmingly, as suggested by Figure 8). Notably, because diameters are obtained at the midpoint, the diameter at the larger ends of logs would not be reflected by the data, therefore, the overall diameter differences are perhaps more prominent than visualized in Figure 8A. The zonal size differences could also be attributed to the stability of pieces in relation to their orientation in the channel. Perhaps only the larger pieces of LWD that span multiple zones (i.e. angled or perpendicular pieces) are able to resist entrainment of stream flow because a portion of the log resides beyond the bankfull channel (Zone 4) and serves to anchor the log. Indeed, logs spanning multiple zones were more likely to be stable than pieces wholly within a zone, and the stability of many of these logs was due to being pinned against riparian trees when a portion of the spanning logs extended into Zone 4.

Compared to the findings of Ralph et al. (1994), the combined proportion of wood influencing the low-flow channel are similar; however, when these proportions are separated by wood wholly within and partially within the low-flow channel, there is a significant difference. This is likely due to differences in methods, where wood from their study had minimum LWD criteria of 3 m while this study used 2 m, where larger pieces tend to be more stable and resist

entrainment from the low-flow channel. Furthermore, the methods of this study did not differentiate the quantity of pieces wholly and partially within Zones for large groups (>10 pieces). The fact that more wood *volume* was observed in Zone 1 (the low-flow channel) for large groups (Figure 5B) in this study suggests that more LWD *pieces* are likely to be located in Zone 1. Thus, the two studies are perhaps similar, although it cannot be verified due to subtle differences in methods.

4.5. Jam Composition

The percentage distributions of LWD within jams according to diameter classes (Figure 9) suggests that few large pieces (e.g. key pieces) form the catalyst for retaining copious numbers of smaller LWD pieces during jam development. The stability of these large pieces relative to the channel reduces their potential to be mobilized during high-flows, where they serve to intercept smaller entrained LWD. Over time, the accretion of racked-member LWD continues, while the addition of large pieces is often relatively rare but proportional, resulting in a consistent proportion per jam size. This also suggests that if jams accrue a disproportionate number of smaller, racked member LWD, the jam may be unstable and eventually break apart, or a portion of the racked members may be lost from the jam, potentially reforming jams downstream to maintain the relative ratios exhibited in Figure 9.

4.5.1. Length and Diameter Distributions

The observation that the mean LWD piece length increased with piece diameter classes in jams is likely an artifact of merely tree geometry and fiber strength, but the fact that mean piece lengths increased as jam size increased within each diameter class is likely a function of the fluvial forces that mobilize wood. Logs with greater diameters are presumed to be more resistant to breakage than smaller logs, and plausibly trees with larger diameters (e.g. at breast height [dbh]) grow to greater heights than trees with smaller diameters. As a result, larger diameter LWD is likely to be longer on the average, as reflected in Figure 10. The observation that the piece lengths within each diameter class increased with jam size is likely a result of a similar situation as discussed in the preceding paragraph: larger jams are typically formed in larger channels (Figure 2), which have a greater ability to mobilize longer pieces. Smaller length pieces are thus more likely to be moved through the system, increasing the median lengths with larger group sizes. The insignificant differences in lengths between groups of the >70 cm diameter class LWD suggests

that these pieces are less likely mobilized even at the shortest observed lengths of the class; however, these lengths were indeed greater than those of any other diameter class and hence most resistant to mobilization.

4.6. LWD Piece Orientation

The observation that the frequency of LWD aligned parallel to flow increased as channels increase in size is likely due to stream forces and the physical shape of logs, whereas the greater frequency that LWD is aligned perpendicularly in smaller channels is likely due to channel shape, relative wood size, and recruitment processes. Wood is more buoyant in larger, deeper streams and thus is more readily mobilized during high flows. As flows recede or if a channel becomes shallow, the end of the log that protrudes the deepest into the water column (usually the larger end) contacts the channel bed first, pivoting the moving log longitudinally in the channel with the deepest protruding end upstream, stranding it into a parallel position until the next high flow. Certainly, this phenomenon is augmented by the presence of a rootwads, as shown in Figure 11. Rootwads are more likely to have greater friction with the channel bed than merely the large end of a log devoid of a rootwad, since roots typically extend perpendicularly greater distances from the bole and serve as "rakes" to catch the streambed and anchor the log. Contrarily, small channels lack the same buoyant forces as large channels relative to the size of recruited wood. As trees fall across the channel, small streams will have less ability to move the piece as compared to larger streams. Consequently, wood often resides in small channels "as it fell." Based on the observation that riparian trees often lean toward the opening in the canopy created by the stream corridor, it can be surmised that they will often fall in the same direction and thus are oriented perpendicularly to the channel with the small end towards the channel center. Compounded with the confined morphology common with small channels that will often suspend at least one end, wood pieces in these channels will often have a greater proportion in Zone 4 (beyond the bankfull edge) (e.g. Figure 5) that enhances stability and resistance against fluvial forces to move the piece from the perpendicular position it fell. Furthermore, logs with rootwads are typically more stable than fragmented pieces, further enhancing stability that likely contributes to the observed higher proportions of perpendicular LWD frequencies in small channels.

The analysis of the eleven finite orientation classes offer further insight to observed frequencies of natural piece positions and functions. Interestingly, the range of frequencies to which pieces store sediment for all orientation classes does not differ greatly, with means ranging

between 44% and 65% (Figure 12). Notably, some of the more important functions of pieces in these orientation classes are not revealed by the ability to store sediment, such as the ability to retain entrained wood. For example, pieces oriented in the "A" class (Category 1) are common positions of key pieces that catalyze jam formations. Indeed, jams are perhaps one of the more prominent instream features that influence channel morphology; however, the orientation of those key pieces that initiate this formation was not assessed if the group size was greater than 9 pieces. Therefore, the importance of piece orientation should not only consider its probability to store sediment, but also consider other important physical and biological functions beyond the ability of this analysis.

Comparing the results of this study to those of Bilby and Ward (1989) confirm some of their results, as well as provide statistical verification for some non-significant trends observed in their analysis. Bilby and Ward (1989) found significantly greater-than-expected frequencies of wood oriented perpendicular to flow only in channels less than 7 m. This study confirms these author's findings for channels less than 7 m, but also that the frequency of LWD to perpendicular orientations decreases with increasing channel size; larger channels had less-than-expected frequencies of perpendicular pieces. Bilby and Ward also found significantly greater-than-expected frequencies of wood oriented in a downstream direction in the larger channel classes (>7-10 m and >10 m BFW); however, statistical tests with the data of this study could not confirm any differences among channel sizes. Also, Bilby and Ward hypothesized that the lower-than-expected frequency of pieces angled upstream (Category 5) suggested that these pieces were less stable. Indeed, factors of stability were significantly less frequent with pieces in this Category (as well as Category 2), statistically verifying Bilby and Ward's conclusions. Finally, Bilby and Ward did not find a significant correlation with the frequency of parallel pieces to channel size in their study; this is likely due to the fact that their stream size were smaller (≤20 m) and subsequently had less fluvial forces than streams of this study. Therefore, significant differences between the two studies, such as the frequency of pieces oriented parallel to flow, could potentially be explained by differences in channel size. Notably, the general percent distributions between the four orientation categories (lumping parallel pieces of this study into one category) are remarkably similar between this study and Bilby and Wards, especially between the BFW classes <20 m. Also, the larger data set herein that afforded greater statistical power, finding significance where Bilby and Ward's data may only indicate visual trends without significance.

4.7. Restoring Heterogeneity With Instream Wood Enhancement: Guidance For Managers

When restoration projects involving the artificial placement of instream wood are warranted, the characteristics of instream wood in natural systems as provided in this study offer guidance for restoring the heterogeneity and structure of wood in adversely impacted systems. The following steps provide the procedures for implementing these findings into a restoration endeavor:

1) Through monitoring and assessment, determine the current status of instream wood in a potential restoration project reach.

2) Using recommendations for LWD quantity and volume (e.g. Fox 2001), assess if wood additions are warranted, and how much more is needed to attain natural loads.

3) Determine where to fill voids in the ranges of natural wood organizations in the project reach using the appropriate LWD group size distributions of Figure 2.

4) Design LWD group structures using the ratio of key pieces per racked member ranges of Figure 4, the diameter and length distributions of Figures 8, 9 and 10, the lateral channel distributions of Figures 5 and 6, and piece orientations of Figures 11.

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, re-establishing values within the historic range that "pull" the mean closer to the historic mean will likely better serve to restore 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 restore the natural ranges of heterogeneity. In order to pull the mean closer to the historic condition while staying within the historic range, my recommendations for restoration of wood conditions are to use portions of the distribution (e.g. between the 25th and 75th percentiles) that will reestablish the central tendencies of natural distributions. Thus, basin restoration approaches may provide perspectives on the ranges of existing conditions, and what is needed to promote conditions toward those observed in natural systems.

4.8. Conclusions

Inferences drawn from these characterizations should serve as a guidance template for habitat restoration, enhancement, and mitigation projects, as well as provide a means for evaluation of wood characteristics in managed or impacted systems in Pacific Northwest Forests. Based on the

assumption that natural systems process instream wood in a manner to which salmonids have adapted, maintaining or re-establishing the range of conditions to restoration sites will help to maintain diversity and provide greater certainty that restoration and enhancement projects will be successful at increasing or maintaining salmonid populations until natural processes can resume. With the understanding that natural systems provide the range of conditions to which salmonids have become accustomed, we can make the assumption that mimicking these ranges and patterns in impacted systems will help re-establish habitat structure necessary to facilitate historical salmonid production.

5. FIGURES-CHAPTER 1

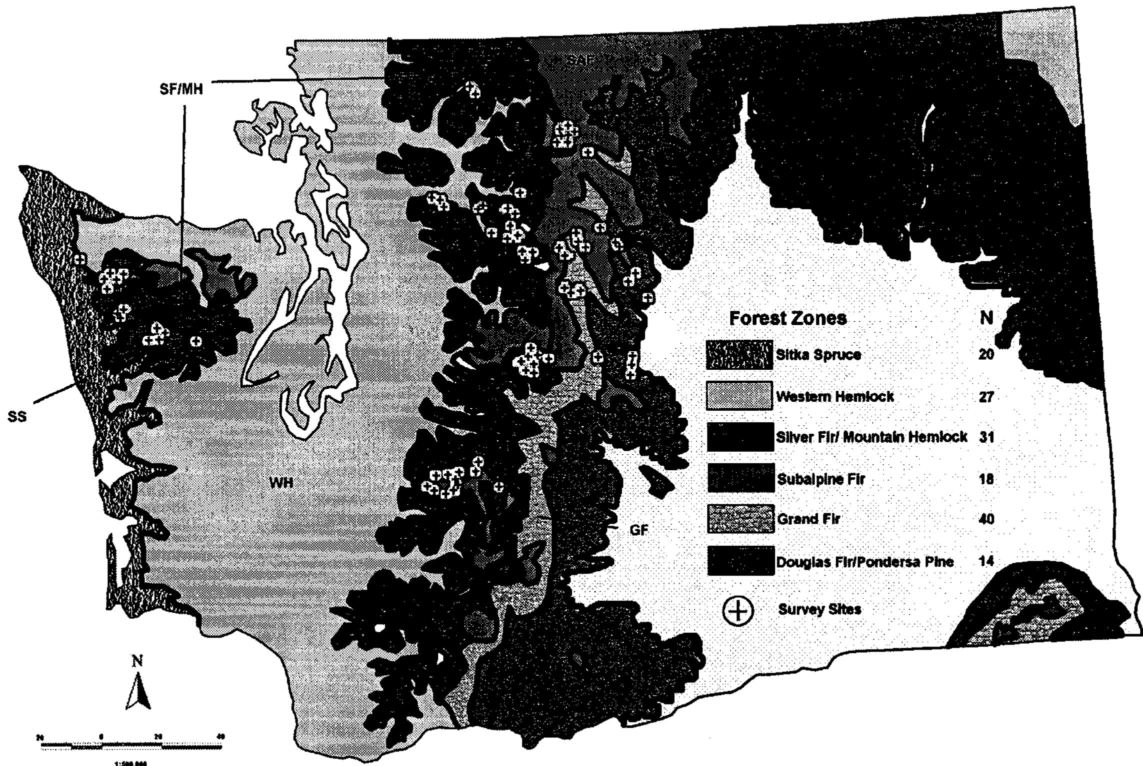


Figure 1. Survey site distribution according to forest zones across Washington State. Each point represents one or more streams (n = 150). The polygons represent forest zones (also labeled), a vegetation classification system largely based 1) natural fire succession and potential climax tree species, 2) elevation, and 3) climate. The forest zones boundaries depicted in this illustration are greatly simplified, and multiple plant associations used to characterize forest zones can be found isolated within these polygons due to microclimatic differences [after Franklin and Dyrness (1984); Henderson et al. (1992); and Agee (1993)].

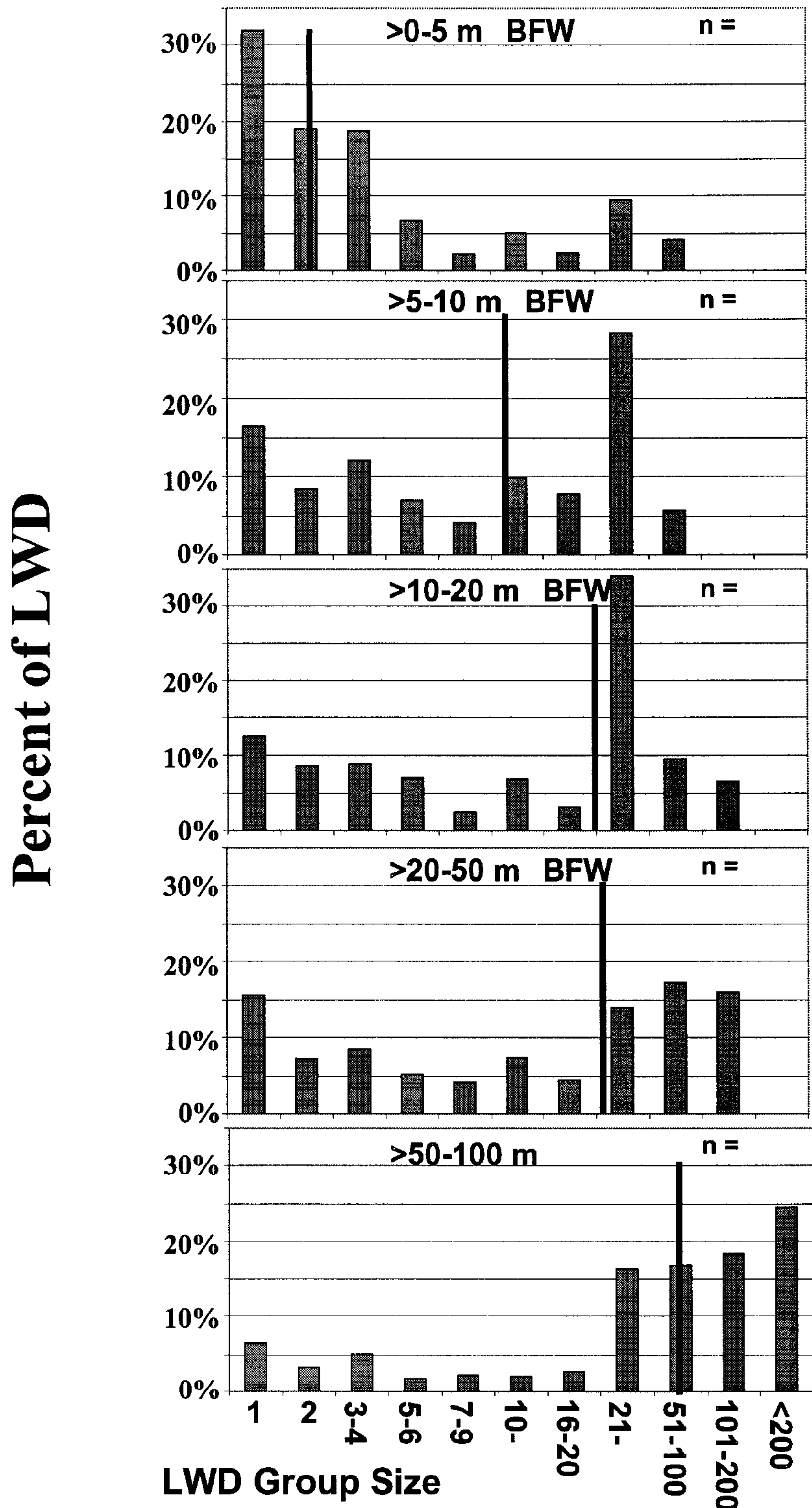


Figure 2. The percent distribution of LWD to group size class according to five bankfull width classes. The vertical bars in each chart represent the median.

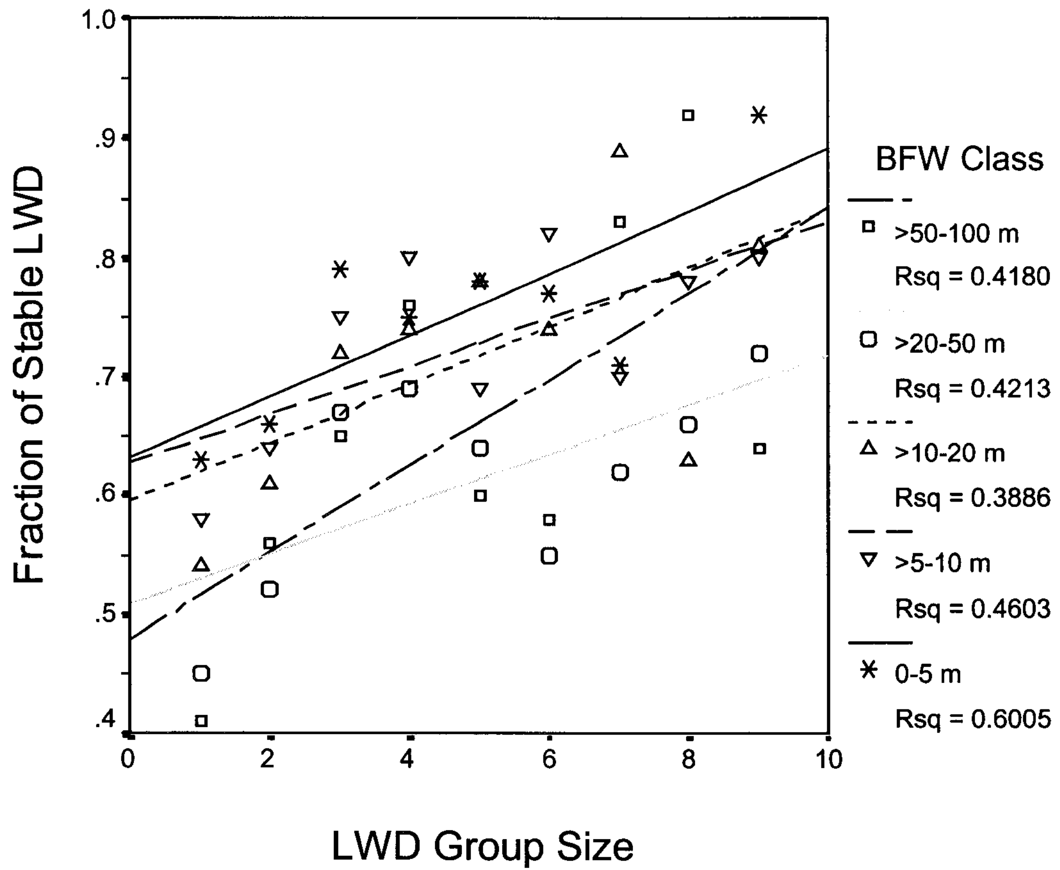
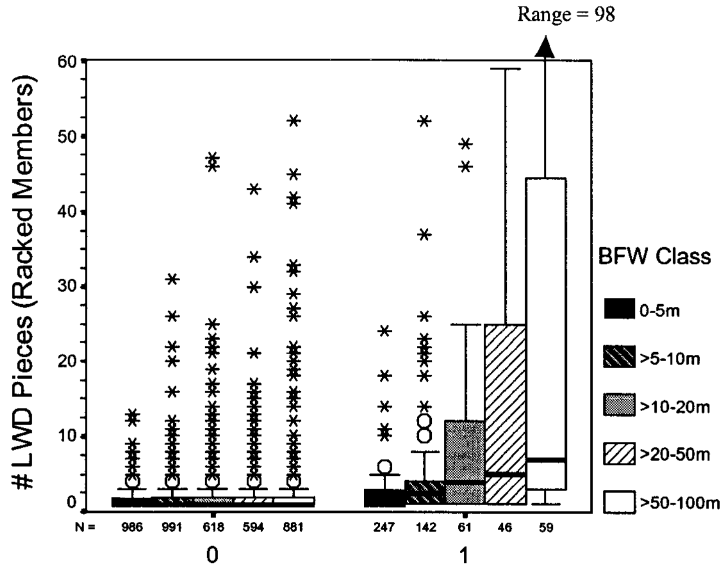
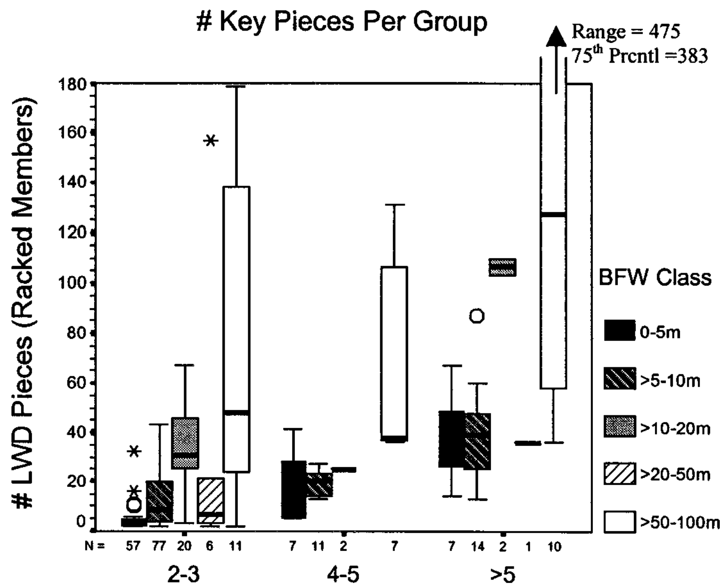


Figure 3. The relationship of the fraction of stable LWD with LWD group size (groups <10 pieces), as categorized by five bankfull width classes.





BFW Class	Regression Equation	R^2	SE	N
0-5 m	Y = 3.03x + 1.01	0.49	2.7	1429
>5-10 m	Y = 4.50x + 1.85	0.52	4.7	1280
>10-20 m	Y = 11.16x + 2.27	0.55	7.0	749
>20-50 m	Y = 13.2x + 2.7	0.16	13.1	673
>50-100 m	Y = 24.8x + 3.36	0.61	21.9	968

Figure 4. The quantity of "racked member" LWD to the number of key pieces per group, as categorized by five bankfull width classes. Key pieces of 2 or more requires a scale change in the y-axis for better visibility, thus the relationship is divided into two figures. The table below these figures presents the regression statistics of these relationships, where X is the number of key pieces per group and Y is the predicted number of racked member LWD per group. N is the number of LWD groups evaluated.

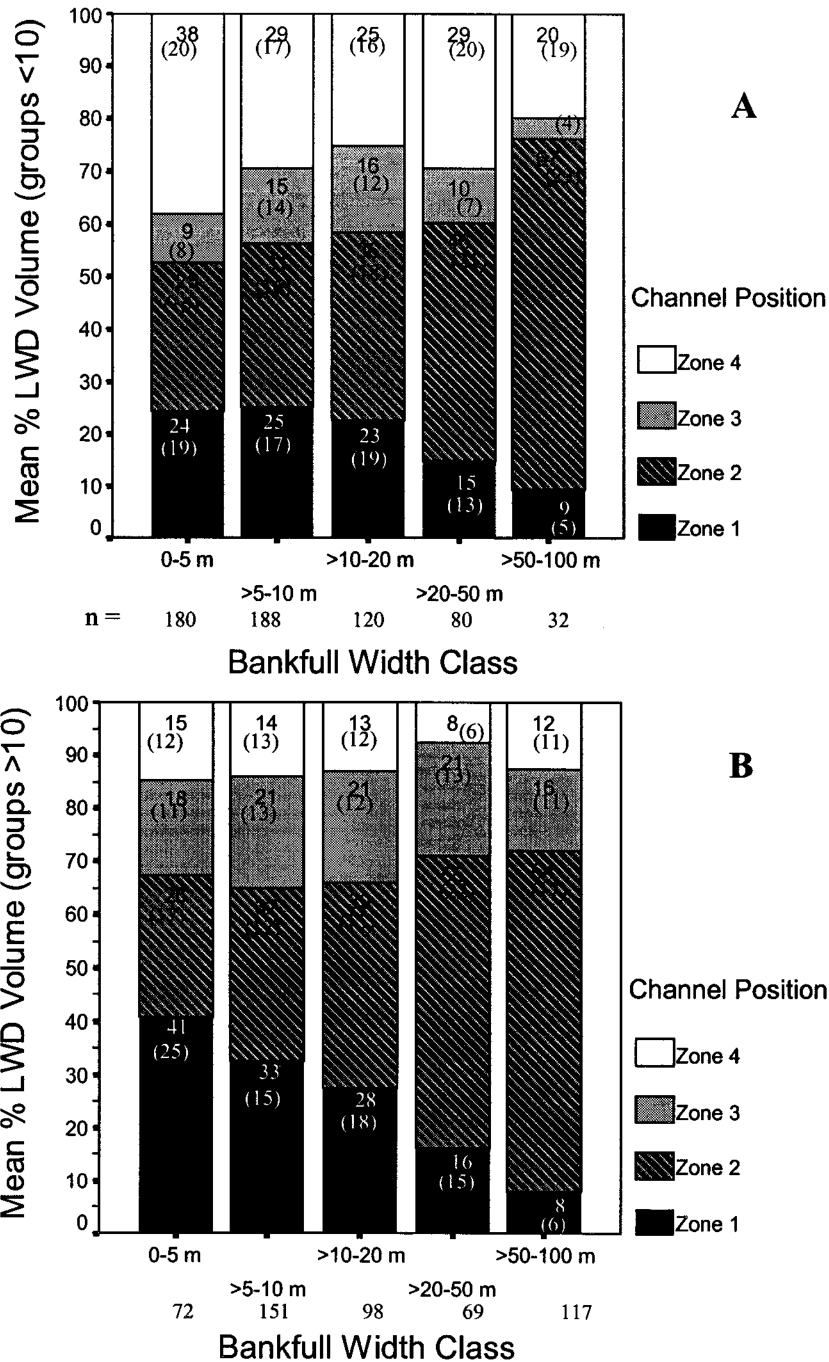


Figure 5. Comparison of the mean percent LWD volume by four lateral zone distributions between A) small groups (<10 pieces per group) and B) large groups (≥10 pieces per group) according to five bankfull width classes. Zone 1 is the wetted low-flow channel and Zone 2 is above the wetted low-flow channel but below the horizontal axis of the bankfull channel, Zone 3 is above the high-flow channel but within the vertical confines of bankfull, and Zone 4 is laterally beyond the bankfull width. The numbers in parentheses are the standard deviations, and n= the number of LWD groups.

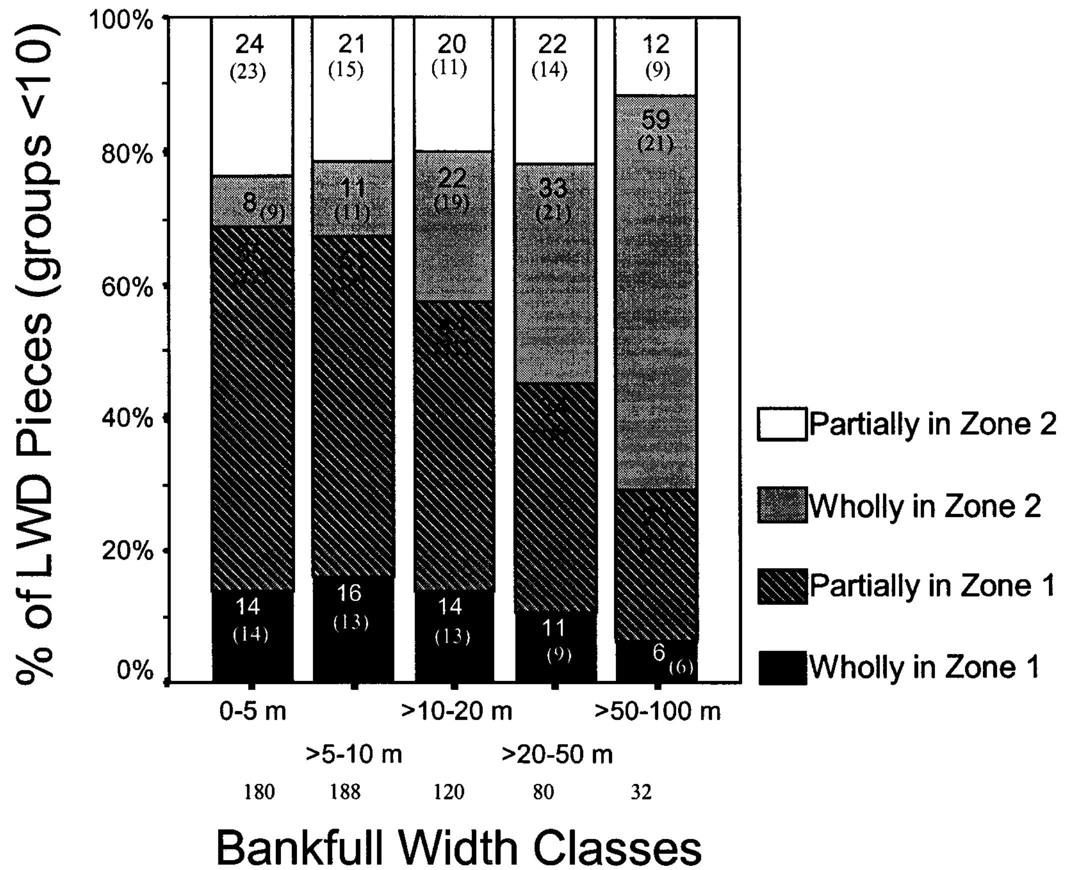


Figure 6. The distribution of LWD (from groups <10) by bankfull width classes, according to lateral channel position. Zone 1 is the wetted low-flow channel and Zone 2 is above the wetted low-flow channel but below the horizontal axis of the bankfull channel. Pieces that are partially in a zone extend outwards (e.g. a piece partially in Zone 2 does not extend into Zone 1). The numbers in parentheses are the standard deviations and N = the number of groups.

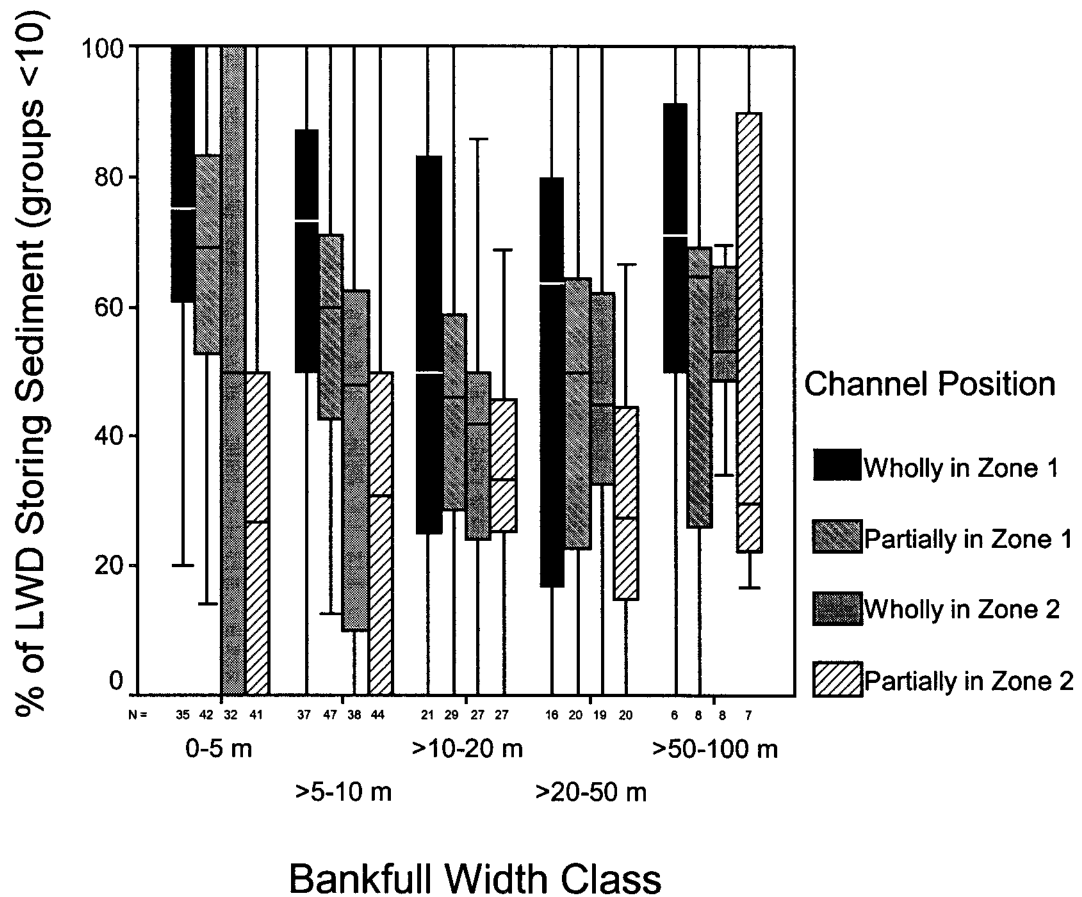
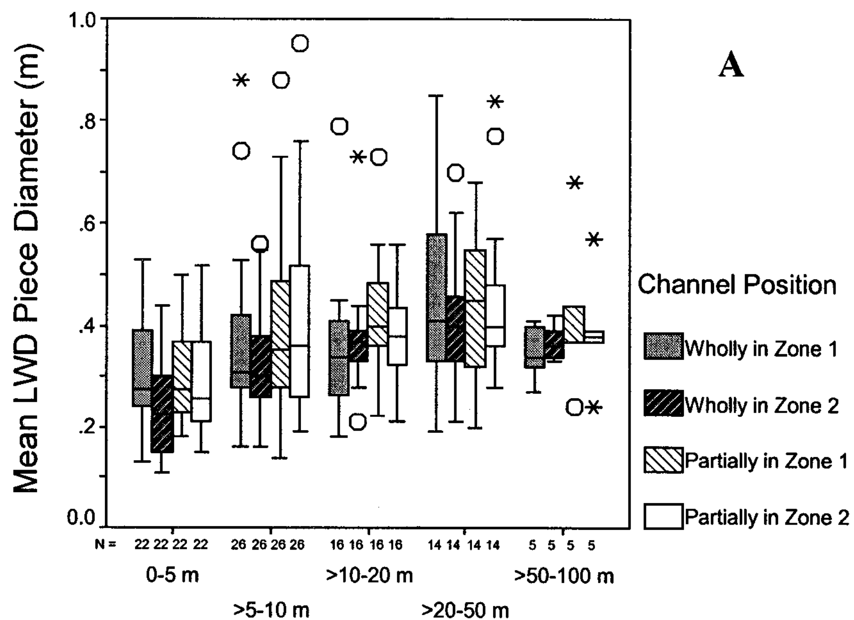


Figure 7. The percentile distributions of the percent LWD (in groups <10) that store sediment by channel position, as grouped according to five bankfull width classes. Zone 1 is the wetted low-flow channel and Zone 2 is above the wetted low-flow channel but below the horizontal axis of the bankfull channel. Pieces that are partially in a zone extend outwards (e.g. a piece partially in Zone 2 does not extend into Zone 1). Plots are of reach means, and n = valid reaches.



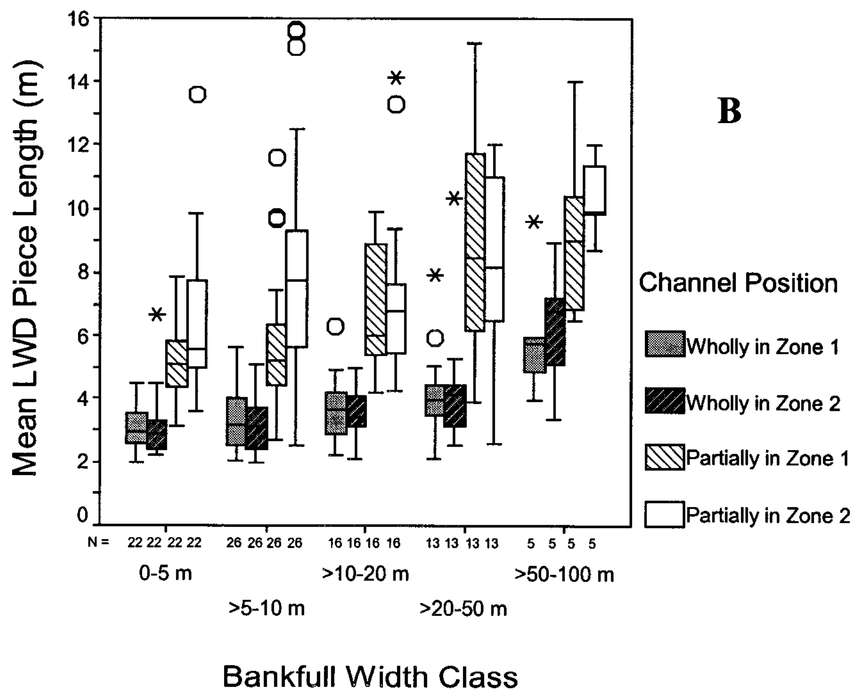


Figure 8. The percentile distribution of mean LWD diameters (A) and lengths (B) for five bankfull width classes, according to channel zone. Zone 1 is the wetted low-flow channel and Zone 2 is above the wetted low-flow channel but below the horizontal axis of the bankfull channel.

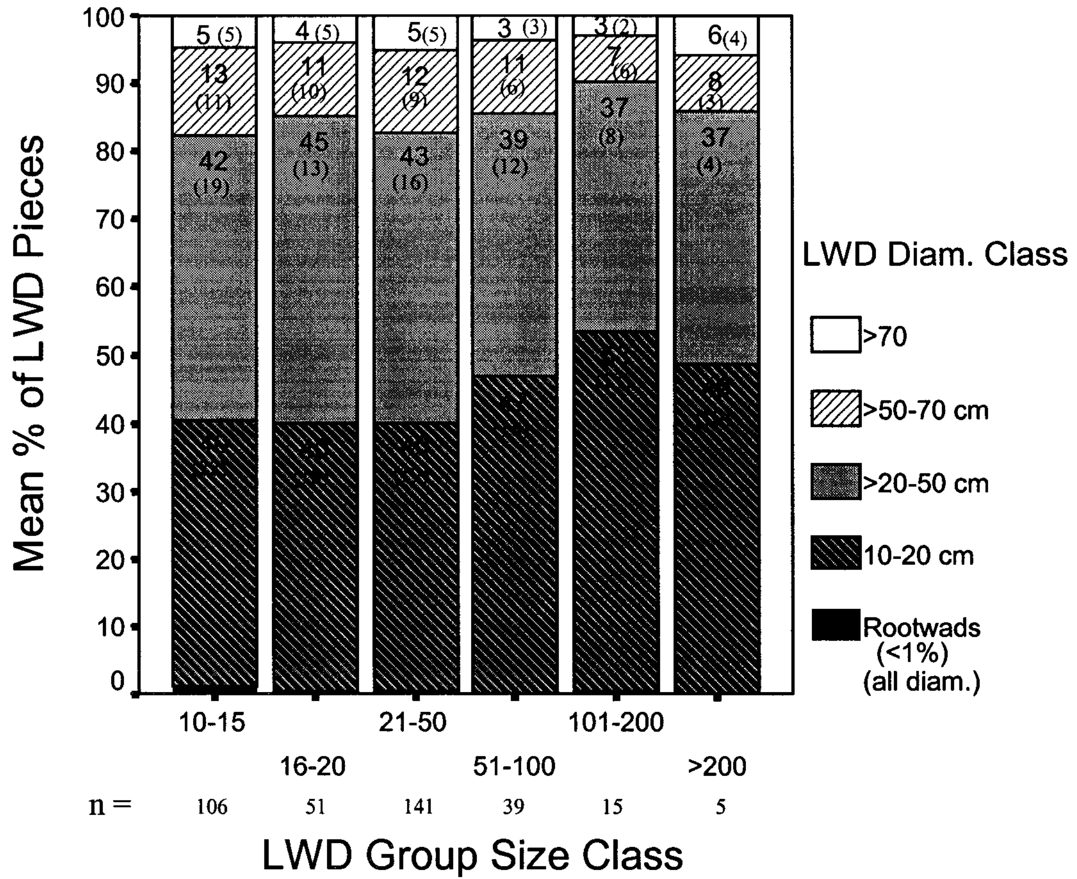


Figure 9. The mean percent distribution of LWD pieces by diameter class according to LWD group sizes (groups >10 or "jams"). The labels within each bar are the reported percents, and the sample size (n) is the number of jams surveyed within each group size class. N= the number of groups, and the numbers in parentheses are the standard deviations.

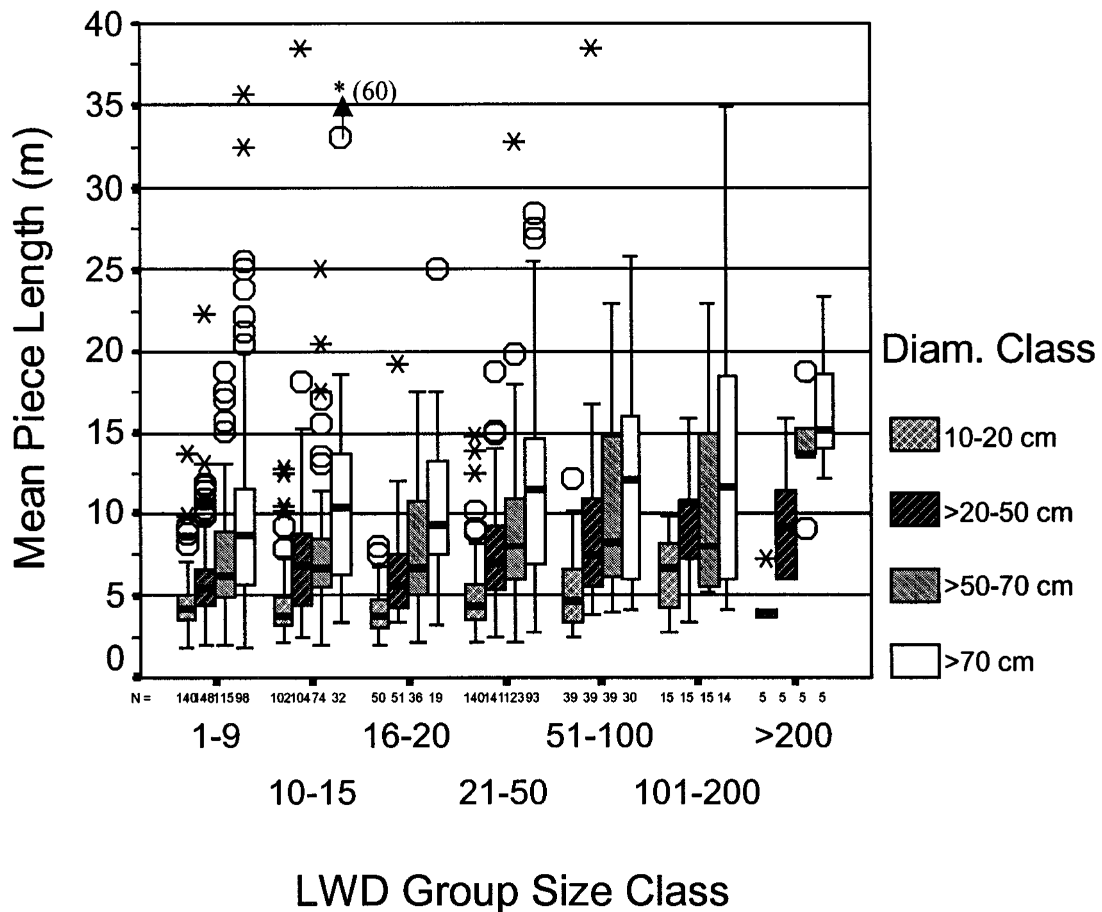


Figure 10. The percentile distributions (i.e. box plots) of mean LWD piece lengths by diameter class, according to LWD group size class.

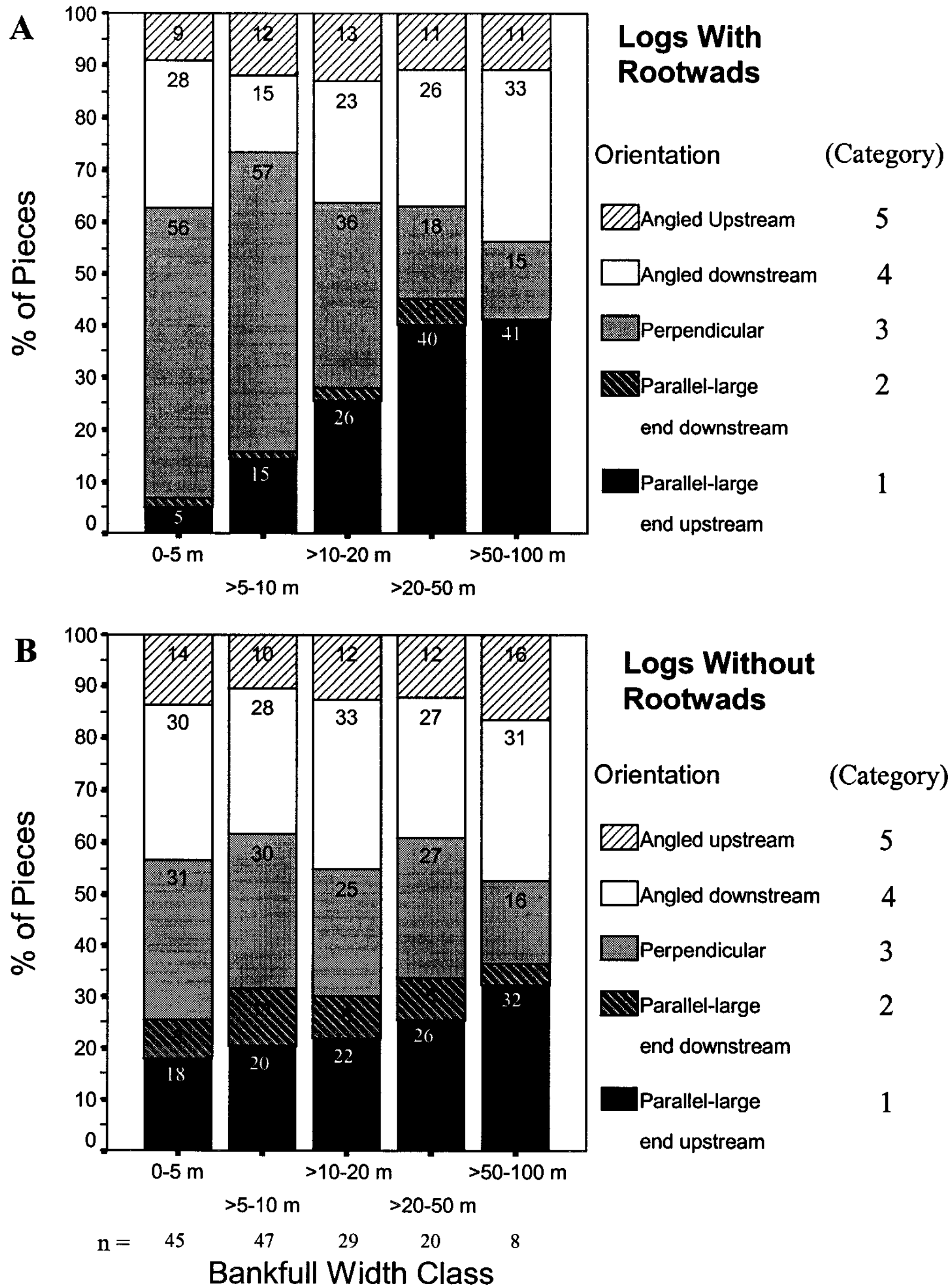
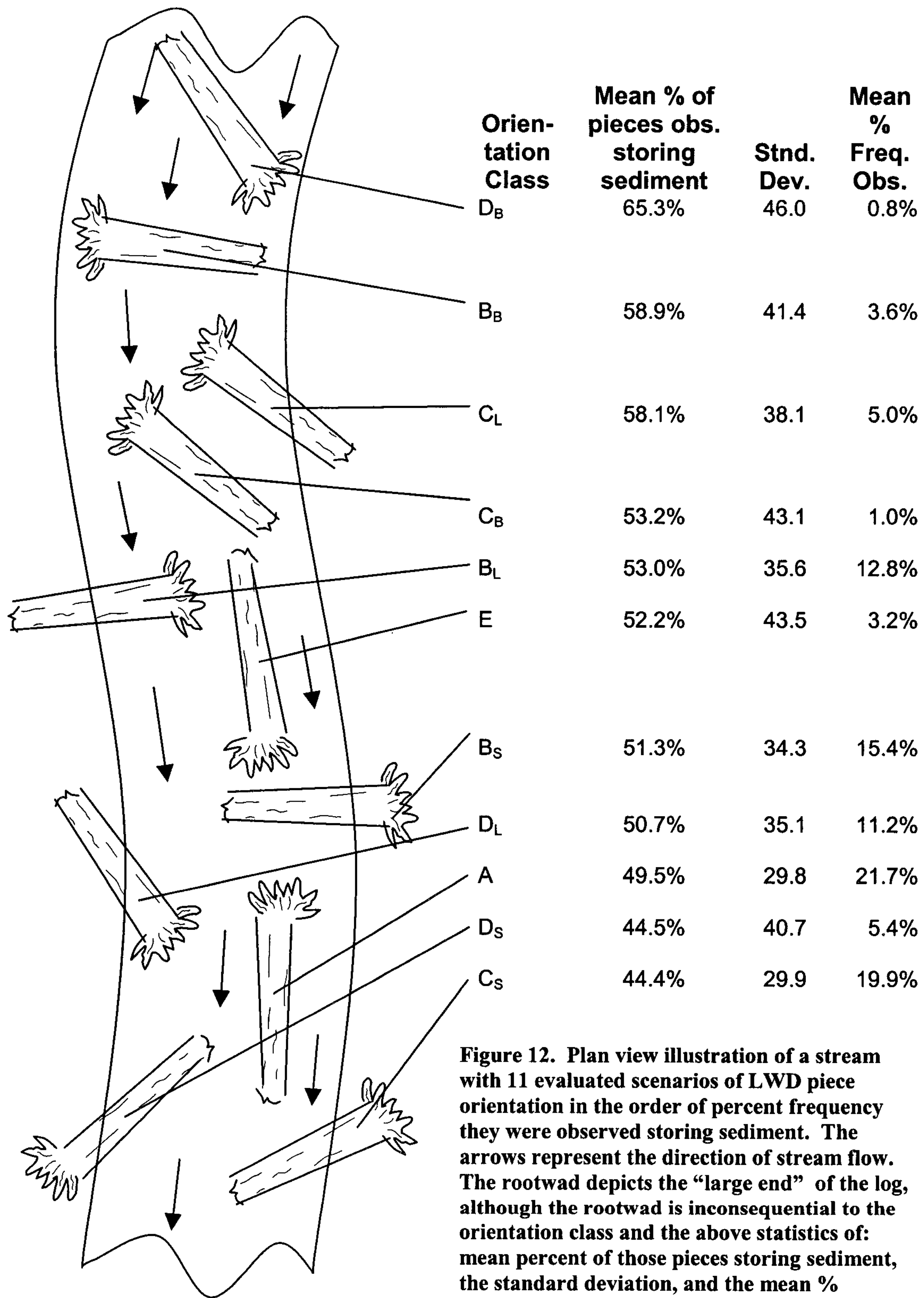


Figure 11. The mean reach percent frequency of mainstem channel LWD piece orientation (groups <10) by five bankfull width classes for logs with attached rootwads (A) and without (B). The bar labels present the mean percent for each orientation class.



Orientation Class	Mean % of pieces obs. storing sediment	Stnd. Dev.	Mean % Freq. Obs.
D_B	65.3%	46.0	0.8%
B_B	58.9%	41.4	3.6%
C_L	58.1%	38.1	5.0%
C_B	53.2%	43.1	1.0%
B_L	53.0%	35.6	12.8%
E	52.2%	43.5	3.2%
B_S	51.3%	34.3	15.4%
D_L	50.7%	35.1	11.2%
A	49.5%	29.8	21.7%
D_S	44.5%	40.7	5.4%
C_S	44.4%	29.9	19.9%

Figure 12. Plan view illustration of a stream with 11 evaluated scenarios of LWD piece orientation in the order of percent frequency they were observed storing sediment. The arrows represent the direction of stream flow. The rootwad depicts the "large end" of the log, although the rootwad is inconsequential to the orientation class and the above statistics of: mean percent of those pieces storing sediment, the standard deviation, and the mean % frequency that pieces were observed aligned to the orientation class.

Chapter 2:

Characteristics of Natural Riparian Forests and Large Woody Debris Input to Streams

6. INTRODUCTION

6.1. The Role of Riparian Forests

Riparian forests, because of their multiple ecological and dynamic functions, have become a subject of particular interest for resource managers. Riparian vegetation, and the organic debris it produces, influences stream morphology, water quality, and aquatic and terrestrial ecosystems (Shields and Nunnally 1984; Bisson et al. 1987; Abbe and Montgomery 1996). Riparian contributions of large woody debris (LWD) to streams is an important influence on stream function and channel form (Lisle and Kelsey 1982; Bilby and Ward 1991; Montgomery et al. 1995; Abbe and Montgomery 1996; Spence et al. 1996; Beechie and Sibley 1997; Massong and Montgomery 2000), which forms favorable fish habitat (Larsson 1985; Bisson et al. 1987; Bjornn and Reiser 1991; Schuett-Hames et al. 1994), and provides food sources for fish (Naiman and Sedell 1979; Cederholm et al. 1989; Bilby et al. 1996; Spence et al. 1996). The size and functions of instream wood are correlated to basin riparian characteristics (Bilby and Ward 1991; Ralph et al. 1994), and the regional characteristics of riparian areas as represented by discrete forest zones influence the quantities and volumes of LWD (Fox 2001). Because riparian trees provide much of the wood recruited into streams as well as an array of other physical and biological functions and processes, they are an important management component in watersheds.

6.2. Riparian Structure

Due to the lack of comprehensive studies on riparian-stand attributes, riparian forests are often characterized with general forest attributes; however, some distinctions are likely to exist between upland and riparian stands. Naiman et al. (1998) reports the basal area of riparian forests is generally as great or greater than that of upland forests; evidence supports the concept that riparian forests have relatively high rates of biomass production in comparison with upland

forests, likely influenced by moisture, nutrients, and temperature gradients. Furthermore, riparian forests are often favorable for deciduous seral species regeneration in response to channel-associated disturbances (Naiman et al. 1998). Gregory et al. (1991) and Pollock et al. (1998) found that microclimate gradients can also contributed to greater plant and animal species diversity in riparian forests as compared to upland forests. Seemingly, riparian forest structures and characteristics are different from general upland forests.

6.3. Factors That Influence the Character of Riparian Forests

Geomorphic processes, disturbance patterns, and regional climate differences influence the structure and composition of riparian forests both spatially and temporally. Geomorphically, the riparian floodplains of large, unconfined channels are developed by fluvial disturbances that promote the colonization of deciduous species (Naiman et al. 1992; Fetherston et al. 1995; Johnson et al. 2000). Conversely, Palik et al. (1998) found that non-fluvial tree mortality was highest along stream reaches having narrow valleys riparian landforms elevated above the channel while it was lowest in reaches having wide valleys and low landform elevations. In terms of disturbance, fire is a dominant influence, varying by forest type (Agee 1993) that affects timber age (Henderson et al. 1992). Timber age in turn influences mean tree diameter (Rot et al. 2000) and tree height (Agee 1993; Henderson et al. 1992). Patches of timber unscathed by a fire (often termed fire refugia) can diversify timber ages along riparian areas (Camp et al. (1996).

Floods can cause channel avulsion, accelerate lateral migration, and topple trees from riparian areas (Johnson et al. 2000). Deciduous trees typically are first to colonize riparian areas following disturbances due to debris flows (Grant et al. 1984; Wilford et al. 1998) and snow avalanches (Fetherston et al. 1995; Cushman 1981). Following these disturbances, conifer succession may not occur for 80 years or more (Jenkins and Hebertson 1998). Other forms of natural riparian disturbances include wind throw, insect infestations, drought, disease, ice storms, and others.

Regionally, climatic variations control the characteristics of forest vegetation. These influences promote disparate forest “zones, types, or series” (Franklin and Dyrness 1973; Henderson et al. 1992; Agee 1993), as characterized by potential (climax) species, tree size, and density of forest stands. Each forest zone within western and eastern Washington has unique differences. Local climate and fire history of these forest zones influence species diversity as well as other stand attributes. Although riparian forests have some structural disparities from their

upland counterparts, these regional climatic influences that classify forest zones can also provide inferences on the general characteristics of riparian areas.

Within Washington State, four major forest zones west of the Cascade mountain crest and four to the east are commonly described in the next section.

6.3.1. Western Washington Forests

Although many unique forest types occur in within western Washington, the four major zones are the *Picea sitchensis* (**Sitka spruce [SS]**), *Tsuga heterophylla* (**Western hemlock [WH]**), *Abies amabilis* (**Pacific Silver fir [SF]**), and *the Tsuga mertensiana* (**Mountain hemlock [MH]**) forest zones. These forest zones are typically dense conifer, the product of wet temperate climates, naturally long-lived, and are among the largest biomasses in the world (Franklin and Dyrness 1973). Basal areas can exceed 100 m^2/ha, tree heights reach 50-75 m at maturity, and some species live beyond 800 years (Franklin and Dyrness 1973). Indeed, Fowells (1965) reports that the life-span of seral Douglas-fir in Western hemlock forests can reach between 800-1200 years, and complete succession by climax species in these forests would take >1200 years (Franklin and DeBell 1988). Tree mortality is generally continuous through forest life-histories (Franklin et al. 2002), but some authors have observed a bimodal distribution in mortality rate. Agee and Huff (1987) report that downed fuels (i.e. coarse woody debris) are high within the first 100 years following fire disturbance, then low over the next 300-400 years as vigorous stands mature, and then high again after approximately 450-500 years as aging stands produce increased inputs of downed wood through succession. Huff (1995) observed a similar phenomenon with tree mortality following fire, where stands had high levels of mortality due to stem exclusion during the first 100-years, followed by little mortality over the next 400 years, and higher levels of Douglas-fir mortality (the seral species) at about age-500. Franklin et al (2002) also note that coarse woody debris are at minimal levels during the sere.

6.3.2. Eastern Washington Forests

Coniferous forests occupy the dry interior regions of the eastern slopes of the Cascades and extend across the northern portion of the state to the Rocky Mountains in the extreme northeast corner of Washington. More than nine climax species have been identified in the forest associations of eastern Washington due to the diverse ranges of climate and elevation (Franklin and Dyrness 1973). The more significant forest zones of eastern Washington are the *Abies*

lasiocarpa (**Subalpine fir [SAF]**), *Abies grandis* (**Grand fir [GF]**), *Pseudotsuga menziesii* (**Douglas-fir [DF]**), and the *Pinus ponderosa* (**Ponderosa pine [PP]**) forest zones.

The subalpine fir forests are generally found along the Cascade crest, and the interior of the Pasayten Wilderness in the North Cascades at elevations above 1,300 m amsl. The prolonged winter snow-pack (often between 7-8 m in wetter zones), along with the coldest winter temperatures of all Pacific Northwest forests, limits growth as compared to trees in lower elevation forests (Agee 1993). Subalpine fir (SAF) and co-dominants are not well-adapted to surviving fires (Agee 1993) and fire return intervals, estimated to be around 250 years (Fahnestock 1976), or 109-137 years (Agee 1990), are often points of stand origin.

Grand fir are typically found at elevations between 1100-1500 m east of the Cascade crest, although populations of Grand fir can be found at low elevations of inland western Washington (Agee 1993). Rarely is GF the late-successional dominant species.

Douglas-fir/ Ponderosa Pine Forests are typically found in dry, lower elevation (1,200-1,800 m) sites east of the Cascades (Franklin and Dyrness 1973). Douglas-fir is always the co-dominant species in this forest type, and is typically suppressed by fire (Agee 1993). Agee (1993) reported natural fire-recurrence intervals of these forests to be typically between 11-24 years. Due to frequent burns, fires are typically of low intensity; therefore, the older Ponderosa Pines are rarely killed due to their thick bark unless fires are fueled by excess wood build-up in the under-story (Franklin and Dyrness 1973; Agee 1993). As a result, these forests typically have a diverse array of seral stages.

6.4. Processes of Natural Wood Recruitment to the Channel

The quantity of wood in a stream at any point in time is a result of input and output balances over the previous centuries (Swanson et al. 1982; Martin and Benda 2001). There are several means by which LWD finds its way into a stream. At the reach scale, trees can fall directly into a channel due to bole breakage or by being uprooted. These are often the result of various forms of chronic tree mortality such as stem suppression/exclusion, wind throw, disease, old age, and the result of fluvial processes such as channel avulsion or lateral migration and bank erosion. At the watershed scale, other processes such as debris flows and snow avalanches can deliver trees into downstream channels (Cushman 1981; Grant and Swanson 1995). The river can also exhume buried wood within flood plains (Fetherston 1995).

Instream LWD biomass is positively correlated to tree density (Bilby and Wasserman 1989), tree maturity (Bilby and Ward 1991; Rot et al. 2000), and the percent of conifers (Harmon et al. 1986). Source distance is correlated to tree height (McDade et al.1990; Robison and Beschta 1990), but McDade et al. (1990) could not attribute 47.7% of identified wood pieces to an adjacent source, suggesting that many pieces are routed in from upstream sources. Clearly, instream wood loads are dynamic and fluctuate according to various natural processes at the reach and watershed scale.

6.5. Riparian Management

The effects of timber management have altered riparian structure, which in turn has directly affected streams. The quantity of woody debris in channels in the Pacific coastal forest types have decreased over time as a result of various land-use practices such as clearing of riparian trees (Bilby and Bisson 1998). Wind-throw accelerates mortality in riparian areas abutting newly harvested forests, disrupting the rate of recruitment to streams (Grizzel and Wolff 1998). Changes in tree species composition, abundance, and input rates to streams resulting from forest management practices have differed according to location in the watershed and many physical and biological processes have been altered by these changes in the river system's debris load (Bisson et al. 1987; Hogan et al. 1998).

To promote the protection of salmonids and other aquatic organisms as well as the habitats that support them, resource managers often attempt to manage riparian areas in a manner that will provide long-term wood recruitment. For example, the Washington State Forest Practices Board (WFPB) has adopted rules (WFPB 2001) that require landowners to leave trees in riparian management zones (RMZs) following timber harvest for purposes such as providing future sources of instream wood. The quantity, size, and arrangement of leave trees as well as the width of buffers vary according to region, stream size, existing stand density and composition, and site class. The objective of the prescribed riparian management is to produce conditions emulating mature riparian stands in the future. The WFPB rules set basal area management targets, which is a commonly used indicator for the productivity of timber in a stand. These basal area targets are designed to achieve a basal area comparable to an unmanaged stand by age 140. The WFPB (2001) forest practices rules have basal area requirements for five site classes, which are an index of soil conditions based on the State Soil Survey that are presumed to influence potential tree growth, which is in turn used to scale riparian prescriptions (WFPB 2001). In this

system, site class one (I) is presumed to be the most productive for tree growth, while site class five (V) the least. Requirements range from 45 m^2/ha (190 ft^2/ac) for site class V to 67 m^2/ha (285 ft^2/ac) for site class I. Other prescriptions used in riparian management that rely upon site classification include thinning, the application of variable buffer widths, and the culling of hardwoods. Each has the intent of promoting conditions for long-term riparian functions such as wood recruitment for the benefit of aquatic species.

Despite efforts to improve riparian management to promote favorable stream responses, there is yet much to learn about maintaining sustainable riparian structure that promotes instream habitat heterogeneity. In essence, the diversity of conditions has become homogenized from past management, and may continue to do so if conforming to management standards devoid of diversity. Also, there is uncertainty that trajectories set to stand conditions at 140 years will achieve characteristics of older natural forests, or is applicable in all forest zones, especially with repetitive "edge-effect" that makes riparian trees more susceptible to wind throw (Grizzel and Wolff 1998) with each successive harvest rotation (typically 40-60 years in Pacific Northwest forests). Also, some attributes of riparian stands are often characterized by elements perhaps more relevant to upland forests due to the unavailability of information specific to riparian areas. Riparian forests may differ from uplands with distance to the stream, geomorphic influence, and small and large scale climate disparities. Without better understanding of the holistic processes promoting long-term natural processes and heterogeneity in systems, objectives of maintaining and restoring favorable stream habitats and salmonid production may not be fully realized.

Because of the reliance upon riparian management to provide adequate quantities and volumes of instream wood to promote salmonid habitats, a need exists to refine current riparian management targets to those representative of conditions to which salmonids have adapted, as well as for variation attributed to regional and geomorphic influences. By refining current riparian performance targets that address this variability, it should be possible to develop more accurate riparian characteristics for management. To accomplish this, an accurate characterization specific to riparian areas is needed. If we presume that salmonids have generally been successful under natural wood-loading rates, unmanaged riparian stands should provide suitable reference conditions for the range of stand characteristics that promote and maintain favorable salmonid habitat.

6.6. Objectives

The objective of this study is to assess riparian characteristics of forests subject to a natural disturbance regime across multiple landscapes of Washington State. Variables characterizing the stand structure such as basal area, stem density, tree height, species composition and richness, and other features will be determined. Applicable stand attributes of natural riparian forests will be compared to existing management targets and trajectories. The quality of these riparian areas will also be compared to their associated instream wood loads. Finally, recommendations for management that promote the conditions of natural forests will be provided.

7. METHODS

7.1. Site Selection

To best characterize natural riparian forest structure and composition across regions of Washington State, survey sites were chosen within stream basins relatively unaffected by anthropogenic disturbance. These basins are characterized by forests that are loosely termed as "old-growth," and which meet the following criteria: 1) no part of the basin upstream of the survey site was ever logged according to forest practices commonly employed since European settlement; and 2) the basin upstream of the survey site contains no roads or human-made modifications to the landscape that potentially could affect the hydrology, slope stability, or other factors potentially disturbing riparian corridors or the stream channel. These basins will hereafter be referred to simply as "unmanaged" or "natural" basins, although it can be acknowledged that some basins are "managed" to remain pristine, and may also include fire suppression.

Assumptions

This study is based on the assumption that natural riparian characteristics, as influenced by natural disturbance cycles, are those to which terrestrial and aquatic species have adapted, and hence should provide a reasonable reference condition for management purposes. This assuption has guided the selection of sites in unmanaged forested basins.

To isolate variability in riparian structure, sites were randomly chosen within geomorphic and regional stratifications. Channel sizes were found to correlate with other geomorphic influences such as gradient, confinement, and drainage area (Fox 2001); channel size is used as a rudimentary stratification to represent geomorphic influences. Regional stratifications were

accomplished using the eight forest zones described previously. Due to similarities in basal area and species composition; however, the Silver fir (Abies amabilis) and the Mountain hemlock (Tsuga martensiana) Forest Zones were combined to increase statistical power as were the Douglas-fir (Pseudotsuga menziesii) and the Ponderosa pine (Pinus ponderosa) Forest Zones. Classification of field sites into respective forest zones were accomplished by riparian tree species data and the physical descriptions of these zones cited in the literature.

7.2. Field Methods

7.2.1. Riparian Surveys

To characterize riparian structure and tree composition, surveys were conducted using the Point-Centered Quarter (PCQ) method (Cottam and Curtis 1956). According to this method, the distance to the four closest trees in each of four quadrants was measured at five points along a 65 m transect perpendicular to the stream. Each tree was measured for diameter and classified to species. Five to six transects were taken per site to provide a reach mean. All trees greater than 10 cm at diameter breast-height (dbh) were included. Co-dominant tree heights were obtained to help characterize riparian areas and determine site class. Methods to determine site class were consistent with WFPB (2001) guidelines, using site index equations for major tree species published by Hegyi et al. (1979). Sites were characterized for natural disturbances (fire, debris flows, snow avalanches) using the methods of Fox (2001). Instream wood loads were obtained using the Timber/Fish/Wildlife Monitoring Program Methods Manual (TFW-MPMM) for the "Large Woody Debris Survey" (Schuett-Hames et al. 1999) conducted using Level 2 surveys as described in Fox (2001). Each piece of wood was evaluated to determine whether or not it could be identified to an adjacent source, such as a fallen tree, broken bole, top, branch, etc. This method likely underestimates the amount of LWD recruited from adjacent sources since broken tops, limbs, and other point-sources may sometimes be obscured by the canopy. Jam LWD pieces (groups $\geq$10 pieces) were excluded from this analysis due to time, safety, and uncertainty due to obscuration of jams and fluvial relocation. Because of jam exclusion and potential observer error, the assessed proportions of wood with an identifiable source were likely underestimated and are hence regarded as an indicator of recruitment source rather than an absolute value. A species richness index is developed based on the observed number of species from linearly sampled center-points (four trees are sampled from each point, and 5-6 points are obtained per distance along transects in a reach (i.e. at 5 m, 20 m, etc.). Because the Cottam and

Curtis (1956) method cannot determine total species present in a reach, the index is merely a measure of the diversity within the sample rather than comprehensive of the stand; however, we will assume that it provides a relative indicator of diversity for comparison. Quality Assurance/Quality Control surveys were conducted on surveyors to increase observer consistency and reduce error. QA/QC methods were based on replication and consistency among surveyors in select control reaches. Based on the positive results of the QA/QC surveys, confidence in the quality and accuracy of the data are high.

8. RESULTS

A total of eight hundred and twenty-five transects were sampled to characterize riparian areas from 150 stream reaches in six forest zones (Figure 1), where 20 different tree species were identified. Stem diameters (dbh) ranged between the method minimum (10 cm) and 3.25 m (0.33-10.7 ft), basal areas ranged between 0 and 286 m^2/ha (0-1,245 ft^2/ac.), tree densities between 0 and 1,291 trees/ha (0-523 trees/ac.), tree heights between 4 and 87 m (13- 286 ft), and stand ages between 35 and 900-years old (at the time of the 1999-2000 surveys). Due to the extent of area that some of the major burns covered in the last 1000 years, many sites had similar year-of-origins which created natural breaks in which to form age classes. Mean annual precipitations of survey sites ranged between 56 and 508 cm (22-200 inches), and elevations ranged between 7-1,906 m (23-6,254 ft).

8.1. Species Diversity

The analysis of riparian data suggests tree-species distributions are quite diverse within as well as between forest zones. Riparian composition consisted of 8 to 17 tree species within each forest zone, with the climax, seral, and most common species typical to each zone as described in section 1.3.3. Deciduous species comprised a range between 3% to over 25% of species frequency within riparian areas. Although species distribution reflects stem frequency, it does not necessarily indicate the dominant species or other physical aspects. For example, some species will often dominate in number but comprise little of the riparian basal area, or vice-versa. Finally, the WH, SF/MH, and GF forests exhibited the greatest tree species richness among forest zones. Table 1 presents the list of the identified riparian tree species, and the percent frequency and basal areas for six forest zones across Washington State.

8.2. Riparian Stand Attributes

8.2.1. Geomorphic Influence

Geomorphic influences upon riparian area were typically a result of fluvial disturbance. Channels that are most susceptible to fluvial disturbance were typically unconfined with an active flood plain, such as large alluvial rivers. Deciduous species were commonly observed colonizing riparian areas following fluvial disturbance, thus influencing riparian character and stand attributes. Indeed, riparian areas adjacent to large streams (>20 m BFW) contained significantly more deciduous trees than smaller channels ($P<0.001$, ANOVA, Tukey's HSD) (Figure 13A). Large channels have a greater mean number of side channels than small channels (Figure 13B), which signifies a greater proclivity for avulsion and subsequent riparian disturbance.

8.2.2. Regional Influences

Forest Zones

Riparian stand attributes also vary among forest zones. Riparian forests in western Washington typically had greater mean stem diameters and basal area than those in eastern Washington. Generally, stands with greater mean tree heights also had relatively fewer trees/ha, and taller, greater diameter trees with fewer stems per hectare produce stands with the greatest basal areas. The exception to this is the DF/PP forest zone, which had a relatively low basal area despite having tall trees with few per hectare. Box plots of mean riparian tree diameter, mean tree heights, mean number of stems per hectare, and mean basal area per hectare, as grouped by forest zone are presented in Figure 14.

8.2.3. Disturbance Influence

Fire

Fire return intervals often dictate the age of riparian forests. Fires in the SAF, SF/MH, WH, and SS forest zones (from the Cascade crest westward) typically create even-age stands that enable the determination of the date of stand origin. Contrarily, fires in the GF and DF/PP forest zones (east of the Cascade crest) are typically more frequent, but often create uneven-age stands. Because of this, tree ages do not represent stand date-of-origins in the GF and DF/PP forests. Therefore, age classes as determined from fires are only presented herein for the SAF, SF/MH, WH, and SS forest zones. Because stand age is often dictated by fire-return intervals, and both fire-return intervals and forest zones are typically dictated by climate influence, it follows that there should be a correlation between stand age and forest zone. Indeed, the climatic influence of

mean annual precipitation can be used as a predictor of stand age in the SAF, SF/MH, WH, and SS forest zones ($P<0.001$, $R^2=0.62$, regression). Because of this correlation, as well as the fact that forest zones lack a diverse array of age classes within them, forest zones were lumped for the purposes of evaluating stand age influences upon riparian stands.

Riparian stem-diameter distributions vary with stand age. As forests grow older, more trees reach greater diameters, although all forests regardless of age will contain a substantial number of smaller diameter trees resulting from chronic disturbances or merely as suppressed stems in the understory. The number of smaller diameter trees in riparian forests remains relatively constant with age until approximately 800 years or more, where the proportion of small stems decreases with an increase in large stems. In all forest zones, the greatest numbers of trees were distributed to the 0.2 to 0.35 m diameter class, and fewer stems in the larger diameter classes. Stem diameter distributions are presented by age class (for the combined SAF, SF/MH, WH, and SS forest zones) in Figure 15. Other characteristics of riparian areas are also influenced by fire history as it relates to stand age. Mean stem diameter, basal area, and tree height increase with stand age, while the number of trees per hectare decrease (each at $P\leq0.003$, regression).

Debris Flows and Snow Avalanches

Other riparian-zone disturbances, such as debris flows and snow avalanches, can also "restart the clock" for tree age; however, these factors typically only affect narrow tracks through stream corridors. Due to the limited extent of this influence, riparian surveys extending outwards from the channel for 65 m documented significant basal area reductions for only 3 of 13 riparian areas adjacent to channels with evidence of snow avalanches, and only 2 of 8 riparian areas adjacent to channels with evidence of debris flows. Due to: 1) the small sample size of these types of disturbances, 2) the extent beyond disturbance tracks that riparian surveys incorporate, and 3) the fact that stems smaller than 10 cm (approx. 4 inches) are not included by the riparian survey methods, significant disparities in reach-total stand attributes such as basal area, stem density, tree height, and mean diameter between disturbed and undisturbed sites could not be detected. Descriptively, however, channels that experienced recent debris flows or snow avalanches (<15-years) had a higher deciduous riparian component than undisturbed channels, typically comprised of vine maple, young alder, and other deciduous species, often at a densities greater than 5,000 stems per acre (est.). Although these types of disturbances likely alter riparian characteristics, a study design that selects for these variables is likely needed.

Other observations reveal how riparian areas can resist the extent of disturbance. Field observations in riparian corridors disturbed by snow avalanches and debris flows suggest that large diameter conifers often minimize the width of the disturbance path. Broken and uprooted small diameter trees were often pinned on the upstream sides of standing large diameter trees and likely contributed to energy dissipation of the disturbance. Therefore, these types of disturbances are likely to be more extensive in younger forests than older forests.

8.3. Changes in Riparian Characteristics With Distance From The Channel

Comparing tree distributions by center-points, spaced at 15-m intervals along the 65-m survey transect aligned perpendicularly to the channel suggests that stand attributes of near-channel riparian trees are different than trees further from the channel. Combining bankfull width classes, stem densities at the 5-m and 20-m center-points had significantly greater number of trees per hectare (mean = 648/ha) than those at the 50-m and 65-m center-points (mean = 563/ha) ($P=0.02$, paired t-test) (Figure 16A). Basal areas of near-channel trees were slightly greater than those further from the channel; however, this difference was not significant ($P=0.16$, paired t-test), although basal area comparisons among forest zones reveal that this difference is significant in the DF/PP forests ($P<0.001$, paired t-test) (Figure 16B). In regards to disturbance, riparian areas adjacent to channels that have experienced recent snow avalanches had significantly lower stem densities ($P=0.04$, two-sample t-test) at the 5- and 20-m center-points than at the 35, 50, and 65 m center points.

Species richness also varies with distance from the channel. Comparing the number of tree species observed among center-points along the perpendicular transect, a significantly greater number of species were observed at the 5, 20, and 35-m points from the channel than at the 50 and 65 m points (Figure 17A) ($P=0.007$, ANOVA, post-hoc Tukey's HSD). The reader must be cautioned that these numbers should be regarded as an index rather than absolute values due to the limitations of the methods (section 2.2.1). Intuitively, one would hypothesize that the differences that drive this species richness are attributed to the presence of deciduous species resulting from near-stream disturbances. This proves to be the case for the 5 m points, but not for the other near-stream points. With an analysis without deciduous species, riparian stands still exhibit greater species diversity of conifers at 20 and 35 m from the channel than at 50 and 65 m (Figure 17B).

8.4. Riparian Attributes As They Relate To Instream Large Woody Debris

One of primary questions in riparian management is "How do the characteristics of riparian forests influence instream wood loads?" Firstly, we will evaluate relationships of instream wood with stand attributes, and secondly, evaluate the sources from which instream wood originates.

8.4.1. LWD Abundance and Volume

Several riparian stand attributes influence the abundance and volumes of instream LWD. For one, riparian stand age is significantly correlated to instream wood loads. More LWD volume was found in channels adjacent to older riparian stands than younger stands (Figure 18A), also significantly expressed by regression analysis using continuous data ($P<0.001$). Conversely, the number of LWD pieces is relatively high in streams adjacent to riparian stands ≤150-years old; it falls to relatively low values for 300 years before returning to high levels at age 550, and then decreases again with age after 800 years (Figure 18B).

Other stand attributes also significantly influenced instream wood loads. Number of LWD pieces and volumes increase with riparian basal area ($P=0.021$ and $P=0.002$, respectively, regression), and LWD volumes increase with mean co-dominant riparian tree height and mean diameter ($P=0.002$ and $P<0.001$, respectively, regression).

8.4.2. LWD Sources

The source of most instream wood pieces could not be identified. Only a mean of 28% of LWD could be attributed to an adjacent tree, stump, rooting site, etc. suggesting that the majority of instream wood comes from either upstream sources (e.g. routed into reaches by fluvial processes) or were pieces from the canopy whose origin could not be determined. This is significantly less than the 47.7% found by McDade et al. (1990) ($P<0.001$, one-sample t-test), even when scaled to match these author's site criteria consisting of 1st-3rd order streams (Strahler 1957). The mean lengths of pieces attributed to an adjacent source were significantly longer than those that were not ($P<0.001$, paired t-test) as illustrated in Figure 19A for all five channel sizes. This suggests that pieces not attributed to an adjacent source are more likely to be smaller and more readily entrained by flow. Following this logic, larger channels should have fewer pieces of wood that can be linked to the adjacent riparian area due to the greater fluvial forces available to transport

wood. Indeed, as channels increase in size, the percent of pieces that could be identified to an adjacent source decrease (Figure 19B) ($P<0.001$, regression with continuous data). The median number of LWD pieces with an identifiable source in channels between 0-5 m BFW was 37%, whereas the median was only 13% in channels >50-100 m BFW. Contrarily, the volume of wood attributed to adjacent sources remained relatively constant (mean = 47%) and did not significantly differ among channel width classes ($P=0.785$, ANOVA) (Figure 19B). This suggests that fewer pieces originating from the adjacent riparian areas provide more of the volume as channel size increases, indicating greater mean size per piece. More wood pieces in the side channels of the larger streams (>20 m BFW) were attributed to an adjacent source than those compared to LWD in the mainstems ($P=0.007$, paired t-test).

9. DISCUSSION

9.1. Stand Structure and Species Diversity

Riparian areas appear to be different from upland stands described in the literature, although the major facultative tree species potentially found in the general forest zones (including uplands) were also present in the riparian areas surveyed. In this study, deciduous species comprised between 3% to over 25% of riparian areas wheras Kuchler (1946) reported a deciduous component consisting of only approximately 1/10th of a percent for the mean forest structure. This suggests that at least hardwood composition is potentially greater in riparian areas. Also, basal areas of many riparian forests in this study exceeded 250 m^2/ha, where Franklin and Dyrness (1973) noted that upland stands merely *can* exceed 100 m^2/ha. This vast difference suggests that riparian areas contain larger, more closely spaced trees than upland stands. Potential reasons for the differences between upland stands to riparian areas are described in more detail in the sections that follow.

Basal area distributions of riparian trees are indicative of stand dynamics and climax species rather than species distribution. Due to the exponential relationship that basal area has with stem diameter, a few large-diameter trees can account for a substantial amount of basal area compared to many smaller diameter trees. Thus, basal-area distributions are perhaps more representative of the dominant or climax species of forest types than frequency.

Tree species richness appears to correlate with forest zones having the greatest climatic diversity. Table 3 indicates that the greatest numbers of species were observed in forests at mid-

elevations or transitional zones of the Cascades, suggesting that species presence is sensitive to local variations in precipitation, temperature, aspect, and other complexities found within these forests. Certainly, the literature notes that many sub-zones exist within forest zones due to local climate variation, contributing to a greater amount of species diversity. Forest zones with more consistent climate such as the temperate SS forest zone, or those limited by an extreme climate such as DF/PP forest zone (high summer temperatures) and the SAF (low winter temperatures and long winters), exhibit the lowest species diversity. Therefore, the ranges of climate patterns in these forest zones, if not at an extreme that may be limiting, do influence species diversity.

Noteworthy is the fact that no low-elevation sites meeting the site criteria were available within the WH stands, and thus the WH forest zone is represented by sites having moderate elevations (yet still WH). Perhaps this representation contributes to the greater species diversity of this forest zone, and the fact that there are more Mountain hemlock than Western hemlock trees in these stands (Table 1). It is possible that if lower elevation sites existed within this forest zone, the species composition may be different.

9.2. Riparian-Stand Attributes

Stand attributes and characteristics of riparian forests vary at multiple scales. At the large scale, regional differences in riparian structure pertain to discrete forest zones influenced by climate. At the small scale, differences can arise from local influence such as channel geomorphology and disturbance, which result in a heterogeneous range of attributes within regions. The following describes these processes.

9.2.1. Geomorphic Influence

Influences upon the adjacent riparian areas by channel morphology are typically an artifact of disturbance regimes characteristic to the channel type. With deciduous colonization following disturbances such as channel avulsion and bank erosion, stand characterizations are manifested by temporal changes. The size of the stream as well as channel confinement are indicative of the propensity for lateral migration, as illustrated in Figures 13A and B. Lateral migration, avulsion, and bank erosion disturbs and removes trees in the riparian forests, where deciduous species are often the first to colonize. This phenomenon of flood plain disturbance followed by deciduous colonization is supported by Fetherston et al. (1995), Naiman et al. (1998), and others, where channel avulsion and braiding is common in large, unconfined systems. Coniferous succession is

often precluded in flood plains due to the frequency of disturbance in these channels, which maintains the deciduous component to the riparian areas. Thus, channel geomorphology influences riparian characteristics by facilitating patterns of disturbance.

9.2.2. Forest Zones and Climate

The stand attributes of mean basal area, stem density, stem diameter, and tree height vary among forest zones. These differences are predominantly due to climate influences such as elevation, precipitation, temperature, topographic soil moisture, soil, etc. Complex interactions of these variables result in an array of vegetation zones across the State, and subsequently contribute to the differences in stand attributes. Therefore, each forest zone typically represents the culmination of these influences that are reflected in respective stand attributes.

9.2.3. Fire, Snow Avalanches, and Debris Flows

Stand age as influenced by fire are reflected in the riparian attributes. Intuitively, younger riparian stands contain a greater proportion of small-diameter trees as compared to other stand age classes. With the various forms of mortality to which trees are subjected, relatively few of the stand-origin stems will reach old age and achieve larger diameters. The youngest age class (<150-years) contained the highest proportion of stems in the two smallest diameter classes; however, a few large-diameter trees were nevertheless present. Even the youngest stands (1965 year-of-origin) contained a few large-diameter stems, indicating that some trees do indeed survive stand-replacing fires (of the Cascade crest and westward). As riparian stands mature, more trees in the large-diameter classes are apparent, indicating that tree diameters continue to increase as trees grow older.

Interestingly, the proportion of trees in smaller diameter classes do not change until riparian stands reach 800 years in age. As such, even these stands have a high component of small stems in the diameter distribution. The observation that riparian communities nearly always have smaller stems available illustrates various stages of structural developmental throughout much of the sere until succession of the climax species is complete. Gap-level and chronic disturbances such as wind throw and root rot provide continuous opportunities for cohort establishment. As forest mature, there is re-establishment of the understory community with shade-tolerant trees (Franklin et al. 2002). Because of these continuous opportunities for tree regeneration, small-diameter stems are ubiquitous in the understory but proportionately less in

stands where succession is mostly complete, as illustrated in Figure 15. Other stand attributes relating to stand age reflect growth patterns established in the literature. The relationship of both tree height and diameter follow the general trends and values of predictive models such as the Forest Vegetation Simulator (FVS) (Stage 1973) as used in Beechie et al. (2000); however, the FVS model is intended for younger stands (<150 years), which are ranges not well represented in the data of this study (n=5).

Several qualifications of the data are worthy of note. Four of the 5 stands in the <150 yr age class were in the SAF forest zone. Therefore, attributes such as basal area and stem density expressed for this age class are more representative of the SAF forest zone than of lower elevation forests. Because SAF stands typically have fewer and smaller trees due to climate and the frequency of open meadows and parklands, general characterizations based on this age class will likely be underestimated for all western Washington forests such as those occurring at lower elevation. Also noteworthy is the fact that fires occurring before fire suppression efforts (i.e. the early part of the 20th century) often burned large tracts of forest. Subsequently, many stands have the same date-of-origins due to the extent of these fires, which can be observed by the linear-clusters in Figure 21.

Snow avalanches and debris flow typically only removed a corridor of riparian trees (of variable widths), but infrequently they obliterated the entire lateral extent reached by the surveys (approx. 65 m). As noted in the results, infrequent events appeared to be slowed by standing trees, especially those with large diameters. Corridors in riparian areas with disturbances recurring before trees can mature (e.g. annual snow avalanches) often were the widest, suggesting that without large diameter trees to dissipate energy, avalanches were more devastating to riparian vegetation. This exacerbated impact to riparian vegetation not only affects tree laterally from the channel, but in the downstream alluvial fan and beyond. Indeed, some streams that were particularly susceptible to frequent occurrences of snow avalanches had tracks or vegetation disturbance that not only reached the valley bottom but also extended for many hundred meters upslope on the opposite side of the valley.

9.3. Changes in Riparian Characteristics With Distance From the Channel

The difference in the density of riparian trees between near-channel areas and those furthest away can likely be attributed to disturbance and increased sunlight. The greater densities, yet similar

basal areas of trees closer to the channel suggest that these trees are smaller in diameter and subsequently younger in seral stages than those further from the channel. As debris flows, snow avalanches, floods, channel avulsion, and other forms of episodic and catastrophic channel disturbances topple riparian trees, new growth is smaller in diameter and more closely spaced than the undisturbed trees further from the channel edge. Indeed, for channels affected by snow avalanches, the differences between the inner and outer riparian center-points is significant. Channel disturbance through fluvial processes are a major factor in stream geomorphology, wheras these processes are absent in upland stands. Large-scale disturbances in upland stands typically stem from fire, slope failures, wind throw, disease, whereas riparian areas nearest the channel are often vulnerable to these forms of disturbance in addition to fluvial disturbances; therefore, riparian trees that are closest to the channel are likely disturbed more frequently than riparian trees further from the channel. Also, most stream corridors create openings in the forest canopy. Thus, the trees closest to the stream will often receive more sunlight, varying with orientation and aspect of the stream. As sunlight penetrates into the riparian zone, the understory of subdominant and suppressed trees will have better opportunity to establish, thus increasing in numbers. However, it is likely that these trees will remain small due to the establishment and domination by the overstory and remain suppressed until release. Therefore, the mean diameter of the trees closest to the stream should be inversely proportional to stem density.

Figure 17A suggests that most of the tree species richness associated with riparian areas is within approximately 35 m of the stream. The index number of observed species drops abruptly at the next 15-m interval (at 50 m), suggesting that changes in moisture, sunlight, disturbance patterns, and other influences attributed to the stream occur on average at that distance. The number of species drops incrementally at 50 and 65 m rather than reaching a plateau, suggesting that the effects of the stream upon tree species diversity may occur beyond 35 m. The observation that a greater number of tree species are found closest to the stream roughly parallels trends for other plant species richness in western Oregon and Washington reported by Naiman et al. (1998). The work of these authors indicates that plant species richness decreases beyond 65 to 180 m, supporting the hypothesis that the stream corridor may influence tree species diversity beyond 65 m. Species diversity nearest the channel can be attributed to fluvial disturbances such as bank erosion, channel avulsion, lateral migration, etc., where deciduous species are typically the first to colonize; however, beyond 5 m from the channel, this diversity is more prominent in coniferous species. This suggests that disturbance may drive diversity by increasing deciduous

colonization, but that other effects of the stream and corridor (e.g. moisture, sunlight penetration, etc.) drive coniferous species richness.

9.4. Riparian Attributes Related to LWD loading

9.4.1. Forest Age

The relationship of age to LWD quantity follows general principles of stand dynamics. As trees age, their diameters increase. Subsequently, recruited trees into the stream are likely to be larger and possess more volume. Because volume increases exponentially with diameter, fewer larger diameter LWD pieces can achieve greater instream wood volumes than moderately greater numbers of smaller pieces. This may explain why channels that have greater LWD volume do not necessarily have greater number of LWD pieces as indicated by the contrast between Figures 18A and 18B. In Figure 18B, the distribution of number of LWD pieces by age class suggest that stem exclusion processes provide large initial inputs of wood over the first 150 years. For the next 400 years following this phase, wood recruitment (piece number and volume) is relatively low as stands mature, while much of the stem exclusion process has occurred and before age-related mortality takes place. As late-successional processes approach completion at approximately 550 years, the mortality of the remaining older seral species is perhaps more prominent, combined with some mortality of late-successional dominants associated with aging stands. This likely explains the increases of instream LWD volumes at this age class in Figure 18A, as well as the fact that these large trees are likely to be more stable and resist entrainment, and so more readily accumulating in the channel. At 800 years, younger trees are released by canopy openings during vertical stratification of late-successional stands and the mortality rate decreases, resulting in a decrease of instream LWD abundance. The indication that riparian stands do not reach a peak/plateau of instream LWD volumes until age 550 (Figure 18A) suggests that dominant tree diameters have reached a near-maximum, combined with the increase in recruitment of wood (Figure 18B) due to the final stages of competitive tree mortality as the stand shifts to non-competitive forms that promotes the vertical diversification of late-successional stands.

These findings for instream wood loads are consistent with the tree mortality patterns reported by Agee and Huff (1987) and Huff (1995) (section 1.3.3), suggesting that instream wood recruitment patterns associated with stand age are analogous to forest floor coarse woody debris delivery. Although the delivery of downed wood is a continual process (Franklin et al. 2002),

Huff (1995) illustrates that significant mortality of Douglas-fir occurs at around 400-500 years, supporting the patterns evident in Figure 18B. The abrupt rise in quantities and volumes of wood at this age is likely compounded by disturbance and long-term wood loading. Older, undisturbed stands (>550 years) have accumulated more wood over time, whereas younger stands (<550) may reflect disturbances that have depleted instream wood loads while "re-setting" stand age. These younger stands therefore have not had sufficient time to reload the stream with wood, especially when younger, smaller diameter trees are more easily exported from the system. Thus, wood loads are perhaps highest when stands have matured and have had centuries to load the stream with increasingly larger pieces, unabated by stand-replacing disturbances. This concept is supported by the findings of McDade et al. (1990) who report that approximately half of the LWD found in the channel adjacent to second-growth forests came from the previous old forest rather than from the newly regenerated stands.

9.4.2. LWD Source

The observation that most wood pieces could not be attributed to an adjacent source suggests that upstream riparian areas and basin processes may provide a better predictor to instream wood quantities than adjacent riparian areas. Alternatively, adjacent riparian areas are perhaps the better predictors of the larger LWD pieces (i.e. key pieces), which are less easily entrained and thus more readily remain in close proximity to their origin. This is evident in Figure 19B, where as the percent of LWD quantities that could be associated with an adjacent riparian source decreased with channel width classes, the percent of LWD volume remained the same. This suggests that fewer pieces originating from the adjacent riparian areas provide more of the volume as channel size increases, indicating greater mean piece size. This is also supported by the greater lengths of pieces attributed to a source as channel size increases (Figure 19A). The fact that more wood in side channels could be attributed to an adjacent source follows this logic; the smaller side channels have less force to mobilize wood that has fallen from adjacent riparian areas than mainstem reaches, enabling a better likelihood of linking it to a source.

The disparity that exists in these data compared to the findings of McDade et al. (1990) for the percent of pieces that could be attributed to adjacent sources could be the result of several factors. For one, the methods of these studies are slightly different in determining countable pieces. The methods of McDade et al. (1990) favor greater minimum piece size than this study and included channel-straddling pieces whereas this study did not. Straddling pieces can usually

be linked to an adjacent source since fluvial processes have not moved pieces, and larger LWD pieces are likely more resistant to move from the original recruitment position. Both of these factors would thus favor more pieces to be counted that are in proximity of their recruitment source. Additionally, some of the differences likely reside in observer error of this study. The primary objective of McDade et al. (1990) was to determine source distance, and therefore they likely devoted more time and rigor to finding recruitment point sources. Subsequently, their surveyors likely developed better observational skills with this parameter than surveyors collecting data for this study.

Adjacent riparian stand characteristics represent only one component of instream wood loads. Since LWD sources can be attributed to both adjacent and upstream riparian areas, we can draw inferences that instream wood loads and characteristics are perhaps representative of the basin rather than merely what exists adjacent to the stream. Having study sites in basins without upstream harvest or alteration of natural basin processes certainly may afford this latitude, where riparian characteristics are more uniform than fragmented systems and more representative of basin conditions. Nevertheless, characteristics of riparian stands are often managed at the reach scale to maintain instream wood quantities and volumes. Therefore, riparian management must extend beyond the reach scale to the watershed scale.

9.5. Comparison To The WFPB Riparian Management Targets for Desired Future Conditions

9.5.1. Site Class

The WFPB (2001) site classification system is intended to be an index of forest productivity; however, discrepancies with this system exist with some riparian stand attributes. With site class I (the highest) presumed to be the most productive for tree growth (V being the least), stand characteristics of mean tree height, and diameter (dbh) verify this system (Figures 20A and 20B) ($P<0.001$, binary regression). There is no significant difference in basal area between site classes ($P=0.051$, ANOVA) (Figure 20D), however. This is likely due to the fact that stem density increases with site class (Figure 20C).

Thus, the current use of the WFPB site classification system does not appear to adequately predict riparian stand productivity. Although this system appears to be a reasonable predictor of mean tree height and diameter, it does not appear to predict basal area of a stand. The observation that stem density decreases while mean stem diameter increases with smaller site

classes may partially explain why there is no significant differences in basal are area between site classes; despite greater diameter trees in lower site classes, there are also fewer of them. Existing WFPB rules and DFC targets for riparian management are based on basal area requirements that are adjusted by site class. The observation that the WFPB site class system has insignificant bearing on basal area predictions is also corroborated in Schuett-Hames et al. (2003), where these authors also found no relationship between basal area and site classes.

9.5.2. Basal area targets at age 140

Because the analysis on basal area suggests that there is no difference among site classes, testing the different values listed in Table 2 are therefore irrelevant. The relationship of basal area to stand age for all site classes can be expressed by the logarithmic equation

$$y = 32.05\text{Ln}(x) - 78.93$$

where y is the basal area in m^2/ha and x is the riparian stand age in years. Based on this equation, the predicted basal area is approximately 79.5 m^2/ha (346 ft^2/acre) at 140 years. Comparing this value to those in Table 2 suggests that the WFPB targets for all site classes are low. Indeed, the highest basal area target of 285 ft^2/ac (65.4m^2/ha) (site class one) is below the 90% confidence bar fitted to the regression (Figure 21).

The predicted trajectory fit to these data are similar to regressions of McArdle et. al. (1949) where those authors predicted basal area of 77.6 m^2/ha (338 ft^2/ac) at age 140. Additionally, Schuett-Hames et al. (2003) observed a mean of 76.1 m^2/ha (331.6 ft^2/ac) for combined site classes at age 140 during preliminary analyses of data. Notably, the data of this study in the younger age ranges of this regression are few, and furthermore, those that define the younger stands are mostly from the SAF forest zone rather than equally representative of other western Washington forest zones. This could respectively increase error and bias the regression slope by under-predicting values for lower elevation stands. The SAF forest zone has lower mean basal areas than other forest zones in western Washington (Figure 14D); therefore, basal areas at age 140 in this zone are likely to be lower than basal areas for other western Washington forest zones. Consequently, the regression for these data are likely under-estimated for basal area at age 140. This, in addition to the work of others, suggests that forest management targets relying on a

trajectory to meet stand characteristics at 140-years are lower than expected for natural riparian stands.

9.6. Guidance for Forest Managers

Assuming that natural riparian characteristics as influenced by natural disturbance cycles as found in these basins are those to which terrestrial and aquatic species have adapted, these data should provide a reasonable reference for management purposes intended to improve and/or maintain these habitats. The following provides a summary of key findings in this study that can be used to guide riparian management.

• Riparian areas should be managed for a diversity of tree species. Typically, riparian stands contained at least 8-10 tree species (Figure 14), which are influenced by forest zones. Deciduous species are a natural component of riparian areas, especially adjacent to larger streams. Due to the important functions of some deciduous species such as nitrogen fixation (Naiman et al. 2002), the culling of these species to promote conifer regeneration may not be prudent nor reflect the natural riparian character of some stream morphologies. Also, the distribution of tree species should not only consider frequencies, but the natural hierarchical arrangement of dominants, co-dominants, subdominants, suppressed, etc. typical to the seral stage of the targeted stand.
• Riparian characterization and stand attributes as grouped by the six forest zones described herein provide a reasonable means to represent natural climatic influences. Stand age, as dictated by natural fire recurrence cycles, elevation, and precipitation, is a characterization of forest zones that influence stand attributes. Discrete ranges of mean basal area, stem density, height, and diameter distributions vary according to these variables, which are typically represented by forest zones (Figure 18). Managing stand attributes to the potentials of each forest zone will therefore promote riparian characteristics and wood loads assumed to provide favorable habitat.
• Features such as stem density and species diversity change with distance from the stream. Greater densities and diversity are found closest to the stream (i.e. 35 m), but occur over a gradient with increasing distances from the channel. The zone of riparian influence is likely to extend beyond 65 m based on the absence of an observed equilibrium in these features as well as inferences drawn from the literature. Maintaining these densities and species diversity along this gradient will therefore provide heterogeneity in riparian stand characteristics and resemble natural structure.

• Stream buffer widths should consider the potential for disturbances such as snow avalanches and debris flows, which often influence stand attributes for at least 20 m each side of the channel but can alter trees beyond 65 m. This is dependent upon disturbance frequency and the presence of large conifers in these tracks, which reduce energy and the impacts associated with these disturbances. Therefore, maintaining stream buffers along these channels must take into consideration these potential impacts.

• Instream wood volumes may not peak until riparian stands reach 550 years or more (Cascade crest and westward). Stands that reach this age typically contain larger diameter trees that are likely representative of the growth potential, since non-competitive mortality appears to recruit more trees into the stream (and remain in place) at this age. To provide stream channels with the full potential LWD that riparian areas can deliver, riparian stands should use management trajectories to at least this age in order to not limit potential wood recruitment opportunity.

• High amounts of wood quantities are delivered to the stream during the first 150 years. This suggests that stem exclusion and self-thinning processes are an important sequence in wood recruitment during the early stages of forest development. Therefore, intensive thinning of stands through riparian management will likely reduce the short-term amount of wood delivered to the stream.

• Existing riparian management targets in WFPB (2001) do not follow natural riparian stand trajectories, and site class is not a viable predictor of basal area. Since site class and basal area are primary tools guiding riparian management prescriptions in these regulations, riparian management objectives of resource protection that use these targets and criteria are likely to be compromised. A revised or alternate rule system that is based on natural stand potentials as described herein should be developed for riparian management for the benefit of aquatic habitats. Furthermore, trajectories set for management could also consider stand conditions at greater ages that are within the potential of each forest zone. As stands increase in age, so do tree sizes. Merely meeting riparian conditions at age140 may not include trajectories for longer-term stand structures necessary to maintain riparian functions and stream processes for optimal resource benefits. This is bolstered by the fact that instream wood loads may not reach optimum volumes until stands are fully mature (i.e. ≥550-years)(Figure 18).

• Finally, riparian management objectives based on the purpose of maintaining instream wood loads should not focus merely on stands adjacent to stream reaches in need of wood, but on basin-wide riparian areas. Adjacent riparian areas are reasonable predictors of large pieces of LWD (e.g. key pieces) in the adjacent stream channel; however, the upstream basin characteristics and

processes are likely responsible for most of the LWD quantities, particularly in larger channels. Therefore, riparian managers should not base the reach-scale condition of instream wood merely on stream-adjacent sources, but must manage riparian areas at the watershed scale in addition to the processes associated with wood delivery.

10. CONCLUSION

Riparian areas are likely to be different from uplands stands; therefore, management targets must be based on riparian-specific characteristics rather than what is typical for upland forests. The influences of moisture, aspect, disturbance, and other factors associated with stream corridors has an effect upon stand attributes; therefore, it follows that riparian management prescriptions should reflect these disparities in order to meet the intended functions in the riparian corridor for adequate resource protection. The relationships and characterizations established in this study can serve as a riparian management reference in order to promote characteristic similar to that of natural systems.

11. FIGURES-CHAPTER 2

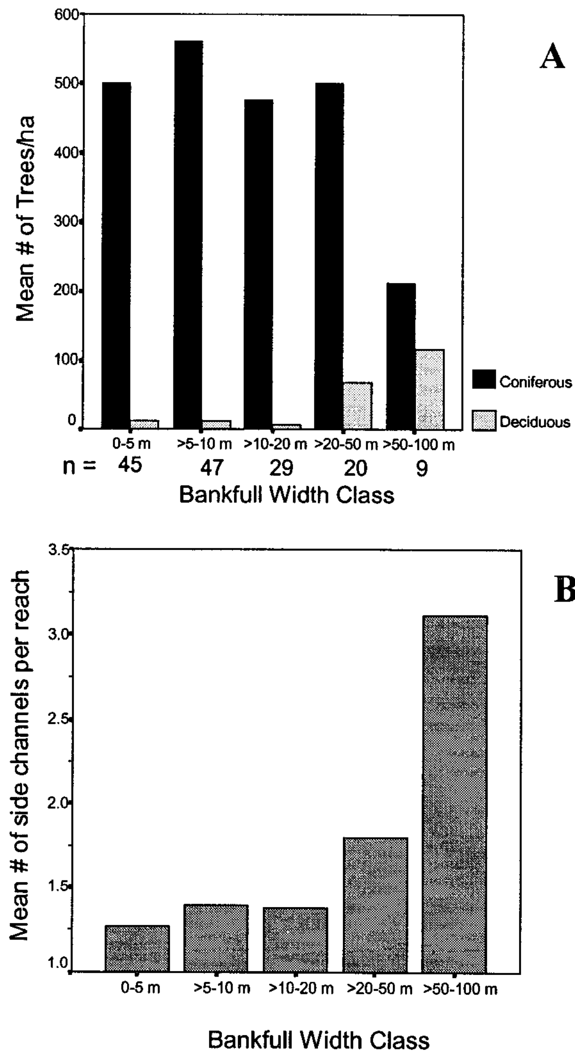


Figure 13. The mean number of coniferous and deciduous riparian trees per hectare by five channel size classes (A), along with the mean number of associated side channels per channel size class (B).

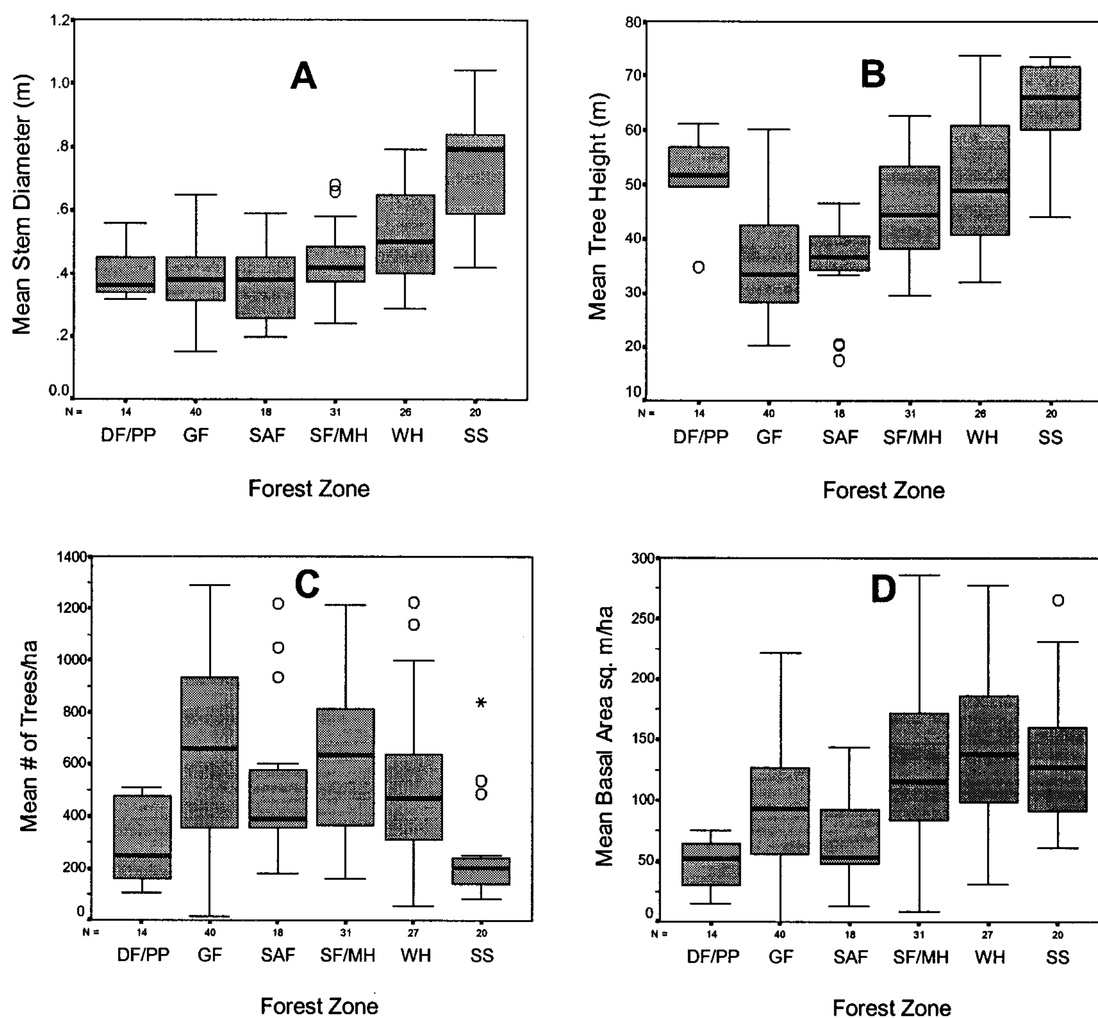


Figure 14. Box plots of A) mean riparian tree diameter (m) at breast height (dbh), B) mean tree heights of the upper riparian canopy, C) mean number of stems per hectare, and D) mean basal area per hectare, each grouped by forest zone: SS= Sitka Spruce, WH = Western Hemlock, SF/MH=Silver Fir/ Mountain Hemlock, SAF=Sub-Alpine Fir, GF= Grand Fir, DF/PP=Douglas Fir/ Ponderosa Pine

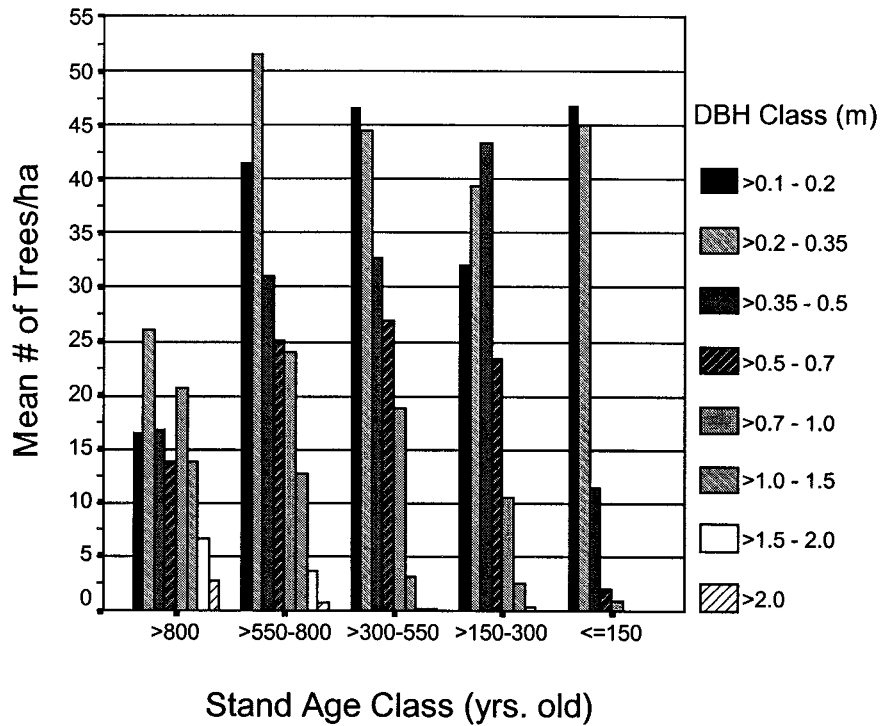


Figure 15. The mean number of riparian stems per hectare for eight diameter at breast-height (DBH) classes, grouped by age classes. Age classes apply to riparian stands in the SAF, SF/MH, WH, and SS only.

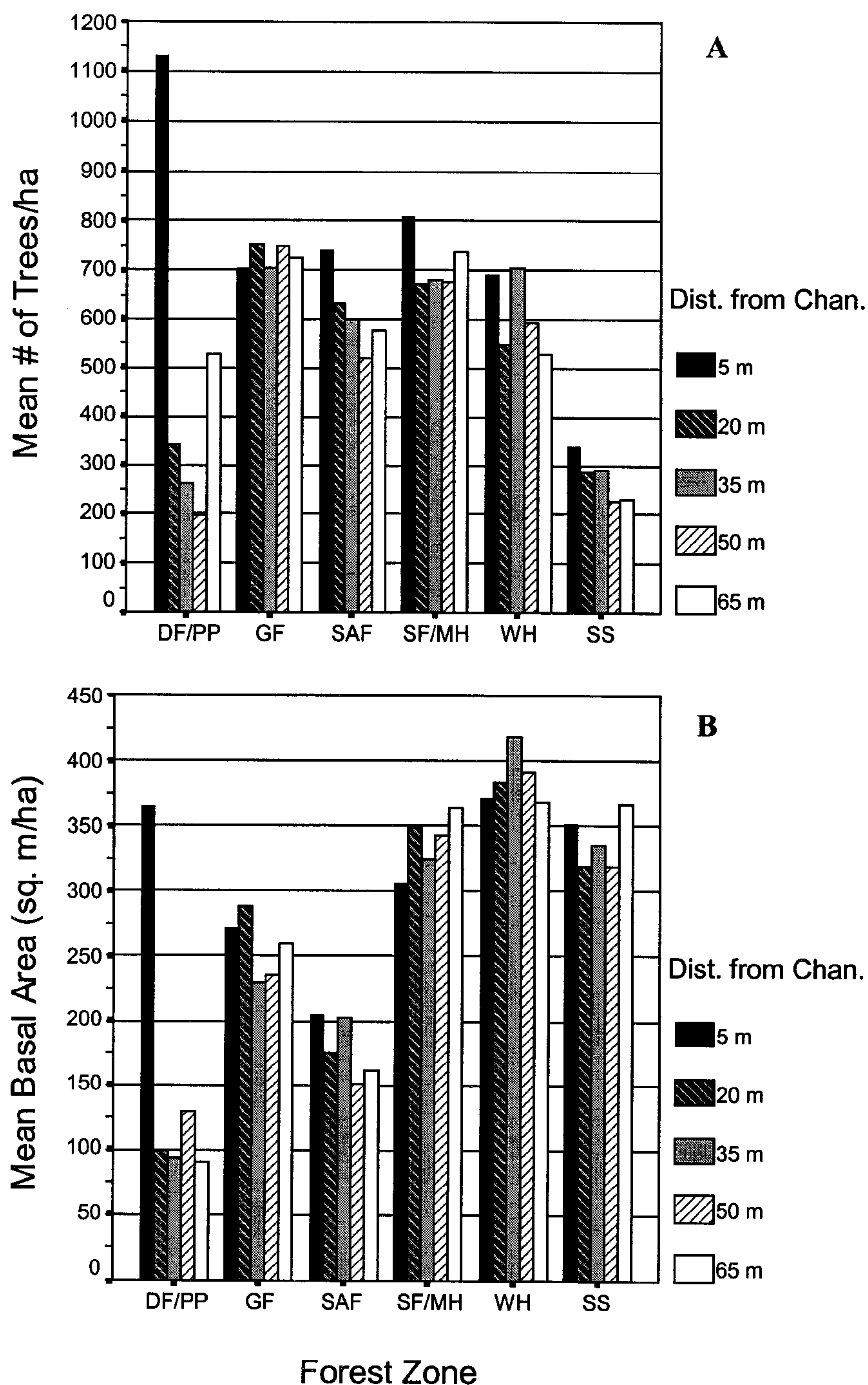
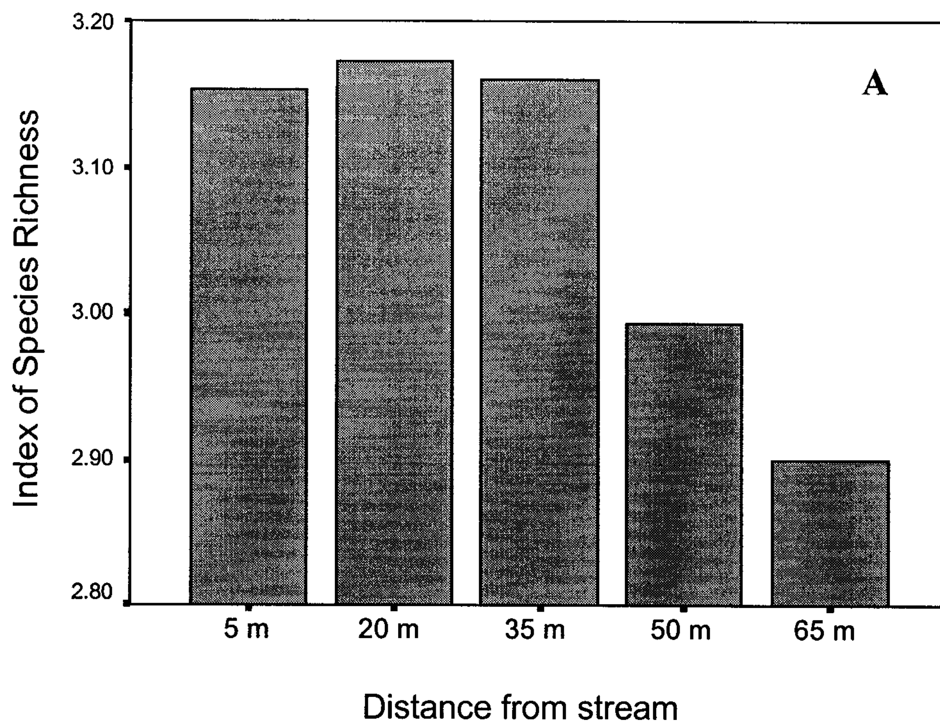


Figure 16. Mean stem density (A) and basal area (B) along a perpendicular gradient from the bankfull channel edge for six forest zones. SS= Sitka Spruce, WH = Western Hemlock, SF/MH=Silver Fir/ Mountain Hemlock, SAF=Sub-Alpine Fir, GF= Grand Fir, DF/PP= Fir/ Ponderosa Pine



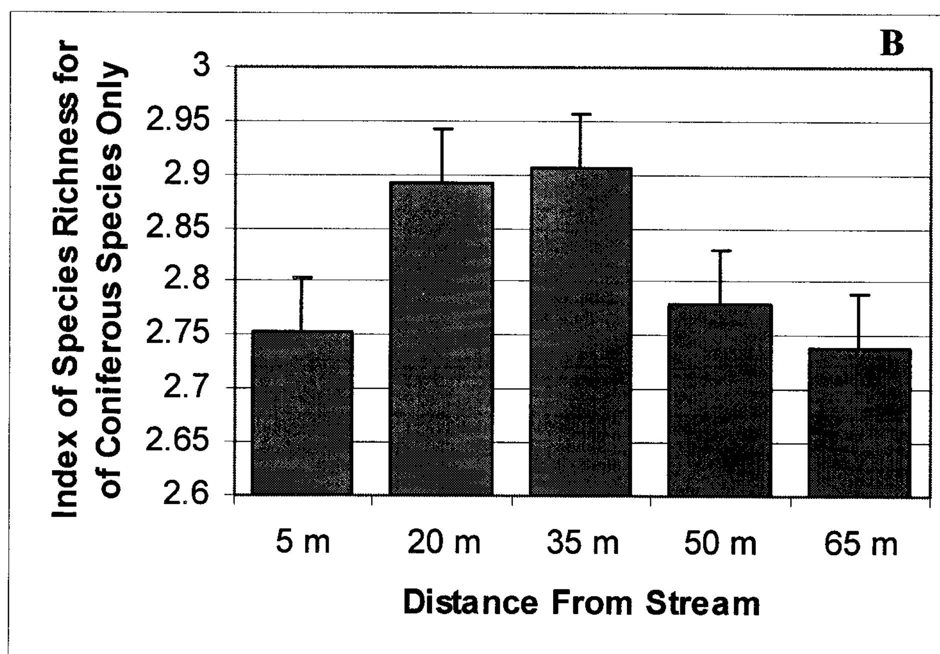


Figure 17. Index of species richness at points along a perpendicular transect from the stream channel. The number on the y-axis indicates the mean of reach means of species observed at each center-point (i.e. out of 20-24 total trees). All species are presented in (A), while only the coniferous species are presented in (B). Error bars in B represent one standard deviation.

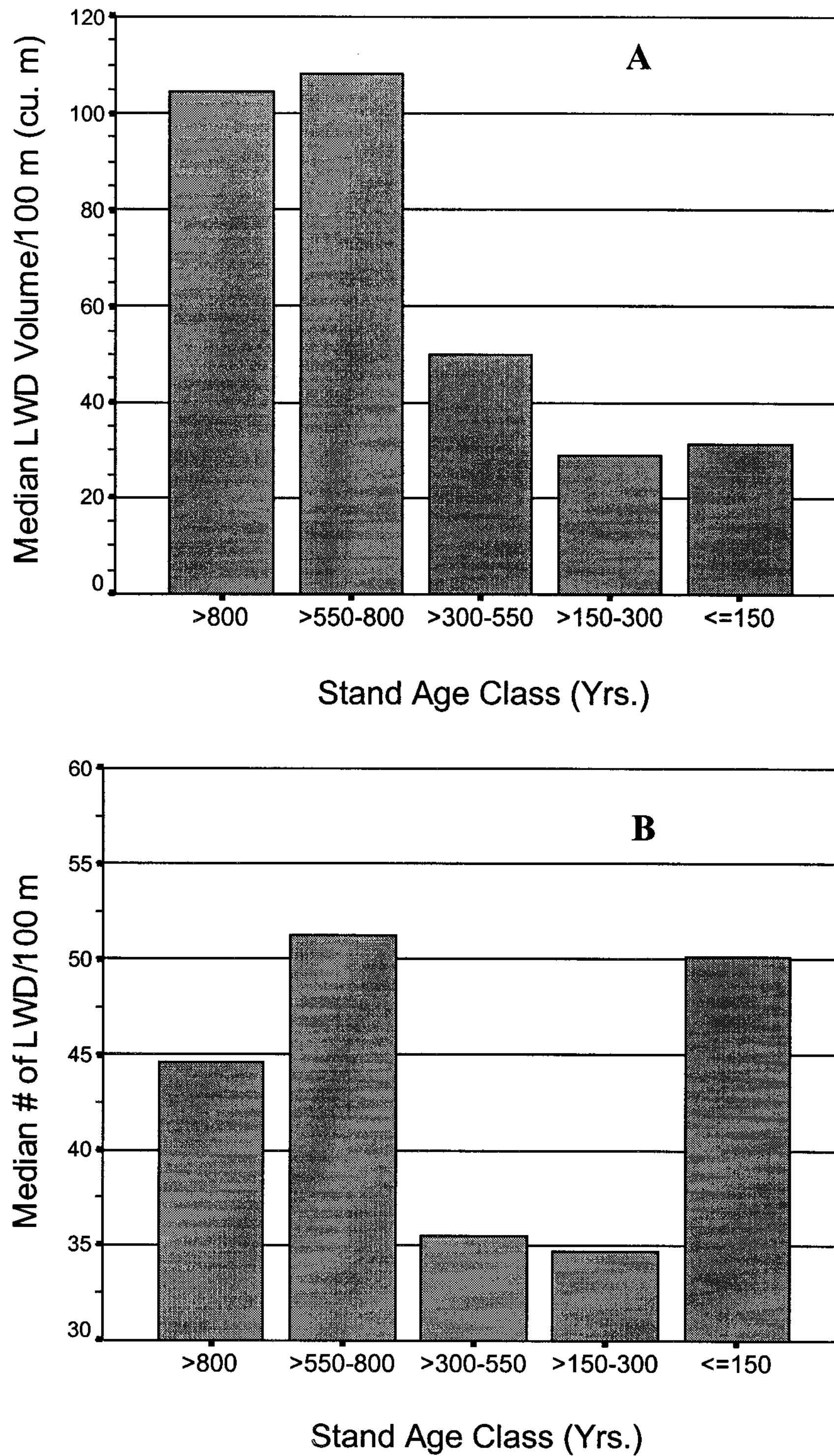
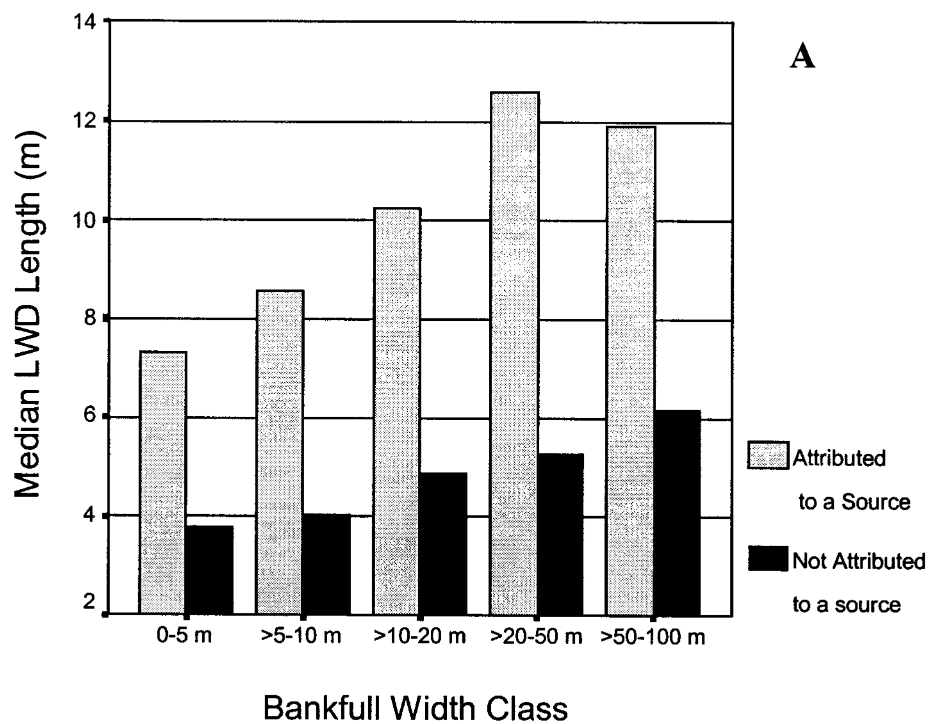


Figure 18. The median instream LWD volume (A) and quantity (B) according to adjacent riparian stand age class, at the time of the 1999-2000 surveys. Age data source: courtesy of Jan Henderson, unpublished data, USDA Forest Service.



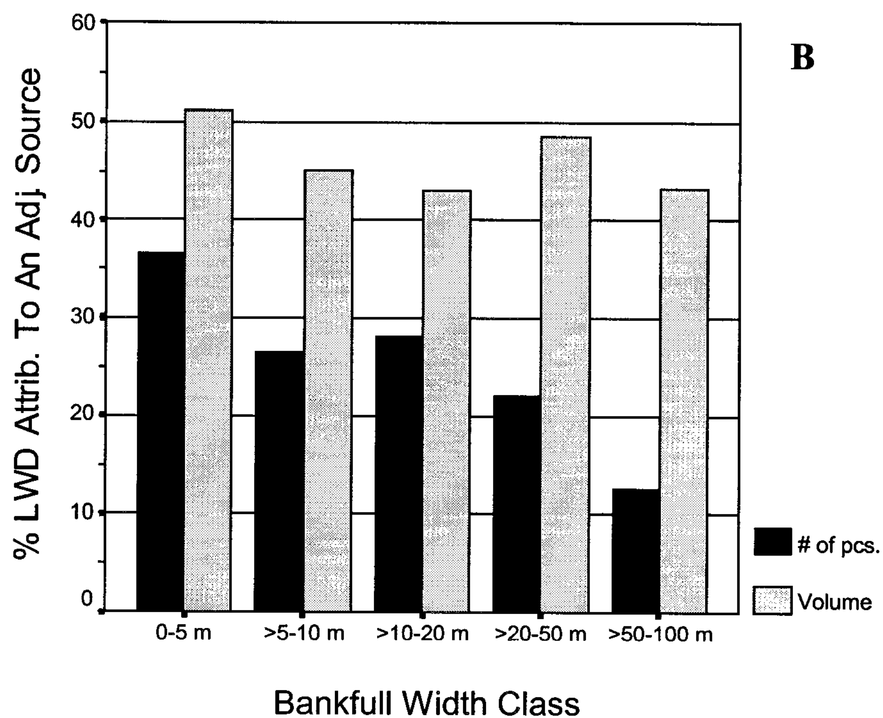


Figure 19. The median length of LWD for pieces that could and could not be identified to an adjacent source (A) and the percent of LWD quantity and volume that can be identified to an adjacent source (B), both grouped by channel width classes. Data represent reach means.

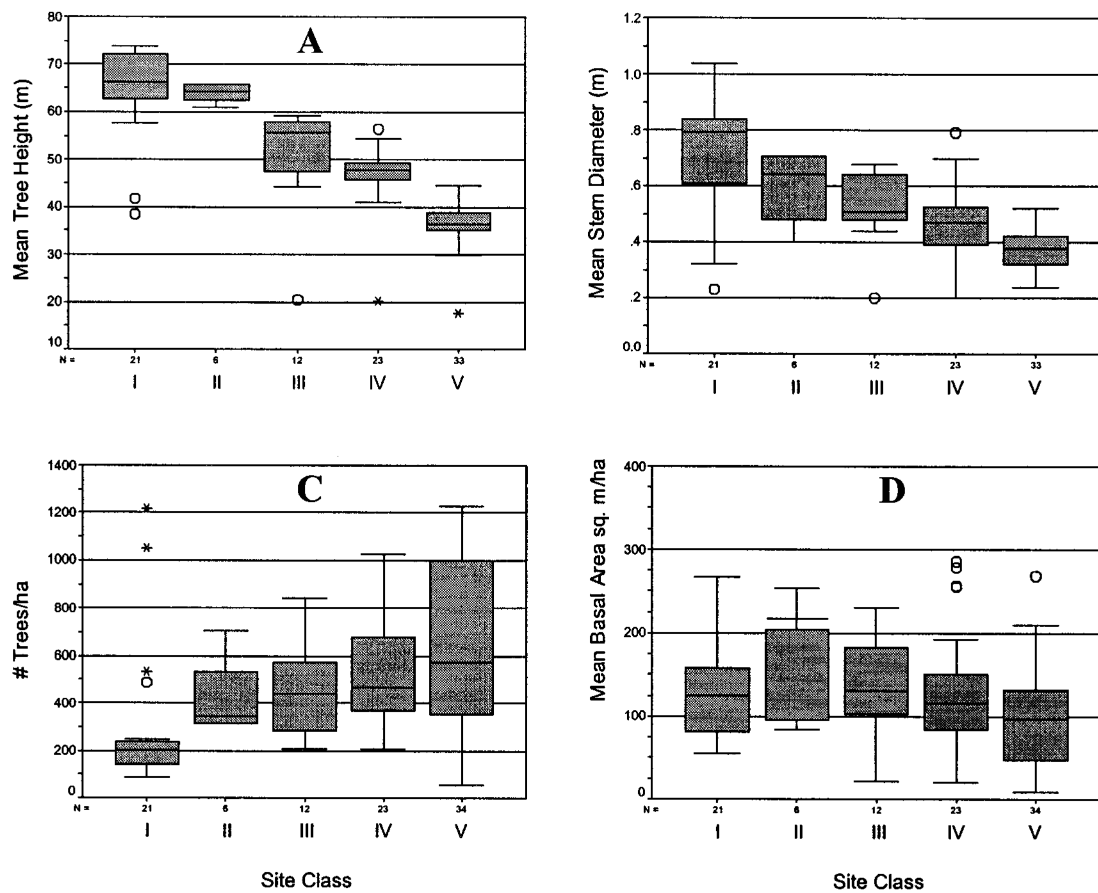


Figure 20. Attributes of mean tree height (A), diameter (dbh) (B), stem density (C), and basal area (D) according to WFPB (2001) site classes.

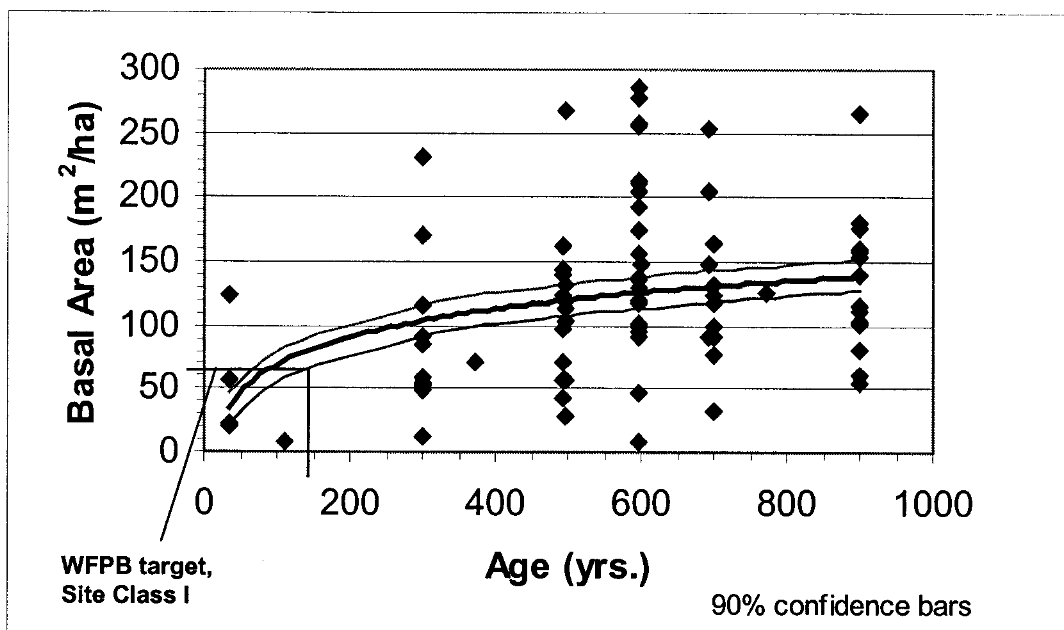


Figure 21. The relationship of basal area to riparian stand age for western Washington. The horizontal and vertical bar intersects represent the DFC basal area target for the highest site class (I) at age 140 of 65.4 m2/ha (285 ft2/ac) used in the WFPB (2001) forest practices rules, in relation to the 90% confidence bars.

12. TABLES-CHAPTER 2

Table 1. The observed percent stem frequency and the percent basal area by forest zone of riparian tree species identified in the surveys.

Common Name	Genera and Species	Forest Zone: DF/PP Stem %	DF/PP BA %	GF Stem %	GF BA %	SAF Stem %	SAF BA %	SF/MH Stem %	SF/MH BA %	WH Stem %	WH BA %	SS Stem %	SS BA %
Western Hemlock	Tsuga heterophylla	1.2	1	0.03	2	0	0	11.7	5.2	21.5	15.8	37.9	9.5
Sitka Spruce	Picea sitchensis	0	0	0	0	0	0	0	0	0.5	6.2	12.2	38.6
Pacific Silver Fir	Abies amabilis	0	0	44.4	5.3	13.7	13.5	24	7.6	24.5	9.8	2.1	0.2
Mountain Hemlock	Tsuga mertensiana	2.7	1.8	8.9	2	11.5	35.8	29.6	16.6	30.5	5.4	10.4	3.6
Noble fir	Abies procera	0	0	6.3	7.3	12.9	6.6	1.8	1.5	1.4	2.1	0	0
Engelmann spruce	Picea engelmanni	0	0	1	2.7	6.3	11.7	0	0	0	0	0	0
Subalpine fir	Abies lasiocarpa	0	0	0.1	0.1	46.4	24.7	0	0	0	0	0	0
Western red cedar	Thuja plicata	0.3	1.4	3.6	13.3	0	0	9.4	23.7	8.7	28	5.9	23.4
Grand fir	Abies grandis	2.2	0.7	22.2	16	3.3	3.9	1.3	1.3	1.9	1.5		
Douglas-fir	Pseudotsuga menziesii	65.6	29.3	8	42.4	2.2	2.7	18.5	42.3	3.5	24.1	6	17.5
Lodgepole pine	Pinus contorta	0	0	2.8	0.4	3.8	1.2	0	0	0	0	0	0
Ponderosa pine	Pinus ponderosa	17.1	51.9	0.3	0.6	0	0	0	0	0	0	0	0
Black cottonwood	Populus balsamifera	1.6	5.5	0.6	2.6	0	0	0.3	0.5	1.4	1.7	0	0
Big leaf maple	Acer macrophyllum	3.2	2.7	0.6	0.9	0	0	0.7	0.2	1	0.5	6.6	5.2
Red alder	Alnus rubra	0.5	0.4	0.1	0.6	0	0	2.3	1	5.1	1.7	18.9	2
Tamerack larch	Larix laricina	5.6	5.2	0.3	0.5	0	0	0	0	0	0	0	0
Pacific yew	Taxus brevifolia	0	0	0.4	0.7	0	0	0.4	0.1	0.01	3.1	0	0
Pacific willow	Salix lasiandra	0	0	0.1	0.6	0	0	0	0	0.01	0.01	0	0
	Total Species Obs.	10		17		8		11		13		8	
	n	14		40		18		31		27		20	

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14. APPENDICES

14.1. Appendix A. Site Summary Table

Stream Name	Trib. To (at Rkm)	Trib. To (at Rkm)	Trib. To (at Rkm)	Reach Number	RKm to Rkm	Date Surveyed	Latitude (Reach Midpoint) (degrees, min., sec.)	Longitude (Reach Midpoint) (degrees, min., sec.)
Little Ranger Cr.	White R. @94.1	Puyallup R. @16.6	Puget Sound (P.S.)	0	0.145-0.3	6/24/2000	N47 1.399'	W121 32.010
Dry Cr.	White R. @ 95.9	Puyallup R. @ 16.6	P.S.	1	0.4-0.9	6/25/1999	N47 0.469'	W121 31.101
Ranger Cr.	Carbon R. @ 43.04	Puyallup R. @28.9	P.S.	2	0.49-1.06	7/2/1999	N46 59.407	W121 50.906
Ranger Cr.	Carbon R. @ 43.01	Puyallup R. @28.9	P.S.	3	2.11-2.32	7/12/1999	N46 58.830'	W121 51.428'
Falls Cr.	Carbon R. @ 40.9	Puyallup R. @ 28.9	P.S.	4	0.1-0.54	6/29/2009	N46 59.624	W121 52.535'
Lost Cr.	Huckleberry Cr. @ 9.9	White R. @ 85.4	Puyallup R. @ 16.6	10	1.2-2.2	6/29/1999	N47 0.00'	W121 36.25'
Ipsut Cr.	Carbon R. @ 45.6	Puyallup R. @ 28.9	P.S.	8	0.26-0.8	7/13/1999	N46 58.544	W121 49.886

Stream Name	Trib. To (at Rkm)	Trib. To (at Rkm)	Trib. To (at Rkm)	Reach Number	RKm to Rkm	Date Surveyed	Latitude (Reach Midpoint) (degrees, min., sec.)	Longitude (Reach Midpoint) (degrees, min., sec.)
Unnamed	White R. @99.62	Puyallup R. @ 16.6	P.S.	9	0.0-0.2	6/30/1999	N46 59.675	W121 32.374
Ipsut Cr.	Carbon R. @ 45.6	Puyallup R. @ 28.9	P.S.	12	1.5-1.9	7/14/1999	N46 57.951	W121 50.164
Ipsut Cr.	Carbon R. @ 45.6	Puyallup R. @ 28.9	P.S.	14	1.5-2.7	7/19/1999	W46 57.4791	W121 51.283
Fish Cr.	Tahoma Cr. @4.6	Nisqually R.	P.S.	15	0.0-2.0	7/7/1999	N46 47.052	W121 53.256
Fish Cr.	Tahoma Cr. @4.6	Nisqually R.	P.S.	16	2.0-2.9	7/7/1999	N46 46.414	W121
Paradise R.	Nisqually R. @	P.S.		18	0.68-1.43	10-112-99	N46 45.999'	W121 46.804
Klickitat Cr.	White R. @109.2	Puyallup R. @16.6	P.S.	21	0.6-1.7	10/26/1900	N46 54.020'	W121 33.058
Klickitat R.	White R. @109.2	Puyallup R. @16.6	P.S.	22	1.73-2.9	7/23/1999	N46 53.5	W121 32.98

Stream Name	Trib. To (at Rkm)	Trib. To (at Rkm)	Trib. To (at Rkm)	Reach Number	RKm to Rkm	Date Surveyed	Latitude (Reach Midpoint) (degrees, min., sec.)	Longitude (Reach Midpoint) (degrees, min., sec.)
Chinook Cr.	Ohanepecosh R. 19.35	Cowlitz R.	Columbia R.	23	2.8-4.5	2,8,15	N46 49.747'	W121
Chinook Cr.	Ohanepecosh R. @ 15.94	Cowlitz R. @ 215.6	Columbia R. @ 109.5	24	0.76-1.8	7/20/1999	N46 50.738	W121 32.138
Needle Cr.	chinook Cr. @ 4.75	Ohanepecosh R. @ 15.94	Cowlitz R. @ 215.6	25	0-1.1	7/13/1999	N46 50.235	W121 32.656
Unnamed	Ohanepecosh R. @13.65	Cowlitz R. @215.6	Columbia R. @109.5	26	0.45-0.92	7/30/1999	N46 45.385'	W121 33.877'
Falls Cr.	Ohanepecosh R. @14.05	Cowlitz R. @215.6	Columbia R. @109.5	27	0.6-0.7	8/3/1999	N46 45.753'	W121 33.693'
Falls Cr.	Ohanepecosh R. @14.05	Cowlitz R. @215.6	Columbia R. @109.5	28	0.94-1.06	8/4/1999	N46 45.910'	W121 33.811'
Ollallie Cr.	Ohanepecosh R. @ 12.49	Cowlitz R. @ 215.6	Columbia R. @109.45	29	0.0-0.2	8/4/1999	46 46.427'	W121 33.189'
Ollallie Cr.	Ohanepecosh R. @ 12.49	Cowlitz R. @ 215.6	Columbia R. @109.45	30	2.5-3	8/2/1999	46 46.500'	W121 35.135'

Stream Name	Trib. To (at Rkm)	Trib. To (at Rkm)	Trib. To (at Rkm)	Reach Number	RKm to Rkm	Date Surveyed	Latitude (Reach Midpoint) (degrees, min., sec.)	Longitude (Reach Midpoint) (degrees, min., sec.)
Ohanepecosh R.	Cowlitz R. @ 215.6	Columbia R. @ 109.45	Pacific	31	15.37-15.57	10/10/1999	N46 46.246	W121 33.046
Crystal Cr.	White R. @106.7	Puyallup R. @ 16.6	P.S.	32	1.1-1.5	7/21/1999	N46 55.255	W121 31.817
Unnamed	Ohanepecosh R. @ 15.63	Cowlitz R. @ 215.6	Columbia R. @ 109.45	33	0.3-0.5	8/3/1999	N46 47.614	W121 33.568
Deadwood Cr.	White R. @108.7	Puyallup R. @16.6	Puyallup R. @16.6	34	0.98-1.4	7/28/1999	N46 54.229	W121 32.305
Cle Elum R.	Yakima R. @298.8	Columbia R.@ 537.7	Pacific Ocean	35	55.7-56.4	8/13/1999	N47 32.860'	W121 6.447'
Unnamed	Cle Elum R. @56.0	Yakima R. @ 298.8	Columbia R. @ 537.7	37	0.4-0.8	8/9/1999	N47 33.353	W121 6.295
Unnamed	Cle Elum R.@ 56.0	Yakima R. @ 298.8	Columbia R. @537.7	38	0.8-1.3	8/10/1999	N47 33.3022'	W121 5.893
Unnamed	Cle Elum R. @56.4	Yakima R. @298.8	Columbia R. @537.7	39	0.1-0.3	8/10/1999	N47 33.447	W121 6.672

Stream Name	Trib. To (at Rkm)	Trib. To (at Rkm)	Trib. To (at Rkm)	Reach Number	RKm to Rkm	Date Surveyed	Latitude (Reach Midpoint) (degrees, min., sec.)	Longitude (Reach Midpoint) (degrees, min., sec.)
Unnamed	Cle Elum R. @ 56.4	Yakima R. @ 298.8	Columbia R. @ 537.7	40	0.4-0.8	8/11/1999	N47 33.474'	W121 6.280'
Unnamed	Cle Elum R/ @57.4	Yakima R. @298.8	Columbia R. @537.7	41	0.0-0.2	8/9/1999	N47 33.632'	W121 6.943'
Cle Elum R.	Yakima R.@ 298.8	Columbia R. @ 537.7	Pacific Ocean	42	59.0-59.0	8/19/1999	N47 34.619'	W121 7.923
Unnamed	Cle Elum R. @59.0	Yakima R. @ 298.8	Columbia R. @537.7	43	0.0-0.1	8/23/1999	N47 34.666'	W121 8.240'
Unnamed	Cle Elum R. @59.5	Yakima R. @ 298.8	Columbia R. @ 537.7	44	0.1-0.2	8/18/2000	N47 34.797'	W121 8.135'
Unnamed	Cle Elum R. @ 59.5	Yakima R. @ 298.8	Columbia R. @ 537.7	45	0.1-0.4	8/17/1999	N47 34.861'	W121 78.833'
Unnamed	Cle Elum R. @58.5	Yakima R. @298.8	Columbia R. @ 537.7	46	58.0-58.5	8/24/1999	N47 34.336'	W121 7.652'
Unnamed	Chiwawa R. @ 46.5	Wenatchee R. @77.9	Columbia R. @753.7	49	0.3-0.8	9/2/1999	N48 3.831'	W120 50.741'

Stream Name	Trib. To (at Rkm)	Trib. To (at Rkm)	Trib. To (at Rkm)	Reach Number	RKm to Rkm	Date Surveyed	Latitude (Reach Midpoint) (degrees, min., sec.)	Longitude (Reach Midpoint) (degrees, min., sec.)
Waptus R.	Cle Elum R. @35.0	Yakima R. @298.8	Columbia R. @ 537.7	50	3.0-3.8	8/25/1999	N47 26.168	W121 6.784
Chiwawa R.	Wenatchee R. @ 77.9	Columbia R. @ 753.7	Pacific	51	50.5-51.1	8/31/1999	N48 5.465'	W120 52.102'
Waptus R.	Cle Elum R. @ 35.0	Yakima R. @298.8	Columbia R. @537.7	53	3.5-3.8	8/16/1999	N47 26.437	W121 7.153
Hour Cr.	Waptus R. @ 3.5	Cle Elum R. @35.0	Yakima R. @298.8	57	0.0-0.3	8/17/1999	N47 26.3691'	W121 7.218'
Hour Cr.	Waptus R. @ 3.5	Cle Elum R. @ 35	Yakima R. @298.8	58	0.6-0.9	8/18/1999	N47 26.519'	W121 7.583'
NF Skokomish R.	Skokomish R @ 11.0	Puget Sound		65	17.97-19.3	9/7/1999	N47 31.51	W123 20.68
White R.	Wenatchee R. @ 94.2	Columbia R. @753.7	Pacific	68	63.0-63.8	9/4/1999	N47 58.503	W120 57.273
Boulder R.	N.Fk Stillaguamish R. @ 41.8	Stillaguamish R. @ 28.6	P.S.	71	10.1-10.6	9/7/1999	N48 14.027	W121 48.306

Stream Name	Trib. To (at Rkm)	Trib. To (at Rkm)	Trib. To (at Rkm)	Reach Number	RKm to Rkm	Date Surveyed	Latitude (Reach Midpoint) (degrees, min., sec.)	Longitude (Reach Midpoint) (degrees, min., sec.)
Boulder R.	N.Fk Stillaguamish R. @ 41.8	Stillaguamish R. @ 28.6	P.S.	72	10.8-11.3	9/8/1999	N48 13.210	W121 46.912
Hoh R.	Pacific Ocean			77	56.3-59	9-33-99	N47 51.82	W123 54.90
Queets R.	Pacific Ocean			78	38.3-41.7	8-16-99,10-18-99	N47 37.62	W123 59.95
Sams Cr.	Queets R. @ 23.0	Pacific Ocean		79	0.25-0.45	10/19/1999	N47 37.276'	W124 0.699'
White R.	Puyallup R. @ 16.6	P.S.		80	111.2-114.1	9/14/1999	N46 53.988'	W121 34.599'
Frying Pan Cr.	White R.@113.1	Puyallup R.	Commencement Bay	81	0.85-1.65	9/13/1999	N46 53.094	W121 36.711
Ingalls Cr.	Peshastin Cr. @ 14.2	Wenatchee R. @27.1	Columbia R. @ 743	99	1.69-2.39	10/4/1999	N47 27.541'	W120 41.110'
Bumping R.	Naches R. @45.8	Yakima R. @80.25	Columbia R. @321	101	36.0-36.2	10/16/1999	N46 50.13'	W121 22.36

Stream Name	Trib. To (at Rkm)	Trib. To (at Rkm)	Trib. To (at Rkm)	Reach Number	RKm to Rkm	Date Surveyed	Latitude (Reach Midpoint) (degrees, min., sec.)	Longitude (Reach Midpoint) (degrees, min., sec.)
Bumping R.	Naches R. @45.8	Yakima R. @80.25	Columbia R. @321	102	35.7-35.9	10/16/1999	N46 49.855'	W121 22.669'
Bumping R.	Naches R. @45.8	Yakima R. @80.25	Columbia R. @321	103	36.7-36.9	10/16/1999	N46 49.388'	W121 22.846'
Bogachiel R.	Pacific Ocean			115	27.1-28.9	10/25/1999	N47 52.930	W124 13.756
Sunrise Cr.	White R.@100.8	Puyallup R. @16.4	Puget Sound	144	4.84-6.0	9/23/1999	N46 56.098	W121 34.409
Quinault R.	Pacific			180	22.04-23.9	9/25/1999	N47 33.486	W123 36.651
Icicle Cr.	Wenatchee R @35.72	Columbia R. @753.7	Pacific O.	185	19.1-19.7	10/2/1999	N47 37.010'	W120 57.323
Mill Cr.	Lankam Cr. @0.3	Nason Cr. @ 32.24	Wenatchee	230	7.8-8.0	11/1/1999	N47 43.574	W121 4.191
Early Winters Cr.	Methow R.@111.0	Columbia R. @ 833		269	24.9-25.1	11/2/1999	N48 30.825	W121 38.486

Stream Name	Trib. To (at Rkm)	Trib. To (at Rkm)	Trib. To (at Rkm)	Reach Number	RKm to Rkm	Date Surveyed	Latitude (Reach Midpoint) (degrees, min., sec.)	Longitude (Reach Midpoint) (degrees, min., sec.)
Bridge Cr.	Stehekin R. @22.5	Lake Chelan	Columbia R.	270	19.2-19.5	11/2/1999	N48 30.309	W120 43.312
Blum Cr.	Baker R. @ 33.3	Skagit R. @ 88.0	P.S.	275	0.3-0.5	11/5/1999	N48 45.186'	W121 32.610'
Unnamed	Quinalt R. @86.0	Pacific Ocean		277	0.3-0.9	11/6/1999	N47 33.113	W123 37.427
Unnamed	NF Quinault R. @4.6	Quinault R. 82	Pacific Ocean	278	0.1-0.4	11/6/1999	N47 34.132	W123 39.266
Snow Cr.	Icicle Cr. @8.73	Wenatchee R. @41.2	Columbia R. @743	288	2.3-3.0	10/3/1999	N47 31.691	W120 42.8791
Mission Cr.	Wenatchee R. @ 16.0	Columbia R. @743	Pacific	311	16.52-17.5	8/28/2000	N47 23.670	W120 30.086
Unnamed	Mission Cr. @ 2.91	Wenatchee R. @16.0	Columbia R. @753.7	312	0.01-0.11	8/28/2000	N47 22.430'	W120 30.862'
Unnamed	Mission Cr. @ 3.17	Wenatchee R. @16.0	Columbia R. @743	313	0.05-0.25	8/28/2000	N47 22.266'	W120 30.802

Stream Name	Trib. To (at Rkm)	Trib. To (at Rkm)	Trib. To (at Rkm)	Reach Number	RKm to Rkm	Date Surveyed	Latitude (Reach Midpoint) (degrees, min., sec.)	Longitude (Reach Midpoint) (degrees, min., sec.)
Unnamed	Mission Cr. @ 7.39	Wenatchee R. @16.0	Columbia R. @753.7	314	0.025-0.125	8/29/2000	N47 20.439	W120 29.356
Mission Cr.	Wenatchee R. @16.0	Columbia R. @ 743	Pacific	315	7.39-8.29	8/29/2000	N47 20.450	W120
Unnamed	Mission Cr. @6.68	Wenqatchee R. @16.0	Columbia R. @753.7	316	0.16-0.216	8/29/2000	N47 20.554	W120 29.692
Unnamed	E.Fk Mission Cr. @ 2.7	Mission Cr. @16.42	Wenatchee R. @16	318	0.15-0.55	8/31/2000	N47 22.558	W120 28.892
Rag Cr.	E.Fk Mission Cr. @ 2.31	Mission Cr. @16.42	Wenatchee R. @ 16.0	319	0.02-0.42	8/31/2000	N47 22.769'	W120 28.977'
Unnamed	Sand Cr. @ 1.6	Mission Cr. @ 12.3	Wenatchee r. @ 16.0	320	0.70-0.27	8/31/2000	N47 25.880'	W120 31.603'
Bridge Cr.	Icicle Cr. @15.4	Wenatchee R. @ 41.2	Columbia R. @ 753.7	321	0.13-0.26	8/31/2000	N47 33.766'	W120 46.736
Chatter Cr.	Icicle Cr. @ 27.1	Wenatchee R. @41.2	Columbia R. @743	322	0.67-0.87	8/31/2000	N47 36.743'	W120 53.328'

Stream Name	Trib. To (at Rkm)	Trib. To (at Rkm)	Trib. To (at Rkm)	Reach Number	RKm to Rkm	Date Surveyed	Latitude (Reach Midpoint) (degrees, min., sec.)	Longitude (Reach Midpoint) (degrees, min., sec.)
Surprise Cr.	Tye R. @ 13.4	S.Fk. Skykomish R. @ 31.5	Skykomish R. @ 19.63	330	0.7-1.1	9/2/2000	N47 42.328'	W121 9.395
Unnamed	Surprise Cr. @ 4.9	Skykomish R. @ 80.47	Snohomish R. @ 41.8	331	0.45-0.65	9/3/2000	N47 39.672'	W121 8.707'
Unnamed	Surprise Cr. @ 4.9	Skykomish R. @ 80.47	Snohomish R. @ 41.8	332	1.1-1.2	9/3/2000	N47 39.735	W121 8.353
Unnamed	Surprise Cr. @ 4.9	Skykomish R. @ 80.47	Snohomish R. @ 41.8	333	0.21 to 0.61	9/3/2000	N47 40.114	W121 8.258
Cutthroat Cr.	Early Winters Cr. @ 18.64	Methow R. @ 111	Columbia R. @ 833	340	3.83 - 4.23	9/5/2000	N48 32.858	W121 40.373
Pine Cr.	Early Winters Cr. @17.0	Methow R @ 111.0	Columbia R. @833.0	341	0.2 to 0.4	9/5/2000	N48 34.693	W120 37.693
Cutthroat Cr.	Early Winters Cr. @ 18.64	Methow R. @ 111.0	Columbia R. @833	342	4.68-4.78	9/5/2000	N48 32.565	W120 40.864

Stream Name	Trib. To (at Rkm)	Trib. To (at Rkm)	Trib. To (at Rkm)	Reach Number	RKm to Rkm	Date Surveyed	Latitude (Reach Midpoint) (degrees, min., sec.)	Longitude (Reach Midpoint) (degrees, min., sec.)
Blue Lake Cr.	State Cr. @ 2.68	Bridge Cr. @18.75	Stehekin R. @ 24.75	344	1.53-1.73	9/6/2000	N48 30.497	W120 40.338
Blue Lake Cr.	State Cr. @ 2.68	Bridge Cr. @18.75	Stehekin R. @ 24.75	345	0.26-0.96	9/6/2000	N48 30.809'	W120 41.141
Lewis Cr.	Granite Cr. @26	Ruby Cr. @8.75	Ross Lake (Skagit @ 170)	346	0.01 to 0.81	9/6/2000	N48 31.795	W120 45.249
Copper Cr.	Bridge Cr. @ 18.49	Stehekin R. @24.75	Lake Chelan @ 81.5	347	0.34-0.54	9/7/2000	N48 29.526	W120 41.971
Rainy Cr.	Bridge Cr. @20.6	Stehekin R. @24.75	Lake Chelan @81.5	348	0.55 - 0.65	9/7/2000	N48 30.324	W120 43.739
Unnamed	Bridge Cr. @ 21.27	Stehekin R. 24.75	Lake Chelan 81.5	349	0.18	9/7/2000	N48 30.671	W120 44.104
Lake Ann Cr.	Bridge Cr. @20.64	Stehekin R.@24.75	Lake Chelan @81.5	350	0.5-0.6	9/7/2000	N48 30.295	W120
Porcupine Cr.	Granite Cr. @ 26.25	Ruby Cr. @8.75	Ross Lake (Skagit @170)	351	0.3-0.7	9/7/2000	N48 31.869	W120

Stream Name	Trib. To (at Rkm)	Trib. To (at Rkm)	Trib. To (at Rkm)	Reach Number	RKm to Rkm	Date Surveyed	Latitude (Reach Midpoint) (degrees, min., sec.)	Longitude (Reach Midpoint) (degrees, min., sec.)
Jackson Cr.	Hoh R. @37.5	Pacific Ocean		501	0.84-1.44	9/14/2000	N47 50.990	W123 55.117
Unnamed	Hoh R. @34.8	Pacific Ocean		502	1.63-1.83	9/14/2000	N47 50.420'	W123 55.903
Unnamed	Hoh R. @34.8	Pacific Ocean		503	0.33-0.73	9/14/2000	N47 50.769	W123 56.539
E. Twin	Twin Cr. @ 0.3	Hoh R. @32.6	Pacific Ocean	504	0.38-0.78	9/12/2000	N47 50.135	W123 59.324
Unnamed	E. Twin Cr. @0.33	Hoh R. @32.6	Pacific Ocean	505	0.39-1.19	9/12/2000	N47 50.130	W123 59.390
Twin Cr.	Hoh R. @32.6	Pacific Ocean		507	0.06-0.36	9/12/2000	N47 49.979	W123 59.485
Cougar Cr.	Hoh R. @40.7	Pacific Ocean		508	0.11-0.41	9/13/2000	N47 51.804	W123 51.382
Cougar Cr.	Hoh R. @40.7	Pacific Ocean		509	0.5-0.8	9/13/2000	N47 51.922	W123 51.922

Stream Name	Trib. To (at Rkm)	Trib. To (at Rkm)	Trib. To (at Rkm)	Reach Number	RKm to Rkm	Date Surveyed	Latitude (Reach Midpoint) (degrees, min., sec.)	Longitude (Reach Midpoint) (degrees, min., sec.)
Unnamed	Hoh R. @41.85	Pacific Ocean		510	0.02 to 0.22	9/13/2000	N47 52.188	W123 50.112
Mount Tom Cr.	Hoh R. @39	Pacific Ocean		511	0.87	9/13/2000	N47 51.680	W123 53,247
Mount Tom Cr.	Hoh R. @39.0	Pacific Ocean		512	1.8-2.4	9/13/2000	N47 51.361	W123 52.923
Mount Tom Cr.	Hoh R. @39	Pacific Ocean		513	2.67 to 3.67	9/13/2000	N47 51.158	W123 57.319
Cannings Cr.	Quinault R. @47.1	Pacific Ocean		515	0.23-0.33	9/14/2000	N47 31.926	W123 40.606
Cannings Cr.	Quinault R. @47.1	Pacific Ocean		516	0.33-0.43	9/14/2000	N47 31.878	W123 40.597
Sloan Cr.	N.Fk. Sauk R. @ 44.2	Sauk R. @ 64.2	Skagit R. @ 108.0	601	10.61-10.81	9/21/2000	N48 0.192	W121 14.847
Sloan Cr.	N.Fk. Sauk R. @ 44.2	Sauk R. @ 64.2	Skagit R. @ 108.0	602	10.81-11.41	9/21/2000	N47 59.934	W121 12.887

Stream Name	Trib. To (at Rkm)	Trib. To (at Rkm)	Trib. To (at Rkm)	Reach Number	RKm to Rkm	Date Surveyed	Latitude (Reach Midpoint) (degrees, min., sec.)	Longitude (Reach Midpoint) (degrees, min., sec.)
White Chuck R.	Sauk R. @52.5	Skagit R.@ 108	PS	603	20.23-21.0	9/22/2000	N48 9.126'	W121 15.204'
Cougar Cr.	N.Fk. Sauk R. @ 8.0	Sauk R. @ 64.2	Skagit R. @ 108	604	0.013-0.213	9/20/2000	N48 4.713'	W121 18.782
Unnamed	Cadet Cr. @ 0.9	Sloan Cr. @4.07	N.F. Sauk @75.5	605	0.29-0.49	9/21/2000	N48 1.321	W121 18.210
NF Sauk R.	Sauk R. @ 64.2	Skagit R. @ 108	P.S.	608	75.6-76.6	9/21/2000	N48 3.211	W121
NF Sauk R.	Sauk R. @ 64.2	Skagit R. @ 108	P.S.	609	76.6-77.1	9/21/2000	N48 3.190	W121
Lost Cr.	N.F. Sauk R. @ 6.91	Sauk R. @ 64.2	Skagit R. @ 108	610	4.3-4.78	9/19/2000	N48 6.149	W121
Lost Cr.	N.F. Sauk R. @ 6.91	Sauk R. @ 64.2	Skagit R. @ 108	611	4.78-5.33	9/19/2000	N48 6.164	W121
Suiattle R.	Sauk R. @23.4	Skagit R. @108	P.S.	612	43.1-44.8	9/22/2000	N48 13.906'	W121 10.595

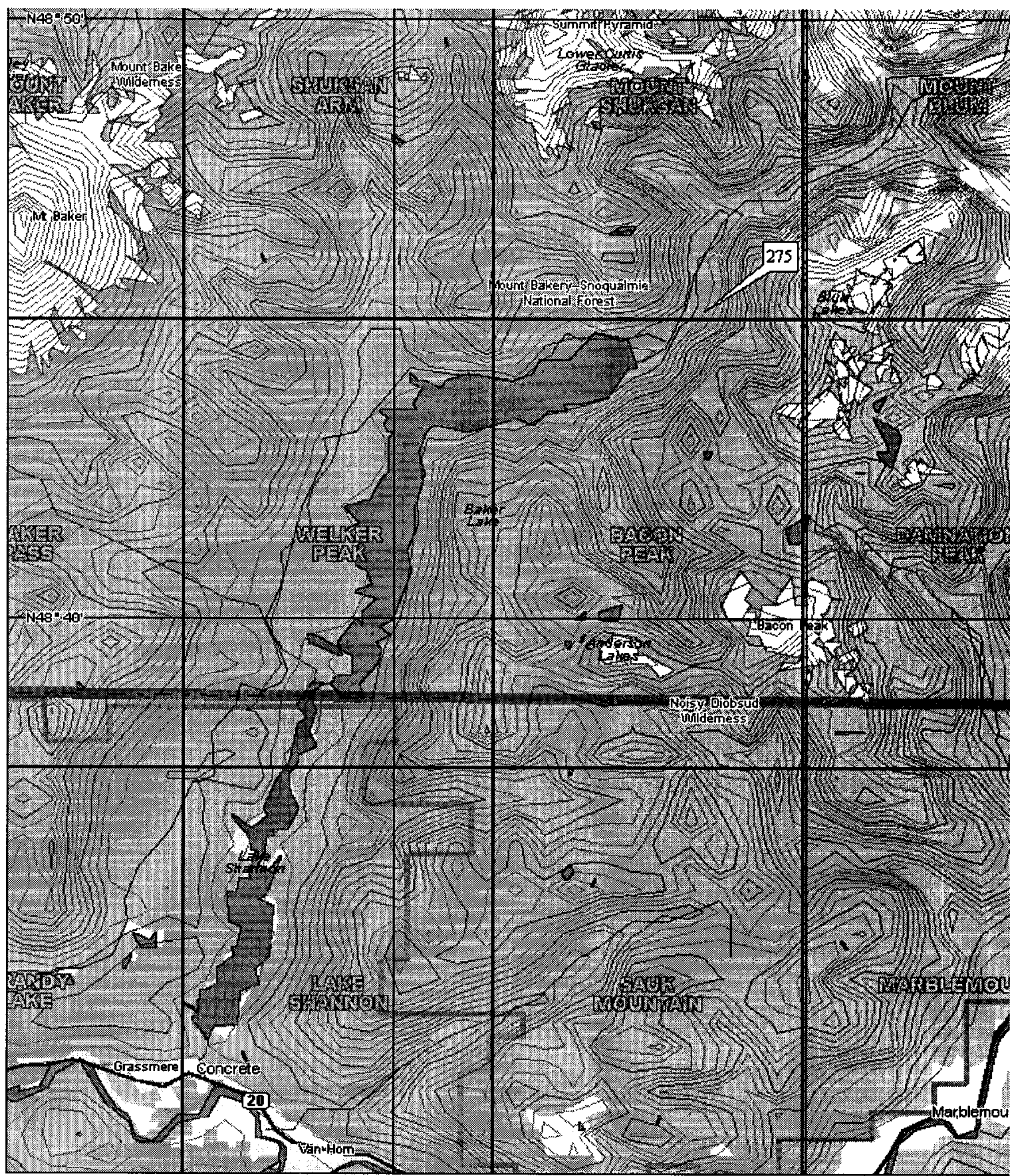
Stream Name	Trib. To (at Rkm)	Trib. To (at Rkm)	Trib. To (at Rkm)	Reach Number	RKm to Rkm	Date Surveyed	Latitude (Reach Midpoint) (degrees, min., sec.)	Longitude (Reach Midpoint) (degrees, min., sec.)
Unnamed	Cle Elum R. @ 36.1	Yakima R. @ 298.8	Columbia R. @ 537	701	0.1-0.2	9/28/2000	N47 34.248	W121 7.691
Delate Cr.	Cooper R. @14.79	Cle Elum R. @30.9	Yakima R. @298.8	703	0.0-0.06	9/29/2000	N47 27.350	W121 12.914
Spanish Cr.	Icicle Cr. @ 35.72	Wenatchee R. @41.19	Columbia R. @753.7	706	0.24-0.44	10/1/2000	N47 38.203'	W120 57.595
Lemah Cr.	Cooper R. @16.57	Cle Elum R. @30.9	Yakima R. @298.9	708	3.2-3.7	9/29/2000	N47 28.578'	W121 15.121
Chiwaukum Cr.	Wenatchee R. @ 57.76	Columbia R. @ 753.7	Pacific Ocean	710	2.08-2.28	10/1/2000	N47 41.219	W120 44.794'
Huckleberry Cr.	White R.@ 85.4	Puyallup R. @16.6	Commencement Bay, Puget Sound	720	9.8-10.1	10/3/2000	N46 59.781'	W121 37.142'
Buck Cr.	Chiwawa R. @55.25	Wenatchee R. @ 77.9	Columbia R. @753.6	721	0.3-0.4	10/6/2000	N48 6.428	W120 53.512
Buck Cr.	Chiwawa R. @55.25	Wenatchee R. @ 77.9	Columbia R. @753.6	722	0.2-0.3	10/6/2000	N48 6.426	W120 53.402'

Stream Name	Trib. To (at Rkm)	Trib. To (at Rkm)	Trib. To (at Rkm)	Reach Number	RKm to Rkm	Date Surveyed	Latitude (Reach Midpoint) (degrees, min., sec.)	Longitude (Reach Midpoint) (degrees, min., sec.)
Unnamed	Chiwawa R. @ 49.0	Wenatchee R. @77.9	Columbia R. @ 753.7	723	0.97-1.27	10/6/2000	N48 3.979'	W120 51.033'
Anthem Cr.	Entiat R. @66.83	Columbia R. @ 778.1	Pacific	724	0.01-0.31	10/7/2000	N48 2.713'	W120 41.562'
Entiat R.	Columbia R. @778.1	Pacific		725	63.21-63.51	10/7/2000	N48 1.491	W120 39.468
Chinook Cr.	Ohanepecosh R. @ 15.94	Cowlitz R. @ 215.6	Columbia R. @ 109.5	24a	4.8-5.5	7/12/1999	N46 50.258'	W121 32.332'
Falls Cr.	Ohanepecosh R. @14.05	Cowlitz R. @215.6	Columbia R. @109.5	27a	0.7-0.9	8/3/1999	N46 45.845'	W121 33.718
Falls Cr.	Ohanepecosh R. @14.05	Cowlitz R. @215.6	Columbia R. @109.5	28a	1.06-1.26	8/4/1999	N46 45.915'	W121 33.932'
Ollallie Cr.	Ohanepeocsh R. @ 12.49	Cowlitz R. @ 215.6	Columbia R. @ 109.45	29a	0.2-0.3	8/4/1999	N46 46.449	W121 33.359
Unnamed	E.Fk Mission Cr. @1.72	Mission Cr. @16.42	Wenatchee R. @16	319a	0.13-0.23	8/31/2000	N47 22.807'	W120 29.392

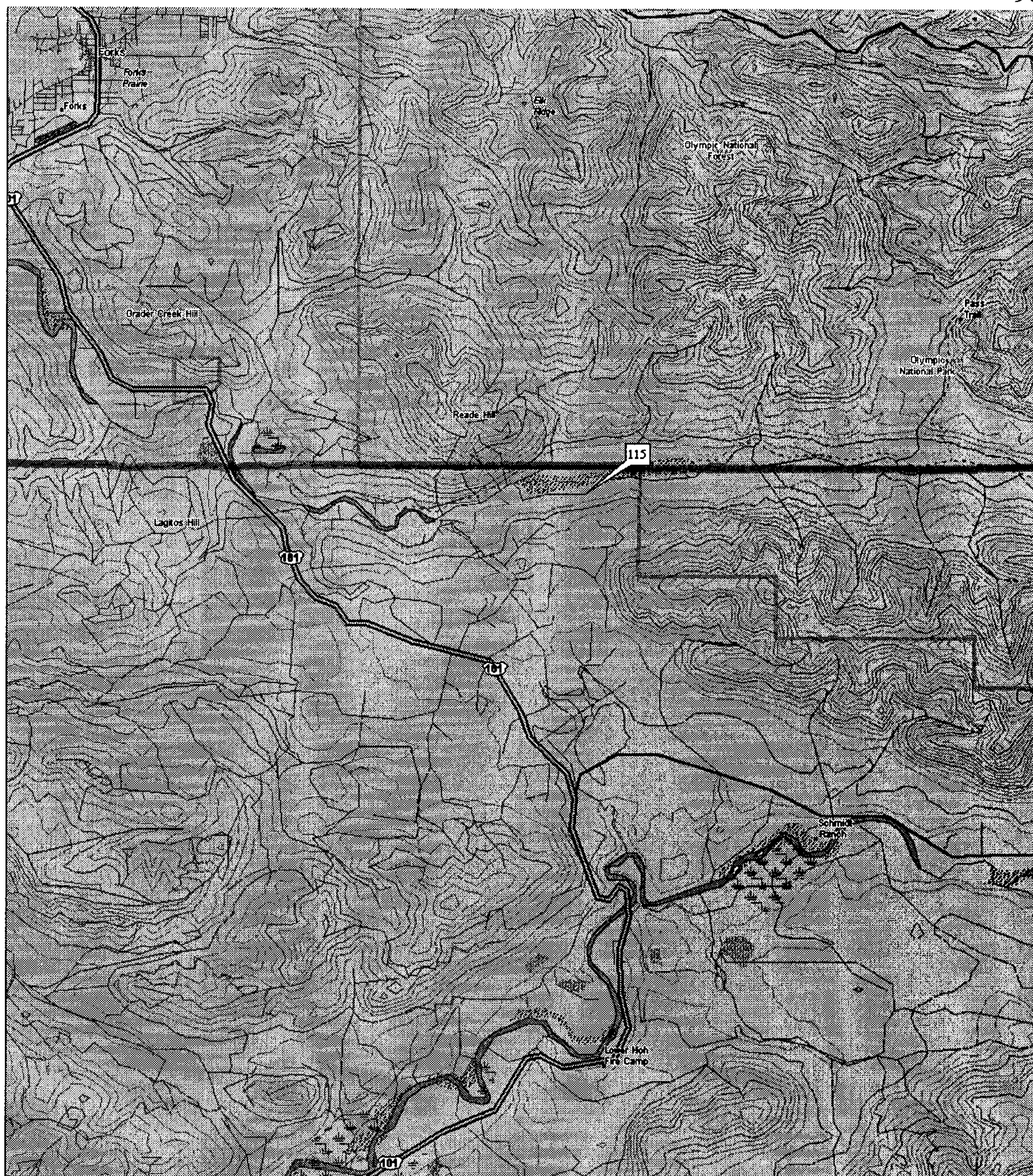
Stream Name	Trib. To (at Rkm)	Trib. To (at Rkm)	Trib. To (at Rkm)	Reach Number	RKm to Rkm	Date Surveyed	Latitude (Reach Midpoint) (degrees, min., sec.)	Longitude (Reach Midpoint) (degrees, min., sec.)
Ohanepecosh R.	Cowlitz R. @ 215.6	Columbia R. @ 109.45	Pacific	31a	15.7-15.9	10/10/1999	N46 46.336	W121 33.007
Ohanepecosh R.	Cowlitz R. @ 215.6	Columbia R. @ 109.45	Pacific	31b	15.77-15.97	10/10/1999	N46 46.670	W121 33.219
Unnamed	Ohanepecosh R. @ 15.63	Cowlitz R. @ 215.6	Columbia R. @ 109.45	33a	0.2-0.3	8/3/1999	N46 47.606	W121 33.411
Unnamed	Cle Elum R. @56.4	Yakima R. @298.8	Columbia R. @537.7	39a	0.0-0.2	8/10/1999	N47 44.445	W121 6.771'
Ranger Cr.	Carbon R. @ 43.04	Puyallup R. @28.9	P.S.	3a	2.32-2.52	7/12/1999	N46 58.798	W121 51.502'
Unnamed	Cle Elum R. @ 57.4	Yakima R. @ 298.8	Columbia R. @537.7	41a	0.3-0,4	8/9/1999	N47 33.618'	W121 66.840
Unnamed	Cle Elum R. @59.0	Yakima R. @ 298.8	Columbia R. @537.7	43a	0.1-0.2	8/23/1999	N47 34.672'	W121 8.223'
Unnamed	Cle Elum R. @59.0	Yakima R. @ 298.8	Columbia R. @537.7	43b	.3-0.4	8/23/1999	N47 34.670	W121 8.362'

Stream Name	Trib. To (at Rkm)	Trib. To (at Rkm)	Trib. To (at Rkm)	Reach Number	RKm to Rkm	Date Surveyed	Latitude (Reach Midpoint) (degrees, min., sec.)	Longitude (Reach Midpoint) (degrees, min., sec.)
Unnamed	Cle Elum R. @59.5	Yakima R. @ 298.8	Columbia R. @537.7	44a	0.2-0.3	8/18/1999	N47 34.838'	W121 8.255'
Unnamed	Cle Elum R.@59.5	Yakima R. @56.0	Columbia R.@ 537.7	44b	59.5-59.7	8/18/1999	N47 34.824	W121 8.421
Chiwawa R.	Wenatchee R. @ 77.9	Columbia R. @753.7	Pacific	50a	50.1-50.6	8/30/1999	N48 5.199'	W120 51.951'
White R.	Puyalllup R. @ 16.6	P.S.		80a	111.0-111.2	9/15/1999	N46 53.694'	W121 35.507
Laughingwater Cr.	Ohanepecos h R. @ 9.1	Cowlitz R. @ 215.6	Columbia R. @109.45	A-1	1.64-1.8	8/5/1999	N46 45.260'	W121 32.576'
Laughingwater Cr.	Ohanepecosh R. @ 9.1	Cowlitz R. @ 215.6	Columbia R. @109.45	A-2	1.8-2.0	8/5/1999	N46 45.304'	W121 32.441'
Laughingwater Cr.	Ohanepecosh R. @ 9.1	Cowlitz R. @ 215.6	Columbia R. @109.45	B	1.56-1.8	8/6/1999	N46 45.2441'	W121 32.599'
Cooper R.	Cle Elum R @ 31.24	Yakima R. @ 298.8	Columbia R. @537.7	C	2.25-2.61	8/26/1999	N47 24.490'	W121 6.367'

14.2. Appendix B. Site Maps



Blum Creek, tributary to the Baker River, N. Cascades



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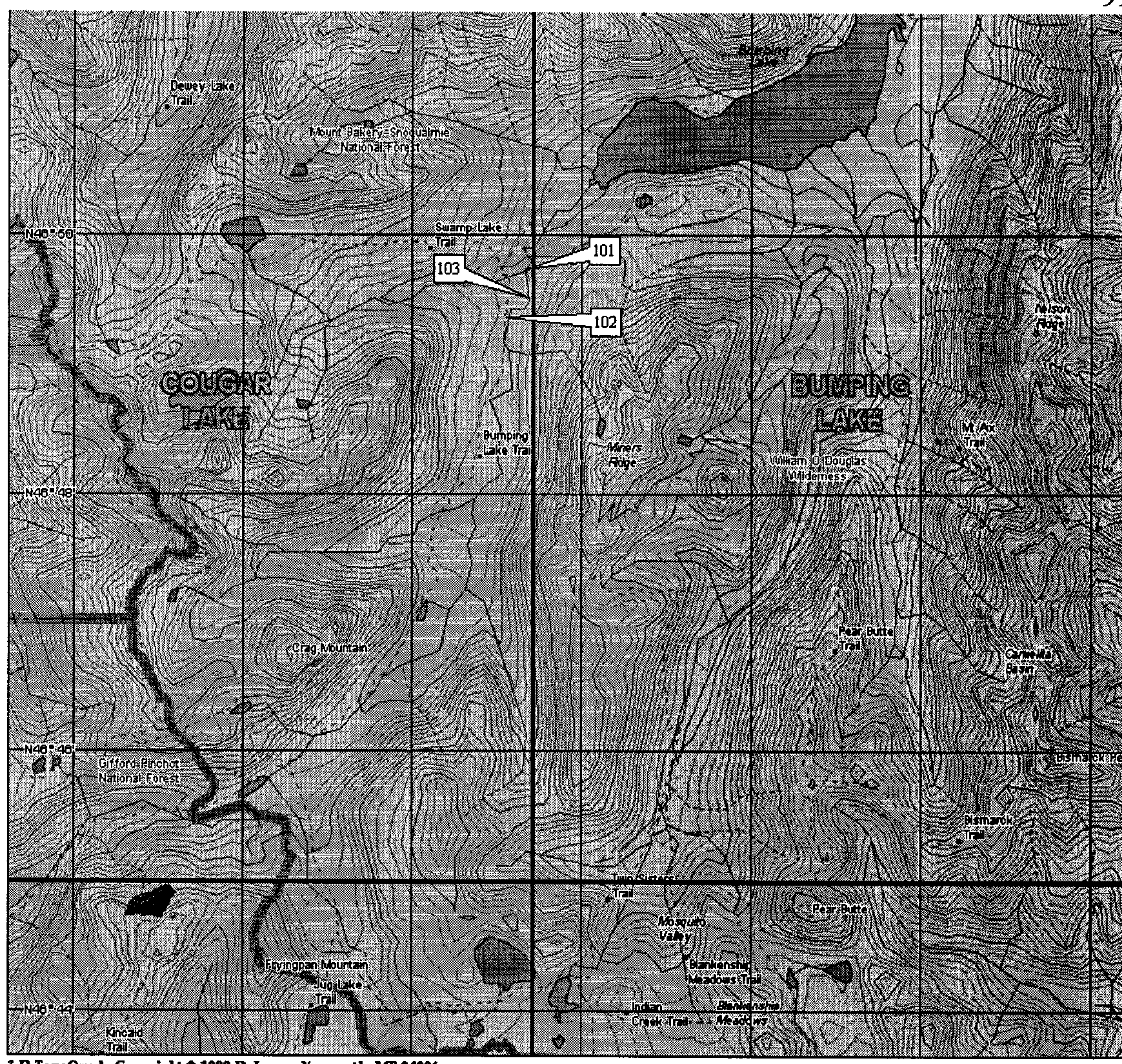
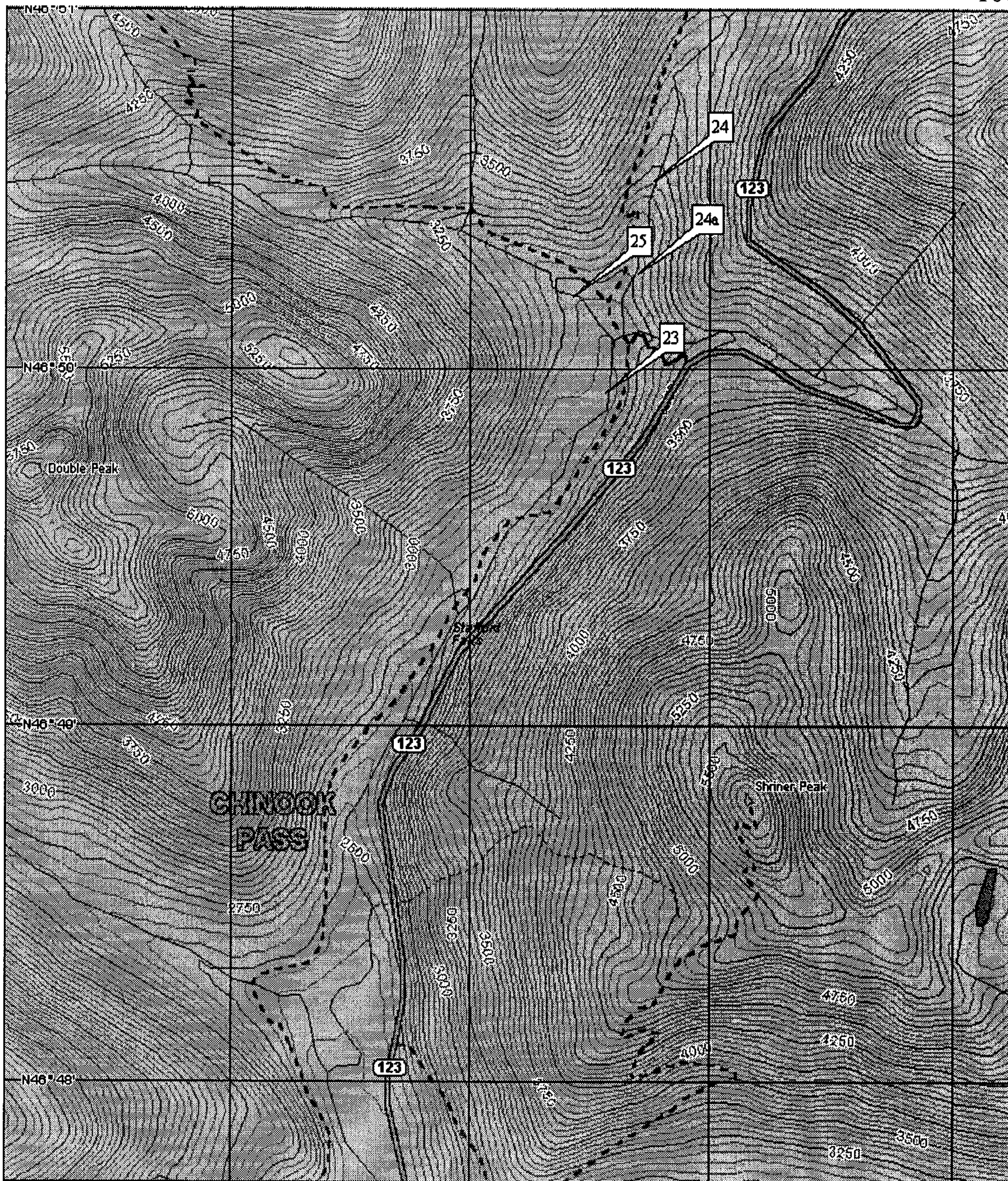
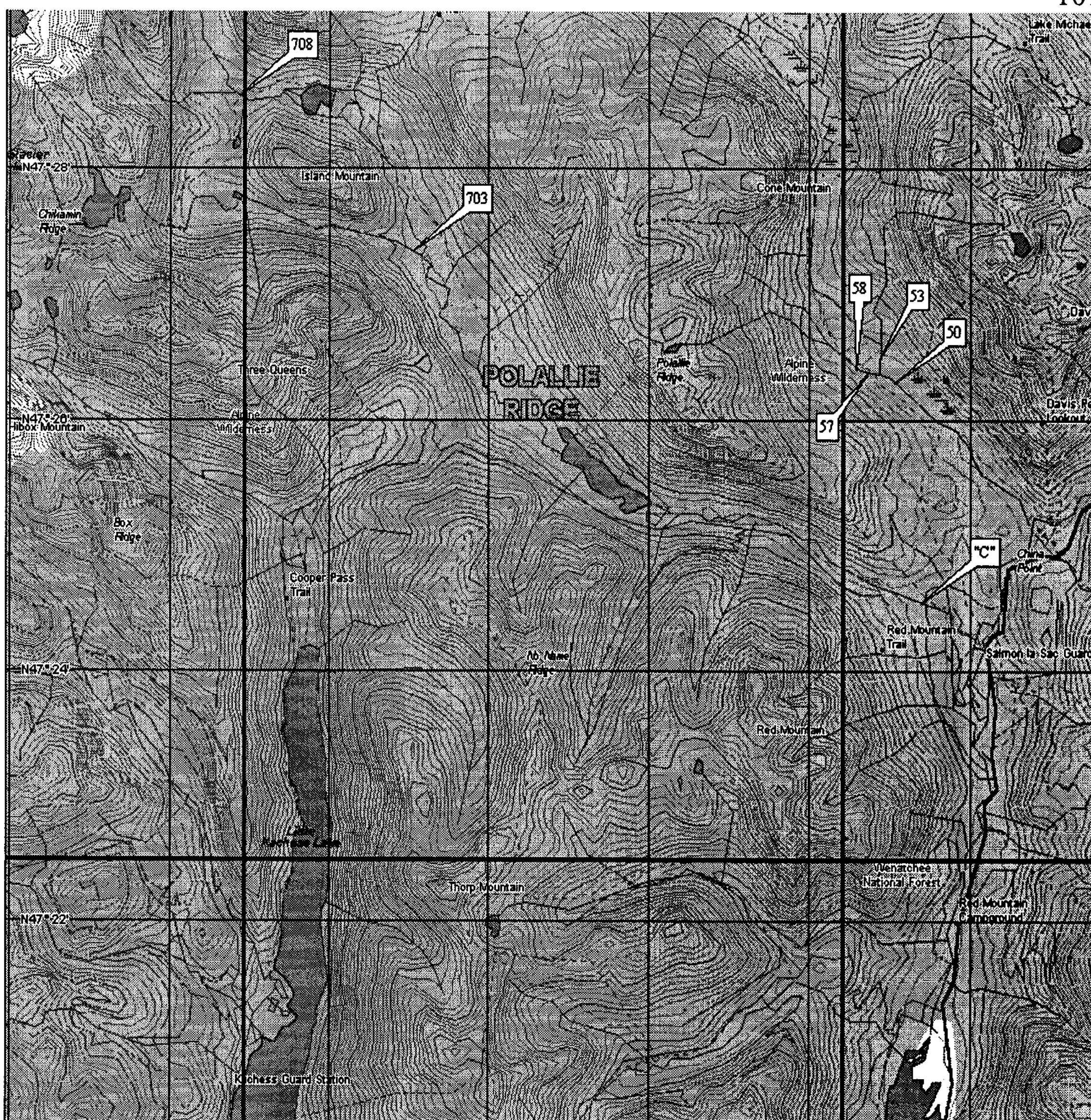
Bogachiel River, western Olympic Peninsula



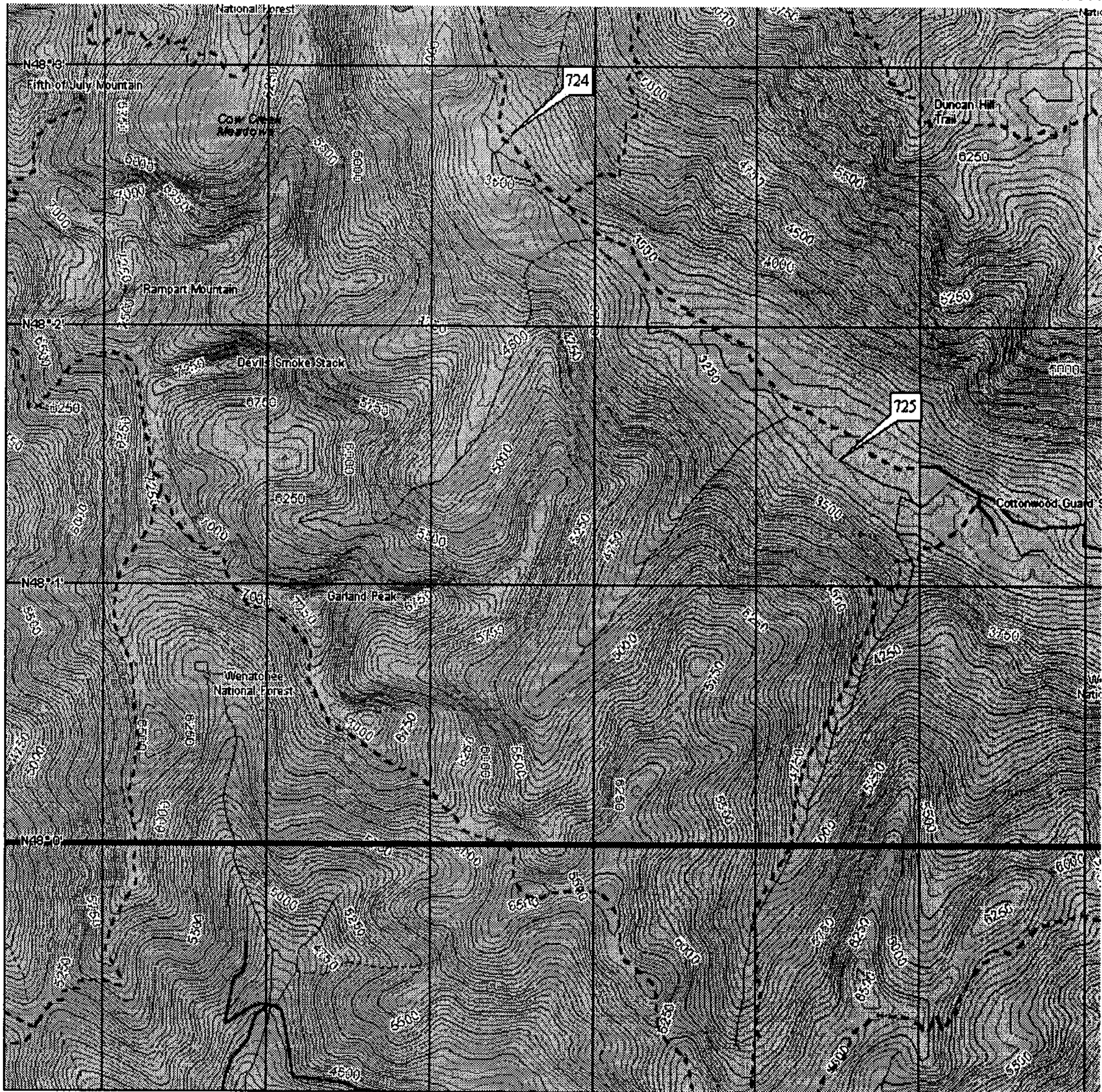
Bumping Lake, south-central Cascades



Chinook Cr., Mt. Rainier N.P.



Cooper Lake, Alpine Lakes Wilderness



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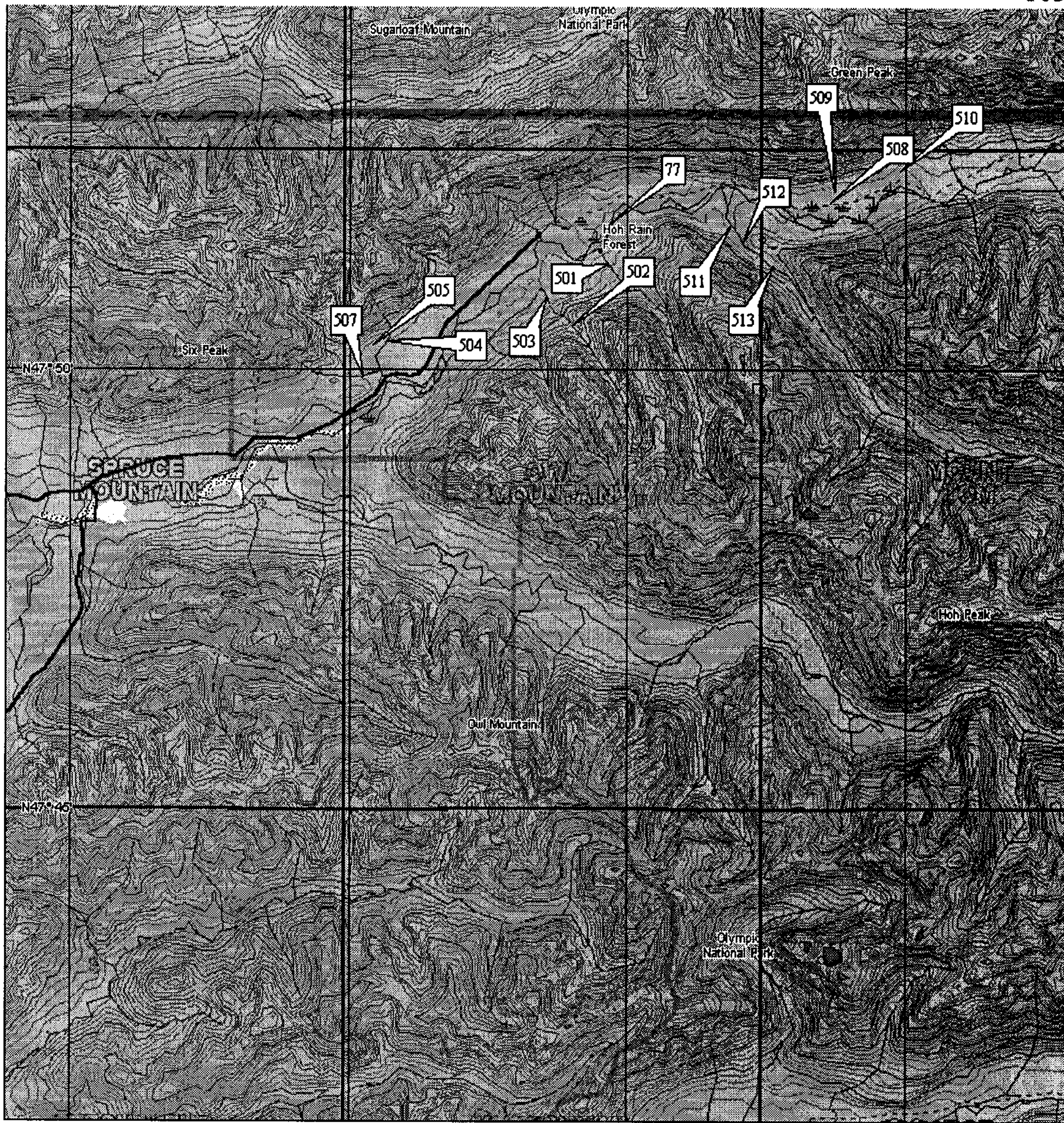
Entiat River



Hoh River

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Hyas Lake, Cle Elum R., Alpine Lakes Wilderness

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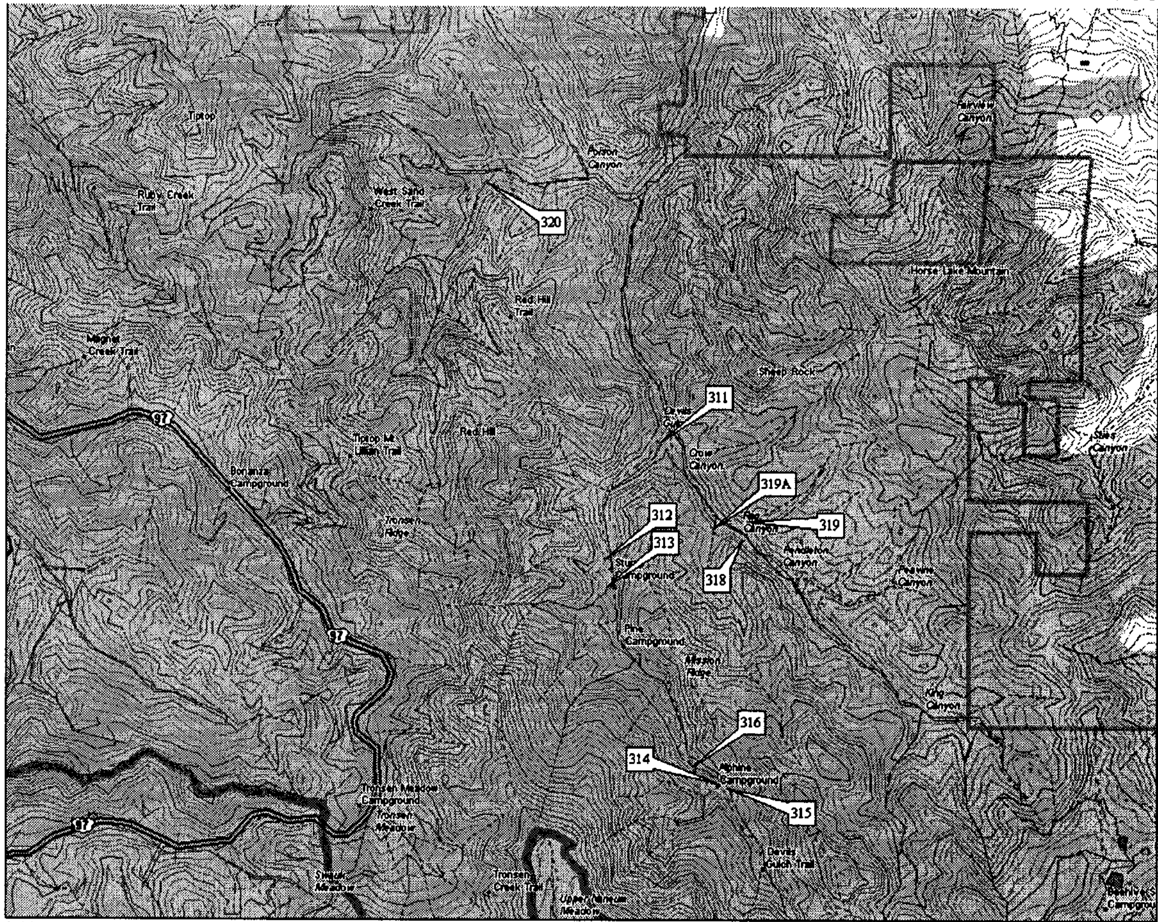
1 mi Scale: 1 : 200,000 Detail: 10-0 Datum: WGS84

Icicle R., Chiwawa, and Ingalls Cr.



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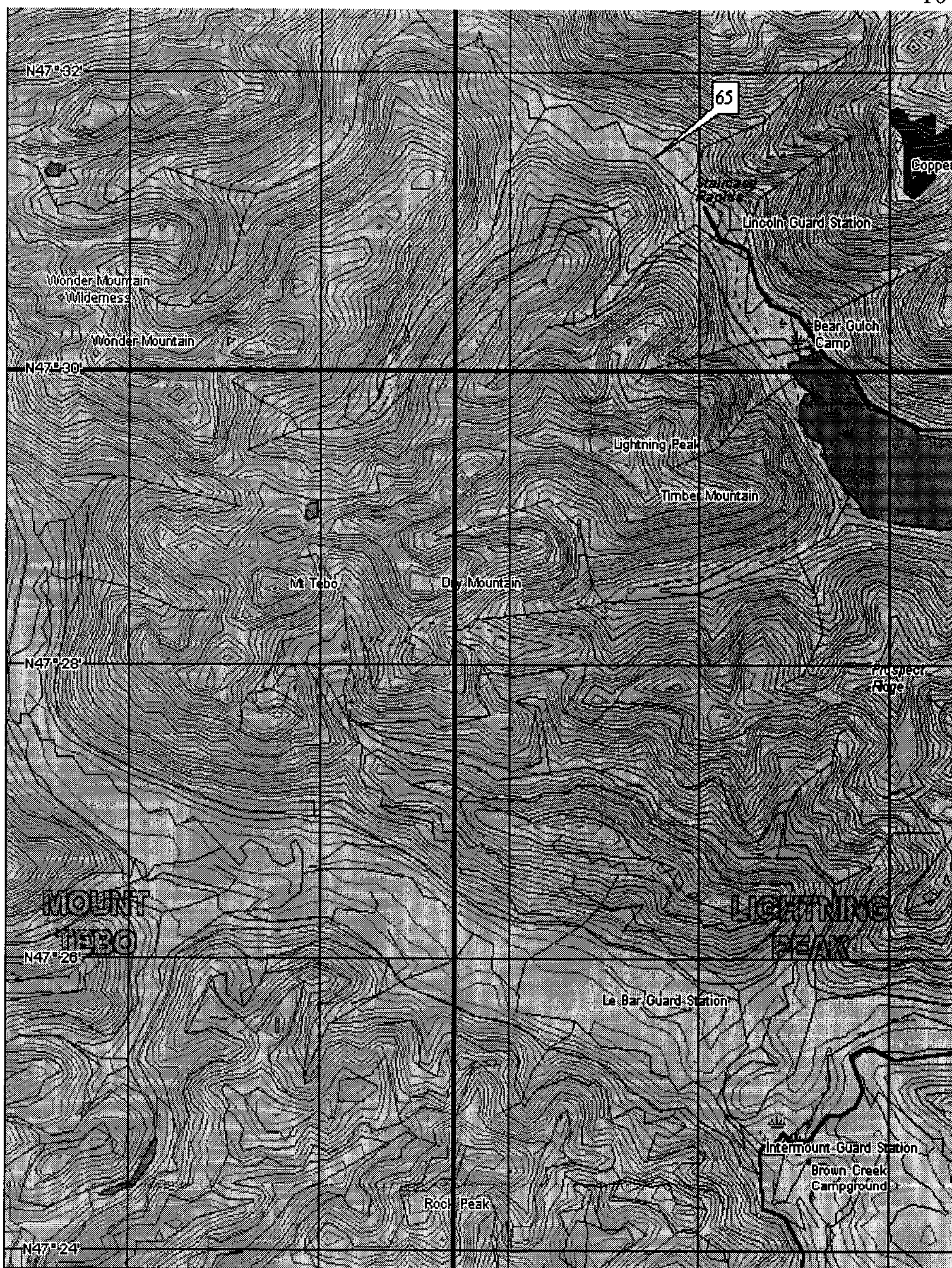
Mission Creek and Tributaries, Swauk Late-Successional Reserve



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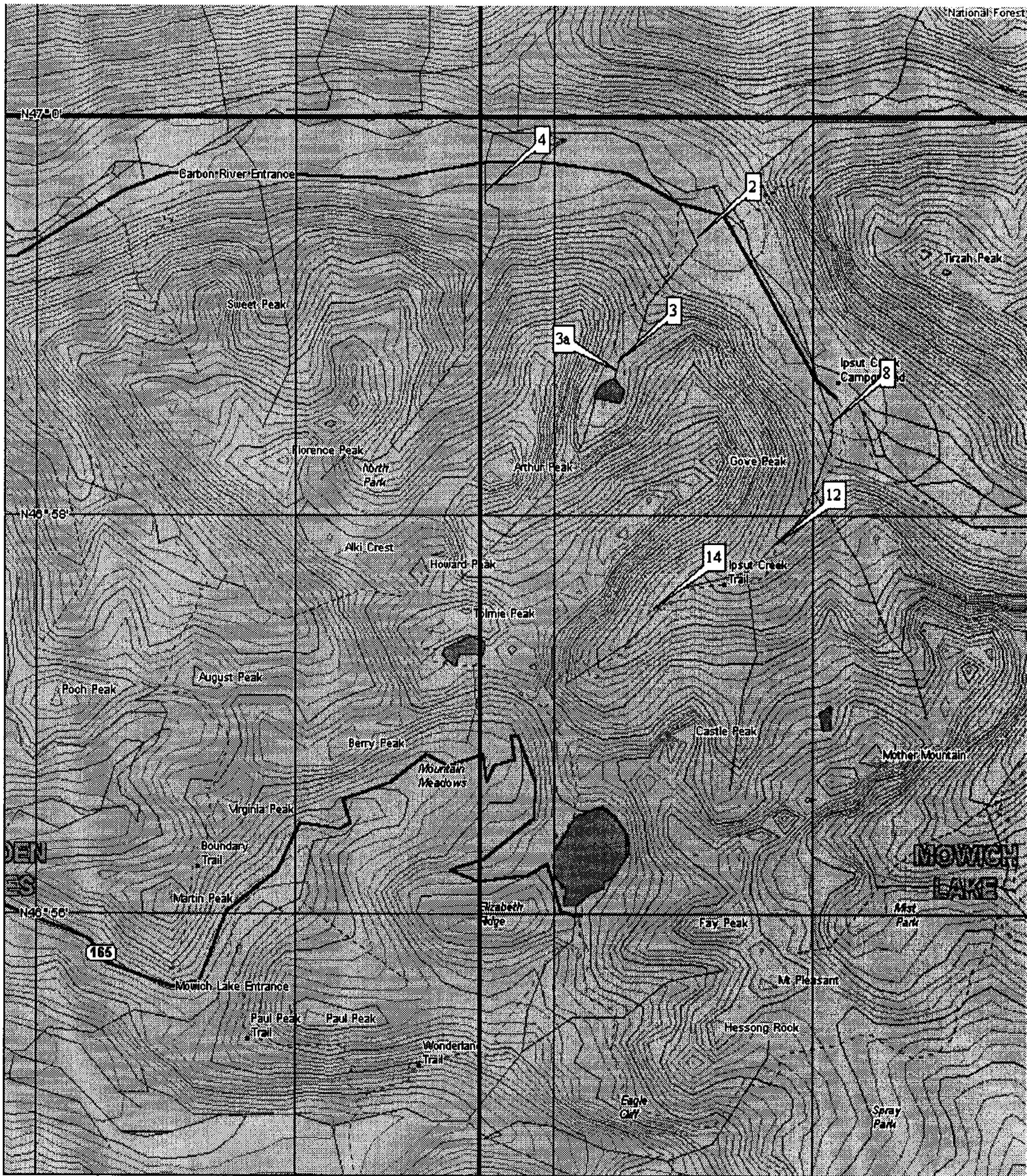
N.F. Skokomish R.



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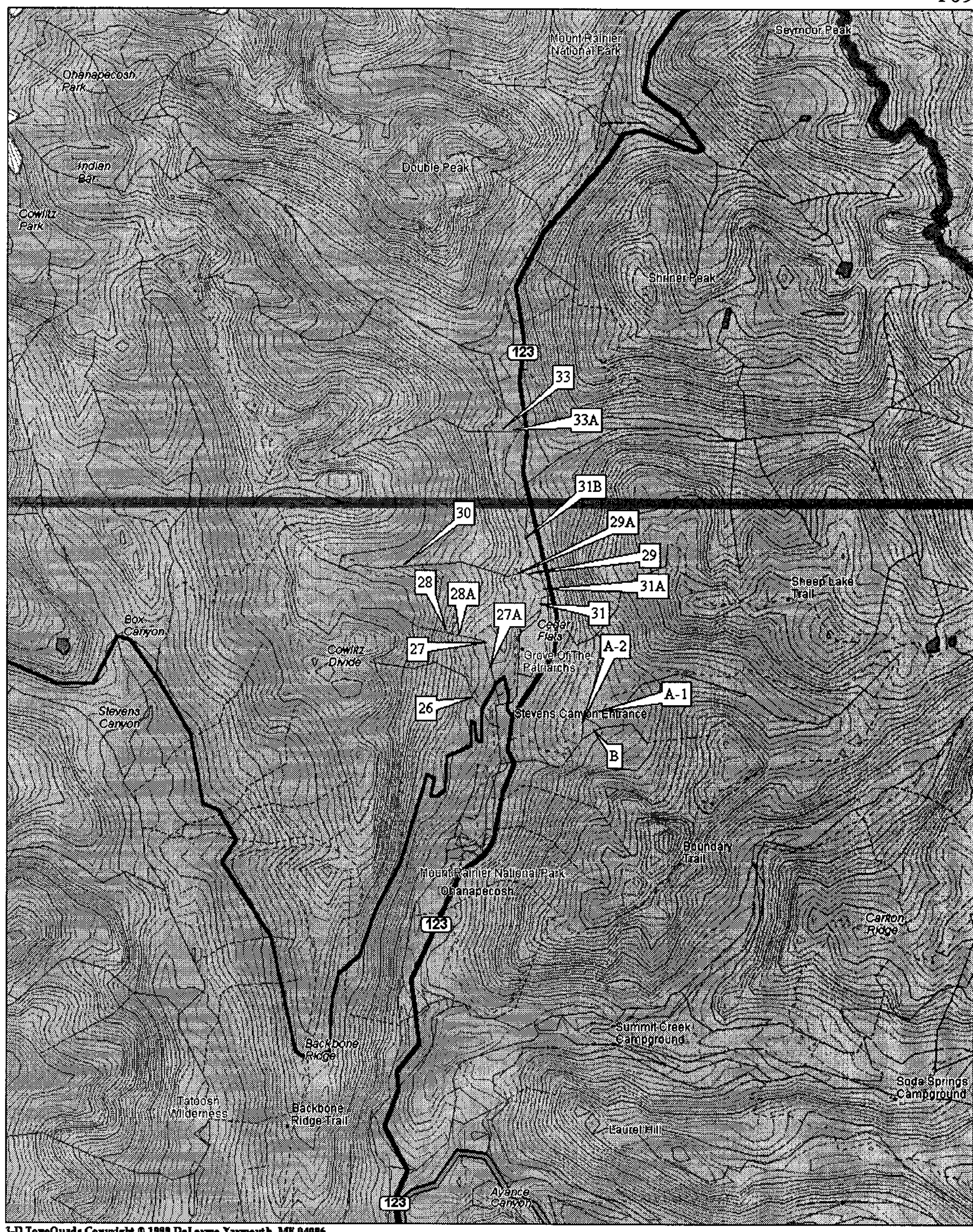
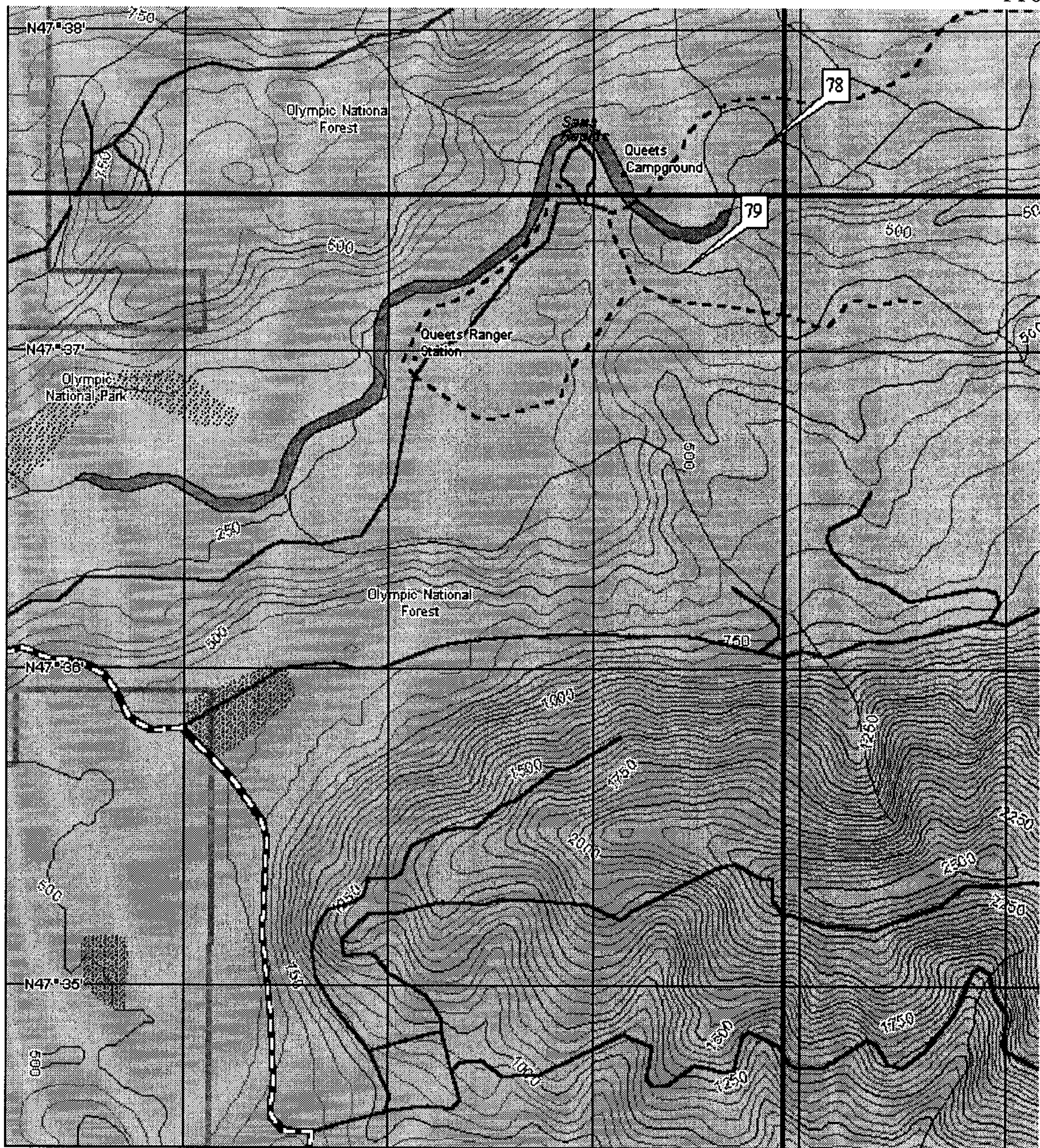
NW Mt. Rainier N.P.

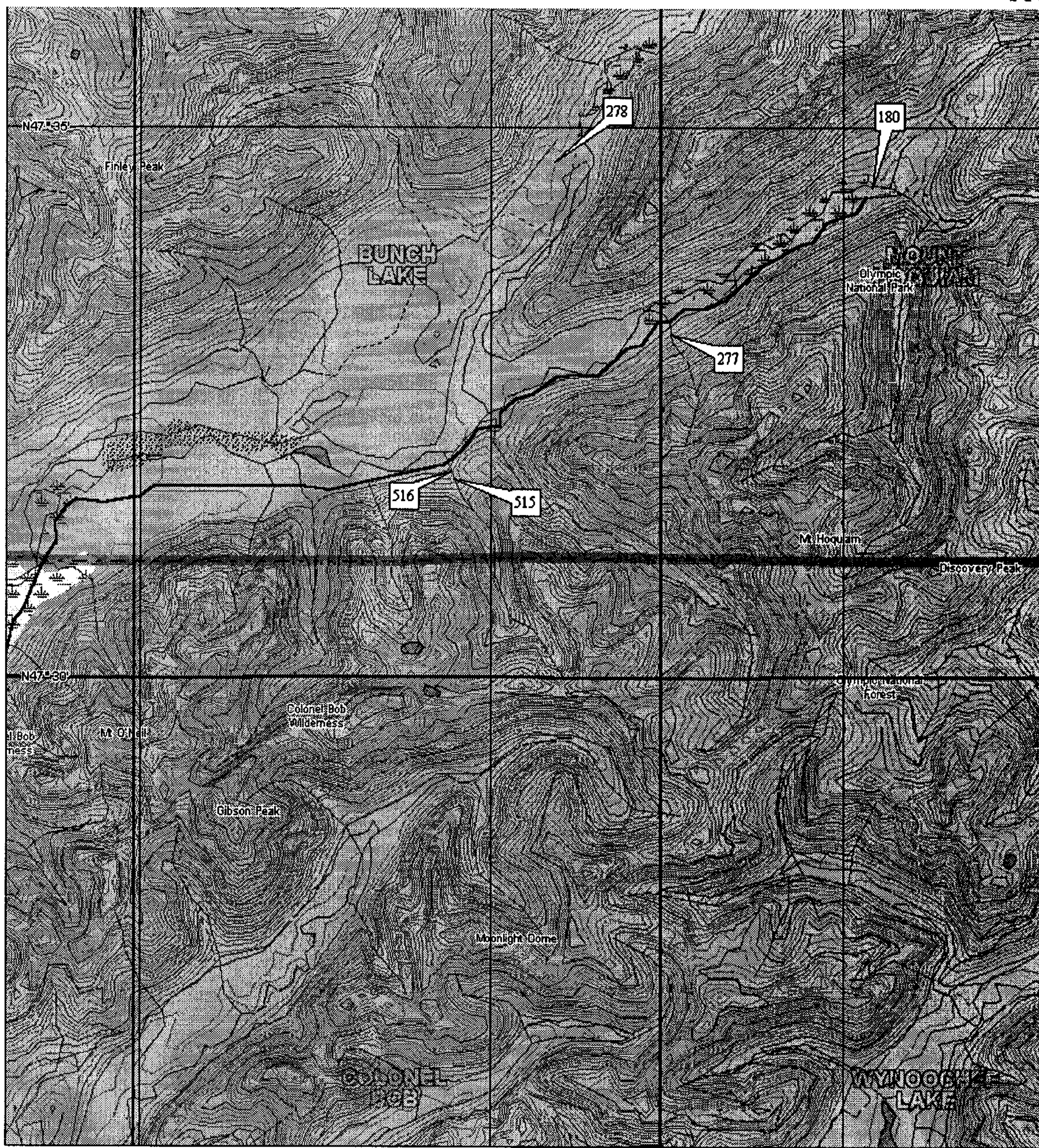


Ohanepecosh River and Tributaries, Mt. Rainier N.P.

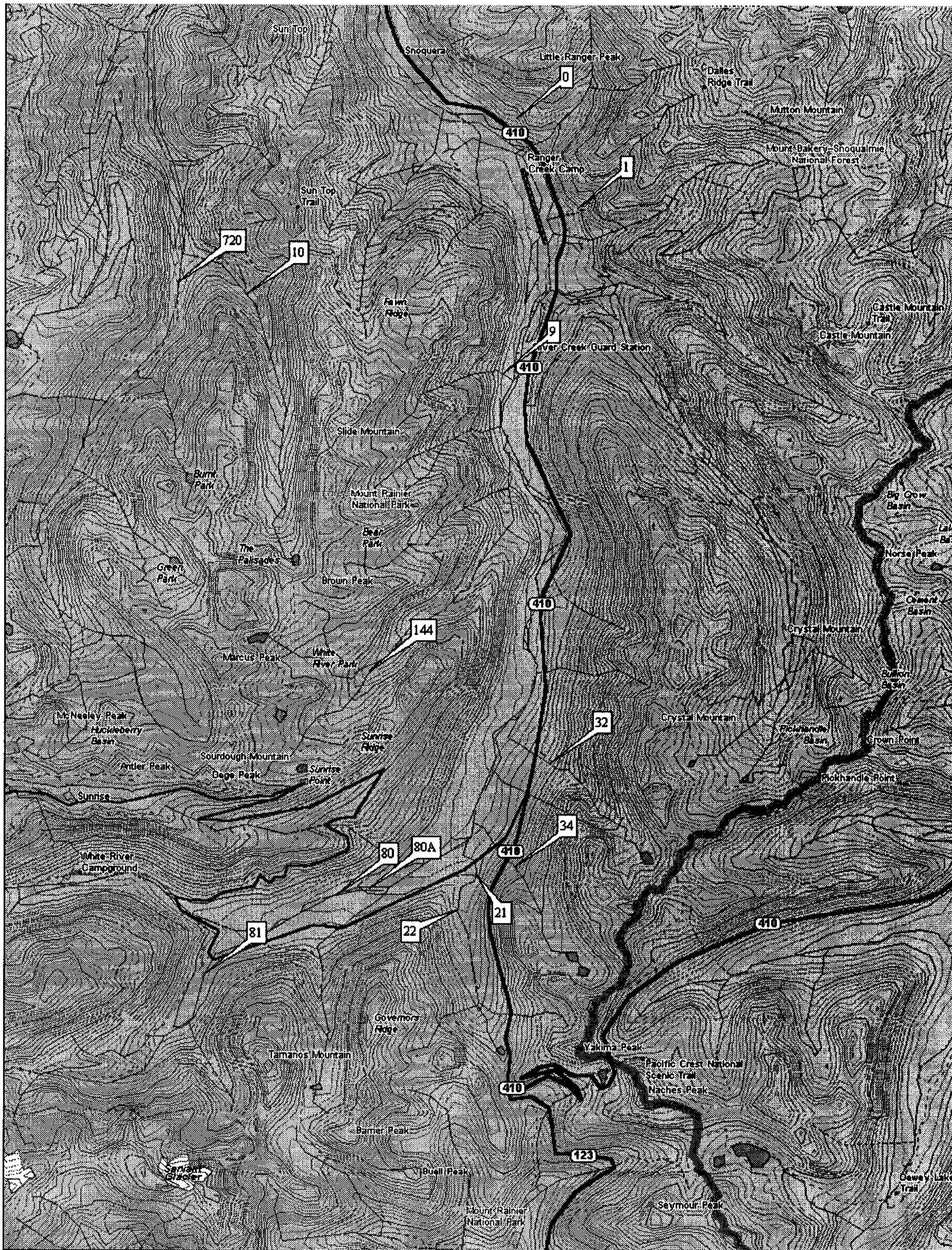


3-D TopoQuads Copyright © 1999 DeLorme Yarmouth, ME 04096 1000 ft Scale: 1 : 46,875 Detail: 12-1 Datum: WGS84

Queets R. and Sam's Creek, western Olympic Peninsula



Quinault R. and Tributaries, western Olympic Peninsula



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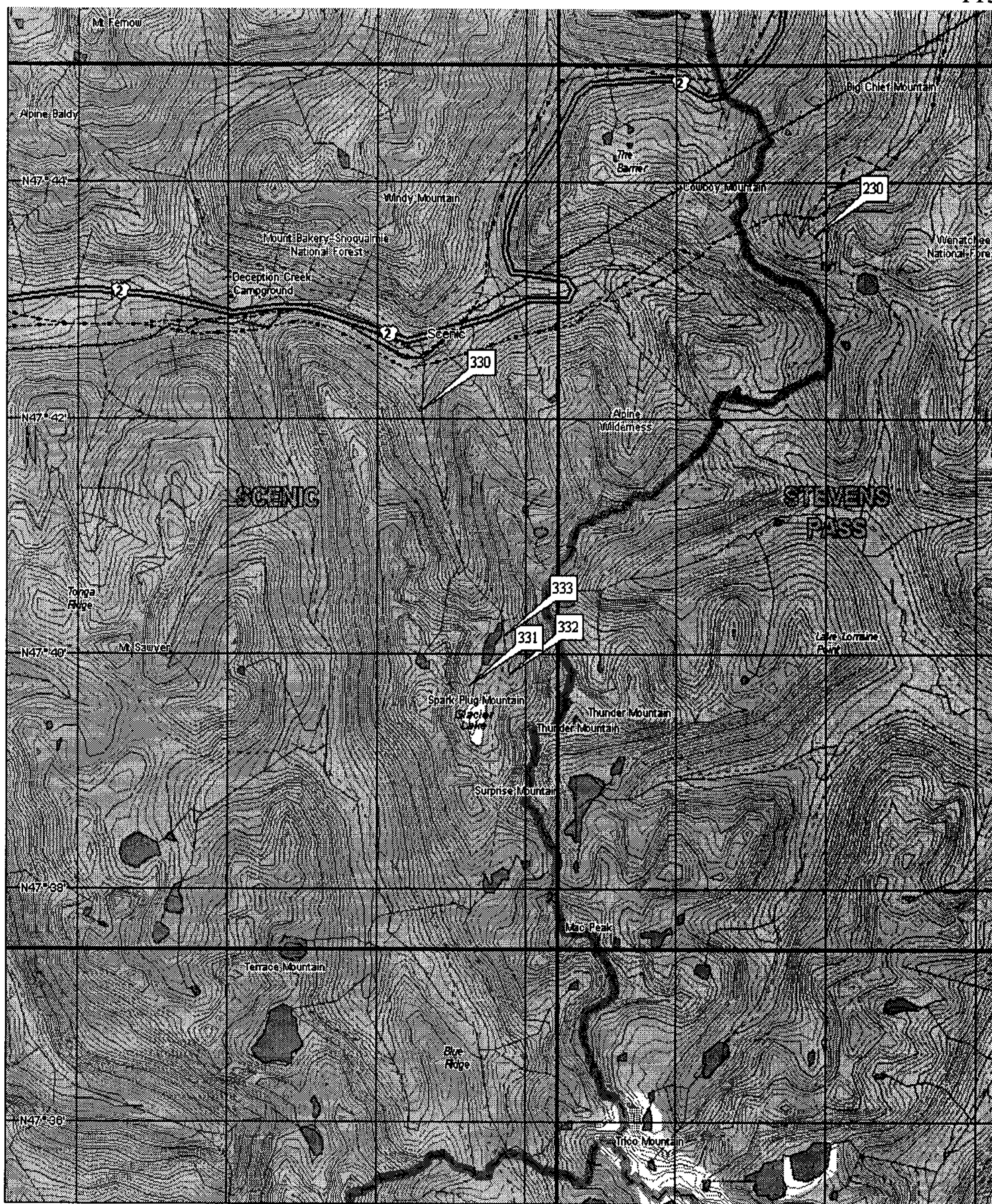
Ranger Creek and White River, NE of Mt. Rainier N.P.



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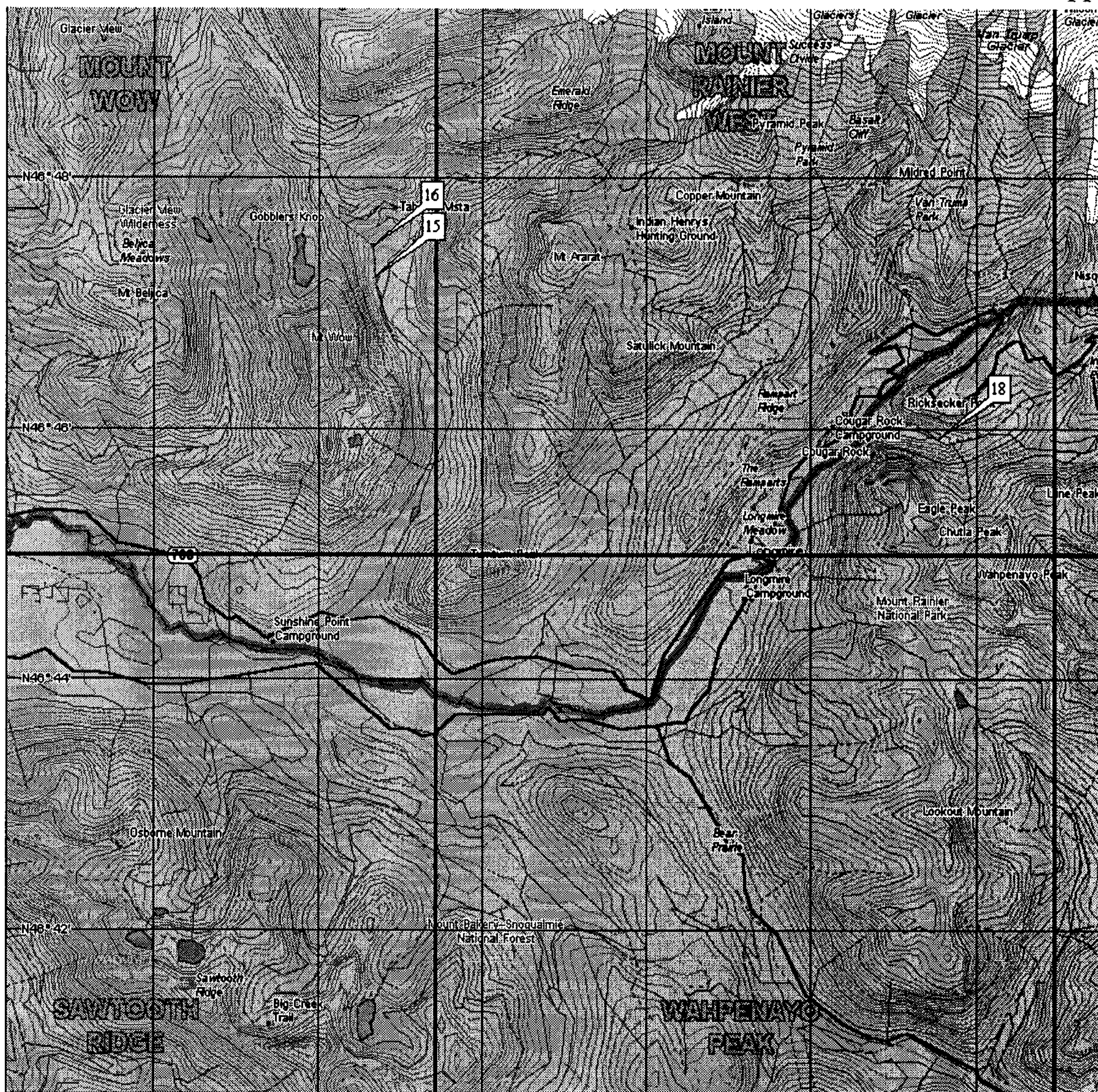
Stevens Pass Area



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3000 ft Scale: 1 : 100,000 Detail: 11-0 Datum: WGS84

SW Mt. Rainier N.P.

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2000 ft Scale: 1 : 81,250 Detail: 11-0 Datum: WGS84

Trinity area and the Chiwawa R., and the White River, Glacier Peak Wilderness.

Washington Pass Area, North Cascades

White Chuck, Suiattle area and the N. F. Sauk River

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5000 ft Scale: 1 : 175,000 Detail: 10-2 Datum: WGS84

NF. Sauk, Sloan and Cadet Creeks

Boulder River Wilderness

Vita

The great-grandson of Columbia Basin pioneers, Martin Fox was raised in Kennewick Washington with an appreciation for salmon and rivers, along with a historical perspective of changes to their habitat. He earned a Bachelor of Science degree in Fisheries Biology from the University of Washington in 1986, and a Master of Science degree in Forest Engineering and Hydrology in 2001, and a Doctor of Philosophy in Forest Engineering and Hydrology in 2003, also from the University of Washington. He has spent much of his professional career working for the Muckleshoot Tribe, tasked with salmon habitat protection. Currently, he lives with his wife, Cindy, near Roslyn Washington. Current publications include the following:

Fox, M.J., Bolton, S., Conquest, L. 2003. Reference conditions for instream wood in western Washington. *In* Restoration of Puget Sound Rivers. Edited by Montgomery, D.R., S.M. Bolton, and D.B. Booth. University of Washington Press, Seattle.

Fox, M.J. 2001. A new look at the quantities and volumes of instream wood in forested basins within Washington State. Master of Science thesis. College of Forest Resources, University of Washington, Seattle.

Fox, M. 1997. Fish Habitat Assessment, in Upper Green River and Sunday Creek Watershed Analysis. Plum Creek Timber Company, L.P., Seattle, WA

Fox, M., and E. Cupp. 1996. Fish Habitat Assessment, in Lester Watershed Analysis. Plum Creek Timber Company, L.P., Seattle, WA

Schuett-Hames, D., Pleus, A.E., Ward, J., Fox, M., and Light, J. 1999. TFW Monitoring Program Methods Manual for the large woody debris survey. Prepared for the Washington State Dept. of Natural Resources under the Timber, Fish, and Wildlife Agreement. TFW-AM9-99-004. DNR #106. March.