The Role of Large Woody Debris in Lowland Puget Sound Streams and Rivers

By

Derek B. Booth, Ph.D., P.E., P.G.[1]
Martin J. Fox, Ph.D.[2]

September 10, 2004

Center for Water and Watershed Studies
University of Washington
Seattle, WA 98195-2100

[1] Research Associate Professor, Departments of Civil & Environmental Engineering and Earth & Space Sciences; and Director, Center for Water and Watershed Studies, University of Washington, Seattle, WA 98195
[2] Research Assistant, College of Forest Resources, Box 352100, University of Washington, Seattle, WA 98195

1. INTRODUCTION

Wood derived from fallen trees is ubiquitous in many undisturbed stream and river channels, not only in the Pacific Northwest but also in forested landscapes throughout the world. These pieces of large woody debris (LWD) have many roles in these systems, including trapping sediment, diverting low and high flows, and providing cover and shading for aquatic organisms. Although the influence of any particular piece of LWD is difficult to predict and likely to change over time, both functionally and spatially, the collective effects of LWD can be substantial and very persistent. LWD is a key ecosystem component for stream organisms, particularly fish and notably anadromous salmon. It has been part of virtually all temperate Pacific Northwest freshwater systems for many thousands of years, and its role is significant at every life stage of most salmonids.

The recent history of LWD in rivers and streams has been much more varied. The removal of wood from streams (also known as "stream cleaning") was once common practice in the Pacific Northwest (Bisson et al. 1987), particularly between the 1950s and 1970s. To "improve" upstream fish passage, 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). In more urbanized environments LWD is often rare, and for many years any possible benefits of such material were ignored. Instream wood was recognized only for its ability to block culverts or to lodge under bridges. Its presence in the active flow complicated any estimates of roughness or channel capacity, and the scour imparted by associated flow deflections was seen as a threat to bank stability and to orderly channel geometry.

Habitat-restoration efforts have increased dramatically since the early 1980s. In the Pacific Northwest, these efforts accelerated once the importance of woody debris in forming salmonid habitat became widely accepted (Bilby and Likens 1980; Bisson et al. 1987). The paucity of instream wood due to land-use practices and past stream cleaning have led wood-placement projects to become a common method of restoring or enhancing salmonid habitat (Kauffman et al. 1997). The use of LWD has also been incorporated into bank protection, wherein the practice of substituting logs for rock as bank armoring is intended to prevent lateral migration or avulsion (Babakaiff et al. 1997). In some cases, this practice is intended to slow bank erosion rates accelerated by the denudation of riparian vegetation until this vegetation can return. In most cases, however, these measures have been employed to protect a road, bridge, building, property, or other anthropogenic feature located in the floodplain (Nichols and Sprague 2003), largely independent of its ecological effects.

In summary, several factors in recent decades have driven significant reevaluation and revision of the perceptions of LWD:

- Recognition of adverse changes in stream-channel morphology and stability following the removal of LWD that has historically accompanied land-use changes;
- Realization that traditional stormwater management techniques, particularly detention ponds, may not be fully adequate to mitigate the effects of development and other human disturbances on stream channels; and

- Increasing public interest in restored biological productivity, particularly fish, which in turn requires recovery of habitat-forming processes and elements.

To support this reevaluation of LWD, particularly in the context of King County's continuing use of LWD in stream- and river-enhancement projects, this paper has three interrelated goals:

1. To characterize the occurrences and functions of LWD in pre-disturbance rivers and streams of western Washington, spanning both the range of riverine systems and the variety of topographic settings across this region;
2. To describe the variety of influences that changing land use has imposed on the occurrences and functions of LWD, particularly as a result of agricultural practices and urban development in the lowlands of Puget Sound; and
3. To articulate the range of functions that instream LWD might be expected to perform successfully in post-disturbance watersheds, defining targets for future stream-rehabilitation projects that acknowledge the physical and biological changes imposed on rivers and streams by agricultural or urban land uses.

This summary is based primarily on the scientific literature of the past quarter-century, largely but not exclusively from field studies in the Pacific Northwest. It provides a foundation for any subsequent planned discussions that would provide more specific guidance on use of LWD in streams and rivers of western Washington in general, and of western King County in specific.

It is worth noting that even with widespread usage in both scientific and agency literature, "Large Woody Debris" has no universal definition. Although the type of material—logs, branches, rootwads—is generally accepted by all, there are no absolute size criteria for what is sufficiently "large." Minimum diameters of between 10 and 25 cm (4-10 in) are common criteria in the published literature (Bilby and Ward 1989; Beechie and Wyman 1992; Montgomery et al. 1995; Schuett-Hames et al. 1999; Fox 2001). The minimum length of LWD, however, has less agreement. Bilby (1984) suggests that any piece shorter than 2 m may be unstable, and Bilby and Ward (1989) counted none shorter than 2 m in their study; Montgomery et al. (1995) counted any piece longer than 1 m; Oregon Department of Forestry (1995) requires a length double to that of the bankfull width. In this report, we will specify minimum dimensions only where necessary for clarity.

2. NATURAL OCCURRENCES AND FUNCTIONS OF LWD IN LOWLAND PUGET SOUND STREAMS AND RIVERS

2.1. Ecology of Puget Lowland forests

Regionally, climatic variations control the characteristics of forest vegetation, which in turn influence the nature of the riparian vegetation and thus the long-term source of inputs of LWD to rivers and streams. These climatic variations 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 Washington has unique differences. Local climate and fire history of these forest zones influence species diversity as well as other stand attributes.

Western Washington forests, the product of our wet temperate climate, are typically dense naturally long-lived conifers and 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 take over 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. Following fire disturbance, Agee and Huff (1987) report that downed fuels (i.e. coarse woody debris) are high within the first 100 years, 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 competition between individual trees 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.

2.1.1. *Upland forests*

Although many unique forest types occur in western Washington, most of King County in pre-settlement time was dominated by either *Tsuga heterophylla* (Western hemlock) forest zones, or at higher elevations the *Abies amabilis* (Pacific Silver fir) or *Tsuga mertensiana* (Mountain hemlock) forest zones. These are described as follows:

The Western Hemlock forests. Generally found in the interior low elevations of western Washington such as the greater Puget Sound and inland SW regions, this forest type is the most extensive vegetation zone in western Washington and once covered most of the area of western King County. The elevation of this forest type is typically less than 800 m (amsl), although this may vary $\pm$ 60 m depending on aspect and local climate differences (Henderson et al. 1992). Dominant tree species are the Western Hemlock with Douglas fir co-dominant (Agee 1993), but large areas are often occupied almost exclusively by Douglas fir (Franklin and Dyrness 1973). The dryer summers in this zone are reflected in a wide spectrum of plant associations (Zobel et al. 1976). Fire frequency intervals are generally less than 750 years, although ignitions from Native Americans may have increased this frequency in some areas (Agee 1992).

The physical characteristics of the timber in the Western Hemlock forest zone are well documented. Spies and Franklin (1991) reported that the average stem densities of Douglas fir (>100 cm diameter at breast height) in late-successional stands ranged from 18-29 trees/ha, while Hershey (1995) reported 6-90 trees/ha of stems >54 cm. Tappeiner et al. (1997) reported basal areas in old-stands range between 46-91 m^2/ha, with a median of 66 m^2/ha.

High-elevation forests. On the west slopes of the Cascade Range, above the level of the Puget Lowland in the headwaters of King County's major rivers, two other forest types predominate. The Silver Fir forest type is generally found at moderate to upper elevations on the west-slope of the Cascades. The typical elevation is between 800-1,200 m (amsl), although this may vary ± 60 m depending on aspect and local climate differences (Henderson et al. 1992). Dominant tree species are the Pacific Silver fir (*Abies amabilis*), with co-dominants of Western Hemlock and Douglas fir at lower elevations and Mountain Hemlock (*Tsuga mertensiana*) co-dominant at upper elevations (Agee 1993). Fire return intervals are estimated to be between 300-600 years but can be more frequent (100-300 years) at lower elevations (Agee 1993). Silver fir trees seldom survive major fires (Agee 1993); thus, fire-return intervals often are times of stand origin.

Overlapping but generally higher than the Silver fir forests are the Mountain Hemlock forests, typically found between 1000-1,375 m (amsl) with variations depending on aspect and local climate differences (Henderson 1992). Dominant climax tree species are Mountain Hemlock, with the Pacific Silver fir and Subalpine fir (*Abies lasiocarpa*) as co-dominants (Agee 1993). Fire-return intervals are estimated to be around 500 years (Dickman and Cook 1989).

2.1.2. *Riparian forests*

In much of the forestry literature, riparian forests are characterized with general forest attributes only. However, significant distinctions are likely to exist between upland and riparian stands. Naiman et al. (1998) reported that the basal area of riparian forests is generally as great as or greater than that of upland forests; riparian forests have relatively high rates of biomass production in comparison with upland forests, likely influenced by moisture, nutrients, and temperature gradients. Riparian forests often promote deciduous seral species regeneration in response to channel-associated disturbances (Naiman et al. 1998). Collins et al. (2003) tallied the occurrence of tree species along the major rivers of western Washington as reported in surveyors' notes from the mid- to late 19th century; they found an average of 84% hardwood species by stem count and about 55% by biomass, particularly from the presence of red alder (*Alnus rubra*). This contrasted to the dominance of Douglas fir and Western Hemlock on adjacent upland terraces, together with a significant component of riparian western red cedar (*Thuja plicata*). Finally, Gregory et al. (1991) and Pollock et al. (1998) found that microclimate gradients also contribute to greater plant and animal species diversity in riparian forests than in upland forests. Riparian forest structures and characteristics are thus apparently different from, and generally more productive than, typical upland forests.

2.1.3. *Natural cycles of growth and recruitment of riparian trees in streams and rivers*

Geomorphic processes, disturbance patterns, and regional climate differences influence the structure and composition of riparian forests, both spatially and temporally. Geomorphically, the effects of fluvial activity are predominantly associated with large rivers, because smaller streams do not have the same energy and consequent rates of channel migration and bank erosion sufficient to affect large swaths of riparian forest. In contrast, 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). During periods of high flows, channel avulsion, accelerated lateral migration, and bank landsliding can topple trees from riparian areas (Johnson et al. 2000). Deciduous trees typically are first to colonize riparian areas following disturbances, whose causes can be both direct channel action and debris flows (Grant et al. 1984; Wilford et al. 1998) or 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 disturbances in riparian areas include wind throw, insect infestations, drought, disease, ice storms, and fire. Fire is a particularly 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).

In riparian stands that are completely replaced by a new generation following fire, succession as the trees mature is an important process that selectively thins stands, which in turn recruits wood into streams (often referred to as the "stem exclusion stage"). This occurs in stands <220 years old (Rot et al. 2000). Trees recruited to a stream by stem exclusion are likely to be smaller than the surrounding forest, since they have been out-competed by larger, more dominant trees. This may also explain why measured instream LWD volumes increase as stands become older, since the recruited trees are larger (Fox 2001). Data from Tappeiner et al. (1997) and Rot et al. (2000) suggest that instream wood is influenced by riparian characteristics, particularly tree diameter. Since tree age is strongly correlated with mean tree diameter and basal area (a function of diameter and stem density), one would expect greater LWD volumes to be recruited to channels with older riparian timber.

The relationship of riparian age to LWD quantity follows general principles of stand dynamics. Fox (2003) found a relationship between instream wood loads and riparian stand age as a good indicator of succession. In that study, the distribution of number of LWD pieces by age class suggested that stem-exclusion processes provide large initial inputs of wood over the first 150 years (Figure 1A and 1B). Wood recruitment (piece number and volume) is relatively low as stands mature over the next 400 years, after much of the stem-exclusion process has occurred but before age-related mortality takes place. This figure also suggests that as late-successional processes approach completion at approximately 550 years, the mortality of the remaining older seral species becomes most 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 (Figure 1A), as well as the fact that these large trees are likely to be more stable and resist entrainment, and so more readily accumulate 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 seemingly paradoxical decrease of instream LWD abundance.

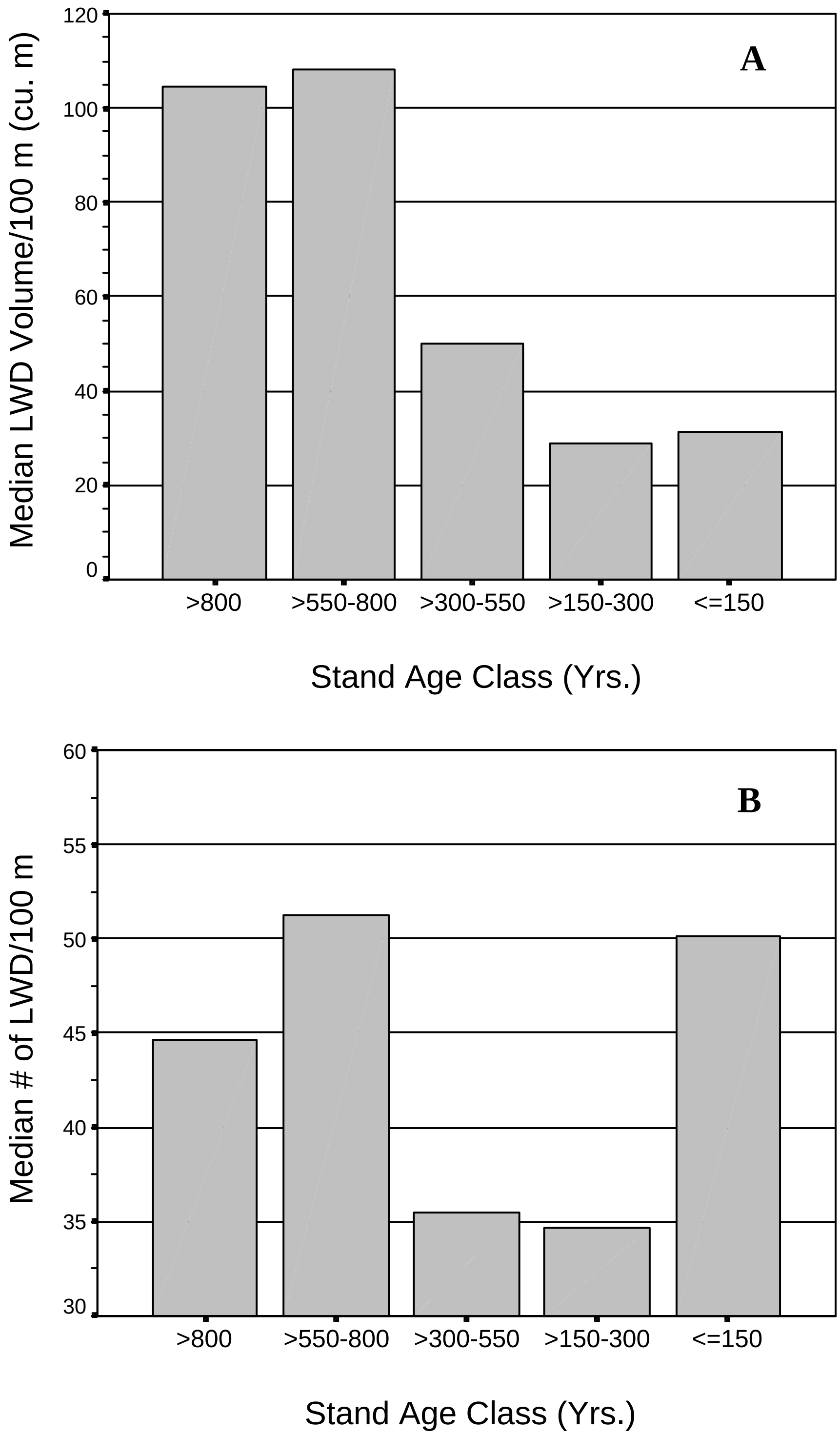

Figure 1. The median instream LWD volume (A) and number of pieces (B) according to adjacent riparian stand age class, at the time of the 1999-2000 surveys. (Age data source: courtesy of Jan Henderson, unpublished data, USDA Forest Service). Source: Fox (2003)

These findings for instream wood loads are consistent with the tree mortality patterns reported by Agee and Huff (1987) and Huff (1995), suggesting that instream wood recruitment patterns associated with stand age are analogous to coarse woody debris delivery to the forest floor. 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 1B. 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 years) may reflect previous large flood(s) that have depleted instream wood loads while "re-setting" the riparian 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 newly regenerated stands.

2.1.4. *Sources and variability of instream LWD loads*

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 suppression or exclusion of stems by overcrowding, wind throw, disease, old age, and the result of fluvial processes such as channel avulsion or lateral migration and bank erosion. Other processes such as debris flows and snow avalanches can deliver trees into downstream channels from steeper parts of the channel network (Cushman 1981; Grant and Swanson 1995). The river can also exhume buried wood within floodplains (Fetherston 1995). Ultimately, 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).

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 riparian source—thus nearly half of the instream wood may be routed in from upstream sources. Clearly, instream wood loads are dynamic and fluctuate according to various natural processes at the reach and watershed scale. The following paragraphs elaborate on these processes.

Geomorphic influences. Channel size influences the quantity of instream wood, but few studies have systematically explored that variability. In streams draining basins fully unaffected by human activity (i.e. no timber harvest or other management, except regional fire suppression), Bilby and Ward (1989) found that mean length and diameter of wood pieces increased as channel width increased but that the number of pieces declined with increasing channel width. Their frequencies of instream wood decreased by almost an order of magnitude, ranging from 0.8 pieces/m in the smallest channels to 0.1 pieces/m in their largest systems. Over a broader range of channel sizes, Fox (2001) found an increase in LWD piece numbers and volumes as channels increase in width: 0.38 pieces/m in the smallest channels (>0-6 m BFW) and 2.08 pieces/m in the largest rivers (30-100 m BFW).

Fox (2001) observed that small channels, and confined channels of any size, are likely to obtain a significant proportion of riparian trees for instream wood by bole breakage and passive tree mortality, rather than by active recruitment such as lateral migration or channel avulsion common to larger rivers. He observed that confined reaches often had resistant banks, which likely slow the rate of avulsion as compared to banks composed of unconsolidated material or floodplain sediments. Due to the resistance to lateral migration, trees adjacent to these channels are afforded greater intervals between disturbances and thus have the potential to grow older and perhaps larger. As a result, confined channels often have greater potential to recruit fewer but larger trees than unconfined channels, where lateral migration across the floodplain limits tree growth.

Natural disturbance. Instream wood loads vary over space and through time due to an array of natural disturbance processes. Wood accumulations thus are not constant but rather fluctuate with disturbance cycles. The amount of instream wood, therefore, represents the time since the last disturbance and conditions during the recovery period. Four types of disturbances commonly found in forested streams of western Washington are discussed below:

Fire**—**Disturbances that kill some or all the vegetation in a particular location, such as fire, are an intrinsic part of ecosystem development (Raup 1957; Oliver 1981). The return intervals for fires vary by ecoregion (Agee 1993) and affect timber age (Henderson et al. 1992). Timber age in turn influences mean tree diameter and thus the diameter of instream wood (Rot et al. 2000). Timber age also influences tree height (Agee 1993; Henderson et al. 1992), and wood recruitment distance is a function of height (McDade et al. 1990). Thus fire affects both LWD diameter and zones of recruitment.

Fires do not burn forests evenly. Patches of timber unscathed by a fire (often termed fire refugia) can diversify timber ages along stream riparian areas. Camp et al. (1996) found that late-successional fire refugia were more commonly found on north-facing slopes. In some cases, only the understory is subject to fire mortality, leaving the dominant trees (Agee 1993).

Floods**—**Floods recruit LWD by bank erosion and channel avulsion, and by entraining wood from areas adjacent to stream reaches during floodplain inundation. Palik et al. (1998), for example, found an average of 22 new trees/km recruited into a coastal plain stream during a large flood. High flows associated with floods increase the shear stress and buoyancy on instream wood and carry wood downstream or perhaps completely out of a system. Braudrick and Grant (2000) found that wood entrainment is a primarily a function of piece angle relative to flow direction, the density of the log, and its length and diameter. Intact root wads, however, inhibit LWD movement by anchoring logs to the streambed, increasing drag and thus decreasing mobility (Abbe and Montgomery 1996).

Despite the potential mobilization of wood due to floods, Fox (2001) found that floods had little influence on the overall instream wood loads of natural systems, for two likely reasons. First, much of the wood in these systems has previously resisted mobility during large floods, as broadly interpreted by the overall age of pieces (as estimated by decay classifications) found in the channel during the surveys. Even small pieces of wood in some streams had advanced decay that suggests these pieces have prevailed within the system despite floods. Second, floods may replace wood flushed from a system with newly recruited trees. For both reasons, a net loss of wood from floods may not occur in unmanaged basins. In contrast, heavily managed watersheds with altered hydrological regimes may have increased transport of wood without commensurate recruitment due to hardened banks, or conversely the suppression of peak discharges by flood-control dams may be sufficient in itself to reduce or eliminate most recruitment altogether.

Debris Flows**—**Debris flows and landslides are disturbances that affect stream channels and influence the quantity, quality, and distribution of instream wood. The often-violent mobilization of material in channels where this occurs, commonly in the aftermath of fire, logging, or poorly implemented road construction, may either transport wood out of a reach or bring in new wood from upstream sources. Debris flows tend to deposit wood on slopes of 3-6 degrees (approx. 5-10% gradient) (Ikeya 1981; Costa 1984; Benda and Cundy 1990; Fox 2001) and remove it from streams with gradients >10% (Fox 2001). In older forests, large standing trees and instream logs can retard debris flow propagation and reduce the distance that it travels, compared to debris flows in more intensively managed forests (Coho and Burges 1993).

Snow Avalanches**—**Snow avalanches also are natural channel process that recruit wood into streams (Keller and Swanson 1979) and influence the riparian vegetation (Fetherston et al. 1995). Snow avalanche paths are typically less confined than debris flows, and they often form a broad fan where the channel gradient flattens, such as at the channel bottom intersecting with the floodplain of a larger system. Snow avalanches are most common in small headwater channels within the snow zone (Keller and Swanson 1979). Due to the snow-pack buffering of the channel bed, substrates are often undisturbed following a snow avalanche; however, most trees larger than 10-15 cm in the path are sheared off at the level of snow depth (Fox 2001) and delivered to the valley downstream. Although not a significant process in most of the channels in western King County, it is likely a significant upstream source of LWD that eventually moves lower into the channel network.

Wind throw**—**Wind throw is a significant source of LWD recruitment to the stream (Lienkamper and Swanson 1987; Robison and Beschta 1990). In old-growth riparian forests, windthrow does not topple whole trees as much as it recruits a greater proportion of branches and treetops to the channel than in younger riparian stands, especially in areas prone to strong winds or heavy snowfall (Bisson et al. 1987). However, wind-throw accelerates mortality in riparian areas abutting newly harvested forests, disrupting the rate of recruitment to streams (Grizzel and Wolff 1998). A riparian stand's orientation to prevailing winds and soil wetness can exacerbate windthrow (Bisson et al. 1987).

2.2. Quantity and distribution of LWD in streams and rivers

2.2.1. *Historic wood loading conditions in the Puget Lowland*

Historically, wild anadromous fish stocks evolved with stream systems that were obstructed by fallen trees, beaver dams, and vegetation growing in and beside the channels (Sedell and Luchessa 1981). Using historical data, journal accounts, and a relatively undisturbed reach of the Nisqually River, Collins et al. (2002) determined that wood loads in some lowland Puget Sound rivers were ten to over a hundred times greater prior to European settlement.

On an examination of the Stillaguamish River made in August 1879, the Army's Robert A. Habersham reported:

> "….From the head of tide-water to the forks, 17 miles, the current is rapid, and the channel, which is from 125 to 200 feet wide, much obstructed by snags and trees embedded in the bottom, and at six points completely closed by rafts, which have diverted the current so as to cut out minor channels, forming small islands.…The snags are numerous and large, and so deeply imbedded in the bottom that a steam snag-boat would be required for five or six months to open a channel 100 feet wide…" [U.S. War Department 1881 *in* Collins et al. 2002)

The presence of wood and large jams influenced channel meandering and width to a great degree. As R.H. Thomson reported from the Puyallup River (in Roberts 1920):

> "The presence of drift and the constant formation of jams prevents the maintenance of a permanent channel. These jams force the river from one side to the other and cause the river to erode a very wide channel. As an example of this might be mentioned that portion of the river between the point of emergence from the foothills and a point 4,000 feet below the Northern Pacific bridge, where the channel ranges in width from 1,000 to 2,500 feet. In the lower river the cutting is continually occurring on the outside of all sharp bend, with a result that the channel has a width of from 1,000 to 1,500 feet in many places."

The amount of wood was so abundant and well-lodged into riverbeds that logging and upstream settlement was stymied until settlers and the Army Engineers could pull, blast, and cut wood from rivers in the 1870s-1890s (Sedell and Luchessa 1981). Collins et al. (2002) found reports between 1889 and 1909 that the annual maximum diameter of removed logs ranged from 3.6 to 5.3 m (U.S. War Department 1889–1909), based on snagboat captain's records and confirmed by engineers' observations (e.g., U.S. War Department 1895).

2.2.2. *Quantities of instream LWD*

The composition and character of riparian vegetation can dictate the species composition, numbers, size, and volume of LWD recruited to the channel, and lateral and vertical distribution of that LWD within the channel (Grette 1985; Bisson et al. 1987; Bilby and Wasserman 1989; Bilby and Ward 1991; Ralph et al. 1994; Bryant and Sedell 1995; Bilby and Bisson 1998; Fox

2001). Factors that influence the spatial distribution of instream wood include both regional context and local geomorphic setting.

Regional context. Regional factors influence the quantities of wood in a system but do not appear to vary their spatial organization. Fox (2003) found that forest regions did not have a pronounced effect upon the grouping or clustering of LWD pieces, which were proportionally the same in streams of similar widths regardless of forest type. Based on data from unmanaged western Hemlock forests, the dominant forest type in King County, observed LWD quantities are given in Table 1 and Figure 2, using data only from fully unmanaged watersheds. The watersheds in this data set are characterized by forests that are all 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 according to 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. Some of these basins may be "managed" to remain pristine, however, which may also include fire suppression.

Table 1. Summary of percentile distribution statistics for instream wood quantity and volumes according to BFW classes for undisturbed western Washington watersheds, based on the box plots in Figure 2. LWD is defined as a piece >10 cm diameter and >2 m in length. Volumes are estimated by $\Pi r^2 L$ where L is the piece length, and r is the piece radius at the mid-point. n= the number of reaches sampled. Source: Fox (2001)

LWD Piece Quantity: Number of Pieces Per 100 m of Channel Length

BFW Class	75th Percentile	Median	25th Percentile	Standard Deviation	Range	n
0-20 ft (0-6 m)	38	29	26	16	68	19
>20-100 ft (6-30 m)	63	52	29	33	132	43
>100-330 ft (30-100 m)	208	106	57	127	4353	16

LWD Volume: Cubic Meters Per 100 m of Channel Length

BFW Class	75th Percentile	Median	25th Percentile	Standard Deviation	Range	n
0-30 m	99	51	28	62	285	62
>30-100 m	317	93	44	201	750	16

Key Piece Quantity: Number of Pieces Per 100 m of Channel Length

BFW Class	75th Percentile	Median	25th Percentile	Standard Deviation	Range	n
0-10 m	11	6	4	6	26	38
>10-100 m	4	1.3	1	3	18	40

Table 1 (cont.)

Minimum Piece Volume to Define Key Pieces (all regions)

Bankfull Width Class	Minimum Piece Volume (m^3)
0-5 m	1*
>5-10 m	2.5*
>10-15 m	6*
>15-20 m	9*
>20-30 m	9.75
>30-50 m	10.5**
>50-100 m	10.75**

* Existing WFPB (1997) definitions   ** Wood piece must have an attached root wad.

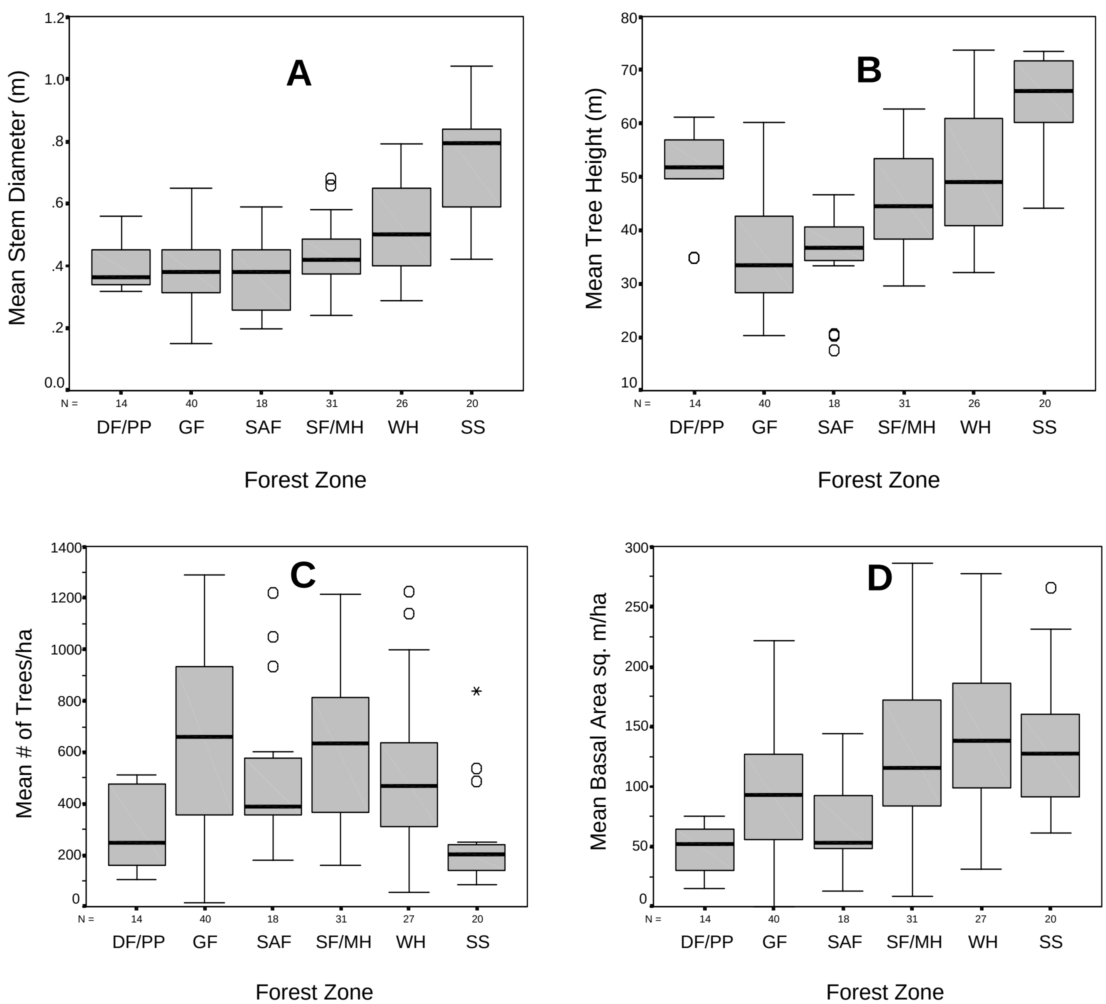

Figure 2. Box plots from unmanaged watersheds of (A) mean riparian tree diameter (m) at breast height (dbh), (B) mean tree heights of the upper riparian canopy, (C) mean number of stems per hectare, and (D) mean basal area per hectare, each grouped by forest zone: SS= Sitka Spruce, WH = Western Hemlock, SF/MH=Silver Fir/ Mountain Hemlock, SAF=Sub-Alpine Fir, GF= Grand Fir, DF/PP=Douglas Fir/ Ponderosa Pine. The forest zones applicable to western Washington are the SS, WH, and the SF/MH zones. Source: Fox (2003)

Geomorphic factors. Geomorphic factors such as channel size, gradient, confinement, bedform, origin, and reach morphology can also influence instream wood quantity and organization. Keller and Swanson (1979), Swanson et al. (1982), Bisson et al. (1997), Bilby and Bisson (1998), and Fox (2003) have observed that wood becomes more clumped as streams become larger. Fox (2001) reported that wood volume per 100 m increases as channels become wider, and that greater volumes per 100 m occur in unconfined streams than in confined streams. Bedforms are another geomorphic influence upon wood distributions. Fox (2001) reported that in all but the smallest basins (<4 km^2), more wood volume was observed in confined alluvial channels as compared to confined bedrock channels. In basin draining 70 km^2 or more, streams originating from glacial sources have more wood volume per 100 m than streams fed predominantly with snowmelt and rain (Fox 2001). This may be related to the larger number of side channels in streams originating from glacial sources. Montgomery and Buffington (1997) and Fox (2001) also found that pool/riffle channels commonly exhibit greater volume per 100 m than plane-bed, step-pool, or cascade morphologies.

2.2.3. *LWD accumulation sites in channels and floodplains*

Wood accumulations vary by channel size. In small channels, wood can be found virtually anywhere in and along the channel. Small streams lack the power and buoyant forces to mobilize wood, creating a nearly random distribution dictated by riparian inputs: wood tends to remain in the locations "as it fell," and attrition of these pieces often occurs only during large episodic events (floods, debris flows, dam-break floods, etc.) or through decay. In large rivers that are many times as wide as LWD is long, however, wood accumulations are primarily organized by fluvial forces. Abbe et al. (1993) and Abbe and Montgomery (1996) categorize these large-river LWD accumulations based on the presence or absence of key members, source and recruitment mechanism of the key members, jam architecture, the jam's geomorphic effects, and patterns of vegetation on or adjacent to the jam. Abbe et al. (2003) et al. describe these accumulation types and their functions as follows:

> ***Bar apex jams*** tend to be catalyzed by a single key piece oriented parallel to the channel with the root-wad upstream. These jams accumulate racked member and small woody debris against the upstream end of the root wad, slowing the water velocity to enable sand and gravel deposition along the key piece, ultimately forming a gravel bar. Bar apex jams are responsible for much of the channel complexity, including island and pool formation, in these systems. They are a principal mechanism contributing to the formation of anastomosing channel systems in the Pacific Northwest.
>
> ***Step jams or multi-log weirs*** are found in relatively small channels with a wide range of gradients. These structures can account for more than 80% of the head loss in a channel (Abbe 2000) and provide almost all of the hydraulic and habitat diversity within the channels where they occur.
>
> ***Valley jams*** are large, complex grade-control structures found in steep channels with gradients ranging from 2 to over 20%. These structures are typically composed of tens or hundreds of trees.

Bench jams are typically found in relatively small, steep channels where large logs become wedged into the margins of a channel and create local revetments protecting floodplain deposits and vegetation.

Flow deflection jams are found in relatively large channels with moderate gradients. These structures form initially when large trees (key members) fall into the river and deflect flow. But with time these structures become integrated into a new river bank and are thus classified as bank protection or revetment-type structures as opposed to flow-diversion structures.

Meander jams are large flow-diversion channels found in large alluvial rivers. As the channel laterally migrates, meander jams form hard points or resistance along the bank, thus impeding bank erosion (Daniels and Rhoads 2001). These structures offer a model that has been successfully emulated to limit channel migration, protect banks, and restore aquatic habitat and riparian forests (e.g., Abbe et al. 2003). Natural meander jams are a principal cause of channel avulsions in Pacific Northwest rivers, in that arrest of gradual lateral migration can eventually lead to abrupt channel switching in natural systems.

2.2.4. *LWD in small vs. large channels*

LWD quantities and geomorphic function vary by stream size. Although small channels have less wood per unit length than large channels, LWD in small channels have a particularly critical role in storing sediment. In the absence of wood, channels scoured to bedrock by a debris flow may lack the capacity to store sediment and can persist in a bedrock state (Massong and Montgomery 2000; May and Gresswell 2001). May and Gresswell (2001) concluded that with an adequate supply of wood, low-order channels can store large volumes of sediment in the interval between debris flows and can function as one of the dominant storage reservoirs for sediment in the channel network. Fox (2003) observed that sediment storage by wood residing in the low flow channel was highest in small streams. Wood in small channels is also a strong determinant of geomorphic channel type at moderate stream gradients, controlling whether a forced pool-riffle or plane bed channel morphology will occur along particular reaches of a channel network and determining much of the physical attributes of the channel of ecological significance (next section).

Large channels and their associated floodplains also are geomorphically influenced by wood, but in different ways. Compared to smaller streams, Bilby and Bisson (1998) observed that wood has less effect on channel form in larger streams. LWD jam accumulations located in the floodplain, however, reduce flood velocities and provide foci for side channel development, sediment storage, and valley formation (Prestegaard and Folk 2001). Wallerstein et al. (1997) found that debris-induced sediment retention tends to exceed debris-induced channel scour, indicating that debris jams generally achieve net sediment storage along the channel reach.

2.3. Ecological characteristics of LWD in lowland Puget Sound streams and rivers

2.3.1. *Physical processes*

Effect on stream morphology. Instream wood influences stream morphology 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), creating structural heterogeneity and thus fish habitat via pools, back eddies, side channels, alcoves, and increased channel sinuosity (Bisson et al. 1987, Spence et al. 1996). LWD deposited in the active channel and floodplain provides sites for vegetation colonization, forest island growth and coalescence, and forest floodplain development (Fetherston et al. 1995; Bilby and Bisson 1998).

The linkage of pool formation to instream wood is omnipresent in the literature. Bilby and Bisson (1998) note that LWD is a primary determinant of channel form in small streams, creating pools and waterfalls and affecting channel width and depth. Evans et al. (1993) found that more wood was present in pool than in non-pool sections of old native forest streams and the frequency of pools per unit length formed by woody debris was greatest in these streams. Nakamura and Swanson (1994) report that the amount of coarse woody debris and the number of pool-forming pieces are relatively high in wide, sinuous reaches, where a complex structure of floodplains and riparian forests develops in association with a braided channel pattern. Pool spacing (expressed as the number of channel widths between pools) decreased as the number of LWD pieces increased, with the strongest relationship in moderate-slope (>2% and <5%) channels (Beechie and Sibley 1997). Gurnell and Sweet (1998) found an overall decrease in the number and size of pools along a section of small stream that was cleared of LWD dams over a 14-15 year period. Clearly, instream wood is strongly and positively associated with pools. Analytical predictions of the formation of pools by scour around LWD, however, are still fairly rudimentary and show only fair correlation with field data (e.g., Wallerstein 2003).

Wood-formed pools potentially provide better physical habitat for coho salmon (*Oncorhynchus kisutch*) than rock-formed pools. Kaufmann (1987) reported that the area of low-velocity habitats increased with discharge in channels with woody debris, but they were static with discharge in channels around rocks. Because juvenile coho are known to prefer low-velocity habitats, especially for winter rearing, wood may provide more favorable rearing areas than rock. Bilby and Ward (1991) reported that larger pieces of wood more frequently formed plunge pools than smaller wood in small channels, and larger quantities of wood retained larger quantities of organic matter such as fine woody debris and detritus. LWD-formed plunge pools contained the largest coho than other pools in four western Washington streams. Bisson et al. (1981) and Herger et al. (1996) found the most cutthroat trout (*Salmo clarki*) biomass in wood-dammed pools in small Rocky Mountain streams.

Energy dissipation. LWD dissipates flow energy, which is an important feature of good salmonid habitat. By slowing water velocities via pool formation and turbulence associated with flow deflection, LWD aids metabolic conservation (Bustard and Narver 1975). Angermeier and Karr (1984) found that LWD removal in a small stream was followed by increases in current velocity. Dudley et al. (1998) measured water slope, velocity, and depth in a channel prior to and following the removal of woody debris and found that the average Manning's n value was 39 percent greater, and thus the average velocity correspondingly slower, when woody debris was present. McMahon and Hartman (1989) found that coho salmon would emigrate during a simulated freshet unless low-velocity habitat created by wood was present.

Sediment retention. LWD retains sediment in stream channels of all sizes, but position and orientation determine the effectiveness. Fox (2003) observed that LWD closest to the active channel stored the most sediment, and that pieces with the large ends influencing the high-flow channel more commonly stored sediment than pieces with the small ends influencing the high-flow channel. These patterns are probably a consequence of stability and the frequency with which the LWD interact with channel flow. Perpendicular pieces generally stored more sediment than parallel pieces. LWD can form dams that in turn create pools and sediment traps; for example, O'Conner (1986) found that organic debris dams retain sediment on their upstream side and retard the rate of material transport downstream.

2.3.2. *Chemical processes*

Far less work has been done on the influence of LWD on the chemistry of rivers and streams than on their physical conditions, most likely reflecting the historic focus of land and fisheries managers independent of whether that emphasis is warranted. Despite the relative paucity of published information, several aspects of the chemical influence of LWD have been explored in some detail.

Input of organic matter from forests to streams. LWD is a source of organic matter to the stream. Wood provides favorable instream biological conditions for nutrient loading (Naiman and Sedell 1979; Wei and Kimmins 1998), and it provides nutrients and food sources directly to aquatic biota (Bilby and Likens 1980; Bisson et al. 1987). Several types of organic matter pass regularly from forests to streams; leaf litter and woody debris, in particular, are important sources of carbon for stream ecosystems (Malanson and Kupfer 1993).

Role of LWD in trapping nutrients. Wood traps nutrients in streams. Experiments by Aumen et al. (1990) in recirculating chambers showed that woody debris and cobbles exhibited higher nitrate and phosphate uptake per unit surface area than sand/gravel or fine particulate organic matter, probably because the relative stability of woody debris and cobbles makes them more suitable for colonization by heterotrophic microorganisms and algae. Although wood probably does not strongly influence nutrient retention at the reach level because of its low surface area relative to other substrates, these authors note that wood may be locally important at small spatial scales because of its high uptake activity. Wallace et al. (1995) found that at log-addition transects, coarse and fine particulate organic matter increased dramatically and invertebrate community structure changed significantly.

Wood also retains other organic material in the form of leaves, needles, and small woody debris (SWD) delivered from the adjacent riparian areas. This material serves as an important food source for invertebrates in the stream, which ultimately generates food for salmonids. LWD formations trap leaf packs and other accumulations of organic matter by retarding flow, creating depositional zones (Bilby and Likens 1980). Bilby and Likens (1980) also found that the removal of all organic debris dams from a 175-m stretch of a second-order stream of the Hubbard Brook Experimental Forest in New Hampshire led to a dramatic increase in the export of organic carbon from this ecosystem.

Organic nutrients in Pacific Northwest stream ecosystems can be locally dominated by salmon carcasses in systems with large anadromous fish runs, and LWD has an important function in the retention of those carcasses (Cederholm et al. 1989; Bilby et al. 1996; Spence et al. 1996). Bilby et al. (1996), for example, reported that up to 60 percent of salmon carcasses can be associated with presence of coarse woody debris.

2.3.3. *Biological processes*

The integration of physical and chemical influences makes LWD a key ecosystem component for stream organisms, particularly fish and notably anadromous salmon. Wood has been ubiquitous in temperate Pacific Northwest freshwater systems throughout the recent evolutionary history of salmon (Pess et al. 2003), and its role is significant at every life stage. Wood provides cover in pools to facilitate summer and winter rearing for juvenile salmonids (Hartman 1965, Bustard and Narver 1975; Murphy et al. 1984, Bisson et al. 1987, Everest and Chapman 1972, Glova 1986, Cederholm et al. 1988, Shirvell 1990, Nickelson et al. 1992), and cover for juvenile downstream migration (Larsson 1985). Wood cover also reduces predation (Bilby 1984; Everett and Ruiz 1993; Nielsen et al. 1994; Peterson and Quinn 1994). It reduces overall bed scour and increases structural heterogeneity via pools, side channels, alcoves, and increased channel sinuosity. These diverse geomorphic conditions provide favorable fish habitat (Larsson 1985; Bisson et al. 1987; Bjornn and Reiser 1991; Schuett-Hames et al. 1994; Reeves et al. 1995). The evidence is overwhelming that anadromous salmon have evolved in consort with abundant LWD in the rivers and streams of the Pacific Northwest, and that the presence of LWD is a key element of their continued survival.

3. EFFECTS OF CHANGING LAND USE ON THE OCCURRENCES AND FUNCTIONS OF LWD

The absence of LWD in developed and developing parts of the world is widespread, even where vast forests once blanketed the landscape (e.g., Wiltshire and Moore 1983; Petts et al. 1989). Hydraulic considerations, particularly land drainage and reduction of flood stage, once motivated widespread removal of riparian vegetation and instream obstructions. On large rivers any logs or snags reduced navigability; on small streams mobile debris can be seen to lodge under bridges and clog culverts. Even anadromous fish were thought to suffer from the migration-blocking effects of LWD accumulations, and so removal was mandated in the Pacific Northwest under commercial forestry permits of the 1970’s and early 1980’s.

3.1. Loss of LWD in small streams

In both agricultural and urban settings, LWD is rarely abundant; more commonly, it is absent altogether. The magnitude of the loss of LWD is best demonstrated by the pattern in progressively more developed watersheds, where the frequency of LWD irregularly but inexorably decreases. Data from Horner et al. (1997) show abundant scatter but a clear general trend (Figure 3)—in all-too-many cases, there is no LWD whatever in the most urban channels. Although not as well documented, similar patterns are visible in agricultural landscapes as well. A number of processes are responsible for this change from undisturbed watersheds:

Human removal—In agricultural streams, this is the most likely mechanism for the loss of LWD. It commonly occurs as a matter of necessity—streams provide drainage for fields that would otherwise tend to revert to the alluvial valley-bottom wetlands that made them potentially suitable for farming (and for few other human uses) in the first place. Hydraulic obstructions such as logs are thus contrary to their intended human activity. For augmenting the goal of enhanced drainage, such channels are also commonly straightened or relocated altogether, creating an initial wood-free condition. Narrow (or nonexistent) riparian buffers eliminate the possibility of LWD replenishment in such settings.

In urban landscapes, the importance of human removal is more difficult to document because land ownership is fragmented and most activities occur in the privacy of individual back yards. Although no controlled studies have been found to document the actions of residential property owners on the persistence of LWD in channels, subjective opinions on the suitability of LWD in streams are becoming especially important as water-resource design increasingly moves out of the forestland (where it has proceeded almost unnoticed for decades) into restoration and rehabilitation of urban systems (where everybody has an opinion).

Despite the paucity of well-controlled data, collective observations suggest a marked correlation between residential backyards and adjacent LWD-free channel reaches that is best explained by intentional removal of debris and subsequent lack of recruitment. Whether motivated by aesthetics or a desire to "improve" the habitat for fish can only be speculated, but related studies suggest that visual appearances are probably of particular importance. Gregory and Davis (1993) asked people to rate the attractiveness of two lowland British streams. They found strong preference for more "natural" channels with clean flowing water and without artificially reinforced or armored banks. However, they also found that woodland channels without LWD were clearly favored over those with woody debris, despite the ecological advantages that such debris in fact provides. Kaplan (1977) found that people already living nearby a stream were more likely to accept more natural, "unkempt" views of a channel than those without that prior experience.

Preferred characteristics of bank vegetation were investigated in more detail by House and Sangster (1991) in Britain, and in a more limited study in King County by Salisbury (1997). House and Sangster found preferences for (1) trees, ideally a deciduous canopy; (2) a multiplicity of understory vegetation that does not encroach on the channel itself; and (3) some degree of vegetation management (e.g., short mown grass rather than long grass). Salisbury found that streambank scenes that included LWD were commonly preferred over those that featured riprap, but that the preference for logs was by no means universal. Those scenes with "grass and brush" or "heavy brush" (Salisbury 1997, her table 10) were most consistently preferred.

Beyond the action of individual homeowners, the past enthusiasm of public works agencies at removing potential culvert-clogging debris from channels is anecdotally well known. The effectiveness of such actions, however, would always have been limited by the minimal length of most urban streams on public right-of-way. Where public stormwater facilities impound a stream itself, however, collection points for large (and small) woody debris are inadvertently created as well. Examples of massive debris removal from around the region, sometimes on an emergency basis to protect the safe functioning of the facility, are known and recounted by many—most recently during the large 1996-1997 winter storms.

In addition to the removal of LWD from the channel, clearing trees from the riparian corridor is a commonly recognized outcome of urban development that affects the future input of wood. Recent analyses of riparian zones show close association between urban development and riparian clearing throughout multiple sites across the Puget Lowland (Booth et al. 2001, Morley and Karr 2002, Segura Sossa 2003).

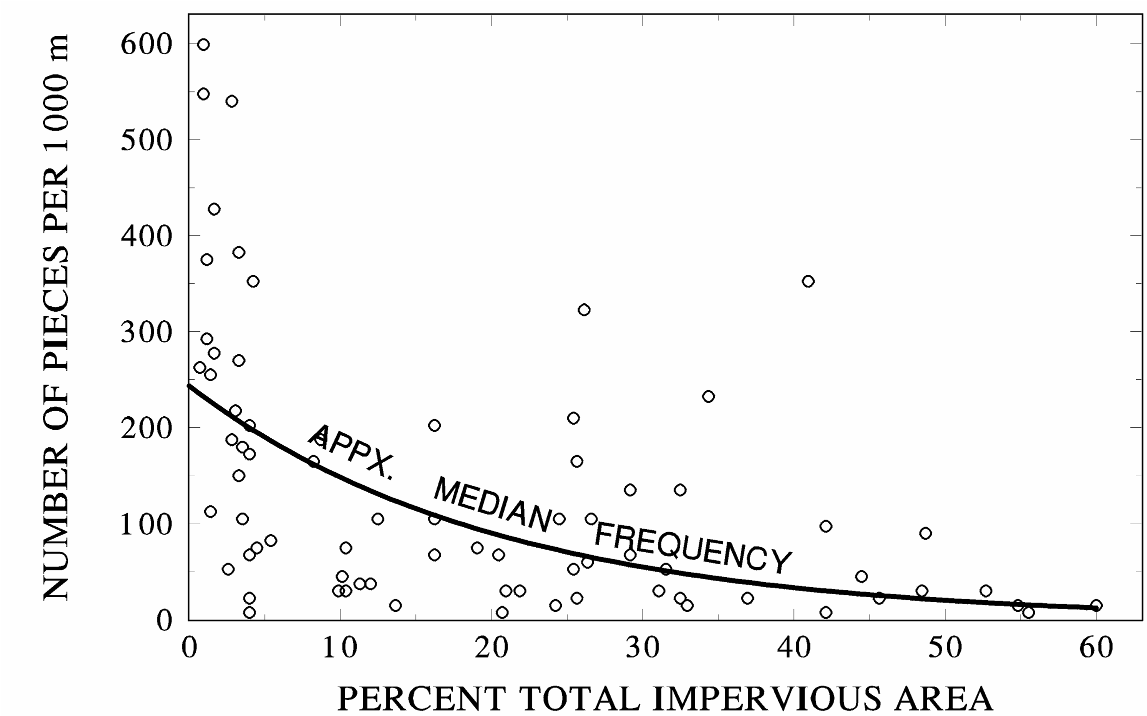

Figure 3. Decline in the frequency of LWD accompanying an increase in urbanization, here measured as the percentage of imperviousness in the contributing watershed. Data from Horner et al. (1997).

***Washout*—**Although increased discharges are not well documented in agricultural settings, they are the hallmark of watershed urbanization. By any measure, the magnitude of urban channel flows increase: using the most common metric, increasing peak discharges, annual and multi-year floods increase by typically two- to five-fold (Hollis 1975), depending on the degree of urban development and the frequency of the flood event. The aggregate duration of flood flows may increase more than ten-fold, as once-rare discharges become more commonplace (Barker et al. 1991). Finally, the frequency of major sediment-transporting events increases by as much as 50-fold, as discharges with a recurrence of five or ten years in the pre-urban condition can become monthly events after full watershed development (Booth 1991).

The consequences of these flow increases include a dramatic increase in frequency of flows capable of removing normally immobile channel obstructions. The change in the flow regime also tends to expand the cross-sectional area of the channel through both widening and deepening (Booth 1990). Local data suggest that the increase in bankfull channel dimensions crudely follows the downstream hydraulic geometry relationships of Leopold et al. (1964), wherein both width and depth increase in fractional proportion to the increase in bankfull discharge (normally approximated in hydrologic modeling by the 1.5-year or 2-year discharge) raised to a power of about 1.4. Thus a 5-meter-wide channel, responding to a two- or three-fold urban-induced increase in two-year discharge, will expand several meters in width and several tenths of a meter in depth, which may expose and undermine most or all of any LWD that was previously well-anchored or buried.

Stranding via channel incision—Where the longitudinal stream gradient has not been established by a nonerosive bed or a fixed base level, a second consequence of the increased sediment transport of an urbanized channel can occur. In the pre-development state, channel gradient can remain stable because sediment transport resistance, sediment supply, and flow energy, integrated over the suite of flows that has moved down the channel, are in balance. Where that balance is disrupted by dramatically increased discharges, downcutting may proceed almost unchecked until a much flatter gradient associated with a deeply incised new channel reduces the competence of the urban discharges (Booth 1990). This can also result from channel straightening in either urban or agricultural settings. The immediate consequence of incision is a deep and narrow channel whose bed has dropped below any LWD that once was in contact with it. The LWD may still be lodged in the bank and so immobile, but it is ineffectually suspended above any contact with the flow. This process is particularly pernicious, for as the incipient incision begins to strand LWD the very source of channel resistance is eliminated and so the rate of downcutting accelerates.

3.2. Loss of LWD in large rivers

In contrast to the multiple causes of low modern LWD loads in small streams, changes in LWD occurrence in the region’s largest rivers has a simple explanation. Removal of wood from the rivers of the Puget Lowland was a major, well-documented endeavor from the late nineteenth century through the mid-twentieth century (Collins et al. 2002). The early part of this period demanded the greatest efforts, because clearcutting of the Lowland was well underway during this time and the rivers were the primary highway for the transport of logs to the mill. A choked waterway was worthless for this purpose. Even after this period of intense logging, removal of hundreds or even thousands of snags per year by the U.S Army Corps of Engineers continued in the region’s rivers through at least 1960 (Collins et al. 2003). Since that time, further such work by state and local road engineering and public works departments has continued but left a much more fragmented, and currently unassembled, record of removal rates.

The consequences of these activities on the occurrence of LWD in lowland rivers of western Washington are best described by comparisons between modern rivers of the Puget Lowland, of which many run for hundreds or thousands of meters with almost no LWD except that sporadically encountered along the banks, and a description of the rivers of the nineteenth century:

> "…channels are strewn with immense trunks, often two hundred feet long, with roots, tops, and all…[forming] jams, which frequently block the channels altogether." (1907 quote from Hiram Chittenden, in Collins et al. 2003)

3.3. Changes in the function of LWD in disturbed watersheds

In the modern streams and rivers of the Puget Lowland, LWD plays both similar and different roles from what is known from undisturbed watersheds. Most importantly, LWD has no role at all in the channels now devoid of wood. These are most commonly in agricultural streams, in highly urban streams, and along much of the large rivers of the region. These channels continue to pass flows, transport sediment, and maintain populations of fish and other organisms, but they do so in ways that are significantly different as a result of their loss of wood. Although specific studies on the effects of wood loss on Puget Lowland watercourses have not been published, broad consequences are readily inferred from the previous sections: pool habitat and instream cover in small streams are much reduced; sediment transport is more vigorous and channels are more prone to incision and further degradation of physical habitat; and the associated loss of forested riparian zones result in altered nutrient and food inputs, increased stream temperatures, and the unlikelihood of any recovery of LWD without intensive management intervention.

Where LWD remains (or has been reintroduced) in smaller urban and agricultural streams, its effects are unlikely to replicate precisely those observed in undisturbed systems. Studies that evaluate the relative influence of watershed-scale and near-stream disturbance, specifically urbanization, on instream biological condition show that both are important (Morley and Karr 2002; Booth et al. in press). Thus a "local" condition such as LWD, even if replicating predisturbance loadings and placement, is very unlikely to create biological conditions equivalent to those of undisturbed systems if the watershed as a whole has been altered. A specific investigation of the biological effectiveness of six LWD placement projects in six urban streams in King County found almost no improvement in a measure of biological health directly resulting from the LWD itself (as evaluated using B-IBI, a multimetric index of benthic macroinvertebrates; Karr and Chu 2000) (Larson et al. 2001). On the other hand, this study also found that increased numbers of pools could be attributed directly to the LWD, in addition to some degree of grade stabilization and an increased volume of sediment retained in the treated reaches. This confirms more anecdotal reports from around the region of visible improvements in physical channel attributes, even in highly urbanized systems, from LWD (see, for example, http://www.ci.seattle.wa.us/util/About_SPU/Drainage_&_Sewer_System/Projects/Creek_Restoration/index.asp).

Altered hydrologic conditions, notably an increase in the frequency and magnitude of high flows, may also change the physical response to LWD, particularly if loadings are sufficient only to deflect flows against erosive channel banks but insufficient to materially reduce the sediment-transporting energy of the moving water through turbulent dissipation. In such settings, a single piece of LWD may paradoxically create more erosion, greater sediment loads, and consequently poorer instream habitat than if it had been absent altogether. This does not contradict the value of LWD, but it serves to remind that a simple "more-is-better" approach needs to be tempered with understanding of what has changed in the watershed as a whole.

In large rivers, the present-day functions of remaining or reintroduced in-channel wood are more difficult to unravel. Conventional wisdom holds that LWD in large rivers is intrinsically less important than that in small channels (e.g., Bilby and Bisson 1998). Although perhaps true in some regards, this attitude may simply reflect the complete modern absence of LWD at predisturbance loadings in the Puget Lowland, and thus our inability to appreciate the functions performed by these now-vanished kilometers-long jams and snags (Collins et al. 2003). LWD still remaining in these larger rivers are likely to perform significant functions only to the extent that they are stable and (relatively) abundant, conditions that are likely only where multiple pieces have been anchored by mechanical means or burial, or where they have been arranged in engineered jams designed to withstand a range of flood flows (e.g., Abbe et al. 2003). In such settings, evidence remains largely anecdotal but suggests that LWD functions can include local protection from bank erosion, local improvement in fish habitat and fish use, and a reduction in the quantity of LWD and SWD drifting downstream (Abbe et al. 2003). To date, however, the volumes of LWD so introduced into large rivers is but a scant fraction of the loadings from predisturbance times, and so the functions of this modern wood can only be shadows of their former effects.

4. APPROPRIATE REHABILITATION GOALS USING LWD IN URBAN AND AGRICULTURAL WATERSHEDS

Virtually all modern stream- and river-enhancement projects have the same overall goal: to improve both human and ecological conditions and functions of the system. In some settings, this has required an emphasis on one or the other of these perspectives—so, for example, a river adjacent to urban development may be managed with the primary objective of minimizing bank erosion to protect adjacent development; a rural stream once-damaged by outmoded logging practices may be rehabilitated with the primary intent to maximize fish utilization. Rare today is the setting where either perspective can be ignored altogether. The increasing use of LWD in stream-enhancement projects has emerged in concert with the increasing emphasis on ecological goals for stream and river projects, even for projects that are motivated primarily by social concerns such as channel erosion or flooding. The focus of this discussion is thus on ecological applications, noting only those uses of LWD in channel stabilization that appear to hold greater promise than traditional engineering methods.

4.1. Setting goals for LWD enhancement projects

4.1.1. *Opportunities and limitations*

In disturbed watersheds, rarely does the loss of LWD occur in isolation—normally it accompanies upland changes, such as clearing for agricultural production or urban development, that initiate significant changes in runoff and sediment-delivery patterns and in riparian vegetation. Thus the consequences of LWD loss in these channels can only be partly isolated, because those consequences are amplified by other, concurrent changes as well. Conversely, the mere replacement of lost LWD cannot reverse all stream-channel changes, in large measure because only a fraction of the causal mechanisms of degradation are directly addressed by such an action.

If the goal of river and stream enhancement is a system that resembles, in form and function, its undisturbed counterpart, then LWD is a necessary, but not sufficient, component. The evidence is overwhelming that LWD plays critical roles in both the physical and the biological behavior of aquatic systems of the Pacific Northwest, and the previous sections of this report show no evidence that other materials or strategies can replace the unique attributes of wood.

Yet the simple reintroduction of LWD via agricultural and urban channel-rehabilitation projects typically occurs in the context of massive watershed changes. Thus complete restoration of these systems through wood placement alone is probably unattainable. Nor are these efforts misguided, however, for two reasons:

1. Irrespective of what else has occurred in the watershed that affects the stream channel, loss of LWD almost certainly *has* occurred in any once-forested lowland setting, and its functions will need to be replaced at some stage of any comprehensive rehabilitation effort.

2. LWD replacement is commonly the only practical stream-restoration activity that can occur in the early stages of a stream or watershed enhancement effort. Other actions that directly address flow changes, sediment-delivery changes, or riparian conditions are much more expensive, contentious, and slow to implement. Yet better instream and local riparian conditions can have a beneficial effect on stream ecology independent of other conditions at a watershed scale (e.g., Roni and Quinn 2001, Morley and Karr 2002). Such improvements can be commonly achieved with LWD placement or buffer planting.

Several methods to prioritize stream-enhancement projects have recently been published. Roni et al. (2002) presented a hierarchical strategy for restoration based on three elements: (1) understanding and maintaining the principles of watershed processes, (2) protecting existing high-quality habitats, and (3) current knowledge of the effectiveness of specific techniques. Cederholm et al. (1997a) had similar logic, and they developed a flow chart to determine candidate streams for restoration by first evaluating and repairing upstream processes (Figure 4). These methods both emphasize fixing defects in natural processes first before working down to the scale of an individual reach. This approach is logical—maintaining or reestablishing natural processes first, and then "jump-starting" habitat quality in select places through site-specific efforts such as LWD placement until natural processes can take over. For achieving long-term success this strategy is probably essential, but in practice it may not always be feasible. Alternatives likely do exist that can provide some benefits, albeit short-term only, with less comprehensive effort.

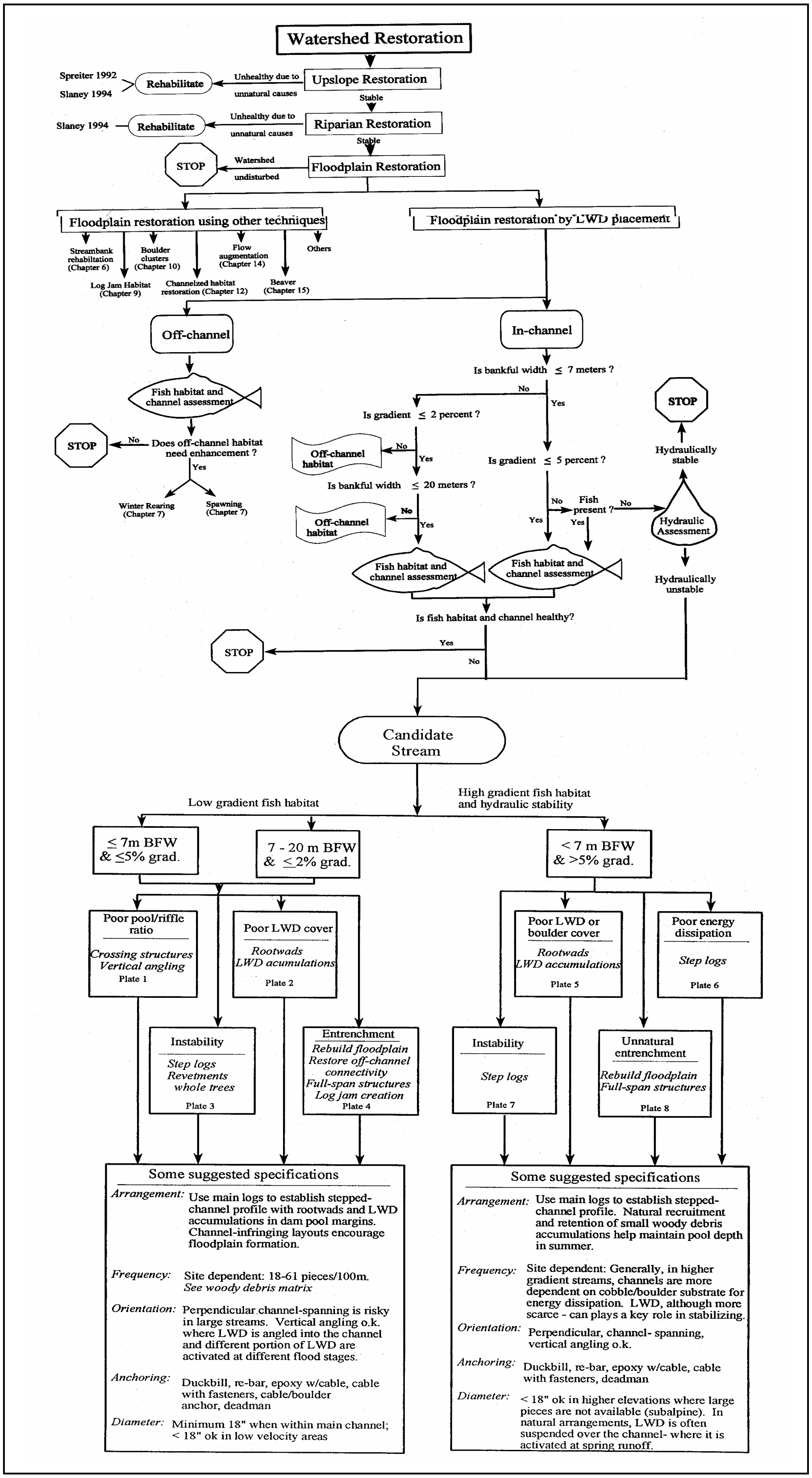

Figure 4. Flow chart for determining candidate streams for rehabilitation (Cederholm et al. 1997).

4.1.2. *Using predisturbance conditions as a template for LWD projects*

Although the elements of "preferred" or "optimal" fish habitat are often hypothesized, a more conservative and readily defensible approach to LWD project design is simply to replicate those conditions we know have been successful in producing salmonids, namely those to which salmonids have adapted. The key elements of these conditions are heterogeneity in habitat structure, a dynamic continuum of stream and riparian processes, and a natural rate of disturbance operating at multiple spatial and temporal scales.

LWD structures that help modern rivers and streams mimic natural channels in terms of size, spatial distribution, orientation, and shape should provide conditions to which wild salmonids have adapted. Recent assessments of wood enhancement in streams follow this concept. For example, Roy and Nislow (2002) advocate "natural channel" design techniques to restore channel form, function and stability in addition to enhancing habitat through placement of LWD. Bethel and Neal (2003) offer two overall goals for small-stream LWD projects, namely "to establish the channel morphology appropriate to the topographic, geologic, and hydrologic setting, and to establish the channel and riparian habitat that support a diverse native plant and animal community appropriate to the setting." Conversely, placing wood into channels in a manner inconsistent with historical distributions may not serve restoration purposes. For example, single log structures in large rivers may not survive high flows as well as log jams, where jams are more representative of the natural wood distribution (Abbe and Montgomery 1996; Bilby and Bisson 1998; Fox 2003).

4.1.3. *Incorporating biological needs*

Variable effects on salmonid abundance are reported from wood-placement projects, which in part correspond to freshwater life-history requirements for salmonids.

Winter rearing. For juvenile salmonid winter rearing, the geomorphic and physical functions provided by wood are important for survival. Juvenile coho, steelhead, and cutthroat seek deep pools formed by wood for cover and refuge from high winter flows as their metabolic activity slows with decreases in water temperature (Bustard and Narver 1975). Grette (1985) and Murphy et al. (1986) also found that densities of rearing coho juveniles were correlated with wood quantity during winter rearing, and Quinn and Peterson (1996) positively correlated LWD volume to winter survival.

Not surprisingly, the placement of wood structures for winter-rearing habitat enhancement has also shown favorable salmonid response. Channel-spanning logs creating pools with wood added for cover increased winter-rearing coho abundance in two Oregon coastal streams (Solazzi et al. 2000), resident trout in northern Colorado streams (Riley and Fausch 1995), and overwinter survival in a stream on Queen Charlotte Island, British Columbia (Poulin and Tripp 1986). Nickelson et al. (1992) found increased winter densities of juvenile coho in wood-constructed pools in several Oregon coastal streams. Roni and Quinn (2001) also reported increased coho, age-1+ cutthroat and steelhead densities (3.2 times and 1.7 times the control reach, respectively), in winter-rearing habitats with wood treatments. Cover created by bundles of brush was found to increase winter coho densities when placed in dammed pools of coastal Oregon (Nickelson et al.

1992) as well as in coastal Washington (Peters et al. 1992). Supplementation of wood to form pools and cover in off-channel habitats increased juvenile coho winter survival by over 500% (Cederholm et al. 1988). Salmonid response to wood is clearly positive for winter rearing.

Summer rearing. Because pools provide slow-water sites for summer-rearing habitat, and because wood forms pools (Montgomery et al. 1995), LWD should also be an important component of summer-rearing habitat. Yet measured salmonid responses to wood placement projects intended to increase summer-rearing habitat are mixed. Channel-spanning wood structures in Tobe Creek, Oregon resulted in a 300% increase in summer juvenile coho (House and Boehne 1986). Nickelson et al. (1992) found increased summer densities of juvenile coho in constructed pools in several Oregon coastal streams. Roni and Quinn (2001) reported a 1.8-fold increase in summer-rearing coho densities in wood-enhanced treatment reaches compared to untreated control reaches, but they saw no difference in cutthroat or steelhead densities. Schult et al. (in review) found significant increases in summer trout densities using pools created by wood structures in Potlatch Creek, Idaho. However, Murphy et al. (1986) found no correlation between summer coho densities and LWD in SE Alaska streams. Similarly, Cederholm et al. (1997a) found no significant differences in the coho populations during spring and fall with two treatment types of wood and a reference site. This absence of a relationship with coho was also acknowledged in the Keogh River, British Columbia by Slaney *in* Cederholm et al. (1997b). Riley and Fausch (1995) also found no change in summer trout populations between their control and treatment areas. Overall, salmonid response to wood structures in summer-rearing areas is generally not as positive as it is for winter-rearing areas.

Spawning. In high-energy channels, LWD functions to retain spawning gravel and can provide physical cover for spawning adult salmonids (Schuett-Hames et al. 1994), although the conditions for success are probably dependent on a range of factors beyond the influence of any given LWD project. Salmon were found to use gravels retained by channel-spanning logs placed in the Nestucca River, Oregon (House et al. 1991), and in the North Fork Porter Creek, Washington (Cederholm et al. 1997a). However, in a study in four managed streams in British Columbia, log structures failed to change spawning gravel composition (with respect to the median grain size) even though gravel accumulations occurred following high flows (Poulin 1991).

The success of instream wood placement to augment spawning habitat likely depends on stream geomorphology and the type of structure. If the intent of the structure is to store gravels, the structure must be 1) dynamic to move vertically with the stream bed (not become buried or suspended), 2) large enough to resist mobilization, and 3) located in a stream that has the power for fluvial transport to move gravels. Finally, gravel of the sizes favorable to the targeted species must be in adequate supply upstream, which may be problematic downstream of dams or in many urban systems.

4.1.4. *Flux and permanence of LWD*

LWD, as described in Section 2.1, is not a static component of river systems. Even in undisturbed watersheds it is episodically removed by high flows or abandoned by migrating channels, and this attrition must be balanced by further inputs if instream LWD is to remain. In human-influenced watersheds this loss is even more rapid. Thus, long-term, the physical habitat created by LWD (or any other physical manipulation) is only temporary without the maintenance of wood-replacing, habitat-forming processes. In human-dominated landscapes these wood-replacing processes may not be feasible or tolerated (e.g., large streamside trees adjacent to houses and roadways falling into adjacent watercourses). Nevertheless, their functions are still necessary, implying that permanent, deliberate replacement of LWD is a necessary but commonly forgotten long-term component of any such projects.

4.2. Designing LWD enhancement projects

4.2.1. *Objectives*

The objectives articulated for wood-placement projects are varied. They mainly focus on one or more of the primary functions of wood in natural streams, namely:

- ***Hydraulic roughness***, which may increase by 50 percent or more through the disruption of flow imposed by a high concentration of logs, stumps, or debris jams (Manga and Kirschner 2000);
- ***Sediment storage*** behind channel-spanning logs that create a stepped bed profile with a wedge of trapped sediment just upstream, large log jams in major rivers, or individual obstructions that result in a (normally smaller) zone of deposition in the eddy just downstream (Keller and Swanson 1979);
- ***Creation of habitat diversity*** by the variety of bedforms, sediment-transport zones, and sheltered areas that typically accompany LWD in the active flow of streams. Pool formation, in particular, can be almost completely determined by the presence and location of LWD in forested channels of this type, with pool frequencies two or three times greater than in LWD-free streams (*e.g.*, Andrus et al., 1988; Robison and Beschta, 1990; Smith et al., 1993; Montgomery et al., 1995); and
- ***Bank protection*** through a combination of deflecting flow and providing general hydraulic roughness, which can reduce the overall rate of sediment transport. This objective is frequently problematic, however, because (1) flow deflection can locally *increase* bank erosion and bed scour, and (2) simply armoring streambanks to reduce channel migration, though a common river-management goal to protect floodplain structures, is generally detrimental to fish habitat by eliminating a key process for creating side channels and recruiting gravel and trees into the river.

Given the behavior of LWD in undisturbed channels, any or all of these objectives should be feasible. Note, however, that they are all physical objectives, not biological ones. Although examples show demonstrable success for the latter as well, the influence of other watershed factors unrelated to LWD make the achievement of biological targets much less certain (Larson et al. 2001).

4.2.2. *Influence of agricultural or urban land uses on LWD project objectives*

Even with the guidance provided in Section 2 on natural LWD characteristics, projects constructed in disturbed channels are not guaranteed to succeed because conditions of an agricultural or urban channel may be sufficiently different from predisturbance conditions that once-stable placements are no longer reliable. Projects that do not consider these conditions increase the risk of both physical and biological failure, or of otherwise unintended consequences. Roni and Quinn (2001) note that streams subject to outmoded forest practices and with initially low amounts of wood prior to treatment generally had the most dramatic increases in habitat quality and fish abundance following LWD reintroduction. This is a logical outcome where the absence of LWD is a result of physical removal, rather than a change that has accompanied pervasive watershed alteration.

In urban systems, however, little has been published on the success or even the response of channels to LWD projects. In one of the few such studies, Bethel and Neal (2003) described several examples but emphasized institutional factors, particularly the make-up of the project team and the need to embed such projects in a whole-watershed assessment, as critical factors for success. They also note a general absence of proven design standards in this setting, which suggests that projects should be modeled on the template provided by natural systems, imperfect as that template may be for systems with altered hydrology and potential disconnection from the adjacent floodplain—there is simply nothing else available to work from.

4.2.3. *Basis for LWD design parameters*

The precise quantity, volume, and organization of wood needed by salmonids for successful production are not precisely known. Statistically sound studies to link instream wood loads and organization to salmonid production are unavailable; even if such a study were undertaken, it would be expensive and have high levels of uncertainty due to the multiple variables influencing salmon production. Due to the effect of past management practices on instream wood, impacted streams commonly display loadings well *below* the historic range, particularly in urban and agricultural settings. Thus, merely managing for the mean or median will not restore the natural ranges of heterogeneity across a watershed or a landscape. To pull the regional mean of wood loading closer to the historic condition while staying within the historic range, Fox et al. (2003) recommended using that part of the LWD distribution between the 25^{th} and 75^{th} percentiles to better reestablish central tendencies of natural distributions.

Various other target conditions have been developed in the state of Washington to evaluate the adequacy of wood quantities. The targets established in the Washington Forest Practices Board (WFPB) Manual (1997) for conducting "Watershed Analysis" rate LWD quantity in terms of "pieces per channel width," where a qualifying wood piece is >10 cm diameter and >2 m in length. For channels < 20 m bankfull width (BFW), they use >2 pieces as "Good," 1-2 pieces as "Fair," and <1 pieces as "Poor" condition. The WFPB (1997) also recognizes key pieces as a necessary component of wood quantities for use in state Watershed Analysis, and it defines "key pieces" as a log and/or root wad that is independently stable in the stream bankfull width (not functionally held by another factor, i.e., pinned by another log, buried, trapped against a rock or bed form, etc.) and is retaining or has the potential to retain other pieces of organic debris. The WFPB manual criteria for "Key Pieces" are >0.3 pieces per channel width in streams <10 m BFW, and >0.5 pieces per channel width in streams 10-20 m BFW. More recently, the LWD target for "Properly Functioning Conditions" defined by the National Marine Fisheries Service (NMFS) specify >50 pieces/km, where a qualifying piece is at least 15 m long and 0.6 m in diameter.

Fox et al. (2003) note that their field data suggest that the WFPB target is probably too low for channels <20 m BFW, and that the key-piece targets are too low for the smaller class of channels and too high for the larger class. They also observed that only 11 of their 78 sampled streams in unmanaged watersheds of western Washington met the NMFS target, suggesting that it is probably set too high to approximate undisturbed conditions.

Reference conditions of instream wood in natural systems can offer guidance for restoring not only the quantity but also the heterogeneity and structure of wood in adversely impacted systems. The following steps provide an example of how to use such comparisons to proceed with a restoration endeavor, based on the findings of Fox (2003):

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

2) Based on natural distributions of LWD piece numbers and volumes, assess if wood additions are warranted, and how much more is needed to attain natural loads. Table 1 provides a summary of natural LWD distributions based on Fox (2001).

3) Organize spatial wood distributions according to those found in natural systems. Figure 5 provides the natural distribution of wood to various group sizes based on Fox (2003), enabling a comparison to the existing organization of wood in the stream targeted for restoration. The filling of voids in this distribution within the project area can then be facilitated in order to mimic a more natural spatial distribution.

4) Organize lateral wood distributions according to those found in natural systems. Figure 6 provides the natural distribution of wood according to lateral channel zones based on Fox (2003), enabling a comparison to the existing organization of wood in the stream targeted for restoration. The filling of voids in this distribution within the project area can then be facilitated in order to mimic a more natural distribution.

Wood size and organization are both important for creating favorable refuge areas. House and Boehne (1986) affirmed that structures composed of larger wood increased coho biomass more effectively than smaller wood structures in Tobe Creek, OR. The design of wood placement structures to target specific habitat preferences has also helped achieve positive fish response. Roni and Quinn (2001) found that glides and shallow pools held the highest densities of juvenile coho during summer. Juvenile coho are known to occupy pools, glides, and other low-gradient habitats during summer but are almost exclusively found in pools and slack-water habitats during winter (Bustard and Narver 1975; Bisson and Sedell 1982). Therefore, structures that create or provide cover to these types of habitat are more likely to elicit a favorable response in coho production. For coho, more benefit for a given effort may come from designing structures for restoration or enhancement of winter habitats. Nickelson et al. (1992) concluded that the development of off-channel habitat has the greatest potential to increase wild coho production in their studied streams. Based on successful wood placement projects, the creation or enhancement of winter-rearing areas where they are presently lacking should help increase coho, steelhead, and cutthroat trout production.

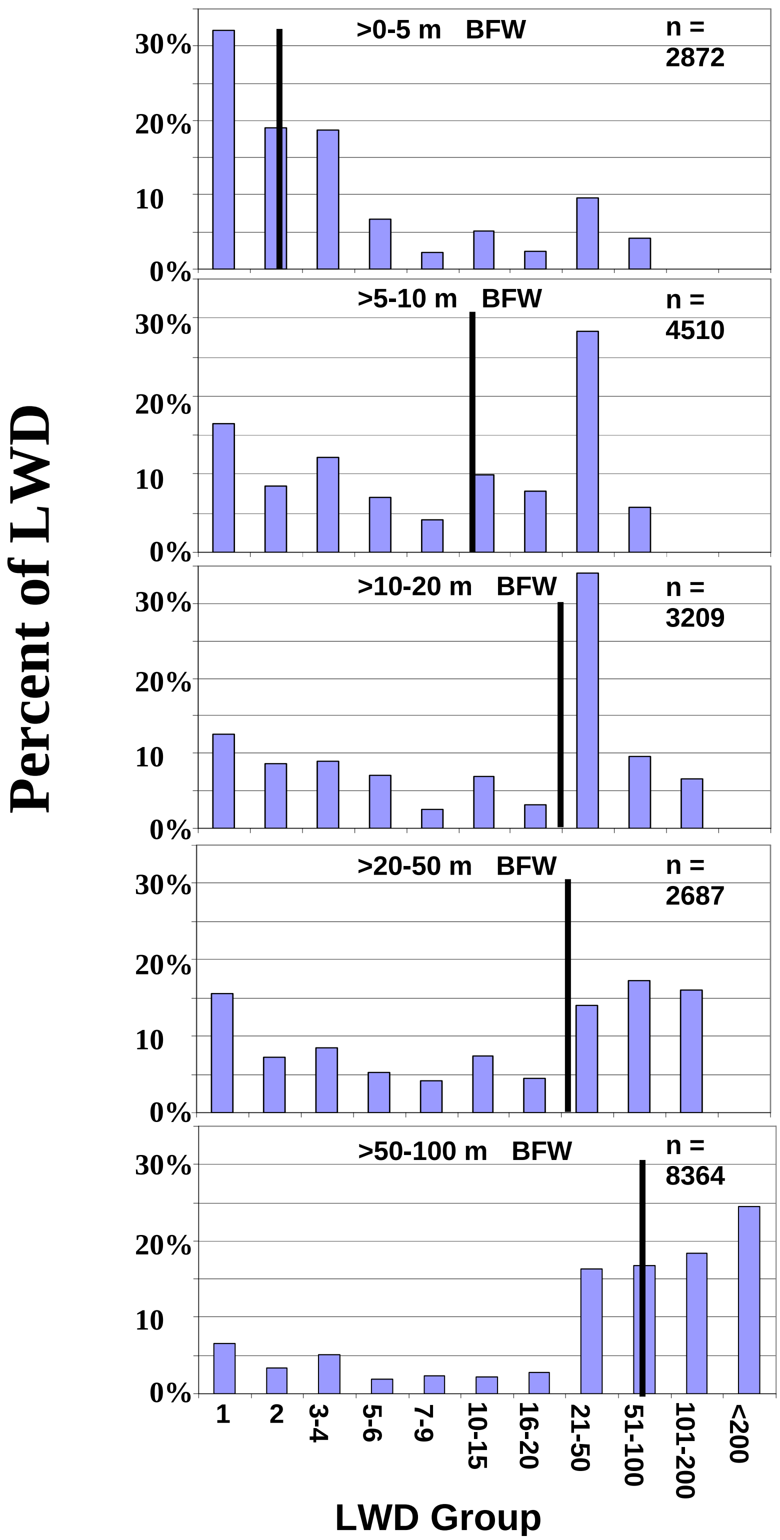

Figure 5. The percent distribution of LWD to group size class according to five bankfull width classes. The vertical bars in each chart represent the median. Source: Fox (2003)

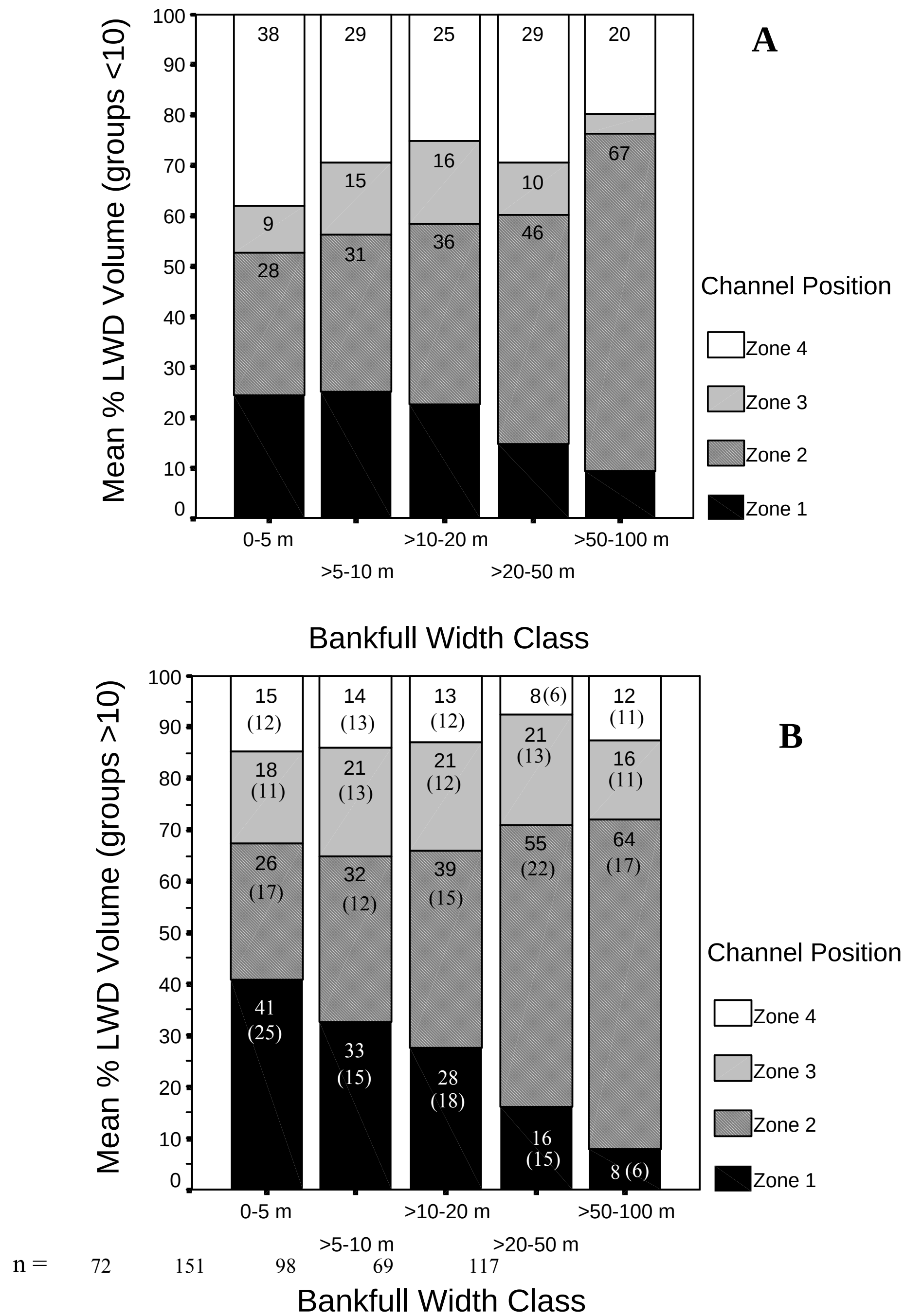

Figure 6. Comparison of the mean percent LWD volume by four lateral zone distributions between (A) small groups (<10 pieces per group) and (B) large groups (≥10 pieces per group) according to five bankfull width classes. Zone 1 is the wetted low-flow channel, Zone 2 is above the wetted low-flow channel 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. Source: Fox (2003).

The physical in-channel influences of LWD also argue for using predisturbance loadings and placement in design. Individual logs (i.e. buoyant cylinders with diameters less than the flow depth and lengths less than the channel width) would never be an obvious engineering choice for such functions as bank protection, pool formation, or sediment storage. Yet in sufficient numbers and when spatially well-organized, LWD has been shown to completely alter the physical condition of the channel (Section 2.3.1). As a first approximation, the loadings seen in stable systems provide a clearly defensible starting point for design.

In urban systems, however, other physical and hydrologic changes within the channel have the potential to alter the role, or at least the performance, of instream LWD. High discharges, widened and incised channels, and flow-confining disconnections from the adjacent floodplain can all increase the mobility of individual logs and render once-stable structures prone to failure and washout. No reports have been published to systematically document these phenomena, but the accumulation of such urban-related effects suggests that design-by-analogy is progressively less wise in increasingly disturbed basins. Engineering analysis, in turn, becomes more clearly warranted as flows increase, total numbers and size of naturally occurring LWD decline, and the unanticipated consequences of failure become more costly to bear.

Despite these concerns, abandoning LWD is not necessarily warranted in these highly disturbed environments. The traditional engineering alternatives to such physical problems as bank erosion and excessive sediment flux are generally “successful” only at the cost of massive ecological damage—smoothed and hardened streambanks, immobile beds, or habitat-destroying (and maintenance-demanding) sediment traps. With this legacy for comparison, the task of defining appropriate design standards and project objectives for LWD placement in urban channels appear well worth the challenge, even if the use of LWD does not provide immunity from the potential to cause ecological damage.

4.2.4. *LWD project performance*

Successful instream LWD projects can be readily found in the published literature. Expectations of success are reasonable, given the correlations wood loading has to channel morphology, aquatic habitat, and salmonid production, and due to the paucity of instream wood stemming from past and present land-use practices and stream cleaning (Bisson et al. 1987; Ralph et al. 1994). Wood-placement projects have thus become a common method for restoring or enhancing salmonid habitat (Kauffman et al. 1997; Bethel and Neal 2003). 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). At the local scale, salmonid abundance has increased in association with wood structures with all life-history stages (Murphy et al 1986; Cederholm et al. 1988; Riley and Fausch 1995; Spalding et al. 1995; Roni and Quinn 2001). Tripp and Poulin (1986) and Cederholm et al. (1997a) reported coho smolt outputs several times higher following restoration with wood structures. The placement of wood structures has apparently had some success for increasing salmonid abundance, and so it is a demonstrably viable method for increasing populations.

Wood projects also can fail to meet their stated objectives. Sometimes the reasons are obvious; other times they are enigmatic. “The masking effect of multiple environmental influences coupled with typically large changes in year-to-year abundance [of fish] make detection of wood restoration effectiveness statistically daunting" (Bisson et al. 2000). Some of the known causes reflect both physical and biological problems, which are described below:

Physical problems. Physically, structures can succumb to hydrological forces, which can be exacerbated by upstream anthropological disturbance or modification. For example, Hartman and Miles (1995) found that there was only a 50-55% success rate of projects reported within the British Columbia Ministry of Environments, Lands, and Parks since the mid-1980s. Additionally, of 243 structures in Potlatch Creek, ID, 17% failed due to flooding (Schult et al. in review). This rate is similar to that found by Roper et al. (1998) who reported a 16% total failure for structures in lands managed for timber production in Washington and Oregon streams. Cederholm et al. (1997a) also reported that 7 of 250 placed and anchored LWD pieces were lost over a 6-year period in Porter Creek, Washington, which was subjected to several large floods. Most physical failure results from high flows and flooding, high sediment loads, unstable channels (Frissell and Nawa 1992), high stream power (Roper et al 1998), or inadequately sized or improperly placed LWD pieces for the fluvial system of interest (Booth et al. 1997, Abbe et al. 2003).

The mere displacement or migration of LWD, however, may be a "failure" only in the context of a project site. Mobility of LWD is well-documented in undisturbed watersheds, and it is problematic only if (1) downstream constrictions (e.g., a road culvert) are intolerant of floating debris or (2) natural recruitment (or, in its absence, regular project maintenance) is inhibited. The first condition is a commonly articulated concern in developed areas, although almost no data support this issue (and some examples document downstream debris *reduction* below a well-constructed LWD jam; e.g., Abbe et al. 2003). Natural recruitment, however, is almost uniformly reduced in human-disturbed areas, and so loss of installed LWD may require a similarly deliberate response if the project site is to meet objectives. Without that, the loss of once-placed wood will preclude any expected physical or biological response.

Biological problems. Physical loss is by no means the only reason why biological response to an LWD project may not meet project goals. Because biological health depends on more than just physical habitat (Table 2; Karr 1995), many broad biological goals are simply inappropriate for a LWD project. Because LWD most directly influences only physical habitat and secondarily food supply (but little or no mitigation for other critical factors), its mere introduction into a river or stream cannot guarantee favorable biological outcomes.

Table 2. Five features of water resources altered by the cumulative effects of human activity with examples of degradation associated with urbanization (modified from Karr 1995).

Features	Human actions	Components altered	Urban stream degradation
Flow regime	Altered land cover that affects upland soil structure and reduces soil-moisture content Dams and levees Water withdrawal	Temporal distribution of floods and low flows, magnitude of uncommon and extreme events	Channel erosion, altered channel morphology, washout of biota, unseasonable drying of stream and streambed; disconnection from and loss of floodplains
Physical habitat structure	Channelization, Remove organic material, sedimentation, debris flows	Substrate type, water depth and speed, spatial and temporal complexity of physical habitat	Sedimentation and loss of spawning gravel, impediments to migratory movements, lack of woody debris, destruction of riparian vegetation and overhanging banks, lack of deep pools
Water quality	Industrial effluent CSO contaminants Domestic effluent Atmospheric deposition, road deicing measures	Temperature, turbidity, dissolved oxygen, acidity, alkalinity, organic and inorganic chemicals, heavy metals, toxic substances	Increased water temperature, turbidity, oxygen sags, nutrient enrichment, chemical contaminants
Energy sources	Altering riparian cover, removing organic material	Type, amount, and size or organic particles in stream, seasonal pattern of energy availability, allochthonous vs. autochthonous production	Altered supply and kind of organic material for food web, reduced availability of fish carcasses
Biotic interactions	Overharvest Alien introductions Riparian vegetation management Human intrusions	Competition, parasitism, disease, predation	Increased predation on young-of-year fish; genetic swamping from hatchery fish; alien plants, fish, invertebrates, diseases, and parasites, altered riparian vegetation

Even where just the physical conditions in a degraded stream are problematic, LWD structures may not produce the desired habitat for the limiting life-history requirements of fish. Some logs or structures are too small to form deep pools for summer and winter rearing, or to store gravel for spawning for a given size channel, and therefore they do not provide adequate habitat to facilitate salmonid production. Also, some structures are constructed in channel locations that could never provide the critical habitat for a particular limiting life-history stage, or are installed to perform functions such as bank armoring that themselves tend to degrade fish habitat.

Although localized increases in salmonid abundance from wood placement projects have been recorded, they cannot always be interpreted as causing a net population gain. For example, Smokorowski et al. (1998) concluded that success was often measured by evaluating the desired changes in habitat, but some restoration projects that look at fish abundance only estimated fish numbers in the immediate project vicinity, making it difficult to determine if changes in fish abundance near the structures represent an actual increase in production.

Several studies have been careful to make this distinction, however, and they do suggest a basis for anticipating success. Both Cederholm et al. (1988) and Murphy (1995) found overall increases in coho smolt yield several-fold from streams enhanced with wood. Reeves et al. (1991) cited eight projects using wood structures that have increased salmonid numbers, biomass, and angler catch. Tripp (1986) reported coho smolt outputs several times higher following restoration with wood structures. Riley and Fausch (1995) found that although summer trout populations in their treatment areas did not change, downstream migrants the following year did increase relative to the control section. Of the studies that made this distinction, only Reeves et al. (1997) did not find significant increase in coho population following restoration; however, they noted that the percentage of “fast water” habitats (i.e. riffles and cascades) actually increased after restoration, suggesting poor project design or physical failure of the structures.

4.3. Establishing basin recovery goals

Restoring the natural processes that sustain recruitment of LWD into rivers and streams is a critical component of watershed restoration (Berg et al. 2003)—just adding wood to streams will not accomplish long-term recovery goals. The following are riparian management recommendations for Puget Sound rivers and streams based on the findings of Fox (2003), who summarized his conclusions based on empirical data analyses of the characteristics of natural riparian areas to form riparian management recommendations. They are spelled out not because they are necessarily feasible in all parts of King County (particularly the most urbanized), but because they define the target conditions that are needed to sustain the persistence and functions of the LWD in rivers and streams. The extent to which these recommendations cannot be met is an indication of the shortfall that must be “made up” by active management of instream LWD, for as long as the project is intended to be effective:

- Riparian areas should be managed for diverse tree sizes, ages, and species. Typically, riparian stands of the Puget Lowland contained at least 8-10 tree species, 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 (Berg et al. 2003). Also, the distribution of tree species should not only consider frequencies but also the natural hierarchical arrangement of dominant, co-dominant, subdominant, and suppressed species typical to the seral stage of the targeted stand.

- Riparian areas should also be managed for the kind of spatial diversity recognized from reference areas. Features such as stem density and species diversity change with distance from the stream. Greater densities and diversity are found closest to the stream (<35 m) but express a gradation 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.

- Riparian stands throughout a watershed should be managed for multi-century succession in order to not limit potential wood recruitment opportunity, given that instream wood volumes in systems west of the Cascade crest may not peak until riparian stands reach 550 years or more. Even along urban and agricultural streams where this is a seemingly infeasible time horizon, riparian management farther upstream may result in a significant contribution of LWD to downstream channels, and they are probably the only feasible locations for extensive riparian management.

4.4. Next steps

By itself, this review of LWD in the streams and rivers of western Washington is not sufficient to provide design-level guidance for stream projects. It does offer a foundation, however, for the steps still needed to improve the effectiveness and value of LWD projects. Several follow-up efforts are anticipated to make the information presented here of direct utility to the efforts of King County to enhance river and stream conditions for both human and ecological benefits.

4.4.1. *Guidance for evaluating prospective LWD project sites*

Principles. Site conditions and the choice of project objectives determine the prospects for using LWD. If project objectives are primarily for ecological improvement, then the sites that are likely to show the greatest biological response are those where physical disturbance of the channel is the greatest substantive impact (in contrast to, for example, hydrologic alteration or water-quality degradation) and where recruitment potential from adjacent and upstream riparian areas is high. If these conditions are not met, LWD will be a necessary but not sufficient component of ecosystem improvement; in addition, active support for long-term recruitment will be needed. If the project is being constructed primarily for channel stability and (or) grade control, few sites are precluded outright if LWD will be used as an engineered bed or bank reinforcement. But, as with other channel-stabilization methods, success is likely to be limited during a phase of active channel deepening or steepening (e.g., Simon 1989).

Next steps. To provide concrete guidance, future work on this topic needs to develop the means to:

- Determine relative degrees of physical and non-physical disturbance affecting prospective project sites,
- Characterize project objectives,
- Define site and watershed constraints on long-term recruitment of LWD, and
- Recognize the stage of channel adjustment and the suitability of engineering stabilization methods (of any kind).

4.4.2. *Design specifications for LWD placement in urban streams*

Principles. Because urban streams have attributes that differ from other channels, design specifications for the use of LWD (or any other engineered component) are likely to differ as well. These uniquely "urban" attributes include generally higher discharges, less tolerance of channel migration and of free-floating logs, less opportunity for long-term riparian zone management, greater proximity of people, and a greater overall magnitude of watershed-scale problems. If these imposed constraints are not addressed, then the ecological benefits of LWD are limited regardless of the details of project design. For ecological applications, there is no reason not to seek loadings and spatial organization of LWD similar to those reported from undisturbed channels (e.g., Fox et al. 2003), although if applied in an urban channel they will clearly be insufficient for success. For bank or grade stabilization, LWD should be treated as an engineered object using design guidelines, based on stability calculations or empirical results from past projects, as appropriate. In all cases, a set of design criteria that do not currently exist is needed (Miller and Skidmore 2003).

Next steps. Design criteria and design specifications for LWD projects should be developed and should include:

- Loading and spacing of LWD, based on channel size
- Stability criteria for logs
- Structure and organization of LWD for typical project objectives (e.g., pool formation, bank protection, grade control)
- Basis for reconciling ecological and channel-stability project goals

4.4.3. *LWD project evaluation and monitoring*

Principles. Because channels respond most directly to LWD placement through physical changes, physical elements should be the focus of follow-up evaluation—e.g., pools, bank position, hydraulic roughness, and permanence of wood structures. Yet maintaining the stability and permanence of LWD (typical project objectives) can conflict with the habitat-forming adjustment of channels to obstructions. Thus projects with ecological goals require different evaluation criteria than those with a more narrowly engineering focus, and the two may not always be in perfect agreement. Explicit biological monitoring for LWD projects does not appear to be generally warranted, because biological health is dependent on many factors of which physical habitat is only one. Such monitoring is surely worthwhile (Karr and Chu 1999) but should be implemented in the context of watershed planning, not LWD project construction alone.

Next steps. Monitoring plans cannot be developed independent of project design; the two must be designed together in acknowledgement of the uncertainties that remain in implementing LWD projects (Ralph and Poole 2003). Given the current state of monitoring, elements that still require further guidance include:

- Project design(s) that facilitate rapid evaluation and the opportunity for adaptive change,
- Post-construction time to initial measurement and frequency of measurement,
- Elements and protocols for measurement, and
- Triggers for remedial action(s).

4.4.4. *LWD project maintenance*

Principles. No matter how carefully engineered, LWD is not a permanent material. It shifts, it scours out, it is buried by sediment, it rots. Western King County has no fluvial systems where natural processes of succession and natural rates of recruitment can be expected. Not enough information is yet available, however, to judge rates of necessary replacement, maintenance, or outright reconstruction of LWD projects in urban and agricultural watersheds. For well-designed projects that approach pre-disturbance loadings, the time frame for required maintenance is probably decadal. For less ambitious projects, maintenance will probably be much more frequent. In determining the need for maintenance, lessons from forestland management may not be directly transferable to urban areas, because the close approach of people lowers the tolerance for failure and raises the possibility of unanticipated intervention (e.g., removal). Empirical data are needed in this environment, because understanding how LWD works in unmanaged basins cannot predict how limited-scope projects, subject to disturbed hydrology and unpredictable property owners, will respond.

Next steps. Systematic review of existing LWD projects in urban areas is needed to determine the typical level of maintenance required for projects of different ages, with different designs, in different types of settings. None of the existing literature offers much guidance, except the occasional example showing that 2- to 10-year flows are sufficient to create unanticipated changes in LWD structures. Thus, almost no project is "too young" to be excluded from such an inventory. The goal of this effort should be to characterize stream size and types, common failure modes, association with surrounding riparian and watershed land use, and the type of maintenance and (or) reconstruction that would be needed to return the project to a functional condition.

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