Forest Development, Wood Jams, and Restoration of Floodplain Rivers in the Puget Lowland, Washington

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Abstract

Historically in Puget Lowland rivers, wood jams were integral to maintaining an anastomosing channel pattern and a dynamic channel–floodplain connection; they also created deep pools. In the late 1800s, wood was removed from most rivers, rivers were isolated from their floodplains, and riparian forests were cut down, limiting wood recruitment. An exception to this history is an 11-km-long reach of the Nisqually River, which has natural banks and channel pattern and a mature floodplain forest. We use field and archival data from the Nisqually River to explore questions relevant to restoring large rivers in the Pacific Northwest and other forested temperate regions. In particular, we focus on the relation between recovery of in-channel wood accumulations and valley bottom forest conditions and explore implications for river restoration strategies. We find that restoring large rivers depends on establishing riparian forests that can provide wood large enough to function as key pieces in jams. Although the frequency of large trees in the Nisqually valley bottom in 2000 is comparable with that of 1873 land surveys, many formerly more abundant *Thuja plicata* (western red cedar) were cut down in the late 1800s, and now hardwoods, including *Populus trichocarpa* (black cottonwood) and *Acer macrophyllum* (bigleaf maple), are also abundant. *Pseudotsuga menziesii* (Douglas fir) and fast-growing *P. trichocarpa* commonly form key pieces that stabilize jams, suggesting that reforested floodplains can develop naturally recruited wood jams within 50 to 100 years, faster than generally assumed. Based on the dynamic between riparian forests, wood recruitment, and wood jams in the Nisqually River, we propose a planning framework for restoring self-sustaining dynamic river morphology and habitat to forested floodplain rivers.

Key words: fluvial geomorphology, river restoration, riverine forests, wood jams.

Introduction

Studies in recent decades have demonstrated that wood is integral to the architecture of Pacific Northwest streams (for a review, see Bilby & Bisson 1998). However, the importance and functions of wood in larger rivers have only recently been appreciated. Field studies and analysis of archival materials indicate that before mid-nineteenth century European settlement, many rivers in western Washington had multiple channels, forested islands, and floodplain sloughs (Sedell & Luchessa 1981; Sedell & Froggatt 1984; Collins & Montgomery 2001). This complex and dynamic morphology created diverse and abundant habitats for salmonids and other organisms (Beechie et al. 1994; Reeves et al. 1998). In particular, wood jams were integral to creating and maintaining these channels and habitats by creating pools (Abbe & Montgomery 1996; Collins et al. 2002), causing avulsions (switching of flow from one channel to another channel), maintaining multiple channels, and regulating the flow of water into perennially flowing floodplain sloughs.

In the last century and a half, wood was systematically removed, while riparian logging and the establishment of levees and bank revetments reduced wood recruitment (Sedell & Luchessa 1981; Sedell & Froggatt 1984; Collins et al. 2002). In the low-elevation region between the Cascade Range and Olympic Mountains of Washington (known as the "Puget Lowland"), rivers typically have been subject to a century and a half of modifications. They now lack stable wood jams and have small amounts of wood with little geomorphic function (Collins et al. 2002). Interest in river and habitat restoration motivates an inquiry into the conditions that favor restoring stable accumulations of wood to rivers.

This study of the lower Nisqually River concentrates on the only reach of a major Puget Lowland river that has

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natural banks, numerous large wood jams, multiple main channels and floodplain sloughs, and an extensive mature riparian forest, making it close to historical or "reference" conditions. Because the most abundant riparian tree species before the era of European settlement, *Thuja plicata* (western redcedar), was heavily logged late in the nineteenth century, the Nisqually also provides an opportunity to examine the manner and time scale in which the river recovers historic levels and dynamics of physical functioning in response to riparian forest recovery.

Here we describe field and archival investigations into current (2000) and historic (1873) forest conditions of the study reach and current (1998–1999) in-channel wood. We use these data to explore questions relevant to restoring large rivers of the Pacific Northwest and other forested temperate regions: How critical are wood accumulations to river function? What conditions (e.g., tree species, diameters, and distributions) are necessary in valley bottom forests to recover in-channel wood accumulations? What in-channel wood characteristics can result from specific forest conditions? How long does it take to recover in-channel wood?

Study Area

The Nisqually River drains 1,890 km^2 of the west slope of the Cascade Range in Washington state and originates from the Nisqually Glacier in Mount Rainier National Park. The LaGrande and Alder high-head hydroelectric dams are at river km 68 and 71. Downstream of the dams, the river flows through a mix of forested, agricultural, and rural areas. It then borders the Fort Lewis Military Reservation between river km 4 and 31 and the Nisqually Indian Reservation between km 8.6 and 17.6. The study reach is between river km 7.4 and 18.7 (approximately 47° 00′ N and 122° 20′ W). The river downstream from km 4 is mostly within the Nisqually National Wildlife Reserve.

In the study reach, the river has incised a Holocene valley ~70 m deep into the general land surface created by the last glaciation (approximately 14,000 years ago). The valley bottom ranges between 0.6 and 1.1 km in width. The bankfull channel width averages 100 m, and the gradient (measured from 1:24,000-scale topographic maps) ranges between 0.002 and 0.005. The study reach is upstream from tidal backwater influence. The mean annual discharge between 1948 and 1999 was 37.3 m^3/sec at a gage at km 35.1. The largest flood on record, on 8 February 1996, estimated as 1,416 m^3/sec, was nearly twice that of the second largest event, 729 m^3/sec on 1 January 1965 (U.S. Geological Survey, unpublished data).

The study area has been relatively unaffected by human activities. The valley bottom was historically within the territory of the Nisqually Indians. The Nisqually ceded most of their land to the federal government in the 1854 Treaty of Medicine Creek but retained rights to a reservation that included most of the study area. The original land survey notes and maps from 1858 to 1876 show Indian dwellings but no clearings or homesteads on either side of the valley bottom. Whereas other Puget Lowland riparian forests had been cleared by the end of the nineteenth century, the Nisqually was not (Plummer et al. 1902). Late in the nineteenth and early in the twentieth century, logging was limited to selective removal of *Thuja plicata*, which was cut into bolts and floated downstream to a shake mill (G. Walter, Nisqually Tribe, unpublished data). We also observed stumps of old-growth *Pseudotsuga menziesii* (Douglas fir), indicating some logging of this species took place along with the cedar. In 1917, the U.S. military annexed 13.6 km^2 of the Nisqually Indian Reservation for Fort Lewis, including the north side of the valley bottom. On private land downstream of the Reservation in the lowest 1 km of the study reach, some forest was converted to agricultural and residential uses before 1910 (Mangum 1912). There is no substantial development other than two fish hatcheries operated by the Nisqually Tribe.

Methods

Historic Forest Composition

To describe nineteenth century forest characteristics, we used General Land Office survey notes from 1873 (for overview of the uses and limitations of historic land survey records, see Whitney 1996; Collins & Montgomery 2001; Whitney & DeCant 2001). Survey notes describe forest trees at two types of locations. The first includes bearing trees at section corners and fractional corners. Although in most areas of the country survey points were established at quarter sections, on Indian reservations such as the Nisqually, control points were established at the corners of 1/16 sections, resulting in a grid of points spaced at a distance of 402 m (20 chains or 1,320 ft; White 1991). We refer to these locations as "valley bottom" in this study. The second is of bearing trees on river banks (established at ordinary high water; for detail see instructions to surveyors in White 1991) at points established where section lines or fractional lines intersected the river. We term these "streamside." We identified 111 bearing trees within the study area, 64 in valley bottom and 47 in streamside locations, respectively.

2000 Forest Composition

We field sampled the forest composition in May and June 2000. To replicate the 1873 sampling, we used a differential GPS to relocate survey points established in the original survey. To replicate streamside points in cases where the river had moved, we established points at the bankfull edge of the present channel location. At each point, we selected bearing trees using the published instructions to surveyors that were current for the region in 1873 (White 1991). We interpreted the instructions as giving emphasis to (and we thus used as our field criteria) selecting trees that are, in decreasing order of importance, (1) greater than 7.5 cm (3 inches) in diameter, (2) in opposite directions from the survey point, (3) closest to the point, (4) alive, and (5) within 60.25 m (three chains) of the survey point. Although the instructions indicate a 6-cm (2.5-inch) minimum diameter, we used 7.5 cm (3 inches). In inspecting several thousand bearing-tree records from western Washington, we found very few that were less than 7.5 cm, indicating the lower limit surveyors actually used.

At the same points, we made a second inventory, in which we measured the diameter of all trees more than 1 cm in diameter within a 10-m radius from the survey point. For streamside points we marked out rectilinear plots that extended 10 m from the bank and followed the bank for 15.7 m upstream and the same distance downstream to sample the same size area as the 10-m radius plots. We established 26 points, at which we documented 56 bearing trees and 1,275 trees within the 314-m^2 plots. By making the two types of inventories and comparing the results, we were able to evaluate biases in historical bearing tree records, to the extent to which our reading of the instructions is the same as the methods used by the surveyors in 1873.

In-Channel Wood

We collected field data on in-channel wood by boat in 1998–1999. We counted wood within or partially within the bankfull limits of the active channel only. The minimum size of wood we surveyed was 15 cm in diameter and 2 m in length. We recorded whether wood was on the banks, bars, low-flow channel margins, or low-flow channel middle. We also measured the dimensions of wood jams (i.e., width, length, thickness, and height) and recorded dimensions of key pieces that appeared instrumental in initiating the jam. We used the jam dimensions to estimate the number of pieces in each jam, along with planar transects on several jams orthogonal to "racked" pieces in which we counted the number of pieces intersected. (Here we use "racked" to refer to the pieces that have accumulated on "key" pieces that appear to have initiated a jam.) From this we estimated the percent void space in the jam and then back-calculated the number of pieces in each jam by using a distribution of calculated piece volumes (see Collins et al. 2002 for detail).

To characterize wood debris, we measured piece length and diameter, maximum and minimum rootball dimensions, and species of each wood piece encountered along transects on three jams and for all wood present on one bar. We assigned pieces to one of three simplified recruitment classes. "Recent" wood had most of its bark and some limbs attached. "Old" wood had no bark or limbs, and "intermediate" pieces were intermediate in characteristics. To characterize growth rates of four common tree species—*Pseudotsuga menziesii*, *Populus trichocarpa* (black cottonwood), *T. plicata*, and *Acer macrophyllum* (bigleaf maple)—we took increment borings of wood pieces and also counted rings of pieces that had been sawed for firewood.

Channel Dynamics and Wood Jams

In autumn 1999 and summer 2000 we field mapped floodplain sloughs that diverge from and later reenter the river. We mapped these onto 1:12,000-scale black and white orthophotographs from 1999, making supplemental use of 2-foot contour mapping by Thurston County. We mapped only sloughs that appeared to flow perennially, based on our field inspections in 1998–2000 and on aerial photographs.

Results

1873 Forest Composition

The basal area of valley bottom bearing trees was primarily (80%) conifer. "Cedar" (*Thuja plicata*, western redcedar) accounted for 67% of basal area (Fig. 1). (Surveyors recorded common names of trees. On first use, we indicate common names as recorded and the likely species.) "Maple" (*Acer macrophyllum*, bigleaf maple) and "fir" (*Pseudotsuga menziesii*, Douglas fir) each accounted for 13% of basal area. *Thuja plicata* and *A. macrophyllum* had the greatest diameter, with mean diameters of 74 and 62 cm (median of 61 and 61 cm; Fig. 2), respectively.

In the immediate streamside area, conifers accounted for somewhat less basal area than in the valley bottom sample (61%; Fig. 1). *Thuja plicata* was less dominant (39% of basal area), with *P. menziesii* (16%), "alder" (*Alnus rubra*, red alder, 13%), vine maple (*Acer circinatum*, 13%), and *A. macrophyllum* (9%) also important. "Cottonwood" (*Populus trichocarpa*, black cottonwood) was more important than in the valley bottom forest where it was virtually absent, but nonetheless accounted for only 3% of the streamside basal area (we combined "balm" with cottonwood). *Thuja plicata*, *P. menziesii*, and *A. macrophyllum* were the largest streamside trees (Fig. 2).

2000 Forest Composition

We found that the basal area indicated by our 2000 bearing trees agreed reasonably with that measured in the 2000 plots (Fig. 1), indicating the historic bearing tree

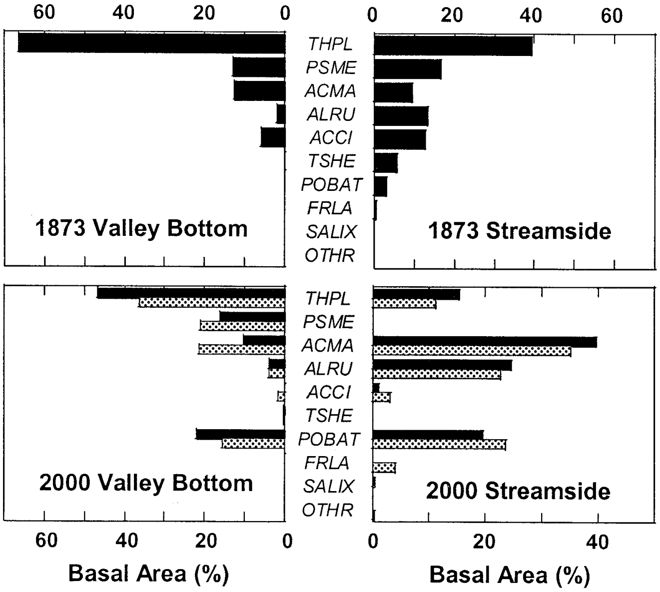

Figure 1. Valley bottom forest composition in 1873 and in 2000. Bearing trees are shown with a solid bar and plot data with a lighter bar. A single very large *Pseudotsuga menziesii* was excluded from the 2000 streamside data (see text). PSME, *Pseudotsuga menziesii*; THPL, *Thuja plicata*; TSHE, *Tsuga heterophylla*; ACMA, *Acer macrophyllum*; ALRU, *Alnus rubra*; POBAT, *Populus trichocarpa*; FRLA, *Fraxinus latifolia*; ACCI, *Acer circinatum.* "Other" species include *Cornus nuttallii* (western flowering dogwood), *Corylus cornuta* var. *californica* (beaked hazelnut), *Oemleria cerasiformis* (Indian plum), *Rhamnus purshiana* (cascara), and *Sambucus racemosa* (red elderberry).

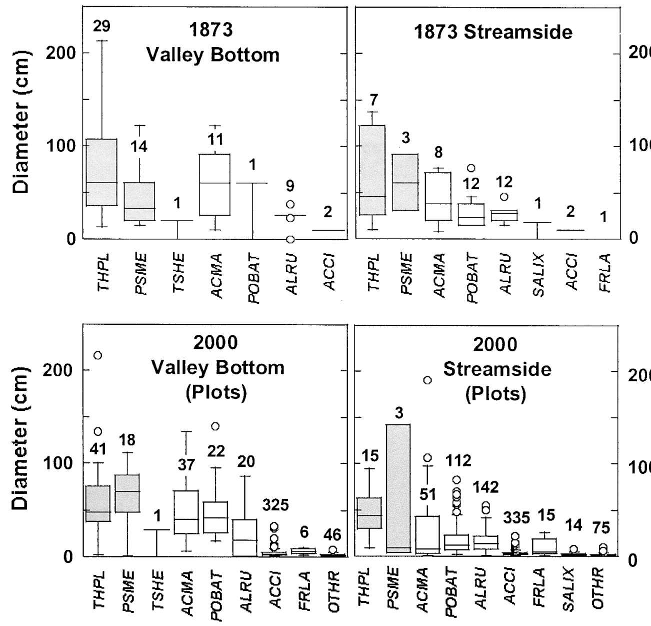

Figure 2. Average tree diameter, by species, from 1873 General Land Office notes in valley bottom and streamside samples and from 2000 plots. Each box encloses 50% of the data with the median value displayed as a line. The lines extending from the top and bottom of each box indicate the minimum and maximum values, except outliers (circles) or points with values greater than the inner quartile plus 1.5 times the inner two quartiles. Numbers are sample size. Conifers have shaded boxes.

records provide a usable estimate of the historic basal area. The two methods did not indicate similar distributions of tree frequency. This is because the bearing tree sample, which excludes trees less than 7.5 cm in diameter, is biased against smaller diameter trees such as *A. circinatum*, which was the most common tree in the plots.

Conifers are less dominant in the 2000 valley bottom forest than in the 1873 forest, accounting for 63% or 57% of basal area, in the bearing tree and plot samples, respectively (Fig. 1). *A. macrophyllum* (10% and 21% of basal area in the bearing tree and plot samples) and *P. trichocarpa* (22% and 16% of basal area in the two samples) are the dominant deciduous species, with *P. trichocarpa* accounting for considerably more basal area than in the historic valley bottom forest. *Pseudotsuga menziesii*, *T. plicata*, *A. macrophyllum*, and *P. trichocarpa* are the largest valley bottom trees (Fig. 2).

The streamside forest underwent a greater shift toward deciduous species than the valley bottom, with deciduous species accounting for 85% or 89% of basal area, according to the bearing tree and plot measurements, respectively (Fig. 1). (In Fig. 1, we excluded one unusually large-diameter *P. menziesii*, which was the only *P. menziesii* among streamside bearing trees; the tree is included in diameter distributions [Fig. 2] and frequency calculations [Figs. 7 and 8].) *Acer macrophyllum* is more common in the streamside forest than in the valley bottom, and *P. trichocarpa* is of roughly equal abundance. *Alnus rubra* accounts for 25% or 23% of the basal area. *Thuja plicata* accounts for only 15% or 11% of the streamside basal area. *Pseudotsuga menziesii*, *T. plicata*, *A. macrophyllum*, and *P. trichocarpa* are the largest diameter streamside trees (Fig. 2). The overall increase in hardwoods from 1873 to 2000 presumably reflects in part the effects of historic logging of the larger cedar and fir.

Quantity and Characteristics of In-Channel Wood

We estimated the Nisqually's wood abundance in 1998 as 135 pieces per channel width or 1,400 pieces per river kilometer (Fig. 3). Of this, 90% was in wood jams. One or more key pieces typically initiate and stabilize jams made of many racked pieces (Fig. 4) (Abbe & Montgomery 1996; Abbe 2000). In the Nisqually River, key pieces were larger in diameter than racked pieces (98 ± 34 cm compared with 64 ± 36 cm [mean ± SD], median 58 and 92 cm, respectively; Fig. 5) and half again as long (24.3 ± 8.6 m compared with 17.2 ± 9.6 m, median

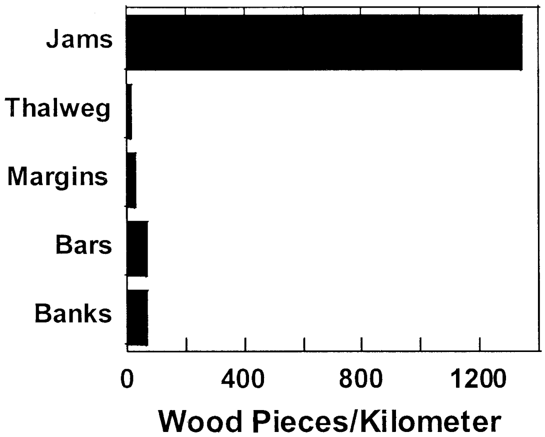

Figure 3. Number of pieces of wood in the Nisqually River per kilometer in jams, on banks, bars, or in the low-flow channel (divided into the main area of flow, or thalweg, and the channel margins) from summer 1998 field survey.

25 m and 17 m, respectively). Nearly all key pieces (97%) had rootballs, whereas 54% of racked pieces had rootballs. The average diameters of rootballs (calculated as the average of the largest and smallest dimensions) on key pieces were one-fourth again as large as those of the average racked piece (13.1 m ± 6.9 m compared with 9.5 m ± 7.2 m; median 12.3 m and 8.5 m). Most racked pieces were recently recruited, with 51% being in the recent decay class.

Figure 4. A 115-m long 5-m high jam at river km 12.1. The view is upstream from a vantage point atop the rootball of a dead *Populus trichocarpa* that functioned as a key piece.

Racked pieces, by frequency, were predominantly *P. menziesii*, *P. trichocarpa*, *T. plicata*, and *A. rubra* (Fig. 6). "Other conifer" could not be identified to species; however, because of the scarcity of other conifer species (e.g., one *Tsuga heterophylla* [western hemlock] among 1,275 sampled trees), they are likely *P. menziesii*. *Populus trichocarpa* were the largest diameter pieces and *P. menziesii* second largest (Fig. 5). *P. trichocarpa* pieces were also longest; *P. menziesii* and *P. trichocarpa* had the largest rootball dimensions. By contrast, *P. trichocarpa* accounted for a disproportionate number of key pieces (Fig. 6); *P. menziesii* is the second most common key piece. *A. macrophyllum* and *T. plicata* account for the remaining key pieces. *T. plicata* were less frequent as key pieces than as racked pieces. *P. trichocarpa* and *T. plicata* were the largest diameter key pieces (Fig. 5).

Forest Composition and In-Channel Wood

The 2000 forest, although differing in composition from the 1873 forest, had a comparable number of large trees in both the valley bottom and streamside bearing tree samples (Fig. 7). Of the 1873 and 2000 valley bottom bearing trees, 45% and 50% of trees, respectively, were greater

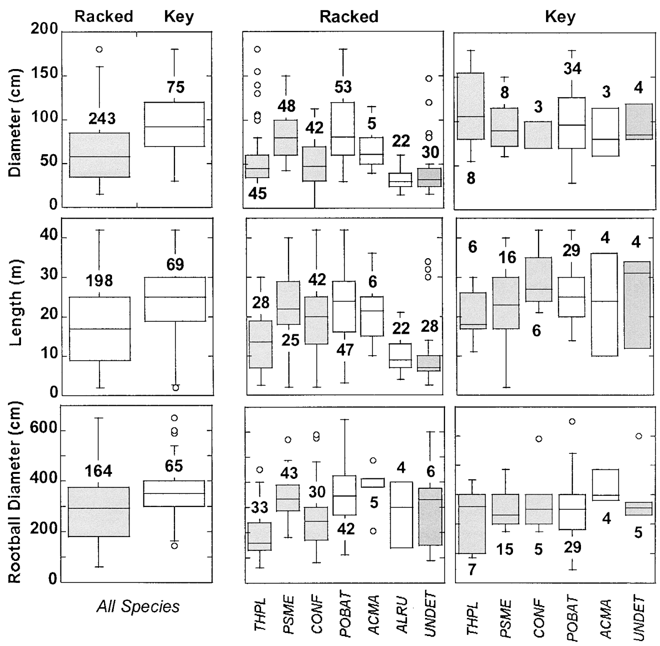

Figure 5. Diameter, length, and average rootball diameter (average of maximum and minimum dimension) of racked and key pieces of wood debris in jams. Numbers are sample size. Box plot diagrams are as described for Figure 2.

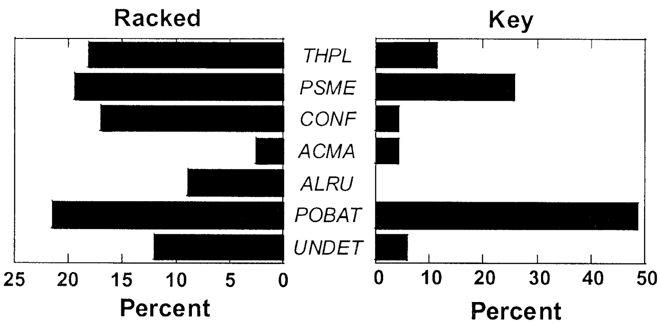

Figure 6. Frequency of key pieces (n = 70) from all jams and racked pieces (n = 247) sampled in three jams by species.

than 50 cm and thus potentially could form key pieces. Among 1873 and 2000 streamside bearing trees, 20% and 30%, respectively, were larger than 50 cm. These bearing tree records exclude smaller trees; our 314-m^2 plot data indicate that of all trees larger than 1 cm in diameter, 10% of valley bottom and 7% of streamside trees were greater than 50 cm in diameter. However, comparison of the bearing tree records from 1873 and 2000 is the only reliable comparison between conditions in the two centuries. Of these larger (i.e., >50 cm diameter) trees, *T. plicata* was most abundant historically, whereas in 2000 *A. macrophyllum*, *P. menziesii, T. plicata*, and *P. trichocarpa* are all important constituents (Fig. 8).

Characteristics of forest trees influence their relative abundance as key pieces and racked pieces. For example, *P. trichocarpa* grows faster than other species in the valley bottom (Fig. 9); this may account for its being a common key piece. *P. menziesii* grows more rapidly than *T. plicata* (Fig. 9), which also partly explains its frequency as a key piece. Based on the several older cedar (~160–210 years) that we aged, we found that remnant old-growth *T. plicata* grew much more slowly than second-growth cedar, presumably reflecting the effects of canopy closure in old-growth forests. *Acer macrophyllum* also forms key pieces, despite being slower growing than *P. trichocarpa* and *P. menziesii* in the study area (Fig. 9). However, the tree commonly grows with multiple stems sharing a common rootball; in our valley bottom plot samples, 36% of *A. macrophyllum* larger than 50 cm in diameter branched into multiple stems below 1.3 m (e.g., diameter at breast height) in height. As a consequence, *A. macrophyllum* creates large pieces of wood. By contrast, the slower-growing *T. plicata* tapers rapidly, reducing length and mass relative to diameter. *Populus trichocarpa* and *P. menziesii* both taper considerably less.

Thuja plicata was the most abundant and largest tree in the mid-nineteenth century forest. We expect that historically *T. plicata* would have formed more key pieces than are currently found in the river. *Thuja plicata* grows more slowly than some other valley bottom species, and thus in the Nisqually's present-day forest, in which many cedar were logged roughly a century ago, few *T. plicata* are large enough to function as key pieces.

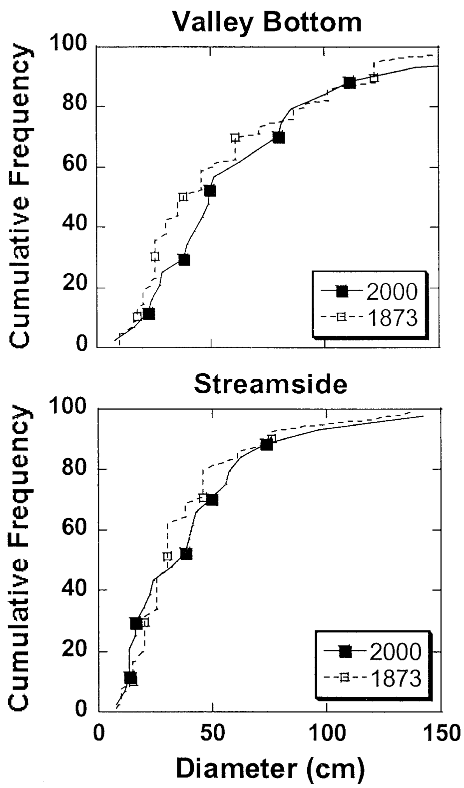

Figure 7. Cumulative frequency of diameters of all tree species in 1873 and 2000 for valley bottom and streamside bearing trees.

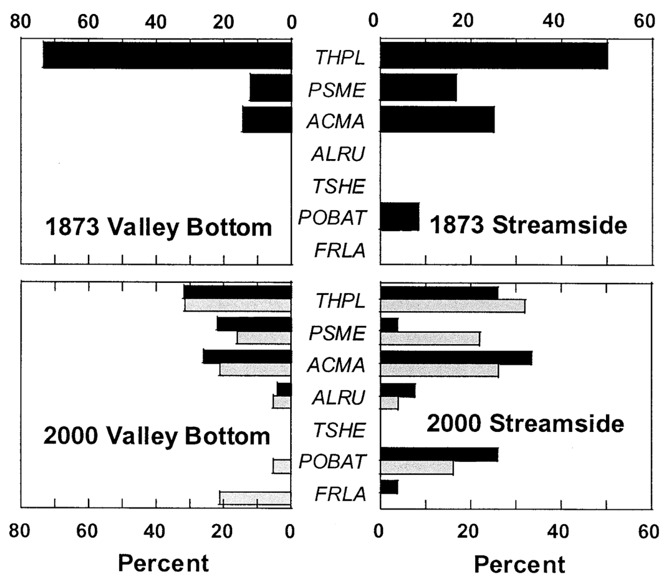

Figure 8. Frequency of bearing trees more than 50 cm in diameter in 1873 and bearing trees (solid bar) and trees in plots (lighter bar) in 2000.

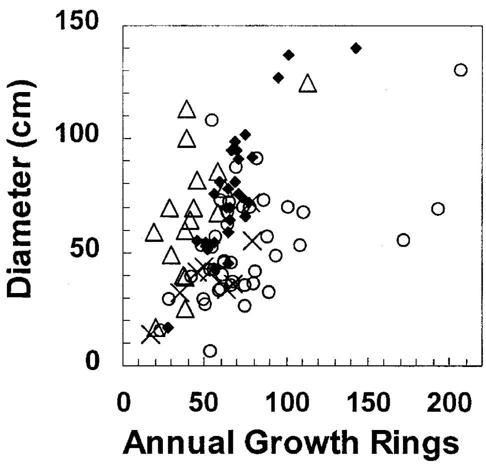

Figure 9. Relation between number of annual growth rings and wood diameter in the Nisqually River: △, *Populus trichocarpa*; ◆, *Pseudotsuga menziesii*; ×, *Acer macrophyllum*; ○, *Thuja plicata.*

At present, key pieces in the Nisqually are predominantly species that grow to a large diameter more rapidly than does *T. plicata*, or have a spreading shape, in the case of *A. macrophyllum.*

Wood Jams and Channel Pattern

Field observations and inspection of historical maps and photos indicate that wood jams in the Nisqually River are integral to maintaining a multiple-channel pattern and in causing and mediating avulsions. A preliminary analysis of a series of aerial photographs from 1937 through 1999 shows that flow splits can form at a migrating river bend, when the river intersects an abandoned main channel, diverting flow into it. Jams then commonly form at that split, stabilizing it. In addition, the growth of jams at such splits can gradually reduce flow to one branch, eliminating it, or reducing it to a perennial slough. Jams also cause avulsions by accumulating in and plugging channels, diverting flow into a relict channel, which then becomes the main channel. Jams at the mouth of the now-abandoned channel then regulate flow into it, causing it to flow perennially as a floodplain slough.

Such mediating of avulsions, by "metering" flow into floodplain sloughs, is common. In 1998 we field-identified 18 channels that received water from the main river during low-flow discharge. Each of these floodplain channels had a jam associated with its inlet (Fig. 10). In each case, the jam regulated flow into the slough, preventing or delaying the river from avulsing into it. Most of these sloughs were located in what could be identified as a relict main channel on historic aerial photographs.

In the study area, jam-mediated avulsion and the resulting switching back and forth in state from abandoned channel/floodplain slough to main channel are considerably more common than the more typical avulsion process that is associated with channel migration and meander cutoff. The Nisqually River has not migrated through a number of locally higher floodplain patches during the 140-year period of map and photo record (1859–1999); instead, it has avulsed around

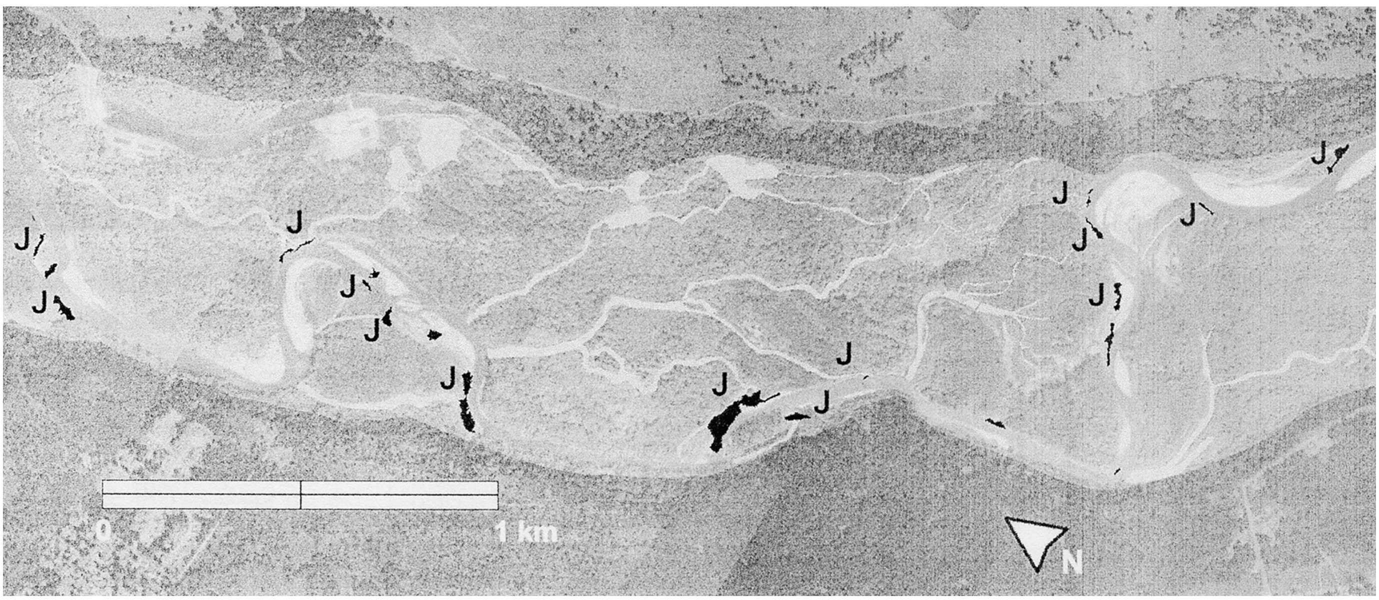

Figure 10. A portion of the study area in a 1999 1:12,000-scale orthophotograph. Perennial floodplain channels obscured by tree cover on the photographs are drawn with gray. "J" indicates a jam (highlighted with black) at the inlet to a floodplain channel.

them. Abbe (2000) found on the Queets River that similar "hardpoints," or patches, maintained their stability for up to hundreds of years and were created by stable persistent wood jams at their upstream ends.

Discussion

What Does It Mean to "Restore" a River in the Pacific Northwest?

The Nisqually River contrasts with other Puget Lowland rivers that have been significantly modified by human actions in the last century and a half, and which we found to have considerably less wood (Collins et al. 2002). For example, reaches of the Stillaguamish (1,770 km^2 drainage area) and Snohomish (8,270 km^2 area) rivers sampled in summer 1998 had 7 and 18 pieces per channel width, respectively, one to two orders of magnitude less than the Nisqually. In addition, there were few or no jams, and wood was dominated by individual pieces of old predominantly waterlogged cedar embedded in the bed at the channel margins, generally lacking rootballs, and having little geomorphic function. Recently recruited mostly small deciduous wood tended to be on banks. The lack of jams in the Snohomish and Stillaguamish rivers is likely due to the absence of very large wood with rootballs that can function as key pieces and low rates of wood recruitment because of levees that prevent channel migration (Collins et al. 2002).

Recent investigations into the pristine Queets River on the Olympic Peninsula and our work on the Nisqually River indicate that wood in large unmodified Pacific Northwest rivers had a dominant influence on morphology and habitat across a wide range of temporal and spatial scales (Abbe & Montgomery 1996; Abbe 2000; Collins et al. 2002). At the largest valley bottom scale, large channel-spanning wood jams could influence the routing of water, sediment, and wood and moderate processes of floodplain formation and floodplain hydrology (Collins et al. 2002). At the reach scale, jams were integral to the maintenance of a multiple-channel pattern and numerous floodplain sloughs in some Puget Lowland rivers historically (Collins & Montgomery 2001). At the channel-unit scale, wood pieces and jams are important in creating pools. We measured 85 pools in the study reach, equivalent to 1.4 channel widths per pool (Collins et al. 2002). Wood was the most common pool-forming factor, accounting for 62% of pools. This was similar to the finding of Abbe and Montgomery (1996) in a 25-km-long reach of the Queets River, where wood jams formed 70% of observed pools. Pools associated with jams in the Nisqually, as well as the Queets, were considerably deeper than other pools. In the Nisqually, on average, pools associated with jams were three times deeper than free-formed pools (Collins et al. 2002). Wood-formed pools also create more habitat than pools lacking the cover or complexity created by wood, especially for salmonids (e.g., Beamer & Henderson 1998). Measuring pools in 1998 in the Stillaguamish and Snohomish rivers suggests the transition of Puget Lowland rivers from a freely migrating river with mature riparian forest to a leveed river with little riparian recruitment has reduced the number of pools by two to three times (Collins et al. 2002).

It is likely that wood jams were formerly important to rivers not only in the Pacific Northwest but throughout forested temperate regions of the world. The eastern United States and Europe, for example, had extensive clearing of forests and in-channel wood (for review, see Montgomery et al. 2002). In the Pacific Northwest, stream and aquatic habitat restoration efforts have focused on steep, forested, headwater streams and most commonly have emphasized structural approaches rather than reestablishing processes (Reeves et al. 1991; Frissell & Ralph 1998). In the Pacific Northwest, efforts to restore larger rivers have included restoring flow processes in regulated rivers (e.g., Stanford et al. 1996) and constructing log structures, in a few cases under experimental conditions (e.g., Abbe et al. 1997). However, restoration efforts have not included reestablishing the dynamics between forests, wood recruitment, and wood jams. In Europe, the difficulties of process restoration in lowland rivers, which are generally in heavily populated areas, have similarly limited efforts to rehabilitating selected features or functions (e.g., Kern 1992; Brookes 1996; de Waal et al. 1998).

The Nisqually River provides insight into some of the questions about how to restore functional wood to large rivers having an historically anastomosed pattern: What tree species are important for encouraging rapid (i.e., within a few decades) restoration? How many years are required for a reforestation plan to succeed in restoring wood loads and river dynamics? Nearly all wood in the Nisqually River jams is from trees less than 80 years old, including key pieces, which are dominated by fast-growing *Populus trichocarpa* and *Pseudotsuga menziesii* 40 to 80 years old. This suggests that wood jams can be restored in a time frame of 50 to 100 years if fast-growing species (which can provide key pieces) are available to the river. The Nisqually River shows that key pieces can be any species that develops a large size. In the Nisqually, although slower-growing cedars can provide more durable key pieces in the longer term, deciduous trees (*P. trichocarpa* and *Acer macrophyllum*) and faster-growing conifers (*P. menziesii*) are important for more rapid restoration.

Long-Term Restoration Strategy for Pacific Northwest Rivers

The importance of wood accumulations to fluvial processes argues that planning for sustainable river resto-

Table 1. Conceptual framework for use of "restoration succession" in restoring wood jams and river dynamics.

	0 years	*1–50 years*	*50–100 years*	*100 + years*
Actions	Riparian reforestation	In-stream structures	Naturally-recruited logjams	Naturally recruited logjams
	Includes fast-growing species	Includes placing key pieces of building wood jams	Fast-growing species form key pieces	Slower-growing species form key pieces
	Levee setback or removal			
Results and Functions	Initiate future supply of wood	Short-term pool-forming and channel-switching functions	Long-term sustainable supply of wood jams	
	Restore lateral erosion and avulsion	Stable sites for forest regeneration	Long-term sustainable pool-forming and channel-switching functions	

ration in temperate forested regions such as the Pacific Northwest consider the recovery of in-channel wood and how the composition and extent of the riparian forest translates into the quantity and function of wood, particularly wood jams. We suggest that restoring self-sustaining river systems with wood jams depends on recruitment of trees large enough to create key pieces. To create jams, rivers must also have access to a large number of recruitable trees by bank erosion and avulsion. These conditions in turn imply the presence of large trees in the riparian forest, a dynamic flow regime capable of eroding forested floodplain, and banks that will allow channel migration. Structural approaches (e.g., building wood jams) are not sustainable without continued intervention.

Based on our analysis of the Nisqually River system and experience with other Pacific Northwest rivers, we propose a strategy to reestablish a self-sustaining dynamic river morphology and habitat in wood-depleted areas. First steps in river restoration include levee setbacks and riparian planting, including tree species near the river that will rapidly develop to a large size (Table 1). However, the forested corridor width needed to provide a sufficient long-term source of wood and to allow for channel migration and avulsion depends on the local geomorphic context. For example, floodplain restoration strategies for large, historically meandering, single thread rivers in which wood may have played a less dynamic role would involve different corridor design than for highly dynamic anastomosing channels.

In the first few decades of a restoration plan, engineered solutions may provide short-term functions and hasten riparian forest regeneration. In systems with adequate recruitment but an absence of pieces large enough to form key pieces, such actions include placing key pieces or, in systems lacking both recruitment and key pieces, constructing log jams (Abbe et al. 1997), which may provide short-term functions and hasten riparian forest regeneration. Within 50 to 100 years, self-sustaining wood jams should develop if key pieces of sufficient size and racked pieces of sufficient quantity are available. Although differences in durability between hardwood species and conifers have recently been shown to be less in submerged conditions (Bilby et al. 1999) than in terrestrial conditions (Harmon et al. 1986), few key pieces we observed were fully submerged, and thus key pieces of deciduous wood would be expected to be considerably less durable than conifers. This durability may be inconsequential for the primary function of key pieces, because a jam is likely to be incorporated into the floodplain within one to two decades as the river migrates or avulses away from the jam and forest trees colonize it. However, the river is also likely to eventually re-entrain wood from most such abandoned jams, thereby allowing key pieces to be "recycled" into the river for potential reuse as a key piece. Hardwoods may only be durable enough to function once as key pieces. For this reason, in the longer term, slower-growing and more durable species—in the Nisqually, *Thuja plicata*—are also important sources of key pieces.

This framework calls into question some assumptions now common in river restoration in the Pacific Northwest. First, most restoration efforts have focused on static habitat creation ("instream structures" in Table 1). However, forest restoration is critical to river restoration. Because conifers have been logged from essentially all lowland rivers in the region, it is likely that riparian hardwoods are now more common in riparian areas than they were historically, and restoration strategies commonly include converting from hardwoods to conifers. However, because large trees are necessary to provide key pieces for jams, this suggests that riparian forests be managed at least initially to produce large trees from a mix of species. Moreover, historic land survey records show that, unlike the Nisqually River where conifers were more common than hardwood trees, deciduous trees historically dominated the valley bottoms of most Puget Lowland rivers (Collins, unpublished data). Second, riparian restoration plans often assume a timeframe of a century or centuries, the time needed to develop large *T. plicata*. However, an emphasis in riparian reforestation on including fast-growing species can produce large trees that are essential for creating key pieces within much less time. River restoration can be accomplished in a series of stages, from engineered jams initially (1–10 years), to jams initiated by fast-growing largely deciduous pieces (50–100 years), followed in the longer term (100+ years) by slower-growing but more durable pieces. The strategy outlined above defines a new approach to coupling river and forest restoration that relies on a "restoration succession" that seeks to restore key processes on the way to achieving restoration objectives rather than attempting to create desired conditions through direct intervention.

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