Historical changes in the distribution and functions of large wood in Puget Lowland rivers

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Abstract: We examined changes in wood abundance and functions in Puget Lowland rivers from the last ~150 years of land use by comparing field data from an 11-km-long protected reach of the Nisqually River with field data from the Snohomish and Stillaguamish rivers and with archival data from several Puget Lowland rivers. Current wood abundance is one to two orders of magnitude less than before European settlement in the Snohomish and Stillaguamish basins. Most importantly, wood jams are now rare because of a lack of very large wood that can function as key pieces and low rates of wood recruitment. These changes in wood abundance and size appear to have fundamentally changed the morphology, dynamics, and habitat abundance and characteristics of lowland rivers across scales from channel unit to valley bottom. Based on our field studies, rivers had substantially more and deeper pools historically. Archival data and field studies indicate that wood jams were integral to creating and maintaining a dynamic, anastomosing river pattern with numerous floodplain channels and abundant edge habitat and routed floodwaters and sediment onto floodplains. Establishing the condition of the riverine landscape before European settlement sets a reference against which to evaluate contemporary conditions and develop restoration objectives.

Résumé : La comparaison d'observations de terrain sur un tronçon protégé de 11 km de la rivière Nisqually à des données provenant des rivières Snohomish et Stillaguamish, ainsi qu'à des données anciennes sur plusieurs rivières des terres basses de Puget nous ont permis d'étudier les changements dans l'abondance et le rôle du bois dans ces rivières au cours d'approximativement les dernières 150 années d'utilisation des terres. L'abondance actuelle du bois est de 10 à 100 fois moins grande qu'avant la colonisation des bassins de la Snohomish et de la Stillaguamish par les européens. Ce qui est plus important, c'est la rareté des embâcles à cause de l'absence de très grandes pièces de bois pour servir de structures maîtresses et des taux réduits d'apport de bois. Ces changements dans l'abondance et la taille du bois semblent avoir modifié de façon fondamentale la morphologie, la dynamique, ainsi que la densité et les caractéristiques des habitats dans les rivières des terres basses à diverses échelles, depuis les unités individuelles de lit de rivière jusqu'à l'ensemble du fond de la vallée. D'après nos observations de terrain, les rivières avaient des cuvettes plus nombreuses et plus profondes dans le passé. Nos données d'archives et nos études récentes sur le terrain indiquent que les embâcles jouaient un rôle essentiel dans la création et le maintien d'une structure fluviale dynamique et anastomosée, caractérisée par de multiples chenaux sur la plaine d'inondation et de nombreux habitats de lisière, de même que dans le déversement des eaux de crue et des sédiments sur la plaine d'inondation. L'établissement des conditions du paysage fluvial existant avant la colonisation européenne fournit un point de référence pour évaluer la situation présente et fixer les objectifs de restauration.

[Traduit par la Rédaction]

Introduction

Numerous studies have established that wood has a primary influence on channel form in small forest streams, but less is known about wood in larger rivers. Recent literature summaries indicate that the influence of wood "decreases with increasing channel size" (Bilby and Bisson 1998). However, in large rivers of the Pacific Northwest, 19th and 20th century stream cleaning greatly diminished wood abundance, and riparian forest clearing and levee construction reduced the potential for lowland floodplain rivers to recruit wood (e.g., Sedell and Luchessa 1981; Sedell and Frogatt 1984). This suggests that the current condition of regional rivers is not representative of their historical condition and highlights the need for a benchmark against which to assess restoration efforts. Recent work on the Hoh and Queets rivers in Washington's Olympic National Park (Sedell et al. 1984; Abbe and Montgomery 1996) shows how wood shapes large channels and their aquatic habitat. The purposes of this paper are (*i*) to document historical conditions in

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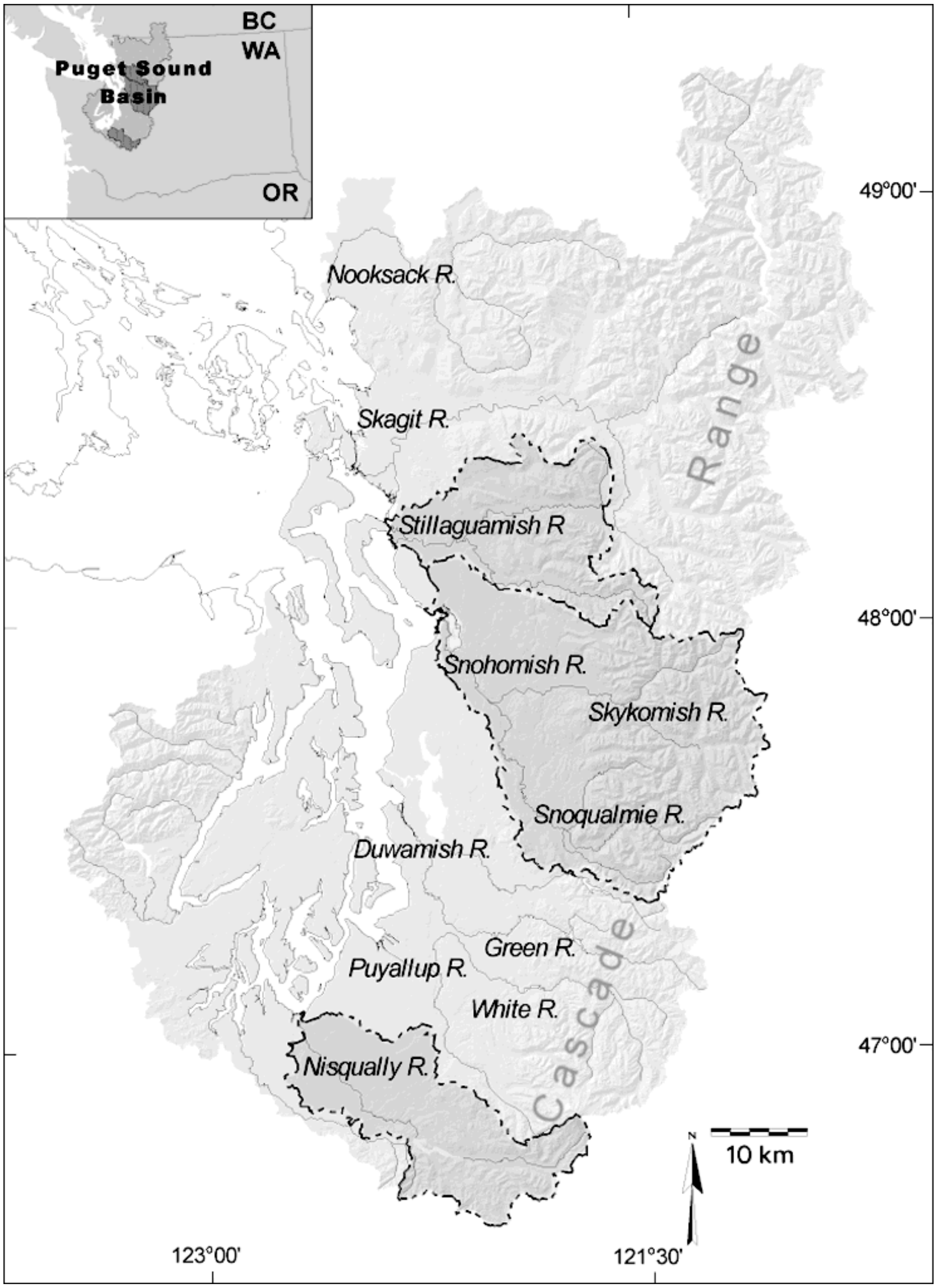
Fig. 1. Locations of Puget Lowland rivers and study sites on the Nisqually, Snohomish, and Stillaguamish Rivers, Washington State, U.S.A.



Puget Sound rivers, to compare to current conditions documented in the Olympic Peninsula studies for assessing these studies' geographic generality, and to extend those studies by evaluating a broader range of wood structures and effects; (*ii*) to document changes that have occurred since European settlement; and (*iii*) to use these changes as a long-term removal experiment and to evaluate hypotheses about wood functions. We do this by comparing the role of wood in Puget Lowland rivers under current and historical conditions by assessing amounts and types of wood accumulations, and their influence on channel structure, in relatively developed and undeveloped rivers using both field and archival studies.

To investigate representative current conditions, we examined the Snohomish and Stillaguamish rivers. In the past ~150 years, both rivers have been snagged, leveed, and isolated from their floodplains, which have been drained, ditched, and converted to agriculture and other uses. Their land-use history and current condition is typical of other rivers in the region (Sedell and Luchessa 1981).

We took two approaches to investigating the historical condition of Puget Sound rivers. We collected field data from a reach of the Nisqually River (Fig. 1) that has been protected from development in the 20th century on the assumption that it has retained characteristics of the pre-European-settlement condition. The river has natural banks, and logging of the valley-bottom forest was limited to the larger conifers late in the 19th century. There are no other undeveloped rivers in the Puget Sound region, which limits the extent to which it can be inferred that the Nisqually

River represents historical conditions. To provide context for interpreting the regional significance of the Nisqually data, we also use archival sources, including annual reports of the Army Engineers (Annual Reports of the Chief of Engineers, U.S. War Department, 1875–1980; hereafter referenced as U.S. War Department), settlers' accounts, maps and reports by the U.S. Coast and Geodetic Survey, U.S. General Land Office, U.S. Department of Agriculture, U.S. Geological Survey (USGS), and other agencies. Archival and process studies are complementary; field studies provide detail on and generate hypotheses about physical processes, whereas archival studies help characterize regional variation (which is not possible from field studies when the number of field sites is limited) and the applicability of hypotheses generated from field studies (Collins and Montgomery 2001). Additionally, archival studies can describe processes and features at the river-valley scale that may no longer be present owing to human changes to the landscape.

Study areas

The Nisqually River begins at the terminus of the Nisqually Glacier in Mount Rainier National Park (Fig. 1) and drains an 1890 km^2 basin. The LaGrande and Alder hydroelectric projects are at river kilometres 68 and 71, respectively (Ames and Bucknell 1981). The dams are not operated for flood control, but reduce some flood peaks. Below these dams, the Nisqually River passes through a mix of agricultural, forested, and rural land and then traverses or borders the Fort Lewis military reservation, between river kilometres 4 and 31. (River kilometres are from USGS topographic maps or Ames and Bucknell (1981).)

The study reach is between river kilometres 7.4 and 18.7, above tidal influence, where the river has incised a valley ~70 m deep into the land surface since the last glaciation, which ended ~14 000 years ago. The forested valley bottom is between 0.6 km and 1.1 km wide and includes numerous floodplain channels. Bankfull channel width in 1999 averaged 100 m, and gradient ranges between 0.002 and 0.005. The mean annual discharge between 1948 and 1999 was 37.3 $m^3 \cdot s^{-1}$ at a gage at river kilometre 35.1. The largest recorded flood, on 8 February 1996, was estimated as 1416 $m^3 \cdot s^{-1}$ (USGS 1997).

The reach is unique in the Puget Lowland in having a mature valley-bottom forest and no artificial levees or bank protection because it has been protected within the Nisqually Indian Reservation and Fort Lewis. The Nisqually Indians ceded most of their land to the federal government in the 1854 Treaty of Medicine Creek, but they retained rights to a reservation that included most of the study area. Although other Puget Lowland riparian forests had been cleared by the end of the 19th century, the Nisqually was not (Plummer et al. 1902) other than selective logging of conifers (primarily *Thuja plicata* (western red cedar) and secondarily *Pseudotsuga menziesii* (Douglas fir)), which were cut into bolts and floated downstream to a shake mill (George Walter, Nisqually Indian Tribe, 12501 Yelm Hwy. SE, Olympia, WA 98513, U.S.A., personal communication). In 1917, the United States annexed 3370 acres of the Nisqually Indian Reservation for Fort Lewis, including the north side of the valley. In the most downstream 1 km of the study reach on private land downstream of the reservation, some forest was converted to agricultural and residential uses before 1910 (Mangum 1911). Elsewhere, two fish hatcheries operated by the Nisqually Tribe are the only substantial developments.

The Skykomish and Snoqualmie rivers join to form the Snohomish River, which flows westward 34 river kilometres to Possession Sound at the city of Everett (Fig. 1). The river gradient declines downstream from 0.0004 to 0.00006. It splits into several major sloughs (Steamboat, Ebey, and Union sloughs) and the main river, which is dredged to maintain its navigability in its lowest approximately 5 km. Because of the river's low gradient, tidal backwater extends to about river kilometre 29.

The North and South forks of the Stillaguamish River (1770 km^2) join at Arlington, at river kilometre 29. From there, it flows westward to Port Susan and Skagit Bay. The Stillaguamish is steeper than the Snohomish; its gradient declines from 0.0009 to 0.0003. The Stillaguamish splits into two channels between kilometres 18 and 10, the approximate upper limit of tidal influence. It then flows into Port Susan through Hat Slough. Before ~1906, the river flowed instead northwest through what is now a minor tidal slough (U.S. Army Corps of Engineers 1929). Levees and bank armoring are extensive on the Stillaguamish and Snohomish rivers, and agriculture dominates both valley bottoms. Riparian forests are generally either absent or narrow and dominantly small deciduous trees.

Methods

In-channel wood

To determine the abundance of wood and its location in the channel, we inventoried wood and wood jams in the Nisqually River in September–October 1998. We noted all wood greater than 0.15 m in diameter and 2 m in length and having any portion within the bankfull limits of the active channel. We recorded whether wood was on a bank, bar, low-flow channel margin, or low-flow channel middle. We measured dimensions (i.e., width, length, thickness, and height) of 40 jams and recorded dimensions of 80 key pieces. We use "key" to refer to pieces that appear to have initiated jams and "racked" to refer to all other pieces in a jam. We estimated the number of pieces in jams by first measuring the percent void space in four jams along planar transects orthogonal to racked-piece orientation. We then used a distribution of calculated piece volumes from our wood dimension measurements (see below) to estimate pieces per unit space. Finally, we measured the width, length, and height of all jams and the average piece per unit space to estimate the number of pieces in each jam.

To characterize the size, species, and age of wood in the Nisqually River, we also recorded characteristics of 173 wood pieces in three jams and on one bar. Jams were sampled along transects at a right angle to racked pieces, and the bar sample included all pieces. For both, we measured piece length and diameter, maximum and minimum rootball dimensions, and visually identified species. In these four samples, we also assigned pieces to one of three simplified decay classes: "recent" wood had most of its bark and had some limbs attached; "old" wood had no bark or limbs; and "intermediate" pieces were intermediate in characteristics.

We conducted a similar inventory on the Snohomish River during seasonal low flow in August–October 1998 to document location, spacing, and size distribution of wood. We made this inventory in locations selected visually to represent upstream, middle, and downstream parts of the Snohomish River (river kilometres 32.2–33.9, 27.1–28.7, and 17, respectively). We measured or visually estimated diameter and length of 456 pieces and visually assigned each a decay class and species. For each piece, we noted the location as “on bar”, “on bank”, “snag” (a portion of the piece was emerging from the low-flow water surface), “submerged” (entirely beneath the low-flow water surface), or “embedded in bar”.

We made an additional inventory in both the Snohomish and Stillaguamish rivers to estimate wood abundance. In this inventory, we counted 436 pieces in six 1-km-long reaches of the Stillaguamish River, separated by 3-km-long intervals. We also noted the channel location and depth of wood to allow us to compare current low-flow channel wood abundance to wood abundance inferred from late 1800s and early 1900s snagging documented in annual reports of the Corps of Engineers (U.S. War Department 1880–1910). Similar to the first inventory, we counted pieces according to their location on a bar, on a bank, or as a snag, or if submerged, we subjectively determined whether wood was in the thalweg of the river (in the main area of flow) or in the low-flow margins. We also noted the depth (0–0.6 m below the surface, 0.6–1.2 m below the surface, or >1.2 m below the surface). We counted 1245 pieces in the Snohomish River, counting wood in the thalweg for the entire river and the entire channel (i.e., in the low-flow margins, banks, and bars) in 10.9 km of representative locations. In the lower, tidally influenced portions of both rivers, we confined our work to minus tides to enhance our view of submerged wood. However, water clarity and visibility of wood in the deeper, tidal area of both rivers varied with turbidity and weather.

Pools

In each river, we measured pool depths using a hand-held sonar device while navigating in a canoe, rubber raft, or jet boat. We measured pool lengths and widths with a laser range finder or made visual estimates. We confirmed pool depth measurements at most jams using a stadia rod while standing at the jam edge. For each pool, we noted the dominant pool-forming influence. These include the following: free formed; wood jam (and jam type); individual wood pieces (including whether or not a rootball was attached); and valley wall or boulder forced.

Riparian forests

We documented riparian forests along the three rivers in 1866–1873, which was before widespread riparian logging, using field notes of the General Land Office cadastral surveys, which include the size and species of trees that served as witness trees at survey control points in valley-bottom forests. Surveyors were instructed to identify witness trees, four trees nearest to the survey point in each of four quadrants at section corners and two trees at midpoints between corners and at banks of navigable streams (White 1991). Field surveys of the Nisqually River riparian forest indicate that these data underrepresent smaller-diameter species such as vine maple (*Acer circinatum*) but adequately characterize the basal area (Collins and Montgomery 2002). In Indian reservations such as the Nisqually study area, survey control points were established at every quarter mile including section interiors. For clarity, we refer to these points in the immediate streamside area as “streamside” and to the regularly spaced points at section corners and fractional corners as “valley bottom”.

Results

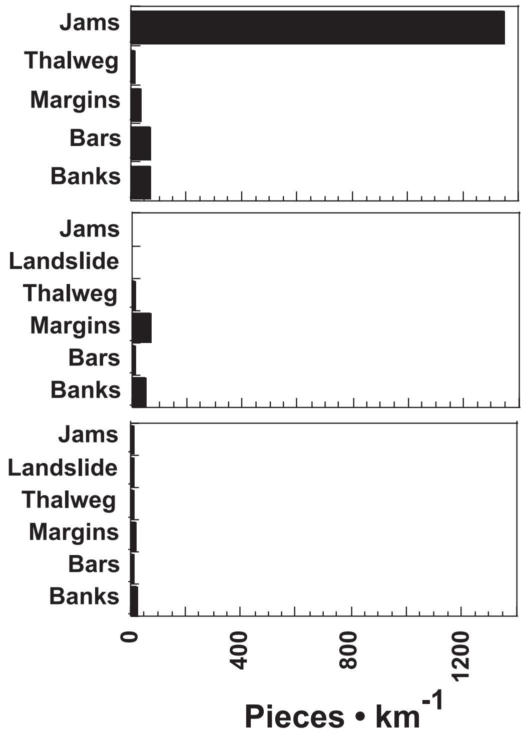
Quantity and location of wood

Wood is considerably more abundant in the Nisqually River compared with the other two rivers. The Nisqually’s abundance of wood in jams accounts for most of the difference; about 90% of pieces in the Nisqually River are in jams (Fig. 2), followed by bars and banks, for a minimum total of 1400 pieces·km^{-1} or 135 pieces·CW^{-1} (channel width), including jams. Excluding jams, there were 170 pieces·km^{-1} or 17 pieces·CW^{-1}. In contrast, neither the Snohomish nor Stillaguamish rivers had significant amounts of wood in jams (Fig. 2). In both, most wood was scattered on banks or on the bed at the margins of the low-flow channel. The total abundance in both was much lower than the Nisqually: 116 pieces·km^{-1} (18 pieces·CW^{-1}) in the Snohomish and 52 pieces·km^{-1} (5.4 pieces·CW^{-1}) in the Stillaguamish. Because most wood is in jams, wood distribution in the Nisqually River is highly “bunched” longitudinally. By contrast, in the Snohomish River, wood is relatively evenly distributed. (As indicated above, our point survey of abundance in the Stillaguamish did not permit assessment of clumping.) The spatial density of wood increases in the upper 10 river kilometres of the tidally influenced reach, with the greatest amount of wood along the thalweg being at the head of tidal influence. The highest density of wood on the banks and especially the low-flow margin was in the uppermost kilometre, below where the steeper Skykomish enters the Snohomish and where, unlike downstream, banks are not armored.

Age and species of wood

Recent pieces accounted for roughly one-half (48%) of the wood pieces measured in three jams and one bar in the Nisqually (Table 1). In contrast, in the Snohomish River, old pieces accounted for 59, 41, and 96% of wood for which age-class could be determined in three sample areas, from upstream to downstream, respectively (Table 1). (A portion (28, 27, and 0%) could not be assigned to any age-class. This was typically because wood could often not be clearly viewed beneath the water surface, and so it is likely that most of these pieces not assigned to an age-class were also old because most identifiable submerged pieces were old.) Recent wood in the upstream, middle, and downstream samples accounted for only 16, 18, and 2%, respectively, of pieces that could be assigned to a decay class. Overall, wood was old, with most recent and intermediate pieces on banks; nearly four-fifths of pieces on banks were either “young” (33%) or intermediate (46%). There were also a number of recent snags in the middle and upper river samples, where eroding banks are a local source. In contrast, pieces submerged on the bed were nearly entirely old (89% of identifiable pieces).

Fig. 2. Distribution of wood pieces in the sampled reach of the Nisqually River (upper panel), the Snohomish River (middle panel), and the Stillaguamish River (lower panel) study reaches.



In the Nisqually River, just over half of the wood that could be identified was conifer, distributed throughout age-classes (Table 1). In the Snohomish River, conifers (primarily cedar) dominated the population of older pieces (Table 1), whereas deciduous species were the most common recent and intermediate species.

Size and shape of wood

In the Nisqually River, recently recruited pieces are greater in diameter and length than older pieces (Fig. 3*a*), whereas in the Snohomish River, wood was dominated by smaller, older pieces (Fig. 3*b*). Wood on banks was smallest in diameter, averaging 0.33 m. Wood averaged between 10 and 12 m in length, except on bars, where wood was slightly longer, averaging 14 m. Cedar pieces were more than twice as large in diameter (mean ± standard deviation (SD) of diameter = 0.67 ± 0.29 m; unless otherwise indicated, subsequent figures also refer to mean ± SD) as alder or unidentified deciduous pieces (0.30 ± 0.06 m and 0.22 ± 0.07, respectively). Cedar was roughly half as long (6.8 ± 4.3 m) as alder or unidentified deciduous pieces (11.9 ± 4.8 m and 12.3 ± 8.6 m, respectively). Cottonwood pieces were the largest overall, with the greatest length (12.3 ± 8.6 m) and the second greatest diameter (0.35 ± 0.15 m).

Most pieces in the Nisqually River (68%) had rootballs (Fig. 3*c*). By contrast, relatively few (22%) had rootballs in the Snohomish (Fig. 3*d*); more than twice as many recent pieces as old pieces had rootballs (36 and 15%, respectively). In addition, rootballs were generally small in the Snohomish; cross-sectional area (measured as the product of the maximum and minimum rootball dimensions) averaged 2.7 ± 2.4 m^2 compared with 9.5 ± 7.2 m^2 for racked pieces in the Nisqually River. The rootballs of recent pieces in the Snohomish were slightly larger (3.3 ± 2.9 m^2) compared to those of old pieces (2.7 ± 2.2 m^2).

Most jams in the Nisqually had identifiable key pieces. Compared with racked pieces, they were longer (mean ± SD of length = 24.3 ± 8.6 m vs. 17.2 ± 9.6 m), larger in diameter (mean diameter 0.98 ± 0.34 m vs. 0.64 ± 0.36 m), and more likely to have rootballs (97% vs. 54%). Rootballs were also larger on key pieces than on racked pieces (13.1 ± 6.9 m^2 vs. 9.5 ± 7.2 m^2). Key pieces in the Nisqually ranged from 0.2 to 0.9 times the bankfull depth of 2.6 m (Fig. 3*d*). By contrast, in the Snohomish River, there were no pieces with a diameter larger than 1 m, and none of these had a rootball (Fig. 3*d*).

Historical accounts and archival data on the historical condition of Puget Lowland rivers

How representative is the Nisqually River of the mid-19th century condition of Puget Lowland rivers? Early accounts document that rivers transported vast amounts of wood. For example, in a report on the White River (Fig. 1), the Army Corps' Major Hiram Chittenden wrote

> …the channels are strewn with immense trunks, often two hundred feet long, with roots, tops, and all …[forming] jams, which frequently block the channels altogether. This drift constitutes the gravest feature of the flood problem, for the supply is practically unlimited, and the quantity carried by a great flood is such that very little can be done with it at the time by human agency. Levees or other protection works are of little avail in the presence of these drift jams, and it seems like an almost useless expense to built such works so long as they are menaced by so great a certainty of being destroyed or otherwise rendered useless. [Chittenden 1907]

In addition to such anecdotal accounts, archival sources also provide descriptions and quantitative information useful for characterizing the types, locations, amount, and size of wood in rivers draining to Puget Sound.

Types and locations of wood accumulations from historical archives

Raft jams

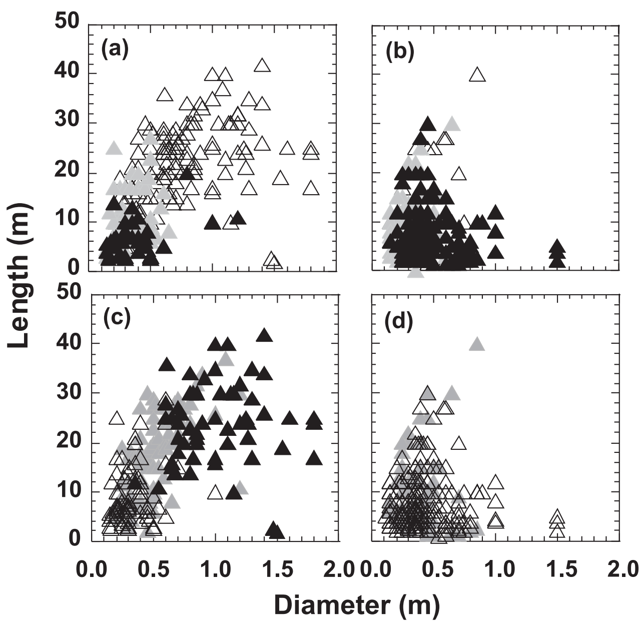
Maps and reports show that wood accumulations took various forms. "Raft" jams that formed the largest accumulations, as much as 2 km in length, were documented in the Nooksack, Skagit, and Stillaguamish rivers. These jams filled rivers from the bed to above the bank and spanned from bank to bank. A jam on the Skagit River at the town of Mount Vernon was described as 9 m deep, consisting of "from five to eight tiers of logs, which generally ranged from three to eight feet [0.9–2.4 m] in diameter" and existed for at least a century, as its surface supported live trees 0.6–1.2 m in diameter (Interstate Publishing Company 1906). A settler similarly describes "large trees growing in the midst of" (Judson 1984) a 1.2-km-long channel-spanning jam at river kilometre 8 in the Nooksack River (Fig. 1). Settlers and the Army Corps cleared mainstem-plugging jams between the late 1870s and late 1880s (U.S. War Department 1881, 1889, 1930). Individual jams of this size could have stored several hundred thousand pieces of wood.

Table 1. Age-class and type of wood in sampled reaches of the Snohomish (SN) and Nisqually rivers.

	Age-class of wood piece														
	Unknown			Old			Int.			Recent			Total		
Location	U	C	D	U	C	D	U	C	D	U	C	D	U	C	D
SN km 32–34	21	0	5	44	55	15	10	2	40	0	5	27	75	62	87
SN km 27–29	10	4	4	9	17	3	8	4	21	3	1	11	30	26	39
SN km 17	0	0	0	91	27	1	0	0	5	0	0	2	91	27	8
Nisqually	2	0	0	25	10	6	2	12	32	2	57	25	31	79	63

Note: Int., intermediate; U, unknown; C, conifer; D, deciduous.

Fig. 3. Wood length, diameter, and age-class in (*a*) Nisqually River and (*b*) Snohomish River. Solid symbols, "older" pieces; shaded symbol, "intermediate" pieces; open symbols, "recent" pieces. Wood length, diameter, and presence or absence of rootballs in (*c*) Nisqually River and (*d*) Snohomish River. Open symbols, "racked" pieces without rootball; shaded symbols, "racked" pieces with rootball; solid symbols, "key" pieces with rootball.



Distributary-plugging drift jams

Extensive drift jams formed in tidal distributary channels. For example, such jams were pervasive in the Skagit River: "Only one small channel can now be navigated by steamers, the others being stopped with drift…the largest is filled from bank to bank for 3 miles" (Nesbit 1885). The regions' tidelands were reportedly characterized by "hundreds of miles" of old channels that were choked with wood, filled with sediment, and abandoned (Nesbit 1885).

These channel-plugging jams were likely important in the evolution of estuarine sloughs and marshes. Such jams are also documented in the Stillaguamish, Snohomish, and Nooksack deltas; in some cases, logging activities promoted their formation (U.S. War Department 1889–1904).

Non-channel-spanning jams and snags

Although historical maps show non-channel-spanning jams and snags, these features were not mapped systematically. However, the Army Corps of Engineers, from 1881 to the present, systematically documented their efforts to remove channel wood, or snags, to improve navigation in a federal program, concentrating on mid-channel snags. According to the Army's annual reports, snags were less abundant in the Snohomish compared with the adjacent Skagit River (U.S. War Department 1875). Settlers and surveyors indicate that snags and jams were also abundant in the Stillaguamish (General Land Office 1875; U.S. War Department 1881; Eide 1996). On an examination 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]

Quantity of wood inferred from historical records

The Army's de-snagging records can provide an indication of historical wood abundance (e.g., Sedell and Frogatt 1984). In the Puget Sound area, nearly all snagging occurred after raft jams and much of the riparian forest had already been cleared, so the number of snags recorded would be significantly less than that which would have been present under pristine conditions. Nonetheless, from 1880 to 1980, 150 000 snags were removed from five rivers, including the Stillaguamish and Snohomish, more than half from the Skagit (Fig. 4). The diminishing rate of snag removal indicates in part the decline in recruitment of large wood that would be large enough to lodge in the riverbed and remain stable. This in turn presumably reflects effects of riparian logging, especially of the largest trees, levees, and bank protection.

Earliest snagging records provide a rough, minimum estimate of historical wood recruitment. If it is assumed that snagging removed all large wood, then the amount removed in subsequent years would reflect the amount recruited to the river in the intervening winter. The inferred recruitment is likely a minimum estimate of pre-European-settlement recruitment because streamside logging had already diminished riparian recruitment. In the Snohomish River (which had fewer snags than the adjoining Stillaguamish and Skagit), initial removal (1881–1909) averaged annually 15 snags and leaning trees per river kilometre. This rate is roughly equal to the number of pieces (21 pieces per river kilometre) found in the Snohomish River in 1998 in the low-flow middle channel within 1.2 m of the low-flow surface

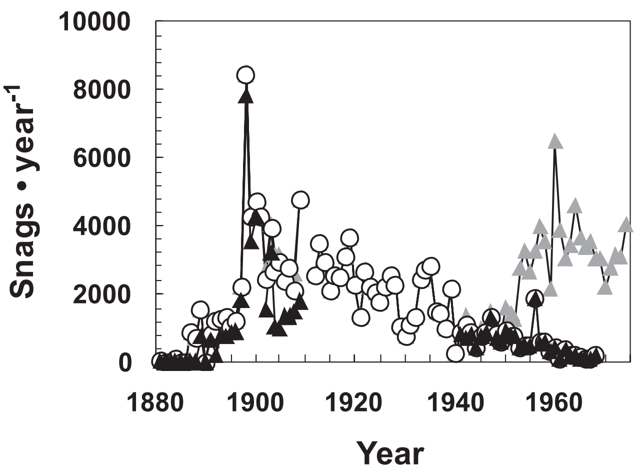


Fig. 4. Snags removed from Puget Sound rivers, 1881–1970. Open circles, all Puget Sound rivers; solid triangles, Skagit River only; shaded triangles, all Puget Sound rivers and harbors.

(Table 2), which we assume are the pieces a snagboat operator is most likely to have removed. About four pieces per river kilometre of these were recent. If we assume that recent wood encompasses pieces at most 10–20 years old, then this represents 0.2–0.4 pieces per river kilometre per year, or two orders of magnitude less than possible snag recruitment rates suggested by data from 1881–1909. In the Stillaguamish, our sampled reaches were upstream of the historically snagged reach, which was primarily the lowest few kilometres.

Size and species of wood from historical records

We know of two quantitative indicators of the size of historic wood in Puget Lowland rivers. The snagboat captain's records, which include the largest diameter of snags and trees annually removed, indicate that very large pieces were represented in the wood load, the annual maximum diameter between 1889 and 1909 ranged from 3.6 to 5.3 m (U.S. War Department 1889–1909). These very large diameters are confirmed by engineers' observations (e.g., U.S. War Department 1895).

Witness tree records in field notes of the federal General Land Office cadastral surveys include tree size and species. These are a second, more extensive data source, indicating the diameter of trees potentially recruited to the river. These trees include a significant number with diameters large enough to form key pieces in jams. For example, on the floodplains of the Nisqually, Stillaguamish, and Snohomish rivers, the largest 40, 20, and 30%, respectively, of witness trees were greater than 0.5 m in diameter, and 15, 7, and 7%, respectively, were larger than 1.0 m in diameter (Fig. 5). Trees were smaller in the immediate streamside (riparian) areas (Fig. 5). Comparing these tree size distributions with the minimum diameter of wood that form key pieces in the Nisqually, about 40% of witness trees on the Nisqually floodplain and 30% of streamside witness trees were large enough to potentially form key pieces (Fig. 3*c*).

Historical changes in geomorphic- and habitat-forming processes

To explore how historical changes in the type, size, and frequency of wood accumulations may have influenced river processes and morphology, we evaluate aspects of the riverine system at three scales: pools; channel pattern; and wood, sediment, and water routing.

Pools

We measured 85 pools in the Nisqually River study reach, a pool spacing equivalent to 1.4 CW·pool^{-1}. Roughly one-third were formed without influence of wood, 31% were formed by flow convergence at the outside of bends or at flow confluences, and 8% were formed where the river flowed against a valley-wall bluff (Fig. 6*a*). Individual wood pieces formed 18% of pools, and multiple wood pieces augmenting free-formed pools also formed 18%. Jams created the remaining one-fourth (26%). In total, wood was the dominant factor forming 61% of pools. This is similar to the finding of Abbe and Montgomery (1996; Fig. 3) in a 25-km-long reach of the Queets River where wood formed 70% of observed pools. Jam-formed pools in the Nisqually River were on average three times deeper than free-formed pools and two times deeper than pools formed by individual pieces having attached rootballs, augmented by wood, or formed by banks (Fig. 6*a*).

In the Stillaguamish River, we measured 84 pools in three sample reaches (Fig. 6*b*). Pool spacing ranged between 3.0 and 5.0 CW·pool^{-1} in the three subreaches, or one-half to one-third as many pools as in the Nisqually River. More than half formed along riprap-armored banks. Another one-quarter (27%) were free-formed alluvial pools. Only 11% were formed by wood. The remainder (10%) formed along valley-wall banks, bedrock, or boulders. Average residual pool depth was significantly greater for pools formed by riprap vs. pools along natural banks.

In the Snohomish River, we measured 18 pools in an 8.5-km-long reach, beginning at the confluence of the Snoqualmie and Skykomish rivers (Fig. 6*c*) for a pool spacing of 3.0 CW·pool^{-1} (i.e., half the number of pools in the Nisqually River). Wood formed only one relatively shallow pool. Riprap banks were the most common pool-forming factor and also formed the deepest pools (Fig. 6*c*); one such pool was 7 m deep. Several rock outcroppings in the reach were the second most important pool-forming influence and formed the second deepest pools on average.

Channel pattern and channel–floodplain interactions

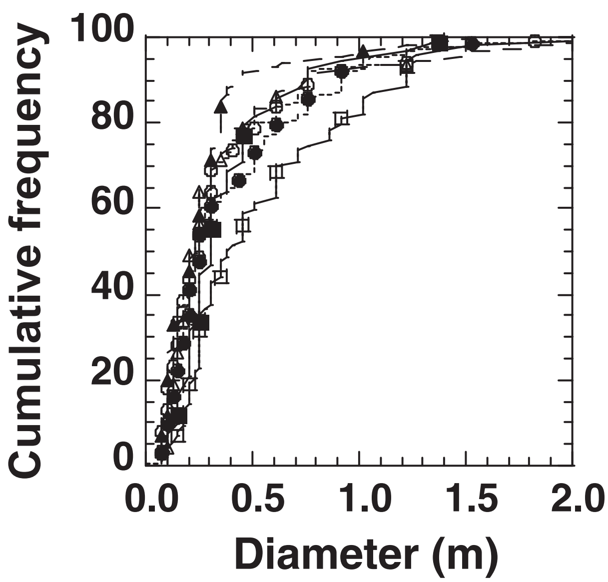
The Nisqually River has an anastomosing channel pattern, with multiple main channels and numerous perennial floodplain sloughs connecting at both ends with a main channel (fig. 6*a* in Collins and Montgomery 2001). This contrasts with the Stillaguamish River, which has a single channel, except for one remaining flow split, and no floodplain sloughs. Maps and aerial photos indicate that the Stillaguamish River formerly had a channel pattern similar to that of the Nisqually (fig. 6*b* in Collins and Montgomery 2001). This same anastomosing pattern characterizes historical map and aerial photo views of several other Puget Lowland rivers. Our field studies of the Nisqually, combined with analyses of aerial photos of the river valley from 1937 to 1999 and maps beginning with 1859, indicate that wood jams caused frequent avulsions that helped to maintain multiple channels

Table 2. Average number of wood pieces per river kilometre at different depths in the low-flow channel of the sampled reaches of the Snohomish and Stillaguamish rivers for use in comparison to de-snagging records (see text).

Depth category	Snohomish River, mean ± SD (pieces·km^{-1})	Stillaguamish River, mean ± SD (pieces·km^{-1})
Low-flow margin	48.5 ± 52.6 (*n* = 12)	22.67 ± 19.3 (*n* = 6)
>1.2 m	4.1 ± 8.1	0.0
0.6–1.2 m	12.1 ± 20.2	0.0
0–0.6 m	13.6 ± 13.3	3.5 ± 5.5
Snag	18.7 ± 15.6	19.2 ± 17.3
Low-flow middle	24.1 ± 50.0 (*n* = 21)	9.3 ± 9.8 (*n* = 6)
>1.2 m	3.4 ± 4.9	0.0
0.6–1.2 m	2.6 ± 4.2	0.3 ± 0.8
0–0.6 m	4.7 ± 12.1	0.5 ± 0.8
Snag	13.4 ± 35.6	8.5 ± 9.5
Total	72.6	32.0 ± 28.7

Note: Depths were visually estimated or measured. Sample size is the number of reaches. Reaches are all 1 km in the Stillaguamish; reaches of varying length in the Snohomish are normalized by reach length. SD, standard deviation.

Fig. 5. Cumulative frequency distribution of witness tree diameters from field notes of the General Land Office for the Nisqually (squares and solid lines), Stillaguamish (triangles and long-dashed lines), and Snohomish rivers (circles and short-dashed lines) in the study reaches. Solid symbols represent "streamside" trees and open symbols represent "valley bottom" trees.



and perennial floodplain sloughs (Collins and Montgomery 2002).

Water, sediment, and wood routing at the valley-bottom scale

Early descriptions indicate that raft jams diverted high flows onto floodplains. Field reports by the Army Engineers indicate that such a jam on the Skagit River at Mount Vernon (Fig. 7*a*) caused floodwaters to frequently recharge extensive (~150 m^2, U.S. War Department 1898) wetlands.

> The obstruction caused by this jam to the free flow of the flood waters prevented the low lands farther down the river being flooded, but it caused the flooding of the entire country known as the Olympia and Beaver Marsh country, to the west of the Skagit River, between the present location of the town of Avon and Padilla Bay. [U.S. War Department 1898]

Removal of the jam shifted flooding downstream and allowed settlers to drain wetlands and establish farmland (U.S. War Department 1881 (Fig. 7*b*). Enhanced routing of high flows onto the floodplain would have also routed larger amounts of fine sediment to floodplains rather than to estuarine environments. It is possible that raft jams in the region induced deposition of sediment wedges, as documented for historical Red River rafts (Triska 1984; Harvey et al. 1988).

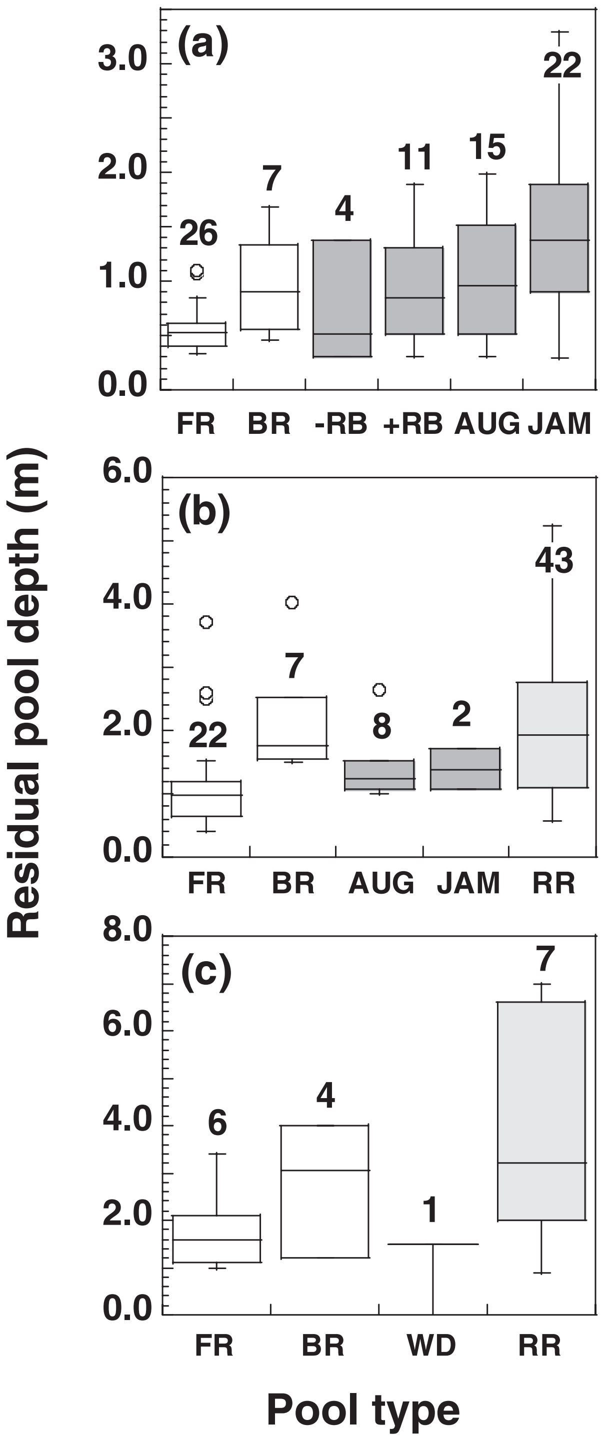
Jams also shaped the geomorphic evolution of deltas. Removal by settlers in 1892–1893 of a jam at the head of Hat Slough, formerly a minor distributary slough on the Stillaguamish River, shifted the river's main flow into it, which has subsequently shifted the location of delta and progradation and marsh creation. Changes to a jam on the Nooksack River (Fig. 1) caused a similar course change in the mid-1800s (U.S. War Department 1893).

Discussion

Archival materials suggest that the study reach of the Nisqually River is in many respects relatively unchanged from its mid-19th century condition. The present-day distribution of tree sizes on the Nisqually floodplain closely resembles the size distribution in 1873 (Collins and Montgomery 2002), and the present-day channel pattern is similar to earlier aerial photos dating to 1937 and maps dating to 1859. It also appears reasonable to compare the Nisqually River with the historical Stillaguamish River. The mid-19th century valley-bottom forests of the Stillaguamish had tree sizes comparable to those of the Nisqually. Archival accounts indicate wood jams were abundant in the Stillaguamish River; the Stillaguamish, with a similar width as the Nisqually, formerly had an anastomosing pattern similar to that of the Nisqually.

The Nisqually is less comparable to the Snohomish. Although the Snohomish River had a riparian forest comparable with those of the other two rivers, it does not appear to

Fig. 6. Number of pools (above bars) and residual pool depth, by primary pool-forming factor, in the (*a*) Nisqually, (*b*) Stillaguamish, and (*c*) Snohomish rivers. Pool-forming factors: FR, free-formed alluvial; BR, bedrock forced; –RB, wood piece without rootball; +RB, wood piece with rootball; AUG, wood augmented; JAM, wood jam; RR, riprap armored bank; WD, wood. Numbers on plots are the sample size.



have had as much wood. This may be due in part to the larger size of the Snohomish. Perhaps more importantly, early maps show that the Snohomish did not have an anastomosing pattern but instead had a single, meandering channel with associated oxbow lakes and extensive floodplain wetlands (Collins and Montgomery 2001). Early mapping also shows that the Snohomish is similar in this regard to other rivers in broad, low-gradient valleys created by Pleistocene subglacial runoff (e.g., the Snoqualmie, Duwamish, and lower Nooksack). The Stillaguamish and Nisqually, on the other hand, are typical of rivers in valleys formed by postglacial incision (e.g., the upper Nooksack, Skykomish, and Skagit). It is possible that the two different types of river dynamics and morphologies, created by contrasting late Quaternary histories, also had different wood loads and wood functions; in particular, the less dynamic, meandering rivers in Pleistocene glacial valleys (such as the Snohomish) had less wood. Artificial channel straightening, levees and bank hardening, and the loss of streamside forests have caused the two different river morphologies and dynamics to converge in their current condition, obscuring differences that existed before European settlement that now can only be discerned from the archival record.

Comparing the Nisqually to the other two rivers in their contemporary condition shows strong contrasts. The Nisqually River had 8 and 21 times more wood than the Snohomish and Stillaguamish, respectively. Wood jams account for most of the difference; excluding jams from the Nisqually wood count, the amount was comparable with the other two rivers. We suspect that few jams occur in the Snohomish and Stillaguamish rivers for two reasons. One is the absence of long, large-diameter pieces with rootballs, which in the Nisqually River act as key pieces that initiate and stabilize jams. These largest pieces of wood are no longer available to the Snohomish and Stillaguamish rivers, which have lacked mature riparian forests for more than a century (e.g., Plummer et al. 1902). Recent wood recruitment is dominated by smaller, more readily transportable, and less decay-resistant younger hardwoods.

Another reason for fewer wood jams in the Snohomish and Stillaguamish relative to the Nisqually is the lower recruitment rate of wood, because the leveed rivers cannot laterally erode their floodplain (which also generally lacks a riparian forest). The presence of two upstream dams on the Nisqually River makes that river's greater accumulation of wood all the more remarkable and points to the importance of local wood recruitment. In contrast, neither the Stillaguamish nor Snohomish is dammed and thus have no limit on wood transport from upstream. Finally, the Snohomish and Stillaguamish rivers probably retain less wood for less time than the Nisqually, because wood is more readily transported through a river that does not trap it in jams. Jams potentially retain wood for years to decades in the active channel and then for decades to centuries or more in the floodplain when the river migrates or avulses away from a jam.

The change in size and quantity of wood that may be recruited may partially account for the paradigm that "wood is more easily transported in large channels [of the Pacific Northwest], leading to a reduction in the amount and aggregation of the remaining pieces" (Bilby and Bisson 1998). But in the Nisqually River, the abundance of wood is much greater per channel width than predicted by extrapolating from data from smaller streams (fig. 13.2 in Bilby and Bisson 1998). Thus, to some degree the generalization that wood plays a diminishing role in channel structure as

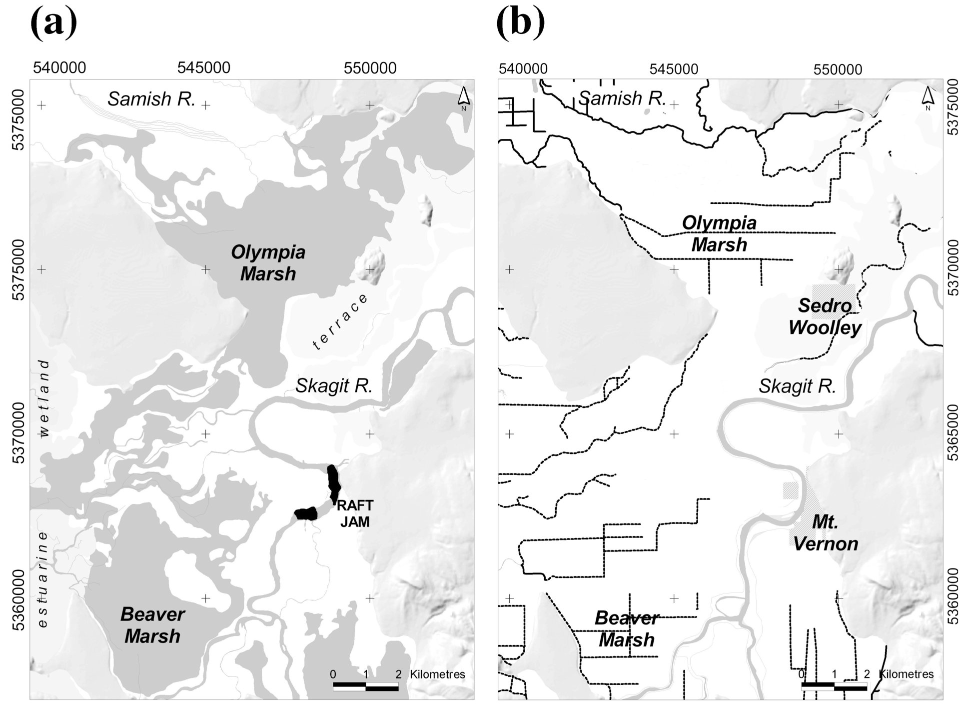


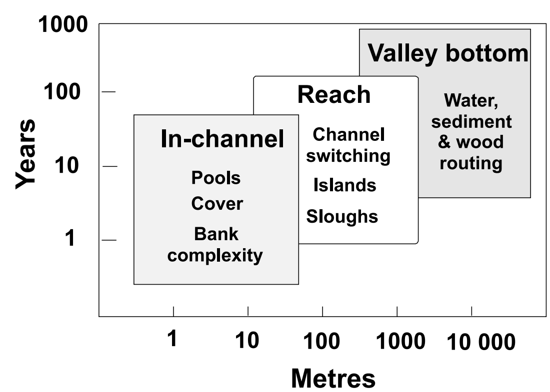
Fig. 7. (*a*) Freshwater wetlands, channels, and raft jams on the Skagit River delta in the late 1800s. Mapping is from General Land Office plat maps and field notes (1866–1873) and U.S. Army Corps of Engineers 1898 map “Index map of Skagit River, from its mouth to the town of Sedro, Washington”. (*b*) The same area in 1943 from 1 : 62 500 scale topographic maps.

streams increase in size reflects the cumulative effect of human actions.

Large wood had a dominant influence on the geomorphology and aquatic habitat of large western Washington rivers at different temporal and spatial scales (Fig. 8). At the in-channel scale, wood formed 61% of pools in the Nisqually, comparable with the 70% reported by Abbe and Montgomery (1996) for the Queets River, but wood forms few pools in the present-day Stillaguamish and Snohomish rivers (12 and 6%, respectively). Moreover, wood-created pools, especially those created by jams, are deeper than those not created by wood. Comparing pool data from the Snohomish and Stillaguamish rivers with data from the Nisqually suggests that the transition from a freely migrating or avulsing river with mature floodplain forest to a leveed river with little riparian recruitment has reduced the number of pools by two to three times. Although artificially hardened banks appear to create deeper pools, pool depth alone is not sufficient to create high-quality habitat because wood also adds cover and complexity to pools, increasing their habitat value (e.g., Bjornn and Reiser 1991).

At the reach scale, jams in some rivers maintained multiple channels and islands and created and maintained floodplain sloughs. The historical reduction in the total amount of channel edge in the Stillaguamish River (Beechie et al. 2001) and to a lesser extent in the Snohomish River (Haas and Collins, unpublished data) reflects this simplification of channel pattern. Field studies in the Skagit River indicate that wood (particularly wood jams) significantly increases the fish habitat value of riverbanks; for example, use by subyearling chinook salmon (*Onchorhynchus tshawytscha*) was five times greater when wood was present (Beamer and Henderson 1998).

Fig. 8. The temporal and spatial scales at which wood accumulations influenced lowland Puget Sound rivers.



At the valley-bottom scale, large jams may have had a dominant influence in lower-gradient rivers on the routing of water, sediment, and wood and on floodplain-forming and floodplain-maintaining processes. Jams, especially raft jams, increased flooding and the recharge of vast floodplain wetlands in lower gradient rivers such as the Snohomish and the Skagit deltas. These wetlands would have provided extensive amounts of habitat for fish and wildlife and rearing habitat for juvenile salmonids (Groot and Margolis 1991).

The morphology and habitat of Puget Lowland rivers now differ in fundamental ways from their mid-19th century condition. Moreover, it is likely that wood abundance in rivers such as the Stillaguamish and Snohomish will continue to decline as relict wood decays and is exported; the reduced retention associated with an absence of jams has a positive feedback on wood loss. With minimal replacement from an altered riparian forest, targets or “reference conditions” for river and habitat restoration must take these historical changes, and likely continued change under current conditions, into account. Other temperate forest regions of the world that have experienced historical deforestation and clearing of wood from channels may have experienced changes similar in scope and magnitude to those documented here.

Acknowledgments

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