# 4. Reconstructing the Historical Riverine Landscape of the Puget Lowland

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## ABSTRACT

Human activities in the last 150 years greatly altered the riverine landscape and salmonid habitats of the Puget Lowland. Archival investigations together with field studies of relatively undisturbed rivers make it possible to describe the landscape prior to settlement by Euro-Americans. Landforms, dynamics, and habitats in lowland river valleys and estuaries varied broadly with differences in regional geologic history. Rivers that incised a Holocene valley through Pleistocene glacial sediments typically had an anastomosing pattern with multiple channels, floodplain sloughs, and frequent channel-switching avulsions, due in large part to wood jams. In contrast, rivers in broader, lower-gradient valleys created by runoff below Pleistocene glaciers generally had a single-channel meandering pattern, with oxbow lakes, infrequent meander-cut-off avulsions, and vast floodplain wetlands. Because wood appears to have strongly influenced riverine dynamics at a wide range of scales, floodplain forests are central to river restoration. Archival sources can characterize species and diameters of trees in historical forests and the geomorphic, hydrologic, and geographic variables influencing them; process studies indicate conditions and wood characteristics necessary for jam formation. Regional differences in channel morphologies, processes, suites of valley-bottom landforms, and forests, combined with different land-use histories, have important implications for the rationale, approach, and land area needed in restoring lowland river and forest ecosystems.

## RIVER HISTORY AND THE PUGET LOWLAND

A century and a half of development since European settlement has transformed the appearance and function of Puget Sound's riverine landscape. Human inhabitance has been most extensive and landscape change most noticeable in lowland river valleys, eradicating or degrading much of the region's historically richest and most abundant salmonid habitat (Sedell and Luchessa 1981; Beechie et al. 1994, 2001; Collins and Montgomery 2001). This river-use history is not unique to Puget Sound. The same has occurred worldwide: as riverine landscapes were more intensively inhabited, "civilized" rivers became physically simplified and biologically impoverished (e.g., Vileisis 1997; McNeil 2000). However, the relatively-recently settled Puget Lowland is unusual in having remnant natural areas and a wealth of archival sources describing pre-settlement conditions (we use the term "pre-settlement" as an abbreviated reference to "prior to settlement by Euro-Americans"). These circumstances make it possible to reconstruct on paper the historical river as an aid to undertaking river rehabilitation or restoration.

The problem of reconstructing badly degraded landscapes or landscapes that no longer exist spans the intersection of diverse disciplines including archaeology, ecology, landscape ecology, ethnobotany, palynology, and history, to form the field of historical ecology (e.g., Egan and Howell 2001). Environmental history, which includes a focus on understanding the political, social, and cultural forces behind landscape change and how those changes in turn shape society, overlaps with and complements historical ecology (e.g., White 1992; Whitney 1996). Reconstructing the riverine environment of Puget Sound can draw on the methods of these disciplines but also must be grounded in geology and process geomorphology, because the region's riverine landscape is geologically young and physically dynamic, and its ecosystems are closely linked to physical processes.

### *The Geologic Setting*

Seven major watersheds drain the western Cascade Range to Puget Sound (Figure 1), ranging in size from the 1,770 km$^2$ Stillaguamish to the 7,800 km$^2$ Skagit. Steep mountain headwater slopes lessen in mountain valleys and decrease dramatically in the Puget Lowland. In the lowland, deep, generally north-south trending troughs either partially filled with sediments or by Puget Sound or other water bodies, are a dominant topographic feature (Chapter 2). Repeated advances by the Puget Lobe of the Cordilleran ice sheet created these valleys at least in part by subglacial fluvial runoff (Booth 1994). Sev-

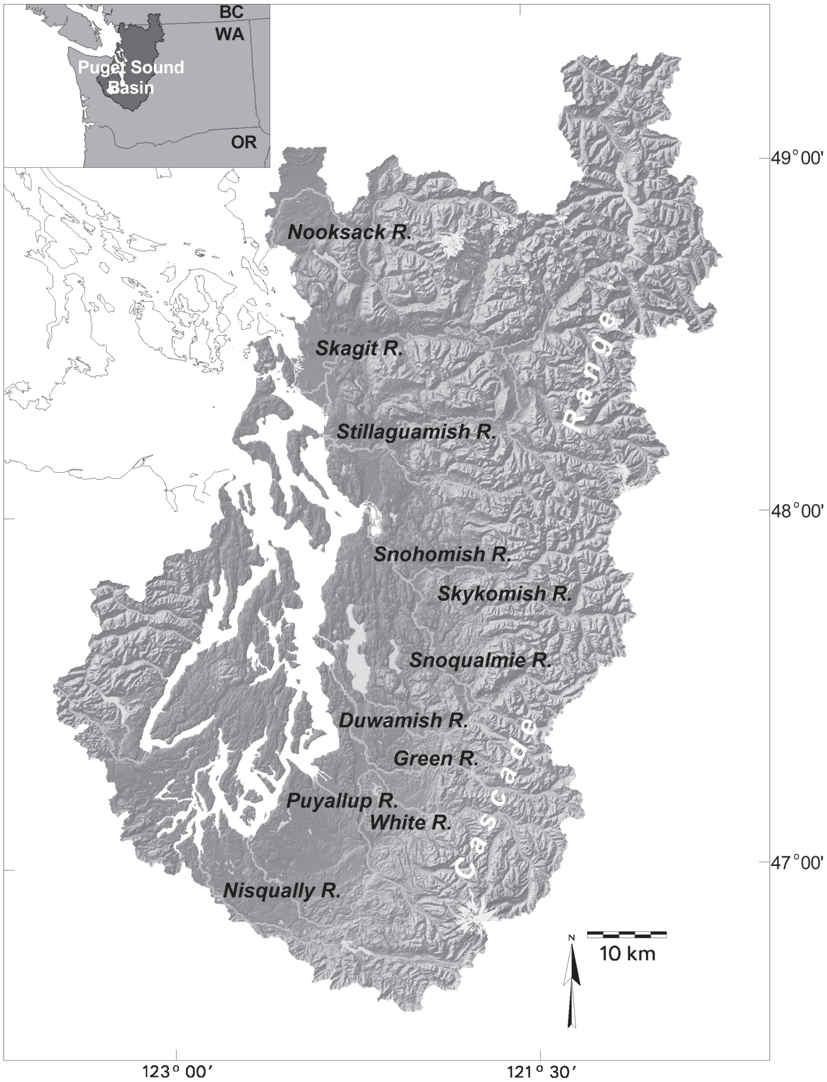


Figure 1. Location of watersheds and rivers in eastern Puget Sound.

eral major rivers have found a post-glacial course through these Pleistocene troughs, including the lower Nooksack, the Snohomish, Snoqualmie, Sammamish, Duwamish, and Puyallup Rivers (Figure 1). These valleys have a low gradient and are typically 3–5 km wide. Other rivers cut across the lowland glacial fabric, and incised steeper and narrower (1–2 km wide) post-glacial (Holocene) valleys. These include the upper Nooksack, the Stillaguamish, and Nisqually Rivers.

Various post-glacial forces modified (and continue to modify) this Pleistocene legacy. Holocene fluctuations of sea level and isostatic rebound changed the extent of subaerial valley bottom (Beechie et al. 2001), especially in north Puget Sound where isostatic effects were greatest (Thorson 1989). Voluminous lahars from eruptions of Glacier Peak volcano inundated the Sauk, Skagit, and Stillaguamish Rivers (Beget 1982); remnants of lahar deposits since incised by fluvial erosion can be found in each of these three valleys. These lahars also extended the Skagit River delta greatly seaward (Dragovich et al. 2000). At least 60 Holocene lahars moved down valleys heading on Mount Rainier (Hoblitt et al. 1998), many of which traveled into the White and Puyallup Rivers (Figure 1). Mount Rainier's National Lahar traveled from the Nisqually River to Puget Sound less than 2,200 ybp (Hoblitt et al. 1998).

These lahars have been most influential in shaping channels and habitats in valleys that are transitional—geographically, as well as in gradient and width—between the mountains and the lowland. In north Puget Sound, these include the Skagit, Sauk, North Fork Stillaguamish, and Skykomish; each valley includes terraces of Pleistocene glacial and Holocene lahar sediments, through which the river has incised (Beechie et al. 2001). In the less-glaciated south, such lowland-to-mountain transitional valleys as the White and upper Puyallup are more heavily influenced by the presence of lahar deposits. For example, the White River is cutting a deep canyon through deposits of the 5,600 years before present (Hoblitt et al. 1998) Osceola Mudflow. In this chapter, we concentrate on lowland rivers, but many of the concepts we develop can be applied to these smaller, transitional, mountain-valley streams as well.

## *Can We Know the Past with any Certainty?*

Our knowledge of historical environments, especially those greatly changed by anthropogenic forces, is inherently uncertain. This uncertainty reflects the incomplete views through the available windows onto past landscapes as well as the spatial and temporal variability of landscape processes. In light of this uncertainty, how reliably should historical reconstructions be viewed?

The answer depends on the methods used. Using independent methods with overlapping temporal and spatial scales, and cross-referencing between archival studies and field investigations can define and reduce uncertainty. By using both cross-referenced and multi-scaled methods, we can hope to see the past clearly enough to confidently develop and evaluate restoration objectives.

Our reconstruction of the landscape is necessarily limited to conditions that existed in the mid 19th century, or around the time when non-native settlers arrived, because for the time prior to the written record we can only make broader, less detailed descriptions using indirect field methods. However, it is possible to supplement this snapshot-in-time with inferences about long-term (Holocene) landscape and ecosystem evolution and more rapid change. For example, forest composition in the region probably attained modern characteristics approximately 6,000 ybp (Barnosky 1981; Leopold et al. 1982; Cwynar 1987; Brubaker 1991). The interplay of isostatic uplift, river incision and sea level change is slow and causes only minor change over the time frame of a few centuries. We have recent analogs to draw on for understanding the effects of intermittent, dramatic disturbances to river valleys such as volcanic lahars (e.g., from the 1980 eruptions of Mt. St. Helens) and earthquake-associated uplift. Archival and field studies can adequately characterize the changes occurring on decadal and more frequent time scales. Moreover, many agents of anthropogenic change over the last ~150 years have been much more rapid than natural processes.

We refer to the “historical” landscape rather than the “natural” environment, because people have inhabited the Puget Lowland at least since the glaciers last retreated. While there are ethnographic studies of fisheries management, few studies exist on native practices that would have modified the ecology or morphology of the riverine landscape, such as by native plant cultivation or gathering (e.g., Gunther 1973; Turner 1995) or burning practices. It should be understood that the landscape we seek to reconstruct was indeed a landscape, resulting from a fusing of cultural and natural influences that included native land-management practices.

## METHODS FOR RECONSTRUCTING THE HISTORICAL LANDSCAPE

### *The Synergy of Archival and Field Studies*

Archival studies and field investigations both contribute toward understanding the historical landscape of Puget Sound. For example, a reach of the lower Nisqually River that passes through the Fort Lewis Army Base and the Nisqually Indian Reservation has retained natural banks and a mature valley-bottom forest throughout the last 150 years, and it displays many of the morphological and biological characteristics of river valleys in their pre-settlement condition (Collins and Montgomery 2001; Collins et al. 2002). It can thus function as an historical analog. Field studies are useful for providing information at a small scale, giving insight into form and process that cannot typically be discerned from archival sources.

However, without an archival reference standard, it is difficult to be certain whether and in what ways this (or any) field site represents pre-settlement conditions. First, an isolated landscape fragment may not necessarily include processes and features that formerly operated at larger scales, for which archival sources may help to generate hypotheses. Second, a single 10 km-long reach cannot represent the variation in river dynamics, geologic setting, and forest conditions throughout the entire region, making archival investigations necessary for describing the historical geographic variability.

The two approaches are thus complementary (Figure 2): Archival sources help in generating hypotheses about processes that formerly operated throughout the historical landscape, for which field studies can then generate particular process models. Such process models provide the basis for designing effective river management and habitat restoration and conservation schemes, and thus the basis for applying models to a given location. Without the perspective of archival sources, there is the risk of focusing only on insights from contemporary process studies and overlooking landscape-scale features and processes that no longer exist. For example, a focus on a 15 m-wide streamside buffer on a leveed, lowland river would neglect the fact that most riverine habitat may historically have been in sloughs, ponds, and wetlands hundreds

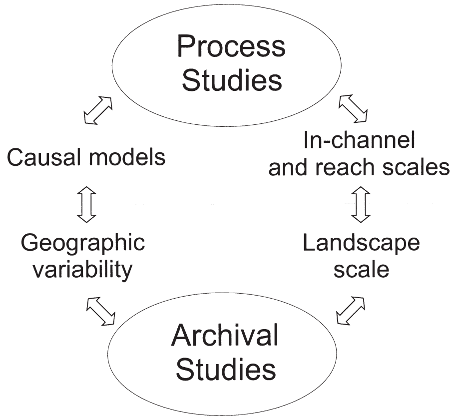


Figure 2. Synergy of archival and field studies in characterizing historical riverine processes and habitats.

or thousands of meters from the river. Without an understanding of the larger scale, management efforts risk managing the microcosm, instead of addressing structures or processes that exist(ed) or operate(d) at a landscape scale. Because of this complementarity of field and archival studies—their different emphases of scale, and process versus regional variability—the two work in an iterative and synergistic way toward characterizing historical riverine processes and environments.

## ***Mapping a Forgotten Landscape***

We are developing a methodology for mapping historical river landscapes and their aquatic habitat that brings archival materials into a geographic information system (GIS), supplementing that data with modern digital elevation models (DEMs), aerial photography, and process understanding gleaned from field studies. The approach synthesizes historical materials and the modern tools of GIS and remotely-sensed imagery (Figure 3).

Maps and field notes of the General Land Office (GLO), which conducted a cadastral survey of the Puget Lowland between about 1850 and 1890, are a fundamental resource. Carried out in nearly all river valleys (and uplands) prior to and in preparation for the arrival of settlers, this survey preceded widespread building of sea or river dikes and stream clearing and floodplain logging. It is a unique resource for characterizing riverine conditions prior to Euro-American settlement.

The GLO field notes include information on natural vegetation, which botanists have used since at least the 1920s (Sears 1925) to reconstruct presettlement vegetation cover (for reviews see Whitney 1996; Whitney and DeCant 2001; for recent examples see Galatowitsch 1990; Nelson et al. 1998). The same information is also useful for characterizing riparian and valley bottom forests, including the size and species of recruitable wood and for mapping and characterizing riverine wetlands (North and Tevarsham 1984; Collins and Montgomery 2001), prairie or savannah areas (Radeloff et al. 1999), and changes to channel widths (Knox 1977).

These data include “bearing” or “witness” tree records from reference points at the corners of mile-square sections and half way between corners (“quarter corner” points), where surveyors measured the distance and compass direction to several nearby trees. Surveyors were instructed to identify four witness trees at section corners and two at quarter-corner boundaries. If there were no trees nearby, surveyors built a mound of earth. In their field notes, surveyors recorded the diameter and common name of each witness tree and the distance and bearing to it. In addition to these regularly-spaced points, survey-

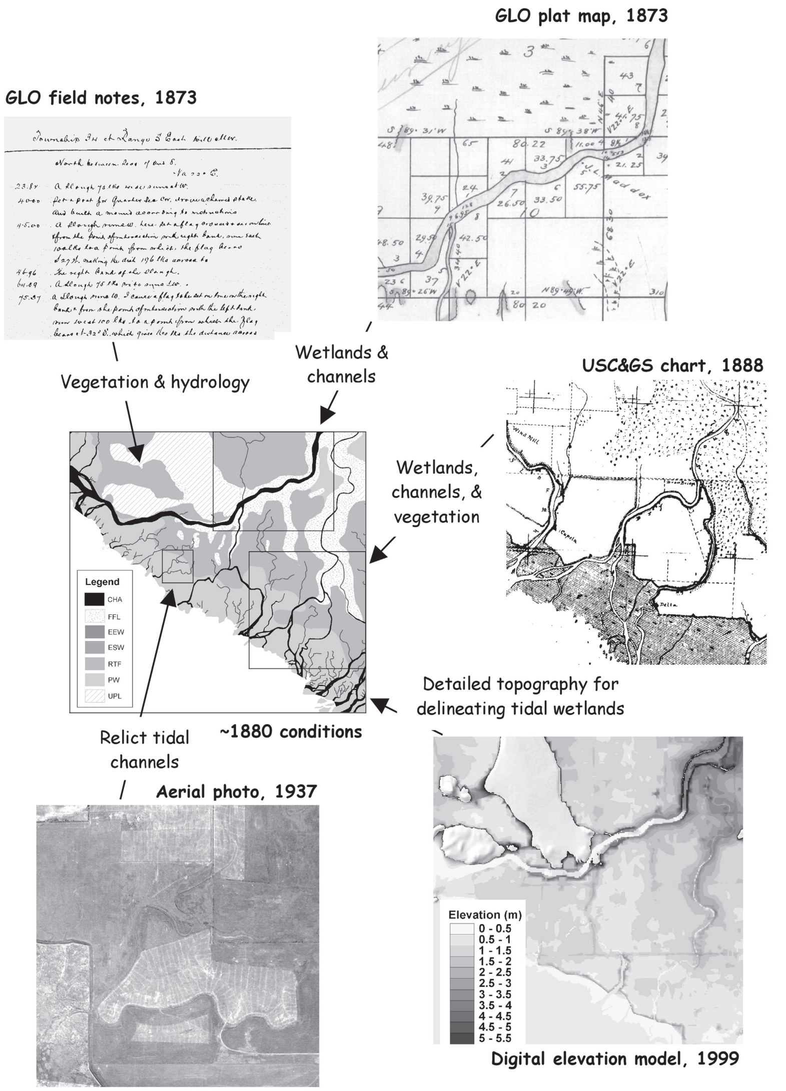


Figure 3. Example of the use of archival materials, field studies, aerial photographs, and digital elevation models (DEMs) in a GIS to map the historical riverine environment.

ors also established “meander corner” points where section lines intersected the banks of navigable rivers and sloughs and documented two bearing trees. These meander points allow us to characterize separately streamside trees from other valley-bottom trees.

Because instructions issued by the GLO evolved over time (see White [1991] for a compilation of instructions to surveyors), field notes must be interpreted in light of the instructions current for that time and region. For example, various criteria for selecting bearing trees were published, which in turn might have differed from actual field practice (see Collins and Montgomery [2002] for details on interpreting field notes in the Puget Lowland). One important bias in characterizing species frequency and size results from bearing trees being greater than 7.5 cm in diameter. This means that bearing tree records under-represent smaller-diameter species (e.g., vine maple [*Acer circinatum*] and willow [*Salix spp*.]). On the other hand, we found that bearing tree records accurately characterize species frequency based on basal area (the percent of the sum of cross-sectional area of all trees accounted for by the cross-sectional area of any one species). We determined this by relocating 1873 survey points in the Nisqually valley bottom and establishing bearing trees following our interpretation of the instructions to surveyors in effect for the 1873 survey, and comparing results to plots in which we recorded species and diameter of all trees larger than 0.01 m in diameter (Collins and Montgomery 2002).

In addition to recording witness trees, surveyors were instructed to note land and water features they encountered, including major changes to the plant community, streams and marshes, and the width of all “water objects.” Springs, lakes and ponds and their depths, the timber and undergrowth, bottomlands, visual signs of seasonal water inundation, and improvements were also to be noted along section lines. The completeness of this information varies from surveyor to surveyor, but it nonetheless provides important secondary data for interpreting the landscape. For example, the date at which observations of water depth were made by surveyors, and their notes on indicators of seasonal water depths can be used to characterize summer and winter water depths in wetlands.

The GLO maps and field notes reflect field observation only along section boundaries and navigable channels. Within sections, the maps include many wetlands with indeterminate boundaries, and wetlands or smaller (non-navigable) channels that are drawn speculatively, sometimes in locations that are improbable or impossible when compared to modern topographic mapping. Other archival sources and modern information can be used to map wetlands and small channels within section interiors and also to confirm or add data along section lines. For example, early U. S. Coast and Geodetic Survey

(USC&GS) charts of coastlines and coastal rivers provide more spatially continuous data to the up-stream limit of navigation (generally a few tens of kilometers inland) than do the GLO maps. The charts also delineate forest, salt marsh, freshwater marsh, and cultivated fields. In eastern Puget Sound, the USC&GS made detailed and accurate charts in the late 1870s to late 1880s at a scale of 1:10,000 or 1:20,000. Although most of the charts post-date some amount of tidewater diking, they are the basis for estimates of estuarine wetland loss in Puget Sound (Bortleson et al. 1980); these earlier estimates thus cannot take into account wetland areas diked prior to the USC&GS mapping.

Beginning in 1876 the U.S. Army Engineers filed annual reports on field investigations of western Washington rivers (Annual Reports of the Chief of Engineers, U.S. War Department; hereafter abbreviated U.S. War Department). Their river descriptions highlighted wood because it created hazards for, or often completely blocked rivers to, steamboat navigation. After 1880, army engineers began clearing this wood and by the end of that decade developed a regular program of "snagging" that continues to this day. Other useful sources of historical information include U.S. Department of Agriculture and Bureau of Soils reports and maps (e.g., Nesbit et al. 1885; Mangum et al. 1909); settlers accounts; contemporary histories (e.g., Interstate Publishing Company 1906); photographs (the earliest useful photographs we have located are from the 1880s); and U.S. Geological Survey (USGS) topographic maps, starting in the 1890s.

More recent imagery and mapping add spatial resolution and accuracy. Modern vertical stereo aerial photography in western Washington began in the 1930s. These early aerial photographs show, for example, relict swales and vegetation patterns indicative of channels filled in during the previous half century, or relict patches of wetland or forest that—when georeferenced and brought into a GIS—can be interpreted, in conjunction with archival map sources. Recent soils mapping (e.g., Debose and Klungland 1983) can also offer clues to historical vegetation and wetlands. Digital elevation models made from aerial photogrammetric data or LIDAR (Light Distance and Ranging) in the last decade, by providing detailed, spatially continuous topography, help to delineate depressional wetlands, or estuarine or riverine-tidal wetlands with elevation-related boundaries (Figure 3). (In describing wetlands, we follow the system of Cowardin et al. [1985], although we use "riverine-tidal" to refer to wetlands created by tidal backwater effects.)

The resulting map interpretations of the historical landscape allow us to strip away the last 150 years of diking, draining, ditching, and channel clearing to gain a new view of river and floodplain morphology, including how valley morphology and river pattern varied throughout the region in response to the Pleistocene glacial legacy.

## Influence of Pleistocene Glaciation on River Pattern

Removing the modern cultural overprint from the riverine landscape reveals how the effects of Pleistocene glaciation fundamentally influence the nature and distribution of present-day (and historical) fluvial landforms and dynamics. The pattern of rivers in Pleistocene valleys created by subglacial runoff strongly contrasts with those in Holocene valleys that have been fluvially eroded. The Snoqualmie River exemplifies the former. This meandering river has a distinct meander belt several meters *higher* in elevation than the surrounding floodplain (Figure 4A). The elevated meander belt results from Holocene fluvial deposition as the river has built its gradient in the broad, low-gradient glacial valley. Topographic maps and DEMs show the same morphology in the Snohomish valley, which was also formed by Pleistocene subglacial runoff (Booth 1994).

Topography of the lower Nisqually River, by contrast, typifies steeper valleys created by post-glacial (Holocene) fluvial incision into glacial deposits (Figure 4B). The lower Nisqually has an anastomosing (or branching, multiple-channel) pattern, with local relief of 2-4 m created by multiple channels and forested islands. Historical maps and photographs and relict topography indicate that other rivers in Holocene valleys, such as the Stillaguamish River, formerly had a similar pattern (see later in this discussion; Figure 6).

The contrast between the two valley types, and the overriding importance of the erosional and depositional effects of Pleistocene glaciation on valley topography and river morphology, is clear in the Nooksack River (Figure 4C). A lobe of the Cordilleran ice sheet that extended southward into the Nooksack valley through the Sumas River drainage (Dragovich et al. 1997) sculpted the lower Nooksack River valley. Consequently, in the Nooksack downstream of the Sumas River drainage, the valley is broader and lower in gradient than upstream. Additionally, the floodplain of the lower Nooksack has extensive areas that are lower in elevation than the river channel, similar to the Snoqualmie River in Figure 4A, whereas upstream of the Sumas, the elevation varies across the valley bottom in association with multiple channels and islands, as in the Nisqually in Figure 4B.

Both types of river—aggrading, meandering rivers in Pleistocene valleys and anastomosing rivers in Holocene valleys—are responding to Pleistocene glaciation, but their responses are opposite. The first type is depositing sediment and building its grade within the gently sloping Pleistocene valleys, while the second is incising into the general Pleistocene drift surface.

These two different river patterns are also associated with very different river dynamics and associated floodplain landforms. For example, in the meandering Snoqualmie River, there are many oxbow ponds and wetlands, but

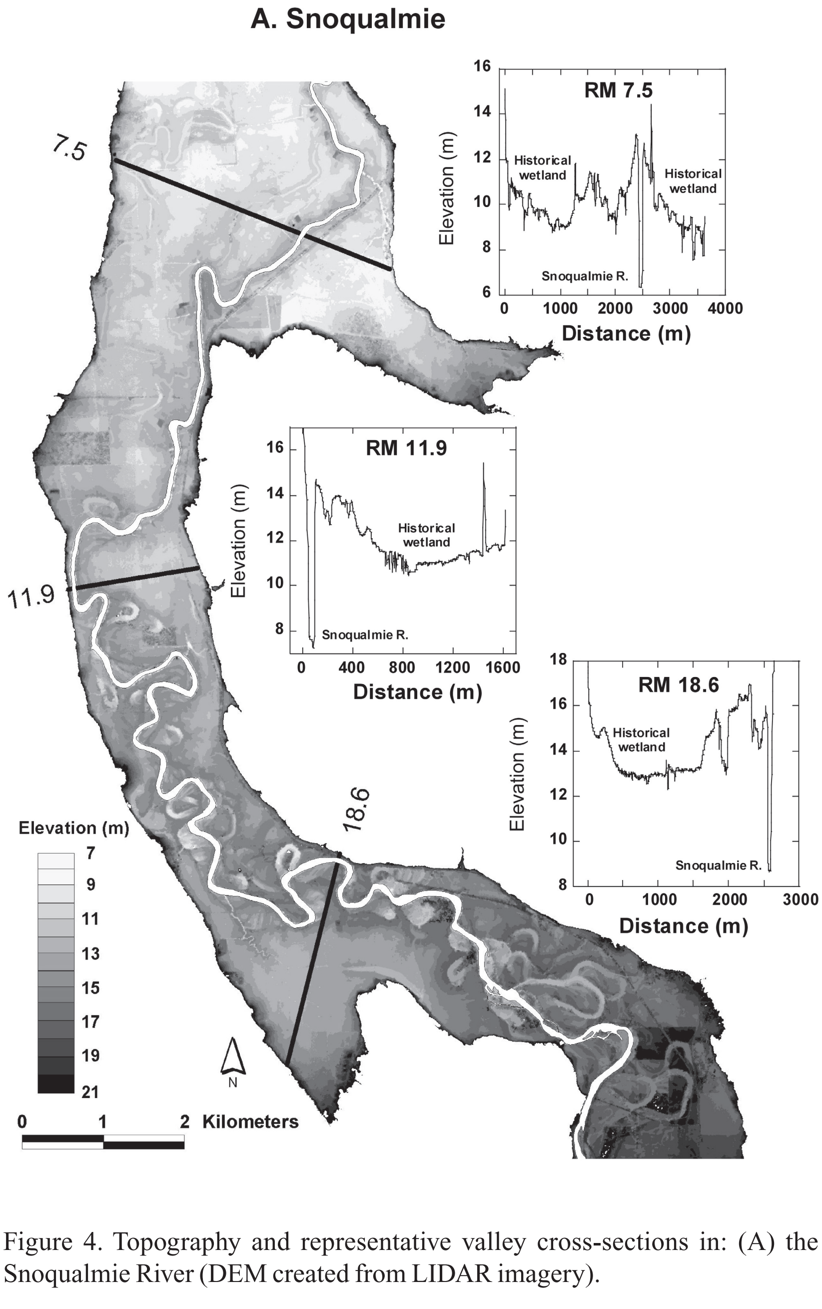
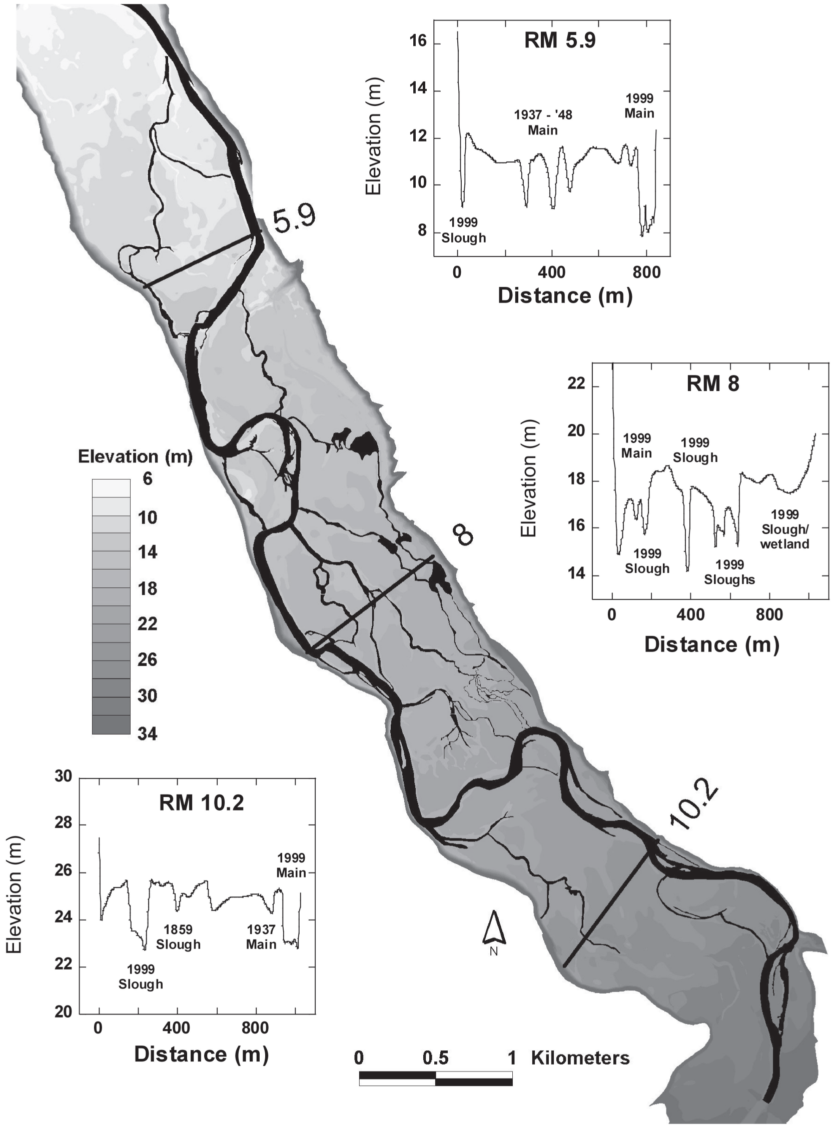


Figure 4. Topography and representative valley cross-sections in: (A) the Snoqualmie River (DEM created from LIDAR imagery).



B. Nisqually

Figure 4 (continued). (B) the Nisqually River (DEM created from topographic mapping from aerial photos).

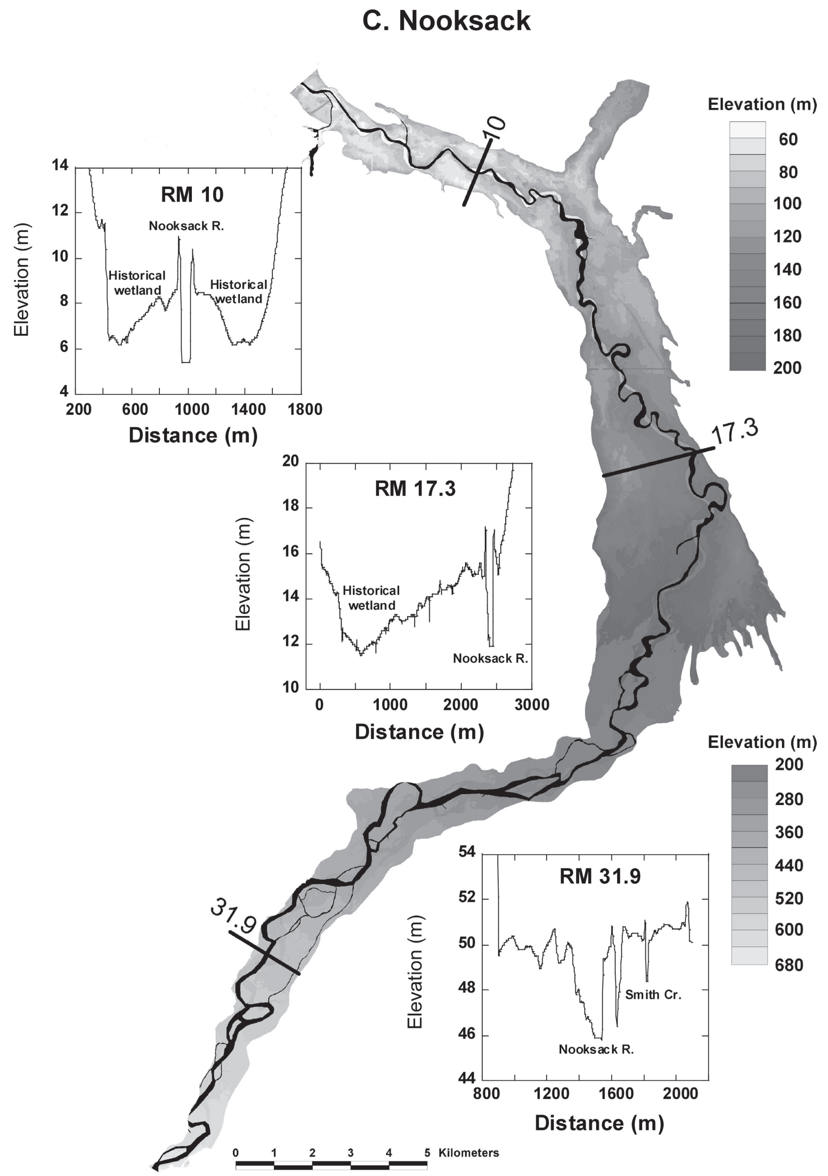


Figure 4 (continued). (C) Nooksack River valley (DEM created from photogrammetric data).

there has been little change in the river or oxbows in the 130 years since the earliest mapping (Figure 5A). Most oxbow lakes now present on the valley were present in 1870 (marked by “1” in Figure 5A). The river appears to migrate slowly and meanders to avulse—the process responsible for creating oxbows—infrequently. The greatest change to the Snoqualmie River valley over the period of historical record is not to channels or to ponds and wetlands formed in oxbows, but is instead the diminution of formerly extensive valley wetlands in low-elevation areas and the clearing of the valley bottom forest (see later discussion of Figure 13).

In contrast, channel positions mapped for the anastomosing Nisqually River over nearly the same period illustrate that river’s more frequent course changes (Figure 5B). In some areas the river migrates and river bends are cutoff, as in the Snoqualmie, and these cutoffs become sloughs. However, a second and more common type of avulsion is the river’s switching back and forth between multiple channels or from main channel to floodplain slough (we use floodplain slough to refer to a smaller, perennial stream that departs from and rejoins the main river, and which is generally formed in a relict main channel). Wood jams are integral to maintaining the Nisqually’s multiple-channel pattern and in causing and mediating avulsions. Preliminary analysis 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 commonly form at that split, thereby 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.

This “metering” of flow into floodplain sloughs, which also mediates the frequency of avulsions, is common. In our study reach 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 (Figure 6A). 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 earlier aerial photographs.

The prevalence of this channel-switching dynamic over more gradual channel migration is due in part to the presence on the floodplain of patches of mature forest. These patches remained uneroded by the Nisqually River during the 130-year period of map and photo record, the river instead avulsed around them. On the Queets River, Abbe (2000) found similar “hard points,”

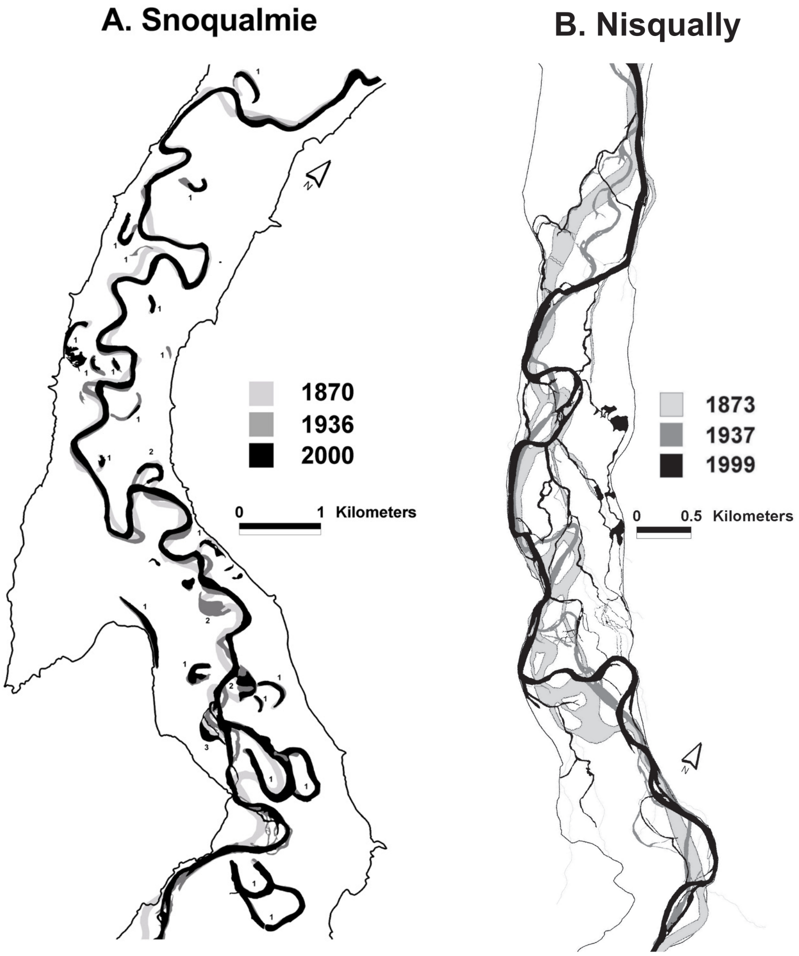


Figure 5. (A) Channel and oxbows in the Snoqualmie River in 1870, 1936 and 2000, and (B) locations of the Nisqually River, 1873, 1937 and 1999. Channel locations in 1870 and 1873 from General Land Office maps; other years are from aerial photos. Numbers in (A) represent year oxbows were first apparent: 1=1870; 2=1936; and 3=2000.

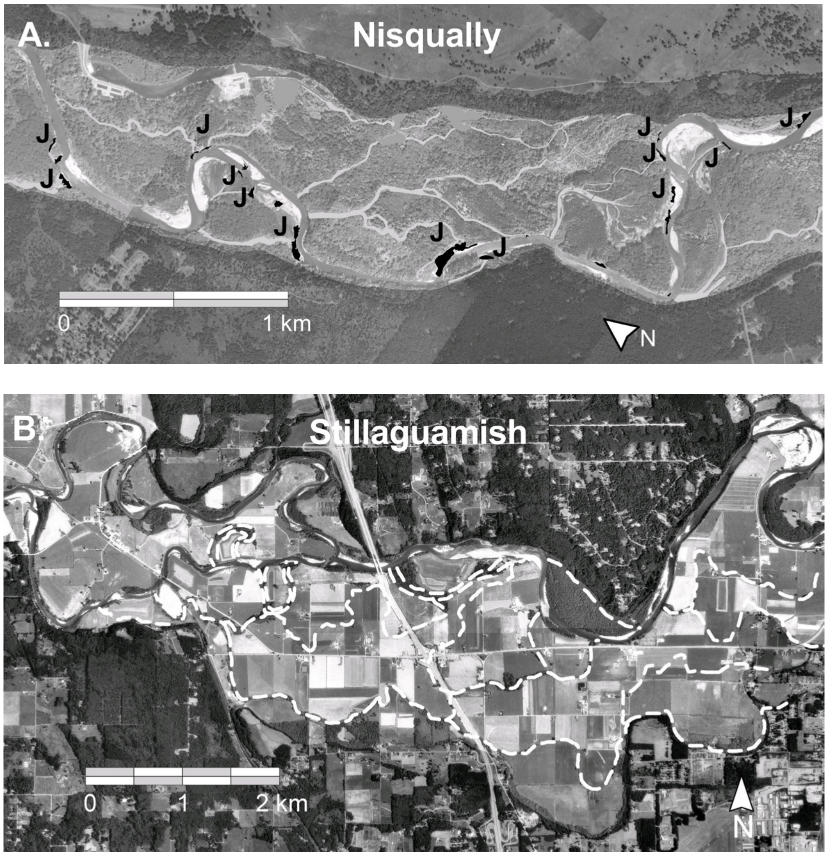


Figure 6. (A) The Nisqually River from 1999 aerial photographs. Those floodplain channels having flowing water in summer 2000, and which are obscured by tree cover on the aerial photographs, are shown with gray, and were mapped from field work in 1998 and 2000 onto 1999 1:12,000-scale ortho-photographs. Large log jams shown with black. "J" indicates a jam that is associated with the inlet to a floodplain slough. (B) The Stillaguamish River from 1990 aerial photographs. Dashed lines indicate relict floodplain sloughs that are no longer present but were shown on 1930 and 1941 maps. Flow in both panels is from right to left. Modified from Collins and Montgomery (2001).

or patches that maintained their stability for up to centuries, created by stable, persistent wood jams at their upstream ends.

Reconstructing channel locations from older maps and mapping relict topography on more recent photographs suggests that the pre-settlement Stillaguamish River had a similar anastomosing pattern as the Nisqually (Figure 6B). Archival sources indicate that wood jams were associated with many of these channel splits in the Stillaguamish. Sedell and Frogatt (1984) showed a correspondence in time between wood removal and simplifications in the Willamette River's pattern. Wood jams, the result of many trees contributed by fluvial erosion of the surrounding forest, appear to have been critical to the dynamics of such anastomosing rivers.

## **Forests, Rivers, and Wood**

### ***The Historical Forest***

Puget Sound's dense river-bottom forest, among the most productive on Earth, has been almost entirely cleared. However, field notes from a century and a half ago include information sufficient to recreate that forest in the abstract: tree diameters, species frequency and distribution, preferred growth environments, and geographic ranges. Besides providing a unique glimpse of the region's pre-logging riverine forest, this information can help guide forest restoration planning.

The mid-19th century, mixed hardwood-conifer, riverine forest was heavily weighted toward hardwoods. Of the approximately 7,000 GLO bearing trees we have georeferenced, 71% are hardwoods (Figure 7). This was especially the case for streamside forests, which were composed of 84% hardwoods (Figure 7B). (These percentages underestimate the relative abundance of hardwoods; as described previously, bearing trees under-represent small-diameter species, which are more commonly hardwoods such as vine maple [*Acer circinatum*], willow [*Salix spp*.], and red alder [*Alnus rubra*].) While less abundant, conifers accounted for the majority of biomass as indicated by basal area (Figure 7D-F). Several coniferous species grew quite large. For example, documented cedar (western redcedar, *Thuja plicata*; on first usage we refer to the common names recorded by land surveyors, and provide the probable species) had a mean diameter of 76 cm (median = 61 cm) and included individuals as large as 381 cm in diameter (Figure 8A). Spruce (Sitka spruce, *Picea sitchensis*) in field notes was as large as 282 cm in diameter (mean = 62 cm, median = 50 cm). Several hardwood species also attained a large diameter; maples (bigleaf maple, *Acer macrophyllum*) were as large as 183 cm

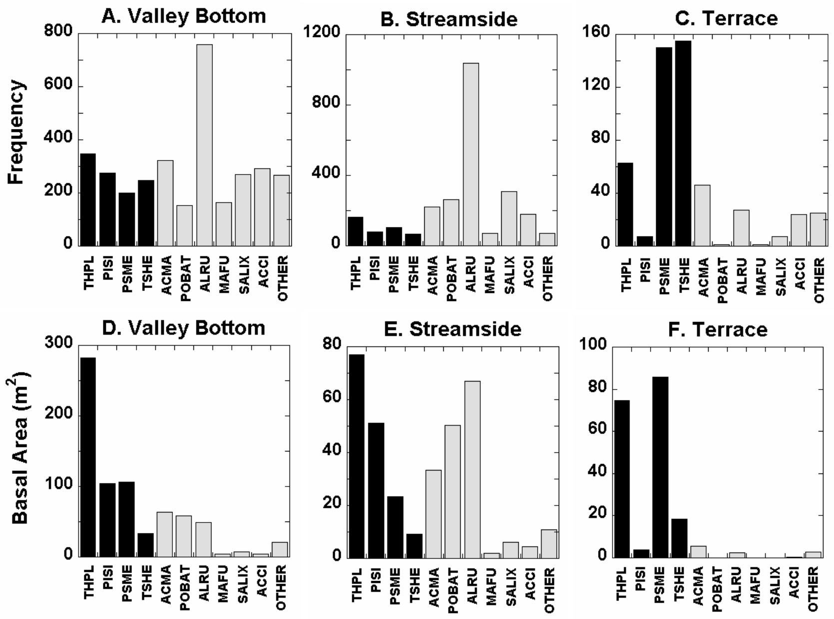


Figure 7. Data on bearing trees from GLO field notes, in eastern Puget Sound river valleys from the Nooksack south to the Nisqually. Frequency of trees in (A) valley bottom forest, (B) stream-adjacent forest, and (C) river terraces. Cumulative basal area in (D) valley bottom forest, (E) stream-adjacent forest, and (F) river terraces. Coniferous species have dark-shaded bar. N=7,348. THPL: western redcedar (*Thuja plicata)*; PISI: Sitka spruce (*Picea sitchensis)*; PSME: Douglas fir (*Pseudotsuga menziesii)*; TSHE: western hemlock (*Tsuga heterophylla)*; ACMA: bigleaf maple (*Acer macrophyllum)*; POBAT: black cottonwood (*Populus trichocarpa)*; ALRU: Red alder (*Alnus rubra)*; MAFU: Pacific crabapple (*Malus fusca)*; SALIX: Willow (*Salix spp.);* ACCI: vine maple (*Acer circinatum)*. "Other" species include: white fir (grand fir, *Abies grandis*), ash (Oregon ash, *Fraxinus latifolia),* dogwood *(*western flowering dogwood*, Cornus nuttallii)*, birch (paper birch, *Betula papyrifera*); hazel (beaked hazelnut*, Corylus cornuta var. californica*); bearberry or barberry (uncertain, possibly Oregon grape, *Mahonia aquifolium*); chittemwood (cascara*, Rhamnus purshiana*), cherry (bitter cherry, *Prunus emarginata);* elder (red elderberry*, Sambucus racemosa*); aspen (quaking aspen, *Populus tremuloides*).

(mean = 35 cm, median = 25 cm), and cottonwoods (black cottonwood, *Populus trichocarpa*) as large as 203 cm (mean = 47 cm, median = 30 cm) (Figure 8A).

Various riverine trees in eastern Puget Sound occurred within distinct elevation and latitude ranges and landforms. Sitka spruce, for example, was the lowest-elevation conifer (Figure 8B), a common (and typically the only) large conifer in tidewater areas; it was less common in the southern Sound (Figure 8C). In contrast, western hemlock, which is the potential climax species throughout the Puget Sound region (Franklin and Dyrness 1988), occurred mostly at higher elevations (Figure 8B), was uncommon in the southern study area (Figure 8C), and was only abundant on river terraces (Figure 7C). Douglas fir and western redcedar occurred throughout the area (Figures 8B and 8C). Neither tree was common in streamside areas (Figure 7B), although the great size of cedar caused it to account for the greatest proportion of streamside arboreal biomass (Figure 7E). Both were somewhat more common in valley-bottom forests outside the immediate streamside area (Figure 7A), but both achieved a dominant frequency only on river terraces (Figure 7C). Trees also had identifiable ranges in elevation relative to the streambank. For example, among bearing trees in the Snoqualmie River valley, spruce was the conifer most tolerant of seasonal flooding, growing 1-2 m below the river bank; alder and willow grew as much as nearly 4 m below the riverbank (Figure 8D). At the other extreme, western hemlock generally occurred several meters above the banks, above the threat of flooding.

### *Rivers of Wood*

Rivers transported not only water but also vast amounts of wood. While settlers' accounts are often more colorful than accurate, they suggest the staggering amounts of wood that choked rivers in flood. For example,

> "The amount of drift which floats down one of these rivers in a freshet is astonishing. It is not unusual, when a river is bank full and the current running 6 miles an hour, to see the channel covered with drift, and the flow kept up twenty-four hours with scarcely a break. Such a flow of drift may be repeated several times in a year on a stream like the Skagit or Snohomish." (Morse, in Nesbit et al. 1885, p. 76)

Not only did wood challenge the conveyance of rivers (and the prose of observers), dead trees were so abundant and well-lodged in 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

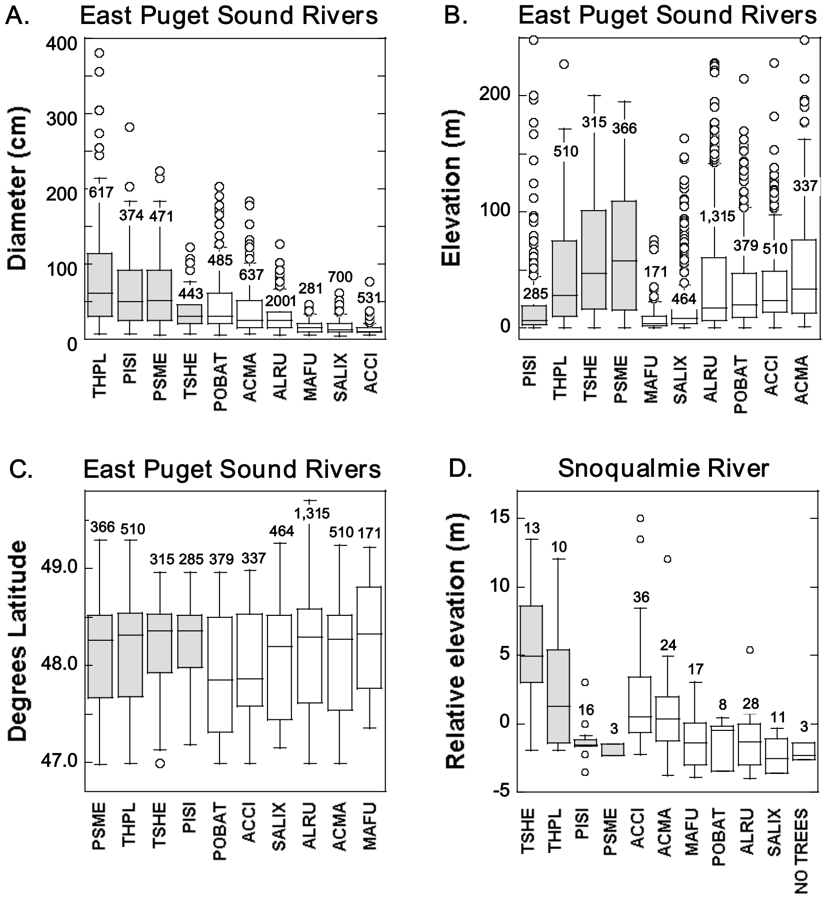


Figure 8. (A) Diameters of the ten most common bearing trees in GLO field notes from eastern Puget Sound river valleys, and their range in (B) elevation and (C) latitude. (D) Elevation of GLO bearing tree species relative to the riverbank elevation in the Snoqualmie River valley. Conifers have shaded bars. Numbers are sample size for each species except “no trees” in panel D, where it refers to number of sites. Species abbreviations are as in Figure 7. Each box encloses 50% of the data. Horizontal line within box represents median. The lines extending from the top and bottom of boxes indicate minimum and maximum values, excepting outlier values (circles) greater than the inner quartile plus 1.5 times the inner two quartiles.

(Sedell and Luchessa 1981; Collins et al. 2002). Logging spread up-valley, and logs could be driven down-river in rafts, once rivers were cleared of blocking wood jams and snags that menaced navigation. Logging and settlement progressed up-valley so rapidly that lowland river valleys had been cleared of nearly all forest by 1900 (Plummer et al. 1902). Thus the evidence of wood in rivers is even more obscured by time and human activities than is that of the historical valley-bottom forests.

We investigated the potential effects of the late nineteenth century removal of riverine wood by collecting field data in 1998 from the Nisqually River and similar data from the Snohomish and Stillaguamish Rivers; from the latter two rivers, wood has been systematically removed, the floodplain forest cut down and converted to agriculture and other uses, and the river banks leveed and hardened. We also used archival sources to determine whether field data from the Nisqually is a reasonable surrogate for historical conditions, to provide information on wood accumulations for which there are no existing analogs, and to describe the geographic variation in wood characteristics (Collins et al. 2002).

In 1998, the Nisqually River had far more wood per channel width than the other two rivers—approximately 8 and 21 times more than the Snohomish and Stillaguamish, respectively. Most of this difference is accounted for by the abundance of wood in jams in the Nisqually River (Figure 9). Excluding jams from the Nisqually, wood abundance was comparable to 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. Large wood pieces with rootballs are no longer present in the Snohomish and Stillaguamish rivers because they have lacked mature riparian forests for more than a century. The other reason is that the two rivers recruit far less wood than the Nisqually because the leveed rivers cannot erode the floodplain, which also generally lacks a riparian forest. The presence of two upstream dams on the Nisqually River makes that river's accumulation of wood all the more striking and points to the importance of local wood recruitment. In contrast, neither the Stillaguamish nor Snohomish have dams, and thus have no limit on wood transport from upstream.

Very little recently recruited wood is found in the Stillaguamish and Snohomish rivers compared to the Nisqually. Most of the older wood in the Stillaguamish and Snohomish is decay-resistant cedar, presumably relict from before forests were cleared a century ago. This reflects, in part, a decrease in wood recruitment from historical conditions. Also, without jams, the rivers retain far less wood. The lack of retention is reinforced by recently recruited wood being small in diameter and readily transported.

The Army's snagging records supplement these field data and provide a quantitative indicator of historical wood abundance in regional rivers and its change through time (Figure 10). Nearly all snagging occurred after huge raft jams had been cleared, and much of the riparian forest had already been cut down, so the number of snags removed would have been less than the amount present under pre-settlement conditions. Yet snags remained a problem. In a 1907 report on the White River (Figure 1), the Army Corps' Major Hiram Chittenden wrote:

> "…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)

Between 1880 and 1980, 150,000 snags were removed from five rivers, including the Stillaguamish and Snohomish, with more than one-half of these from the Skagit. A total of 30,000 snags were removed from the lower Skagit

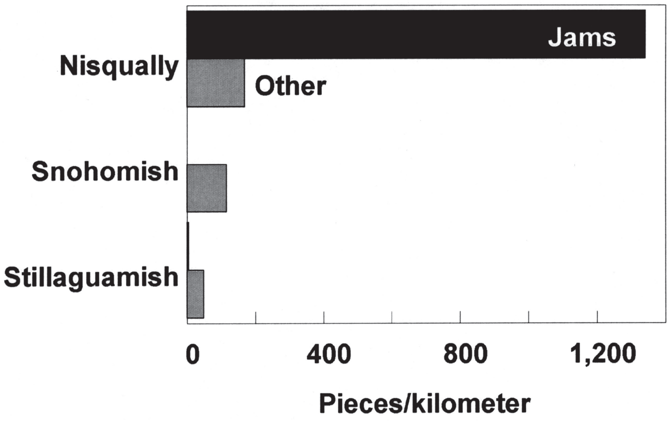


Figure 9. Wood abundance in the Nisqually, Snohomish, and Stillaguamish Rivers, field measured in 1998. Modified from Collins and Montgomery (2001).

River between 1898 and 1908. A diminishing rate of snag removal after 1900 (Figure 10) reflects the decline in recruitment of wood large enough to lodge in the riverbed and remain stable. This in turn presumably reflects the effects of riparian logging (and particularly the removal of very large trees from the valley-bottom forest), leveeing, and bank protection. Snag-boat captains' records indicate that very large pieces were represented in the wood load—the annual maximum snag diameter between 1889 and 1909 ranged from 3.6 to 5.3 m (U. S. War Department 1889–1909), diameters which are confirmed by engineers' observations (e.g., U. S. War Department 1895).

These accumulations were major influences on river channels. Raft jams, the largest accumulations and first to be removed, could be kilometers long, channel spanning, and persist for hundreds of years. For example, a Skagit River jam at the present-day site of Mount Vernon existed for at least a century. A pioneer had learned from the native people that its surface supported live trees two to three feet in diameter (Interstate Publishing Company 1906, p. 206). The jam was packed solidly enough that it could be crossed "at almost any point." The jam was described as 9 m deep, consisting of "from five to eight tiers of logs, which generally ranged from three to eight feet in diameter" (Interstate Publishing Company 1906, p. 114). Beneath the previously described Mt. Vernon raft jam were in some places "furious cataracts,"

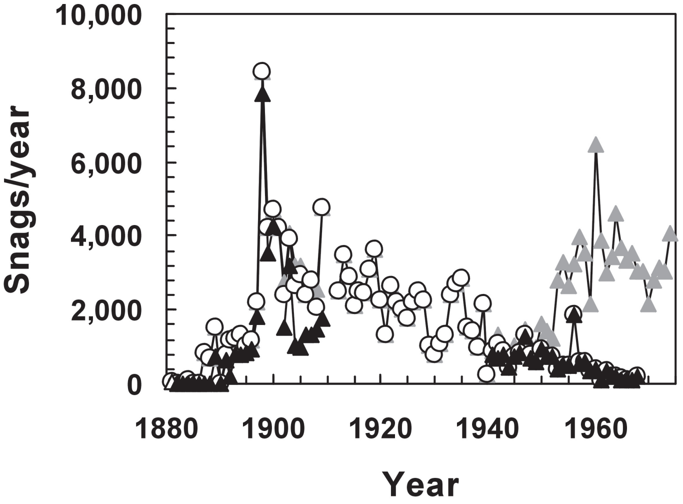


Figure 10. Snags removed from Puget Sound rivers, 1881–1970. Hollow circles: all Puget Sound rivers; solid triangles: Skagit River only; gray triangles: all Puget Sound rivers and harbors. Modified from Collins et al. (2002).

and in others “deep black pools filled with fish” (Interstate Publishing Company 1906, p. 106). The river was as deep as 7 m below the jam at the lowest water stage.

### *The Geomorphic and Ecological Importance of Wood*

Wood accumulations were important to river dynamics at a range of spatial and temporal scales (Figure 11). At the largest scale, raft jams routed water and sediment onto floodplains and deltas. For example, contemporary accounts and map evidence suggest the Mt. Vernon raft jam had a dominant influence on landscape-scale flooding patterns on the lower Skagit River (see Collins et al. 2002). Resulting wetlands would have provided extensive habitat, including habitat ideally suited for salmonid rearing. In the American Midwest, such raft jams retained vast amounts of sediment and dammed tributaries, transforming the valley-bottom environment (Triska 1984).

At the reach scale, as previously described, wood 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 the simplification of channel pattern. Field studies in the Skagit River indicate that wood, particularly wood jams, along banks significantly increases the fish habitat value of riverbanks (Beamer and Henderson, Skagit System Cooperative, LaConner, WA, unpublished data).

Pools exemplify the role of wood at a smaller scale. In autumn 1998, we measured 85 pools in the Nisqually River study reach and found a pool spacing of 1.4 channel widths (CW) per pool (Figure 12). Wood was the dominant factor forming 61% of pools, including 26% associated with mapped, stable jams. This finding is similar to that of Abbe and Montgomery (1996, Figure 3), who found wood formed 70% of observed pools in a 25 km-long reach of the Queets River in Olympic National Park. In the Nisqually, pools associated with jams were considerably deeper than other pools, the mean depth being three times greater than free-formed pools. Jam-associated pools were twice as deep as pools formed by individual pieces having attached rootballs, augmented by wood or formed by banks.

In contrast to the Nisqually, pool spacing measured on the Stillaguamish ranged between 3 and 5 CW/pool in the three reaches, or two to three times less frequent than in the Nisqually. Only one-ninth (11%) of pools in the Stillaguamish were formed by wood. More than one-half formed along riprap-armored banks. Although deep (Figure 12), these pools lacked cover and would provide considerably less habitat value than pools associated with wood. Similarly, in an 8.5 km-long reach of the Snohomish River, beginning at the confluence of the Snoqualmie and Skykomish rivers, wood created only one relatively shallow pool, and the pool spacing of 3 CW/pool was twice that of the Nisqually River, indicating one-half as many pools. Comparing pool data from the Snohomish and Stillaguamish Rivers to the Nisqually suggests that in the Puget Lowland historically freely migrating rivers with mature floodplain forests had two to three times more pools than contemporary, leveed rivers with little riparian recruitment. While artificially hardened banks appear to create deep pools, pool depth alone is not sufficient to create high-quality habitat because wood also provides cover, complexity, and nutrient-rich substrate to pools, increasing their habitat value (e.g., Bjornn and Reiser 1991).

The historical change in size and quantity of recruitable wood may account for the idea 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). In the Nisqually River, by contrast, wood abundance is much greater than predicted by data from smaller streams (see Figure 13.2 in Bilby and Bisson 1998). Thus to some degree the generalization that wood plays a diminishing role in channel structure as streams increase in size is simply a reflection of the cumulative historical effect of human actions.

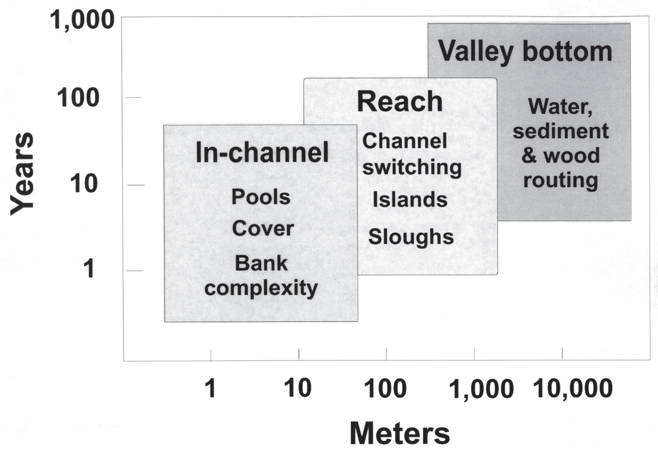


Figure 11. Temporal and spatial scales at which wood accumulations influenced lowland Puget Sound rivers. Modified from Collins et al. (2002).

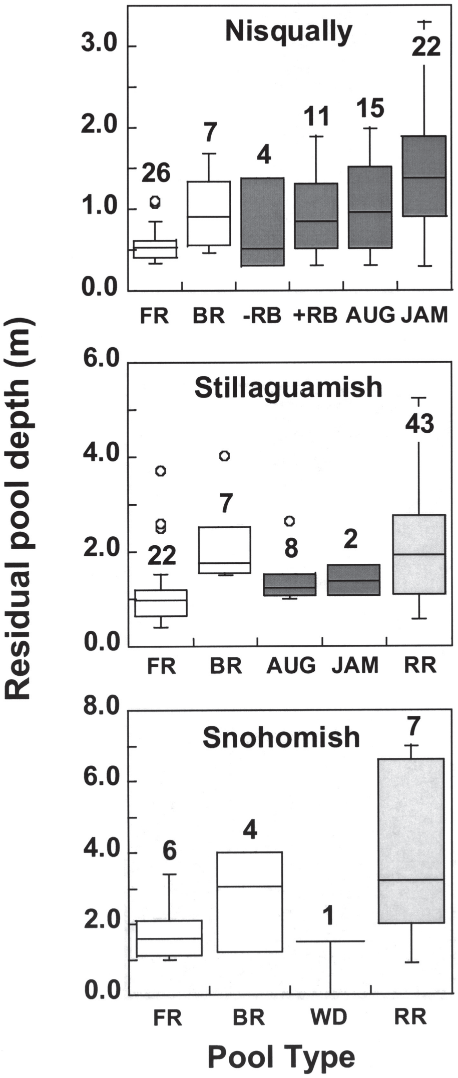


Figure 12. Number of pools, and residual pool depth, by primary pool-forming factor, in the Nisqually River, Stillaguamish River, and Snohomish River. Pool-forming factors: FR: free-formed alluvial; BR: bedrock forced; -RB: wood piece without rootball; +RB: wood piece with rootball; WA: wood augmented; JAM: wood jam; (all wood-related pools have dark-shaded bars); RR: riprap armored bank (light-shaded bars). Numbers on plots are the sample size. Modified from Collins et al. (2002).

## WHERE THE HABITAT WAS (AND WHERE IT WENT)

In the Puget Sound basin, the majority of channel and wetland area accessible to salmonids was in the larger rivers and floodplains of the Puget Lowland (Sedell and Luchessa 1981; Beechie et al. 1994; Collins and Montgomery 2001). The historical abundance of habitat in lowland floodplains and deltas can only be determined from archival materials, because so little remains of these habitats. We are currently creating GIS maps of historical riverine environments of Puget Sound, beginning with the north Sound, and in the following discussion draw on this work in progress to illustrate the nature and distribution of habitats.

In the Snohomish River valley, prior to widespread landscape modifications by settlers, the majority of land area was either channel or wetland (Figure 13A). Vast floodplain wetlands and extensive estuarine marshes accounted for nearly two-thirds (62%) of the valley bottom. By the 19th century's end, much of this wetland had been diked, ditched, and drained; by the end of the 20th century, only small patches remained (Figure 13B). Wetlands were extensive in the Snohomish basin because the Pleistocene glacial-meltwater-shaped valley has a low gradient, a great width, and low elevation relative to the river banks, all favoring extensive wetlands. Especially notable in the Snohomish basin were the vast riverine-tidal wetlands, or freshwater wetlands influenced by the tides. The extensive freshwater "Marshland" wetland (Figure 13A) formed in a portion of the floodplain lower than the river, topographically similar to the Snoqualmie River (Figure 4A), which also had extensive low-elevation wetlands (Figure 13A).

The distribution of habitats in the lower Nooksack mainstem (Figure 14A) was similar to those in the Snohomish basin. The Nooksack's low-gradient delta-estuary had extensive riverine-tidal freshwater wetlands, and upstream of the estuary, the channel meandered between expansive freshwater wetlands on the lower-elevation floodplain. As in the Snohomish basin, most of these wetlands have long been drained and ditched (Figure 14B).

In the upper Nooksack mainstem, upstream of the influence of continental glaciation (Figure 4C), the valley was narrower, steeper, and the channel anastomosed and lacked the wetlands of the lower river (Figure 14B). Similarly in the Snohomish basin, the Skykomish River (Figure 13A) contrasts with the Snohomish and Snoqualmie, in having a multiple-channel pattern. Both the Snohomish and Nooksack basins illustrate the contrasting channel patterns—meandering single thread compared to anastomosed—and the different valley landforms—oxbows and extensive low-elevation wetlands compared to floodplain sloughs—that historically existed in Pleistocene compared to Holocene river valleys.

Both the upper Nooksack mainstem and the Skykomish River now have a simpler channel pattern than they did historically (Figures 13B and 14B). Landscape reconstructions of the upper Nooksack River mainstem in the intervening period (~1910 and 1938) shows that early in the 20th century the river took on a braided pattern, presumably in part because streamside logging weakened banks and contributed coarse sediment to the river. Over the rest of the century, levees confined the channel, creating the present-day relatively straight, confined channel. Meanwhile in the lower Nooksack mainstem, the cutting off of meanders and construction of levees also created a relatively straight confined channel. Land use changes have thus caused the historically very different channel patterns of the upper and lower Nooksack mainstem to converge into relatively similar patterns today.

The Skagit-Samish delta (see later, Figure 15G) is unique in the region because of its large size and unique origin from mid-Holocene (~5,000 ybp) Glacier Peak lahars (Dragovitch et al. 2000). The delta is also unique in its historical quantity and variety of wetland and channel habitats. Estuarine wetlands were extensive in the low-gradient, spreading delta, totaling more than twice as much as those on the other three north-Sound deltas (Nooksack, Stillaguamish, and Snohomish) combined; riverine-tidal wetlands were second in extent only to the Snohomish estuary; and the extent of palustrine wetlands dwarfed those in other estuaries. Numerous distributary sloughs bisected the delta. Most of the wetland habitats were diked and drained by the end of the 19th century excepting a portion of primarily estuarine emergent wetland (Figure 15H)—which is the largest remaining estuarine wetland in Puget Sound—and most of the distributary sloughs closed off to water influx by dikes.

Differences between these North Sound rivers demonstrate the important role of archival sources in characterizing the abundance and variation of aquatic habitats. They also demonstrate that the region’s geologic history created distinct types of valleys and estuaries with broadly similar habitats.

## USING HISTORICAL INFORMATION IN RESTORATION, REHABILITATION, AND CONSERVATION PLANNING

### *Toward What Restoration Needs does Historical Analysis Point?*

We use “restoration” to mean re-establishing a self-sustaining, dynamic riverine landscape closely resembling the pre-settlement condition. We use “rehabilitation” to refer to re-establishing certain historical processes or features, or certain habitats, which probably involves on-going intervention, engi-

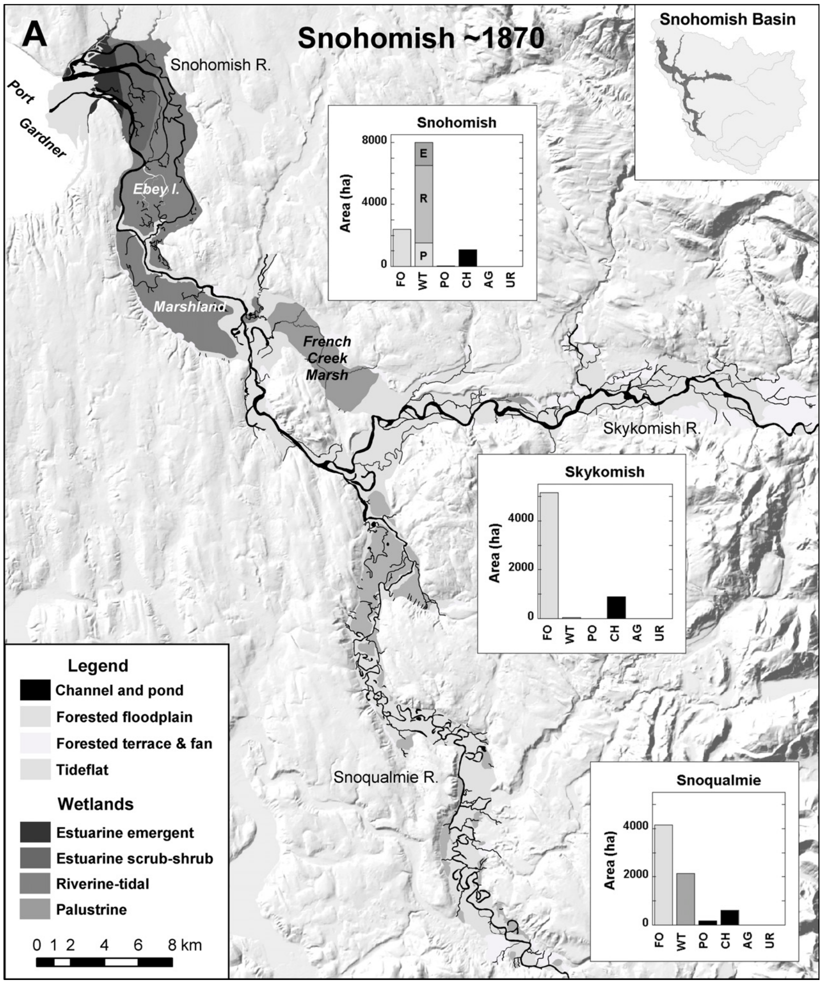


Figure 13. (A) Channels and wetlands in the valleys of the Snohomish, Snoqualmie, and Skykomish Rivers in ~1870, or prior to widespread landscape modifications by settlers, as interpreted from archival sources, primarily GLO field survey records and USC&GS charts. Bar graphs show floodplain area (terraces and fans are excluded) in following categories: FO = forested floodplain; WT = wetland (E = estuarine; R = riverine-tidal; P = palustrine); PO = pond; CH = channel; AG = agriculture/cleared land; urban = urban.

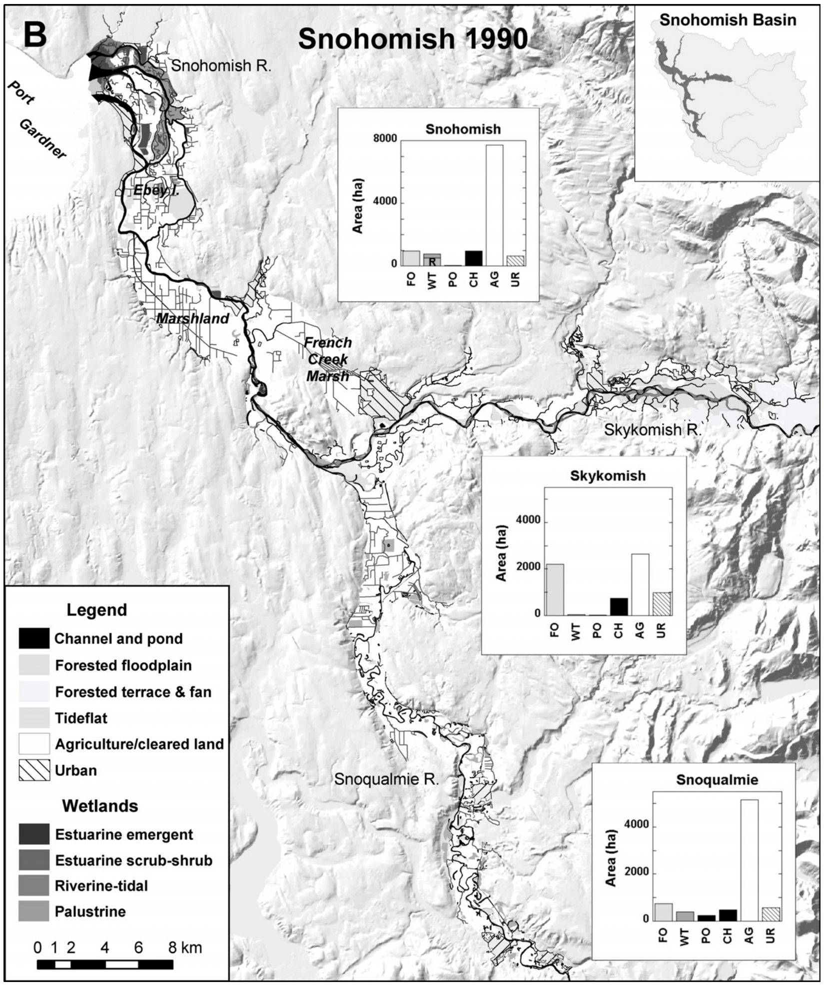


Figure 13 (continued). (B) Conditions in 1990, primarily from aerial photographs, supplemented with hydrography and wetlands from Washington Department of Natural Resources and National Wetland Inventory, and USGS land use and land cover mapping. Abbreviations for bar graphs are the same as in Figure 13A; channel category includes gravel bar (unshaded) and low-flow channel (black).

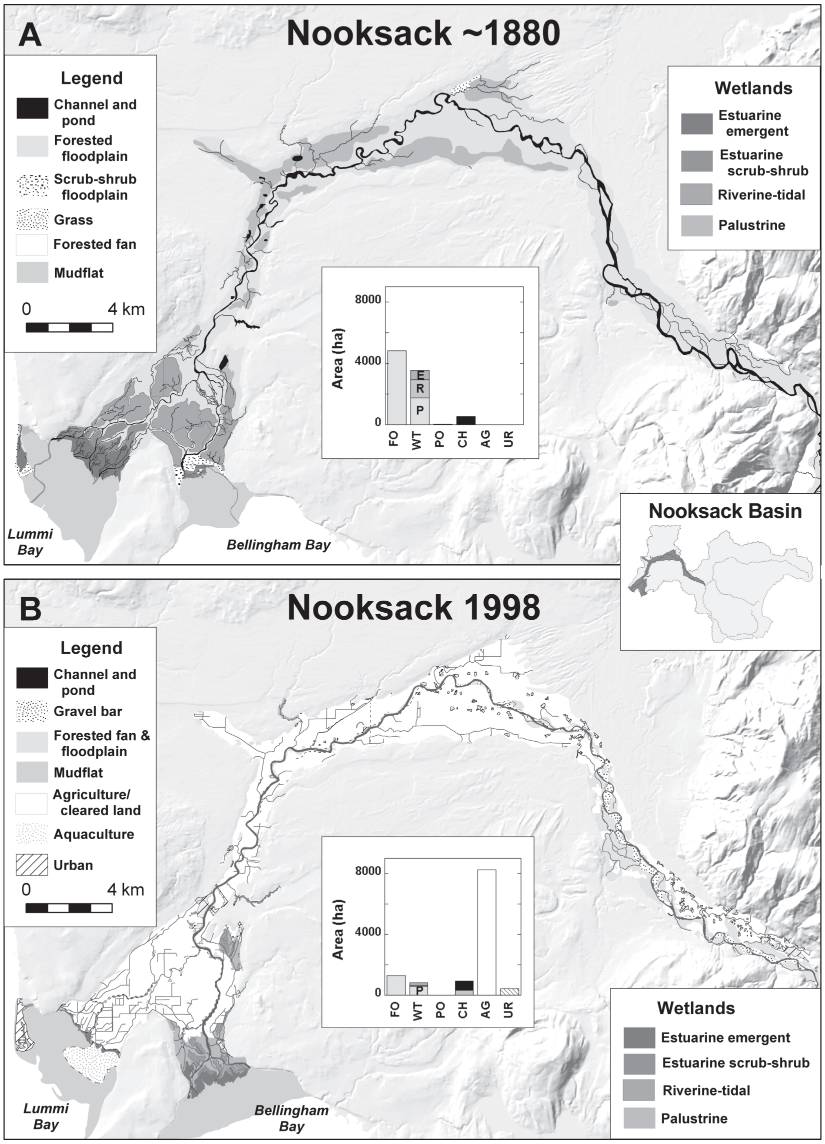


Figure 14. (A) Channels and wetlands in the mainstem Nooksack River valley in ~1880, as interpreted from archival sources, primarily GLO field survey records and USC&GS charts. (B) Conditions in 2000, mapped as in Figure 13B. Abbreviations in bar graphs are the same as in Figure 13.

neering, or maintenance. Historical studies can reveal opportunities and constraints, which in turn may dictate the choice of restoration versus rehabilitation. Because the processes that create riverine landforms, dynamics, and habitats vary between and along rivers, initial planning for restoring a river includes identifying the historically dominant processes. Doing so points toward the appropriate conceptual models of riverine function and restoration. Describing the historical locations and types of riverine habitats associated with these processes then makes it possible to set restoration or rehabilitation targets.

### *Identifying Primary Elements, Issues, and Opportunities*

Restoration opportunities and constraints differ not only with geologic setting and physical dynamics but also with land use history (Table 1). In Pleistocene valleys such as the Snoqualmie, critical opportunities include: connecting oxbow ponds and wetlands to the river; re-establishing riparian forests along oxbows and channels; and re-establishing historically extensive valley wetlands (Table 2). In the Snoqualmie, the riverine system is only moderately degraded because the channel has generally not been hardened and oxbows have not been filled (Figure 15 A-B). On the other hand, channelization has more significantly altered the nearby Sammamish River (Figure 15C-D), which has a similar geologic setting to the Snoqualmie (Table 1). Restoring the Sammamish River would begin with the more intensive task of re-establishing the historical meandering pattern (Table 2). In addition, urban development in part of the Sammamish valley would likely pose more constraints than might the Snoqualmie River valley's agricultural uses. Interbasin water transfers can represent more far-reaching (and more challenging) alterations. For example, in 1916 most all of the Black River's (Figure 15E-F) inflow was eliminated when opening of the Lake Washington Ship Canal lowered the lake's water level (Chrzastowski 1981). Somewhat less radically, the present-day 1250-km$^2$ area of the Duwamish River is much smaller than its historical 4250-km$^2$ watershed, when the basin included the watersheds of the Cedar, Sammamish, and White rivers (Blomberg et al. 1988).

In the Nisqually- and Stillaguamish-type of river (i.e., formerly anastomosing rivers in Holocene river valleys), opportunities include re-establishing floodplain sloughs (Table 2). Such sloughs, and beaver ponds commonly associated with them, were critical rearing habitats for coho salmon (Beechie et al. 2001). However, in contrast to the Snoqualmie, Sammamish, or Black, rivers such as the Stillaguamish were more dynamic, having more rapid river migration and a dynamic shifting of flow from main channel to slough and

Table 1. Categories of river restoration situations, organized by the geomorphic setting and degree of anthropogenic change, and representative reaches.

| | *Extent of Restoration Activity Needed*<br>*(1) Vegetation; (2) Channel; (3) Channel-floodplain connectivity* | | |
|---|---|---|---|
| *Puget Lowland Landform Type* | *A. Less* | *B. More* | *C. Most* |
| | 1. Mature forest or natural vegetation<br>2. Natural banks<br>3. Floodplain channels hydraulically connected to river | 1. Widespread vegetation clearing<br>2. Some hardening and levees<br>3. Floodplain ditched, drained; secondary channels blocked | 1. Most native vegetation removed<br>2. Widespread hardening and levees; channel straightened<br>3. Floodplain ditched, drained; secondary channels filled |
| *I. Delta-Estuary* | Nisqually | Skagit<br>Nooksack | Puyallup<br>Duwamish |
| *II. Pleistocene Glacial Troughs* | Snoqualmie (Snoqualmie Falls to Skykomish R.) | Sammamish | Puyallup (lower)<br>Duwamish<br>Black |
| *III. Holocene Fluvial Valleys* | Nisqually (Fort Lewis and Nisqually Indian Reservation) | Stillaguamish (mainstem) | Cedar (lower) |

from slough back to main channel. This dynamic behavior presents greater challenges for reconciling valley-bottom land uses with river restoration than in relatively static, meandering rivers such the Snoqualmie, because a self-sustaining restoration would involve removing or setting back levees and re-establishing extensive forests. Rehabilitation opportunities, on the other hand, which include engineering flow into static floodplain sloughs, may be more easily compatible with existing land uses. In any case, rivers have commonly incised since historical meander cutoffs or straightening, which could complicate reconnecting floodplain sloughs. For example, channel bed surveys in the Stillaguamish River in the vicinity of several floodplain sloughs currently proposed for reconnection shows that the river downcut by 1 to 2 m between 1929 when sloughs were disconnected and a channel survey in 1991. Elsewhere, many former floodplain sloughs and distributaries have been

Table 2. Typical restoration and rehabilitation actions for rivers in different landforms or geomorphic setting, and resources possibly required.

| *Geomorphic Setting* | *Restoration Actions* | *Restoration Resources* | | |
|---|---|---|---|---|
| | | *Land* | *Financial* | *Time* |
| *I. Delta-Estuary* | Reconnect distributary sloughs | Small | Moderate | Short |
| | Breach or remove dikes to re-establish tidal or freshwater flow | Extensive | Large | Short |
| *II. Pleistocene Glacial Troughs* | Re-establish meanders (channelized rivers) | Moderate | Large | Short |
| | Riparian planting | Small | Small | Mod-Long |
| | Connect oxbows to river | Small | Small | Short |
| | Passive wetland restoration | Extensive | Small | Mod-Long |
| *III. Holocene Fluvial Valleys* | Re-establish meanders (channelized rivers) | Moderate | Moderate | Short |
| | Levee removal or pullback | Extensive | Large | Short |
| | Floodplain reforestation | Extensive | Moderate | Mod-Long |

ditched or filled, in some cases with toxic materials, complicating efforts to restore flow into them.

Still different opportunities exist in estuaries. While the relative amount differs among different estuary types, there is potential to recoup habitat in all estuaries which had extensive distributary and blind tidal channel habitats (Table 2). In moderately altered systems such as the Nooksack (Figure 14) or Skagit basins (Figure 15G-H), there are opportunities to restore flow, including freshwater to now-diked-off distributary sloughs, or tidal flow to estuarine marsh now blocked by sea dikes. Removing, setting back, or breaching dikes or engineering flow through dikes can initiate restoration or rehabilitation of these environments. Analogous to the river incision that may complicate reconnecting floodplain sloughs, land subsidence in historically diked and drained estuarine marshes can complicate marsh restoration (e.g., Zedler 1996). On the other hand, patterns and rates of estuarine sedimentation can change through time, causing historically diked-off marshes to have greater elevations than when they were initially diked. This is the case in the Nooksack River delta (Figure 14), where the Lummi River was formerly the dominant flow channel until around 1860 when changes to a log jam diverted water into the Nooksack, after which the Lummi River gradually dried up. High sediment loads from the watershed have extended the Nooksack delta more than a mile outward, and most modern wetlands are recently created. In the highly industrial estuaries of the Duwamish and Puyallup (Figure 15I-K) rivers, severe constraints created by infrastructure and reshaping of the hydrology

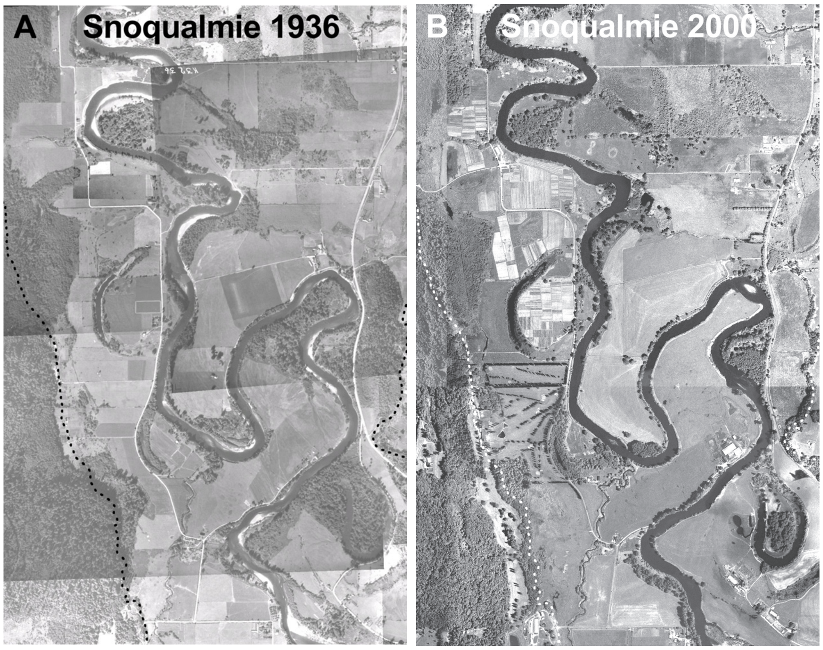


Figure 15. Map and aerial photo views of rivers in Table 3, representing different geologic settings and extent of historical land-use modification: (A) Patches of riparian forest and valley-bottom wetlands remained in 1936 along the Snoqualmie River; (B) In 2000, the river channel and oxbow wetlands were relatively unchanged, but wetlands and forests diminished. Dashed lines show limit of valley bottom.

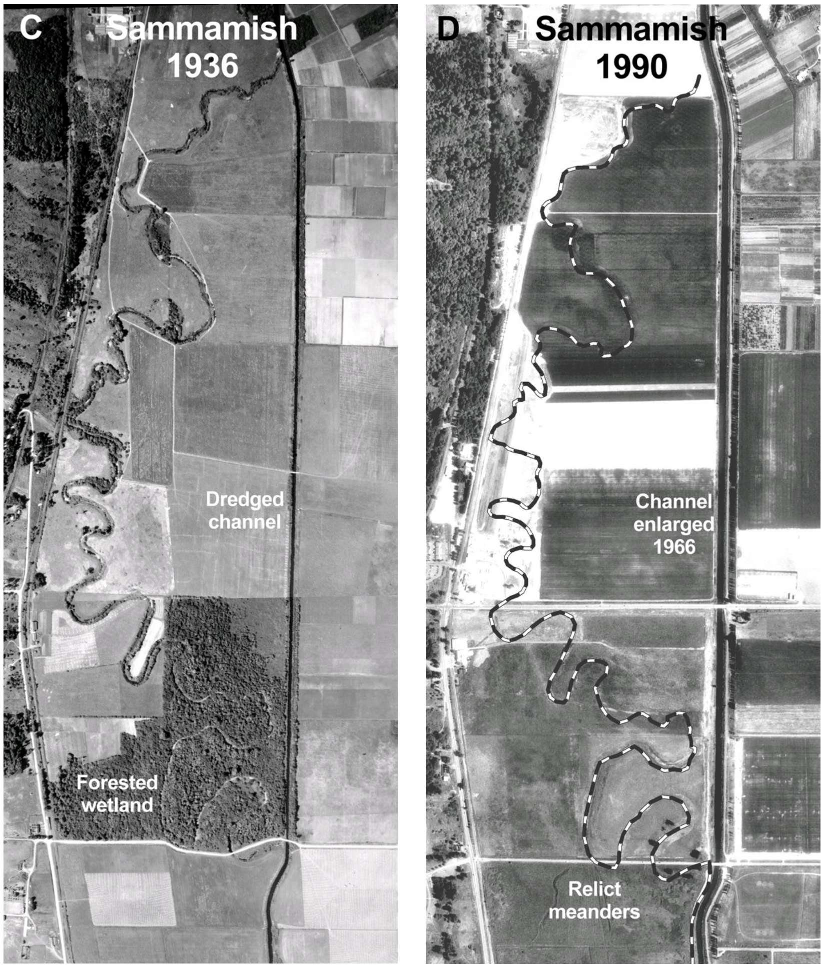


Figure 15 (continued). (C) Small patches of former wetlands that historically nearly filled the Sammamish River valley remained in 1936, along with relict, meandering riverbeds that still functioned during floods. (D) By 1990, the relict meanders were subdued swales in agricultural fields, and an earlier-cut-off ditch had been enlarged to contain the river and most floods.

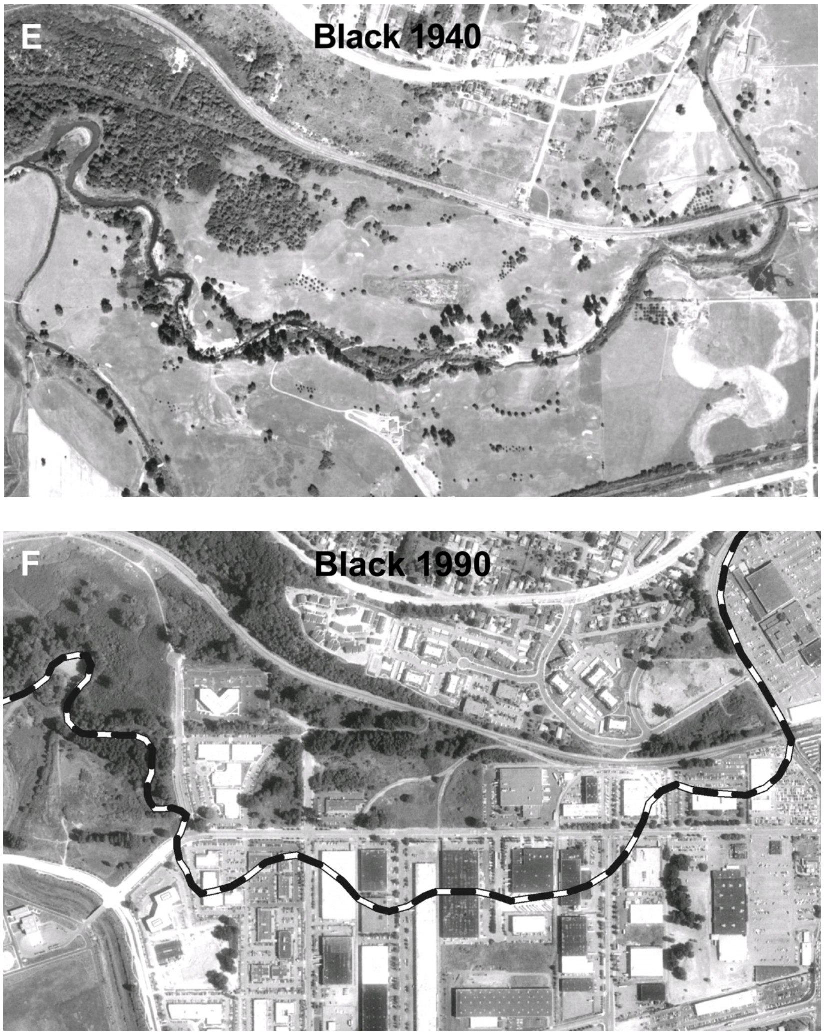


Figure 15 (continued). (E) The Black River retained a natural channel in 1940 with greatly reduced flow. (F) By 1990, the lower river retained a natural environment, but moving successively upstream, the former riverbed is covered by buildings, then becomes coincident with a street, and farthest upstream (out of view) buried by aviation runway.

limit restoration potential to creating or rehabilitating functional habitat elements (Simenstad and Thom 1992).

Regional and within-watershed differences in channel morphologies, processes, and suites of valley-bottom landforms have important implications for whether the central task is to restore valley-bottom forests and river migration or to restore hydrologic connection. For less dynamic rivers in Pleistocene glacial troughs, the forest-river dynamic is less critical. There, the *hydrologic* connection is more important. Emphasis is on restoring the flow of water to valley-marginal wetlands, which can be restored in a "passive" way because of their subdued topographic position relative to the river channel, and on restoring the hydraulic connection between the river and floodplain oxbow lakes. In deltas and estuaries, emphasis is also on hydrologic connection. For restoring moderately degraded anastomosing rivers, such as the Holocene valleys, *riparian forests*, and their connections with the channel are

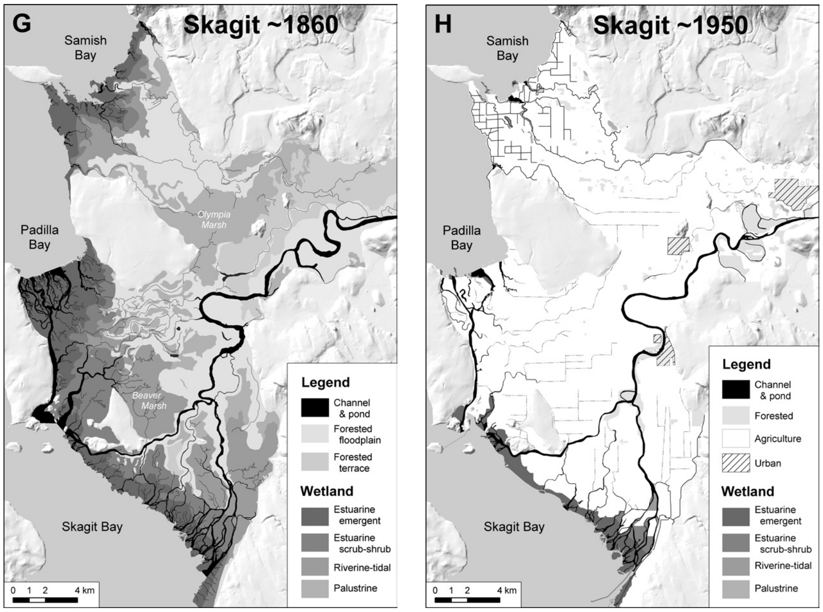


Figure 15 (continued). (G) The Skagit River delta had extensive estuarine, riverine-tidal, and freshwater wetlands prior to ditching and diking that began in the 1860s. Mapping sources are as in Figures 13A and 14A. (H) By the middle of the next century, most wetlands had been diked and drained, and many distributary sloughs closed off. Mapping from USGS topographic maps and aerial photographs.

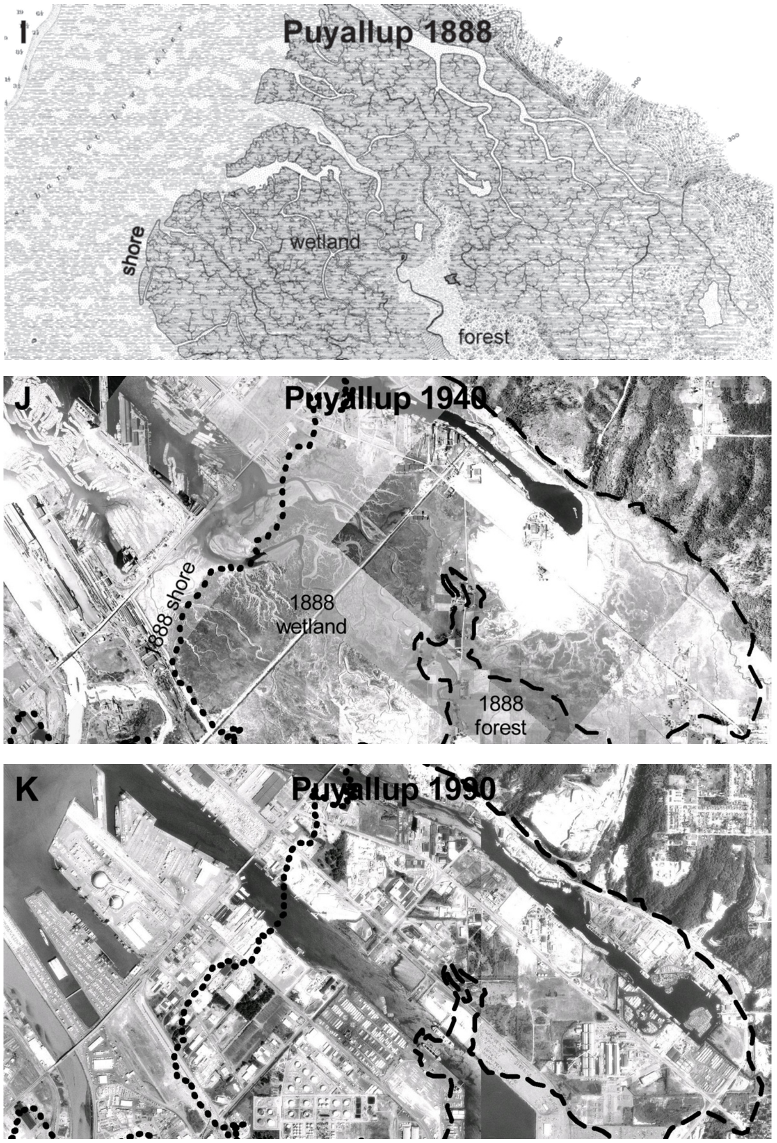


Figure 15 (continued). (I) A portion of the Puyallup River estuary as shown on an 1888 USC&GS chart. (J) Many of the estuarine wetland channels are still present as recently as 1940, when infrastructure had mostly been created upon made-land seaward of the historical delta shoreline. (K) Dense industrial development and dredging transformed the estuary in the late 20th century.

Table 3. Conceptual framework for restoring wood jams and river dynamics to channels in which wood is a dominant element, such as the "Holocene fluvial valleys" in Table 1. From Collins and Montgomery (2002).

| *Steps in Restoring Wood Jams and River Dynamics* | | | | |
|---|---|---|---|---|
| *Years:* | *0–10* | *1–50* | *50–100* | *100+* |
| *Actions:* | Riparian reforestation: Includes fast-growing species.<br>Levee set-back or removal. | Instream structures: Includes placing key pieces or building wood jams. | Naturally-recruited logjams: Fast-growing species form key pieces. | Naturally-recruited logjams: Slower-growing species form key pieces. |
| *Results & Functions:* | Initiate future supply of wood.<br>Restore lateral erosion and avulsion. | Short-term pool-forming and channel-switching functions.<br>Stable sites for forest regeneration. | Long-term, sustainable supply of wood jams.<br>Long-term, sustainable pool-forming and channel-switching functions. | |

important. There, restoration would require removing or pulling back levees and replanting forests (Table 2). However, the sequencing, time required, and overall strategy for doing so can be informed by historical studies.

### *Planning Riverine Reforestation and Wood Reintroduction*

The importance of wood accumulations to fluvial processes (Chapter 3) argues that planning for sustainable large-river restoration in temperate, forested regions such as the Pacific Northwest include 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. Wood large enough to function as key pieces is critical to jam formation and hence to river restoration (see also Chapters 16 and 17). To create jams, rivers must also have access to a large number of trees recruitable by bank erosion and avulsion. Structural approaches (e.g., building wood jams) are not sustainable without continued intervention. A supply of wood large enough to form key pieces implies 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. Such restoration requires sufficient riparian land area, which may not be available in heavily populated areas, where it may only be possible to rehabilitate selected features or functions (e.g., Kern 1992; Brookes 1996; de Waal et al. 1998).

Based on our analysis of the Nisqually River system (Collins and Montgomery 2002) and experience with other large Pacific Northwest rivers, we propose the following outline for a strategy to reestablish a self-sustaining, dynamic river morphology and habitat in wood-depleted areas. First steps include levee setbacks and riparian planting, including tree species near the river that will rapidly develop a large size (Table 3). 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. In the first few decades of a restoration plan, engineered solutions may provide short-term functions and hasten riparian forest regeneration. Such actions include placing key pieces in systems with adequate recruitment but an absence of pieces large enough to form key pieces, or in systems lacking both, constructing wood jams (Chapter 17) 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. While 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 1–2 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. 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 are also important sources of key pieces.

This framework calls into question common assumptions about river restoration in the Pacific Northwest. First, most restoration efforts have focused on static habitat creation ("instream structures" in Table 3) rather than reestablishing processes (Reeves et al., 1991; Frissell and Ralph 1998); forest restoration is a critical additional component to sustainable river restoration. Second, 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 hardwoods to conifers. However, large trees are necessary to provide key pieces for jams, suggesting that riparian forests be managed at least initially to produce large trees from a mix of species. In fact, historical land survey records show that hardwoods dominated most river valleys historically, and several hardwood species could grow to be quite large (e.g., see Figure 7). Third, riparian restoration plans often assume a timeframe of a century or centuries, which can be the time needed to develop large western redcedar. However, riparian reforestation that includes fast-growing species can produce large trees that are essential for creating key pieces within a shorter time frame. River restoration can be accomplish in stages, from engineered jams (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 attempts to create desired conditions through direct intervention.

### *Conservation Planning*

Many processes and environments of lowland river valleys in the Puget Sound basin are inherently buffered from upstream inputs. For example, increased sedimentation or flooding caused by headwater land uses would not markedly affect floodplain habitats because of the immense flood storage capacity and because increased sediment deposition would concentrate in the channel. For this reason, while watershed restoration professionals often emphasize the need to first restore headwater processes, such as reducing erosion associated with logging roads, prior to undertaking restoration projects downstream, lowland restoration does not necessarily depend on prior headwater restoration. Restoring lowland habitats has unique challenges, such as that posed by the inherent invasibility of riparian habitats (Planty-Tabacchi et al. 1996) combined with the abundance of exotic species in lowland environments.

This inherent buffering from upstream impacts, in combination with the historical abundance and variety of lowland habitats, suggests that these mostly vanished or badly degraded habitats, if restored or rehabilitated, could logically serve as refugia for salmonids, supplemental to disturbance-prone headwater areas that are now the focus of conservation planning (e.g., Frissell et al. 1993; Doppelt et al. 1993).

## THE ROLE OF HISTORICAL RECONSTRUCTION

Prioritizing and ordering restoration activities within a watershed and understanding the interactive mechanics of geomorphic processes and riverine habitat and how they differ throughout the region are central to effective restoration planning (see Chapter 9). Historical studies in the Puget Lowland suggest answers to these problems that are contrary to commonly held assumptions about the historical distribution of habitats, the processes that generate them, and how, where, and in what order habitats might best be restored. These counter-intuitive insights support the argument for the importance of undertaking historical analysis early in restoration, rehabilitation, and conservation planning.

It is likely that many of the insights from historical studies in the Puget Lowland are relevant for other regions. For example, wood jams were formerly important to large rivers not only in the Pacific Northwest but also throughout forested temperate regions of the world. Forests and in-channel wood were cleared from the eastern United States and Europe (for review, see Montgomery et al. in press), and a general approach relevant to restoring riverine forests and wood in the Pacific Northwest may have potential for broader application; the same may be true of other facets of reconstructing the Puget Sound's riverine landscape.

Historical landscape studies have application to ecosystems studies and management worldwide. The particular collection of historical materials, methods, and field approaches uniquely useful in the Puget Lowland does not necessarily transfer directly to another environment. For example, in Europe the imprint of agricultural and industrial civilization extends millennia into the past; forest disturbance in Europe has been significant for at least 6,000 years (Williams 2000), and river clearing and engineering date to the Roman era (Herget 2000). Central to European river history are the archival methods of the historian and archaeological approaches unique to the regions' challenges (e.g., Haslam 1991). Nonetheless, while the types of source materials and methods may vary among regions and landscapes, a variety of temporal- and spatial-scale appropriate, cross-referenced and multi-scaled approaches are available for revealing the historical riverine landscape in any environment (e.g., Egan and Howell 2000).

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