Historical aquatic habitat in river valleys and estuaries of the Nooksack, Skagit, Stillaguamish, and Snohomish watersheds

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ABSTRACT

We mapped channels and dominant vegetation communities using a GIS (Geographic Information System), archival maps, field notes, and aerial photographs, and more recent high-resolution DEMs in four North Puget Sound drainages (the Nooksack, Skagit, Stillaguamish, and Snohomish) for the time of early Euro-American settlement, or approximately 1870-1880. We used this mapping to classify and quantify aquatic habitat in channels and wetlands in the study area's estuaries and major river valleys. The channel habitat area aggregated for the four areas totals 11 x 10^3 hectares; one-half of this amount was in the Skagit study area. Wetland area was more than three times (37 x 10^3 hectares) that of channels. We used primarily historical field observations to estimate the seasonal extent of wetland inundation (which we defined as being inundated by at least one foot of water for most of the season). The area of winter wetland inundation (12 x 10^3 hectares) is greater than that of the channel area, and summer inundation about one third as much (4 x 10^3 hectares). An additional 3 x 10^3 hectares wetland area was subject to regular-tidal inundation by freshwater, and 13 x 10^3 hectares by saltwater. About one-half of the winter and summer inundated wetland areas were within the Skagit study area—primarily on the Skagit River delta—and most of the remainder was in the valleys of the Snohomish, Snoqualmie, and lower Nooksack rivers.

INTRODUCTION

Statement of the Problem

Information on an aquatic landscape's historical condition and productivity can inform management and restoration of aquatic resources. This report in particular quantifies and characterizes aquatic habitat for estimating historical salmonid productivity to develop recovery goals for endangered salmon runs.

In landscapes having undergone extensive anthropogenic change, archival studies are the primary opportunity for gaining insight into historical conditions (Collins et al. 2003). Beechie et al. (1994; 2001) previously estimated historical physical aquatic habitats in the Skagit and Stillaguamish watersheds. This study builds on these earlier studies by: (1) making use of a broader range of data sources; (2) quantifying aspects of the aquatic habitat not included in the previous estimates, such as wetlands and tidal creeks; (3) characterizing historical vegetation with an emphasis on its relevance to aquatic habitat; (4) including the Nooksack drainage to the north and the Snohomish to the south; (5) building the estimates with a GIS, thus creating a planning and analysis tool; and (6) integrating into the GIS coverages, and habitat estimates, information on the sources, assumptions, and certainty, important for users of the information.

Here we report historical aquatic habitat estimates and provide context for understanding its potential application to other parts of the Puget Sound basin. The attached appendices include detailed supporting information. Appendix A details our GIS mapping methods. Appendix B provides statistical descriptions of historical forests, and Appendix C provides descriptive detail on historical wetlands, and how we estimated their inundated area.

Study Area

The Nooksack, Skagit, Stillaguamish and Snohomish river basins (Figure 1) drain the north Cascade

Range and northern Puget Lowland. The 7,800 km^2 Skagit is the largest, followed by the Snohomish, the Nooksack, and the smallest 1,770 km^2 Stillaguamish basins. Together they account for two-thirds of the land area of the eastern Puget Sound basin. Each watershed heads in the western Cascade Range, flows through the Puget Lowland and enters Puget Sound. The estuaries and river valleys of these north Sound rivers are dominated by agricultural, rural residential, and forest land uses and are considerably less urbanized than those in southern Puget Sound.

The study areas encompass the rivers' estuaries and major river valleys. The total area of the study area in each of these four river basins is 693 km^2 in the Skagit, 283 km^2 in the Snohomish, 206 km^2 in the Nooksack, and 178 km^2 in the Stillaguamish river watersheds. We restricted our analysis to these areas for several reasons. First, habitats in lowland valley bottoms and estuaries were the most abundant, diverse, and productive historically (e.g. Sedell and Luchessa 1982; Beechie et al. 1994). Second, because anthropogenic change to the valley-bottom and estuarine landscape has been widespread, historical reconstruction is more essential in these areas than in headwater streams, where other approaches can be taken (Beechie et al. 1994, 2001). In addition, and most importantly, the earliest archival materials (primarily the USC&GS charts and GLO plat maps and field notes) are more useful in valley bottoms and estuaries than in headwaters.

OVERVIEW OF THE HISTORICAL LANDSCAPE

Figure 2 depicts the study area as we mapped it. The methods, assumptions, and sources we used to create these maps are detailed in Appendix A.

Regional Geomorphic Template

Generalizing broadly, river valleys (excluding deltas) in the study area can be placed into two groups. The lower Nooksack, the Snohomish, and the Snoqualmie share common characteristics. These valleys have in common their origin as valleys eroded by sub-glacial runoff (e.g. Booth 1994, Dragovich et al, 1997). They are broad (2 to 4 km wide) and have a low valley gradient (valley gradient of 0.0004 to 0.0008). The rivers are meandering, their banks are 2-5 m higher in elevation than the surrounding valley (Figure 3), and have a narrow meander belt with relatively slow rates of channel migration (Figure 4A and 4B). The upper Nooksack, the upper Skagit, Stillaguamish forks, and the Skykomish are in a second group having similar characteristics. These valleys are confined by mountain slopes, half as wide (1-2 km wide) and an order of magnitude steeper (valley gradient of 0.001 to 0.003) than the valleys of the other group. The valleys were sculpted by Pleistocene valley glaciers (Tabor et al 1988; Kovanen and Easterbrook 2001) and some (the Skagit, Sauk, and North Fork Stillaguamish) were subject to Holocene lahar deposition and subsequent incision. Their valley topography is characterized by multiple channels and islands (Figure 3C), and the river dynamics include avulsion between multiple channels combined with relatively rapid meander migration (Figure 4C). The mainstem Stillaguamish River shares characteristics of both groups.

River deltas in the four watersheds each have distributary channels which branch from the main river approximately at the upper end of tidal influence. Historically, wood jams were instrumental in the switching of flow between major distributaries near the head of tidal influence at least three of the four watersheds—the Nooksack, Stillaguamish, and Skagit each had large, persistent wood jams that mediated the flow into distributary channels (Collins et al. 2001; Collins and Sheikh 2002). However, the topography and form of each delta/estuary reflects different geologic histories.

The Skagit-Samish delta is largely the creation of mid Holocene lahars (~5,500 ybp) from Glacier Peak. These lahars prograded the shorefront ~25 km downstream and created the immense, spreading delta (Dragovich et al. 2000). Consequently, there were extensive estuarine wetlands, vast riverine tidal freshwater wetlands, and extensive palustrine wetlands; the Skagit delta is a unique feature in Puget Sound (and unique in the amount and diversity of its historical habitat). The Snohomish has no history of volcanic deposition, making it unique among delta/estuaries of the major rivers of eastern Puget Sound. The present-day form of the valley reflects primarily the effects of valley-carving by subglacial runoff (see above). Consequently, the delta is confined (compared to the spreading delta of the Skagit), and extends a great distance upvalley; the considerable upvalley influence of the tides created the valley's extensive riverine-tidal wetland. Similarly, the Nooksack delta, while different in plan form to the Snohomish, also has a relatively low gradient, and shared with the Snohomish extensive riverine-tidal wetlands.

CHANNEL AND WETLAND CLASSIFICATION SYSTEM

We used a two-part system to classify channels. In the first part of the system, we classify channels by their vegetation community, which in turn is largely a response to the salinity of water in the channels.

(1) *Estuarine Emergent*. Estuarine emergent channels are within the portion of estuaries characterized by emergent vegetation that is regularly inundated by tides. We delineate these channels on the basis of our delineation of estuarine emergent wetland (see below).

(2) *Estuarine Scrub-Shrub*. These channels are within the scrub-shrub vegetation community that generally corresponds to the upper parts of the tidal range. Tidal channels are regularly filled with saltwater, but the marsh surface itself is not regularly covered by tidal influence. The upper extent of estuarine scrub-shrub generally corresponds to the upper limit of the tides.

(3) *Tidal-Freshwater*. Tidal-freshwater channels have dominantly freshwater, and extend from the upper limit of the estuarine influence (dominated by saltwater) to the upper extent of tidal backwater influence. In the study area, the upper limit of the tidal-freshwater area generally corresponds to the upper limit of distributary channels.

(4) *Freshwater*. Freshwater channels are upstream of any estuarine or tidal backwater influence.

In the second part of the scheme, we classify channels on the basis of geomorphic characteristic or size:

(1) *Mainstem*. Mainstem channels are the named rivers of the study area: Nooksack River and its forks; Skagit, Baker, Sauk, Suiattle, and Cascade rivers; Stillaguamish and its forks; and the Snohomish, Skykomish and Snoqualmie rivers. Mainstem channels are distinguished from "tributaries" by being generally greater than 30 m in width.

(2) *Tributary*. Tributaries are generally less than 30 m in width and originate as low-order headwater channels.

(3) *Slough.* Sloughs are small channels that diverge from a larger channel to which they rejoin farther downstream, or they dead-end on the floodplain. Sloughs are distinguished from braids within the active channel, which are mapped as part of the main channel (e.g., mainstem, tributary, etc.) by making a foray beyond the margins of the main channel and typically into forest or other established vegetation communities. We distinguish sloughs from multiple mainstem (or tributary) channels by their being significantly smaller than other branch or branches.

(4) *Distributary.* Mainstem channels become distributaries when they split into diverging channels that ultimately enter Puget Sound rather than rejoining the river. Distributary channels generally branch near the head of tidal influence. In the Nooksack this is at the divergence of the Lummi and Nooksack rivers; in the Skagit at the divergence of the North and South forks; in the Stillaguamish at the divergence of the former mainstem at the head of Hat Slough; and in the Snohomish at the upstream end of Ebey Island.

(5) *Blind Tidal*. Blind tidal channels are primarily created by and drain tidally- or flood-introduced

water (Simenstad, 1983) and are characterized in map-view by a narrowing with increasing distance from the tidal source. We also distinguished channels that connect two blind channel networks as "blind-to-blind" channels.

(6) *Distributary/Blind Tidal*. These channels are recognizable in plan view and by their landscape position as blind tidal channels, but are also fed by significant amounts of freshwater from distributaries, and thus also function as a distributary.

(7) *Connecting.* Channels in which the flow is not clearly seaward; flow connects between two distributary channels (in the estuarine emergent or estuarine scrub-shrub zone; within the riverine-tidal zone, we call this a distributary), between two blind channel networks. In this report, we use "tidal creek" as a shorthand way to refer to estuarine blind-tidal, distributary-blind, and connecting channels collectively.

These two classifications create a binary classification scheme for channels. For example, "estuarine emergent blind-tidal" refers to a blind channel in the emergent zone; "tidal-freshwater distributary;" "freshwater slough" etc.

METHODS FOR QUANTIFYING HABITAT

Appendix A provides detail on methods we used to develop GIS mapping. This section presents the approaches we used to develop quantitative habitat estimate using these GIS layers.

Approach to Quantifying Channel Area

Our channel areas refer to the active channel. This is because GLO field crews appear to have measured the active channel (see discussion in Appendix A), and the USC&GS charts show the bankfull channel consistently, and do not consistently show the extent of the low-flow (MLLW) channel. In a few cases, we are able to distinguish the portion of tidal channels in which the bed is exposed during MLLW, and in these cases we have mapped these channel polygons separately in the GIS layers. However, because we lacked consistent data for mapping the low-flow (or low-tide) channel, we have not made separate areal estimates for this report.

We use "large channels" to refer to channels shown on original source materials (and mapped in our GIS coverages) as polygons. Quantifying large channel area was simply a matter of summarizing polygons in the GIS coverages. Appendix A details the relative accuracy of large channel mapping and how and why accuracy varies within the study area and with different source materials.

We used "small channel" to refer to those channels appearing on source materials as lines, or those not shown on archival maps but shown on 1930s aerial photos, and which we draw in the GIS coverages as arcs. For small channels, we made use of widths field-measured by the GLO survey. These field measurements exist where the GLO survey crossed the creek. Because the GLO did not cross all creeks we mapped, and because the points where they crossed creeks are widely spaced, we extrapolated these field measurements by grouping streams in similar topographic and geomorphic environments.

Approach to Quantifying Tidal Creek Area

Estimating the channel area within the network of tidal creeks presented a special challenge. Excepting a few of the largest tidal channels, the GLO plat maps do not map tidal channel network in detail. The USC&GS charts in other western North America regions sometimes mapped tidal creeks in great detail, for example in the San Francisco estuary (Grossinger 1995) and the Columbia River estuary (based on our examination of T-sheets), but we have not found that to be the case in northern Puget Sound. In addition, in three of the four estuaries (all but the Snohomish) there had been considerable diking of tidelands prior to the USC&GS charting.

To work within these limitations, we identified marshes in the Skagit and Snohomish estuaries where a large amount of tidal network remains or remained at the time of the earliest aerial photos, and in those areas we mapped the channel network from orthorectified aerial photos. We mapped a portion of the Snohomish estuary in the Ebey Slough area from 1938 aerials, and parts of the South Fork and North Fork Skagit estuary, using 2001 aerials. We used the more recent aerials for the Skagit because, while less estuarine marsh remains in 2001 compared to 1937 (when the earliest photos were taken), the 2001 imagery is high resolution and color, which aided in mapping.

Mapping channels on recent imagery makes the assumption that the overall channel density remains relatively unchanged over a number of decades. This appears to be a good assumption in areas where there was not rapid sedimentation or other anthropogenic alteration, because we have compared active tidal channel networks on photos separated by 60-70 years and found in many cases remarkably little change. However, we have not systematically tested this assumption at this time.

We mapped channels to a minimum width of about 0.6 m, which was the lower limit at which we could consistently trace out the channel and measure a width on the aerials. We have not at this time made a rigorous assessment of the proportion of the channel network that we have missed by not mapping channels narrower than about 0.6 m. However, we made a rough assessment by comparing our GIS and aerial photo mapping to the field mapping of three tidal channel networks in the Skagit EEW in May 1997 (Collins 1998, Figures A-2-2 through A-2-4 and unpublished data). Based on this examination, it appears that the aerial photo mapping probably underestimates the total channel network, but by several percent, not by several tens of percent. However, we have not at this time rigorously examined this, and so it should be understood that the tidal channel areas we are developing for this report are low by an unknown amount. Our mapping may more significantly underestimate the channel area in the scrub-shrub wetland where channels are more likely to be obscured by vegetation.

To integrate our aerial photo and GIS mapping of recent tidal networks with the USC&GS mapping, we identified the minimum width of distributary channels that the USC&GS consistently charted, and used this to define polygons in which we measured all channels. In practice, this appears to have been a fairly robust approach, as the US&GS mapped most of the distributary and connecting channels greater than about 15 m in width, and we found few distributaries or connecting channels narrower than this within our polygons. The great majority of channels we mapped were blind channels, with a smaller number of "blind/distributary" channels (see earlier channel classification description). We then excluded from our channel area calculations the tidal channels mapped by the USC&GS within those polygons (most of which appear in our GIS coverages), because the USC&GS tidal channels were not dependably mapped. Finally, we developed average ratios of channel area to polygon area (see below), and applied these to our polygon areas to develop channel area estimates.

Figure 5A shows the relation between the polygon area and channel area in the South Fork Skagit, where we mapped 16 polygons ranging in size from 10 to 120 hectares. Figure 5B shows the range of ratio between channel area and polygon area for the South Fork estuarine emergent and Snohomish estuarine emergent zones; the two ranges are similar, and average about 0.08. The estuarine emergent marsh in the North Fork Skagit generally had much less channel area (Figure 5B). Our hypothesis (untested at this time) is that this stems from the North Fork marsh being recent, mostly accreted within the last 60 years (presumably owing to high 20th century anthropogenic rates of sedimentation), and so presumably lower in elevation, less stable, and with a less well developed channel network. We have assumed that the South Fork Skagit and Snohomish areas, which are both older marshes within a recently stable sedimentation regime, are most representative of historical conditions. The estuarine scrub-shrub area mapped in the South Fork Skagit clustered around 0.05; we have assumed that this figure is the best estimate available of typical historical conditions because our scrub-shrub area in the Snohomish was very small and was relatively obscured by vegetation. We also measured cumulative channel edge in these same areas. The mean channel edge length per hectare of emergent and scrub-shrub marsh was 440 m/ha and 340 m/ha, respectively, excluding the North Fork Skagit.

We could not apply this approach to estimating historical channel area in riverine-tidal wetlands because only small patches of this habitat had survived to the 1930s photos or to the present (e.g. Otter Island in the Snohomish estuary). Moreover, there appears to have been a great deal of variability in hydrological characteristics among the study area's riverine-tidal wetlands (see Figure 2 and Appendix C). For this reason we estimated the tidal-freshwater blind channel network area on a watershed-by-watershed basis. In each case, we measured the area of tidal channel as mapped primarily from channels on 1930s aerials (including relict channels). We then doubled the channel area estimated in this way. We think this is a conservative estimate, because the relict channel network appears to underestimate the historical network by at least a factor of two, based on comparison of estimates of estuarine emergent and estuarine scrub-shrub made from adjoining diked area and undiked areas (using relict channels and extant channels, respectively). The resulting equivalent ratios are between 0.005 and 0.015 (and 0.0003 in the Samish; see Appendix C), considerably less than the 0.05 measured in the estuarine scrub-shrub zone.

Approach to Quantifying Wetland Inundated Area

Appendix C describes in detail the approach we used to quantifying inundation in wetland areas. Briefly, we assembled all descriptive information that we had gathered for each wetland (see Appendix C), then developed "rules" for using that data to estimate inundated area in summer, winter, or during regular saltwater inundation or regular freshwater tidal inundation. For seasonal (non-regular-tidal) inundation, we take as a minimum at least one foot of water for most of the season. In estimating inundated area, we placed a higher priority on historical field observations, primarily from the GLO field notes. For those wetlands lacking such direct historical field observation, for which we relied more heavily on inference, we attempted to conservatively estimate inundated area—in other words, to assume an absence of inundation, lacking direct evidence of strong inferential information to the contrary.

Large wetlands were more likely to have extensive field observations available for them, which means that our estimates of inundated area in the larger wetlands have the highest standard of evidence. The relatively high certainty we can have in our estimates of inundated area for most of the larger wetlands in turn means that inundated area estimates aggregated for entire watersheds are fairly robust. On the other hand, because there is in general a lower level of evidence for smaller wetlands, our characterizations of hydrology in individual small wetlands is less robust. While we expect to refine our methodology (see Appendix C) for smaller wetlands, the difference in data availability and certainty between larger and smaller wetlands inevitably will make characterizations of smaller areas will remain less certain than for larger areas.

ESTIMATES OF HISTORICAL HABITAT

Channel Area

The channel areas given in Table 2 represent the sum of polygons (“large channels”), arcs (“small channels”), and for tidal portions of the study area, estimates of blind tidal channels from our aerial photo mapping, as described above. Figure 6 shows that about one-half of the channel area was in the Skagit. Freshwater mainstem dominated overall; Figure 7 shows the estuarine and riverine-tidal channel areas alone, to show detail on the distribution of habitat types within each.

Wetland Area

The Skagit River estuary had more than one-half of the estuarine wetland area among the four study areas

(Figure 8). The emergent scrub-shrub area was larger in extent than the scrub-shrub in the Skagit, and the opposite was true in the Snohomish. In both cases however the scrub-shrub estuarine marsh was extensive, which is of interest in part because scrub-shrub estuarine marsh was the first to be diked off and converted to agriculture, and thus has been “missing” as habitat for longer. The Stillaguamish estuarine area includes the tidelands to the north of the delta proper, contiguous with the Skagit tidelands. Most of the estuarine marsh in the Nooksack shown in Figure 7 was on the Lummi River side of the Lummi-Nooksack delta (see Figure 2).

Riverine-tidal freshwater marsh was the dominant wetland type in the Snohomish valley (Figure 7). Most of that (the forested riverine-tidal wetland on Ebey Island and surrounding areas) appears to have been tidally inundated on a regular basis, rather than seasonally inundated. The Marshland area (and the similar marsh across the Snohomish River to the north) accounts for most of the seasonally inundated area in the Snohomish riverine-tidal wetland. The Skagit River had more than twice as much seasonally inundated riverine-tidal wetland as the Snohomish, and it accounted for three-quarters of the summer-inundated riverine-tidal wetland in the four-estuary area. The Stillaguamish had much less of this wetland type compared to the other estuaries, and we lacked evidence to consider much of it as seasonally inundated.

The Skagit basin (97% of the wetland area was on the delta) also dominated the north Sound’s Palustrine wetland area (Figure 8A). We lacked sufficient evidence to assume much of the relatively small wetland area in the Skykomish or Stillaguamish watersheds were seasonally inundated (Figure 8B). Most of the seasonally inundated palustrine wetland was in the two “Pleistocene glacial” valleys—the lower Nooksack and the Snohomish-Snoqualmie—or on the Skagit delta (Figure 9B).

Ponds

Table 3 gives pond area mapped in the GIS coverages. These ponds were generally shown on the GLO plat maps, and in a few cases on early topographic maps or on 1930s aerial photos (see Appendix A). We did not separately map or estimate beaver ponds. To some extent beaver dam area is built into our wetland areas. However, beaver dams would also have existed along streams; the GLO field surveyors seldom noted beaver dams at creek crossings. While GLO surveyors may not have noted all beaver ponds that they encountered, at only 2 of 115 crossings in the Nooksack study area and only 2 of 313 in the Skagit mention beaver ponds.

That so few beaver ponds appear to have been present on streams may reflect the effects of fur trappers in the decades preceding the GLO field survey. Our finding, based on the historical record, contrasts greatly with earlier estimates of historical habitat in the Stillaguamish area (Beechie et al. 2001, Pess et al. 2003), which relied on the assumption that beavers would have saturated available stream habitat; this assumption does not appear to be valid for mid-1800s conditions in the study area.

Quantitative Habitat Summary

Winter-inundated wetland slightly exceeded the total channel area in the study area (Figure 9A), and summer-inundated wetland was nearly a third as great as channel area (Figure 9B). An additional 3×10^3 hectares of wetland was subject to regular-tidal inundation by freshwater, and 13×10^3 hectares by saltwater (not shown in Figure 9). Including inundated wetland in historical habitat assessments substantially increases salmonid rearing area over previous estimates, which did not include wetlands (Beechie et al. 2001, Pess et al. 2003). This points to the importance of understanding the historical hydrology and habitat value of different wetland types and particular wetlands. The relative distribution of wetlands in Figure 9 also points both to the specificity of watersheds, and to the importance of the regional geomorphic template in understanding and predicting historical aquatic productivity.

Blind-tidal and blind-tidal/distributary channel accounted for about ten percent of the overall historical channel area (Figures 6 and 7 and Table 2). While this substantially increases the total historical habitat estimates. The historical abundance, and its uneven distribution within the study area, also points to the importance of understanding the habitat value of these environments and their role in shaping the historical distributions and abundances of different salmonid life history strategies in individual watersheds.

NOTES TO THE USER ON ACCURACY, CERTAINTY, AND THE LANDSCAPE VIEW

Historical habitat estimates will always be imperfect. Nor is there a standard approach to making them; we have had to innovate in various aspects of creating these estimates. We can refine individual aspects of our estimates as we refine our methods and as other researchers develop new methods, and as we find it feasible to make finer-scale searches for local information. However, even if we believed our methods and estimates could not be improved upon, historical estimates will always be limited. We weren’t there to see the landscape, and those who were there—the GLO surveyors and others—were not employed to estimate salmonid rearing area. Because we are using data that was not intended to be used in the way we are using it, and because we don’t always have reliable means of checking the data against other sources, there will always be uncertainty in the estimates.

We have made an effort to systematically identify uncertainty by making our mapping methods transparent, as described in Appendix A, as well as our approaches to estimating habitat from our mapping, as detailed for wetlands in Appendix C. It is important that users of this information interpret quantitative estimates in light of the uncertainties that we have identified (and additional uncertainties we may not yet be aware of). The GIS coverages explicitly link certainty and assumptions to each feature.

It is also important to stand back from the thickets of numbers, to take in the landscape view that the regional scope of this project allows. The landscape view is arguably the greatest strength of mapping of the sort we have undertaken—how landforms, ecological communities, and habitat-forming processes vary across the regional landscape—because it provides a basis for understanding the underlying template or process influences, and for making predictions.

Specific points to keep in mind in using the GIS coverages include the following:

(1) Each feature in our mapping has been given a source code that reflects the sources we used, the logic with which we used those sources, and the overall relative strength of evidence (see Appendix A). The relative certainty is not uniform in space and the nature of uncertainty is not uniform among different types of feature.

(2) Large channels mapped by the GLO were meandered (field surveyed), but they were not always accurately drawn. While on average, this does not appear to introduce more than a few percent error in channel dimensions, locally the discrepancy can be greater (see Appendix A).

(3) The GLO rarely mapped smaller floodplain creeks and tributaries. They simply noted the feature when they encountered it along a section line, or while meandering a river, and then sketched in the channels, “connecting the dots.” As described in Appendix A we made use of 1930s aerial photos to adjust the channel locations shown on the GLO maps.

(4) In our study area the Coast Survey rarely mapped tidal creeks in detail. We have mapped many historical tidal creeks from relict channels visible on 1930s photos in diked off land. Our mapping of these features is not uniform across a given study area or between areas. We have attempted to compensate for this incompleteness, in estimating tidal creek area and length, by extrapolating from recent tidal networks, as described in this report.

(5) Recent field studies show that riverine environments of the Pacific Northwest include numerous floodplain sloughs, many of which are difficult to map except by thorough ground surveys or by high-resolution topographic data. It is certain that we have not mapped many of the smaller floodplain sloughs.

(6) We have used a coarse wetland classification, and there would have been quite a bit of variation historically among wetlands within the same map type. While it is likely that we will be able to refine our wetland mapping and classification, it is important to keep in mind that one wetland within the same broad category may differ significantly from another in the same category. Appendix C provides more detail on individual wetlands, and our inundated area classification provides some functional refinement on the classification.

(7) As indicated previously, the accuracy of our wetland descriptions (including wetland area and seasonally inundated area), generally improves as wetland size increases, and because of this inundation information is more reliable for a watershed in aggregate than for individual smaller wetlands.

EXTRAPOLATING TO THE SOUTHERN PUGET SOUND AREA

To guide extrapolating to the southern Puget Sound basin, we review here the dominant patterns we have identified in the geomorphic template of the northern Puget Sound area, and comment on its likely application to the southern Sound. We have not yet mapped habitats in the southern Sound, and thus we are speculating based on broad geomorphic conditions.

North Sound and South Sound Pleistocene "Glacial Valleys"

The commonalities in glacial history of the valleys of the lower Nooksack, Snohomish and Snoqualmie rivers appear to have given rise to similar valley morphologies and river dynamics. These rivers had a meandering form and a low rate of meander migration. Outside the meander belt the floodplain dropped in elevation as it fell away from the river, which gave rise to extensive seasonally-inundated wetlands.

Is this same setting found in the south Puget Sound basin, and if so, is it reasonable to expect habitat assemblages to be similar? The Duwamish-White (present day Duwamish-Green) and Puyallup valleys are similar to the Snoqualmie and Snohomish in their *Pleistocene* origin (Booth 1994, Figure 4). However, both valleys were arms of Puget Sound until the mid Holocene, the Green River's delta in the Duwamish marine embayment was near the town of Auburn, and the delta of the ancient Puyallup River into the Puyallup marine embayment was near Sumner, 50 and 25 km upstream of the present day shorelines in the two valleys, respectively (see Figure 6A, Dragovich et al. 1994). The Osceola Mudflow of around 5,700 years ago and more recent lahars and sedimentation have created about 400 km^2 of new land surface (Dragovich et al. 1994). Mt. Rainier lahars continued massive sedimentation along the length of the Duwamish valley at least as recently as 1,100 years ago, and in the Puyallup as recently as 530 years ago by the Electron Mudflow. Thus, while their broader topographic form was created by Pleistocene subglacial runoff, these valleys are considerably different than the glacial valleys in the northern Puget Sound basin, because of their subsequent *Holocene* history of lahar deposition.

Cursory examination of GLO plat maps in the Duwamish valleys suggests the historical Duwamish and White (now Green River) rivers meandered, similar to the Snoqualmie and Snohomish, but there are also major flow splits evident. Similarly, large valley-bottom wetlands are evident on the GLO plat maps, but they are not as extensive as in the Snohomish-Snoqualmie or Nooksack, or as predictably located in valley margins. Our hypotheses at this time is that the recurrent volcanic deposition in the Duwamish valley may have prevented the development of an elevated meander belt, as in the Snohomish-Snoqualmie trough, and that local patterns of lahar deposition may have localized present-day patterns of valley-bottom relief and channel patterns, in contrast to the valley-scale patterns in the Snohomish and

Snoqualmie. In the Puyallup valley, we do not find evidence of the extensive wetlands that existed in the Snohomish and Snoqualmie.

North Sound Mountain-Lowland Transition Valleys and South Sound "Holocene Fluvial Valleys"

The Skykomish, upper Nooksack mainstem, Skagit, Sauk, and Stillaguamish forks are similar to one another, being in steeper, narrower valleys confined by mountainous valley walls. The generally lack the floodplain wetlands of the Pleistocene subglacial valleys. The rivers are more dynamic than the slowly meandering rivers in the "Pleistocene Glacial" valleys, and show a combination of meandering and anastomosing. These valleys generally have extensive river terraces created by downcutting into glacial sediments or volcanic lahar deposits.

This valley type is not representative of the southern Puget Sound area. Because of the greater distance to the Cascade Mountain front to the Sound in the southern region, and the greater extent of the Pleistocene glacial lowland fill, the southern Puget Sound area also has several rivers that have in the Holocene cut their own valleys through the Pleistocene glacial fill. These include the Nisqually, White, Cedar, and Green rivers. Our ongoing work on the Nisqually and White rivers indicates that these rivers primarily had a highly dynamic, anastomosing pattern, and occupied a large portion of their river valley. While the geomorphic setting differs between the these two types—the "Mountain-Lowland Transition Valleys" of the North Sound and the "Holocene Fluvial Valleys" of the South Sound—and the valley dimensions differ (the latter being narrower than the former), the river dynamics and habitats may turn out to be generally comparable.

Contrasts Among Estuaries

The estuaries of the four northern Puget Sound rivers had some similarities relating to their geomorphic setting, and also differences related to their tidal setting and the histories of volcanic deposition. The

Snohomish and Lummi-Nooksack deltas were formed in low-gradient valleys shaped by glacial or subglacial erosion, and both had extensive riverine-tidal wetlands. The Snohomish was more confined than the Lummi-Nooksack, causing there to be proportionately less estuarine emergent marsh than in the more spreading Lummi, but on the Nooksack side of the Lummi-Nooksack river delta there was almost no estuarine marsh, presumably resulting from a higher energy wave environment. The steeper and narrow Stillaguamish estuary had less wetland than the Snohomish and Lummi. The Skagit delta was a large spreading delta created by mid-Holocene volcanic sediments; this spreading form and low gradient created extensive estuarine and riverine-tidal wetlands; the geographic and topographic complexity of the delta created extensive freshwater wetlands.

The complexity of variables influencing the distribution of habitats among the four northern Puget Sound estuaries does not suggest an obvious extrapolation to the Nisqually, Puyallup and Duwamish estuaries. In both the Nisqually and Puyallup estuaries the USC&GS charts were made early in the diking period, facilitating a broad comparison in the dimensions of the estuarine wetland, in compared to the north Sound estuaries. Neither appears to have had riverine-tidal freshwater wetlands as extensive as on the Lummi-Nooksack and Snohomish. The Duwamish estuary had a more complicated and earlier history of anthropogenic change than the other two, and has a geologic setting complicated by the Seattle Fault which cuts across it; the USC&GS charts are less useful for a quick assessment of its habitat.

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Table 1. Extent of study area in the four watersheds.

WATERSHED	RIVER	EXTENT
NOOKSACK	Mainstem and North Fork Nooksack	RM 0 - RM 56
	South Fork Nooksack	South Fork RM 0 - RM 16
	Middle Fork Nooksack	Middle Fork RM 0 - RM 5
SKAGIT	Skagit River	RM 0 - RM 47
	Samish River	Samish River 0 - 8
	Sauk River	Sauk River RM 0 - RM 24
	Suiattle River	Suiattle River RM 0 - RM 5
STILLAGUAMISH	Stillaguamish	RM 0 - RM 18
	North Fork Stillaguamish	North Fork RM 0 - RM 34
	South Fork Stillaguamish	RM 18 – RM 34
SNOHOMISH	Snohomish	RM 0 - RM 21 (Snoqualmie &Skykomish confluence)
	Skykomish	RM 21 - RM 45
	Snoqualmie	RM 0 - RM 40

Table 2. Summary of channel areas for the four study areas (NKS: Nooksack; SKG: Skagit; STL: Stillaguamish; SNH: Snohomish.

HABITAT ZONE	HABITAT TYPE	**CHANNEL AREA**				
		NKS	**SKG**	**STL**	**SNH**	**TOTAL**
Freshwater	MAIN	1,236.1	3,365.8	782.7	1,478.8	**6,863.5**
	DIST	0.0	26.1	0.0	0.0	**26.1**
	SLOUGH	55.0	133.3	48.4	125.5	**362.2**
	TRIB	87.0	85.7	77.7	52.8	**303.1**
	TRIB-TERR	2.8	25.5	4.8	8.0	**41.0**
	TRIB-FAN	3.4	17.3	1.4	14.5	**36.6**
	TOTAL	**1,384.2**	**3,653.7**	**915.0**	**1,679.5**	**7,632.5**
Tidal-Freshwater	MAIN	0.0	0.0	47.9	187.8	**235.7**
	DIST	57.6	221.5	93.2	267.1	**639.5**
	SLOUGH	0.0	2.3	0.1	52.0	**54.4**
	BLIND	11.8	19.5	7.0	74.6	**112.9**
	TRIB	3.9	18.9	8.3	24.0	**55.1**
	TOTAL	**73.3**	**262.3**	**156.5**	**605.4**	**1097.6**
ESW	MAIN	0.0	0.0	0.0	0.0	**0.0**
	DIST	10.6	122.6	4.2	139.8	**277.3**
	BLIND	11.2	206.5	30.4	59.6	**307.6**
	BLIND/DIST	0.0	73.3	0.0	0.0	**73.3**
	CON	0.0	0.0	0.0	7.8	**7.8**
	TRIB	0.0	9.1	0.0	24.0	**33.0**
	TOTAL	**21.8**	**411.5**	**34.6**	**231.2**	**699.1**
EEW	MAIN	0.0	0.0	0.0	0.0	**0.0**
	DIST	14.7	244.6	84.6	143.2	**487.0**
	BLIND	25.9	318.4	93.2	28.2	**465.7**
	BLIND/DIST	5.4	110.9	0.0	5.9	**122.2**
	CON	1.1	277.8	23.1	1.2	**303.1**
	CON/DIST	0.0	0.0	112.5	0.0	**112.5**
	BLIND/CON	0.0	176.9	0.0	0.0	**176.9**
	TRIB	0.0	11.4	0.0	8.6	**20.0**
	TOTAL	**46.9**	**1,140.1**	**313.3**	**187.0**	**1,687.4**

Table 3. Pond area mapped in GIS coverages in the four study areas.

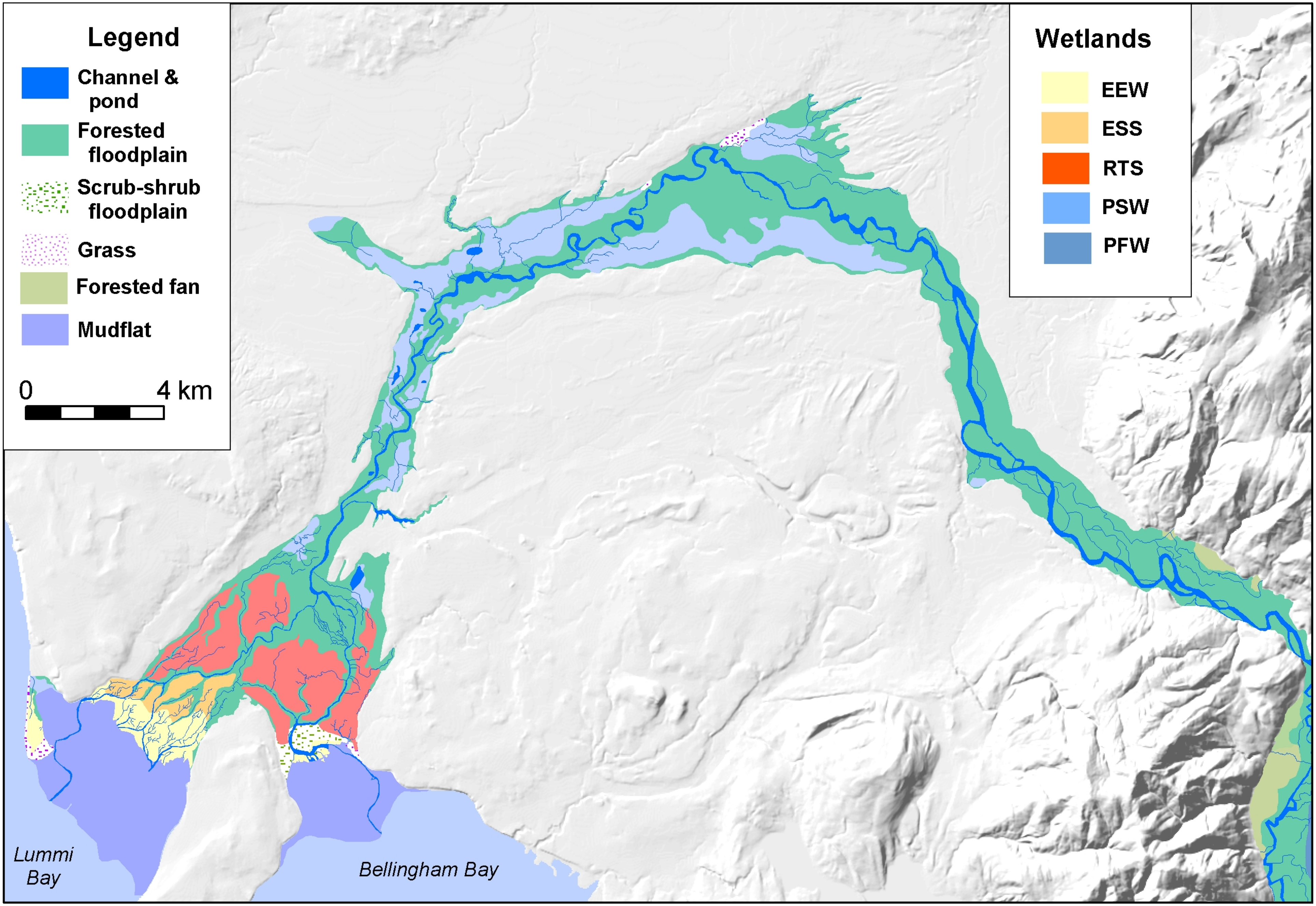
WATERSHED	NUMBER OF PONDS	POND AREA (HECTARES)
Nooksack	13	64
Skagit	8	58
Stillaguamish	2	3
Snohomish	16	41

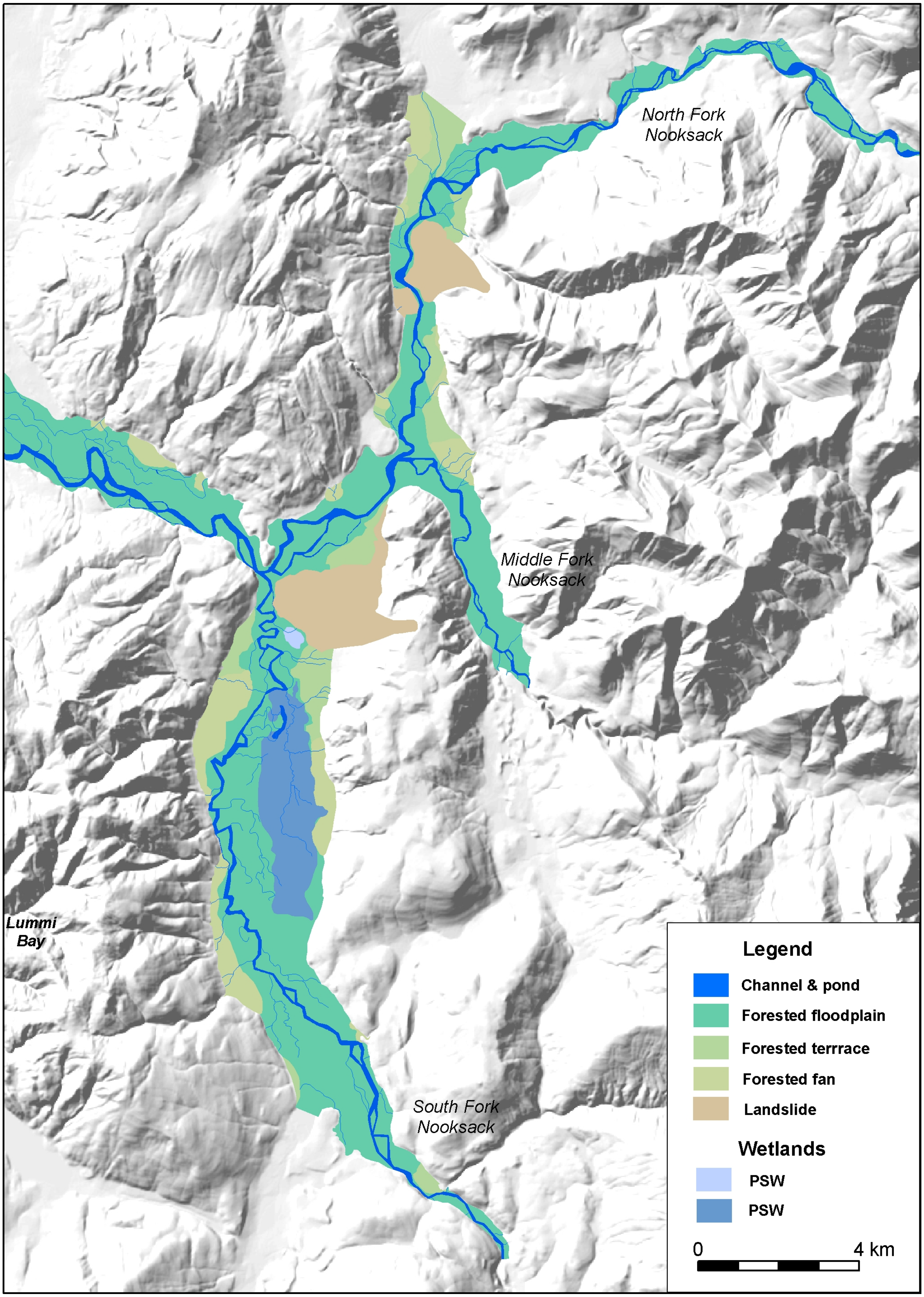
Table 4. Estimated historical inundated wetland area aggregated for individual watersheds.

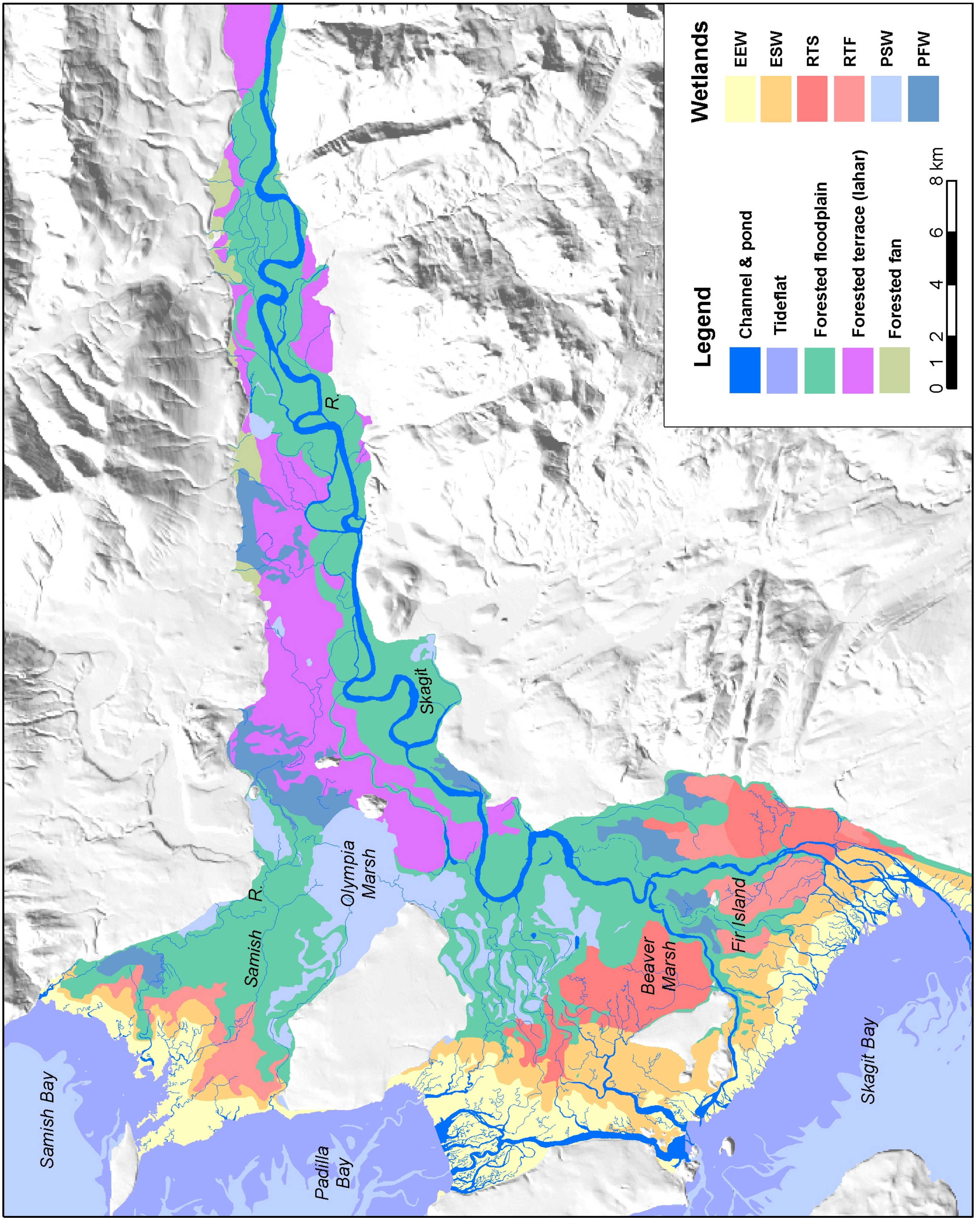
WATERSHED	WETLAND AREA	WINTER INUNDATED AREA	SUMMER INUNDATED AREA	FRESHATER TIDAL INUNDATION	SALTWATER TIDAL INUNDATION
Nooksack	4,500	2,200	1,000	0	600
Skagit	18,900	5,600	2,000	0	8,500
Stillaguamish	3,300	100	<100	0	1,800
Snohomish	7,900	2,600	900	2,900	1,600
Skykomish	200	<100	0	0	0
Snoqualmie	2,200	1,500	<100	0	0

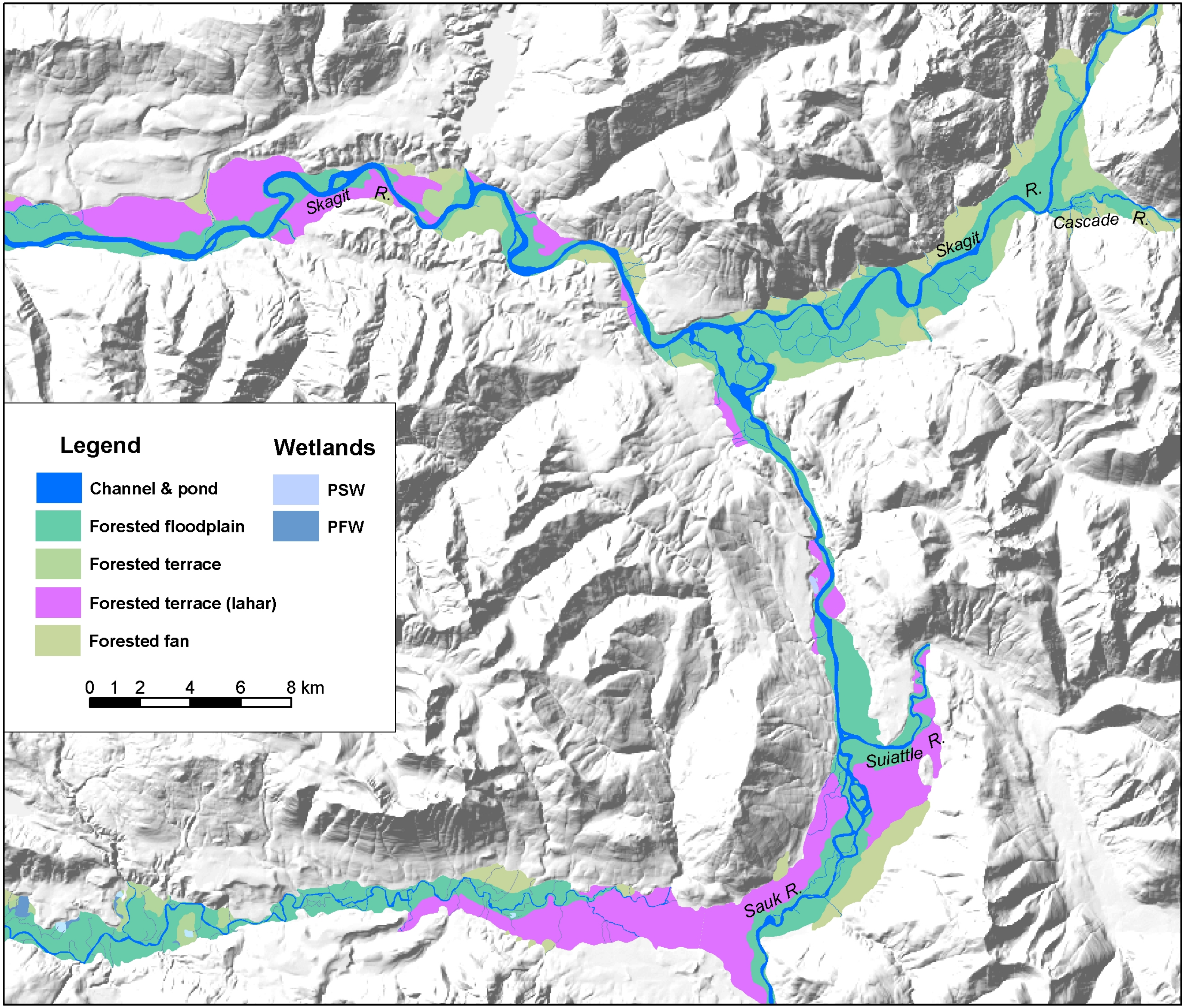
Figure 1. Location of the Nooksack, Skagit-Samish, Stillaguamish, and Snohomish study areas.

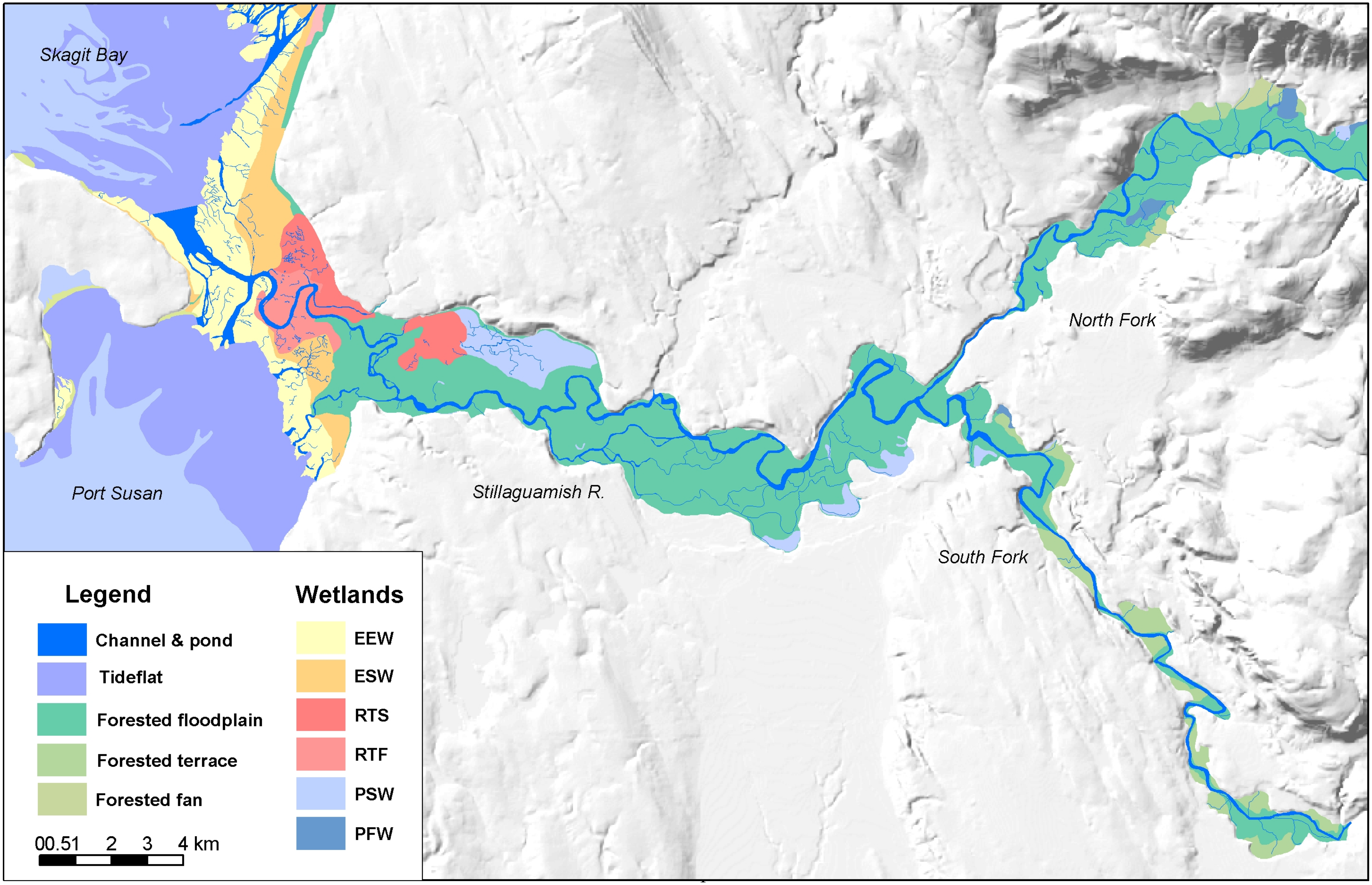
Figure 2. Following pages: Maps of historical conditions, from GIS layers created as described in Appendix A. (A) Lower Nooksack river; (B) upper Nooksack River; (C) Lower Skagit and lower Stillaguamish rivers; (D) Upper Skagit/Sauk and upper Stillaguamish rivers; (E) lower Stillaguamish River; (F) Snohomish River; (G) Skykomish and Snoqualmie rivers.

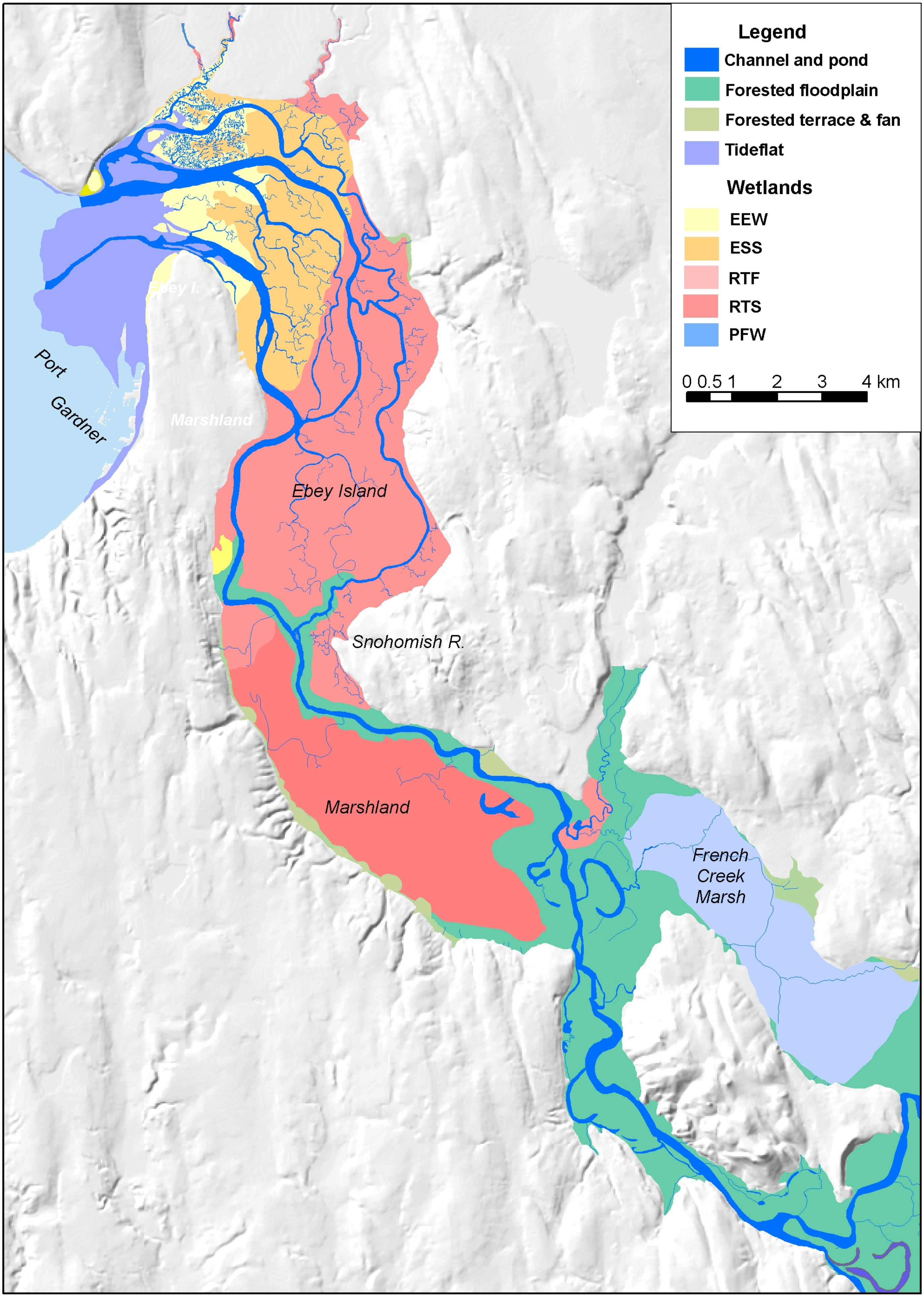

Legend
Channel & pond
Forested floodplain
Scrub-shrub floodplain
Grass
Forested fan
Mudflat
0
4 km
Wetlands
EEW
ESS
RTS
PSW
PFW
Lummi Bay
Bellingham Bay

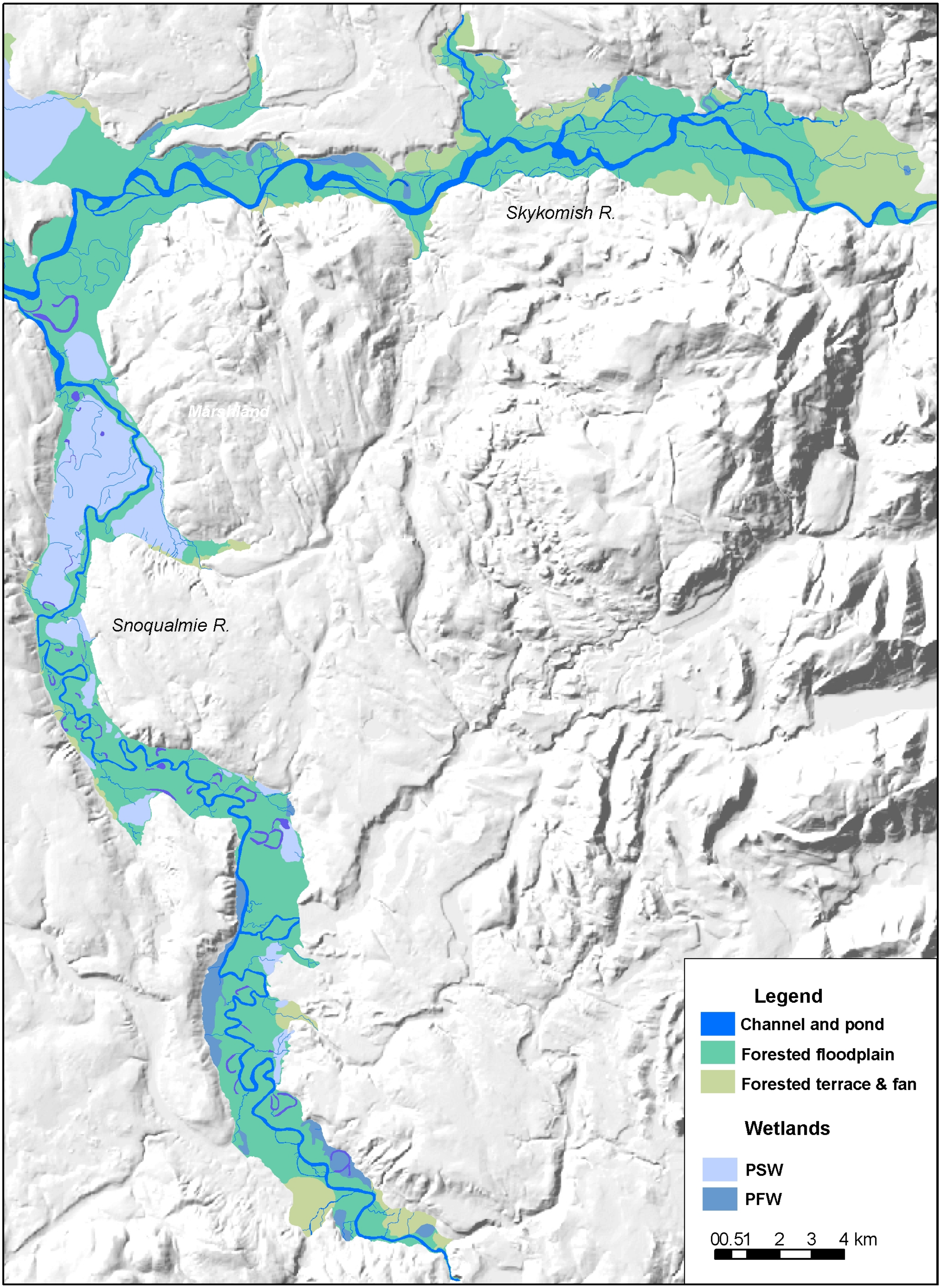

North Fork Nooksack
Middle Fork Nooksack
South Fork Nooksack
Lummi Bay
Legend
Channel & pond
Forested floodplain
Forested terrrace
Forested fan
Landslide
Wetlands
PSW
PSW
0
4 km


Legend
Channel & pond
Tideflat
Forested floodplain
Forested terrace (lahar)
Forested fan
Wetlands
EEW
ESW
RTS
RTF
PSW
PFW
0 1 2 4 6 8 km
Skagit R.
Samish R.
Olympia Marsh
Beaver Marsh
Fir Island
Samish Bay
Padilla Bay
Skagit Bay


Skagit R.
Skagit R.
Cascade R.
Suiattle R.
Sauk R.
Legend
Channel & pond
Forested floodplain
Forested terrace
Forested terrace (lahar)
Forested fan
Wetlands
PSW
PFW
0 1 2 4 6 8 km


Skagit Bay
Port Susan
Stillaguamish R.
North Fork
South Fork
Legend
Channel & pond
Tideflat
Forested floodplain
Forested terrace
Forested fan
Wetlands
EEW
ESW
RTS
RTF
PSW
PFW
00.51 2 3 4 km


Legend
Channel and pond
Forested floodplain
Forested terrace & fan
Tideflat
Wetlands
EEW
ESS
RTF
RTS
PFW
0 0.5 1 2 3 4 km
Ebey I.
Port Gardner
Marshland
Ebey Island
Snohomish R.
Marshland
French Creek Marsh


Skykomish R.
Marshland
Snoqualmie R.
Legend
Channel and pond
Forested floodplain
Forested terrace & fan
Wetlands
PSW
PFW
00.51 2 3 4 km

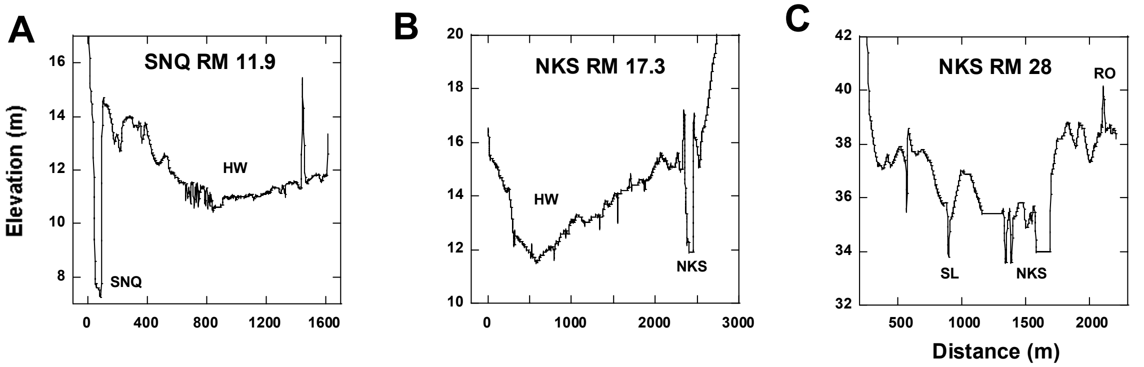


Figure 3. Representative valley cross-sections in the Snoqualmie (SNQ) and Nooksack (NKS) rivers. Locations are given by river mile and are shown in Figure 3. Valley profiles of the Snoqualmie (A) and lower Nooksack (B) are representative of "Pleistocene valleys," and contrast with profiles of the upper Nooksack (D) in "Holocene valleys." HW = historical wetland; SL = slough; RO = road. Profiles are from data described for Figure 3.

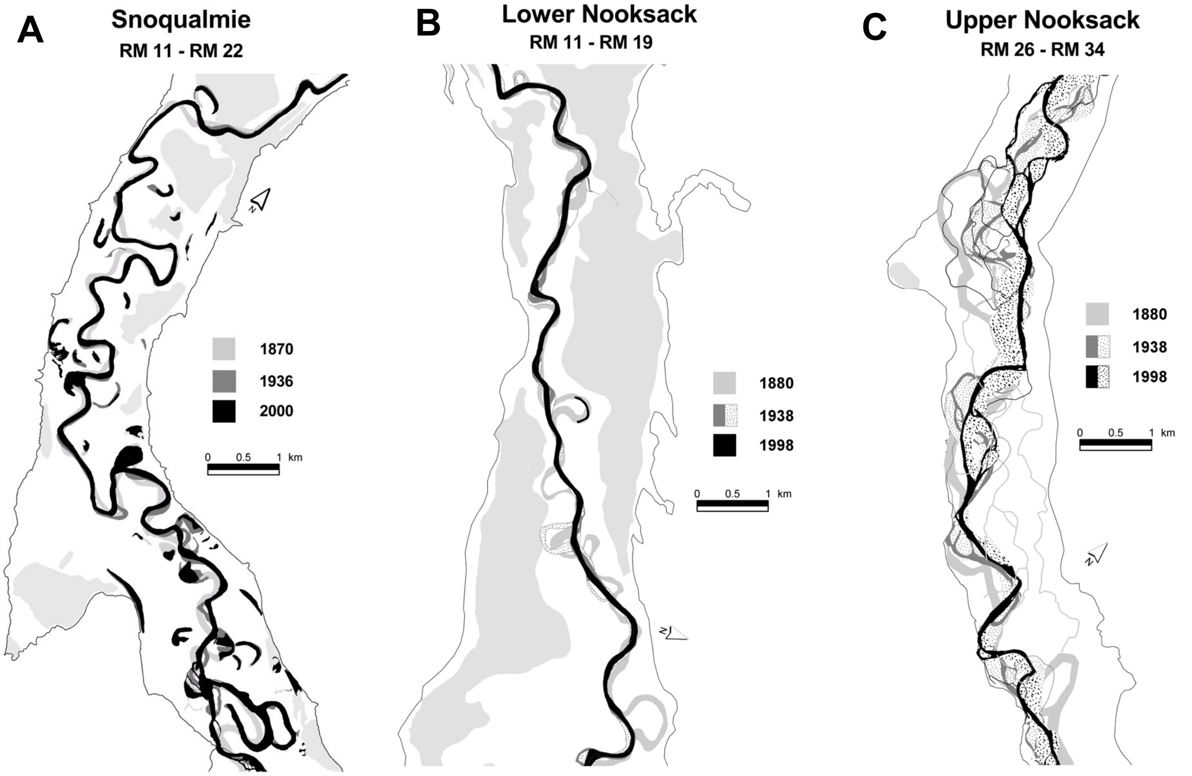


Figure 4. Channels, ponds and wetlands in four river reaches from three time periods: 1870-1880 (General Land Office plat maps), 1936-1938 (1:12,000 aerial photos); 1998-2000 (aerial photos). (A) Snoqualmie River from RM 11 to RM 22. Numbers represent year oxbow lakes were first apparent: 1 = 1870; 2 = 1936; 3 = 2000. For 1936 and 2000, low flow channel (solid pattern) and gravel bars (stippled pattern) are shown. Shaded areas distal from the channel are historical wetlands present in 1870. (B) Lower Nooksack River (RM 11- RM 19). Symbols are as in Panel A. (C) Upper Nooksack River (RM 26 – RM 34). In each panel, tributary creeks are omitted for clarity; only sloughs subsidiary to the main channel are shown.

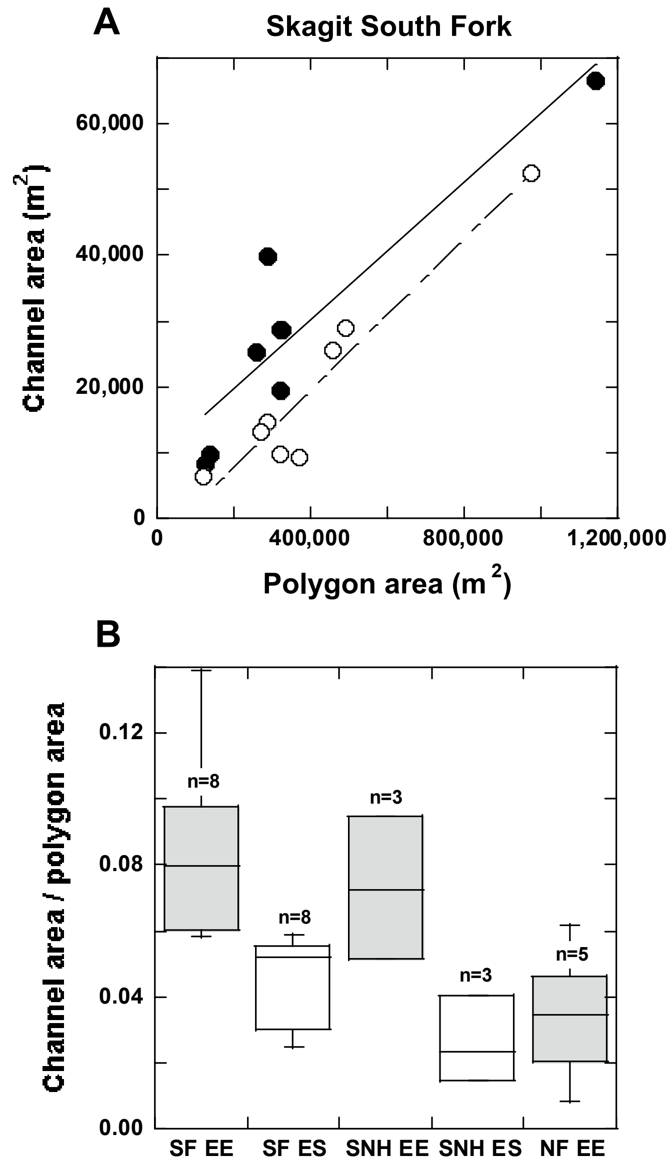


Figure 5. (A) Polygon area (marsh and channels) and channel area, in the South Fork Skagit area, for eight polygons (defined as described in text), for estuarine emergent marsh (solid circles and solid linear regression line) and estuarine scrub-shrub marsh (open circles and dashed linear regression line). (B) Variation in channel area / polygon area ratio for polygons in the South Fork Skagit EEW and ESW, Snohomish EEW and ESW, and North Fork Skagit EEW. EEW samples have shaded boxes, and ESW samples have unshaded boxes. Sample size is number of polygons.

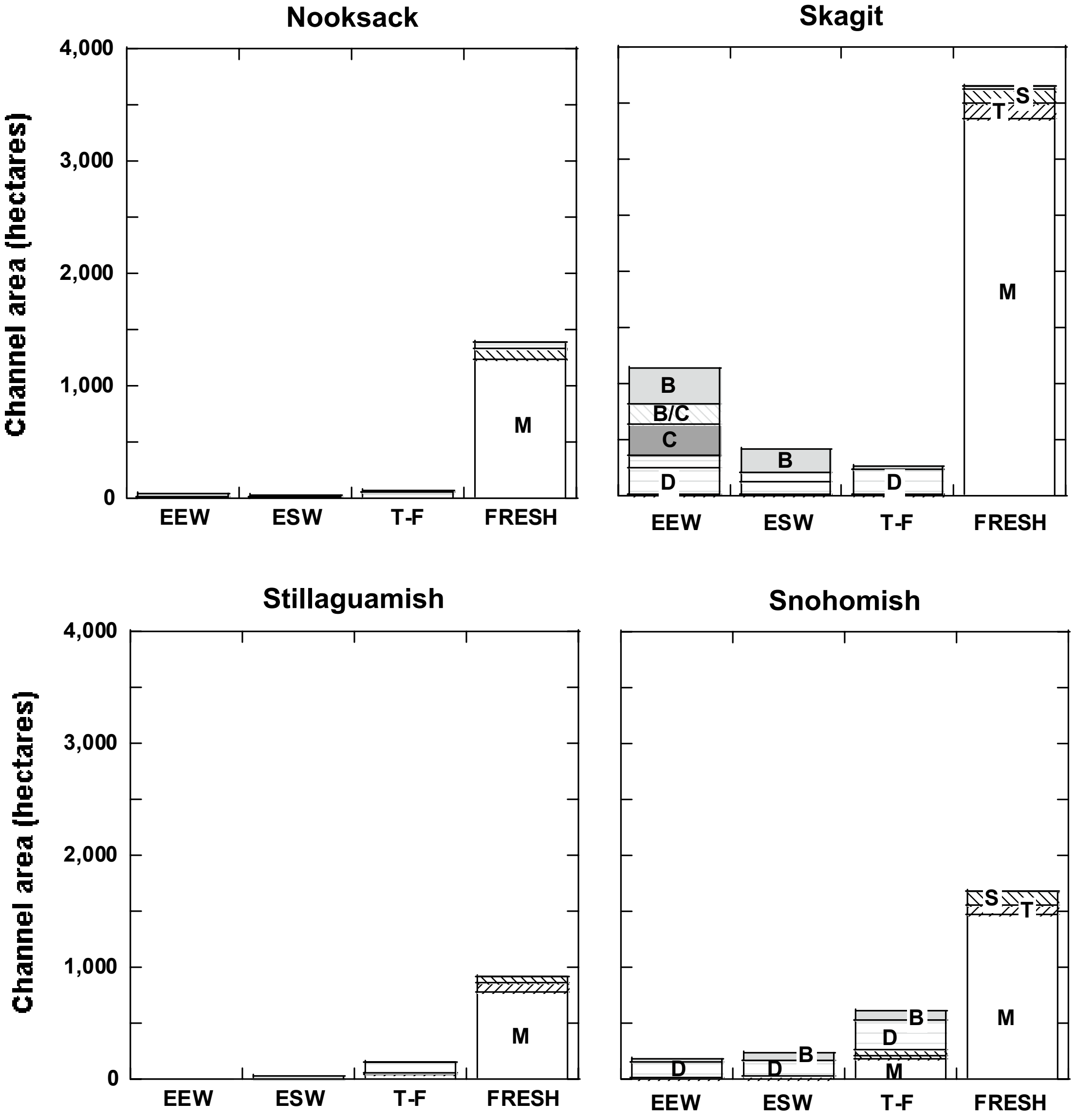


Figure 6. Amount of channel area in the four study areas. B: blind tidal channel; B/C: blind tidal/connection channel; C: connection channel; D: distributary channel; S: slough; T: tributary; M: mainstem channel. See Figure 7 for more detailed view of channel area in the estuarine and tidal-freshwater zones.

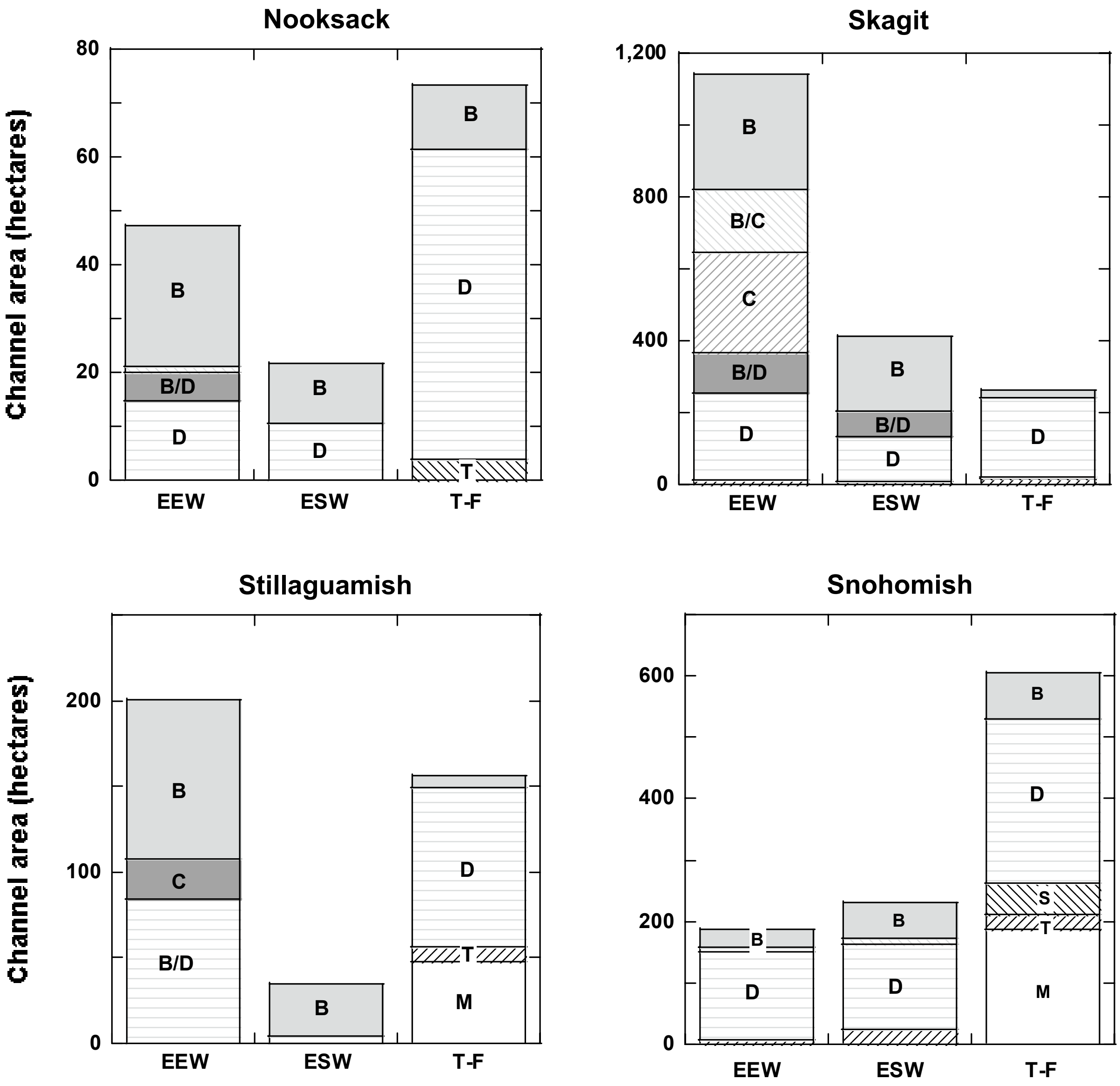


Figure 7. Estuarine and tidal-freshwater channel areas in the four study areas. Scale varies between figures.

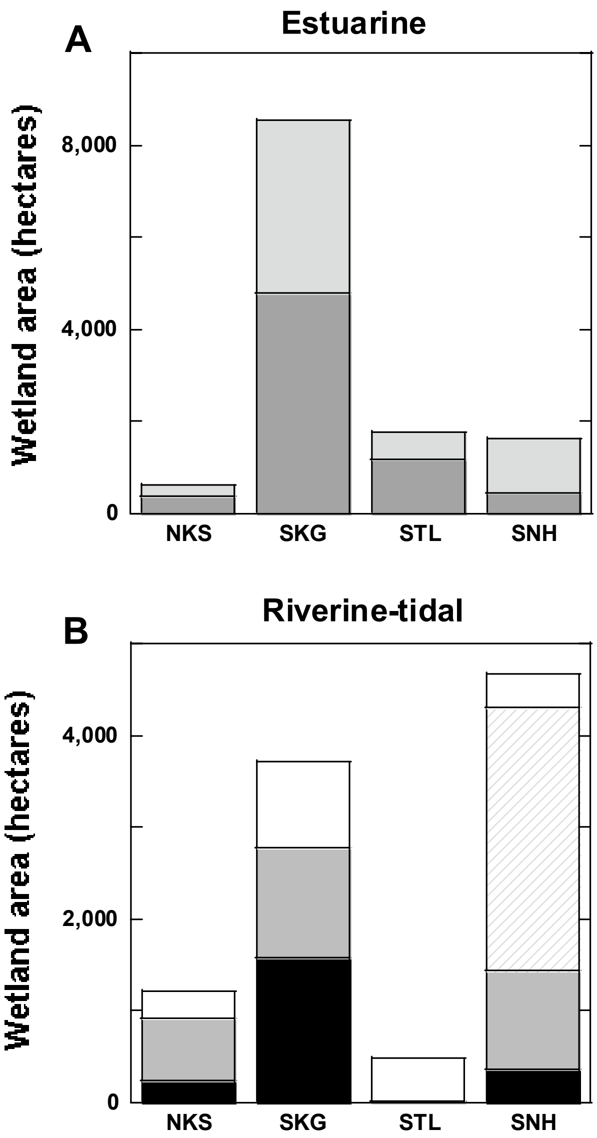


Figure 7. (A) Area of estuarine wetland mapped in the Nooksack (NKS), Skagit (SKG), Stillaguamish (STL) and Snohomish (SNH) river valleys. Dark shade indicates estuarine emergent, and lighter shade indicates estuarine scrub-shrub. (B) Area of riverine-tidal wetland mapped in the Nooksack (NKS), Skagit (SKG), Stillaguamish (STL) and Snohomish (SNH) river valleys. Darkest shade indicates summer and winter inundation, medium shade indicates winter inundation, light shade indicates regularly tidally inundated, and white indicates not inundated.

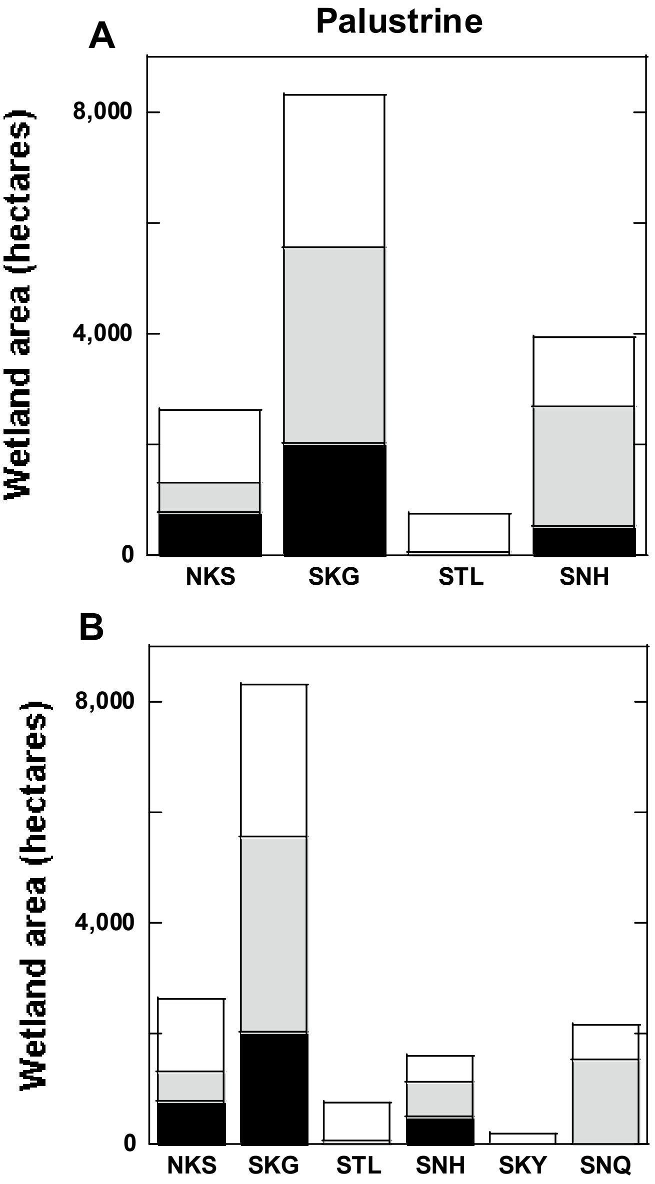


Figure 8. Area of riverine-tidal wetland mapped in the Nooksack (NKS), Skagit (SKG), Stillaguamish (STL) and Snohomish (SNH) river valleys. The lower graph divides the Snohomish study area into Snohomish, Skykomish and Snoqualmie subwatersheds. Darkest shade indicates summer and winter inundation, medium shade indicates winter inundation, light shade indicates regularly tidally inundated, and white indicates not inundated.

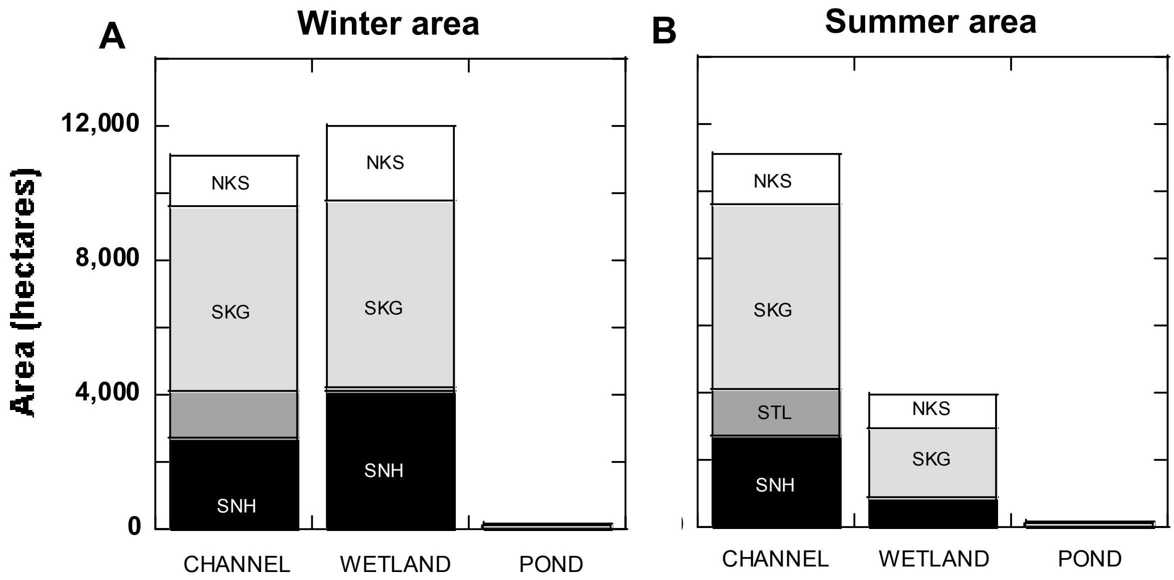


Figure 9. Extent of channel, *seasonally inundated* wetland, and pond area in the four study areas, in winter and summer. The wetland area excludes areas regularly tidally inundated. NKS: Nooksack; SKG: Skagit; STL: Stillaguamish; SNH: Snohomish.