NOAA Technical Memorandum NMFS-NWFSC-137

Monitoring Salmon Habitat Status and Trends in Puget Sound:

Development of Sample Designs, Monitoring Metrics, and Sampling Protocols for Large River, Floodplain, Delta, and Nearshore Environments

https://doi.org/10.7289/V5/TM-NWFSC-137

June 2017

U.S. DEPARTMENT OF COMMERCE
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Reference this document as follows:

Beechie, T. J., O. Stefankiv, B. Timpane-Padgham, J. E. Hall, G. R. Pess, M. Rowse, M. Liermann, K. Fresh, and M. J. Ford. 2017. Monitoring Salmon Habitat Status and Trends in Puget Sound: Development of Sample Designs, Monitoring Metrics, and Sampling Protocols for Large River, Floodplain, Delta, and Nearshore Environments. U.S. Department of Commerce, NOAA Technical Memorandum NMFS-NWFSC-137. https://doi.org/10.7289/V5/TM-NWFSC-137

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Executive Summary

It is the statutory responsibility of the National Marine Fisheries Service (NMFS) to evaluate progress toward recovery of Puget Sound Chinook salmon (*Oncorhynchus tshawytscha*), Hood Canal summer chum salmon (*O. keta*), and Puget Sound steelhead (*O. mykiss*), which were listed under the U.S. Endangered Species Act (ESA) in 1999 and 2007 (NMFS 1999a, 1999b, 2007a). As part of this responsibility, NMFS must assess the status of each listed population every five years, as well as the status and trends of key listing factors. One of the key listing factors for these three Evolutionarily Significant Units (ESUs) is the degraded quantity, quality, and distribution of habitat supporting these species. However, there are no consistent freshwater and nearshore habitat data across Puget Sound with which to assess habitat status or trends. Moreover, there is currently no program established to collect those data for assessing status and trends of salmon habitats in Puget Sound.

Our goal in this project was to develop a habitat monitoring program for the four distinct salmon and steelhead spawning and rearing environments of Puget Sound: large rivers, floodplains, deltas, and the nearshore. This program will provide data to assess habitat changes across each ESU and help determine whether habitat conditions are improving, static, or declining at future status reviews for each of the listed species. We have five objectives for the first year of this monitoring effort: 1) to develop a hierarchical sampling design to monitor habitat status and trends, 2) to identify habitat metrics that are cost-effective and related to Viable Salmonid Population (VSP) parameters (abundance, population growth rate, population structure, and diversity), 3) to develop protocols to measure these metrics, 4) to test satellite, aerial photography, and field observation methods for repeatability and reliability, and 5) to evaluate habitat status to assess the ability of each metric to detect habitat differences among the chosen land-cover strata.

Monitoring Design

Our general approach to monitoring habitat status and trends in Puget Sound relies on a hierarchical sampling design using coarse-resolution satellite data, mid-resolution aerial photography data, and fine-resolution field data. This hierarchical sampling approach gives complete coverage of land-cover changes in Puget Sound using satellite data, high sample-site density with aerial photography data, and lower sample-site density with field data. Because the fine-resolution sample sites are nested within coarser-resolution features, this hierarchical sampling design allows us to 1) stratify fine-resolution sample sites based on coarse-resolution features, 2) interpret finer-resolution content within coarse-resolution features, and 3) scale up fine-resolution data to a larger geographic area (Beechie et al. 2003, Fullerton et al. 2006).

Stratification of Habitat Areas

For each monitoring environment, we stratified sites by natural geomorphic potential, land-cover class, and major population group. For large river and floodplain sites, we stratified by geomorphic process domains as defined in Collins and Montgomery (2011), which include glacial valleys, post-glacial valleys, and mountain valleys (canyons were omitted from the sample frame during the first year of sampling described in this report). We separated the 16 major deltas from the other shoreline types because of their disproportionate importance to salmon as a transition zone between the river and the sea (Simenstad 1983, Bottom et al. 2005b). For the 16 major deltas, we did not stratify sites because we sampled all of them. However, we did subdivide the deltas into river-dominated, wave-dominated, and fan-shaped (the tide-dominated form is not found among the large river deltas of Puget Sound). The remaining (non-delta) shoreline was stratified into open shores and embayments, with open shores subdivided into beaches and rocky shores and embayments subdivided into beaches and lagoons, as defined by Shipman (2008) and McBride et al. (2009). In addition to these four shore types, heavily developed shorelines are classified as modified wherever the natural shore type cannot be identified.

In each habitat area, we stratified by land-cover class using NOAA's Coastal Change Analysis Program's (C-CAP) 2010 data, which we aggregated into five main classes: forest/wetland, agriculture, developed, water, and other. We then assigned each sample unit (e.g., river reach, delta, or shore segment) to a land-cover stratum based on the proportions of each land-cover class. Thus, sample units were assigned to the forest/wetland stratum if more than 50% of the area was forested and/or wetland, agriculture if more than 50% of the area was cultivated and/or pasture, developed if more than 50% of the area was developed, or mixed if no land-cover class exceeded 50%.

We also stratified by major population groups (MPGs) for Chinook salmon and steelhead (there are no MPGs for chum salmon). The Chinook salmon ESU is divided into five MPGs: Strait of Georgia, Whidbey Basin, Central/South Basin, Hood Canal, and Strait of Juan de Fuca (NMFS 2007b). The steelhead ESU is divided into three MPGs: Northern Cascades, South-Central Cascades, and Olympic (NMFS 2011, Hard et al. 2015).

Sample Site Selection

For large river and floodplain environments, sample sites were selected using a Generalized Random Tesselation Stratified (GRTS) design. We sampled 124 aerial photography sites across Puget Sound, ranging in length from 496 to 8,169 m. Field sites were also selected from the GRTS design, with a total of 21 sites sampled in the pilot year of 2014. Sample-site lengths ranged from 233 to 845 m. We measured habitat metrics on all 16 major deltas identified by Simenstad et al. (2011): Nooksack, Skagit, Samish, Stillaguamish, Snohomish, Duwamish, Puyallup, Nisqually, Deschutes, Skokomish, Hamma Hamma, Dosewallips, Duckabush, Big Quilcene, Dungeness, and Elwha. Two of these deltas (Samish and Deschutes) do not have ESA-listed Chinook salmon populations, and two ESA-listed Chinook salmon populations (Sammamish and Cedar) in the Lake Washington system do not currently have a defined river delta habitat area. Nearshore areas were not sampled in our pilot year of 2014.

Monitoring Metric Selection

We identified a suite of potential metrics for each habitat area by convening small groups of experts in the assessment and monitoring of either river–floodplain or delta–nearshore habitats (see Appendix A for meeting summaries). We then evaluated the potential metrics using five criteria:

1. Is the metric related to at least one of the VSP parameters?
2. Is the metric sensitive to land-management or restoration actions?
3. Is the metric related to coarser- or finer-resolution metrics?
4. Is the metric cost-effective?
5. Does the metric have a high signal-to-noise ratio?

We scored each criterion with a value of 0 (no, criterion not met), 0.5 (moderate or context-dependent), or 1 (yes, criterion met); the evaluation tables can be found in Appendix C.) We then summed the five scores and selected metrics that scored 4.5 or higher for our monitoring program.

We evaluated a total of 115 potential monitoring metrics for monitoring large river, floodplain, delta, and nearshore habitats. Only 42 metrics scored 4.5 or higher; they were selected for use in the first year of the monitoring program (Table ES-1). The main satellite metrics in all monitoring environments were percent forest, agricultural, or developed land cover. Aerial photography metrics included a few land-cover or riparian metrics, but more commonly included either complexity or connectivity metrics such as side channel and distributary lengths, node densities, and area of disconnected floodplain or delta. Field metrics included bank armoring in all four environments, as well as a mix of riparian conditions, habitat types and areas, and wood abundance. Most metrics that were not selected for use in the monitoring program scored low for either cost-effectiveness or signal-to-noise ratio.

Results

We focused on answering four key questions in the pilot year (2014) of this monitoring program:

1. How accurate are the land-cover stratifications used in our analyses?
2. How do aerial photography measurements vary among observers?
3. How does the status of habitat vary among steelhead MPGs?
4. How does the status of habitat vary among land-cover strata?

The first two questions address Objective 4 of this study (test various metrics for repeatability and reliability), and the second two questions address Objective 5 (examine the utility of these metrics for detecting differences in habitat conditions among land cover classes or MPGs).

Accuracy of Land-Cover Data

We evaluated the accuracy of land-cover datasets from satellite data and from processed aerial imagery using three separate analyses. The first analysis examined how to produce the most accurate representation of percent forest land cover in either C-CAP or National Agriculture Imagery Program (NAIP) datasets. The second analysis examined the accuracy of the final percent forest and percent developed land-cover metrics. The third analysis described the accuracy of manual land-cover classification from aerial photography to determine if it might be useful as a monitoring method.

Table ES-1. Metrics selected for monitoring large river, floodplain, delta, and nearshore habitats in Puget Sound, grouped by data resolution (satellite, aerial photography, or field).

Data resolution	Metrics (by monitoring environment)			
	Large river	**Floodplain**	**Delta**	**Nearshore**
Satellite	• Percent natural, agricultural, and developed land cover	• Percent natural, agricultural, and developed land cover	• Percent natural, agricultural, and developed land cover • Wetland area, by type	• Percent natural, agricultural, and developed land cover
Aerial photography	• Riparian buffer width and type • Wood jam area	• Percent disconnected floodplain • Side channel length • Area of connected floodplain • Braid ratio (L_{br}/L_{main}) • Side channel ratio (L_{sc}/L_{main}) • Braid node density • Side channel node density	• Proportion of delta behind levees • Length of levees and dikes along distributaries • Tidal channel area • Node density • Wetland area, by type	• Shoreline armoring • Percent impervious • Percent forest • Area of overwater structures • Area of eelgrass • Area of kelp • Embayment area • Connectivity of embayment to nearshore • Length of forested shorelines
Field	• Length of human-modified bank • Riparian buffer width and type • Wood abundance • Edge habitat area, by type (shallow shore)	• Riparian species composition and buffer width • Length of human-modified bank • Pool frequency or spacing • Residual pool depth $(d_{max}-d_{tail})$ • Wood abundance • Area of side channel	• Shoreline armoring • Location of culverts/tide gates blocking access	• Shoreline armoring • Location of culverts/tide gates blocking access

We found that percent forest was underestimated by about 11% when using C-CAP's three forest cover classes. Adding the two forested wetland classes reduced the underestimation somewhat; however, precision was increased substantially (r^2 improved from 0.76 to 0.87). For all subsequent analyses, we used all five C-CAP forested cover classes (conifer, deciduous, mixed, palustrine forested wetland, and delta forested wetland) to calculate percent forest in floodplains, deltas, and the nearshore. We also evaluated various combinations of cover classes from the NAIP data, and found that using only the tree class tended to slightly overestimate percent forest cover, but had a relatively high precision ($r^2 = 0.84$). Adding other tree classes increased the overestimation significantly. Therefore, in all subsequent analyses, we estimated percent forest from the NAIP data using only the tree class.

Regression analyses of manually classified land-cover percentages against percent forest and percent developed land cover from C-CAP and NAIP showed that C-CAP tends to underestimate percent forest and overestimate percent developed, while NAIP tends to overestimate percent forest and underestimate percent developed. Both metrics had roughly the same precision in C-CAP and NAIP. We also evaluated manual classification of changes in riparian cover from aerial photography as one potential monitoring method, but found that observer error was quite high. We therefore opted not to use manual land-cover classification for our monitoring program.

Observer Variability in Aerial Photography Metrics

There was considerable variation among observers for bank and edge habitat types. The greatest mean percent difference among observers for bank type was armored bank length (30%), with lesser differences in levee bank length and natural bank length (15% and 11%, respectively). Variation among observers for habitat edge type ranged from 1% for modified bank edge length to 34% for backwater area. Among the remaining metrics, the greatest mean percent difference was in wood jam area (84%). Mean percent difference in braid length was 19%, and mean percent difference in side channel length was 22%.

To help reduce observer variation (especially for metrics with large differences, such as wood jam area), we examined the digitized metrics from both observers at individual sites so we could ascertain sources of error and identify protocol improvements that could reduce those differences. Examples of improvements to protocols include:

1. To improve the accuracy and repeatability of bank type measurements, we revised the protocols to include use of reference datasets (e.g., existing geospatial data for levees or armoring) and/or field verification where features are not visible on aerial photography.
2. To improve backwater measurements, we refined the definition and illustrated how to identify a backwater unit. We also gave more detailed instruction guiding observers to digitize only visible portions of the backwater unit and not to include estimated areas beneath tree canopy.
3. To improve repeatability of braid and side channel length measurements, we revised the protocols to include more detailed criteria and thresholds for identifying and measuring braids or side channels.
4. To improve wood jam measurements, we revised the wood jam protocols to include a minimum jam area (50 m^2) and specified the level of detail with which the wood jam was to be digitized. We also established that the digitized wood jam areas will be archived, allowing new observers digitizing wood jam areas in the future to reference the prior polygons and identify changes to wood jam areas based on the archived polygons and original aerial photography images.

Status of Habitat by MPG

For most metrics, mean values of the metric were similar across steelhead MPGs.[1] However, land cover, buffer width, and edge habitat types differed across MPGs, likely in relation to the level of development within each. Floodplains in all three MPGs (Northern Cascades, South-Central Cascades, and Olympic) have 42–51% forest cover, but the remaining land cover differs among

[1] Our sample size was too small to evaluate differences in Chinook salmon MPGs in this first year of monitoring, and the chum salmon ESU does not have MPGs.

MPGs. South-Central Cascades has the lowest percentage of lands classified as agriculture (10%) and the highest percentage of developed lands (28%), while Northern Cascades contains the highest percentage of agriculture lands (39%) and the lowest percentage of developed land cover (10%). The average buffer width was the greatest in the Northern Cascades and Olympic MPGs (72 m and 85 m, respectively), where there are more forested sites. Conversely, in South-Central Cascades—where there is more developed land cover—the average buffer width was lowest (51 m).

Habitat edge length by bank type varied considerably among steelhead MPGs. The mean percentage of natural bank edge length was the highest in the Olympic MPG (at 68%), and lowest in South-Central Cascades (37%). Conversely, the mean percentage of modified bank edge length ranged from 35% in South-Central Cascades (where there is more developed land cover) to only 2% in Olympic. The mean proportion of bar edge habitat was similar among all MPGs.

Delta habitat status also varied among steelhead MPGs. South-Central Cascades has the most-developed deltas in Puget Sound, with the Duwamish and Puyallup deltas being over 90% urban. The other two steelhead MPGs are primarily forested, with Olympic having over 75% forest/wetland, and Northern Cascades roughly 50% forest/wetland. Agriculture is most prevalent in Northern Cascades (about 40%). The Northern Cascades steelhead MPG also has the greatest amount of tidal channel habitat by area, with nearly 2.5 times more tidal channel area than South-Central Cascades and 15 times more than Olympic.

Tidal and distributary channel length provides a different perspective of relative habitat abundance within deltas compared to area-based estimates. This is particularly apparent in the Northern Cascades MPG deltas, where large distributary channels dominate habitat area but numerous small tidal channels provide more edge and channel length compared to distributaries. Tidal channel length in deltas in Northern Cascades was almost six times longer than in Olympic, and over four times longer than in South-Central Cascades. Given that juvenile salmonids are more likely to use the edges of tidal channel features as opposed to the middle of a larger channel, edge habitat metrics may provide a more useful context to assess tidal channel habitat with respect to juvenile salmonids.

Status of Habitat by Land-Cover Class

Habitat and riparian attributes generally followed expected patterns with respect to land use. For example, the pressure metrics of percent disconnected floodplain and riparian buffer width were both in the in the best condition in forest/wetland sites, and in the worst condition in developed sites (Figure ES-1). Percent disconnected floodplain was over 50% in developed sites, and only 11% in predominantly forest/wetland sites. The median of riparian buffer widths at forest/wetland sites (72 m) is roughly 30 m wider than the median width at sites classified as agriculture or mixed (40 m and 42 m, respectively), and more than 50 m wider than median widths at developed sites (15 m). Similarly, backwater and wood jam areas were both highest at forest/wetland sites (750 m^2/km^2 and 1,913 m^2/km^2, respectively) and lowest at developed sites (200 m^2/km^2 and 74 m^2/km^2, respectively). Finally, side channels were the longest in forest/wetland sites and shortest in developed sites (side channel length ratios of 0.32 m/m and 0.05 m/m, respectively).

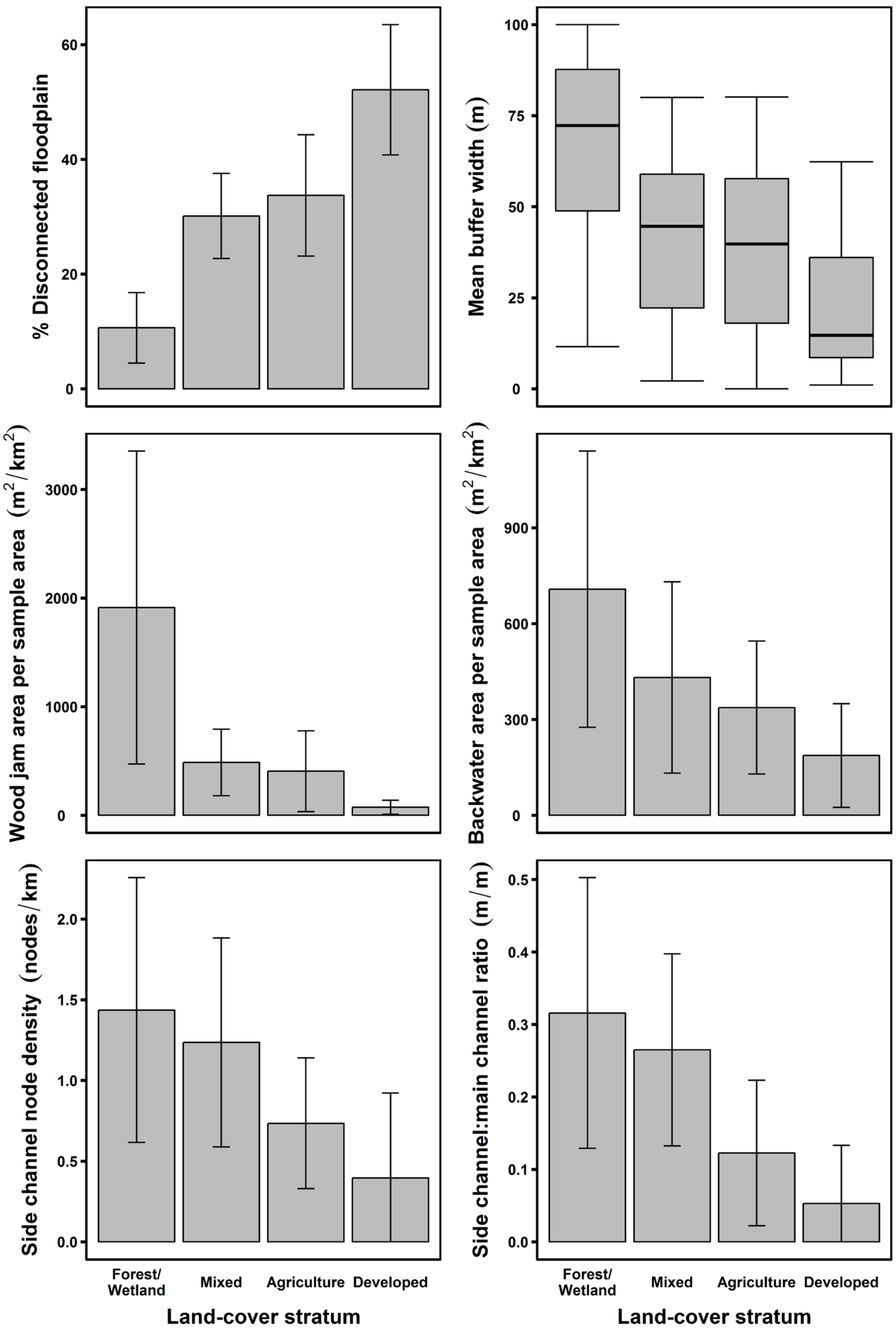


Figure ES-1. Results summary by land-cover class for A) mean percent disconnected floodplain, B) riparian buffer width, C) wood jam area, D) backwater area, E) side channel node density (#/km), and F) side channel length ratio (m/m). In A, C, D, E, and F, bar indicates mean and lines indicate 95% confidence intervals. In B, heavy line indicates median, box indicates 25th and 75th percentiles, and whiskers indicate 10th and 90th percentiles.

Lessons Learned and Next Steps

Our first year of establishing a habitat monitoring program for Puget Sound focused on developing and testing stratification procedures, sampling designs, and metrics for measuring habitat. In this report, we discuss a number of lessons learned, as well as next steps to improve the program.

Lessons Learned

During our pilot study, we found that the sample-site selection process for large rivers and floodplains created many errors in geomorphic reach breaks, geomorphic strata assignment, and land-cover strata assignment, as well as issues of overlapping sample sites. To solve these problems, we created a new floodplain reach map with fully delineated floodplain polygons that were accurately classified by geomorphic valley type and land-cover class, and shifted to a complete census of large river and floodplain features within river basins of Puget Sound, rather than sampling a small number of sites within the area. We developed initial field protocols for large river and floodplain channels, and made many improvements to those protocols during field testing. However, we ultimately determined that the field work was too time-consuming to be cost-effective (i.e., getting an adequate sample size was not within our budget). Therefore, we plan to revise our field effort to focus primarily on ground-truthing our aerial photography measures.

For the delta monitoring, the delta polygon boundaries that we used were developed for the Puget Sound Nearshore Ecosystem Research Project. However, we noted that these polygons do not completely encompass the potential zone of tidal influence within the deltas, and this ultimately restricts the delineation of delta habitat. The next phase of this project should include refining the delta polygons to delineate the full extent of tidal influence within each delta unit.

Next Steps

Future work on this monitoring program will focus on key next steps, including developing nearshore protocols, revising existing protocols, and exploring the relationship of the habitat metrics to salmon population metrics. Additional next steps include examining the sensitivity of metrics to land use with a retrospective aerial photography analysis, developing ground-truthing protocols for aerial photography metrics, and developing pilot studies with collaborators to fill in data gaps.

Acknowledgments

Funding for this work was provided by the West Coast Region of the National Marine Fisheries Service (NMFS), National Oceanic and Atmospheric Administration. Elizabeth Babcock (NMFS), Kim Kratz (NMFS), Barry Thom (NMFS), and Bruce Crawford (Puget Sound Partnership) supported this project from its inception, and backed the development and implementation of the monitoring program. Kara Anlauf-Dunne (Oregon Department of Fish and Wildlife), Sean Gallagher (California Department of Fish and Wildlife), and Chris Jordan (NMFS) provided excellent reviews of early drafts of this report. Our initial direction and first steps in developing this monitoring program were strongly influenced by three expert panel workshops in which experts in their fields shared past experiences and helped us develop our monitoring direction and select monitoring parameters. Panel members were: Kelly Andrews, Kara Anlauf-Dunn, Randy Carman, Paul Cereghino, Treva Coe, Bruce Crawford, Sean Gallagher, Correigh Greene, Eric Grossman, Greg Hood, Kim Jones, Chris Jordan, Chris Konrad, Gino Lucchetti, Sara McArthy, Casey Rice, Hugh Shipman, and Diane Whited. Josh Latterell, Eric Beamer, and Greg Hood also provided invaluable advice on monitoring protocols as we developed them.

Introduction

In 1999, the Puget Sound Chinook salmon (*Oncorhynchus tshawytscha*) and the Hood Canal summer chum salmon (*O. keta*) Evolutionarily Significant Units (ESU) were listed as threatened under the Endangered Species Act (ESA; NMFS 1999a, 1999b). In 2007, Puget Sound steelhead (*O. mykiss*) were also listed as threatened under the ESA (NMFS 2007a). It is the statutory responsibility of the National Marine Fisheries Service (NMFS) to evaluate progress toward recovery, and ultimately to make decisions regarding delisting, of Puget Sound Chinook salmon, Hood Canal summer chum salmon, and Puget Sound steelhead. Therefore, NMFS must assess the status of each listed population based on the four criteria (abundance, population growth rate, population structure, and diversity) that determine Viable Salmonid Populations (VSP), as well as the status and trends of key listing factors such as habitat and harvest. The ESA specifies that this evaluation must happen every five years.

One of the key listing factors for Puget Sound Chinook salmon, Hood Canal summer chum salmon, and Puget Sound steelhead is the quantity, quality, and distribution of habitat supporting these species. Hence, having consistent habitat data across the ESU and each major population group (MPG) within each ESU is an essential component of any five-year status review. This was effectively demonstrated in the recent five-year status review for Oregon coastal coho salmon (*O. kisutch*), where consistent data on habitat trends were essential for determining species status (Stout et al. 2012). Consistent habitat data across the entire ESU are not currently available for Puget Sound. According to Judge (2011), "Habitat status and trends monitoring at the population, major population group, and ESU scales is urgently needed and should be a priority focus for funding." Presently, there are no spatially explicit habitat data that are comparable for all populations in the Puget Sound ESU, nor has a program been established to collect those data for assessing status and trends of salmon habitats in Puget Sound.

Our goal is to develop a habitat monitoring program for four distinct salmon and steelhead spawning and rearing environments—large rivers, floodplain channels, deltas, and the nearshore of Puget Sound—in order to assess changes in salmon habitat across the ESU. Each of these environments provides habitat for key life stages of Chinook salmon, chum salmon, and steelhead. Therefore, each environment should be monitored so that we can determine whether habitat conditions are improving, static, or declining at the next status review. We had five objectives for the first year of this monitoring effort: 1) to develop a hierarchical sampling design to monitor habitat status and trends, 2) to identify habitat metrics that are cost-effective and related to VSP parameters, 3) to develop protocols to measure those metrics, 4) to test the satellite, aerial photography, and field methods for repeatability and reliability, and 5) to evaluate habitat status to assess the ability of each metric to detect habitat differences among our chosen land-cover strata. This report is organized into the following major sections:

1. Study Area
2. Monitoring Approach: A Hierarchical Strategy
3. Sample Design
4. Selection of Monitoring Metrics
5. Overview of Selected Metrics and Protocols
6. Analysis Methods
7. Results
8. Discussion

Study Area

The Puget Sound basin encompasses 16 main river systems and many smaller independent streams that drain a total area of 35,500 km^2 (Ebbert et al. 2000). The basin is bounded by the Olympic Mountains to the west and the Cascade Mountains to the east. The Olympic and Cascade Mountains commonly exceed 1,800 m in elevation, with several volcanic peaks exceeding 3,000 m. Mean annual precipitation ranges from less than 50 cm/year on the northeast Olympic Peninsula to more than 450 cm/year on Mount Baker (PRISM Climate Group 2015). Hydrologic regimes are classified as snowmelt-dominated, rainfall-dominated, or transitional (Beechie et al. 2006b). The snowmelt-dominated regime is at higher elevations (mean basin elevation >1,300 m) where fall and winter precipitation is mainly snow and melts in the spring. Lower-elevation areas (mean basin elevation <800 m) receive most precipitation as rain, and most runoff occurs in fall and winter. The transitional regime is at intermediate elevations and exhibits both fall/winter rainfall and spring snowmelt peaks.

The Cascade and Olympic Mountains are geologically diverse, with lithologies ranging from relatively erosion-resistant igneous and high-grade metamorphic rocks, to more easily eroded marine sedimentary rocks and low-grade metamorphic rocks. Volcanoes of quaternary age (<2 million years old) form the highest peaks in the Cascade Mountain Range (Brown et al. 1987). The lowland Puget trough between the two mountain ranges is filled with glacial sediments, including unconsolidated lacustrine clays, glacial till, and outwash gravels (Brown et al. 1987). Floodplains tend to be relatively narrow in the core of the Cascades and Olympics, where erosion-resistant rocks form steep valley walls (Beechie et al. 2006a). Floodplains are wider in low-elevation valleys (<600 m elevation) bounded by erodible glacial terraces (e.g., Beechie et al. 2001, Collins and Montgomery 2011). Headwater streams are typically steep (channel slope >0.2) and relatively small (bankfull width <5 m), originating on mountain slopes underlain by bedrock. Channel slopes decrease dramatically as streams traverse terraces of glacial deposits (slopes typically between 0.01 and 0.08), and channel slopes are typically <0.01 on contemporary floodplains (Beechie et al. 2001).

A limited number of tree species make up floodplain, delta, and nearshore vegetation in the study area, which is part of the Pacific Coastal Forest extending from Northern California to Alaska. Per Franklin and Dyrness (1973), dominant species include red alder (*Alnus rubra*), black cottonwood (*Populus trichocarpa*), Sitka spruce (*Picea sitchensis*), western hemlock (*Tsuga heterophylla*), western red cedar (*Thuja plicata*), and big leaf maple (*Acer macrophyllum*). The general successional pattern is from hardwood to conifer, with young patches occupied by colonizing species such as alder and cottonwood and old patches occupied by climax species such as Sitka spruce, western hemlock, and western red cedar (Crocker and Major 1955, Fonda 1974, Henderson et al. 1989).

Puget Sound Chinook salmon have diverse life histories, but are classified broadly as Summer or Fall run (later spawn timing and mostly sub-yearling outmigrants) and Spring run (earlier spawn timing and mostly yearling outmigrants). Returning adults of the Summer/Fall runs enter Puget Sound rivers between June and September and typically spawn in September and October (Healey 1991). Fry emerge from the gravel from February to June. Most Chinook salmon fry migrate downstream as sub-yearlings over a period of several months, using primarily edge and backwater habitats on their seaward migration (Beechie et al. 2005). Sub-yearlings then utilize the delta and nearshore, and most reach Puget Sound between June and October (Rice et al. 2011). For Spring runs, adults return to Puget Sound rivers between March and July, and peak spawning occurs in August and September. Juvenile yearling outmigrants rear in rivers for one year before migrating to salt water, and adults rear at sea for three to five years before returning to spawn (Coronado and Hilborn 1998).

Hood Canal Summer chum salmon enter rivers as adults between mid-August and mid-October and spawn in September and October (Johnson et al. 1997). Fry emerge from the gravel in late winter to spring, and migrate to sea within a few days of emergence. Fry tend to move along the shore in edge and backwater habitats, showing little preference among habitat types as they move to the estuary (Beechie et al. 2005). Juveniles then rear in the estuary for up to four weeks before moving out to sea. Chum salmon then rear at sea for 3 to 5 years before returning to spawn (Johnson et al. 1997).

Steelhead also have diverse life histories, with spawning migrations occurring from November through April (Winter run) or May through October (Summer run). Spawning timing for both Summer and Winter run steelhead is from January through June (Busby et al. 1996). In Puget Sound, most juveniles rear in fresh water for two years before smolting, although some smolt at age-1 or -3. In small streams, age-0 and age-1 steelhead do not exhibit strong habitat preferences, although there is a slight preference for low velocity backwater pools at age-0 (Bisson et al. 1988). In large rivers, age-0 juveniles occupy a wide range of edge habitat types and velocity classes in summer, but in winter they choose bank edge habitats with velocities <0.45 m/s (Beechie et al. 2005). Age-1 juveniles focus on bank edge habitats in both summer and winter, although velocity preferences are unclear (Beechie et al. 2005). Ocean age at first spawning is two years for Winter run steelhead, but almost exclusively one year for the Deer Creek Summer run steelhead (Busby et al. 1996).

Monitoring Approach: A Hierarchical Strategy

We evaluate habitat status and trends in four salmon and steelhead spawning and rearing environments: large rivers, floodplains, deltas, and the nearshore (Figure 1; Bartz et al. 2015). We defined large rivers as stream channels with a drainage area >50 km^2 (Konrad 2015), and the analysis area included the riparian buffer extending 100 m landward from each channel bank (Fullerton et al. 2006, Bartz et al. 2015). Rivers with a drainage area of 50 km^2 typically have a bankfull width of 15–20 m. The floodplain environment was defined as the area less than 5 m above the channel elevation in the 10-m National Elevation Dataset (manually corrected to capture the current floodplain where necessary; Beechie and Imaki 2014). The delta analysis area included the 16 large river deltas that drain to Puget Sound. The delta boundaries encompassed historical wetland and intertidal areas, as well as areas draining directly to those wetlands or to the adjacent shoreline. The nearshore environment extended 200 m inland from the ordinary high-water mark of the marine shoreline (Simenstad et al. 2011).

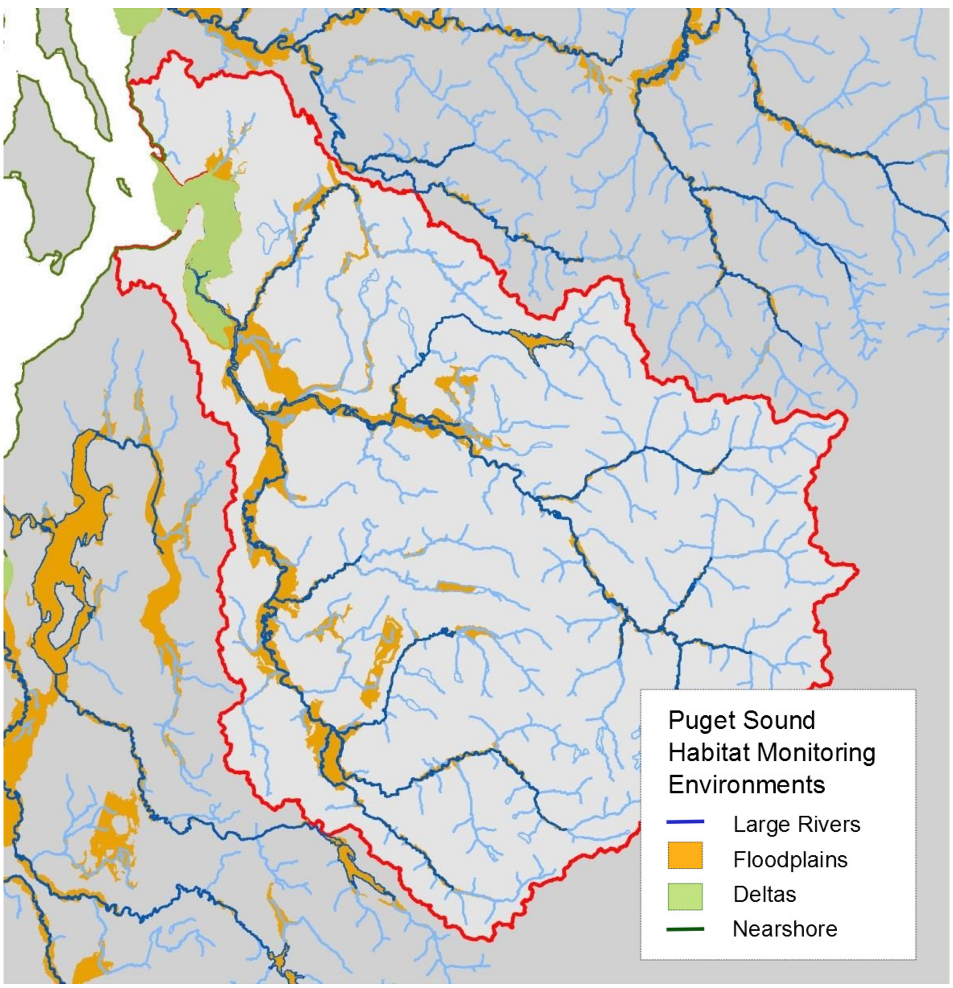


Figure 1. The four key salmonid spawning and rearing environments that will be sampled as part of the Puget Sound habitat status and trends monitoring effort. Map highlights the Snohomish River basin in Puget Sound.

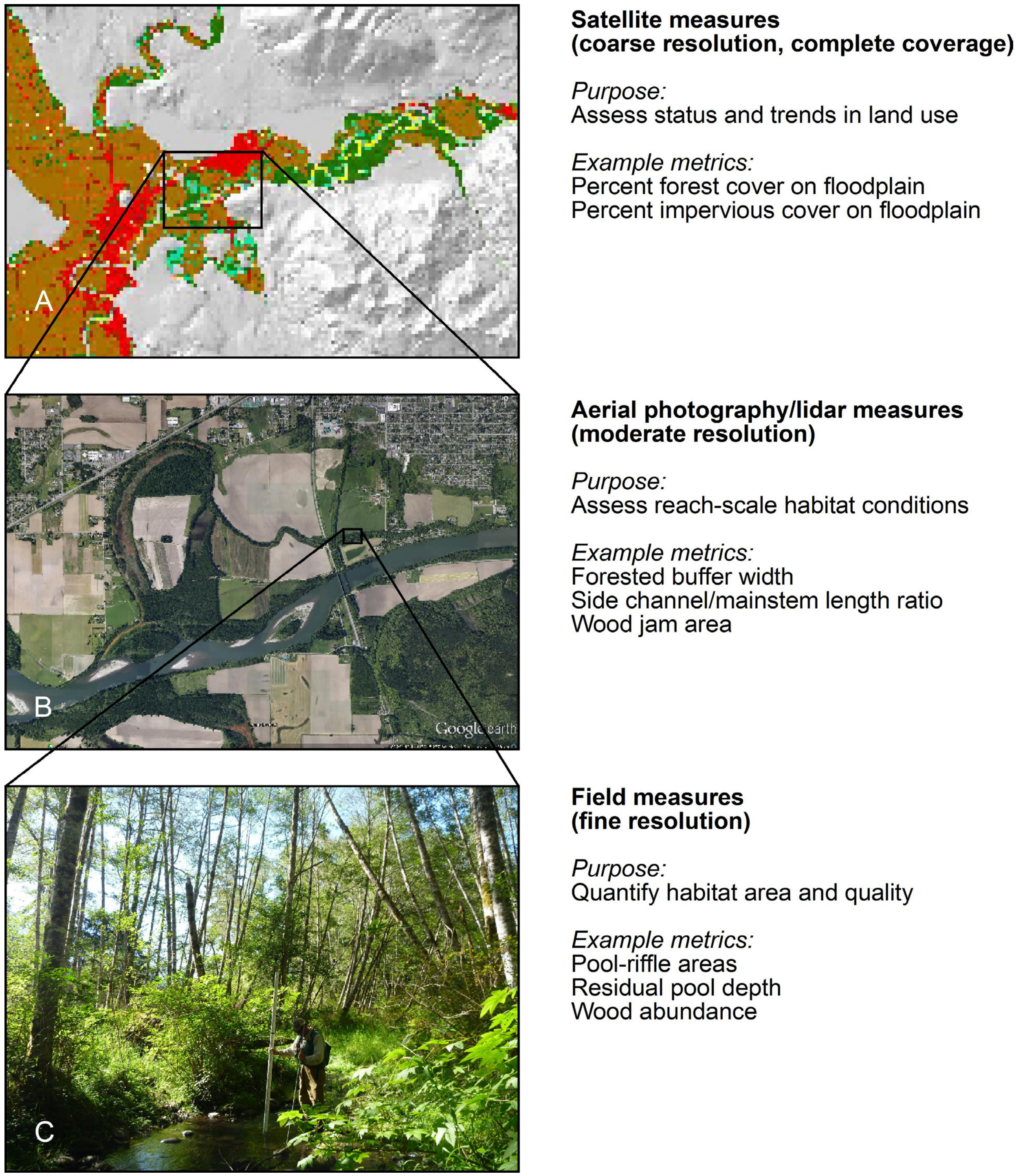


Figure 2. Illustration of the hierarchical sampling framework that will be used for habitat status and trend monitoring in Puget Sound.

In each of the four monitoring environments, the distribution of geomorphic features and physical habitats is influenced by a hierarchy of natural controls and land-use effects (Beechie et al. 2010, 2013). The first-level control is the topographic and geological template, which defines locations of key geomorphic features (e.g., valley types or shore types) and the

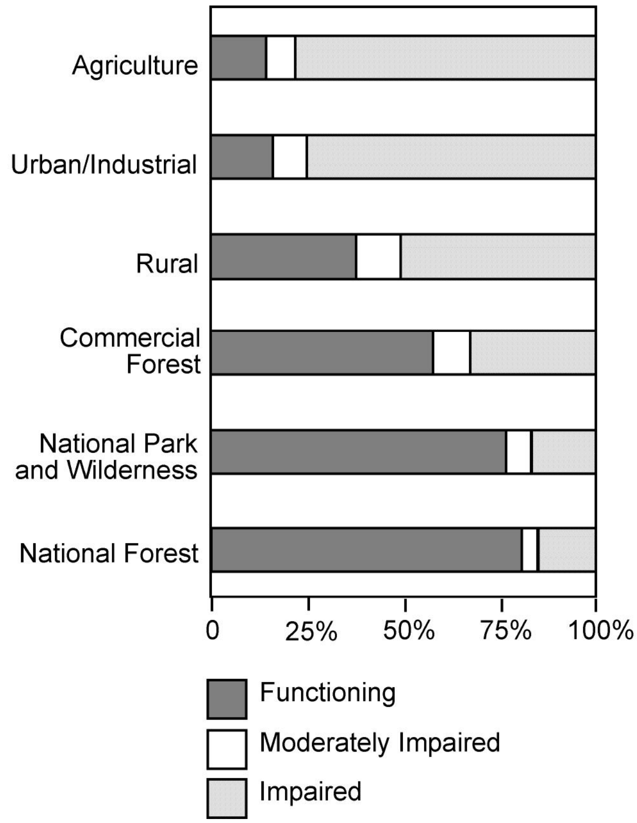


Figure 3. Example of riparian conditions as a function of land cover or ownership in the Skagit River basin. From Beechie et al. 2003.

range of potential habitat conditions that can exist at each location. For example, rocky shores or confined rivers have limited or no ability to express beach or complex floodplain habitats, whereas lagoons and unconfined valleys can express a wide range of habitat conditions (Simenstad et al. 2006, Naiman et al. 2010). Within the limits set by the landscape template, watershed-scale and local processes control habitat conditions at any point in time. In rivers, floodplains, and deltas, second-level controls include the watershed-scale processes of runoff and erosion, which control stream discharge and sediment supply (Beechie et al. 2010). The third-level controls are site- and reach-scale processes such as channel migration, wood recruitment from the riparian zone, and sediment transport or retention. In the nearshore, drift cell-scale processes such as beach erosion, long-shore sediment transport, or riparian functions control local habitat conditions at any point in time within a shore type (Simenstad et al. 2006). The watershed-scale, reach-scale, and drift cell-scale controls are also strongly influenced by land use, so our sampling strategy also incorporates land-cover factors into the stratification of floodplain reaches.

Our general approach to monitoring habitat status and trends for large rivers, floodplain channels, deltas, and nearshore environments in Puget Sound relies on a hierarchical sampling design using coarse-resolution satellite data, mid-resolution aerial photography and lidar data, and fine-resolution field data. This hierarchical sampling approach takes advantage of our knowledge of the process hierarchy described above, and gives complete coverage of land-cover change in Puget Sound using satellite data, high sample-site density using aerial photography data, and lower sample-site density using field data (Figure 2). Because the fine-resolution sample sites are nested within coarser-resolution features, this hierarchical sampling design allows us to 1) stratify fine-resolution sample sites based on coarse-resolution features, 2) interpret finer-resolution content within coarse-resolution features, or 3) scale up fine-resolution data to a larger geographic area (Beechie et al 2003, Fullerton et al. 2006). For example, linking fine-resolution field data on riparian condition with coarser-resolution land-cover data from satellite imagery illustrates how riparian condition varies with land use or ownership (Figure 3). Knowing this, we can extrapolate field data to the larger landscape based on land cover, and we can also create hypotheses of how riparian condition will change in the future as land-use changes (assuming similar implementation of stream-protection regulations).

Sample Design

The key steps in developing the sample design were: 1) stratifying large rivers, floodplains, deltas, and the nearshore by geomorphic type, land cover, and major population group; 2) developing a site-selection process that is statistically robust but also considers the accessibility of sites for field data collection; 3) conducting a power analysis to determine the sample sizes needed for each stratum in each habitat area; and 4) establishing time intervals for site revisits. (Here we use the term *site* to generally refer to large river reaches, floodplain segments, individual deltas, or nearshore segments.) In this report, we describe the stratification of the four monitoring environments and the selection of sample sites. We have not yet completed power analyses nor determined site revisit intervals. Sample sizes in this first year of the project were determined primarily by the time available for sampling. These data will be useful for power analyses to determine appropriate sample sizes.

Stratification of Habitat Areas

The purpose of stratification is to organize sites into meaningful groups, such that within-group variation is reduced and differences between groups are relatively distinct. For each of the four environments, we first classified sites (e.g., river reaches or shoreline segments) by natural physical attributes that are relatively immutable, as well as by land use. The immutable attributes were intended to group sites based on their natural physical potential, whereas the land-use classification was intended to group sites based on the degree of human influence. Details about the methods used for stratification of the landscape can be found in Appendix B.

For each monitoring environment, we aimed to produce the fewest possible strata that effectively group sites by natural potential and land-use impact. Our strata were based first on natural geomorphic potential, because physical features are relatively immutable and control a significant amount of the variation among sites in the absence of land-use effects (Table 1). That is, physical features such as valley geomorphic types or shoreline type largely determine the range of habitat conditions that can exist in each reach or shoreline segment. Other feature types (e.g., hydrologic, chemical, or biological) were not used for stratification because they are sensitive to land use (i.e., they are mutable). Instead, they are included along with other geomorphic attributes as potential monitoring metrics, because they change in response to land use, water use, or restoration actions.

Geomorphic Strata

For large river and floodplain sites, we stratified by geomorphic process domains as defined in Collins and Montgomery (2011), which include glacial valleys, post-glacial valleys, mountain valleys, and canyons (Table 1, Figure 4). Glacial valleys are aggrading because the deep glacial troughs carved by sub-glacial melt are now filling with sediment. Post-glacial valleys are degrading as river channels incise into glacial sediments deposited during the last continental glaciation of Puget Sound. Mountain valleys are at elevations above the glacial fill and likely incising slowly through resistant bedrock. The canyons are typically a short and steep transition zone between the mountain valleys and post-glacial valleys (Collins and Montgomery 2011).

Table 1. Summary of sampling strata for Puget Sound habitat areas. Geomorphic strata for large river and floodplain sites are based on Collins and Montgomery (2011); geomorphic strata for delta and nearshore sites are based on Shipman (2008) and McBride et al. (2009); Chinook salmon and steelhead MPGs are based on NMFS (2011) and Hard et al. (2015).

Habitat area(s)	Geomorphic strata	Land-cover strata	Chinook salmon MPGs	Steelhead MPGs
Large river, floodplain	Glacial (aggrading) Post-glacial (incising) Mountain Canyon	Forest/wetland Agriculture Developed Mixed	Strait of Georgia Whidbey Basin Central/South Basin Hood Canal Strait of Juan de Fuca	Northern Cascades South-Central Cascades Olympic
Delta	River-dominated Wave-dominated Fan-shaped	Forest/wetland Agriculture Developed Mixed	Strait of Georgia Whidbey Basin Central/South Basin Hood Canal Strait of Juan de Fuca	Northern Cascades South-Central Cascades Olympic
Nearshore	Open shore (beach) Open shore (rocky) Embayment (beach) Embayment (lagoon) Modified	Forest/wetland Agriculture Developed Mixed	Strait of Georgia Whidbey Basin Central/South Basin Hood Canal Strait of Juan de Fuca	Northern Cascades South-Central Cascades Olympic

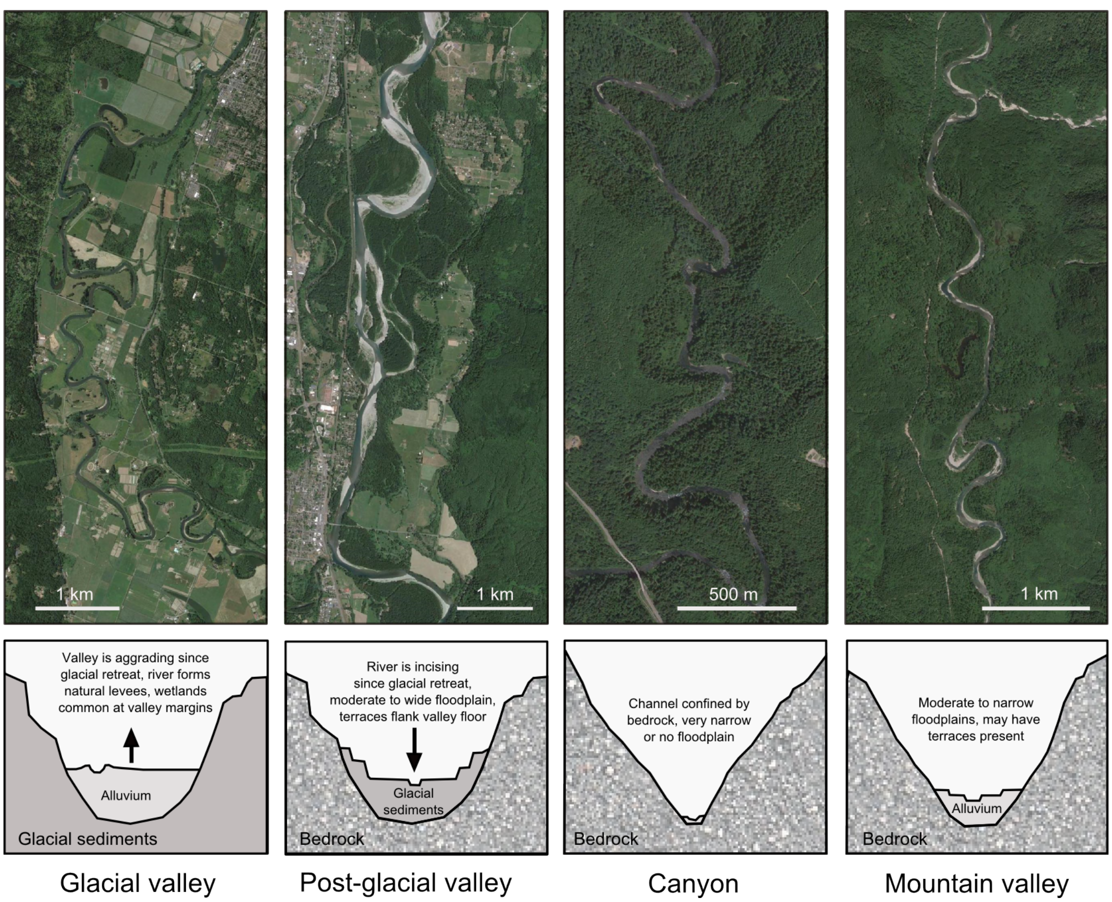


Figure 4. Geomorphic process domains for large river and floodplain strata (based on Collins and Montgomery 2011).

Figure 5. Geomorphic process domains used to classify the 16 major deltas in Puget Sound (based on Shipman 2008).

Because canyons do not have floodplains associated with them, we omitted this channel type from the sample frame during the first sampling year. Canyons are also relatively resistant to changes due to land use, and will therefore only be sampled at a low density in the future.

We separated the 16 major deltas from the other shoreline types because of their disproportionate importance to salmon as a transition zone between the river and the sea (Simenstad 1983, Bottom et al. 2005b). We did not stratify sites for these 16 deltas because we sampled all of them. However, we did subdivide the deltas into river-dominated, wave-dominated, and fan-shaped (Figure 5); the tide-dominated form is not found among the large river deltas of Puget Sound. Most rivers flowing from the Cascades have river-dominated deltas, whereas Hood Canal deltas are predominantly fan-shaped. The remaining (non-delta) shoreline was stratified into open shores and embayments, with open shores subdivided into beaches and rocky shores and embayments subdivided into beaches and lagoons (Figure 6), as defined by Shipman (2008) and McBride et al. (2009). In addition to these four shore types, heavily developed shorelines were classified as modified, and any shore type may be armored by rip-rap, levees, or bulkheads (as, for example, the armored beach in Figure 6).

Land-Cover Strata

In each habitat area, we first classified land-cover using 2010 data from NOAA's Coastal Change Analysis Program (C-CAP), which categorizes land cover into 25 different types. We simplified the classification by aggregating like types into five main classes: forest/wetland, agriculture, developed, water, and other (Table 2). The forest/wetland class was intended to capture all relatively natural land-cover types, agriculture captured cultivated and grazing lands, and developed captured urban areas and other developed lands. In floodplain areas, the dominant natural cover is typically forest, whereas shoreline areas (especially deltas and embayments) may naturally be dominated by wetlands. We then assigned each sample unit to one of four land-cover strata based on the proportions of each land-cover class. As such, the water class was not included among the strata used in the monitoring program.

Figure 6. Examples of shore types used to stratify shoreline segments for sampling. The rocky shore segment is on Orcas Island, the open-shore beach is near Kingston, the embayment beach is on San Juan Island, the lagoon is near Kingston, and the modified shore is in Elliott Bay. Based on Shipman (2008) and McBride et al. (2009).

A sample unit (e.g., river reach, delta, or shore segment) was assigned to the forest/wetland stratum if more than 50% of the area was forested and/or wetland, to the agriculture stratum if more than 50% of the area was cultivated and/or pasture, to the developed stratum if more than 50% of the area was developed, and to the mixed stratum if no land-cover class exceeded 50% (Figure 7).

Table 2. Groupings of original C-CAP land-cover classes into five main classes for stratification of sample sites in Puget Sound large rivers, floodplains, deltas, and the nearshore.

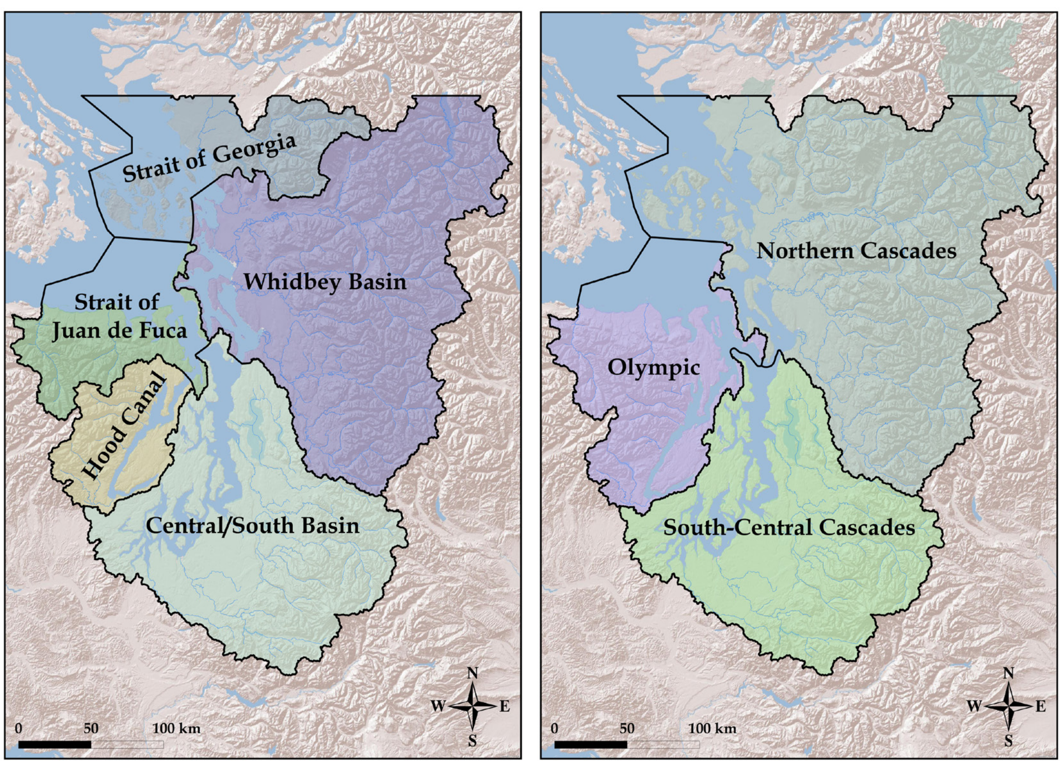
Land-cover class (assigned by monitoring program)	**Original C-CAP cover class**
Forest/Wetland	Grassland
	Deciduous forest
	Evergreen forest
	Mixed forest
	Scrub/shrub
	Palustrine forested wetland
	Palustrine scrub/shrub wetland
	Palustrine emergent wetland
	Delta forest wetland
	Estuarine scrub/shrub wetland
	Estuarine emergent wetland
	Unconsolidated shore
Agriculture	Cultivated land
	Pasture/hay
Developed	High-intensity developed
	Medium-intensity developed
	Low-intensity developed
	Developed open space
Water	Open water
	Palustrine aquatic bed
	Delta aquatic bed
Other	Unclassified
	Bare land
	Tundra
	Snow/ice

Figure 7. Examples of each of the four land-cover strata for large rivers, floodplains, and the nearshore. The 16 major deltas were also classified by land-cover class, but these were not considered strata because we sampled all 16 deltas.

Major Population Group Strata

The Chinook salmon ESU comprises 22 distinct populations that are divided into five major population groups (MPGs): Strait of Georgia, Whidbey Basin, Central/South Basin, Hood Canal, and Strait of Juan de Fuca (Figure 8). For this ESU to be removed from the Endangered Species list, several biological criteria must be met: 1) the viability of all populations must improve, 2) two to four populations in each MPG must be viable, 3) at least one population from each genetic and life-history group historically present within each MPG must be viable, and 4) habitat condition and Chinook salmon production from independent tributaries that are not part of one of the 22 populations must be healthy enough to support recovery (NMFS 2007b). In addition to meeting these four criteria, habitat conditions in each MPG must be sufficient to support sustained recovery of Chinook salmon.

The steelhead ESU comprises 32 distinct populations that are divided into three MPGs: Northern Cascades, South-Central Cascades, and Olympic. For the steelhead ESU to be removed from the Endangered Species list, the biological criteria that must be met are: 1) the majority of populations in each MPG must improve in viability, 2) at least 40% of the populations in each MPG must be viable, 3) a minimum of 40% of Summer run and 40% of Winter run populations historically present within each of the MPGs must be viable, and 4) natural production and diversity of steelhead from independent tributaries that are not part of the 32 populations must be sufficient to support recovery of the ESU (Hard et al. 2015). As with Chinook salmon, habitat conditions in each MPG must also be sufficient to support sustained recovery of steelhead.



Chinook major population groups **Steelhead major population groups**

Figure 8. Major population groups for Chinook salmon and steelhead in Puget Sound.

Sample Site Selection

Large River and Floodplain Sample Sites

For large river and floodplain environments, sample sites were selected using a Generalized Random-Tesselation Stratified (GRTS) design, which helps ensure that sites are distributed evenly across Puget Sound and within designated MPGs. Our aim was to achieve a large sample size within each stratum (i.e., each combination of geomorphic type, land-cover class, and MPG). In general, we anticipated complete coverage of the landscape with satellite data (low resolution), large sample sizes for aerial photography metrics (medium resolution), and small sample sizes for field metrics (high resolution). For our first year of field data collection, we intended to survey both large river habitats and associated floodplain habitats at large river sites selected by the GRTS design. However, very few of the selected large river sites had floodplain habitats within the sample reach. Therefore, we only sampled large river sites in the field this first year.

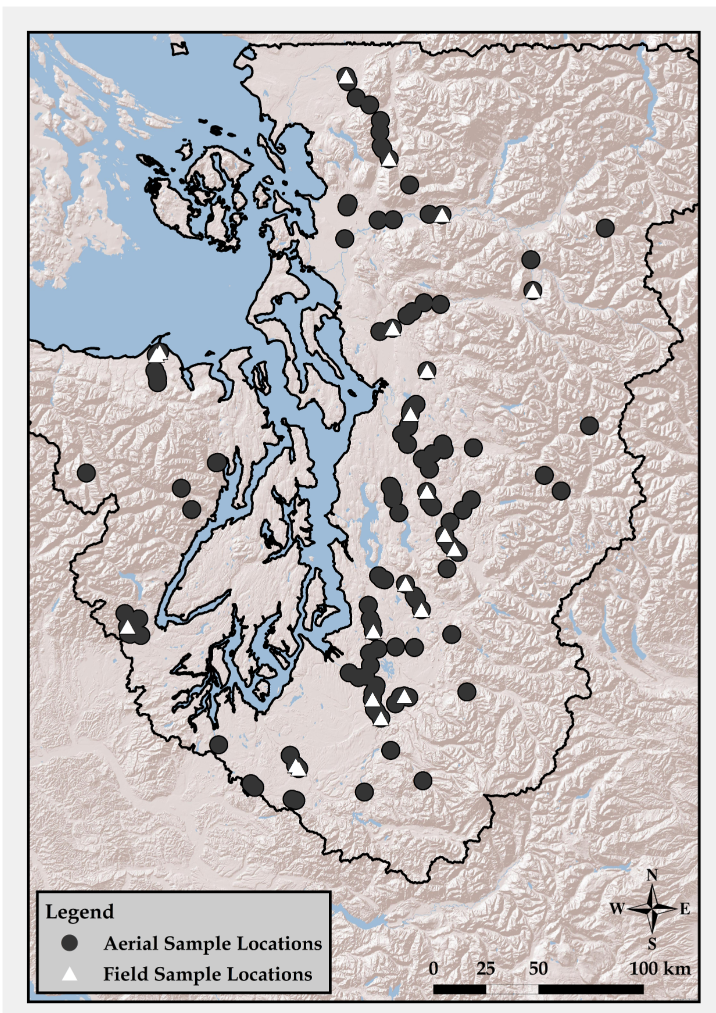


Figure 9. Sample site locations for aerial photography and field sampling of large river and floodplain habitats in Puget Sound.

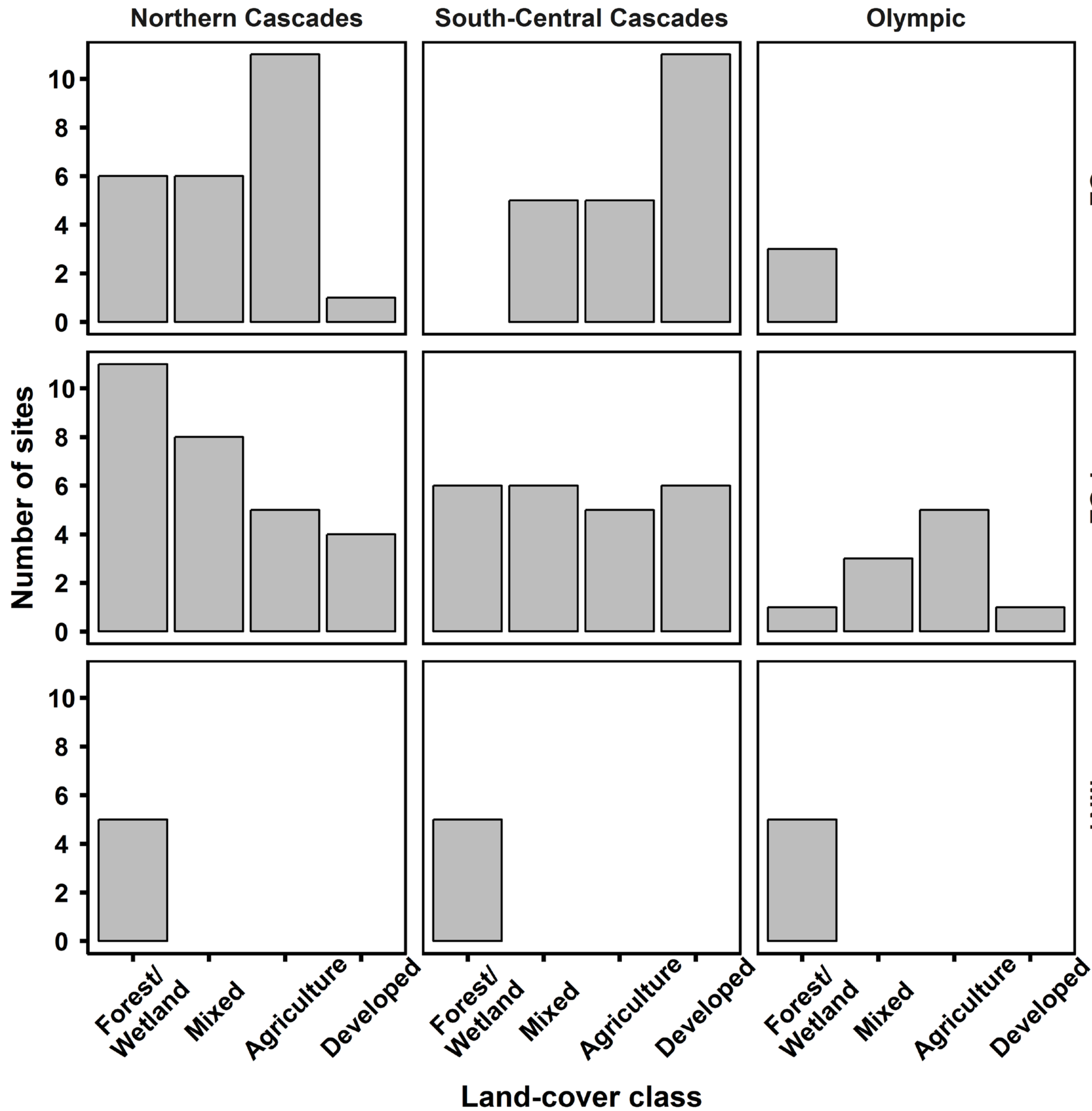


Figure 10. Distribution of aerial photography sample sites assigned to forest/wetland, agriculture, developed, and mixed strata, aggregated by Northern Cascades, South-Central Cascades, and Olympic steelhead MPGs, and by glacial (GL), post-glacial (PGL), and mountain (MNT) geomorphic valley types.

We sampled 124 aerial photography sites across Puget Sound (Figure 9). Sample points were selected using the GRTS design, and reach lengths were set at 20 times the bankfull width of channel (10 channel widths in each direction from the sample point). Sites thus ranged in length from 496 to 8,169 m, and were distributed across geomorphic and land-cover strata as shown in Table 3. Distributions of sites across MPGs are shown in Table 4. An example of the sample-site distribution across 36 strata (for steelhead MPGs) is shown in Figure 10. Sample site distribution by land-cover stratum included 42 sites assigned to the forest/wetland stratum, 31 to agriculture, 24 to developed, and 28 to mixed. Sample distribution by valley type included 48 sample sites

Table 3. Number of sites sampled in each habitat area and stratum.

		Land-cover class			
Habitat area	**Geomorphic stratum**	**Forest/wetland**	**Agriculture**	**Developed**	**Mixed**
Large river/ floodplain (aerial photo)	Glacial	9	16	12	11
	Post-glacial	18	15	11	17
	Mountain	15			
	Canyon				
Large river/ floodplain (field)	Glacial	3	3	3	
	Post-glacial	3	3	3	3
	Mountain				
	Canyon				
Delta (aerial photo)	River-dominated	5		3	3
	Wave-dominated	1			
	Fan-shaped	4			
Nearshore	Open shore (beach)	Nearshore sites have not yet been selected.			
	Open shore (rocky)				
	Embayment (beach)				
	Embayment (lagoon)				
	Modified				

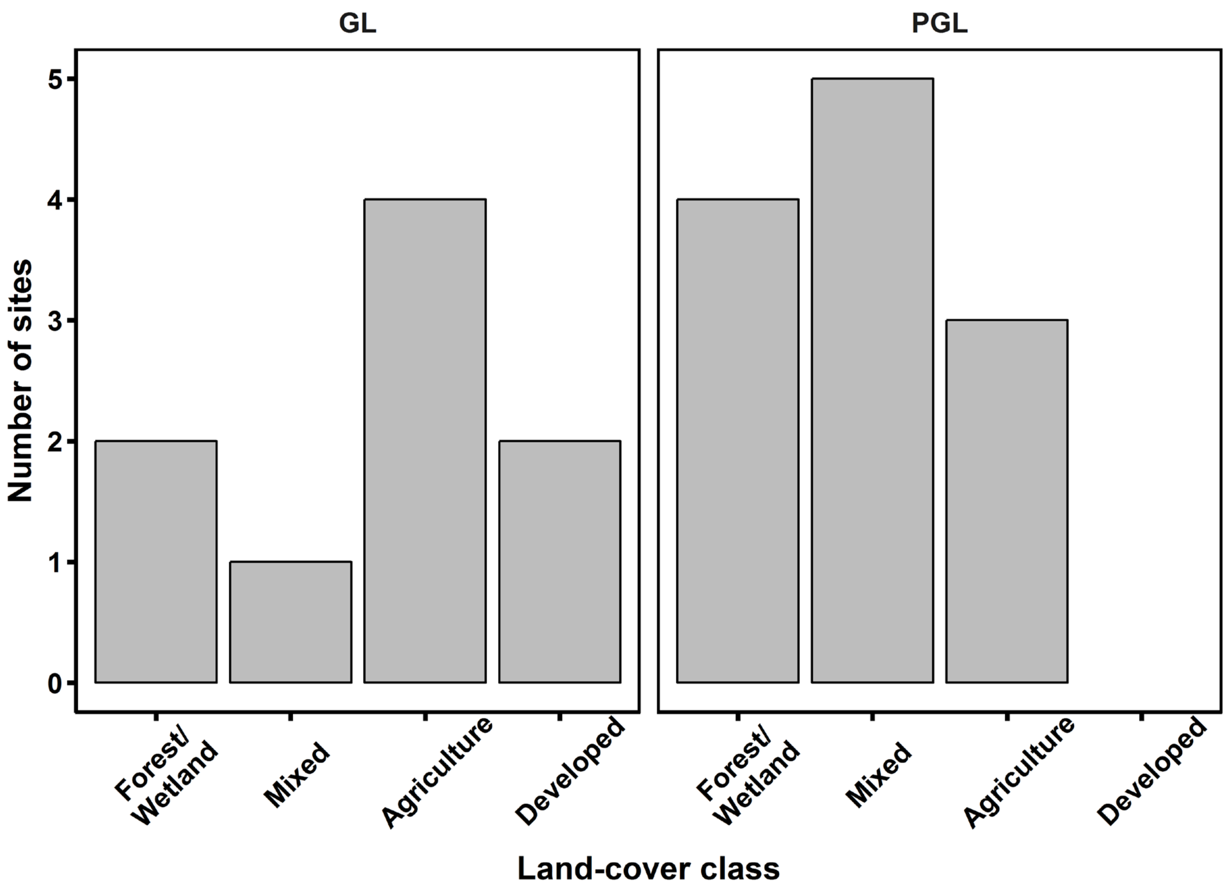


Figure 11. Distribution of field sample sites within forest/wetland, agriculture, developed, and mixed land-cover strata, aggregated by glacial (GL) or post-glacial (PGL) valley types.

Table 4. Number of aerial photography sites sampled in each habitat area and stratum. LR/FP = large river/floodplain sites.

Chinook salmon MPG	LR/FP photo	LR/FP field	Delta	Steelhead MPG
Strait of Georgia	10	2	1	Northern Cascades
Whidbey Basin	46	8	4	
Central/South Basin	50	8	4	South-Central Cascades
Hood Canal	11	1	5	Olympic
Strait of Juan de Fuca	7	2	2	

within glacial valleys, 61 within post-glacial valleys, and 15 within mountain valleys. (Because canyons do not have floodplains associated with them, we omitted this channel type from the sample frame during the first sampling year.) Among the five Chinook salmon MPGs, 10 sample sites were in Strait of Georgia, 46 in Whidbey Basin, 50 in Central/South Basin, 11 in Hood Canal, and 7 in Strait of Juan de Fuca. Among the three Puget Sound steelhead MPGs, 56 sample sites were in Northern Cascades, 50 in South-Central Cascades, and 18 in Olympic.

Field sites were also selected from the GRTS design, with a total of 21 sites sampled in the pilot year of 2014. As shown in Table 3 and Figure 11, we sampled three sites each in the forest/wetland, agriculture, and developed strata in the glacial valley type (9 sites), and three sites in each land-cover stratum in the post-glacial valley type (12 sites). Sample-site lengths ranged from 233 m to 845 m. Land-cover stratum distribution included six sites in the forest/wetland stratum, two in developed, seven in agriculture, and six in mixed. Out of the 21 sites, nine were located in the glacial valley type, and the remaining 12 sites in the post-glacial valley type.

Delta Sample Sites

We measured habitat metrics on all 16 major deltas identified by Simenstad et al. (2011). These deltas are: Nooksack, Skagit, Samish, Stillaguamish, Snohomish, Duwamish, Puyallup, Nisqually, Deschutes, Skokomish, Hamma Hamma, Dosewallips, Duckabush, Big Quilcene, Dungeness and Elwha (Figure 12). Two of these deltas (Samish and Deschutes) do not have ESA-listed Chinook salmon populations, and two ESA-listed Chinook salmon populations (Sammamish and Cedar) in the Lake Washington system do not currently have a defined river delta habitat area. (Historically, the Sammamish and Cedar Rivers once flowed into the Duwamish delta, but are now connected to Lake Union and flow to Puget Sound through the Ballard Locks.)

As seen in Table 3 and Figure 13, the 16 river deltas in Puget Sound were predominantly river-dominated (11 of 16) and covered with forest or wetlands (10 of 16). Only one delta (Elwha) was classified as wave-dominated, and none were classified as predominantly agriculture. The Duwamish, Puyallup, and Deschutes deltas were predominantly developed.

Sample sites in nearshore habitat areas were also selected using the GRTS design in 2015.

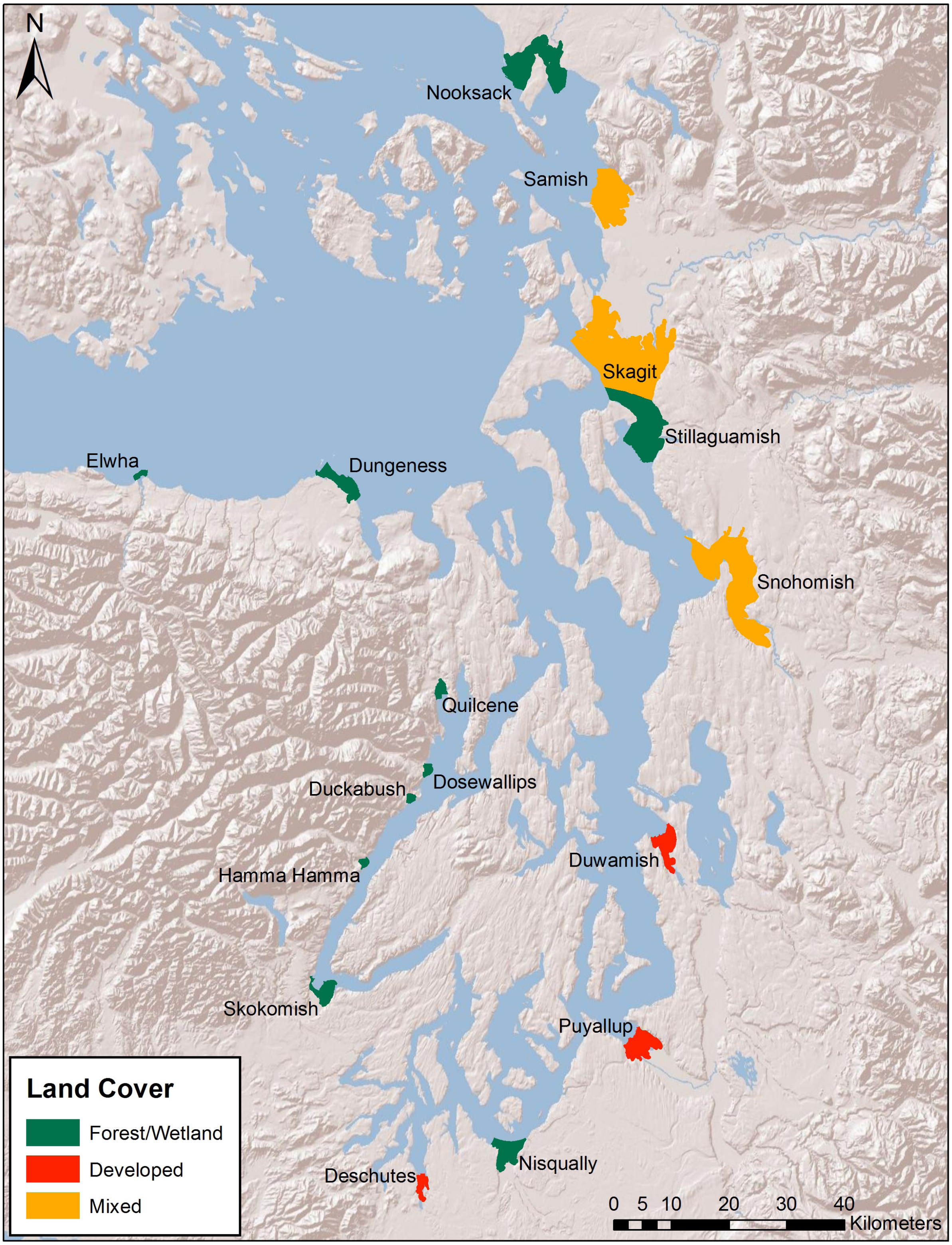


Figure 12. Location of the 16 major deltas in Puget Sound, color-coded by land-cover class.

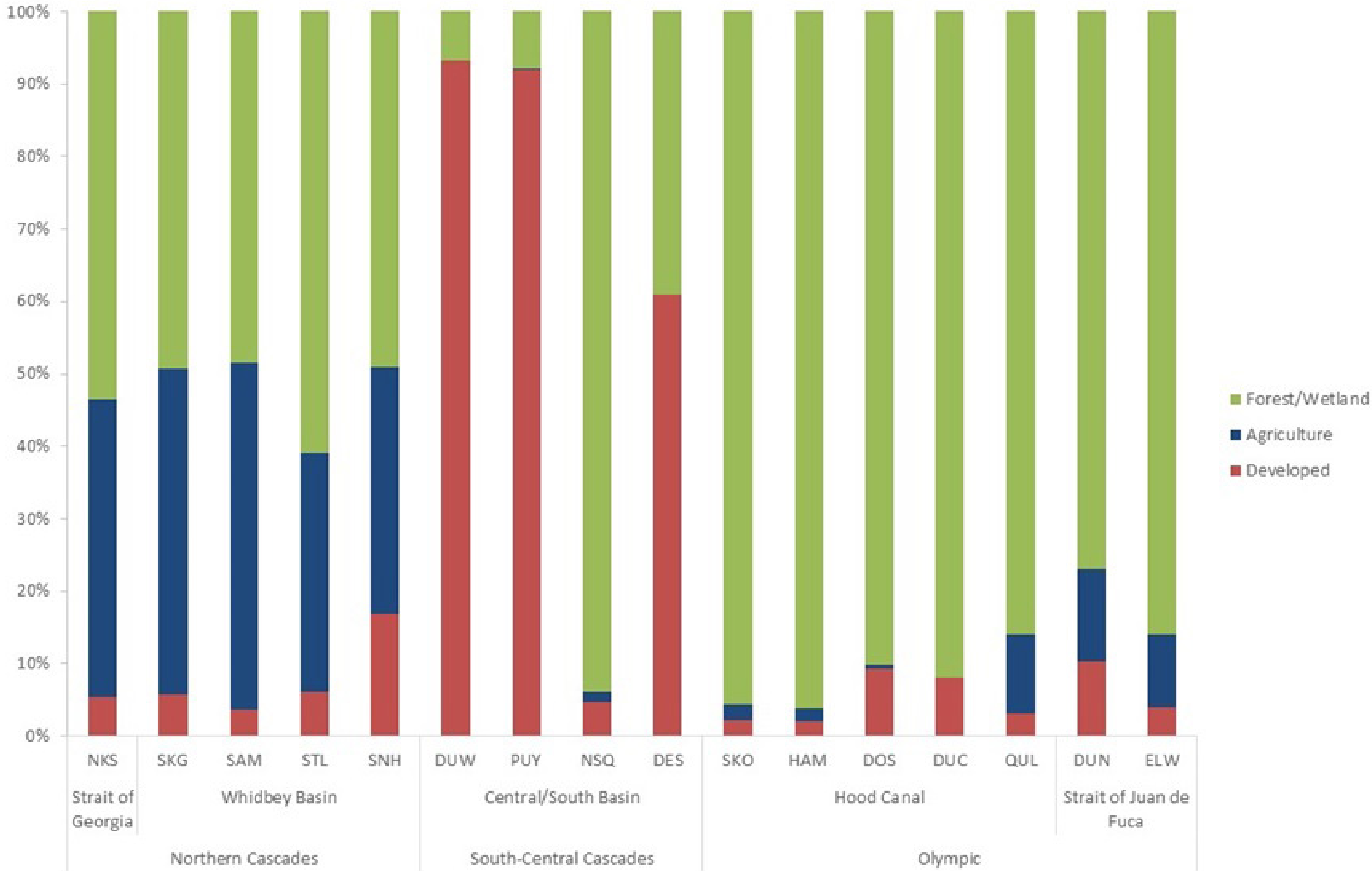


Figure 13. Land-cover distribution for each of the 16 major river deltas in Puget Sound. Labels (top row on x-axis) indicate river names: NKS = Nooksack, SKG = Skagit, SAM = Samish, STL = Stillaguamish, SNH = Snohomish, DUW = Duwamish, PUY = Puyallup, NSQ = Nisqually, DES = Deschutes, SKO = Skokomish, HAM = Hamma Hamma, DOS = Dosewallips, DUC = Duckabush, QUL = Big Quilcene, DUN = Dungeness, and ELW = Elwha. Chinook MPGs (second row) are Strait of Georgia, Whidbey Basin, Hood Canal, Strait of Juan de Fuca, and Central/South Basin. Steelhead MPGs (third row) are Northern Cascades, Olympic, and South-Central Cascades.

Selection of Monitoring Metrics

We identified a suite of potential metrics for each habitat area by convening a small group of experts in either river–floodplain assessment and monitoring or delta–nearshore assessment and monitoring (see Appendix A for meeting summaries). In each meeting, members of the expert panel suggested potential monitoring metrics during brainstorming sessions, with the understanding that all metrics would later be evaluated to determine their feasibility for our monitoring program. For each habitat area, panel members suggested potential metrics for three data types: 1) habitat quantity, 2) habitat quality, and 3) pressures or processes that influence habitat quantity or quality. Within each data type, we also attempted to identify metrics at each of the three levels of data resolution previously described in Monitoring Approach: A Hierarchical Strategy (satellite, aerial photography/lidar, and field). We then evaluated each of the metrics using the evaluation criteria described below, and scored each criterion with a value of 0 (no, criterion not met), 0.5 (moderate or context-dependent), or 1 (yes, criterion met). Evaluation tables appear in Appendix C. Once we completed scoring, we selected only those metrics that had scored 4.5 or higher for our monitoring program. We chose the arbitrary threshold value of 4.5 to give us a reasonable number of metrics (i.e., a small set of metrics that we could monitor with our limited budget) that would still encompass a comprehensive suite of habitat attributes. We also provided citations to support each score, where possible. Citations were generally available for the first three criteria, but only sometimes available for the last two.

We evaluated potential monitoring metrics using a method similar to that used in the California Current Integrated Ecosystem Assessment (Greene et al. 2014), but with fewer evaluation criteria. Our five evaluation criteria were:

1. Is the metric related to at least one of the VSP parameters?
2. Is the metric sensitive to land-management or restoration actions?
3. Is the metric related to coarser- or finer-resolution metrics?
4. Is the metric cost-effective?
5. Does the metric have a high signal-to-noise ratio?

Some of these criteria are based on Anlauf et al. (2011b), and others are based on Greene et al. (2014). Evaluation details for each of the criteria are below.

1. Is the metric related to at least one of the VSP parameters?

Metrics should be related to at least one of the four VSP parameters (abundance, population growth rate, population structure, and diversity). Habitat quantity and quality metrics are generally related to salmon abundance or population growth rate, whereas metrics of habitat diversity are more likely related to population structure or diversity. Pressure/process metrics should influence habitat quantity or quality. The majority of metrics selected for this monitoring program are related to abundance and population growth rate because they mostly reflect the quantity or quality of habitat available to salmon populations. Diversity metrics that affect population structure or diversity are typically measured at the basin scale, whereas most of our metrics are measured at individual sites.

2. Is the metric sensitive to land-management or restoration actions?

Metrics should be sensitive to land-use or restoration actions (i.e., they should be mutable). Examples of mutable metrics include river–floodplain connectivity, forest cover, pool spacing, and wood abundance. Each of these metrics can be reduced or increased based upon land conversion or restorative actions.

3. Is the metric related to coarser- or finer-resolution metrics?

Each metric should preferably link to other metrics at coarser or finer resolutions, either mechanistically or statistically. Mechanistic linkages generally imply that a higher-level metric (e.g., riparian condition) influences a lower-level metric (e.g., wood abundance); statistical linkages are those in which the same metric measured at finer resolution can be used to evaluate measurement error at coarser resolution (e.g., field observations of riparian species composition can be used to evaluate errors in aerial photo observations of riparian species composition).

4. Is the metric cost-effective?

This criterion focuses largely on the efficiency of data collection, and to some extent includes consideration of the accuracy of the data. A key part of our monitoring strategy is to obtain large sample sizes for each metric, which means field measurements in particular should be rapid. Large sample sizes will be required to increase the likelihood of detecting relatively small trends in each metric, which we anticipate based on a prior analysis showing that land-cover change in Puget Sound is generally very slow (Bartz et al. 2015).

5. Does the metric have a high signal-to-noise ratio?

This criterion can be evaluated from two points of view. The first considers the signal to be the change at a site over time, in which case most of the noise is from measurement error (except for discharge-dependent metrics). The second considers the signal to be differences between groups (e.g., differences in wood abundance among land-cover strata), in which case the noise may be dominated by site-to-site variation but also includes measurement error. We focused on the second point of view because signal-to-noise ratios are generally lowest in that case.

In the following sections, we describe the metric selection results for each monitoring environment (large rivers, floodplains, deltas, and the nearshore). We then provide a brief description of each of the selected metrics.

Large River Metrics

We evaluated 34 potential metrics for monitoring the status and trends of large river habitats. Only eight scored 4.5 or higher (see Appendix C for scores) and were selected for use in the first year of the monitoring program (Table 5). We identified suitable habitat quantity metrics only at the aerial photography and field resolutions, and habitat quality metrics only at the aerial photography resolution. Suitable pressure/process metrics were identified at all three data resolutions.

Table 5. Metrics evaluated for large river habitat monitoring. Bold type indicates that the metric scored 4.5 or 5 in the evaluation and was selected for use in the monitoring program. Other metrics (not bold) scored 4 or lower and were not selected.

	Metric, by indicator type		
Data resolution	**Habitat quantity**	**Habitat quality**	**Pressure/process**
Satellite	• Stream type at the network scale	• Hydrologic condition index (flashiness)	• **Percent natural, agricultural, and developed land cover**
Aerial photography/ lidar	• Channel or water surface area • Hydrology (monthly mean, peak flows, etc.) • Pool spacing • Edge habitat length, by type • Passable river miles	• **Sinuosity (L_{main}/L_{valley})** • **Wood jam area** • Riparian forest providing direct shade	• **Riparian buffer width and type** • Percent of large river disconnected from floodplain • Levee length • Bank armoring • Channel migration rate
Field	• Levee length • **Wood abundance** • **Edge habitat area, by type (shallow shore)** • Hydraulic complexity • Pool spacing • Coefficient of variation of thalweg depth • Hydrology (monthly mean, peak flows, etc.)	• B-IBI • Invertebrate drift • Temperature • Dissolved oxygen • Nutrients • Turbidity • Conductivity	• **Length of human-modified bank** • Contaminants • Entrenchment ratio • **Riparian buffer width and type** • Percent of large river disconnected from floodplain

The only satellite data metric that scored 4.5 or higher was the percent of large river riparian forest in various land-cover strata. This metric met all five of the evaluation criteria discussed above, and was selected as the primary pressure metric for floodplain habitats. The "stream type at the network scale" metric scored low mainly because it had low sensitivity to land use (due to its large areal coverage) and a relatively low signal-to-noise ratio. The hydrologic condition index does link to flashiness of stream flows in small watersheds, but we were unable to find support for process links to salmon populations at the scale of river reaches (i.e., we found no citations supporting the hydrologic condition index influencing either habitat conditions or salmon at the scale of large river or floodplain reaches).

We identified suitable aerial photography metrics only in the habitat quality and pressure/process data types. The aerial photography metric for pressures is riparian buffer width and type along the main channel. This metric meets all five evaluation criteria, and has been used in large-scale hierarchical analyses such as ours (Fullerton et al. 2006, Konrad 2015). No aerial photography metrics scored well for habitat quantity, and the suitable habitat quality metrics from aerial photography were sinuosity and wood jam area. The pressure metrics that scored 4.0 or lower were percent of large river disconnected from the floodplain, levee length, bank armoring, channel migration rate, and gage cross-section analysis. Each of these scored low because of low cost-effectiveness and signal-to-noise ratio scores. The habitat quantity and quality metrics also scored low primarily because all had low signal-to-noise ratios.

Suitable field metrics included wood abundance and habitat area for habitat quantity, and riparian buffer width/type and length of human modified bank (levee, rip-rap, etc.) for pressure/process. No suitable field metrics for habitat quality were identified. For pressures, contaminants scored poorly primarily because there does not appear to be a common suite of contaminants that could be useful across Puget Sound. The entrenchment ratio scored low mainly because sensitivity to land use and links to VSP were low. Habitat quantity metrics that scored low (hydraulic complexity, pool spacing, coefficient of variation of thalweg depth, etc.) had low signal-to-noise ratios.

None of the field metrics for habitat quality scored 4.5 or higher, primarily because they were expensive to implement or had low signal-to-noise ratios. However, we may further examine the benthic invertebrate and invertebrate drift metrics and attempt to verify the initial evaluation scores. The drift metric is directly related to salmon abundance and growth, but its signal-to-noise ratio and cost-effectiveness appear low. The benthic metrics (e.g., the Benthic Index of Biotic Integrity, B-IBI) are proven indicators of habitat quality (e.g., Morley and Karr 2002) and relatively easy to collect, but sample processing costs are relatively high. We may also use simple water-quality parameters such as temperature, dissolved oxygen, and conductivity at our sample sites, because the data are inexpensive to acquire. The signal-to-noise ratios are likely low for temperature and dissolved oxygen, but conductivity may be less temporally variable and is therefore a potentially useful habitat quality metric.

Floodplain Metrics

We evaluated 30 potential metrics for monitoring the status and trends of floodplain habitats, and 13 scored 4.5 or higher and were selected for use in the first year of the monitoring program (Table 6). We identified suitable habitat quantity metrics only at the aerial photography and field resolutions. Suitable habitat quality metrics were identified only at the aerial photography resolution, but suitable pressure/process metrics were identified at all three data resolutions.

The only satellite data metric that scored 4.5 or higher was the percent of floodplain in various land-cover strata. This metric met all five criteria, and was selected as the primary pressure/process metric for floodplain habitats. The National Land Cover Dataset (NLCD) is produced at approximately five-year intervals and can be used to track land-cover change with reasonable accuracy (Wickham et al. 2013). The fragmentation metric and hydrologic condition index scored low mainly because they were difficult to link to VSP parameters. The hydrologic condition index does link to flashiness of stream flows in small watersheds, but we were unable to find support for process links to salmon populations at the floodplain-unit scale. Wetland area scored low because satellite data at 30-m resolution are not accurate enough to identify small wetlands or wetlands and ponds that are under forest canopy.

We identified suitable aerial photography metrics for all three data types (habitat quantity, habitat quality, and pressure/process). Aerial photography metrics that scored well for habitat quantity included length of side channel (Beechie et al. 2006a) and area of connected floodplain (Konrad 2015). Percent of side channel disconnected by levees scored low because the metric assumes that side channels disconnected from the large river are still discernable in aerial photography, which is often

Table 6. Metrics evaluated for floodplain habitat monitoring. Bold type indicates that the metric scored 4.5 or 5 in the evaluation and was selected for use in the monitoring program. Other metrics (not bold) scored 4 or lower and were not selected.

	Metric, by indicator type		
Data resolution	**Habitat quantity**	**Habitat quality**	**Pressure/process**
Satellite	• Fragmentation by roads, levees, etc. • Wetland area	• Hydrologic condition index (flashiness)	• **Percent natural, agricultural, and developed land cover**
Aerial photography/ lidar	• **Length of side channel** • Area of side channel • **Area of connected floodplain** • Area of ponded habitat • Percent side channel disconnected by levees	• **Braid ratio (L_{br}/L_{main})** • **Side channel ratio (L_{sc}/L_{main})** • **Braid node density** • **Side channel node density**	• **Percent disconnected floodplain** • Length of human-modified bank • Turnover rate of floodplain surfaces
Field	• **Pool frequency or spacing** • Percent pool area • **Residual pool depth (d_{max}–d_{tail})** • **Wood abundance** • **Area of side channel**	• B-IBI • Invertebrate drift • Temperature • Dissolved oxygen • Nutrients • Conductivity	• Riparian species composition, buffer width • **Length of human-modified bank** • Contaminants

not the case. Area of connected floodplain is modeled using lidar data (Konrad 2015) and will require periodic lidar flights. Area of side channel and area of ponded habitat scored low primarily because of the anticipated low accuracy of measurements in forested areas (Whited et al. 2011). Suitable habitat quality metrics from aerial photography included ratios of braid length to main channel length, ratio of side channel length to main channel length, and braid and side channel node density (the number of channel separations and reconnections per unit length). These metrics can all be easily measured, and can be related to salmon abundance (e.g., Whited et al. 2011, Beechie et al. 2015).

Aerial photography metrics for pressure/process included riparian buffer width and percent of floodplain disconnected from the main channel. Both metrics met all five criteria, and have been used in large-scale hierarchical analyses such as ours (Fullerton et al. 2006, Konrad 2015). Turnover rate of floodplain surfaces scored low mainly because it is difficult to link to VSP parameters and has an unknown signal-to-noise ratio. Length of human modified bank scored low because it is difficult to get accurate data from aerial photography.

We also identified four suitable field metrics for habitat quantity and two for pressure/process. The suitable habitat quantity metrics included pool spacing, residual pool depth, wood abundance, and area of side channel (Beechie et al. 1994, Montgomery et al. 1995, Beechie and Sibley 1997). Percent pool area was not considered suitable because it is flow-dependent and therefore has a low signal-to-noise ratio for trend detection. For pressure/process, we selected riparian buffer width and condition, and length of human modified bank (mainly rip-rap in side channels). Both influence habitat quantity and quality and are sensitive to land use (Bilby and Ward 1989, Fullerton et al. 2006). Contaminants scored poorly primarily because there does not appear to be a common suite of contaminants that could be useful across Puget Sound. Riparian condition is also linked to field metrics for habitat quantity (wood abundance and pool spacing) (e.g., Bilby and Ward 1991).

Table 7. Metrics evaluated for delta monitoring. Bold type indicates that the metric scored 4.5 or 5 in the evaluation and was selected for use in the monitoring program. Other metrics (not bold) scored 4 or lower and were not selected.

	Metric, by indicator type		
Data resolution	**Habitat quantity**	**Habitat quality**	**Pressure/process**
Satellite	• Estuary surface area/drainage area • **Wetland area** • Elevation (sediment accretion)		• **Percent natural, agricultural, and developed land cover** • Length of tidal barriers/levees
Aerial photography/lidar	• **Tidal channel area** • Tidally influenced area	• **Node density** • **Wetland area, by type** • Infrared intensity • Aerial extent of salinity zones	• **Proportion of delta behind levees (connectivity)** • **Length of levees and dikes along distributaries**
Field		• Plant species diversity and composition • Proportion of nonnative species • Wetland type • Temperature • Dissolved oxygen • Extent of salinity zones	• **Shoreline armoring** • **Location of culverts/tide gates blocking access** • Contaminants • Nutrients • Bay fringe erosion rate • Sediment accretion rate

As with the large river metrics, none of the floodplain habitat quality metrics scored 4.5 or higher, primarily because they were expensive to implement or had low signal-to-noise ratios.

Delta Metrics

Puget Sound delta habitats encompass the transitional area between fresh and marine waters (Fresh et al. 2012). We consider the wetted portion of the delta to extend from the head of tide to a depth of about 10 m relative to Mean Lower Low Water (the average of the lower low water height of each tidal day over the National Tidal Datum Epoch[1]). We evaluated 25 potential metrics for monitoring the status and trends of delta habitats, and nine scored 4.5 or higher and were selected for use in the monitoring program (Table 7). We identified suitable habitat quantity metrics at the satellite and aerial photography resolutions, and habitat quality metrics at the aerial photography resolution, while suitable pressure/process metrics were identified at all three data resolutions.

At the satellite resolution, two metrics scored 4.5 or higher: percent forest or developed land cover, and wetland area. The NLCD is produced at approximately five-year intervals and can be used to track land-cover change with reasonable accuracy (Wickham et al. 2013). Wetland area is an indicator of rearing habitat availability, and therefore was classified as a habitat quantity metric.

[1] https://tidesandcurrents.noaa.gov/datum_options.html

We identified seven potential aerial photography/lidar metrics for all three indicator types (habitat quantity, habitat quality, and pressure/process), and considered five to be suitable. The one suitable metric for habitat quantity was tidal channel area, and the two metrics related to habitat quality were node density and wetland area by type. (Infrared intensity did not score high enough for links to VSP or signal-to-noise ratio.) The two aerial photography metrics identified for pressure/process are proportion of delta behind levees and length of human modified bank along distributary channels.

Eleven field metrics were identified for the three indicator types, but only two scored 4.5 or higher and were selected for monitoring. Shoreline armoring along distributaries scored 5, and location of culverts/tide gates blocking access scored 4.5. Wetland vegetation scored 0.5 for link to VSP and signal-to-noise ratio, and was therefore not selected for monitoring (total score = 4). Pressure/process metrics related to water quality and sediment change scored 0 in their ability to link across scales, cost-effectiveness, and signal-to-noise ratio. Water temperature and salinity scored low in cost-effectiveness and signal-to-noise ratio.

Nearshore Metrics

Nearshore habitats are habitats along the shoreline (Fresh et al. 2012), including lagoons, open shorelines, and beaches. We consider the wetted portion of the nearshore zone to extend from the head of tide to a depth of about 10 m relative to Mean Lower Low Water (the average of the lower low water height of each tidal day over the National Tidal Datum Epoch[2]). Adjacent land use can have a significant influence on this wetted habitat (Simenstad et al. 2006). We include a 200-m wide buffer strip along the delta and nearshore shoreline to represent this land/water interface (Fresh et al. 2012, Simenstad et al. 2011).

We evaluated 26 potential metrics for monitoring the status and trends of nearshore habitats, and 12 scored 4.5 or higher and were selected for use in the first year of the monitoring program (Table 8). We identified suitable habitat quantity metrics only at the aerial photography resolution. Suitable habitat quality metrics were identified only at the aerial photography resolution. Suitable pressure/process metrics were identified at all three data resolutions.

The only satellite data metric that was considered and found suitable for our analysis was land cover/land use in the 200-m marine riparian buffer. We will measure the percentages of various nearshore land-cover classes in the adjacent 200-m buffer zone. The NLCD is produced at approximately five-year intervals and can be used to track land-cover changes with reasonable accuracy (Wickham et al. 2013).

Eleven aerial photography metrics analysis were considered, and nine were found suitable. These metrics fit all three data types (habitat quantity, habitat quality, and pressure/process). Three habitat quantity metrics were selected (area of eelgrass, area of kelp, and embayment area), and

[2] https://tidesandcurrents.noaa.gov/datum_options.html

Table 8. Metrics evaluated for nearshore monitoring. Bold type indicates that the metric scored 4.5 or 5 in the evaluation and was selected for use in the monitoring program. Other metrics (not bold) scored 4 or lower and were not selected.

	Metric, by indicator type		
Data resolution	**Habitat quantity**	**Habitat quality**	**Pressure/process**
Satellite			• **Percent natural, agricultural, and developed land cover**
Aerial photography/lidar	• Length of unarmored feeder bluffs • **Area of eelgrass** • **Area of kelp** • **Embayment area** • Beach width	• **Connectivity of embayment to nearshore (width of opening)** • **Length of forested shoreline**	• **Shoreline armoring** • **Percent impervious (in 200-m buffer)** • **Percent forest (in 200-m buffer)** • **Area of overwater structures**
Field	• Elevation of bulkhead toe • Small stream/pocket estuary connectivity	• Beach composition (shells) • Epibenthic taxa richness • Grain size • Area of wood and rack • Temperature • Dissolved oxygen • Turbidity • Condition of pocket estuary and small stream mouth/estuary	• **Shoreline armoring** • **Location of culverts/tide gates blocking access** • Contaminants • Nutrients

two habitat quality metrics were selected (length of forested shoreline and connectivity of the embayment to the nearshore). Pressure/process metrics included shoreline armoring, percent impervious, percent forest, and area of overwater structures.

Fourteen field metrics were proposed, but only two pressure/process metrics were found suitable for monitoring status and trends: shoreline armoring and proportion of culverts and tidegates blocking access. Contaminants and nutrients scored very low for cost-effectiveness and signal-to-noise ratio. Nutrients also scored low for link to VSP. Two metrics for habitat quantity were identified, but both scored too low to be selected for the monitoring program. Elevation of bulkhead toe scored low for linkage across scales, cost-effectiveness, and signal-to-noise ratio, while small stream and pocket estuary connectivity scored low for the linkage across scales and signal-to-noise ratio criteria. Nine metrics were evaluated for habitat quality, but none scored high enough to be selected. Beach composition (shells), epibenthic taxa richness, and grain size all scored very low. The water-quality index, epibenthic taxa richness, grain size, and area of wood and wrack may be further considered if newer supporting data are found.

Overview of Selected Metrics and Protocols

Our monitoring protocols were designed to measure the selected metrics at each sample site. Our aim was to have a suite of metrics that can be measured quickly and efficiently at each site, to achieve a large sample size within each stratum in each monitoring environment. In general, we anticipated that we would have complete coverage of the landscape with satellite data (at a low resolution), large sample sizes for aerial photography metrics (mid-resolution), and small sample sizes for field metrics (high resolution). In this section, we describe our selected metrics, and then briefly explain the sampling protocol for each metric. Detailed, step-by-step protocols for each metric are listed in Appendix D. We describe large river and floodplain metrics together because both are measured at the same sample site (floodplain polygon). We describe delta and nearshore metrics separately because their sample sites do not overlap, and protocols differ between the two environments.

Large River and Floodplain Metrics at Various Resolutions

Percent Natural, Agriculture, or Developed Land Cover (satellite, aerial photography)

Land cover in watersheds has been related to salmon population performance in small streams (Bilby and Mollot 2008), but land cover in floodplains has not yet been directly related to salmon populations in large rivers. However, floodplain land cover is related to riparian conditions (Fullerton et al. 2006), which are in turn related to habitat conditions and salmon abundance (Collins and Montgomery 2002, Naiman et al. 2010). We hypothesized that land-cover metrics would be directly related to quantity of floodplain habitats, because floodplains that are more heavily developed tend to have levees that disconnect the main channel from its floodplain, and therefore have significantly less side channel and floodplain habitat (e.g., Beechie et al. 1994). We tested this hypothesis in our first year of data collection.

In this first year of sampling, we measured land cover from two different datasets: satellite data from C-CAP at 30-m grid cell resolution, and the Washington Department of Fish and Wildlife's digitally processed aerial imagery from the National Agriculture Imagery Program (NAIP) at 1-m grid cell resolution (K. Pierce, Washington Department of Fish and Wildlife, unpublished data). In both cases, we simply extracted the desired metrics from the land-cover datasets in each floodplain polygon using zonal statistics in GIS. Sampling intervals for these metrics depend on the intervals for which each dataset is available. At present, C-CAP data are available every five years, and the NAIP data processed by WDFW are available at two- to three-year intervals. (See Appendix E for evaluations of the land-cover classes that best represented forest cover).

Percent Disconnected Floodplain (lidar)

Floodplain connectivity is simply the area of floodplain separated from the channel by revetments or levees divided by the area of natural floodplain. Important requirements of this metric that will make it useful as a monitoring parameter are that the natural floodplain boundary is consistently defined and mapped among reaches, and that there are consistent rules for determining whether portions of the floodplain are fully or partially isolated from the river by built structures (including levees, revetments, railroad grades, and road fill). This metric should be linked to the braid channel ratio data measured from aerial photography, and will help inform the causal mechanism by which length and area of floodplain habitats are reduced. It is therefore a pressure/process metric that ultimately influences salmon abundance and productivity through changes in habitat quantity and quality.

This metric has been estimated from Konrad's (2015) analysis of lidar data for the major floodplains of Puget Sound. In this first year of the study, we did not attempt to validate this metric or assess error. The sampling interval for this metric is dependent upon flight intervals for the lidar data, which are currently unknown as there is no agency that regularly collects lidar data.

Riparian Buffer Width (aerial photography)

Riparian conditions have a strong influence on habitat structure and food webs in river and floodplain ecosystems in Puget Sound (Collins and Montgomery 2002, Naiman et al. 2010, Collins et al. 2012). Where large river riparian areas are primarily forested (most of western Washington, historically), wood is abundant and a strong control on habitat formation in large rivers (Collins and Montgomery 2002), as well as in small side channels that function similarly to small streams (Montgomery et al. 1995, Beechie and Sibley 1997). Riparian areas provide wood, shade, and leaf litter to large rivers (Naiman et al. 2005), and riparian conditions on floodplains are also sensitive to land use and dams (Fullerton et al. 2006, Kloehn et al. 2008).

Measuring riparian conditions from aerial photography is relatively straightforward (Hyatt et al. 2004, Fullerton et al. 2006), and the signal-to-noise ratio is high enough to detect differences among rivers in different land-cover classes (Fullerton et al. 2006). In this study, we measured widths of the forested or natural riparian buffer in GIS using the NAIP photography as one measure of riparian condition (Fullerton et al. 2006).

Side Channel Length, Sinuosity, and Node Density (aerial photography)

The simplest metrics of floodplain condition are channel pattern classification and the more quantitative metrics of sinuosity and the braid channel ratio or node density. Changes in the number or length of side channels or braids can be monitored using the braid channel ratio and node density, both of which are easily measured from aerial photography, or a more complex metric such as the river complexity index (sinuosity multiplied by the node density, Brown 2002). Sinuosity can indicate whether channels have been artificially straightened (or meanders restored).

In this study, we distinguished braids from side channels and calculated separate metrics for each. Braids were secondary-flow paths separated from the main channel by gravel bars, whereas side channels were secondary-flow paths separated by vegetated islands. We first digitized all side channels, braids, main channels, and valley center lines in GIS. The braid ratio was then calculated as the length of all braids divided by the length of the main channel (L_{br}/L_{main}), and the side channel ratio was length of all side channels divided by the main channel length (L_{sc}/L_{main}) (Friend and Sinha 1993, Beechie et al. 2006a). The node density is the total number of channel junctions per kilometer of valley length (Luck et al. 2010). Sinuosity is the main channel length divided by the valley center-line length (L_{main}/L_{valley}).

Edge Habitat Area by Type (aerial photography, field)

In large rivers, the highest densities of juvenile salmonids are found in slow-water habitats near the edges of channels where water velocity is <0.45 m/s and depth <1 m (Beamer and Henderson 1998, Beechie et al. 2005). Fish densities vary by habitat type, and habitat types are also sensitive to land uses (Beamer and Henderson 1998, Beechie et al. 2005). The signal-to-noise ratio for this metric is unknown, but may be lower than other metrics because habitat types vary with discharge and trends may be difficult to detect. However, we expect the signal-to-noise ratio to be high enough that habitat-type differences among land uses will be statistically significant.

We estimated edge habitat length from aerial photography, and measured edge habitat area in the field. In aerial photography, we digitized each edge unit in GIS, and then calculated the total length of each edge-unit type in each sampling reach. We also assigned a confidence level to each line segment, because confidence in edge-unit typing was often very low (e.g., where overhanging vegetation obscured the channel margin). In the field, we measured length and width of each edge unit and calculated the total area of each edge-unit type within a sampling segment.

Wood Abundance (aerial photography, field)

Wood abundance in large rivers is both sensitive to management and an important habitat feature for rearing juvenile salmonids (Beamer and Henderson 1998, Collins et al. 2002, Beechie et al. 2005). Historically, a number of Puget Sound rivers contained large, fully spanning log jams, but channel clearing for navigation in the 1800s removed all of those large features (Collins et al. 2002). Today, forested areas may still contain significant amounts of large wood (e.g., Abbe and Montgomery 2003, Collins et al. 2012). Research in Puget Sound or other western Washington rivers has also shown that juvenile salmonids tend to select habitat areas with wood cover for rearing (e.g., Beamer and Henderson 1998, Beechie et al. 2005, Pess et al. 2012, Polivka et al. 2015). We anticipate that this metric will have a relatively high signal-to-noise ratio, as many river reaches in Puget Sound agricultural or developed lands have little or no wood (compared to substantial amounts in some of the forested reaches).

In the aerial photography sampling, we digitized the area of wood jams visible within the active channels of large rivers and their floodplains. We included wood that was visible in the water, on gravel bars, and in young vegetation on islands or the floodplains, manually digitizing the perimeters of individual log jams and then summing the area of wood jams within each reach. To improve repeatability among observers, we did not digitize jams smaller than 50 m^2, a size that we chose mainly on the basis that smaller jams were difficult to see and digitize in the 1-m resolution NAIP imagery. In the field, we tallied all pieces of wood that we observed within the bankfull channel out to the river center line from the surveyed bank (only one edge was surveyed in the field). Wood was tallied in three size classes: large (length >5 m and diameter >0.5 m), medium (length >2 m and diameter >0.2 m), and small (length >1 m and diameter >0.1 m).

Length of Human-Modified Bank (field)

Length of human-modified bank indicates both disconnection from the floodplain and alteration of habitat condition along the bank (Beamer and Henderson 1998). Where the modified bank is a levee, the river is disconnected from its floodplain and side channel habitats are lost (Beechie et al. 1994, Hohensinner et al. 2004, Collins et al. 2012). Rip-rap banks also prevent river migration and formation of new habitats, reduce floodplain forest diversity, and alter the quality of rearing habitat (Beamer and Henderson 1998, Naiman et al. 2005). This parameter is relatively straightforward to measure in the field, and some river basins already have inventories of the total length of modified bank (e.g., the Skagit River).

In 2014, we digitized the lengths of human-modified banks from aerial photography, but had low confidence in the results. We digitized visible levees and armored banks, but in cases where the bank was obscured by trees, we could only infer the presence of armoring based on adjacent land use. We do not plan to continue this aerial photography metric in the future. In the field, the length of human-modified bank was measured using Real-Time Kinematic (RTK) GPS. At each sample site, we mapped the extent of armored bank, levees, and dikes along the full length of the surveyed bank. At this time, we plan to continue these measurements in the field.

Side Channel Metrics (field)

Habitat metrics for smaller floodplain channels include pool area (an indicator of habitat abundance), pool spacing, and residual pool depth (indicators of habitat diversity), as well as wood abundance (Bisson et al. 1988, Montgomery et al. 1995, Beechie and Sibley 1997, Mossop and Bradford 2006). Pool area is an important measure of rearing habitat capacity for juvenile salmonids, but as a monitoring metric it has a low signal-to-noise ratio due to its dependence on discharge and difficulty of measurement (Poole et al. 1997). Pool spacing, residual pool depth, and wood abundance have higher signal-to-noise ratios because they are not flow-dependent, and pools can be identified consistently using residual depth thresholds (Lisle 1987, WFPB 2011).

In 2014, we adopted a protocol for side channel surveys based on methods from the Elwha River side channel monitoring program, but were unable to implement the protocol during the field season. The protocol is essentially a continuous longitudinal profile survey in side channels. In the survey, we record all pool tail crest depths, pool maximum depths, and all boundaries between habitat units. We also tally wood pieces in three size classes: large (length >5 m and diameter >0.5 m), medium (length >2 m and diameter >0.2 m), and small (length >1 m and diameter

>0.1 m). From the survey data, we then calculate pool spacing, residual pool depth, and wood abundance in our surveyed side channels. While we have not been able to implement this protocol and have no preliminary results at this point, the method has been used in Puget Sound for the quantification of habitat change due to large-scale increases in sediment supply (East et al. 2015).

Delta Metrics at Various Resolutions

Percent Natural, Agriculture, or Developed Land Cover (satellite)

In a previous study, wetland area in Puget Sound deltas was inversely related to percent developed land cover (Fresh et al. 2012). Therefore, we chose to monitor land-cover change in deltas as an indicator of habitat degradation. In this first year of sampling, we measured land cover from C-CAP (30-m grid cell resolution). For each delta polygon, we simply extracted the desired metrics from the land-cover datasets using zonal statistics in GIS. Sampling intervals for these metrics are dependent on the intervals for which the C-CAP data are available (approximately every five years). See Appendix E for evaluations of the land-cover classes that best represented forest cover.

Wetland Area by Type (satellite, aerial photography, field)

Per Cowardin et al. (1979), wetland type refers to the vegetation type and tidal inundation of wetlands (e.g., emergent marsh, estuary–forest transition, and forested–riverine tidal wetland). Loss of tidal wetland area in deltas has been extensive in all major rivers of Puget Sound (Simenstad et al. 2011). The area, location, extent, and condition of tidal marshes and blind tidal channels are linked to greater life history diversity, delta rearing capacity, and survival of juvenile Chinook (Magnusson and Hilborn 2003, Beamer et al. 2005, Fresh 2006, Beamer et al. 2014). Large losses of wetland area across many deltas has altered delta food webs from diminished inputs of marsh-derived macrodetritus, and may have resulted in lowered rearing capacity for juvenile salmonids in delta habitats (Maier and Simenstad 2009). We have not yet developed a protocol for this metric.

Tidal Channel Area (aerial photography)

Tidal channel area is an important measure of habitat capacity for juvenile salmonids in deltas (Hood 2015). Both distributary channels and blind tidal channels provide corridors for migration as well as access to intertidal marshes (Howe and Simenstad 2015). The edge habitat of tidal channels provides vegetative cover from predation, lower velocity refugia, and is the primary area in which the juveniles feed (Simenstad and Cordell 2000). Therefore, the loss of tidal channel area could potentially decrease the rearing capacity of a delta (Simenstad and Cordell 2000).

We digitized the perimeter of all tidal channels wider than 5 m from aerial photography. The 5-m minimum channel width was based on the poor visibility of smaller channels in the 1-m resolution NAIP imagery. For tidal channels narrower than 5 m, we digitized polylines along the flow path and then buffered the polylines by 1 m to create a polygon feature. The areas of all polygons were then summed to calculate tidal channel area, and the perimeters of all polygons were summed to calculate total tidal channel edge habitat length. In emergent marsh and scrub shrub environments, we also digitized polygons around tidal channel complexes, which contained numerous tidal channels narrower than 5 m. The area of these polygons was summed to give the total area of tidal channel complexes. We also generated tidal channel center lines and summed the length of those lines to derive total tidal channel length.

Node Density (aerial photography)

Node density is one measure of habitat complexity and connectivity in river deltas, and higher node density indicates greater amount and complexity of habitats available to migrating salmonids (Beamer et al. 2005). The location and density of channel junctions, or nodes, have been used in river networks to indicate the complexity and diversity of the networks (Whited et al. 2011). In estuary habitats, marsh channel confluences with large river distributary channels are the primary rearing habitats for coastal cutthroat trout (*Oncorhynchus clarkii*, Krentz 2007). At the landscape scale, salmon densities decrease with distance of migration route to an area (Beamer et al. 2005). Blind tidal channel network complexity within tidal marshes is linked to increased abundance and productivity of juvenile Chinook life stages, species' diets, and species richness (Simenstad and Cordell 2000, Visintainer et al. 2006, Maier and Simenstad 2009).

Nodes were created at the intersections of all tidal channel and distributary center lines (as described previously), and node density calculated as the number of nodes/km of main distributary.

Proportion of Delta behind Levees (aerial photography/lidar)

The proportion of delta area that is behind levees is a measure of the capacity of fish habitat, both historically and currently. Tidal marsh and blind tidal channel networks are typically lost from diking and draining of wetlands, diminishing fish rearing capacity (Magnusson and Hilborn 2003, Bottom et al. 2005a). This parameter is effectively measured using aerial photography. Tidal marsh restoration, dike setbacks, tidegate and culvert removals, and/or improved access will allow increased delta capacity for salmonids in the future. We have not yet developed a protocol for this metric.

Length of Levees and Dikes along Distributaries (aerial photography, field)

The connectivity of delta and nearshore marine habitats is critically important for juvenile salmonids migrating from upstream freshwater natal habitats into Puget Sound (Quinn 2005). The rearing and feeding of juvenile fishes in these habitats is critical to their growth during smoltification, which ultimately influences survival to returning adult (Woodson et al. 2013). Tidal barriers, levees, and other shoreline modifications in both delta and nearshore zones reduce habitat connectivity, thereby reducing habitat quantity and quality for salmonids and other fishes, reducing fish densities (Toft et al. 2007, Fresh et al. 2012, Greene et al. 2012, Morley et al. 2012).

Changes in mean substrate temperatures, epibenthic invertebrate densities, epibenthic taxa richness, and fish densities were also evident at armored sites (Greene et al. 2012, Morley et al. 2012). Fish use is limited in distributary channels with tidegates, even if fish passage mechanisms are used (Greene et al. 2012). We have not yet developed a protocol for this metric.

Length of Armoring (field)

The cumulative impacts of shoreline armoring can result in the loss of tidal wetlands and other delta areas, the loss of embayment shoreforms, altered sediment transport and supply along the nearshore, and a reduced complexity of shoreline habitats (Fresh et al. 2012). Determining the extent of shoreline armoring in delta and nearshore habitats and monitoring changes in the amount of structures over time are thus important to assessing salmon habitat quality, and are directly related to habitat connectivity (PSRITT 2015). We have not yet developed a protocol for this metric.

Culverts/Tidegates Blocking Access (field)

One of the most obvious changes to the deltas and nearshore of Puget Sound is the loss of connectivity between land and freshwater and marine ecosystems (Collins et al. 2003). Culverts and tidegates are typically associated with streams and embayments, and are another way that connectivity is disrupted. Culverts or tidegates are typically located at streams and embayments and restrict the exchange of water, nutrients, sediments, and biota, including fish (Greene et al. 2012). Blockages can be partial or full. For example, a perched culvert can restrict fish movements at low water levels but allow some exchange as water levels increase due to a change in tide and flow increases (Greene et al. 2012). Tidegates are typically used to exclude saltwater, so they are closed by an incoming tide but open when the tide begins to ebb. Where tidegate inventories do not exist, we may use both aerial photography and field verification to identify the number of tidegates and culverts and assess the extent of blockage. We have not yet developed a protocol for this metric. The level of effort put toward this metric will depend on staffing levels.

Nearshore Metrics at Various Resolutions

In 2014, we completed the selection of nearshore metrics, but did not have time to develop protocols for them. Here we describe each of the selected metrics; protocols are currently being developed.

Percent Natural, Agriculture, or Developed Land Cover (satellite)

As with floodplains and deltas, land cover in the nearshore is correlated with habitat degradation (Rice 2006, 2007, Fresh et al. 2012). Therefore, we will monitor land-cover change in the nearshore as a causal factor for habitat degradation. We will monitor land-cover change within 200 m of the shoreline using data from C-CAP (30-m grid cell resolution). For each shoreline segment, we will extract the desired metrics from the land-cover datasets using zonal statistics in GIS.

Percent Forested (satellite, aerial photography)

One of the dominant features of Puget Sound is its long shoreline, which was heavily forested in presettlement condition (Collins et al. 2003). Emerging science suggests that the condition of the marine riparian forest functions similarly to riparian areas along stream and riverine ecosystems (Brennan and Culverwell 2005). Extensive research has recently documented the importance of riparian areas in providing ecological functions. These functions include, but are not limited to, water quality, soil stability, sediment control, microclimate, shade, and habitat structure (Brennan and Culverwell 2005, Brennan et al. 2009). We will use satellite data (C-CAP) and processed aerial photography (NAIP) to measure forest area, and to determine the rate of forest loss or clearing, in the 200-m marine riparian buffer zone.

Percent Impervious (aerial photography)

Developed land cover is a quantifiable and common land-use indicator in stream ecosystems; it correlates closely with a variety of biophysical and chemical changes to aquatic ecosystems. While it is not clear whether impervious surface coverage has the same sorts of impacts in the 200-m marine riparian buffer as in stream systems, it is known that changes in shoreline land cover affect bird species' composition and the spawning and incubation habitats of surf smelt (*Hypomesus pretiosus*; Rice 2006, 2007). Therefore, we hypothesize that higher amounts of impervious surface in the nearshore correlate with degradation of other aspects of nearshore ecosystems, and that increasing amounts of impervious surface can lead to a variety of chemical, physical, and biological changes.

In stream ecosystems, increases in impervious surface are correlated with physical changes to the hydrologic regime, stream channel morphology, and sediment processes (Arnold and Gibbons 1996, May 1996, May et al. 1997, Moscrip and Montgomery 1997). Shorter lag times between onset of precipitation and high runoff peaks, and total volume of runoff into receiving waters, are observed (May et al. 1997, Moscrip and Montgomery 1997). Chemical changes include elevated levels of organic compounds, heavy metals, and nutrients. Biological changes include altered fish and invertebrate community structure (often as represented by the Index of Biotic Integrity, or IBI) and fish communities in stream ecosystems (Richey 1982, Morley and Karr 2002, Booth 1991, Matzen and Berge 2008). There is an identified threshold response by biota of approximately 11% impervious surface in stream ecosystems (Booth 1991, May 1996, May et al. 1997, Morley and Karr 2002). We will use the amount of impervious surface, similar to its use in streams, as a starting point for the potential effects of urbanization on marine shoreline ecosystems. However, we are not aware of any quantitative relationships between the extent and type of impervious area and population characteristics of Chinook salmon (e.g., fish size or abundance) in the nearshore.

Land cover/land use in the 200-m buffer along the nearshore will be analyzed using C-CAP data that are obtained from satellite imagery. This analysis will generate the proportion of different land-cover classes (including area of agriculture) in the 200-m marine riparian buffer, similar to those reported by the Puget Sound Nearshore Ecosystem Research Project (PSNERP; Simenstad et al. 2011). In addition, several other metrics will be generated in the 200-m marine riparian buffer using aerial photography. These are described below.

Length of Forested Shoreline (aerial photography)

We will also measure the length of forested shoreline, as obtained from aerial photography, with the intent to identify the percent of shoreline habitats that have shading vegetation adjacent to the beach interface. This is an indicator of the habitat quality of the marine riparian buffer zone, as well as of nearshore habitat condition. Beaches along modified shorelines without forest cover tend to be hotter and drier than beaches along forested shorelines, and survival of smelt eggs is higher on beaches with forest cover (Rice 2006).

Area of Eelgrass and Kelp (aerial photography)

Eelgrass and kelp are two of the most important types of submerged marine vegetation in shallow coastal areas, because they support a diversity of ecosystem functions (Mumford 2007). Eelgrass is recognized as an indicator of ecosystem health. In shallow subtidal and intertidal areas, its functions include: rearing habitat for Dungeness crab (*Cancer magister*; McMillan et al. 1995); a substrate for epibenthic prey used by juvenile salmon and forage fish to colonize (Simenstad et al. 1988, Simenstad and Fresh 1995); a spawning substrate for Pacific herring (*Clupea pallasii*; Penttila 2007); and a rearing habitat for a variety of coastal species including coastal cutthroat trout and juvenile coho and Chinook salmon (Bottom and Jones 1990, Krentz 2007). Eelgrass can also function as a source of detritus for some coastal food webs that support juvenile salmon and other juvenile fish (Simenstad and Wissmar 1985).

Kelp is also a significant component of the submerged aquatic plant community in Puget Sound. Twenty-six species of kelp grow along Washington State's shorelines, and they are present nearly anywhere there is hard substrate in shallow water, including artificial surfaces (Mumford 2007). Kelp beds are important habitats for commercial and sport fish, invertebrates, marine mammals, and marine birds (Dayton 1985, Duggins et al. 1988). Many factors, both natural and anthropogenic, affect the extent and composition of these important nearshore habitats (Duggins 1980, Foster and Schiel 1985, Mumford 2007). Kelp species can be grouped based on their growth forms: canopy-forming kelp produces buoyant bulbs and blades that spread out on the water surface, with the base of plants as deep as 50 feet (15 m) below the surface (Mumford 2007). Understory kelp canopies extend horizontally near the bottom. Both types of kelp exhibit high interannual variability in distribution. Kelp is most common in rocky, high-energy environments; its greatest abundance is in the San Juan Archipelago and the Strait of Juan de Fuca, with beds decreasing in size and frequency in central and southern Puget Sound (Mumford 2007). The Washington Department of Natural Resources (WDNR) mapped the extent of kelp in Puget Sound as part of the Puget Sound Shore Zone survey in ~2000, and conducts annual surveys in the Strait of Juan de Fuca and along the outer coast (Gaeckle et al. 2011). Protocols for these metrics are currently being developed.

Area of Overwater Structures (aerial photography)

Overwater structures typically include docks, piers, floats, ramps, wharfs, ferry terminals, marinas, structural or supporting pilings, and other structures that are supported from above or float on the water. Overwater structures in nearshore marine environments impact fish habitat through shading, change in littoral vegetation and littoral drift, change in riparian and shoreline vegetation, decreased water quality, increased noise from vessel activities, increased artificial light, and substrate modifications (WDFW 2006). The impacts may be temporary (i.e., during construction) or permanent (as a result of the added structure). These structures can cause direct and continuing impacts to juvenile salmon and steelhead by altering migration routes, behavior, growth, prey availability, and ultimately survival (Nightingale and Simenstad 2001). We have not yet developed a protocol for this metric.

Wetland Area by Type (aerial photography)

The shore form class of embayment lagoons includes a variety of subtypes, such as barrier estuaries, barrier lagoons, and open coastal inlets (Shipman 2008). They are generally isolated from most wave effects by their size and shape or some sort of protective barrier beach. They vary in their configuration and in the amount of freshwater they receive, from entirely marine throughout the year to those that have perennial freshwater inflow. Rain events can cause significant short-term fluctuations in salinity in all embayment lagoons and their associated wetlands. Many embayment lagoons (often called pocket estuaries) are non-natal rearing habitats for Chinook salmon (Beamer et al. 2005, McBride et al. 2005). That is, no Chinook spawning occurs within them, but juvenile Chinook salmon migrate to pocket estuaries from other river systems. Distance between river mouth and pocket estuary was the most important measure of importance for juvenile Chinook salmon (McBride et al. 2005). In addition, use of pocket estuaries appears to represent an alternate life-history pathway that can be important for the viability of some Chinook salmon populations (Beamer et al. 2005, McBride et al. 2005).

Because many embayment lagoons are flat areas along the shoreline, they have been subject to significant anthropogenic impacts (Fresh et al. 2012, Simenstad et al. 2011). Many have been eliminated by fill, while others have been degraded by impacts to connecting watersheds and partial development of the lagoon (Fresh et al. 2012). PSNERP estimated that of the 884 embayments that existed historically, 305 have been eliminated—including systems that did not have a direct connection to Puget Sound (Fresh et al. 2012). Protocols for this metric are currently being developed.

Shoreline Armoring (aerial photography, field)

Shoreline armoring is an obvious indicator of the condition of marine shorelines because it disrupts several major ecosystem processes in Puget Sound, most notably the accumulation and processing of sediments in shallow subtidal and intertidal areas and the connectivity of terrestrial and aquatic systems (Turner et al. 1995, Finlayson 2006, Shipman et al. 2010, Heerhartz et al. 2014). Shoreline armoring refers to the construction of structures along the shoreline for erosion control and the protection of property and infrastructure such as roads and railways. Armoring generally consists of bulkheads, seawalls, and rock revetments, all of which vary considerably in construction and vertical placement along the shoreline (i.e., relative to Mean Higher High Water).

Armoring directly impacts the beach where it is constructed. It restricts access to the beach, causes loss of terrestrial sediment supply and transport, and increases localized beach erosion or changes to sediment transport caused by wave interaction with structures (Woodroffe 2002). In addition, there can be a progressive loss of the beach that occurs when a fixed structure is built on an eroding shoreline (passive erosion), particularly in light of ongoing and future rates of sea-level rise (Fletcher et al. 1997). Other concerns include lost intertidal area due to encroachment into the intertidal zone, changes in groundwater flow, and disruption of detritus and large wood import and export (Shipman et al. 2010, M. Dethier, University of Washington, personal communication). Ecological impacts of armoring include the direct burial and isolation of habitats, the introduction of fill or new substrates, changes to invertebrate communities, loss and degradation of forage fish spawning habitat, and loss of feeding and migration habitats of forage fish and juvenile salmon (Rice 2006, Toft et al. 2007, Shipman et al. 2010, Sobocinski et al. 2010, Morley et al. 2012).

At present, there is no comprehensive, Puget Sound-wide shoreline armoring dataset. There are a variety of different datasets that vary in temporal and spatial extent. PSNERP developed a shoreline armoring dataset for an analysis of nearshore changes that occurred from ~1850 to 2010. This analysis determined that 26% of the shoreline of Puget Sound was armored (Fresh et al. 2012, Simenstad et al. 2011). A new armoring dataset is currently being developed with support from the Puget Sound Partnership (PSP), NOAA, WDFW, and Washington Department of Ecology (WDOE). This new dataset will provide a spatially explicit analysis of the presence or absence of armoring, and is being developed from aerial photography analysis and field verification.

Culverts/Tidegates Blocking Access (field)

As in the deltas, the loss of connectivity between land and freshwater and marine ecosystems restricts the exchange of water, nutrients, sediments, and biota, including fish (Greene et al. 2012). See Culverts/Tidegates Blocking Access in the preceding section on Delta Metrics for additional detail.

Analysis Methods

Our analysis followed a four-step process in which we evaluated 1) the accuracy of land-cover classification, 2) observer variation in aerial photography metrics, 3) the status of habitat and riparian areas among MPGs, and 4) the status of habitat and riparian areas among land-cover classes.

1. Accuracy of Land-Cover Classification

Land-cover classifications from satellite or aerial photography data inevitably contain some level of classification error. While some error analysis has been done in the past for satellite data such as C-CAP (Nowak and Greenfield 2010, Smith et al. 2010, NOAA Coastal Services Center 2014), we are not aware of a similar analysis of the NAIP data. Moreover, the accuracy of our metrics, such as percent forested or percent developed, should be evaluated.

Land-cover metrics were summarized by land-cover strata (forest/wetland, agriculture, developed, or mixed). Sample sites were created using U.S. Geological Survey (USGS) floodplain polygons (Konrad 2015) and reach breaks delineated in aerial photography. Forest/wetland and developed land-cover strata were extracted, and zonal statistics were run in ArcGIS 10.2 using the floodplain polygon layer, C-CAP 2011 Landsat data, and 2011 NAIP data. Proportions of land cover were derived using areas and descriptive statistics in Excel and RStudio.

We evaluated the accuracy of floodplain land-cover metrics generated from the C-CAP Landsat derived land-cover database (30-m grid cell resolution) and the land-cover classification developed by Ken Pierce of WDFW using aerial photography from NAIP (1-m grid cell resolution) in two steps. First, we evaluated the accuracy of alternative groupings of forest classes to determine the most accurate set of classes for estimating percent forest cover. Second, we evaluated each of the land-cover metrics (percent forested and percent developed) by comparing each metric calculated from the remote sensing data to a manual classification of land cover using linear regression. We regressed manually classified land-cover percentages against percent forest and percent developed land cover from C-CAP and NAIP. Regressions with slope nearest 1 and intercept nearest 0 are considered the most accurate, and the highest r^2 value is considered the most precise.

We also evaluated the accuracy of manually identified land cover from aerial photography by comparing aerial photography land-cover classification to field classification. To do this, we first converted our field data on riparian cover types to points using GIS. These points were provided to two independent observers who did not collect the field data. The observers then classified the points on aerial photography using the same cover types from field surveys. We used error matrices to quantify the accuracy of aerial photography land-cover classification for each observer. In the error matrix, low commission and omission errors indicate that the observer rarely assigns a land-cover type that is incorrect, whereas high error rates indicate frequent misclassification.

2. Observer Variability in Aerial Photography Metrics

One important task in developing our new aerial photography monitoring protocols was determining how much interobserver variation occurred in the measurement of each feature from aerial photography. For example, if two observers use slightly different criteria to determine whether a feature is a side channel or not, they may end up with dramatically different lengths of side channel in the database. Here we describe our methods for analyzing observer variation for the large river and floodplain habitat metrics.

Using GIS software and previously defined aerial photography sampling protocols, two observers identified and measured several habitat features in 12 sample sites. Sites were selected with a range of habitat complexity (i.e., single vs. multiple channels, low wood vs. high wood, etc.), and reach sample length and area were defined for each location before sampling took place. Sample locations ranged in length from 497 m to 5,606 m, and in area from 0.1 km^2 to 35 km^2. Sampling encompassed several habitat features, including bank type and length, habitat edge type and length, braid length, side channel length, valley center line length, and wood jam area. Bank type features included armored bank, levee bank, and natural bank. Habitat edge type features included backwater, bar edge, modified bank edge, and natural bank edge. Habitat feature lengths and areas were then normalized by sample reach length or area to account for variation in sample-site size, and mean percent difference in length or area was calculated for each habitat feature. Where there were large differences among observers, we examined individual habitat features to determine the causes of differences and refine protocols.

3. Status of Habitat and Riparian Areas by Major Population Group

We summarized the current status of each of the large river and floodplain metrics by steelhead MPG. For all metrics, we used stratified estimators based on the original land-cover and valley-type strata. Thus, for each metric in each MPG, the estimate was the average of all sample sites in each stratum, weighted by the total large river length in that stratum for that MPG.

Land-cover class was summarized by steelhead MPG within all sampleable floodplains in Puget Sound using USGS floodplain polygons (developed for the Floodplains by Design Project) and C-CAP Landsat 2011 land-cover data regrouped into forest/wetland, agriculture, or developed land cover (Konrad 2015). Zonal statistics were used to extract land-cover types from C-CAP 2011 data within each floodplain polygon. Given that all Puget Sound floodplains in the GIS coverage were evaluated, weighting was not necessary for this analysis.

For the deltas, land cover was summarized within PSNERP delta polygons and C-CAP 2011 land-cover data grouped into forest/wetland, agriculture, and developed land-cover types. The delta polygons used for these summaries do not account for connectivity and do include areas that are not connected to tidal flooding. Given that all deltas were sampled, all metrics were summarized without statistical comparisons, and without weighting by land-cover type.

4. Status of Habitat and Riparian Areas by Land-Cover Stratum

We summarized the current status of each of the large river metrics across our floodplain sample sites by land-cover stratum. For all metrics, we compared mean values among cover types, although for a few we plotted median values (box and whiskers plots) to better indicate the variability among sites within each land-cover stratum. Metrics were unweighted in this case because we are interested in differences among land-cover strata (forest/wetland, agriculture, developed, or mixed), regardless of the aerial extent of each. We did not summarize the delta metrics by land-cover stratum because we sampled all 16 deltas and there was an uneven distribution of land-cover strata (no agriculture-type deltas, and only three developed deltas).

Results

Here we present results of our four major analyses: 1) accuracy of land-cover classification, 2) observer variation in aerial photography metrics, 3) the status of habitat and riparian areas among MPGs, and 4) the status of habitat and riparian areas among land-cover classes.

1. Accuracy of Land-Cover Classification from C-CAP and NAIP

We conducted three separate analyses to evaluate the accuracy of land-cover classification in the C-CAP and NAIP datasets. The first analysis examined which land-cover classes produced the most accurate representations of percent forest land cover. The second analysis examined the accuracy of the final percent forest and percent developed land-cover metrics. The third analysis described the accuracy of manual land-cover classification from aerial photography to determine if it might be useful as a monitoring method.

Evaluation of Forest Land-Cover Classes

An important first step in developing our land-cover protocols was to determine which land-cover classes best represent the metrics we want to monitor over time. For example, we needed to understand whether to use all three forest cover classes and both of the forested wetland types to represent percent forest, or whether some subset of those classes better represented forest cover. In this first section, we describe the accuracy assessments for forest land-cover classifications from both C-CAP and NAIP.

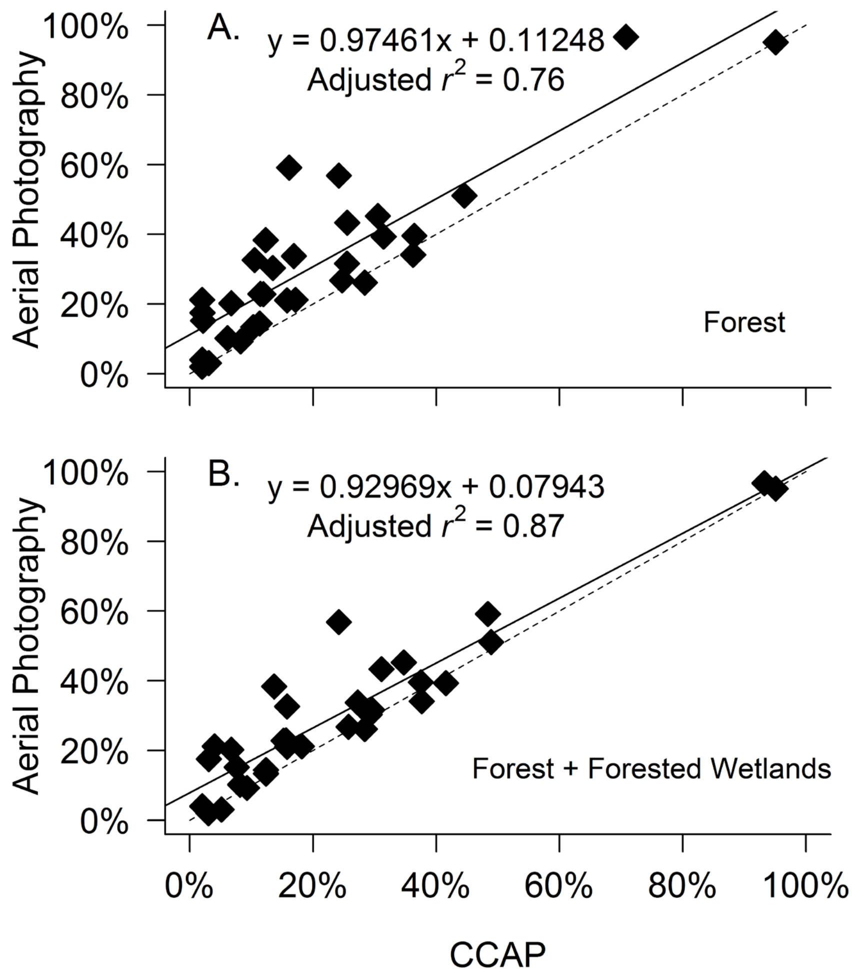


Figure 14. Regression plots for two different groupings of forest land cover from C-CAP data at 32 floodplain sites (points). Percent forest and percent forest + forested wetlands are plotted against observed land cover from aerial photography.

C-CAP forest land-cover classification

In the process of developing the percent forest and percent developed metrics, we first evaluated the accuracy of various combinations of C-CAP land-cover classes to determine which groupings provided the most accurate metrics (Table 2). Initially, we evaluated the percent forest metric using only the three forest classes (conifer, deciduous, and mixed), and found that percent forest was underestimated by about 11% (Figure 14). Visual examination of sites with some relatively large errors indicated that areas that appeared to be forest in aerial photography were often classified as one of two forest wetland types in C-CAP. Addition of the two forested wetland classes (Table 2) reduced the underestimation somewhat (though nearly all sites were still underestimated); however, precision was increased substantially (r^2 improved from 0.76 to 0.87). For all subsequent analyses, we use all five cover classes (conifer, deciduous, mixed, palustrine forested wetland, and delta forested wetland) to calculate percent forest in floodplains.

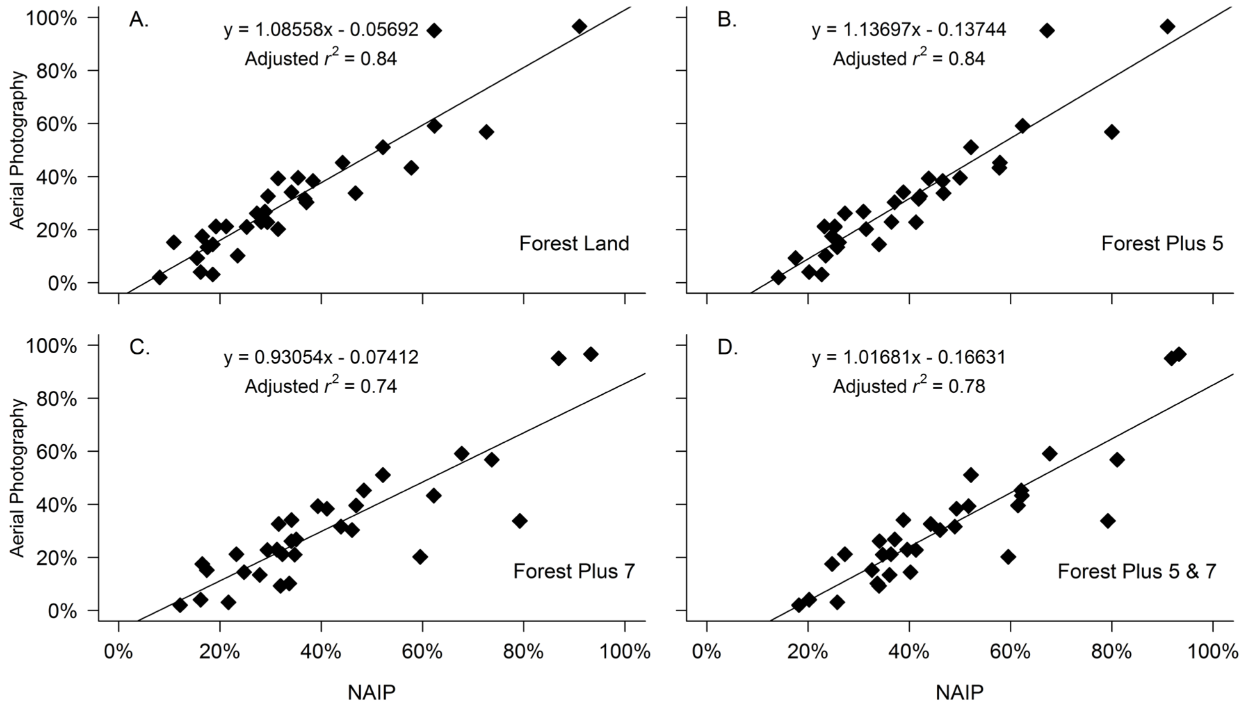


Figure 15. Regression plots depicting the accuracy of four different possible groupings for forest land cover from NAIP data at 32 floodplain sites (points). Based on the closeness of fit with the y-intercept and the adjusted r^2 value, there is no significant benefit to adding other land-cover classes to the "tree" class.

NAIP forest land-cover classification

We also evaluated various combinations of land-cover classes from the NAIP data, and found that using only the tree class tended to slightly overestimate percent forest cover, but with a relatively high precision (r^2 = 0.84; Figure 15). However, several other classes also contained the word "tree," so we examined all combinations of such variables to determine which grouping provided the greatest accuracy. Addition of the other classes (veg/shadow/tree, shrub or tree, and veg/shadow/tree + shrub or tree) increased the overestimation significantly in all cases, while precision remained the same or was reduced. Therefore, in all subsequent analyses we estimated percent forest from the NAIP data using only the tree class.

Accuracy of Percent Forest and Percent Developed Land-Cover Metrics

Regression analyses of manually classified land-cover percentages against percent forest and percent developed land cover from C-CAP and NAIP were used to evaluate the accuracy of the two metrics from each dataset (Figure 16). Each metric from each dataset has a similar r^2 value, indicating that all have roughly the same precision. However, as seen in Figure 16, C-CAP tends to underestimate percent forest and is relatively unbiased for percent developed, while NAIP is relatively unbiased

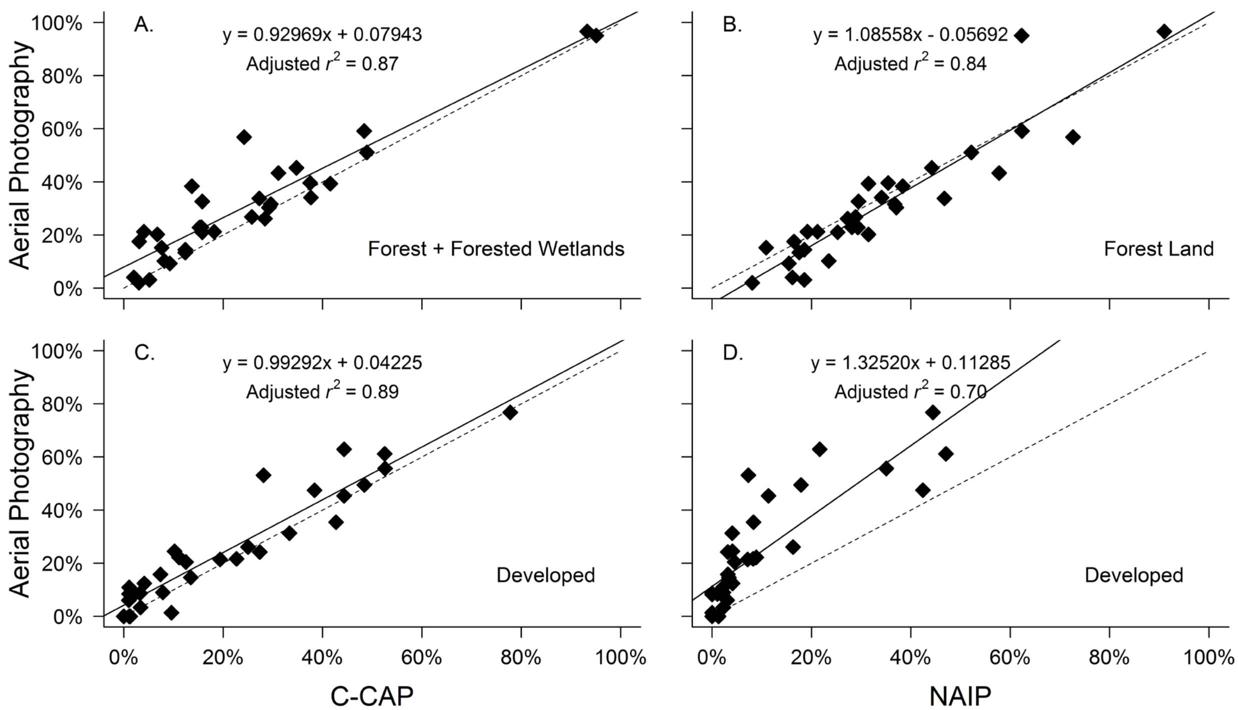


Figure 16. Regression plots with percent forest and percent developed from C-CAP and NAIP data by aerial photography at 32 sites (points).

for percent forest and underestimates percent developed. Recent improvements in the NAIP photo interpretation process may increase its accuracy to above that of the C-CAP data in the future. We hope to reevaluate the NAIP imagery within the next two years. We report our land-cover metrics by MPG and land-cover stratum using both NAIP and C-CAP, since the result of this accuracy assessment demonstrated that there was no consistent difference between the datasets.

Accuracy of aerial photography land-cover classification

We evaluated the potential to classify changes in riparian cover as one potential metric, and generally found that observer error was quite high. We therefore opted not to use manual land-cover classification for our monitoring program. We began our analysis with an accuracy evaluation for eight land-cover classes. Overall classification accuracy of the eight manually classified land-cover classes from aerial photography was 64.5% (118/183) for Observer 1 (Table 9), and 59.0% (108/183) for Observer 2 (Table 10). One major source of error was related to movements of channels and vegetation growth that had occurred between the image date and the field survey dates. The error associated with these changes accounted for 23.1% (15/65) of the misclassifications for Observer 1 and 21.3% (16/75) of the misclassifications for Observer 2. We removed these samples from the error matrix to isolate errors associated with the interpretation of aerial photographs (Tables 11 and 12).

Table 9. Error matrix with all samples and no filtering for Observer 1. Overall classification accuracy was 64% (118/183). *Key*: BG = bare ground, C = conifer, D = deciduous, DI = disturbed impervious, DP = disturbed pervious, G/S = grass/shrub, M = mixed forest, W = water.

	Field										
Aerial photography	**BG**	**C**	**D**	**DI**	**DP**	**G/S**	**M**	**W**	**Total**	**% Correct**	**% Commission**
BG	6		10	2		3		1	22	27	73
C			2				2		4	0	100
D		2	54	1	3	9	6		75	72	28
DI				19	1				20	95	5
DP		1	2	2	28	1	2		36	78	22
G/B			3		3	5			11	46	55
M		3	3			2	4		12	33	67
W	1							2	3	67	33
Total	7	6	74	24	35	20	14	3	183		
% Correct	86	0	73	79	80	25	29	67		64	
% Omission	14	100	27	21	20	75	71	33			

Table 10. Error matrix with all samples and no filtering for Observer 2. Overall classification accuracy was 59% (108/183). *Key*: BG = bare ground, C = conifer, D = deciduous, DI = disturbed impervious, DP = disturbed pervious, G/S = grass/shrub, M = mixed forest, W = water.

	Field										
Aerial photography	**BG**	**C**	**D**	**DI**	**DP**	**G/S**	**M**	**W**	**Total**	**% Correct**	**% Commission**
BG	4		5	1		2		1	13	31	69
C		1	7		1		1		10	10	90
D		1	34			6	1		42	81	19
DI			1	21					22	96	5
DP		1	3	2	28	1	2		37	76	24
G/B	1		8		5	10	2		26	39	62
M		3	12		1	1	8		26	31	69
W	2		3					2	7	29	71
Total	7	6	74	24	35	20	14	3	183		
% Correct	57	17	46	88	80	50	57	67		59	
% Omission	43	83	54	13	20	50	43	33			

Table 11. Error matrix for Observer 1 excluding sites where changes occurring between the image date and survey dates caused misclassifications. Overall classification accuracy was 70% (118/168). *Key*: BG = bare ground, C = conifer, D = deciduous, DI = disturbed impervious, DP = disturbed pervious, G/S = grass/shrub, M = mixed forest, W = water.

	Field										
Aerial photography	**BG**	**C**	**D**	**DI**	**DP**	**G/S**	**M**	**W**	**Total**	**% Correct**	**% Commission**
BG	6			2					8	75	25
C			2				2		4	0	100
D		2	54	1	3	9	6		75	72	28
DI				19	1				20	95	5
DP		1	2	2	28	1	2		36	78	22
G/B			3		3	5			11	46	55
M		3	3			2	4		12	33	67
W								2	2	100	0
Total	6	6	64	24	35	17	14	2	168		
% Correct	100	0	84	79	80	29	29	100		70	
% Omission	0	100	16	21	20	71	71	0			

Table 12. Error matrix for Observer 2 excluding sites where changes occurring between the image date and survey dates caused misclassifications. Overall classification accuracy was 65% (108/167). *Key*: BG = bare ground, C = conifer, D = deciduous, DI = disturbed impervious, DP = disturbed pervious, G/S = grass/shrub, M = mixed forest, W = water.

		Field									
	BG	C	D	DI	DP	G/S	M	W	Total	% Correct	% Commission
Aerial photography BG	4			1					5	80	20
C		1	7		1		1		10	10	90
D		1	34			5	1		41	83	17
DI			1	21					22	95	5
DP		1	3	2	28	1	2		37	76	24
G/B			7		5	10	2		24	42	58
M		3	13		1	1	8		26	31	69
W								2	2	100	0
Total	4	6	65	24	35	17	14	2	167		
% Correct	100	17	52	88	80	59	57	100		65	
% Omission	0	83	48	13	20	41	43	0			

Table 13. Error matrix for Observer 1 with all tree community types (C, D, and M) grouped as forest (F). Overall classification accuracy was 81% (136/168). *Key*: BG = bare ground, DI = disturbed impervious, DP = disturbed pervious, F = forest, G/S = grass/shrub, W = water.

			Field						
	BG	DI	DP	F	G/S	W	Total	% Correct	% Commission
Aerial photography BG	6	2					8	75	25
DI		19	1				20	95	5
DP		2	28	5	1		36	78	22
F		1	3	76	11		91	83	17
G/B			3	3	5		11	45	55
W						2	2	100	0
Total	6	24	35	84	17	2	168		
% Correct	100	79	80	90	29	100		81	
% Omission	0	21	20	10	71	0			

Table 14. Error matrix for Observer 2 with all tree community types (C, D, and M) grouped as forest (F). Overall classification accuracy was 80% (127/158). *Key*: BG = bare ground, DI = disturbed impervious, DP = disturbed pervious, F = forest, G/S = grass/shrub, W = water.

			Field						
	BG	DI	DP	F	G/S	W	Total	% Correct	% Commission
Aerial photography BG	4	1					5	80	20
DI		19		1			20	95	5
DP		2	27	6	1		36	75	25
F			2	66	6		74	89	11
G/B			3	9	10		22	45	55
W						1	1	100	0
Total	4	22	32	82	17	1	158		
% Correct	100	86	84	80	59	100		80	
% Omission	0	14	16	20	41	0			

Another major source of error was the incorrect classification of tree community type in aerial images, which accounted for 36.0% (18/50) of the misclassifications for Observer 1 (Table 11) and 22.0% (13/59) of the misclassifications for Observer 2 (Table 12). Given that the differentiation of tree community types appears to be difficult from aerial image analysis, we grouped all forest community types—conifer (C), deciduous (D), and mixed (M)—into one category, forest (F), and reevaluated the classification accuracy (Tables 13 and 14).

With tree community types thus grouped, overall accuracy was 81.0% (136/168) for Observer 1 (Table 13) and 80.4% (127/158) for Observer 2 (Table 14). The single largest sources of remaining error for both observers were the misclassification of grass (G) and shrub (B) as tree community cover types, and of tree community types as grass/shrub. This represented 43.8% (14/32) of the misclassifications for Observer 1 (Table 13) and 48.4% (15/31) for Observer 2 (Table 14). These errors are most likely associated with the classification of shrub communities as tree cover types or of tree cover types as shrub communities, as opposed to misclassifications of grass as forest or forest as grass. However, our field-survey protocol grouped shrub and grass into one functional community, preventing further segregation of the error matrix using our current field data.

2. Observer Variability in Aerial Photography Metrics

The second important task in developing our new aerial photography monitoring protocols was determining the magnitude of interobserver variation in the measurement of each feature from aerial photography. Here we describe the results of our analyses of observer variation for the large river and floodplain habitat metrics.

The greatest mean percent difference between observers for bank type was armored bank length (30% ± 56%, where ± 56% indicates the 95% confidence interval; Figure 17). Mean percent differences in levee bank length and natural bank length were considerably smaller (15% ± 43% for levee bank length and 11% ± 18% for natural bank length). Variation between observers for habitat edge type features was generally less, ranging from -1% ± 10% for modified bank edge length to 34% ± 80% for backwater area (Figure 18). Mean percent difference in bar edge length was -9% ± 24%, while mean percent difference in natural bank edge length was only 4% ± 36%. Among the remaining metrics, the greatest mean percent difference was observed in wood jam area (-84% ± 42%; Figure 19). Mean percent difference in braid length was -19% ± 46%, and mean percent difference in side channel length was -22% ± 55%. Lastly, there was a very minor difference between observers with respect to length of valley center line (2% ± 2%).

To help reduce observer variation (especially for metrics with large differences, such as wood jam area), we examined the digitized metrics from both observers at individual sites so we could ascertain the primary sources of error and identify potential improvements to protocols. For example, within the armored bank length analysis, the largest differences between the two observers were observed at sample sites 98, 116, and 287 (Figure 20). At sample sites 98 and 116, both observers recognized the banks as modified, but the first observer identified portions of the banks as armored (marked in light blue), while the second observer identified them as levee (marked in light green).

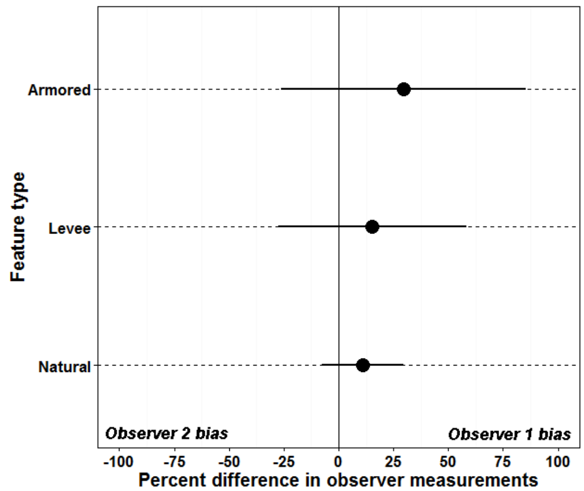


Figure 17. Mean percent difference and 95% confidence interval for armored bank, levee bank, and natural bank.

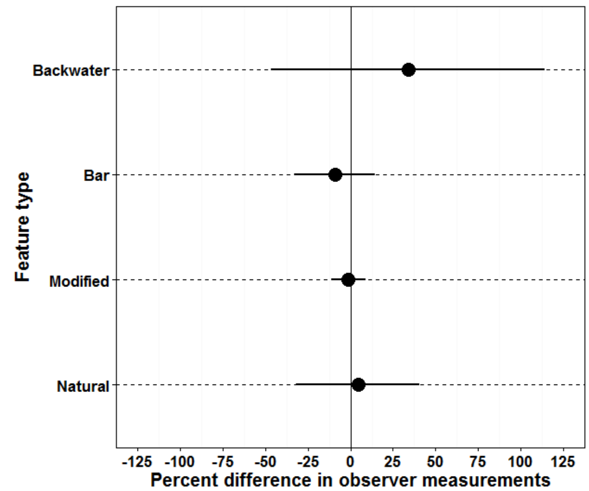


Figure 18. Mean percent difference and 95% confidence interval for backwater area, bar edge length, modified bank edge length, and natural bank edge length.

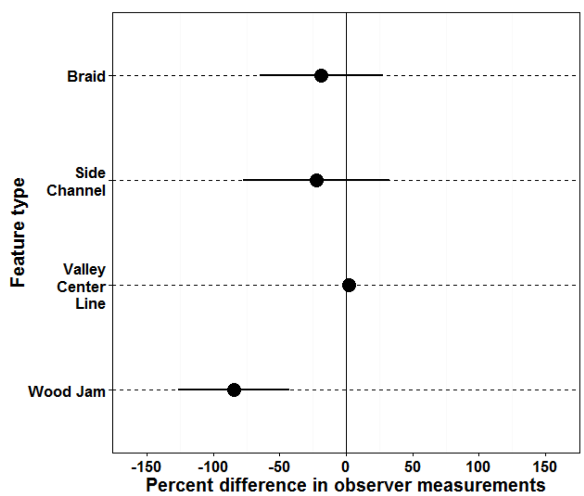


Figure 19. Mean percent difference and 95% confidence interval for braid length, side channel length, valley center line length, and wood jam area.

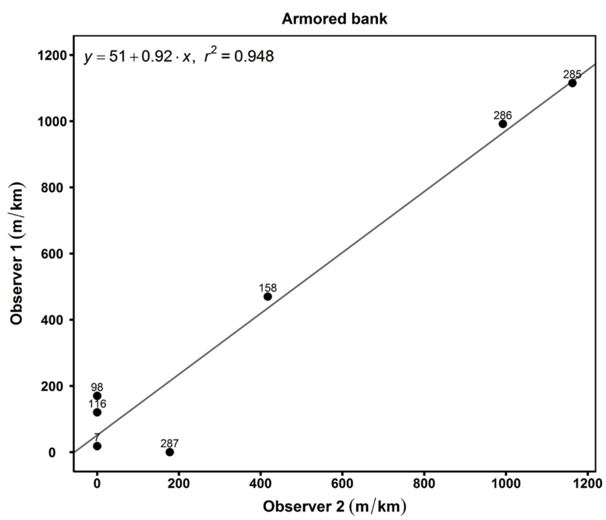


Figure 20. Armored bank length in each sample location, normalized between two observers.

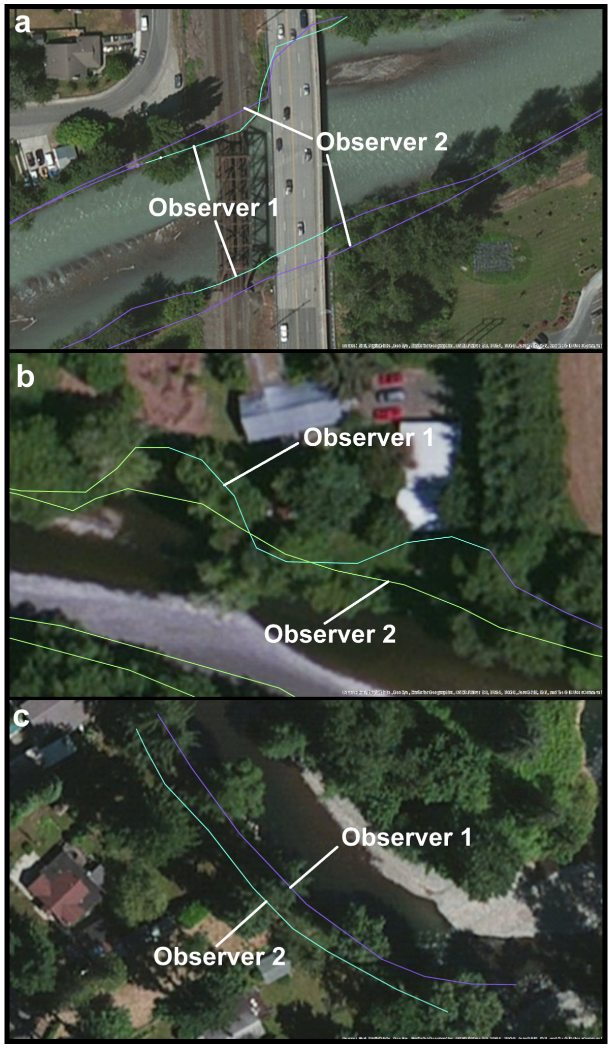


Figure 21. a) Observer differences classifying bank types within sample site 98. Bank marked as armored is light blue, bank marked as levee is light green. b) Observer differences classifying bank types within sample site 116. Bank marked as armored is light blue, levee is light green. c) Observer differences classifying bank types within sample site 287. Bank marked as natural is purple, armored is light blue.

This created a difference in feature length of, at site 98, 170 m/km (Figure 21a). At sample site 116, the difference in feature length was 120 m/km (Figure 21b). Lastly, at sample site 287, the first observer identified a portion of the bank as natural (marked in purple), while the second observer identified it as armored (marked in light blue), creating a difference of 177 m/km (Figure 21c).

Observer differences assigning armored bank lengths at the three sample sites also account for the differences in levee bank, as both classifications were used for the same portions of banks by different observers (Figure 22). Subsequently, a significant difference in levee bank length (273 m/km) was observed at sample site 262. The source of inconsistency at this sample location was the classification of a portion of the bank as natural (marked in light blue) by the first observer, while the same portion of bank was classified as levee (marked in red) by the second observer (Figure 23). Differences between observers in bank classification within these sites also account for the differences in natural bank length (Figure 24).

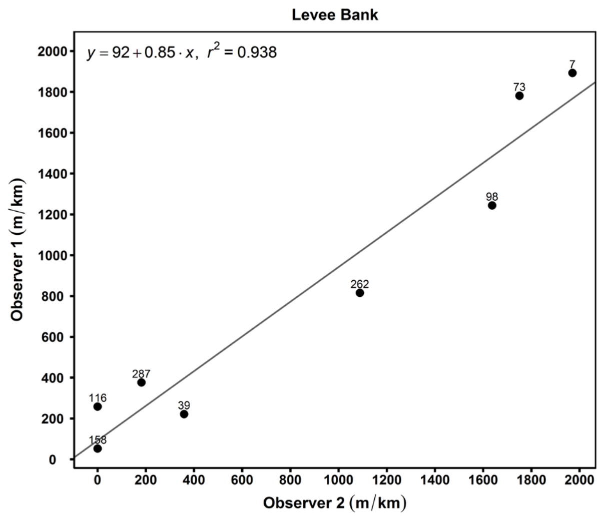


Figure 22. Levee bank length in each sample location, normalized between two observers.

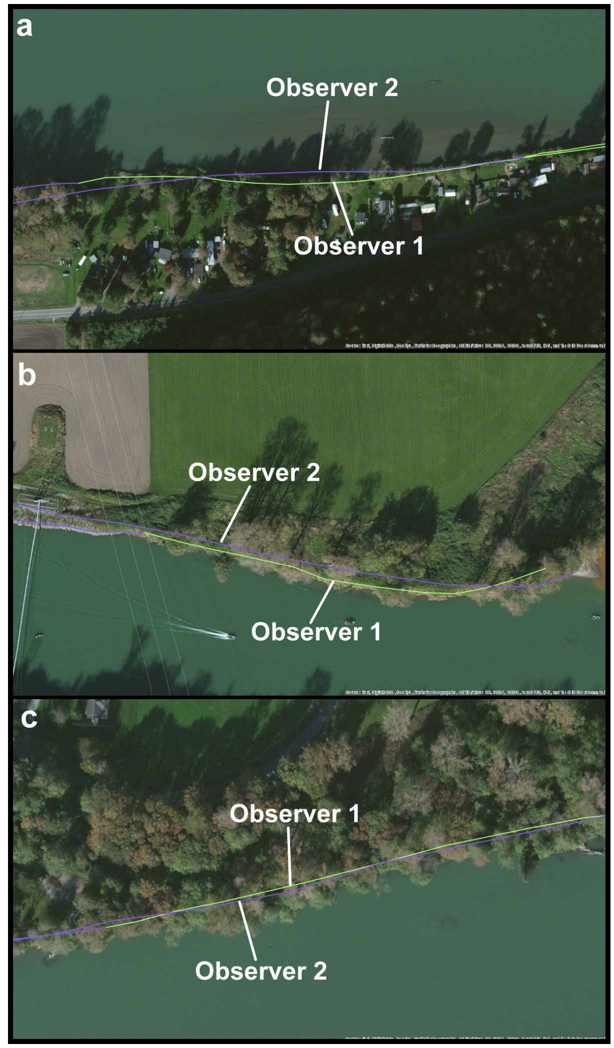


Figure 23. Observer differences classifying bank types within sample site 262. Bank marked as natural is purple, levee is light green.

The largest source of observer variation in identifying bank and edge habitat types was the lack of visibility under shrub or tree canopy. Bank habitat types are particularly difficult to identify, as the majority of banks present at the selected sampling locations were beneath canopy cover. In many cases when canopy was present, observers had to essentially guess the identification of the habitat feature. To improve the accuracy and repeatability of these metrics, we revised the protocols to include use of reference datasets (e.g., existing geospatial data for levees or armoring) and/or field verification where features are not visible on aerial photography. Because observer variation was high enough to cause us to revise our protocols, we will reevaluate observer variability when the revised protocols are implemented.

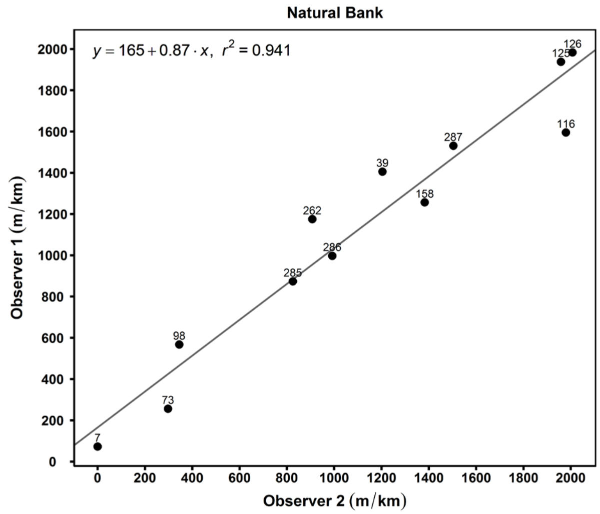


Figure 24. Natural bank length in each sample location, normalized between two observers.

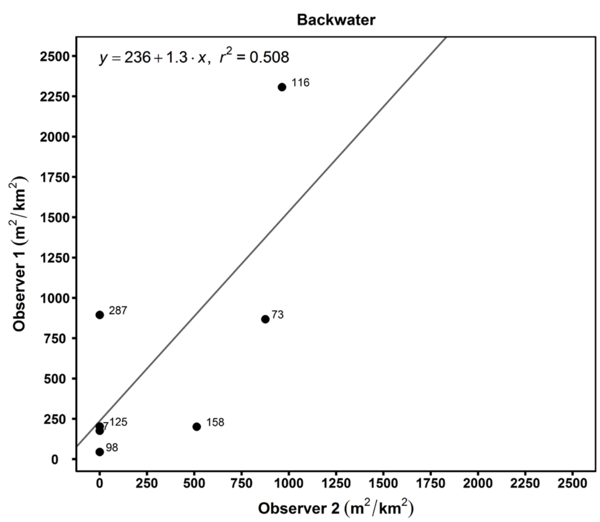


Figure 25. Backwater area in each sample location, normalized between two observers.

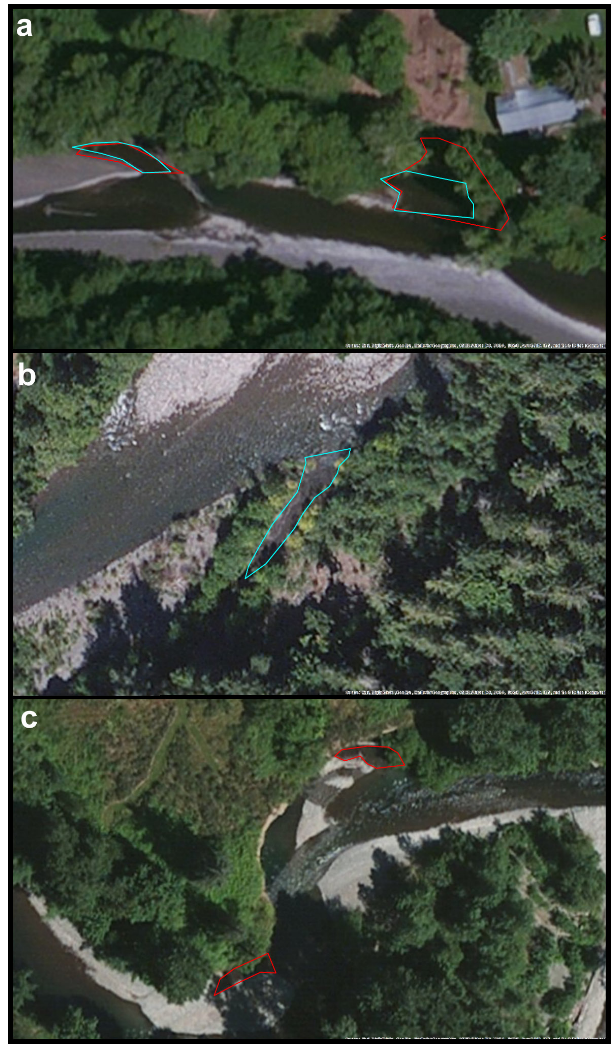


Figure 26. a) Observer differences classifying backwater area within sample site 116. Area marked by Observer 1 is red, area marked by Observer 2 is light blue. b) Observer differences classifying backwater area within sample site 158. Observer 1 is red, Observer 2 is light blue. c) Observer differences classifying backwater area within sample site 287. Observer 1 is red, Observer 2 is light blue.

Significant differences in backwater area classification occurred at sample sites 116, 158, and 287 (Figure 25). A difference of 1,343 m^2/km^2 in backwater area within sample site 116 can be attributed to inconsistent measurements of the same feature by the two observers. The first observer (marked in red) digitized a larger area of the backwater feature, while the second observer (light blue) digitized a smaller area of the backwater (Figure 26a). In sample site 158, a difference of 312 m^2/km^2 in backwater area is the result of misidentification of the feature by the first observer (Figure 26b). By contrast, at sample site 287, the second observer misidentified the feature, resulting in a difference of 894 m^2/km^2 in backwater area (Figure 26c).

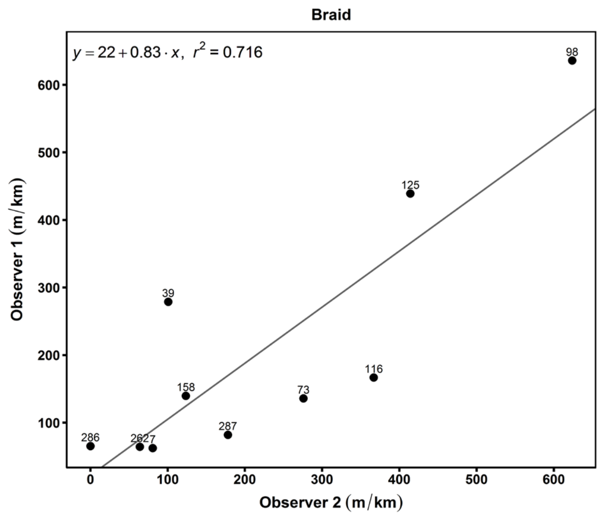


Figure 27. Braid length in each sample location, normalized between two observers.

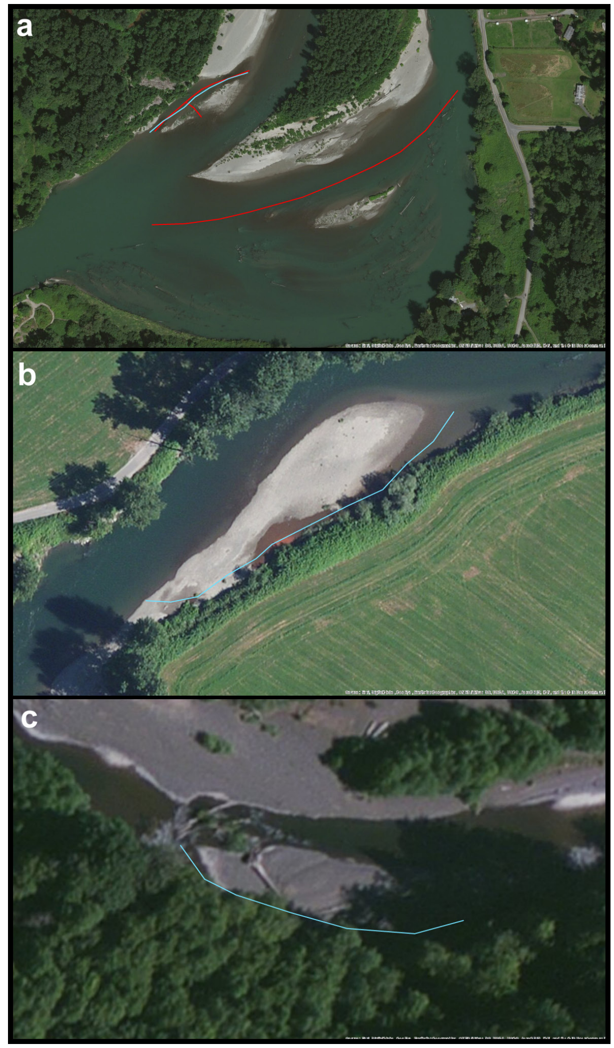


Figure 28. a) Braid length differences between observers within sample site 39. Observer 1 is marked in red. b) Braid length differences between observers within sample site 73. Observer 2 is marked in light blue. c) Braid length differences between observers within sample site 116. Observer 2 is marked in light blue.

We anticipate that more detailed instruction in how to identify and digitize backwaters may improve the repeatability of this metric. In particular, the protocols will better define and illustrate how to identify a backwater unit, and also provide more detailed instruction guiding observers to digitize only the visible portions of the backwater unit and not to include estimated areas beneath tree canopy. The revised protocols are in Appendix D.

There were also differences between observers in braid length (Figure 27). A difference of 178 m/km was observed within sample site 39, where the first observer identified the feature as a braid (Figure 28a). Within sample site 73, the second observer identified the feature as a braid while the first observer did not, resulting in a difference of 140 m/km in length (Figure 28b). Similarly, within sample site 116, only the first observer identified the feature as a braid, creating a difference of 200 m/km (Figure 28c).

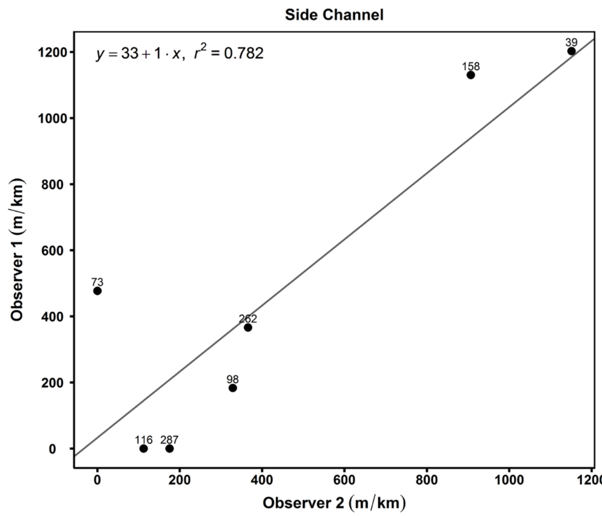


Figure 29. Side channel length in each sample location, normalized between two observers.

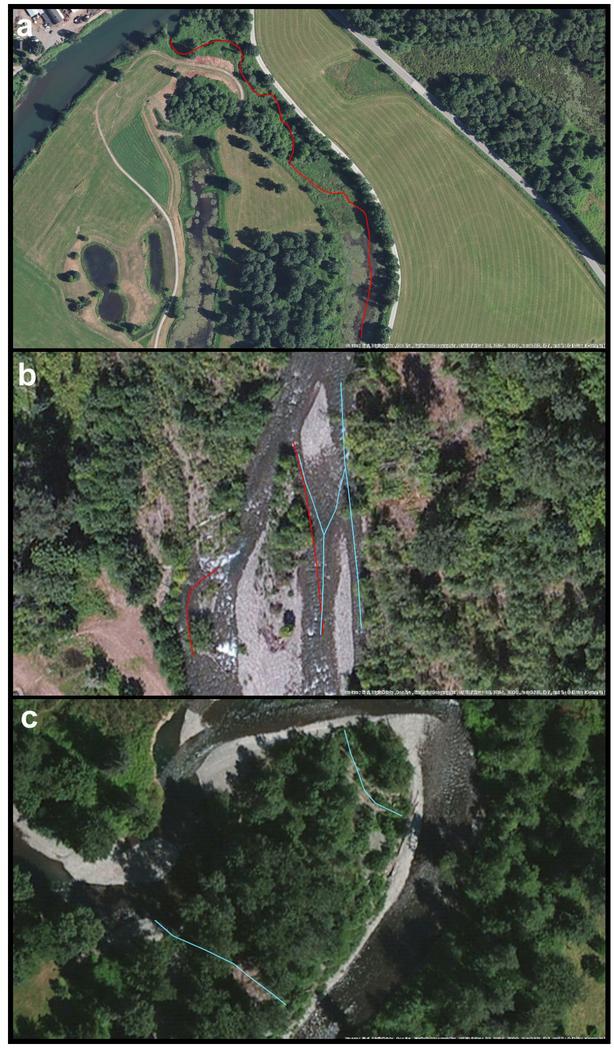


Figure 30. a) Side channel length differences between observers within sample site 73. Observer 1 is marked in red, Observer 2 is marked in light blue. b) Side channel length differences between observers within sample site 158. Observer 2 is marked in light blue. c) Side channel length differences between observers within sample site 287. Observer 2 is marked in light blue.

Relatively large differences between observers were also identified in side channel length within sample sites 73, 158, and 287 (Figure 29). At sample site 73, the first observer (marked in light blue) identified the feature as a side channel, while the second observer did not, creating a difference of 477 m/km (Figure 30a). Within sample site 158, Observer 1 identified all of the features as side channel, while Observer 2 identified a different set of features as side channel, generating a difference of 224 m/km (Figure 30b). Within sample site 287, a difference of 175 m/km (Figure 30c) occurred because Observer 2 identified the features in question as a side channel while the first did not.

To improve the repeatability of braid and side channel length measurements, we revised the protocols to include more detailed criteria and thresholds for identifying and measuring braids or side channels (included in Appendix D). For example, we added the criterion that at least half of the channel length must be visible to be classified as a side channel, and also specified that the side channel or braid line

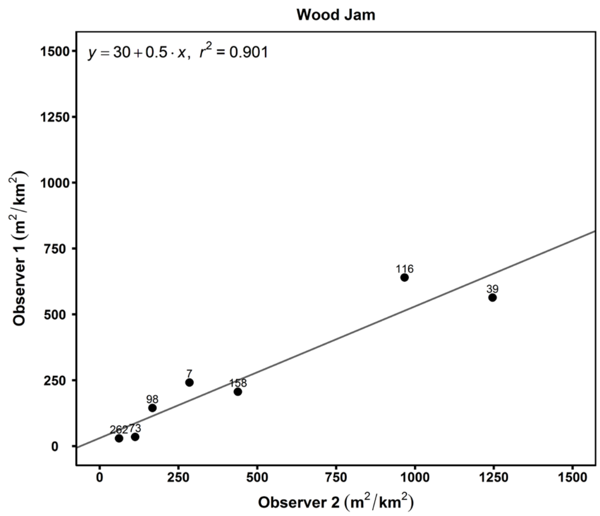


Figure 31. Wood jam area in each sample location, normalized between two observers.

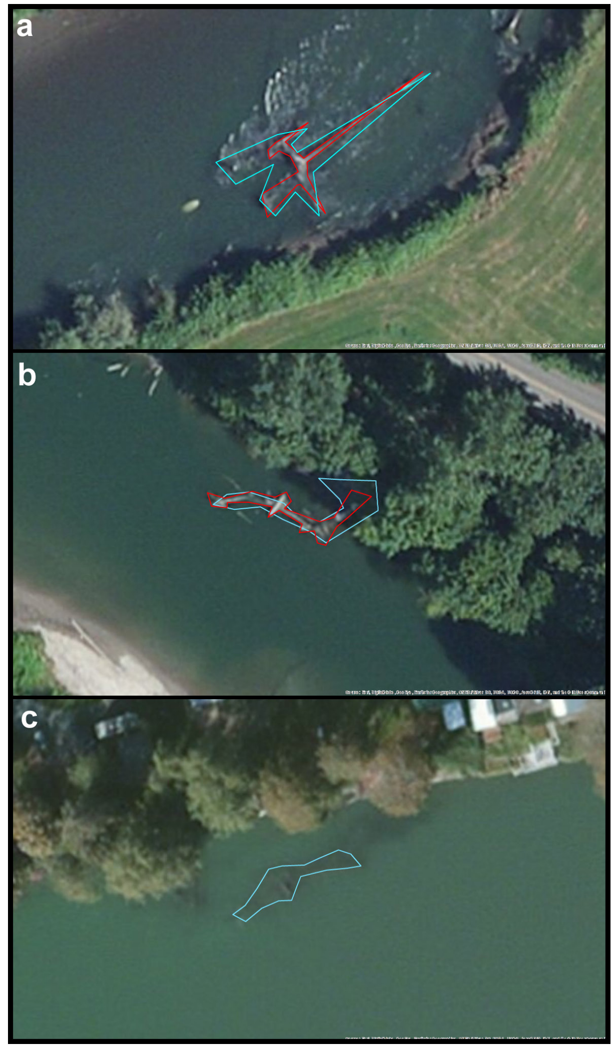


Figure 32. Wood jam measurement differences between observers. Observer 1 is red, Observer 2 is light blue.

ends at the edge habitat line (rather than connecting with the mainstem thalweg line). This improves the reliability of the number of channels identified and the length of channel that is digitized.

The two observers also frequently measured wood jams differently in our initial trials (Figure 31). The most common difference between observers was that one observer consistently measured a much larger feature area than the other (Figure 32). That is, in many cases the second observer estimated a much larger area for each wood jam than the first observer. To correct this problem, we revised the protocols to include a minimum jam area (50 m^2) for inclusion in the wood jam area measurement, and to specify the level of detail to which the wood jam was to be digitized. These revisions are included in the protocols in Appendix D. We also note that the digitized wood jam areas will be archived, so that new observers digitizing wood jam areas in the future can reference the prior polygons, and identify changes to wood jam areas based on the archived polygons and original aerial photography images. Moreover, while we expect edits to past digital records to be rare, the archived information also allows mapped polygons from prior years to be corrected (e.g., if a wood jam has been missed in the past, it can be added to the data record for that photo year).

3. Status of Habitat and Riparian Areas by MPG

Despite the fact that observer variation can be high for some of our metrics, we summarized the status of each of our metrics by steelhead MPG to evaluate whether they would be useful for quantifying differences among MPGs. We chose steelhead MPGs for this analysis because our first year of sampling did not have enough sample sites in the Chinook MPGs for Hood Canal, Georgia Strait, and Strait of Juan de Fuca (which are smaller MPGs). For each metric, a single observer measured all sites, so observer variation will not affect the results of this analysis. Here, we report on the large river and floodplain metrics collected from satellite or aerial photography data (there were not enough field sample sites in each MPG to analyze field data by MPG). We then report the delta metrics collected from satellite or aerial photography data. At this time, we have not yet completed any of the nearshore metrics from remote sensing data, nor the nearshore or delta metrics from field data.

Large River and Floodplain Metrics

In this section, we report on the results for land-cover status, percent forest and percent developed land cover, proportion of disconnected floodplain, riparian buffer width, sinuosity, edge habitat length by type, braid and side channel lengths, braid and side channel node densities, backwater area, and wood jam area.

Land-cover status on floodplains

The South-Central Cascades MPG has the greatest percentage (28%) of developed lands, and the lowest percentage (10%) of agriculture (Figure 33). The greatest proportion of lands assigned to the forest/wetland stratum is within the Olympic MPG (51%). The Northern Cascades MPG contains the lowest percentage of developed land cover (10%) and the highest of agriculture (39%).

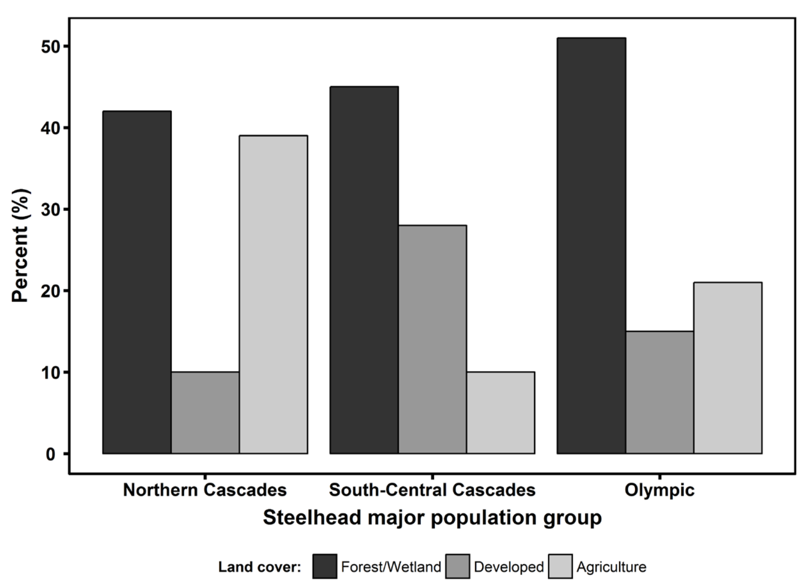


Figure 33. Proportion of land-cover type by MPG in all sampleable floodplains in Puget Sound.

Percent forest and percent developed land-cover on floodplains

Percent forest is highest in Olympic for both C-CAP (32%) and NAIP (37%) data (Figure 34). Northern Cascades has the least land cover categorized as forest by both C-CAP and NAIP datasets (26% and 27%, respectively). For developed land cover, the highest values were in South-Central Cascades (23% for C-CAP and 16% for NAIP). The lowest values for developed land cover were in Northern Cascades (14% for C-CAP and 7% for NAIP).

Percent developed land cover differed between C-CAP and NAIP datasets, especially in South-Central Cascades, which has the largest proportion of developed land cover. This is consistent with the finding that C-CAP tends to overestimate, and NAIP to underestimate, developed land cover. As expected, higher values for percent forest were found within Olympic. While the Olympic MPG is the smallest in area (176,323,791 m^2), proportionately it has more forest within the floodplain boundaries (Figure 34). Likewise, we expected percent developed to be highest in South-Central Cascades, which has the largest proportion of developed land cover (Figure 33). Percent forest and percent developed were both lowest in Northern Cascades, likely due to the higher proportion of agriculture lands (Figure 33).

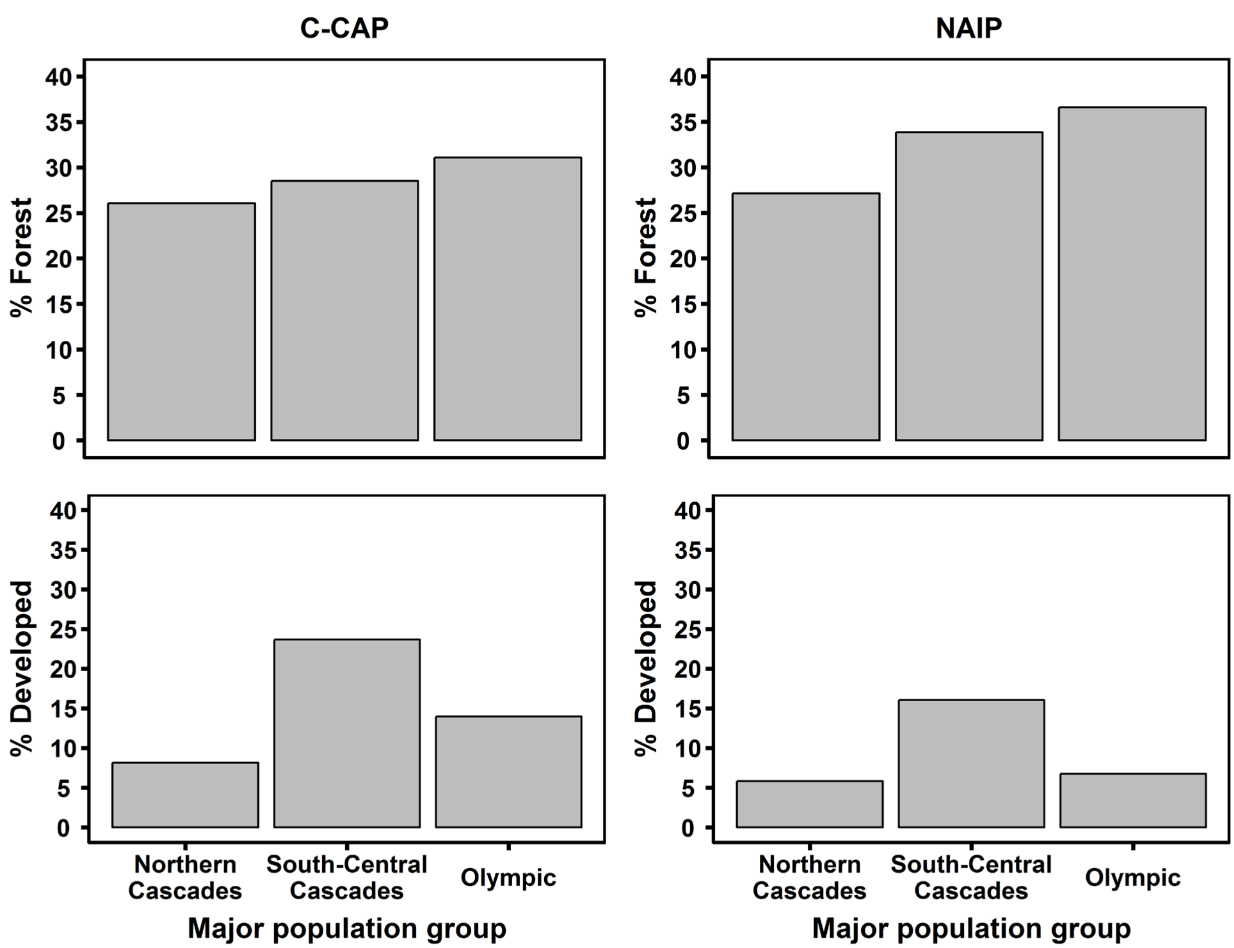


Figure 34. Percent forest and percent developed land cover in Puget Sound floodplains by steelhead MPG.

Riparian buffer width

The average buffer width was the greatest in Olympic (85 ± 11.7 m), where there are more forest/wetland sites. Conversely, in South-Central Cascades, where there are more developed sites, the average buffer width was the lowest, at 51 ± 12 m (Figure 35). The average buffer width within Northern Cascades is 72 ± 7.6 m.

Proportion of disconnected floodplain

The mean proportion of disconnected floodplain was similar among MPGs, but varied among sample sites within MPGs (Figure 36a). The highest was observed in South-Central Cascades (17% ± 9%), while the lowest was observed in Olympic (12% ± 17%). Within South-Central Cascades, the highest mean proportion of disconnected floodplain was observed in the developed land-cover stratum and glacial valley type (67% ± 18%), while the lowest occurred in the forest land-cover stratum and mountain valley type (0%). The highest mean proportion of disconnected floodplain in Olympic was 80% ± 57%, observed in the agriculture land-cover stratum and post-glacial valley type (Figure 36b). In contrast, the lowest mean proportion of disconnected floodplain (0%) was observed in the forest/wetland land-cover stratum and mountain valley type.

Sinuosity

Sinuosity varied little among MPGs (Figure 37a), especially in mountain valleys where sinuosities were consistently near 1.0 (Figure 37b). Mean sinuosity was near 1.5 in some land-cover strata within the glacial and post-glacial valley types. However, landcover classes with high sinuosity were not consistent among valley types or MPGs.

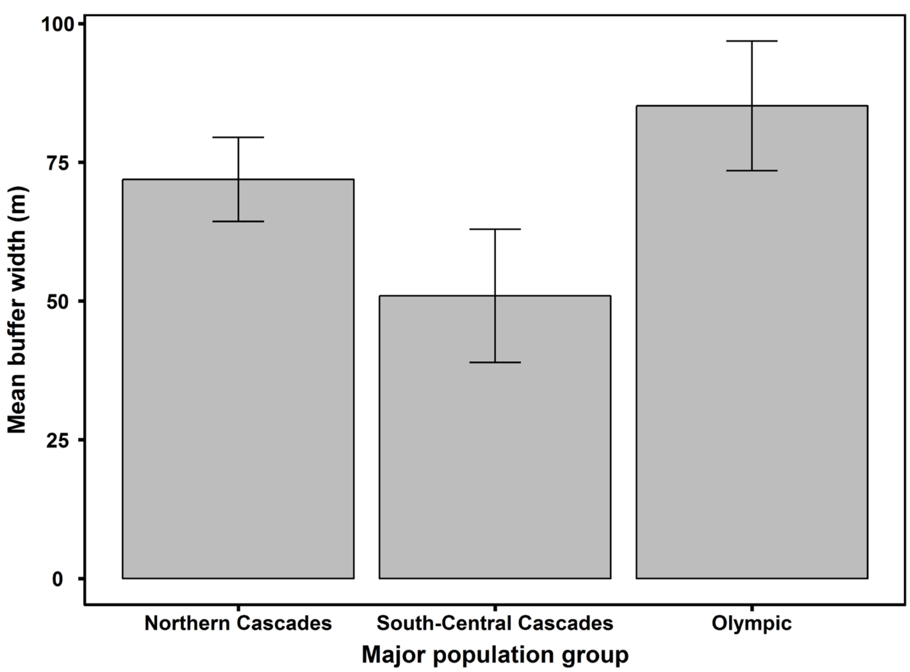


Figure 35. Mean buffer width along Puget Sound large rivers at 124 sites by steelhead MPG. Error bars indicate 95% confidence intervals.

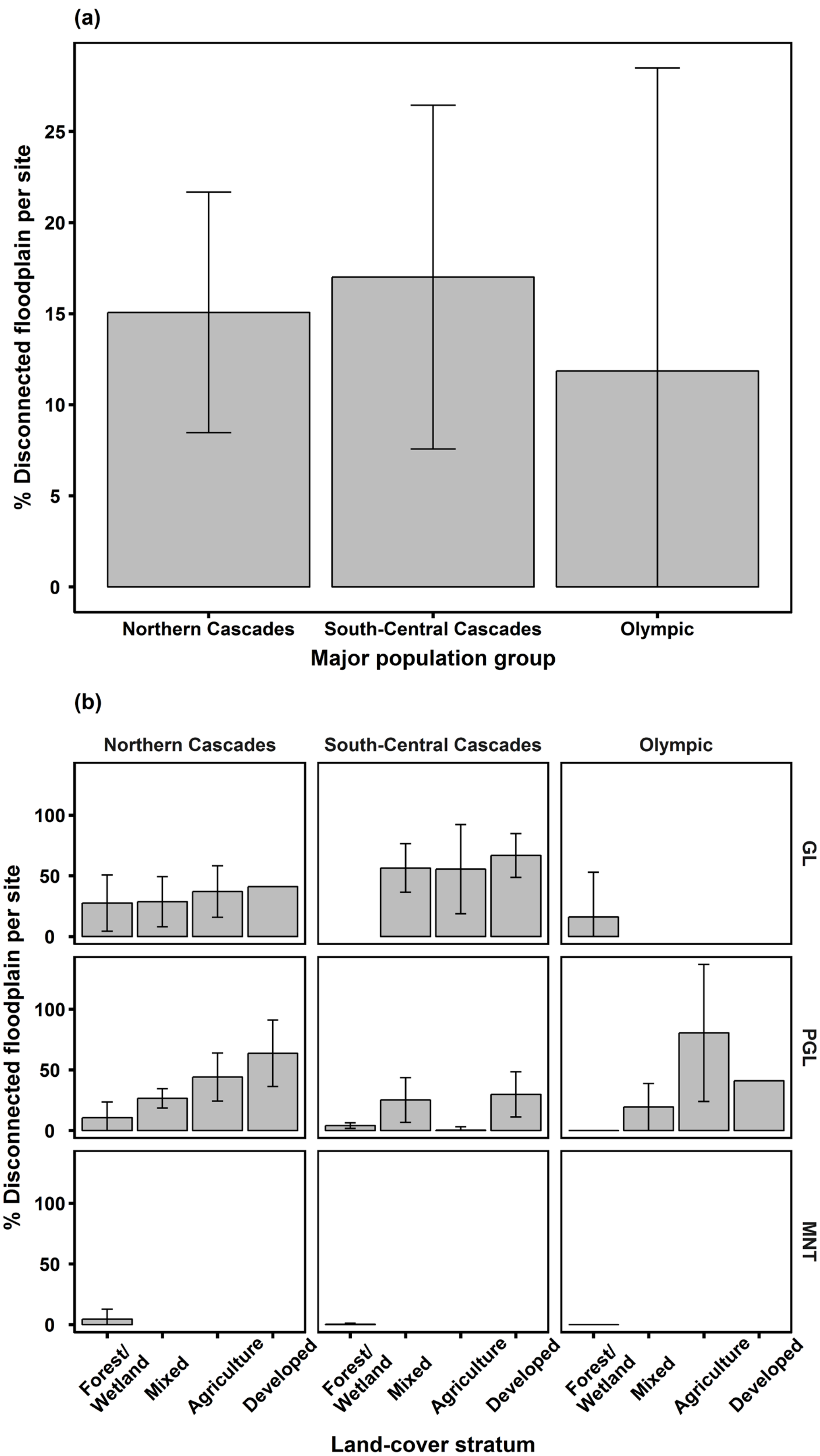


Figure 36. a) Mean proportion of disconnected floodplain aggregated by Northern Cascades, South-Central Cascades, and Olympic steelhead MPGs. b) Mean proportion of disconnected floodplain within steelhead MPGs aggregated by forest/wetland, agriculture, developed, and mixed land-cover strata, and by glacial, post-glacial, and mountain valley types. Error bars indicate 95% confidence intervals.

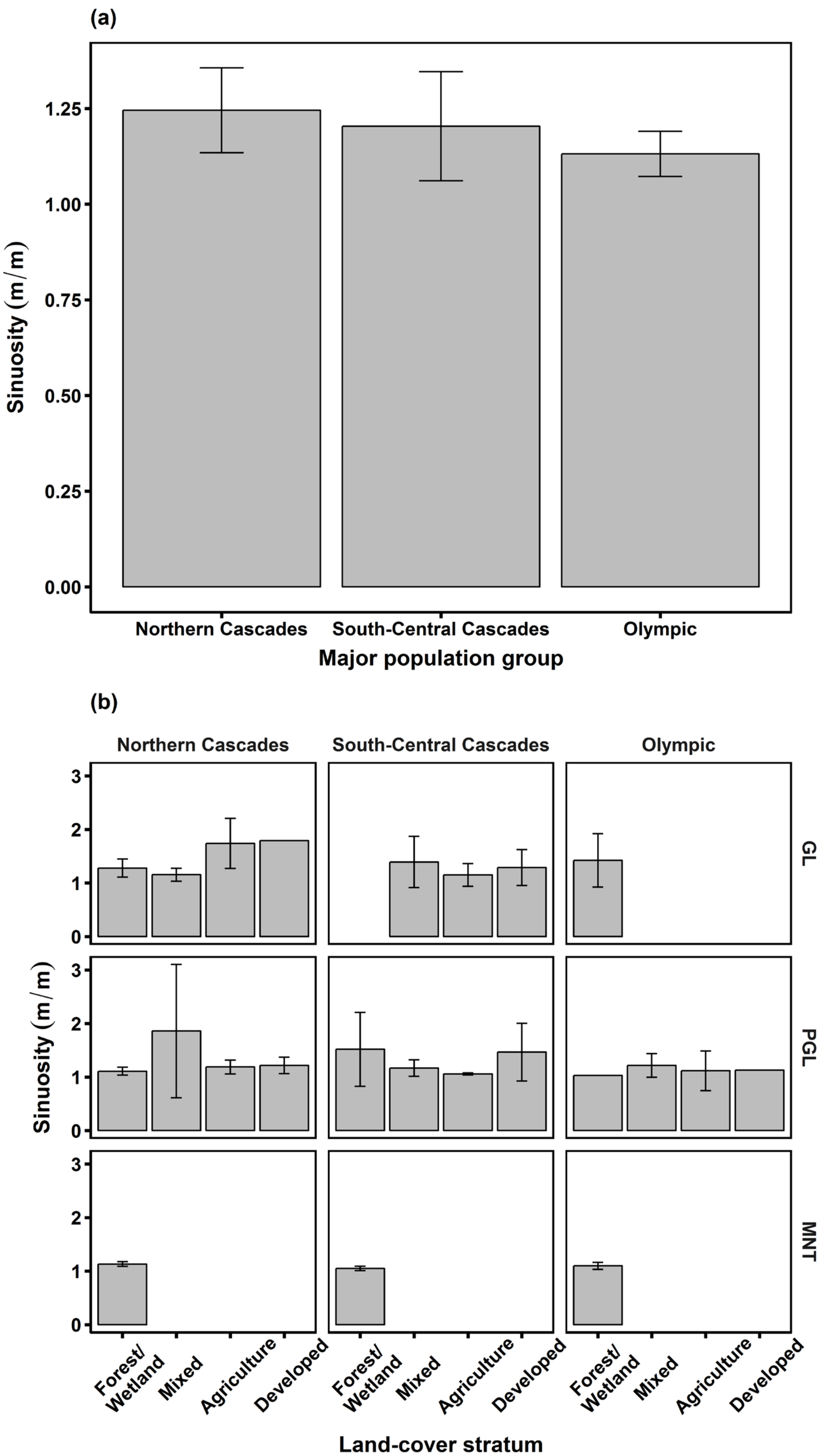


Figure 37. a) Mean sinuosity aggregated by Northern Cascades, South-Central Cascades, and Olympic steelhead MPGs. b) Mean sinuosity within steelhead MPGs aggregated by forest/wetland, agriculture, developed, and mixed land-cover strata, and by glacial, post-glacial, and mountain valley types. Error bars indicate 95% confidence intervals.

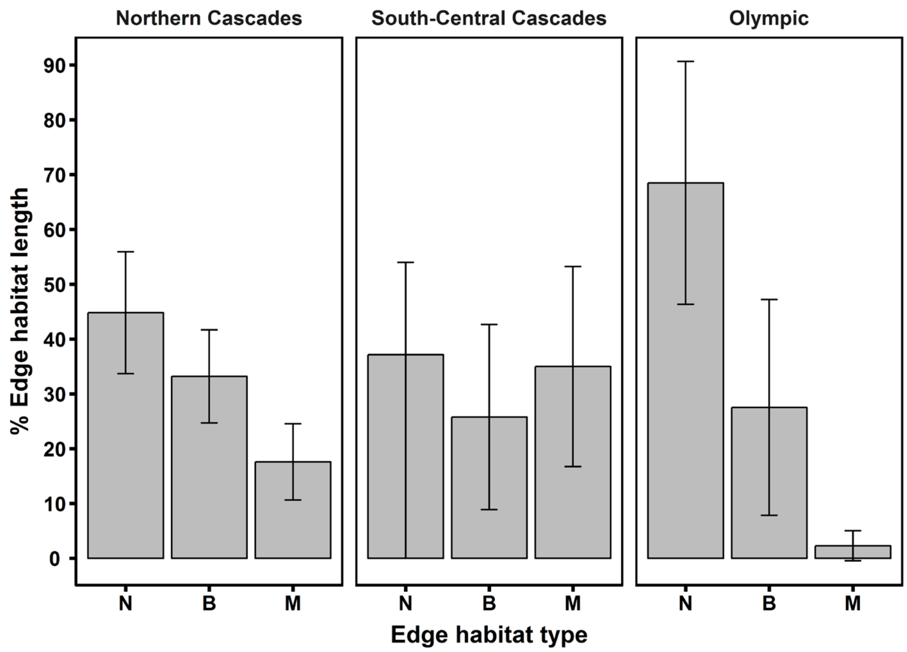


Figure 38. Mean proportion of natural bank (N), bar (B), or modified bank (M) edge length aggregated by Northern Cascades, South-Central Cascades, and Olympic steelhead MPGs. Error bars indicate 95% confidence intervals.

Edge habitat length by type

Habitat edge length by bank type varied considerably among steelhead MPGs and among sample sites within MPGs (Figure 38). The mean proportion of natural bank edge length was greatest in Olympic, at 68% ± 22%, and least in South-Central Cascades (37% ± 17%). Conversely, the mean proportion of modified bank edge length ranged from 2% ± 3% in Olympic to 35% ± 18% in South-Central Cascades. The mean proportion of bar edge habitat was similar between all MPGs, ranging between 26% ± 17% in South-Central Cascades and 33% ± 9% in Northern Cascades.

Within Northern Cascades, the proportion of modified bank edge was highest (70–79%) in developed areas and lowest (4–15%) in forested areas (Figure 39). The highest mean proportion of modified bank edge length was observed in the developed land-cover stratum and post-glacial valley type (79% ± 36%), and the lowest in the forest/wetland land-cover stratum and mountain valley type (4% ± 6%). The highest mean proportion of bar edge was observed in the forest/wetland land-cover stratum and glacial valley type (49% ± 11%), and the lowest in the developed land-cover stratum and post-glacial valley type (6% ± 7%). The highest mean proportion of natural bank edge length occurred in the forest/wetland land-cover stratum and mountain valley type (68% ± 25%).

Within South-Central Cascades, modified bank edge length was consistently high (58–83%) in the agriculture, developed, and mixed land-cover strata, but relatively low (0–27%) in forest/wetland (Figure 40). The highest mean proportion of modified bank edge length was observed in the developed land-cover stratum and glacial valley type (85% ± 12%), and the lowest mean proportion of modified bank edge length was observed in the forest/wetland land-

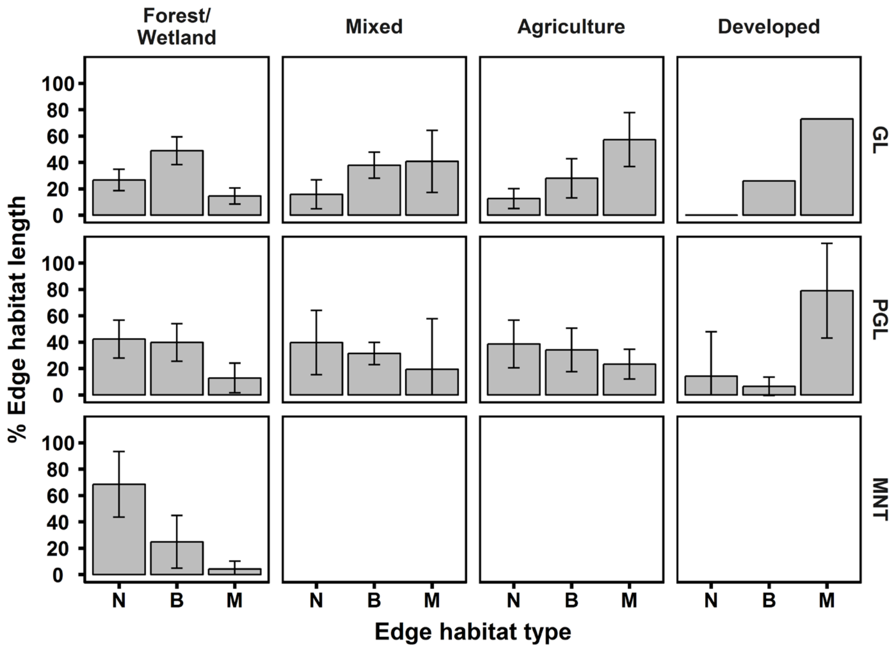


Figure 39. Mean proportion of natural bank (N), bar (B), or modified bank (M) edge length within the Northern Cascades MPG aggregated by forest/wetland, agriculture, developed, and mixed land-cover strata, and by glacial, post-glacial, and mountain valley types. Error bars indicate 95% confidence intervals. Very small (or zero) sample sizes are strata for which sample sites were few or did not exist. For example, there were no developed–glacial sites in this MPG.

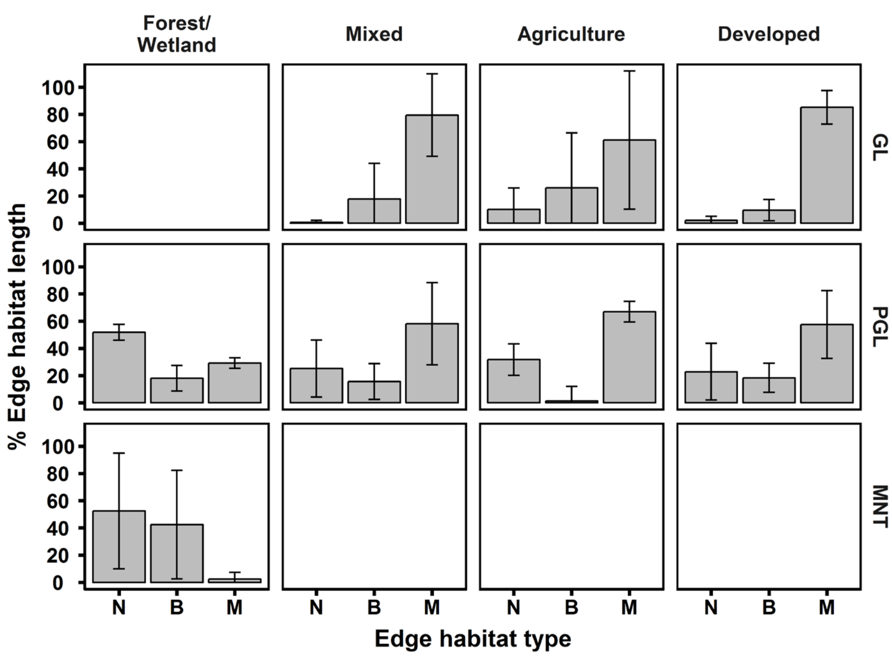


Figure 40. Mean proportion of natural bank (N), bar (B), or modified bank (M) edge length within the South-Central Cascades MPG aggregated by forest/wetland, agriculture, developed, and mixed land-cover strata, and by glacial, post-glacial, and mountain valley types. Error bars indicate 95% confidence intervals.

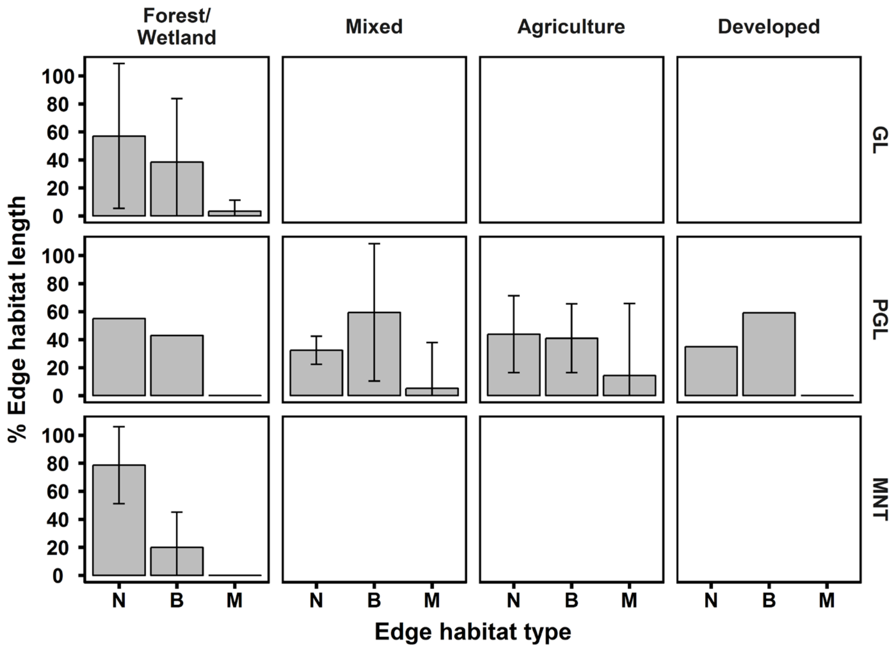


Figure 41. Mean proportion of natural bank (N), bar (B), or modified bank (M)edge length within the Olympic MPG aggregated by forest/wetland, agriculture, developed, and mixed land-cover strata, and by glacial, post-glacial, and mountain valley types. Error bars indicate 95% confidence intervals.

cover stratum and mountain valley type (2% ± 5%). The highest mean proportion of bar edge was observed in the forest/wetland land-cover stratum and mountain valley type (42% ± 40%), while the lowest was observed in the agriculture land-cover stratum and post-glacial valley type (1% ± 11%). The highest mean proportion of natural bank edge length was again in the forest/wetland land-cover stratum but occurred in the post-glacial valley type (52% ± 6%). It was lowest in the mixed land-cover stratum and glacial valley type (1% ± 1%).

Within Olympic, the proportion of modified bank edge was consistently low (0–14%) in all strata and valley types (Figure 41). The highest mean proportion of modified bank edge length was in the agriculture land-cover stratum and post-glacial valley type (14% ± 51%), whereas the lowest was in the forest/wetland land-cover stratum and mountain valley type (0%). The highest mean proportion of bar edge was observed in the mixed land-cover stratum and post-glacial valley type (59% ± 49%), while the lowest was observed in the forest/wetland land-cover stratum and mountain valley type (20% ± 25%). The highest mean proportion of natural bank edge length occurred in the forest/wetland land-cover stratum and mountain valley type (79% ± 27%), while the lowest was found in the mixed land-cover stratum and post-glacial valley type (32% ± 10%).

Braid length

The mean braid length was similar across MPGs (Figure 42a), although there was considerable variation among valley types and land-cover strata within MPGs (Figure 42b). However, no land-cover stratum or valley type was consistently high or low relative to the others.

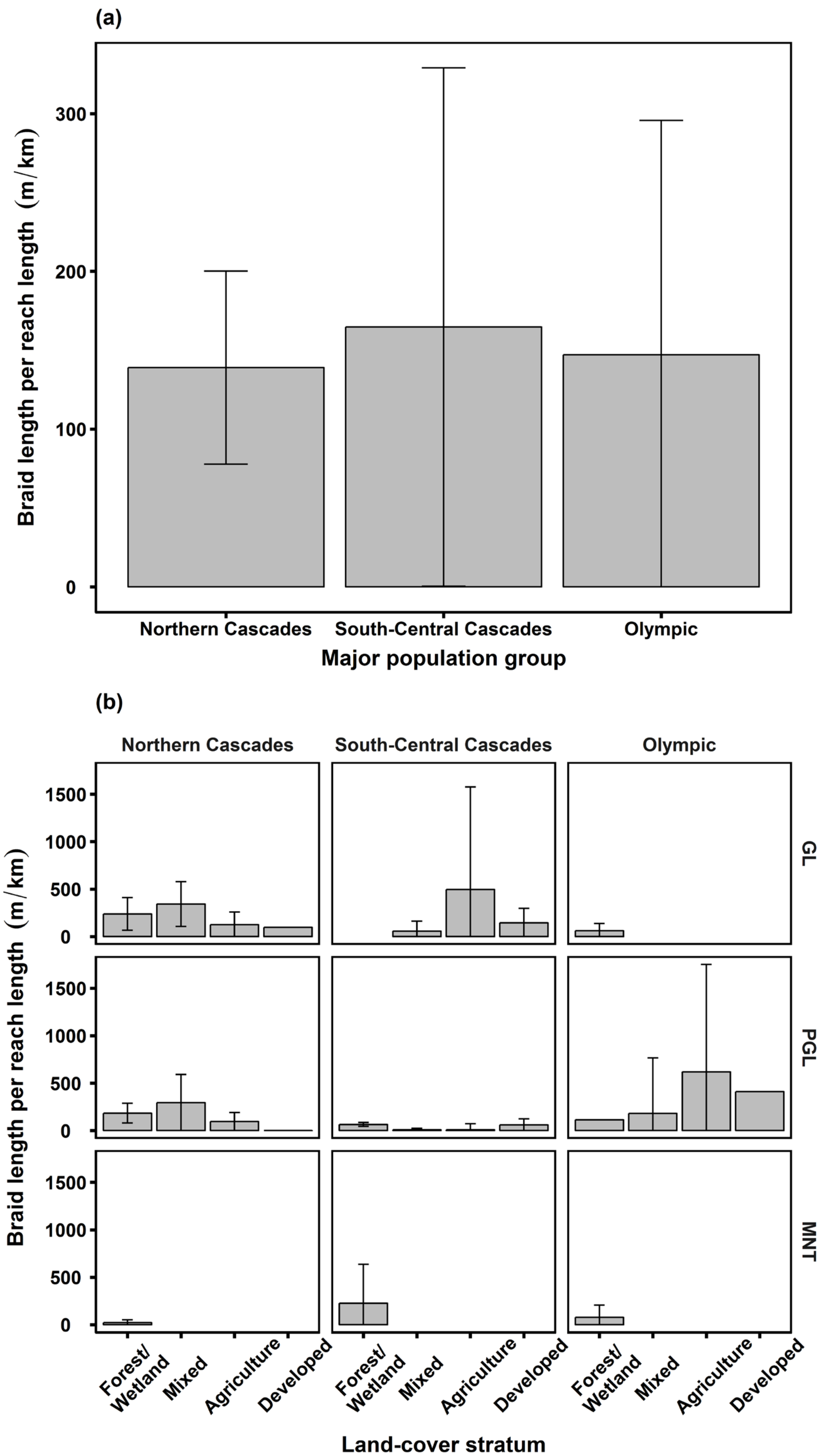


Figure 42. a) Mean braid length aggregated by Northern Cascades, South-Central Cascades, and Olympic steelhead MPGs. b) Mean braid length within steelhead MPGs aggregated by forest/wetland, agriculture, developed, and mixed land-cover strata, and by glacial, post-glacial, and mountain valley types. Error bars indicate 95% confidence intervals.

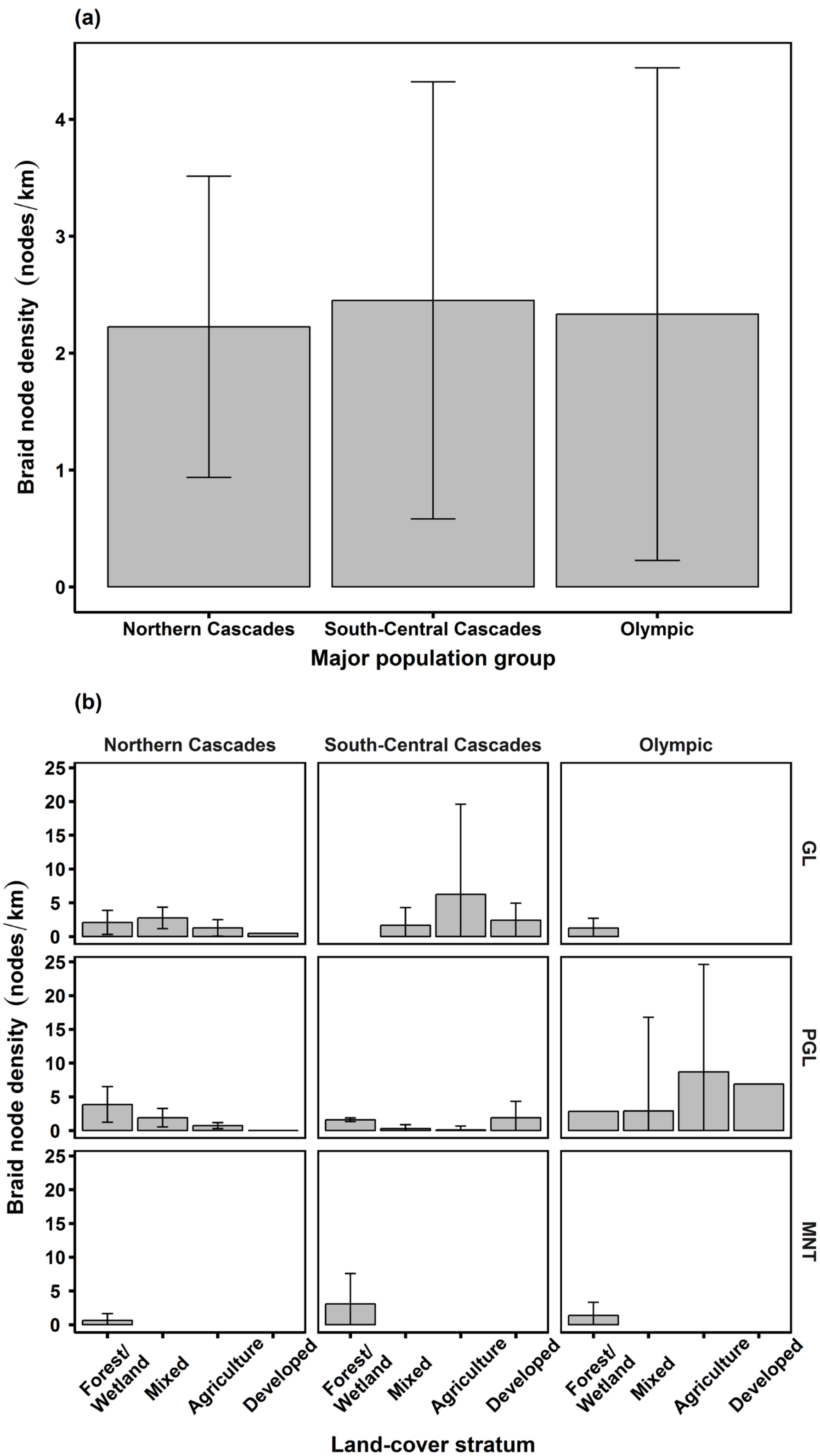


Figure 43. a) Mean braid node density aggregated by Northern Cascades, South-Central Cascades, and Olympic steelhead MPGs. b) Mean braid node density within steelhead MPGs aggregated by forest/ wetland, agriculture, developed, and mixed land-cover strata, and by glacial, post-glacial, and mountain valley types. Error bars indicate 95% confidence intervals.

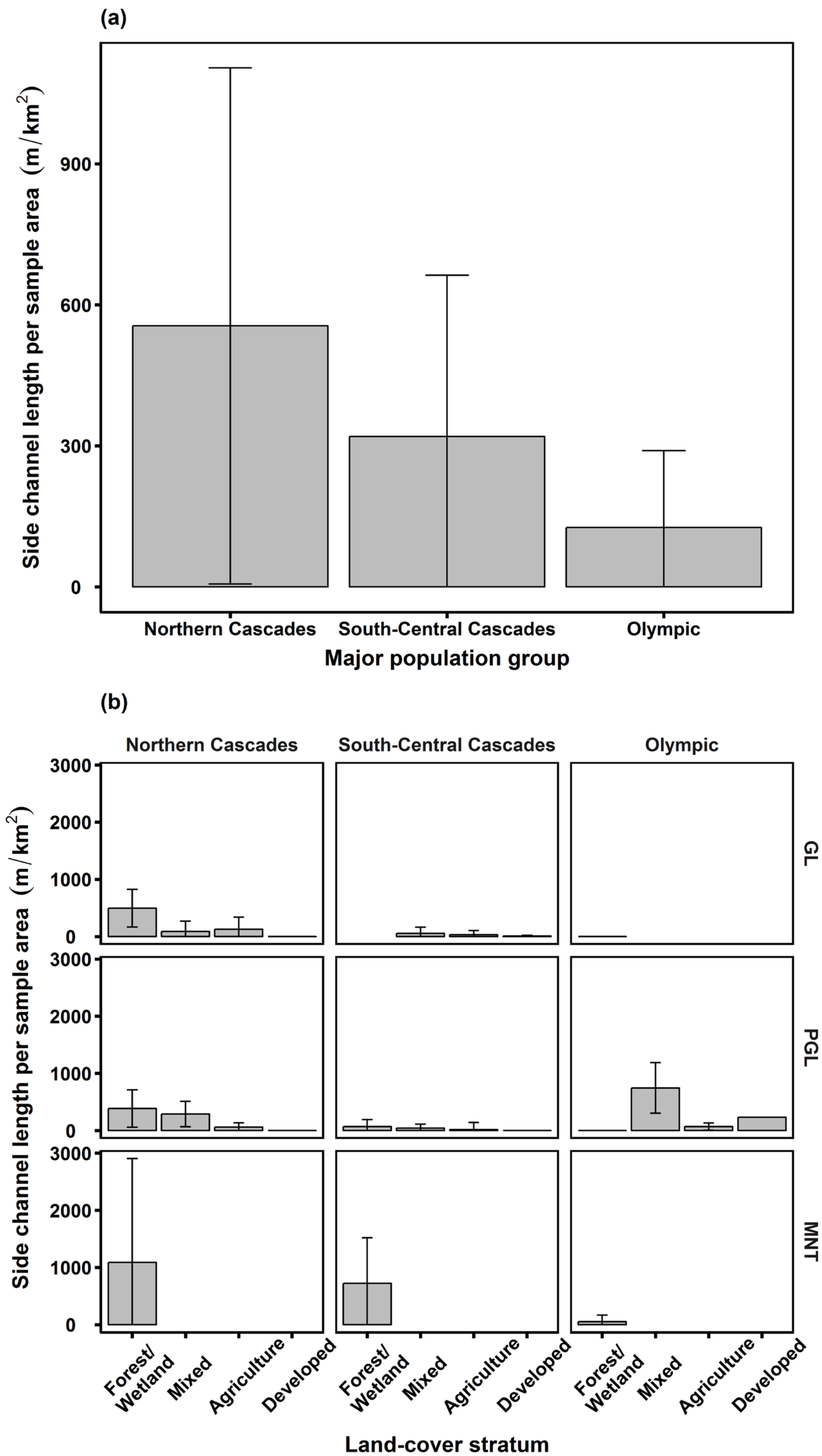


Figure 44. a) Mean side channel length aggregated by Northern Cascades, South-Central Cascades, and Olympic steelhead MPGs. b) Mean side channel length within steelhead MPGs aggregated by forest/wetland, agriculture, developed, and mixed land-cover strata, and by glacial, post-glacial, and mountain valley types. Error bars indicate 95% confidence intervals.

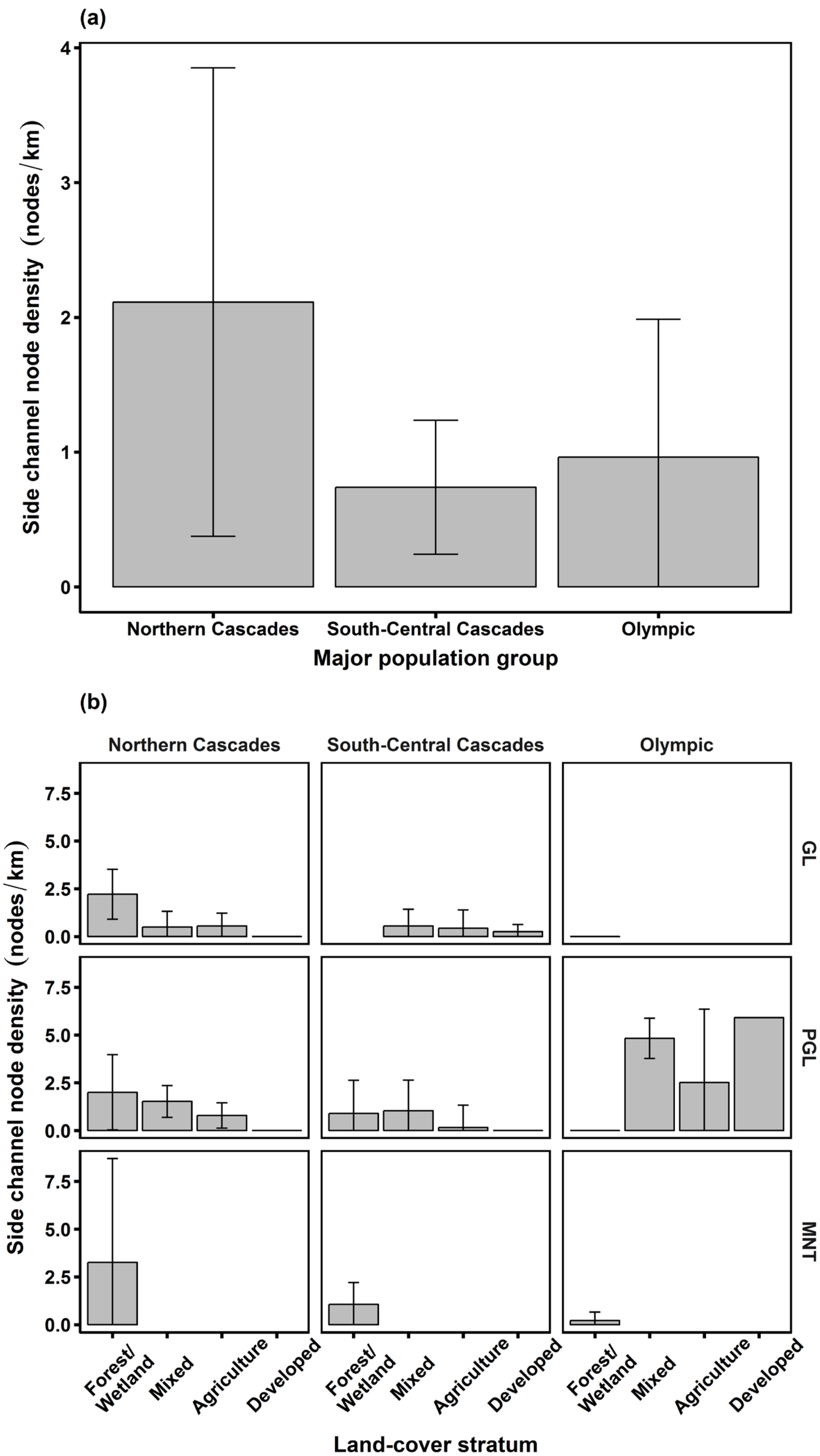


Figure 45. a) Mean side channel node density aggregated by Northern Cascades, South-Central Cascades, and Olympic steelhead MPGs. b) Mean side channel node density within steelhead MPGs aggregated by forest/wetland, agriculture, developed, and mixed land-cover strata, and by glacial, post-glacial, and mountain valley types. Error bars indicate 95% confidence intervals.

Braid node density

The mean braid node density was similar among all MPGs, ranging from 2.2 nodes/km (± 1.3 nodes/km) in Northern Cascades, to 2.4 ± 1.9 nodes/km in South-Central Cascades (Figure 43a). Within Northern Cascades, the highest mean braid density (3.9 ± 2.6 nodes/km) was observed in the forest/wetland land-cover stratum and post-glacial valley type, and the lowest (0 nodes/km) in the developed land-cover stratum and post-glacial valley type (Figure 43b). Mean braid density in South Central Cascades ranged from 0.3 ± 0.6 nodes/km in the developed land-cover stratum and post-glacial valley type, to 6.2 ± 13.3 nodes/km in the agriculture land-cover stratum and glacial valley type.

Side channel length

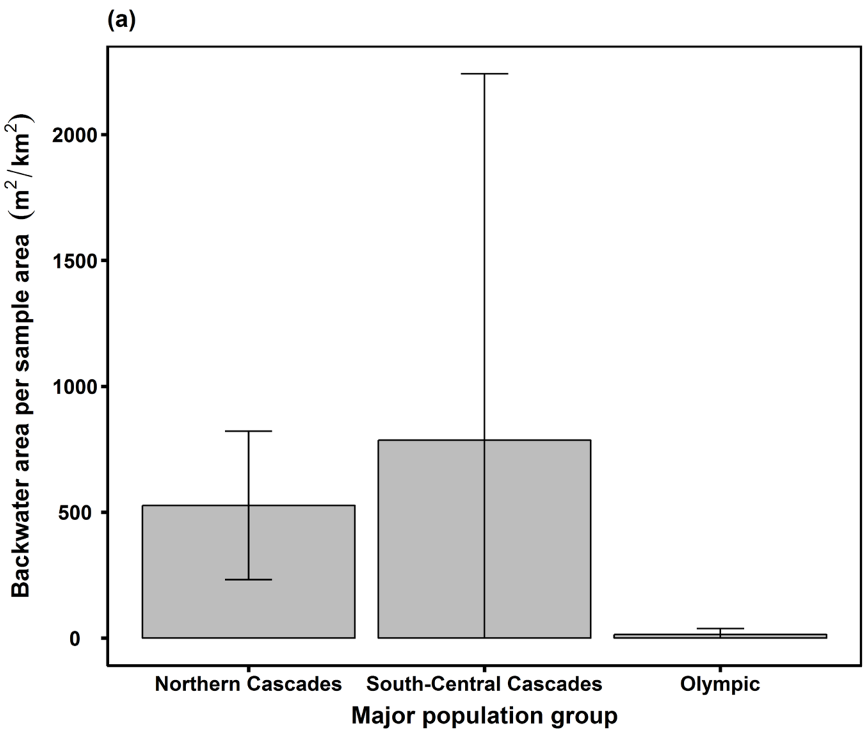
Mean side channel length per sample reach area varied considerably between MPGs, and among sample sites within MPGs. Mean side channel length ranged from a low of 126 ± 163 m/km^2 in Olympic to a high of 555 ± 549 m/km^2 in Northern Cascades (Figure 44a). Within Olympic (Figure 44b), the highest mean side channel length was observed in the mixed land-cover stratum and post-glacial valley type (746 ± 442 m/km^2), while the lowest was in the forest/wetland land-cover stratum and glacial valley type (0 m/km^2). Northern Cascades had its highest mean side channel length in the forest/wetland land-cover stratum in mountain valleys (1,088 ± 1,819 m/km^2) and its lowest in the developed land-cover stratum within the post-glacial valley type.

Side channel node density

Mean side channel node density varied both among MPGs and among sample sites within MPGs. The lowest density (0.7 ± 0.5 nodes/km) occurred in South-Central Cascades, and the highest (2.1 ± 1.7 nodes/km) in Northern Cascades (Figure 45a). Within South-Central Cascades, the highest mean side channel node density (1.1 ± 1.1 nodes/km) was observed in the forest/wetland land-cover stratum and mountain valley type, and the lowest (0 nodes/km) in the developed land-cover stratum and post-glacial valley type (Figure 45b). Conversely, within Northern Cascades, mean side channel node density ranged from 0 nodes/km in the developed land-cover stratum and post-glacial valley type, to 3.3 ± 5.4 nodes/km in the forest/wetland land-cover stratum and mountain valley type. Further, within Olympic, the highest mean side channel node density was observed in the agriculture land-cover stratum and post-glacial valley type (8.69 ± 15.9 nodes/km), and the lowest in the forest/wetland land-cover stratum and glacial valley type (1.2 ± 1.5 nodes/km).

Backwater area

In Olympic, backwater area per square kilometer of active channel (Figure 46a) was very low (near zero) relative to Northern Cascades (500 m^2/km^2) and South-Central Cascades (750 m^2/km^2). The highest mean backwater area (2,000 m^2/km$^{2)}$ was in the forest/wetland land-cover stratum and glacial valley type in Northern Cascades, and most of the other land-cover stratum–valley-type combinations with high backwater areas were also in the Northern Cascades MPG (Figure 46b). In South-Central Cascades, all land-cover stratum–valley-type combinations had low backwater areas, with the exception of the forest/wetland stratum in post-glacial valleys (~1,800 m^2/km^2).



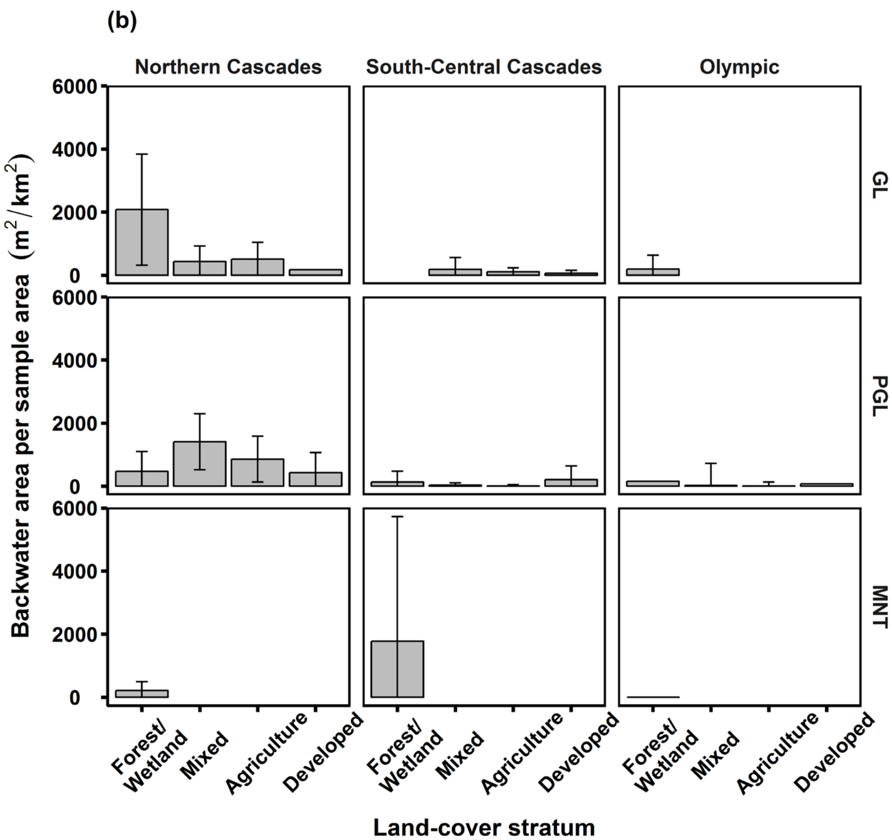


Figure 46. a) Mean normalized backwater area aggregated by Northern Cascades, South-Central Cascades, and Olympic steelhead MPGs. b) Mean normalized backwater area within steelhead MPGs aggregated by forest/wetland, agriculture, developed, and mixed land-cover strata, and by glacial, post-glacial, and mountain valley types. Error bars indicate 95% confidence intervals.

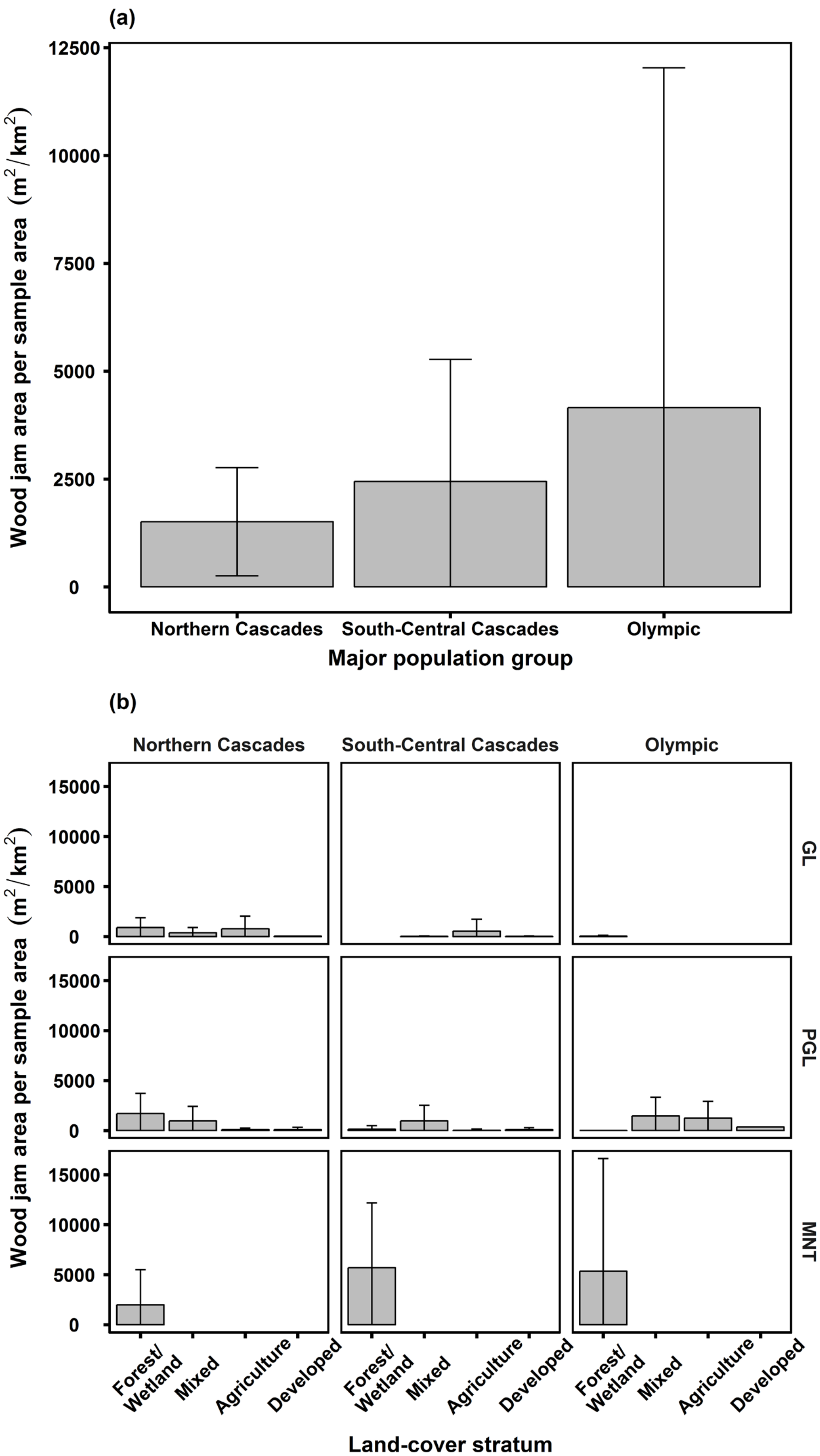


Figure 47. a) Mean normalized wood jam area aggregated by Northern Cascades, South-Central Cascades, and Olympic steelhead MPGs. b) Mean normalized wood jam area within steelhead MPGs aggregated by forest/wetland, agriculture, developed, and mixed land-cover strata, and by glacial, post-glacial, and mountain valley types. Error bars indicate 95% confidence intervals.

Wood jam area

The highest mean wood jam area per sample reach (4,152 ± 7,879 m^2/km^2) was observed in Olympic, and the lowest (1,509 ± 1,252 m^2/km^2) in Northern Cascades (Figure 47a). Within Northern Cascades, the highest mean wood jam area per sample reach (1,989 ± 3,493 m^2/km^2) was observed in the forest/wetland land-cover stratum and mountain valley type, and the lowest (99 ± 232 m^2/km^2) in the developed land-cover stratum and post-glacial valley type (Figure 47b). In all three MPGs, the highest wood jam area was in the forest/wetland land-cover stratum and mountain valley type.

Delta Metrics

In this section, we report on the results for percent forest and percent developed land cover; tidal channel area, edge habitat, and length; and node density in the 16 deltas of Puget Sound.

Table 15. Percent land-cover type by delta and MPG (steelhead MPGs = Northern Cascades, South-Central Cascades, Olympic; Chinook salmon MPGs = Strait of Georgia, Whidbey Basin, Central/South Basin, Hood Canal, Strait of Juan de Fuca) for all 16 major Puget Sound deltas (NKS = Nooksack, SKG = Skagit, SAM = Samish, STL = Stillaguamish, SNH = Snohomish, DUW = Duwamish, PUY = Puyallup, NSQ = Nisqually, DES = Deschutes, SKO = Skokomish, HAM = Hamma Hamma, DOS = Dosewallips, DUC = Duckabush, QUL = Big Quilcene, DUN = Dungeness, ELW = Elwha).

MPG, Delta	% Forest/wetland	% Agriculture	% Developed
Northern Cascades	**51.5**	**40.0**	**8.5**
Strait of Georgia	**53.6**	**41.1**	**5.4**
NKS	53.6	41.1	5.4
Whidbey Basin	**51.2**	**39.9**	**9.0**
SKG	49.3	45.0	5.8
SAM	48.4	47.9	3.6
STL	60.9	33.0	6.1
SNH	49.2	33.9	16.9
South-Central Cascades	**33.5**	**0.4**	**66.1**
Central/South Basin	**33.5**	**0.4**	**66.1**
DUW	6.8	0.0	93.2
PUY	7.9	0.2	91.9
NSQ	93.9	1.3	4.8
DES	39.0	0.0	61.0
Olympic	**89.1**	**5.7**	**5.3**
Hood Canal	**92.7**	**3.5**	**3.8**
SKO	95.6	2.2	2.2
HAM	96.2	1.8	2.0
DOS	90.2	0.6	9.2
DUC	92.0	0.0	8.0
QUL	86.0	10.9	3.1
Strait of Juan de Fuca	**78.0**	**12.4**	**9.6**
DUN	77.0	12.7	10.2
ELW	86.0	10.1	3.9
Total	**51.6**	**32.5**	**15.9**

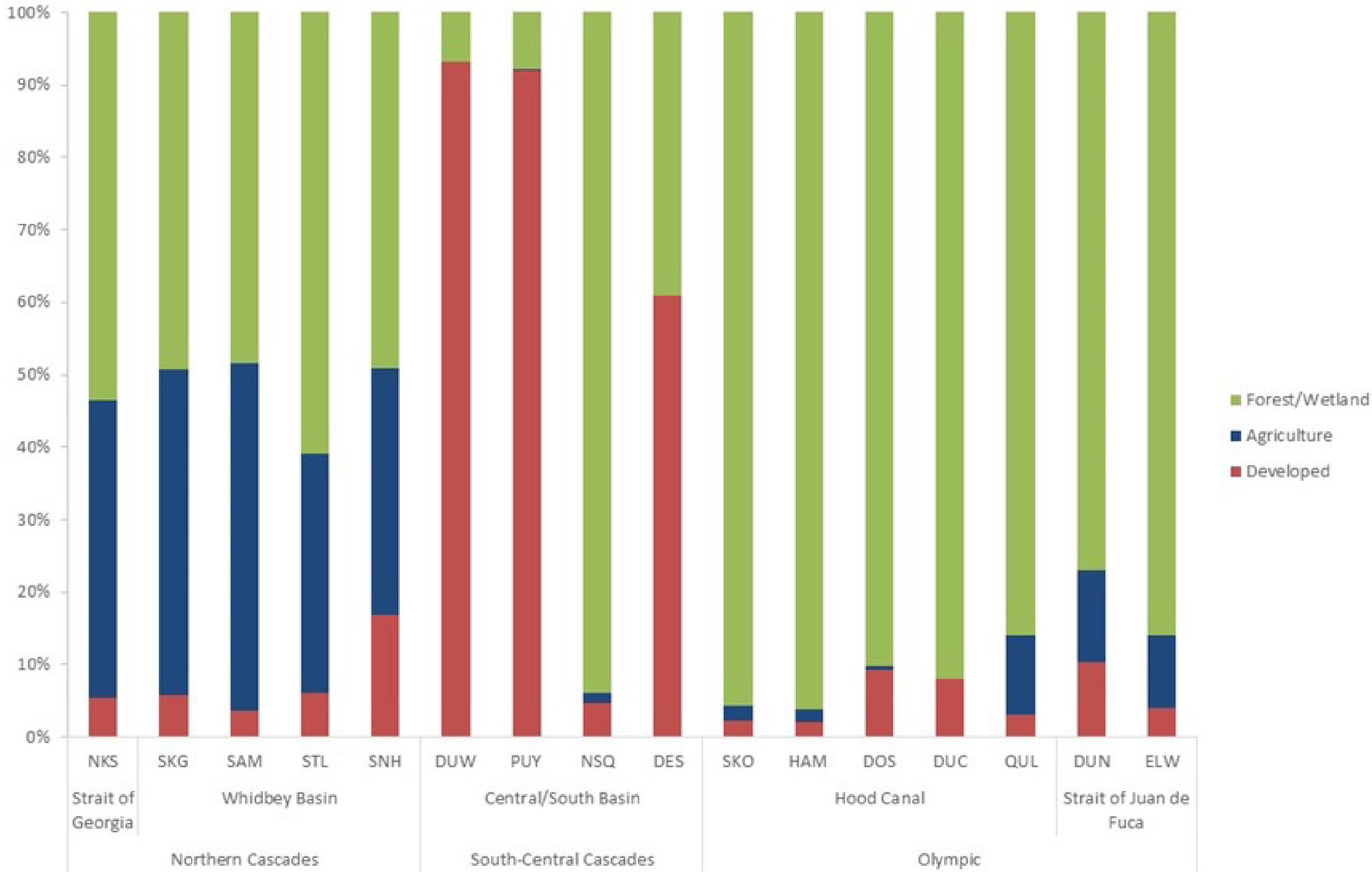


Figure 48. Percent forest/wetland, agriculture, and developed land cover by delta and MPG (steelhead MPGs = Northern Cascades, South-Central Cascades, and Olympic; Chinook MPGs = Strait of Georgia, Whidbey Basin, Central/South Basin, Hood Canal, and Strait of Juan de Fuca) for all 16 major Puget Sound deltas (NKS = Nooksack, SKG = Skagit, SAM = Samish, STL = Stillaguamish, SNH = Snohomish, DUW = Duwamish, PUY = Puyallup, NSQ = Nisqually, DES = Deschutes, SKO = Skokomish, HAM = Hamma Hamma, DOS = Dosewallips, DUC = Duckabush, QUL = Big Quilcene, DUN = Dungeness, ELW = Elwha).

Percent developed and percent forest land cover

The Central/South Basin Chinook MPG and the South-Central Cascades steelhead MPG have the most developed deltas in Puget Sound (Table 15, Figure 48), with the Duwamish and Puyallup deltas being over 90% urban. All other Chinook and steelhead MPGs are primarily forested, with the Olympic steelhead MPG and the nested Strait of Juan de Fuca and Hood Canal Chinook MPGs having over 75% forested land cover. Agricultural land cover is most prevalent in the Northern Cascades steelhead MPG and the nested Strait of Georgia and Whidbey Basin Chinook MPGs, with about 40% agricultural land cover occurring within the Northern Cascades steelhead MPG.

Tidal channel area

The Northern Cascades steelhead MPG has the greatest amount of tidal channel habitat by area, with nearly 2.5 times more tidal channel area than South-Central Cascades and 15 times more than Olympic (Table 16, Figure 49). In Northern Cascades deltas, tidal channel habitat area is primarily dominated by distributary channels (primary and bifurcations combined), with distributaries representing just 58% of tidal channel habitat area. In contrast, distributary channels account for only 18% and 33.9% of tidal channel habitat area in Olympic and South-Central Cascades deltas, respectively. Tidal channels and tidal complex habitat account for a majority of the tidal channel habitat area in Olympic deltas, with 58% of tidal channel habitat being tidal channels and tidal complex habitat. In South-Central Cascades, tidal flats and industrial channel features account for the largest proportion of total channel area relative to other MPGs, with these features accounting for 31% and 24% of total channel area, respectively. Tidal flats in South-Central Cascades are noticeably inflated, however, by the Nisqually delta, where recent restoration projects have created large areas of tidally flooded habitat whose channel features and vegetation have not developed sufficiently to delineate channel flow paths within the delta.

The proportion of forested cover within each delta has a strong positive relationship with the ratio of tidal channel to distributary channel lengths (Figure 50). Deltas with less than 60% forested cover had less tidal channel habitat by length relative to distributary channel habitat, while deltas with more than 60% forested cover had more tidal channel habitat relative to distributary channel length. This suggests that the conversion of forest/wetland to developed or agricultural land-cover types is accompanied by a loss of tidal channel habitat.

Table 16. Area (in hectares) of channel features by delta and MPG (steelhead MPGs = Northern Cascades, South-Central Cascades, Olympic, Chinook salmon MPGs = Strait of Georgia, Whidbey Basin, Central/South Basin, Hood Canal, Strait of Juan de Fuca) for all 16 major Puget Sound deltas (NKS = Nooksack, SKG = Skagit, SAM = Samish, STL = Stillaguamish, SNH = Snohomish, DUW = Duwamish, PUY = Puyallup, NSQ = Nisqually, DES = Deschutes, SKO = Skokomish, HAM = Hamma Hamma, DOS = Dosewallips, DUC = Duckabush, QUL = Big Quilcene, DUN = Dungeness, ELW = Elwha).

MPG, Delta	Primary distributary area (ha)	Distributary area (ha)	Tidal channel area (ha)	Tidal complex area (ha)	Tidal flat area (ha)	Industrial area (ha)	Total area (ha)
Northern Cascades	**1,210.6**	**2,202.4**	**435.4**	**2,143.2**	**1,065.9**	**78.8**	**7,136.4**
Strait of Georgia	**112.9**	**153.2**	**16.3**	**24.8**	**4.9**	**0.0**	**312.0**
NKS	112.9	153.2	16.3	24.8	4.9	0.0	312.0
Whidbey Basin	**1,097.7**	**2,049.3**	**419.2**	**2,118.5**	**1,061.0**	**78.8**	**6,824.4**
SKG	106.7	777.6	220.4	780.3	0.1	0.0	1,885.1
SAM	33.1	15.4	6.9	3.8	192.7	0.0	252.0
STL	107.1	231.1	65.5	939.7	0.0	0.0	1,343.4
SNH	850.9	1,025.1	126.4	394.7	868.1	78.8	3,344.0
South-Central Cascades	**489.7**	**442.8**	**222.2**	**99.8**	**890.8**	**687.2**	**2,832.5**
Central/South Basin	**489.7**	**442.8**	**222.2**	**99.8**	**890.8**	**687.2**	**2,832.5**
DUW	281.3	108.5	4.5	0.0	7.8	30.2	432.3
PUY	112.3	204.4	4.6	0.0	52.4	438.7	812.5
NSQ	49.8	129.9	210.9	95.3	617.7	0.0	1,103.6
DES	46.3	0.0	2.1	4.5	212.9	218.3	484.1
Olympic	**80.8**	**25.6**	**127.9**	**227.3**	**131.5**	**0.5**	**593.6**
Hood Canal	**67.6**	**25.1**	**114.9**	**227.3**	**115.4**	**0.5**	**550.8**
SKO	35.5	15.0	72.5	161.0	90.2	0.0	374.2
HAM	10.2	5.4	6.5	9.1	13.8	0.5	45.6
DOS	6.1	1.2	13.6	3.3	0.5	0.0	24.7
DUC	11.6	0.6	10.4	10.2	1.7	0.0	34.5
QUL	4.2	2.7	11.8	43.7	9.3	0.0	71.7
Strait of Juan de Fuca	**13.1**	**0.6**	**13.0**	**0.0**	**16.1**	**0.0**	**42.8**
DUN	7.1	0.6	7.8	0.0	6.8	0.0	22.4
ELW	6.0	0.0	5.1	0.0	9.3	0.0	20.4
Total	**1,781.1**	**2,670.9**	**785.5**	**2,470.3**	**2,088.2**	**766.5**	**10,562.4**

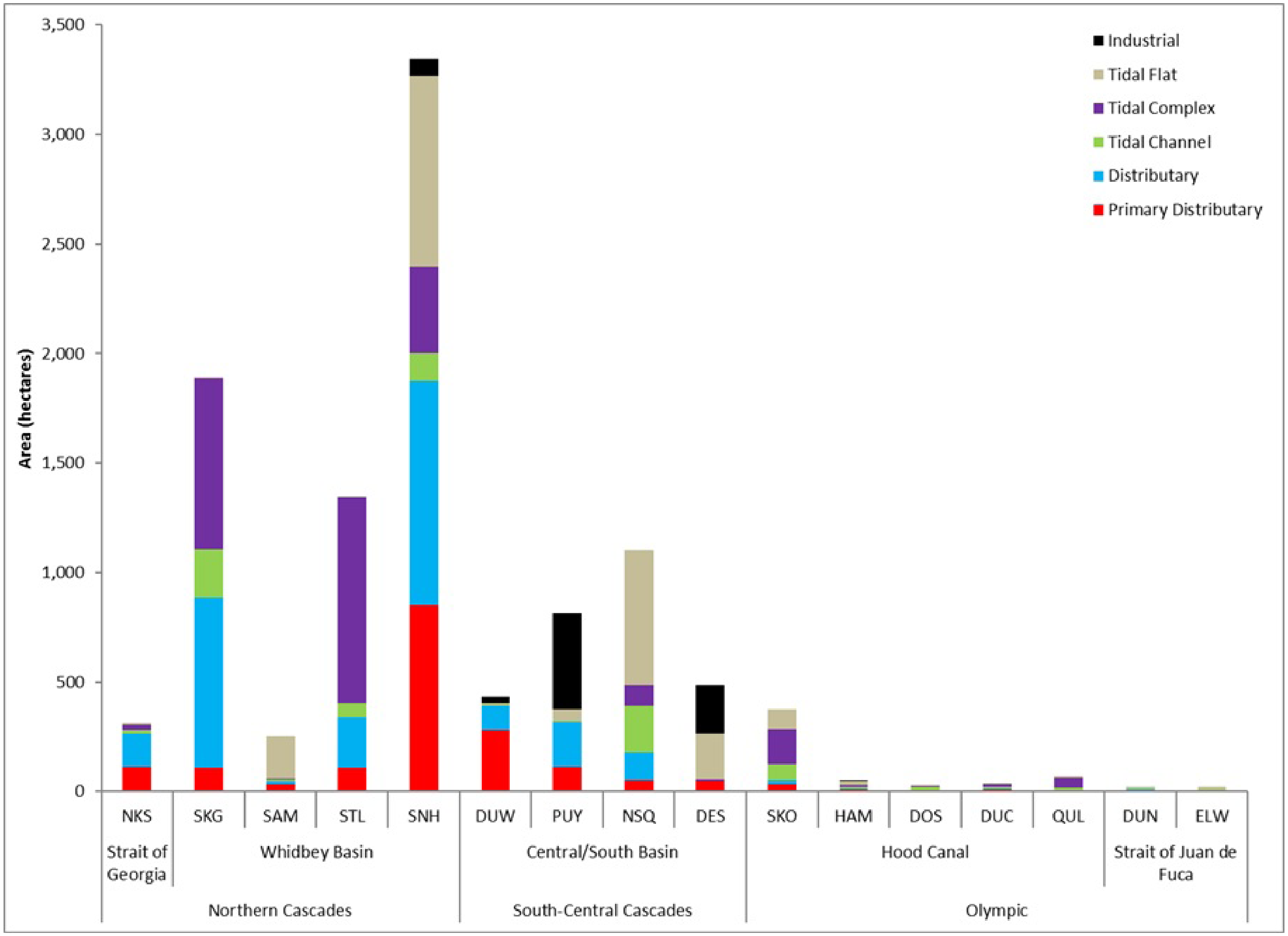


Figure 49. Area (in hectares) of channel features by delta and MPG (steelhead MPGs = Northern Cascades, South-Central Cascades, and Olympic; Chinook MPGs = Strait of Georgia, Whidbey Basin, Central/South Basin, Hood Canal, and Strait of Juan de Fuca) for all 16 major Puget Sound deltas (NKS = Nooksack, SKG = Skagit, SAM = Samish, STL = Stillaguamish, SNH = Snohomish, DUW = Duwamish, PUY = Puyallup, NSQ = Nisqually, DES = Deschutes, SKO = Skokomish, HAM = Hamma Hamma, DOS = Dosewallips, DUC = Duckabush, QUL = Big Quilcene, DUN = Dungeness, ELW = Elwha). Digitized areas included primary distributaries, distributaries, tidal channels, tidal complexes, tidal flats, and industrial waterways. Note that area estimates for tidal complexes and tidal flats are for the total area of the complex features, and do not account for channels narrower than 5 m occurring within the feature.

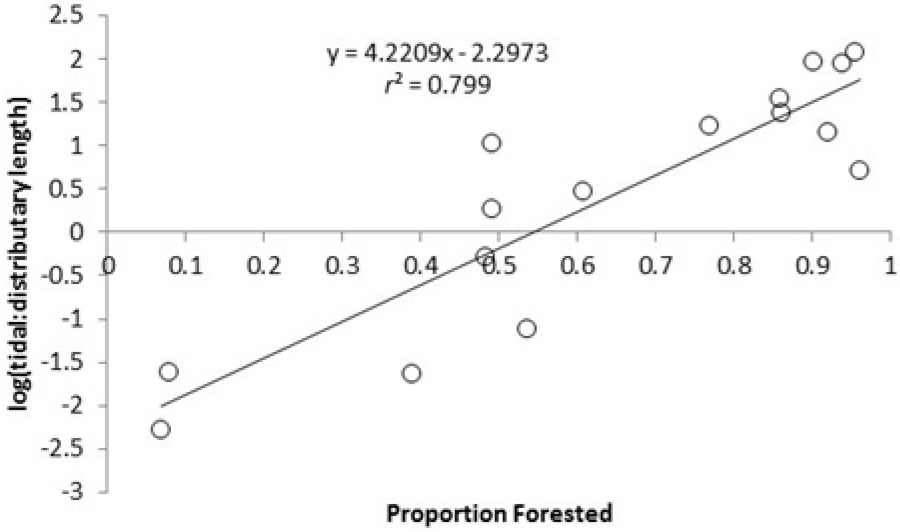


Figure 50. Proportion of forested land cover within a delta, log transformed ratio of tidal channel length to distributary length (primary distributary + distributary), and linear regression trend line. Log transformed ratios greater than 0 represent deltas with more tidal channel length than distributary length, while log transformed ratios less than 0 represent deltas with less tidal channel length than distributary length.

Tidal channel edge habitat

Tidal channel edge habitat, as derived from polygon perimeters, exhibit the same relative patterns in habitat quantity as tidal channel area (Table 17, Figure 51). However, tidal channel edge habitat and channel area estimates do show some differences when comparing deltas. For example, the Snohomish delta has more habitat by area than the Skagit delta, but the Skagit delta has more edge habitat. This indicates that there are many small channels in the Skagit delta and few large channels in the Snohomish. Given that juvenile salmonids are more likely to use the edges of tidal channel features as opposed to the middles of larger channels, use of edge habitat metrics may provide a more useful context to assess tidal channel habitat with respect to juvenile salmonids.

Tidal channel length

Tidal channel length in deltas, as derived from polygon center flow lines, is almost six times greater in Northern Cascades than Olympic, and over four times greater than South-Central Cascades (Table 18, Figure 52). Channel lengths are dominated by tidal channels in all MPGs, with tidal channels representing 62% of channel length in Northern Cascades, 70% in South-Central Cascades, and 84% in Olympic. However, the Nisqually delta is the only South-Central Cascades delta whose channel length is dominated by tidal channels. While the Nisqually delta channel length is 88% tidal channels, the Duwamish, Puyallup, and Deschutes delta channel lengths are only 9–17% tidal channels. After removing the Nisqually delta, the South-Central Cascades delta channel lengths are dominated by distributaries (71–91%).

Channel length provides a different perspective on relative habitat abundance within deltas than area-based estimates. This is particularly apparent in the Northern Cascades MPG deltas, where large distributary channels provide significant contributions to habitat area, but numerous small tidal channels provide more edge and channel length compared to distributaries.

Table 17. Perimeter (in kilometers) of channel features by delta and MPG (steelhead MPGs = Northern Cascades, South-Central Cascades, Olympic, Chinook salmon MPGs = Strait of Georgia, Whidbey Basin, Central/South Basin, Hood Canal, Strait of Juan de Fuca) for all 16 major Puget Sound deltas (NKS = Nooksack, SKG = Skagit, SAM = Samish, STL = Stillaguamish, SNH = Snohomish, DUW = Duwamish, PUY = Puyallup, NSQ = Nisqually, DES = Deschutes, SKO = Skokomish, HAM = Hamma Hamma, DOS = Dosewallips, DUC = Duckabush, QUL = Big Quilcene, DUN = Dungeness, ELW = Elwha).

MPG, Delta	Primary distributary perimeter (km)	Distributary perimeter (km)	Tidal channel perimeter (km)	Tidal complex perimeter (km)	Tidal flat perimeter (km)	Industrial perimeter (km)	Total perimeter (km)
Northern Cascades	**125.4**	**427.3**	**1,231.9**	**361.8**	**127.6**	**7.5**	**2,281.5**
Strait of Georgia	**22.1**	**64.4**	**33.1**	**9.6**	**2.2**	**0.0**	**131.5**
NKS	22.1	64.4	33.1	9.6	2.2	0.0	131.5
Whidbey Basin	**103.3**	**362.9**	**1,198.7**	**352.2**	**125.3**	**7.5**	**2,150.0**
SKG	17.1	146.8	634.7	142.3	0.2	0.0	941.1
SAM	11.9	6.5	15.3	3.0	23.9	0.0	60.7
STL	11.9	63.1	155.6	122.2	0.0	0.0	352.9
SNH	62.5	146.4	393.1	84.6	101.2	7.5	795.3
South-Central Cascades	**53.6**	**47.5**	**262.6**	**52.9**	**138.1**	**53.2**	**607.9**
Central/South Basin	**53.6**	**47.5**	**262.6**	**52.9**	**138.1**	**53.2**	**607.9**
DUW	21.6	8.0	4.8	0.0	4.0	9.1	47.5
PUY	11.7	17.6	7.5	0.0	13.9	34.1	84.7
NSQ	8.9	21.9	247.8	51.0	98.1	0.0	427.6
DES	11.5	0.0	2.5	1.9	22.1	10.0	48.1
Olympic	**28.0**	**16.0**	**237.7**	**98.5**	**58.8**	**0.5**	**439.4**
Hood Canal	**22.5**	**15.1**	**214.7**	**98.5**	**53.6**	**0.5**	**404.9**
SKO	8.7	6.1	122.9	59.9	40.3	0.0	237.9
HAM	3.6	3.0	15.3	6.3	8.3	0.5	37.0
DOS	2.3	0.9	24.3	3.0	0.3	0.0	30.7
DUC	4.5	0.9	15.9	4.8	1.1	0.0	27.2
QUL	3.4	4.3	36.3	24.5	3.5	0.0	72.0
Strait of Juan de Fuca	**5.4**	**0.9**	**23.0**	**0.0**	**5.2**	**0.0**	**34.5**
DUN	3.8	0.9	17.0	0.0	3.5	0.0	25.3
ELW	1.6	0.0	6.0	0.0	1.6	0.0	9.2
Total	**207.0**	**490.8**	**1,732.2**	**513.2**	**324.4**	**61.2**	**3,328.8**

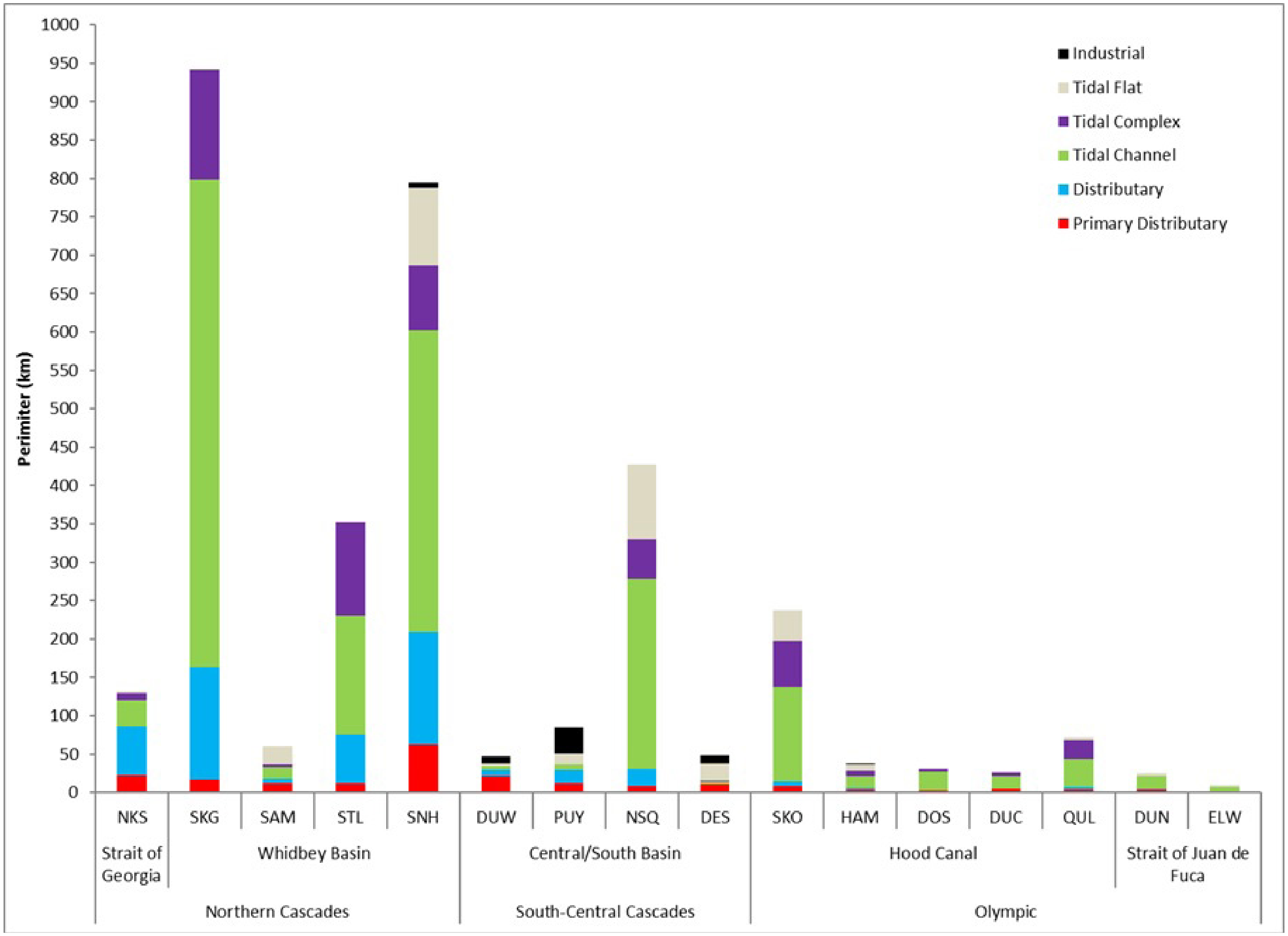


Figure 51. Perimeter of channel features by delta and MPG (steelhead MPGs = Northern Cascades, South-Central Cascades, Olympic; Chinook MPGs = Strait of Georgia, Whidbey Basin, Central/South Basin, Hood Canal, Strait of Juan de Fuca) for all 16 major Puget Sound deltas (NKS = Nooksack, SKG = Skagit, SAM = Samish, STL = Stillaguamish, SNH = Snohomish, DUW = Duwamish, PUY = Puyallup, NSQ = Nisqually, DES = Deschutes, SKO = Skokomish, HAM = Hamma Hamma, DOS = Dosewallips, DUC = Duckabush, QUL = Big Quilcene, DUN = Dungeness, ELW = Elwha). Digitized areas included primary distributaries, distributaries, tidal channels, tidal complexes, tidal flats, and industrial waterways. Note that perimeter estimates for tidal complexes and tidal flats are for the perimeter of the complex features and do not account for channels narrower than 5 m occurring within the feature.

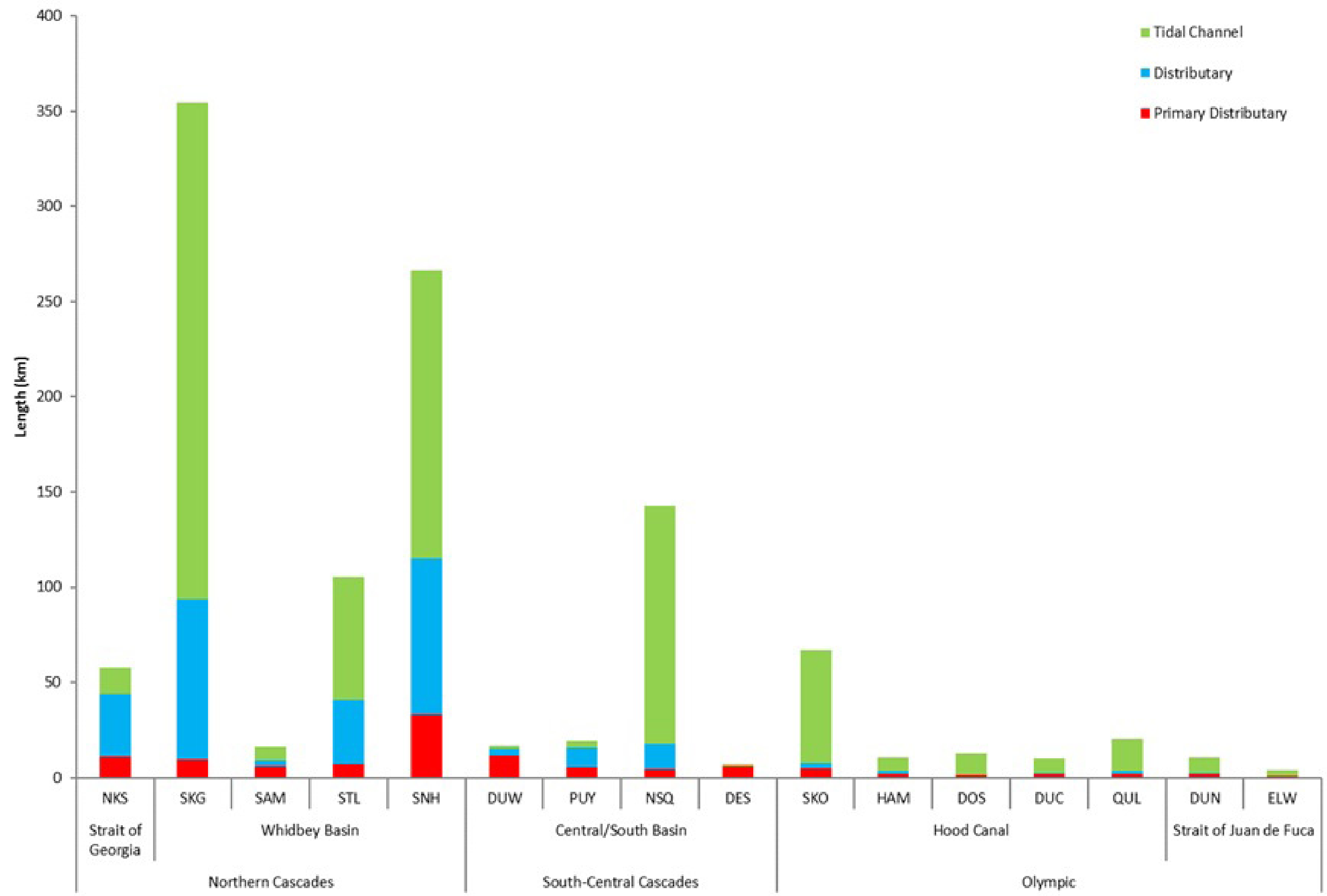


Figure 52. Length of channel features by delta and MPG (steelhead MPGs = Northern Cascades, South-Central Cascades, Olympic; Chinook salmon MPGs = Strait of Georgia, Whidbey Basin, Central/South Basin, Hood Canal, Strait of Juan de Fuca) for all 16 major Puget Sound deltas (NKS = Nooksack, SKG = Skagit, SAM = Samish, STL = Stillaguamish, SNH = Snohomish, DUW = Duwamish, PUY = Puyallup, NSQ = Nisqually, DES = Deschutes, SKO = Skokomish, HAM = Hamma Hamma, DOS = Dosewallips, DUC = Duckabush, QUL = Big Quilcene, DUN = Dungeness, ELW = Elwha). Small channels in tidal complexes and tidal flats less than 5 meters wide are not represented in these totals.

Table 18. Length of channel features, number of channel nodes (intersections of channel features), and channel node density relative to the total length of primary distributary channels by delta and MPG (steelhead MPGs = Northern Cascades, South-Central Cascades, Olympic; Chinook salmon MPGs = Strait of Georgia, Whidbey Basin, Central/South Basin, Hood Canal, Strait of Juan de Fuca) for all 16 major Puget Sound deltas (NKS = Nooksack, SKG = Skagit, SAM = Samish, STL = Stillaguamish, SNH = Snohomish, DUW = Duwamish, PUY = Puyallup, NSQ = Nisqually, DES = Deschutes, SKO = Skokomish, HAM = Hamma Hamma, DOS = Dosewallips, DUC = Duckabush, QUL = Big Quilcene, DUN = Dungeness, ELW = Elwha). Small channels in tidal complexes and tidal flats less than 5 m wide are not represented in these totals.

MPG, Delta	Primary distributary (km)	Distributary (km)	Tidal channel (km)	Total channel (km)	Channel nodes	Channel node density (nodes/km, primary)
Northern Cascades	**66.7**	**235.6**	**498.0**	**800.3**	**6,068**	**90.9**
Strait of Georgia	**11.1**	**32.5**	**14.2**	**57.9**	**224**	20.1
NKS	11.1	32.5	14.2	57.9	224	20.1
Whidbey Basin	**55.6**	**203.0**	**483.8**	**742.4**	**5,844**	**105.1**
SKG	9.5	84.2	260.7	354.4	2,971	312.7
SAM	6.0	3.2	6.9	16.0	105	17.6
STL	6.9	33.7	64.8	105.4	661	95.6
SNH	33.2	81.9	151.4	266.6	2,107	63.4
South-Central Cascades	**27.8**	**26.9**	**130.7**	**185.4**	**1,738**	**62.6**
Central/South Basin	**27.8**	**26.9**	**130.7**	**185.4**	**1,738**	**62.6**
DUW	11.7	3.5	1.5	16.7	28	2.4
PUY	5.6	10.3	3.2	19.1	69	12.4
NSQ	4.7	13.1	124.9	142.6	1,617	347.0
DES	5.9	0.0	1.1	7.0	24	4.1
Olympic	**14.2**	**7.6**	**113.5**	**135.3**	**1,132**	**79.7**
Hood Canal	**11.5**	**7.1**	**102.4**	**121.0**	**1,047**	**91.0**
SKO	4.7	2.8	59.5	67.0	496	105.1
HAM	1.8	1.6	7.1	10.6	104	56.3
DOS	1.2	0.4	11.2	12.8	135	116.0
DUC	2.0	0.4	7.8	10.2	100	49.0
QUL	1.7	1.9	16.8	20.4	212	122.3
Strait of Juan de Fuca	**2.7**	**0.4**	**11.1**	**14.3**	**85**	31.5
DUN	2.0	0.4	8.2	10.6	60	30.7
ELW	0.7	0.0	2.9	3.7	25	33.7
Total	**108.7**	**270.1**	**742.2**	**1,121.0**	**8,938**	**82.2**

Node density

The density of channel connections relative to total primary distributary channel length (node density) was highest in the Northern Cascades deltas, with 45% higher node density than the South-Central Cascades deltas and 14% higher node density than the Olympic deltas (Table 18). However, the comparison by MPG is again skewed by the Nisqually delta in South-Central Cascades. Compared to other South-Central Cascades deltas, the Nisqually delta has 28 to 145 times higher node densities. If we exclude the Nisqually delta from comparisons among MPGs, node density would be 5.2 nodes/km of primary distributary in the South-Central Cascades deltas. With this adjustment, the node densities in the Northern Cascades and Olympic deltas would be 18 and 15 times higher, respectively, than the South-Central Cascades deltas.

4. Status of Habitat and Riparian Areas by Land-Cover Stratum

We also summarized the status of each of the metrics by land-cover stratum. We first report the large river and floodplain metrics collected from satellite, aerial photography, and field data. We then report the delta metrics collected from satellite and aerial photography data. We have not yet completed any of the nearshore metrics from remote sensing data, nor the nearshore or delta metrics from field data.

Large River and Floodplain Metrics

In this section, we summarize the large river and floodplain monitoring results for land-cover status, percent forest and percent developed land cover, proportion of disconnected floodplain, riparian buffer width, sinuosity, edge habitat length by type, braid and side channel lengths, braid and side channel node densities, backwater area, and wood jam area from aerial photography. We also summarize data from limited field testing of length of human modified bank, edge habitat area by type, and wood abundance (counts by size class).

Land-cover status

Most Puget Sound floodplains are forested (44%), with the next most represented being agricultural lands (28%), and the least being developed (16%). Within Puget Sound's floodplains, forest, agriculture, and developed lands represent 88% of the land cover. The remaining 12% consist of bare land, water, and snow/ice (Figure 53).

Percent forest and percent developed land cover on floodplain

Percent forest was highest (52% for C-CAP and 49% for NAIP) at sites classified as predominantly forest and lowest (12% for C-CAP and 19% for NAIP) at sites with predominantly agriculture land cover (Figure 54). Percent developed was greatest in developed sites for both datasets; however, we found a significant difference between the datasets (Figure 54). C-CAP's estimate across sites was 50%, whereas NAIP estimated percent developed land at just over 20% at urban sites. These findings are consistent with the riparian validation results (see Figure 16), which show that C-CAP tends to overestimate developed land cover and NAIP tends to underestimate developed land cover.

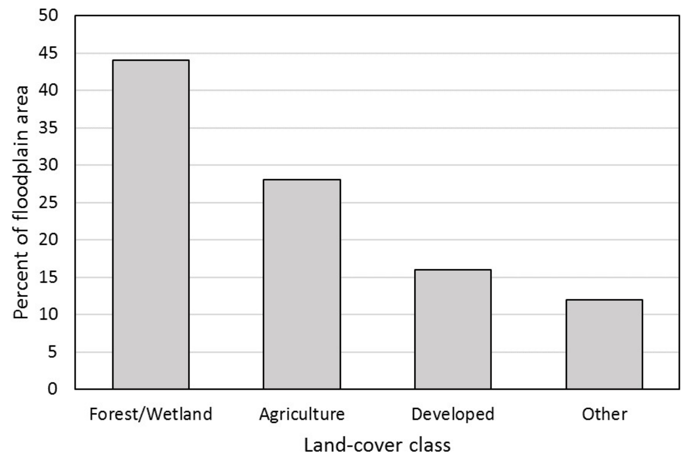


Figure 53. Proportion of major land-cover classes (forest/wetland, agriculture, developed, and other) in all surveyed floodplains in Puget Sound. The *other* category includes bare land, water, and snow/ice.

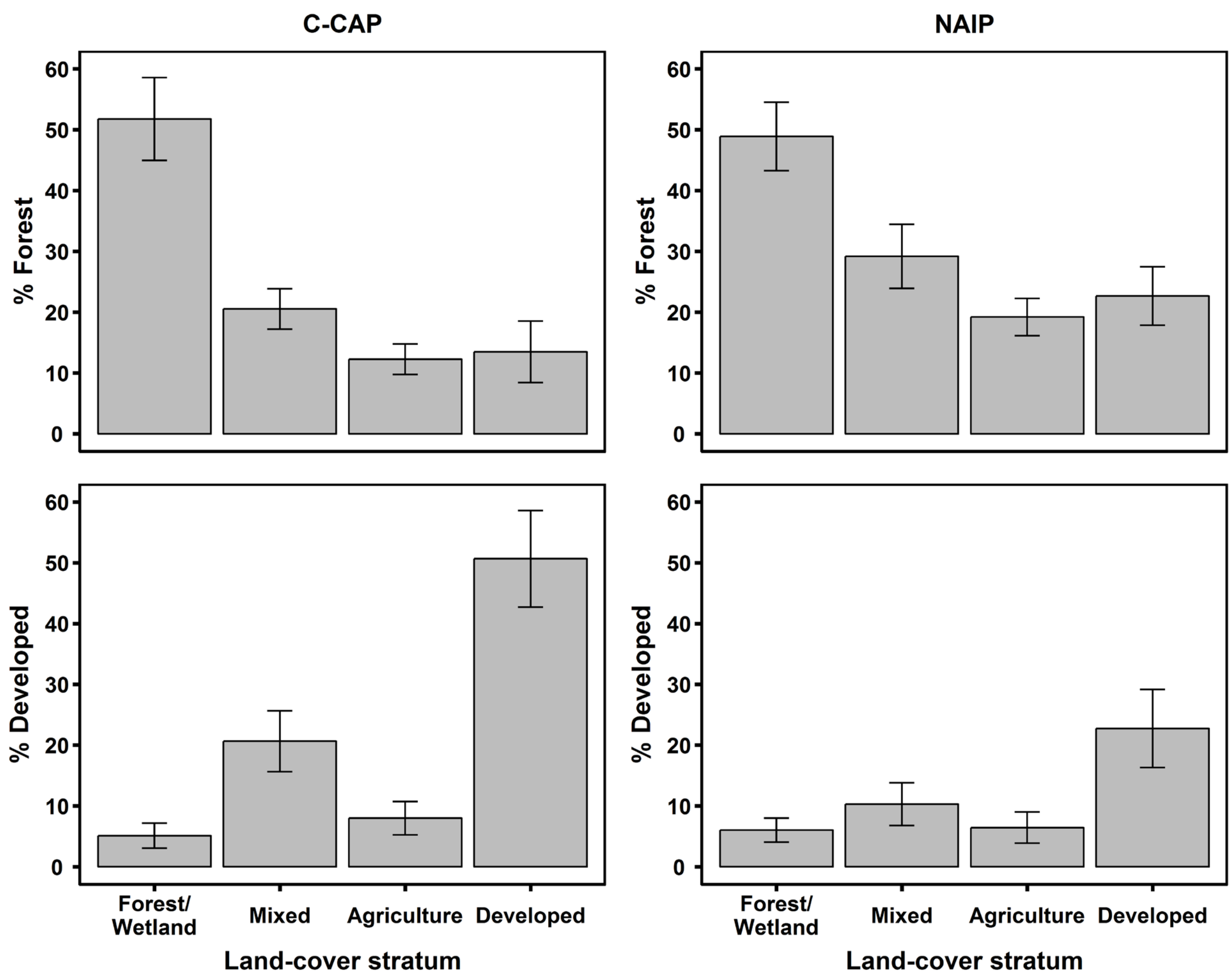


Figure 54. Percent forest and percent developed land cover at 124 sites across Puget Sound by land-cover stratum (forest/wetland, agriculture, developed, or mixed).

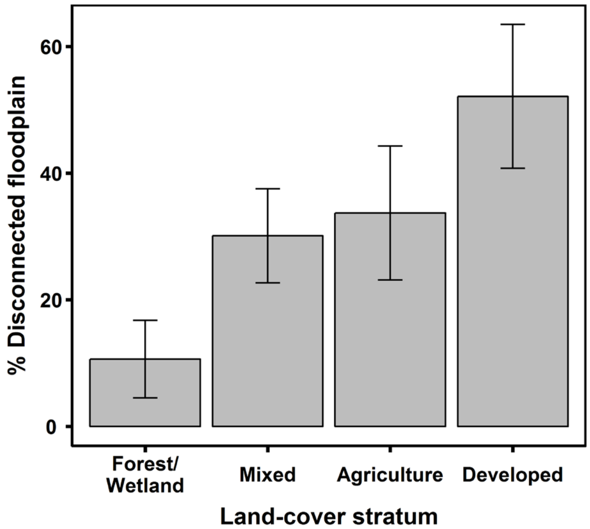


Figure 55. Mean proportion of disconnected floodplain within forest/wetland, agriculture, developed, and mixed land-cover strata. Error bars indicate 95% confidence intervals.

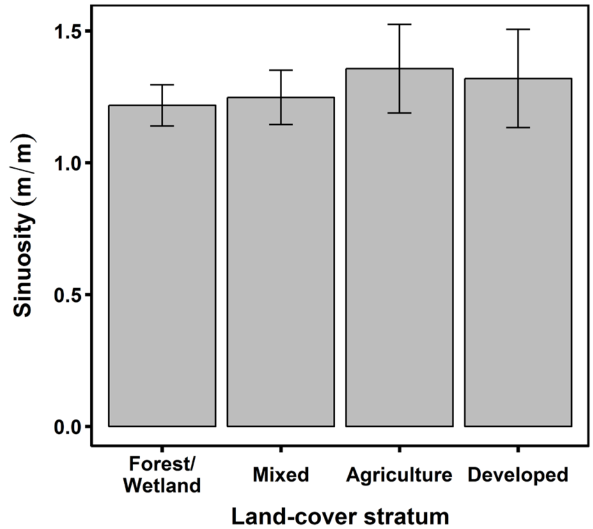


Figure 56. Mean channel sinuosity within forest/wetland, agriculture, developed, and mixed land-cover strata. Error bars indicate 95% confidence intervals.

Percent disconnected floodplain

The mean proportion of disconnected floodplain varied greatly among land-cover strata (Figure 55). The highest mean proportion of disconnected floodplain was observed in the developed stratum, where over 50% of the sites have disconnected floodplains (± 11%), while the lowest mean proportion of disconnected floodplain was observed in the forest/wetland stratum (11% ± 6%).

Sinuosity

Mean channel sinuosity did not vary significantly among land-cover strata, and variation among sites within each land-cover stratum was relatively low (Figure 56).

Riparian buffer width

The median of mean riparian buffer widths by land-cover strata is greatest (72 m) at forest/wetland sites, and lowest (15 m) at developed sites (Figure 57). Median buffer widths at forest/wetland sites are roughly 30 meters wider than the median widths at sites classified as agriculture and mixed (40 m and 42 m, respectively), and more than 50 meters wider than median widths at developed sites.

Edge habitat length by type

The highest mean proportion of bar edge length (33% ± 7%) was in forest-dominated sites, while the lowest (16% ± 7%) was in developed sites (Figure 58). The mean proportion of natural bank edge length ranged from 13% ± 10% in developed sites to 50% ± 9% in forest/wetland sites. The highest mean proportion of modified bank edge length was observed in the developed land-cover stratum (69% ± 13%), and the lowest in forest/wetland sites (14% ± 6%).

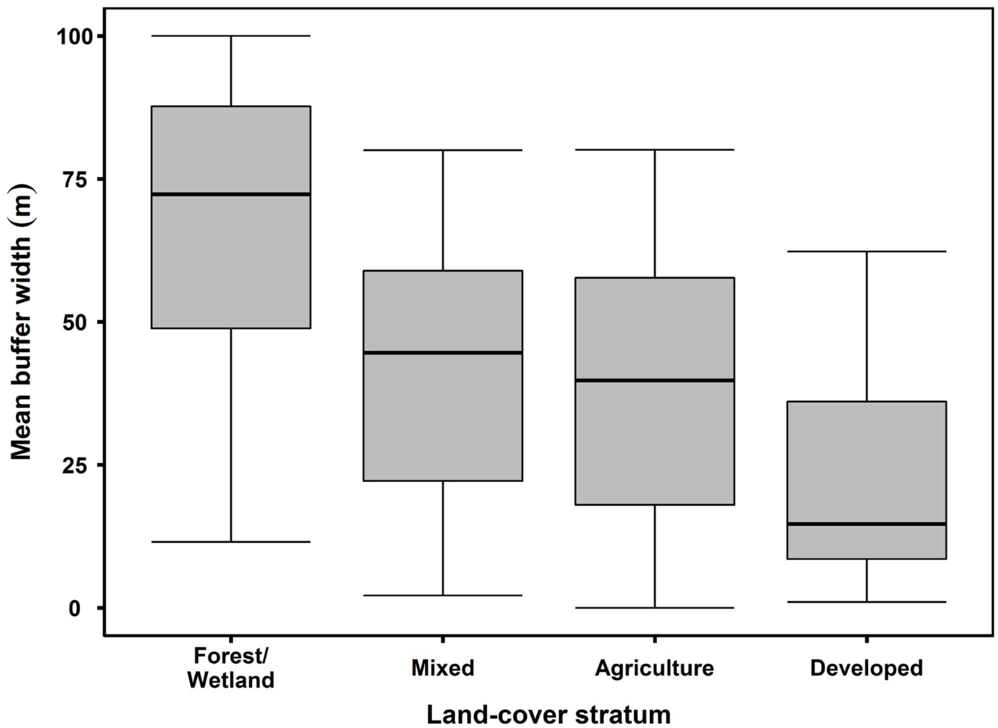


Figure 57. Box plots indicating median (line), upper (75%) and lower (25%) quartiles (box edges), and upper and lower limits (whiskers) of mean riparian buffer widths along large rivers in Puget Sound by land-cover strata (forest/wetland, agriculture, developed, or mixed). Each data point represents one sample reach, and mean buffer width is the mean of 20 width measurements for that sample reach. Error bars indicate 95% confidence intervals.

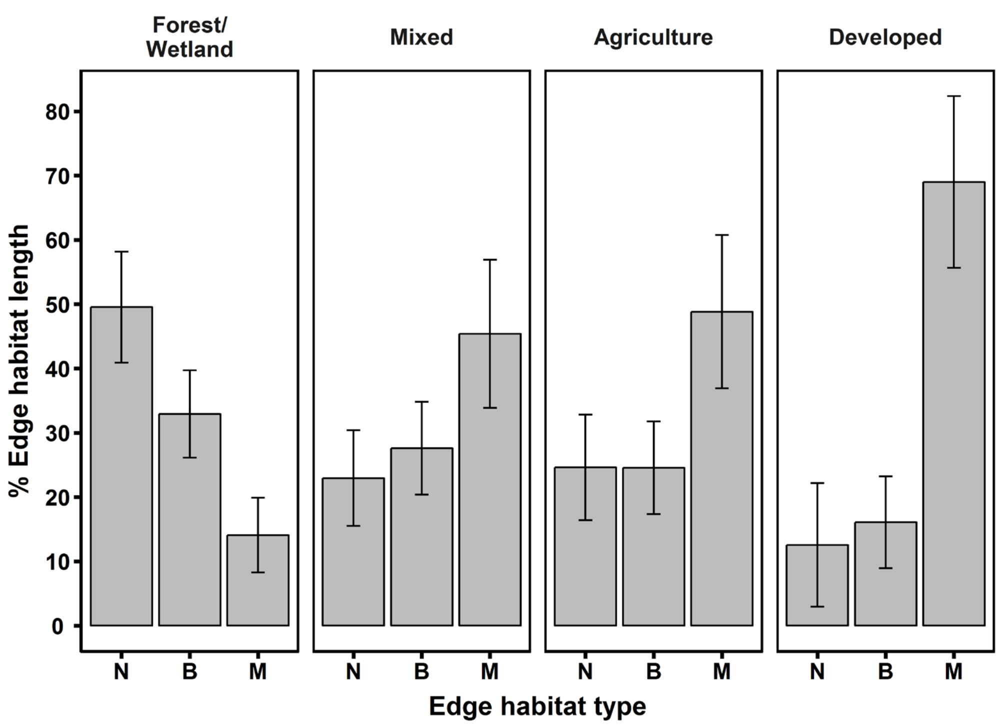


Figure 58. Mean proportion of natural bank (N), bar (B), or modified bank (M) edge length within forest/wetland, agriculture, developed, and mixed land-cover strata. Error bars indicate 95% confidence intervals.

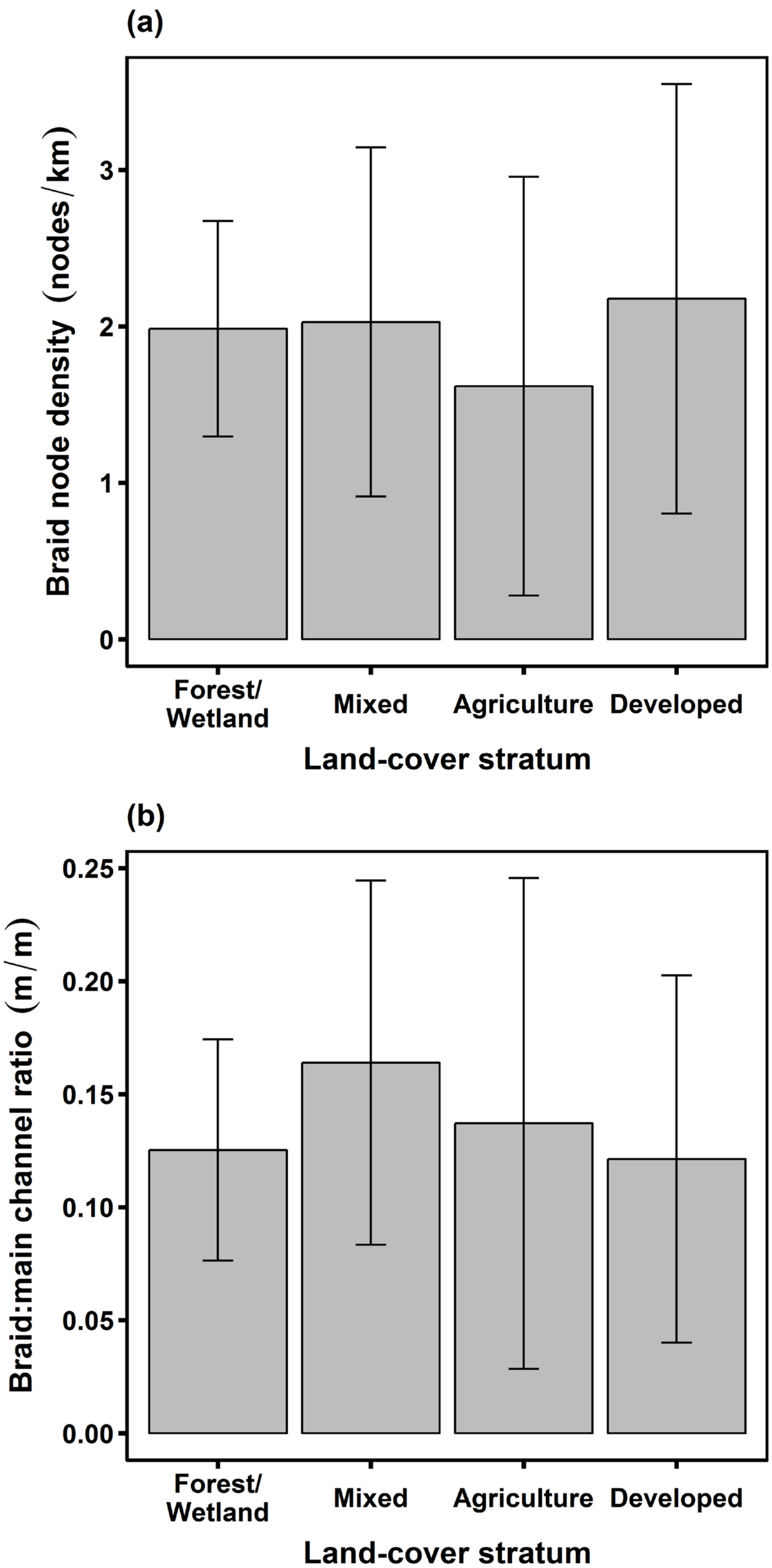


Figure 59. a) Mean braid node density within forest/wetland, agriculture, developed, and mixed land-cover strata. b) Mean braid:main channel ratio within forest/wetland, agriculture, developed, and mixed land-cover strata. Error bars indicate 95% confidence intervals.

Braid node density and braid channel length

The mean braid node density was similar among land-cover strata, with only a slightly higher density in the developed stratum (2.2 ± 1.4 nodes/km) and a slightly lower density in the agriculture stratum (1.6 ± 1.3 nodes/km). However, variation around the mean was high, and the differences were not statistically significant (Figure 59a). Mean braid node density was similar between the forest/wetland and mixed land-cover strata at ~2 nodes/km. Perhaps surprisingly, the mean braid:main channel ratio was not correlated with mean braid node density. Mean braid:main channel ratio ranged from 0.12 ± 0.08 m/m in the developed land-cover stratum, to 0.16 ± 0.08 m/m in the mixed land-cover stratum (Figure 59b).

Side channel node density and side channel:main channel ratio

The mean side channel node density differed among land-cover strata, but also exhibited high variability among sites within each stratum (Figure 60a). Mean side channel node density ranged from 0.4 nodes/km in the developed land-cover stratum to 1.4 nodes/km in forest/wetland. Mean side channel:main channel ratio exhibited a pattern consistent with side channel node density (Figure 60b). The highest mean side channel:main channel ratio was observed in the forest/wetland land-cover stratum (0.32 ± 0.19 m/m), and the lowest in the developed stratum (0.05 ± 0.08 m/m).

Backwater area

Not surprisingly, backwater area was highest in forest/wetland sites and lowest in developed sites (Figure 61). Mean backwater area was nearly 750 m^2/km^2 of active channel in forest/wetland sites, and only about 200 m^2/km^2 in developed sites.

Wood jam area

The mean wood jam area per square kilometer of active channel varied among land-cover strata and among sites within each stratum (Figure 62). The highest mean wood jam area was in the forest/wetland land-cover stratum (1,913 ± 1,440 m^2/km^2), while the lowest was in the developed stratum (74 ± 64 m^2/km^2).

Length of human modified bank (field)

Bank type composition from field surveys varied considerably both among and within land-cover strata (Figure 63). Natural banks dominated the forest/wetland and mixed land-cover strata, while modified banks dominated the agriculture and developed land-cover strata. The lowest mean proportion of modified bank length was observed in the forest/wetland stratum (32% ± 11%). Conversely, the highest mean proportion of modified bank length (100%) was observed in the developed stratum (Figure 63). There were no natural banks present in any of the developed sample sites, but sample size was limited to two sites. The highest mean proportion of natural bank length was in the forest/wetland stratum (84% ± 15%). Over two-thirds of the sites contained modified bank, while over three-quarters of the sites contained natural bank.

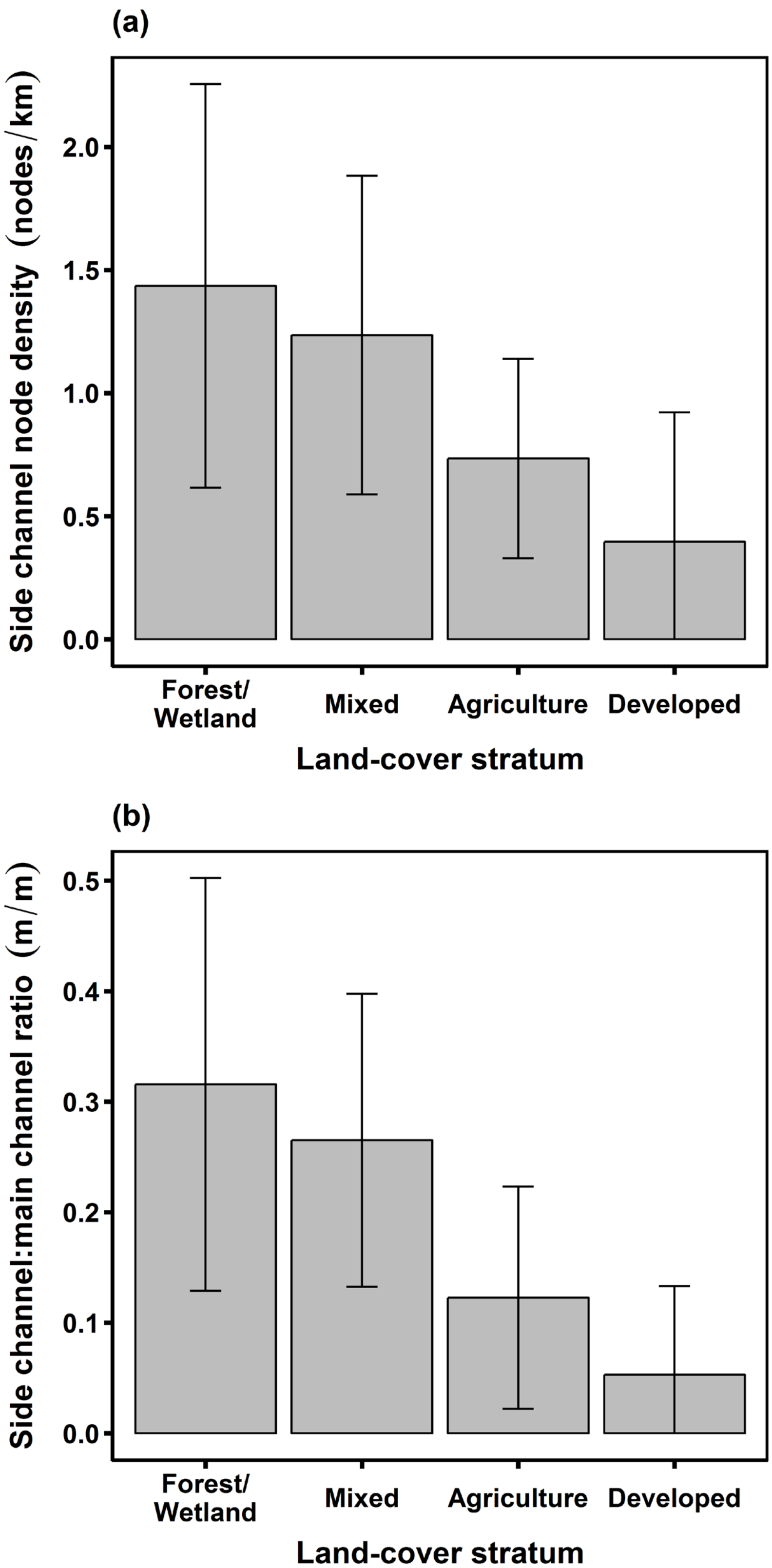


Figure 60. a) Mean side channel node density within forest/wetland, agriculture, developed, and mixed land-cover strata. b) Mean side channel:main channel ratios within forest/wetland, agriculture, developed, and mixed land-cover strata. Error bars indicate 95% confidence intervals.

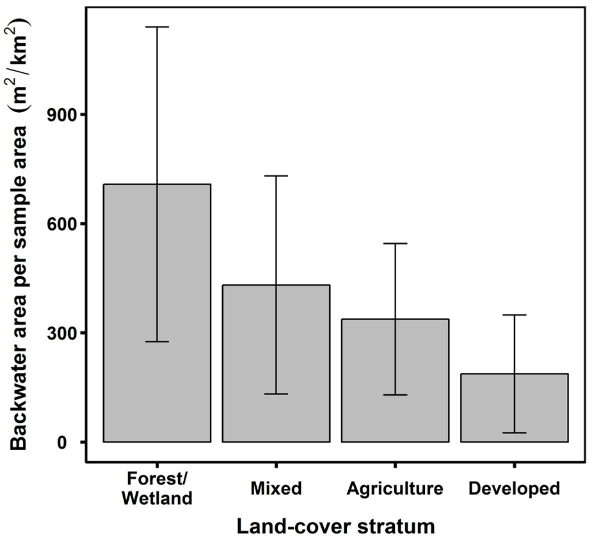


Figure 61. Mean backwater area per sample reach area within forest/wetland, agriculture, developed, and mixed land-cover strata. Error bars indicate 95% confidence intervals.

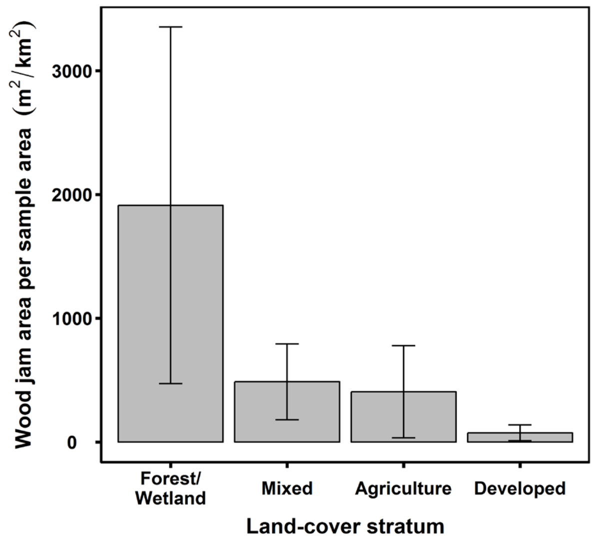


Figure 62. Mean wood jam area per sample reach area within forest/wetland, agriculture, developed, and mixed land-cover strata. Error bars indicate 95% confidence intervals.

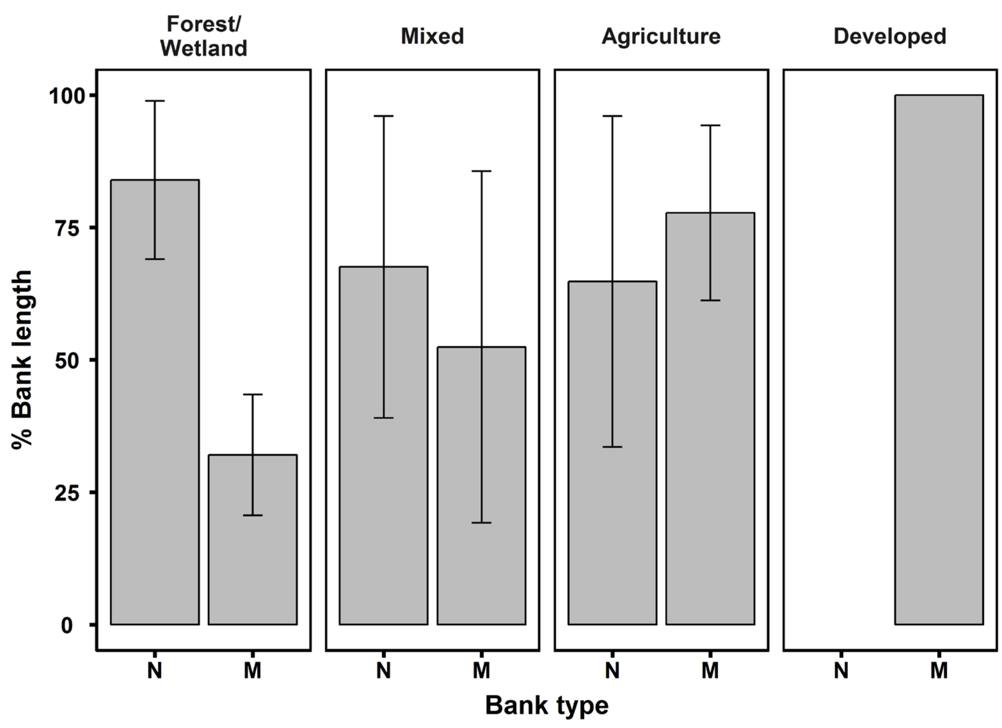


Figure 63. Mean proportion of natural (N) or modified (M) bank length within forest/wetland, agriculture, developed, and mixed land-cover strata. Error bars indicate 95% confidence intervals.

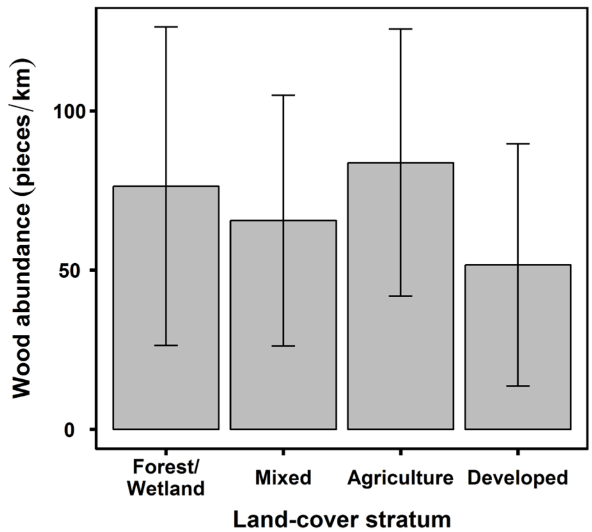


Figure 64. Mean number of wood pieces per reach length within forest/wetland, agriculture, developed, and mixed land-cover strata. Error bars indicate 95% confidence intervals.

Wood abundance (field)

The highest mean abundance of wood from field surveys was in the agriculture land-cover stratum, at 84 wood pieces/km (± 42 wood pieces/km), while the lowest mean abundance (52 ± 38 wood pieces/km) was within the developed stratum (Figure 64). However, differences among all strata were small compared to the variation within strata, and sample sizes were small for all land-cover strata (n = 6 for forest/wetland, agriculture, and urban; n = 3 for mixed).

Habitat edge area by type (field)

The mean percentage of bar edge area identified in field surveys was highest in the forest/wetland, agriculture, and developed land-cover strata, but not in the mixed stratum (Figure 65). The highest mean percentage of bar edge was in the developed land-cover stratum (75% ± 0.5%), while the lowest mean percentage was observed in the mixed stratum (37% ± 25%). Backwater edges were observed within all land-cover strata. The highest mean proportion of backwater edge was present within the mixed stratum, at 17% ± 15%. In contrast, the lowest mean proportion of backwater edge was seen in the developed stratum, at 2% ± 1%. Modified bank edges were observed in all land-cover strata, with the highest mean proportion in the forest/wetland stratum (32% ± 26%) and the lowest proportion in the mixed stratum (18% ± 10%). Natural bank edges were observed in forest/wetland, agriculture, and mixed, but not in developed, strata. The highest mean proportion of natural bank edge was observed in the mixed stratum, at 43% ± 27%.

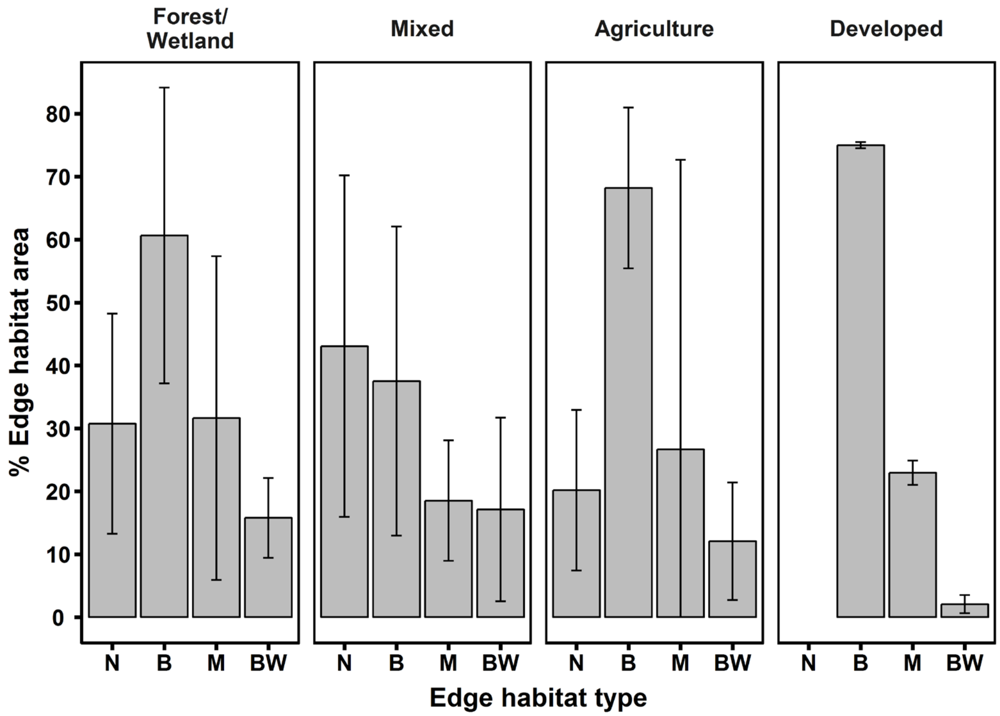


Figure 65. Mean proportion of natural bank (N), bar (B), modified bank (M), or backwater (BW) edge area within forest/wetland, agriculture, developed, and mixed land-cover strata. Error bars indicate 95% confidence intervals.

Discussion

We first discuss two important assessments of the accuracy of our land-cover and large river aerial photography metrics. These analyses ultimately informed our decisions on how to revise our sample design and sample protocols for the second phase of our monitoring effort. We then discuss the current status of habitat and riparian areas in large rivers, floodplains, and deltas by MPG and land-cover strata. Finally, we summarize the lessons we learned and our next steps for the Puget Sound Habitat Status and Trends Monitoring Program.

General Results of Analyses

1. Accuracy of Land-Cover Classification

Percent forest and percent impervious land-cover metrics

Results from a 2010 accuracy assessment of the National Land Cover Database (NLCD), the base dataset used for C-CAP, revealed that tree canopy cover and impervious cover were underestimated by, respectively, 9.7% and 5.7% (Nowak and Greenfield 2010). Similarly, an accuracy assessment of NLCD near Baltimore, Maryland, showed that percent forest and percent impervious were underestimated in NLCD (Smith et al. 2010). Our results were similar for percent forest (underestimated by NLCD), but, in contrast to the previous studies, we found that percent developed cover was relatively unbiased.

Forest cover is probably underestimated in the NLCD, which does not detect small patches of trees within a grid cell dominated by another land use. For example, a 30-m grid cell that is predominantly developed may contain individual trees though the grid cell is classified as developed (Nowak and Greenfield 2010). That is, the "minority" land-cover types within a cell are overlooked in the Landsat classification, but are captured in our point-based classification using aerial photography. We thus assigned a higher percent forest cover in the aerial photography dataset than was captured by the NLCD.

The contrast between our results and those of previous studies for developed or impervious areas likely results from differences in the NLCD datasets used in each study. We used the NLCD developed land-cover classes (low, medium, and high intensity in our analysis), whereas the other two studies used the percent impervious layer from the NLCD. The underestimation of percent impervious in the two published studies likely results from missing small impervious features within a grid cell, similar to the error noted for tree canopy (Nowak and Greenfield 2010).

Percent developed measured with C-CAP and percent forest measured with NAIP are the most accurate of all the land-cover metrics (slope near 1 and intercept near 0), with only a slight tendency to overestimate percent forest and underestimate percent developed. One potential cause of the overestimation of forest in the NAIP data could be that for single trees surrounded by impervious land cover, we classified the point the same as the surrounding land cover. For example, if a point landed on a tree within a completely impervious area or was over a road, that point, though classified as tree in the NAIP dataset, was classified as impervious in our manual observations. By contrast, NAIP underestimates developed area, primarily because our NAIP estimate includes only impervious surfaces, whereas out aerial photography estimates include both developed impervious and developed pervious structures. Because the resolution of the NAIP data is much finer than NLCD (1-m grid cells vs. 30-m grid cells), missed features are not likely a cause of underestimating impervious area, as they may be with NLCD. In future analyses, we will reexamine the accuracy of the NAIP data—taking into account recent improvements to the land-cover classification—and we will examine the use of NLCD impervious surface coverage instead of the developed land-cover classifications that were derived from the original impervious surface classification.

Accuracy of aerial photography land-cover classification

We encountered two main sources of error in classifying aerial photography that significantly reduced the apparent accuracy of manual classification. The first major source of error was related to channel movements or vegetation growth that had occurred between the image date and the field survey dates. The second major source of error was misclassification among the three forest types: conifer, deciduous, and mixed (i.e., a point was classified as one forest type in the aerial image and another forest type in the field). Because identification of tree community types was difficult in the aerial imagery, we grouped all forest community types into one forest category for our final accuracy analysis. The final overall classification accuracy (after removing sample sites where photo age had caused misclassification, and with tree community types grouped) was 81.0% for Observer 1 and 80.4% for Observer 2. The single largest sources of remaining error for both observers were the misclassification of grass/shrub as forest and of forest as grass/shrub. These errors are most likely associated with the classification of shrub communities as tree-cover types or of tree-cover types as shrub communities, as opposed to misclassifications of grass as forest or forest as grass.

We draw three main conclusions from this analysis. First, forest types are difficult to distinguish in aerial images, and grouping forest types into one forest-cover type improves classification accuracy. Second, shrub and grass cover types should be separated in the field surveys. Differentiation between shrub and tree cover types was a large source of error in aerial photography analysis, and distinguishing them in the field would help improve classification accuracy. Third, point samples may introduce errors due to alignment errors and observer interpretation. Because these errors are difficult to overcome with improved protocols, we will no longer attempt vegetation classification from aerial photography. However, we will continue to measure forested and natural riparian buffer widths along large rivers and distributary channels, because detailed land-cover classification is not required in those areas.

2. Observer Variability in Aerial Photography Habitat Metrics

The primary sources of observer variability in aerial photography measurements were: 1) lack of visibility of habitat features, 2) inconsistent feature identification, and 3) measurement error. In many cases, habitat features were hidden by dense shrub or tree canopy, or within shadows created by the canopy. This issue can only be alleviated by field verification, or by the use of field-verified data on features such as levees or riprap. However, there are no complete levee or riprap layers for all of Puget Sound at present.

Modifications to the aerial photography sampling protocol will be necessary to account for the differences in identification and feature measurements between observers. Due to the complex nature of some habitat features (e.g., side channels or wood jams), observers tended to differ widely in feature delineation and measurement. Therefore, we modified protocols to improve consistency among observers. For instance, observers varied in the amount of open space included in the delineation of wood jams, so we specified that wood jams be measured exactly along the edges of all contiguous and stacked pieces of wood. Similarly, we specified that at least half of a side channel must be visible to include it in the side channel:main channel length ratio.

3. Status of Habitat and Riparian Areas by MPG

Most of our metrics indicate that large river and floodplain habitat in the South-Central Cascades steelhead MPG is most impaired, likely because 78% of its sample sites were in agriculture, developed, or mixed land-cover strata. The Olympic steelhead MPG is least impaired, largely because 50% of its sample sites were in the forest/wetland land-cover stratum, which tends to be less altered. However, Olympic also contained the fewest sample locations, which contributed to greater variability in most metrics. Habitat conditions in the Northern Cascades steelhead MPG were slightly more degraded than in Olympic, although 39% of the sites were in the forest/wetland land-cover stratum.

Forested riparian buffer widths were greatest in Olympic, and lowest in South-Central Cascades. While Olympic has the least floodplain area (176 km^2), it has a higher proportion of forested land cover within the floodplain boundaries (Figure 10). The low average forested buffer width in South-Central Cascades was anticipated because that MPG contains the most urban areas and the highest percent developed land cover. Percent forested floodplain was slightly higher in Olympic than in the other two MPGs, although the 95% confidence intervals are large relative to the differences in percent forested floodplain among the MPGs.

The amount of disconnected floodplain was lowest in Olympic, which has the highest amount of forested floodplain. Hence, Olympic may have fewer roads and levees artificially disconnecting floodplains from channels. By contrast, percent disconnected floodplain was highest in South-Central Cascades, which has the highest proportion of floodplains classified as developed and has more levees and transportation infrastructure.

Braid node density in floodplains was similar across all steelhead MPGs, whereas side channel node density and side channel length were highest in Northern Cascades and low in both Olympic and South-Central Cascades. Side channel length is also highest in Northern Cascades and lowest in Olympic. While it may seem counterintuitive that the Olympic MPG has shorter side channels and lower node density, we found that it has considerably narrower floodplains than the South-Central and Northern Cascades MPGs. Olympic consists mostly of post-glacial and mountain valley types, which tend to be smaller and more confined, limiting the formation of side channels. The majority of sample sites within South-Central Cascades were located in areas where bank modification from armoring, levees, or transportation infrastructure confined the channel and eliminated side channels.

Patterns in large river edge habitat distribution within the MPGs are greatly influenced by the proportion of sites that are either agricultural or developed. The low amount of natural bank edge, moderate amount of bar edge, and high amount of modified bank edge in South-Central Cascades are indicative of habitat areas with high anthropogenic effects from rip-rap and bank armoring. In contrast, the high amount of natural bank edge, moderate amount of bar edge, and low amount of modified bank edge in Olympic are likely due to the dominance of forest/wetland land cover, which contains more natural habitat. Northern Cascades is a mix of both forested and anthropogenically altered land-cover classes, and habitat conditions are intermediate between those of Olympic and South-Central Cascades.

The Olympic MPG has the largest area of wood jams, but variation among sample sites is also much greater. Despite having the most developed floodplains, South-Central Cascades did not have the lowest wood jam area. Rather, Northern Cascades had the lowest wood jam area, as well as the lowest variation in wood jam area among sample sites. Differences in wood jam area among steelhead MPGs could be attributed to anthropogenic influences from urbanization and historical land use practices. The low wood jam area in Northern Cascades is likely a result of the high percentage of floodplains in agriculture and the high percentage of disconnected floodplain and modified bank. Large wood pieces with rootwads act as key pieces that promote and stabilize wood jams, and leveed or rip-rap banks reduce wood recruitment rate as natural floodplain would no longer be eroded. Both could reflect past land clearing for agriculture and levee construction (Collins et al. 2002).

Previous inventories of tidal wetland habitat in deltas indicated that Northern Cascades has the most tidal wetland habitat, with Olympic having the second-most, and South-Central Cascades having the least (Collins and Sheikh 2005). By contrast, our metrics show that South-Central Cascades has more tidal channel area than Olympic (Table 16, Figure 49)—but also that Northern Cascades has the most. We found similar opposing results among individual deltas, as well. For example, previous tidal wetland area estimates showed that the Skagit delta has more tidal wetland habitat than the Snohomish delta (Collins and Sheikh 2005), while our measured tidal channel area was larger in Snohomish than in Skagit (Table 16, Figure 49). This difference may be due to the fact that Snohomish is a much longer and lower-gradient delta, which allowed the formation of more large distributaries in the lower river than in the Skagit delta.

4. Status of Habitat and Riparian Areas by Land-Cover Stratum

Land-cover status within floodplains was generally as expected for both the NLCD and NAIP datasets. For example, sites in the forest/wetland stratum had a higher proportion of forest in the NLCD and NAIP datasets, which is unsurprising—in fact, nearly guaranteed—because forest/wetland sites by definition had more than 50% forest in NLCD. Slightly more interesting results appear among the less-common land-cover types within each stratum. For example, percent forest was lower in agriculture sites than in developed sites, suggesting that there is greater tree retention in developed areas than in agricultural lands. Average forested buffer width along large rivers was also highest in forest/wetland sites and lowest in developed sites. However, variability in buffer width was very high in all land-cover strata because most sites contain a mix of narrow and wide buffer segments.

On average, sample sites in the forest/wetland land-cover stratum contained the least disconnected floodplain (11%), while the developed land-cover stratum contained the most (52%). The clear pattern we observed in disconnected floodplain across strata can be attributed to the extent of floodplain disconnecting features within them (roads, railroad grades, or levees). The forest/wetland stratum is likely to be the most natural and contain the fewest roads, railroad grades, or levees, whereas the developed stratum will contain the most levees and transportation infrastructure. The proportion of disconnected floodplain in the agriculture and mixed land-cover strata was moderate (33% and 30%, respectively). Both of these strata likely have fewer levees and roads than the developed land-cover stratum.

Channel sinuosity did not vary significantly among land-cover strata. However, within the agriculture stratum, more than half of the sample reaches were located within the glacial valley type. This type is located lower in the river network and tends to exhibit a much more sinuous, meandering pattern than other valley types (Beechie et al. 2006a, Collins and Montgomery 2011). By contrast, the forest/wetland stratum was predominantly in the post-glacial and mountain valley types, which are typically higher-gradient and less sinuous. In the Puget Sound region, natural channel confinement tends to increase, and sinuosity to decrease, with an increase in stream gradient (Beechie et al. 2006a). This pattern was supported by our data, except that there was high variation in channel confinement within both the glacial and post-glacial valley types.

Forested sites also had the highest average proportion of bar edge and natural bank edge (as measured from aerial photography), while the developed land-cover sites contained the most modified bank edges due to bank armoring with concrete or riprap. We note, however, that edge habitat features were often difficult to identify and measure in aerial photography due to visual obstruction by tree canopy and shadows. Nonetheless, our results from field surveys also showed more natural habitat edge area in the forest/wetland land-cover stratum and more modified habitat edge area within the developed land-cover stratum, suggesting that potential observer error in the aerial photography data was not large enough to obscure the basic relationships among land use and buffer width.

While the braid node density and braid channel ratio were similar across land-cover strata, the side channel node density and side channel length ratio were highest in forest/wetland and mixed land-cover strata and lowest in agriculture and developed strata. We suggest that the restriction of lateral channel movement by levees in the agriculture and developed sites results in bed load being deposited in the large river channels, rather than the historically connected side channels, resulting in transient gravel bars that maintain short braids despite the channel confinement. In the unconfined (mostly forested) sites, lateral migration, channel avulsion, meander cutoffs, and channel switching create and maintain extensive floodplain channels (Beechie et al. 2006a), leading to much higher side channel lengths and side channel node densities in forest/wetland sites.

Finally, forested sites contained a much larger wood jam area, on average, than developed sites. Within forest/wetland sites, natural floodplain erosion allows for recruitment of wood, while locations with a higher amount of human-induced channel confinement restrict natural floodplain erosion, resulting in limited wood recruitment (Schmetterling et al. 2001, Collins et al. 2002). By contrast, wood abundance measured in the field was lowest in developed sites and highest in agriculture sites, but the 95% confidence intervals encompassed the means for all land-cover strata. The main reason for the difference between the aerial photography and field results is that aerial photography protocols include measurement of wood outside the main channel (including side channels and on bars), while the field protocols only count wood within the main channel. Hence, the field protocols do not capture wood that is on vegetated islands or in side channels. This suggests that our protocol for field sampling is not sufficiently sensitive to land-use changes to be retained as a monitoring metric.

Most of the differences among land-cover strata for the large river and floodplain habitat metrics are attributable to the degree of channel confinement by dikes and levees. Riverbank erosion is often considered a hazard, because it commonly results in land loss and damage to property and infrastructure (Piegay et al. 2005). To protect property, revetments and levees are often used to stop lateral bank erosion and bank undercutting (Schmetterling et al. 2001, Piegay et al. 2005, Chone and Biron 2015, Reid and Church 2015). However, natural, erodible banks are a vital component of summer and winter habitats for salmonids (Beamer and Henderson 1998, Beechie et al. 2005).

Artificial channel confinement can significantly limit the processes of lateral migration, channel avulsion, meander cutoff, and channel switching that create and maintain floodplain channels and associated habitats (Beechie et al. 2006a). When large river channels are artificially confined and disconnected from their floodplains by revetments and levees, lateral movement is suppressed and sediment deposition concentrated in the main channel. This leads to the appearance of more transient features such as gravel bars where, historically, side channels would have been created and maintained (Beechie et al. 2001, 2006a). Further, the artificial reduction in floodplain width can lead to an overall reduction in key habitat features such as side channels and oxbows (Chone and Biron 2015).

Restriction of bank erosion also suppresses wood recruitment to channels (Schmetterling et al. 2001). Wood abundance is a critical habitat feature that is significantly influenced by land use and management (Anlauf et al. 2011a, 2011b). Wood in stream channels (length >1 m and diameter >0.1 m) creates pools (Bisson et al. 1987, Beechie and Sibley 1997, Montgomery et al. 1995), promotes sediment storage (Naiman and Sedell 1980, Bilby et al. 1989), increases channel complexity (Abbe and Montgomery 1996), and provides vital habitats for fish and invertebrates (Bisson et al. 1987). Habitat formed by large wood has large impacts on invertebrate production and diversity (Naiman et al. 2002, Pilotto et al. 2014), food availability and cover for salmonids, and habitat complexity (Naiman et al. 2002). Despite the knowledge of the importance of lateral channel connectivity for wood recruitment, floodplains are often disconnected by channel-confining features such as levees, roadbeds, or railroad grades, resulting in decreased amounts of large woody debris, reduced side channel habitat, and diminished riparian forest cover (Blanton and Marcus 2013).

Lessons Learned and Next Steps

Our first year of developing a habitat monitoring program for Puget Sound focused on developing and testing stratification procedures, sampling designs, and measurement of habitat metrics. Here we discuss the lessons learned from our initial results, as well as the next steps we will take in the future.

Lessons Learned: Stratified Sampling Design

In our pilot study sample-site selection process for large rivers and floodplains, we found a large number of errors in geomorphic reach breaks, geomorphic strata assignment, and land-cover strata assignment, as well as issues of overlapping sample sites. These issues forced us to reclassify more than 30% of our sample sites after they had been drawn in our GRTS design, and ultimately contributed to an imbalanced distribution of sample sites among strata. To solve this problem, we have created a new floodplain reach map with fully delineated floodplain polygons that have been accurately classified by geomorphic valley type and land-cover stratum.

We also did not include MPGs as strata because we expected that the GRTS design would distribute sample sites relatively equally across MPGs. This contributed to some Chinook MPGs having too few sample sites for analysis by MPG. However, it is also important to note that the imbalanced distribution of sample sites among other strata was partly the result of natural features and land-use patterns. For example, the Olympic steelhead MPG naturally has very few reaches in glacial or post-glacial valley types, so there are very few sample sites in either of those strata within that MPG. Moreover, most of the landscape remains forested, leaving very few sample sites in the agriculture and developed land-cover strata. In the future we will sample all floodplain polygons, alleviating issues with imbalanced sample sizes among strata.

Lessons Learned: Protocol Development

During the pilot study, we developed initial field protocols for large river and floodplain channels, and made many improvements to those protocols during field testing. However, we quickly determined that the field work was too time-consuming to be cost-effective (i.e., getting an adequate sample size was not within our budget). Therefore, we plan to revise our field effort to focus primarily on ground-truthing our aerial photography measures. We have not yet developed protocols for ground-truthing, but we anticipate completing those in our second year of work.

For satellite and aerial photography metrics, we developed protocols for the large river, delta, and nearshore areas. Two remaining tasks are to resolve whether to use percent impervious area or percent developed area as a land-cover metric, and to reevaluate the land-cover stratum groupings we used in the analysis. We have also completed aerial photography protocols for the large river, floodplain, and delta areas. One remaining task for those metrics is to make minor corrections to the delta protocols. In addition, we may develop protocols for at least one metric of large river or floodplain dynamics, such as channel migration rate or floodplain turnover rate. The intent of these new metrics is to determine if channels are artificially stabilized and therefore prone to gradual declines in habitat quantity or quality.

We found that many of the features we wanted to measure in aerial photography were not visible due to tree cover or shadows (e.g., riprap or edge habitat features), and this contributed to observer variation and measurement error in certain metrics. The acquisition or creation of reference feature layers along large rivers should help improve the accuracy of habitat feature identification and measurement from aerial photography. For example, a layer that includes all levees along the major rivers in Puget Sound could be used as a reference to help improve the accuracy of levee measurements or habitat attributes associated with the stream bank. Improvements to the measurement guidelines and definitions of complex habitat features, such as wood jams, will also help increase the accuracy of identification and measurements between observers.

After we completed our analysis comparing the accuracy of C-CAP and NAIP data for land-cover metrics, in which we found little difference in accuracy between the two, updates to land-cover classifications were made to the NAIP dataset. These updates may increase the accuracy of the NAIP data, potentially justifying its use over C-CAP. In the future, we will conduct another riparian land-cover validation to access the accuracy of the improved NAIP dataset and use this to test percent forest and percent developed by land-cover stratum and steelhead MPG. If accuracy does not improve with the revised dataset, we will simply rely on C-CAP, which is a well-known dataset designed to monitor land-cover change.

The currently used PSNERP delta polygons do not extend throughout the potential zone of tidal influence within the deltas, and this ultimately restricts the delineation of delta habitat. Some PSNERP delta polygons end before the extent of tidal influence, and in some cases the boundary moves up the river within the wetted channel. The next phase of this project should include refinement of the delta polygons to delineate the full extent of tidal influence within each delta unit. The result of this update will likely be the delineation of additional tidally influenced channel habitat. Furthermore, the current analysis did not consider habitat behind tidegates and converted dikes and levees. Developing regional layers of tidegate and culvert locations and tidal connectivity would allow the addition of some tidal channel habitat currently not included in this analysis.

The complexity and small size of tidal channels in the areas defined as tidal complexes made digitizing flow paths impractical at the scale of our analysis. Therefore, we simply digitized polygons around complexes of small tidal channels to quantify habitat area in such places. These polygon-based estimates could be improved by randomly sampling tidal complex polygons to determine the range of channel area and perimeter values that are associated with these feature classes, which would improve the summary of available tidal channel habitats. In addition, delineations of habitat in these complex areas could be improved through the use of higher-resolution imagery and elevation data to determine flow paths. We are developing plans to obtain high-resolution imagery of the full spatial extent of Puget Sound that can be acquired in a relatively short time period (e.g., within the same year), thus providing a valuable dataset to refine the mapping of tidal features within Puget Sound deltas.

Some smaller channels are obscured by canopy cover in forested areas, leading to underrepresentation of channels and potential misclassification of distributary channels as tidal channels in forested cover types. The accuracy of digitized connections and flow paths would be improved by implementing field validations in targeted areas or consulting with individuals who have local area knowledge.

While we have currently only quantified tidal channel habitat area, edge habitat length, tidal channel flow path length, and tidal channel node density, the tidal channel polygons can also be used to derive a suite of additional metrics. For example, derived mean channel widths and widths at channel bifurcations could be used in combination with channel lengths to derive channel bifurcation orders and connectivity indices as described in Beamer et al. (2005). In addition, buffered channel edges can be used to derive land-cover summaries within the delta unit that may provide more useful information on land-cover patterns within the delta relative to where fish are within the delta (e.g., in channels).

Next Steps

Develop nearshore protocols

Our next step is to develop the nearshore sample design and monitoring protocols. Using PSNERP data, we will first create shoreline segments based on shore type, and then create additional shore type breaks based on land cover. Once we have all segments delineated and stratified, we will use GRTS to select sample sites across Puget Sound by Chinook and steelhead MPG. A shoreline armoring protocol and GIS layer are currently under development by the Puget Sound Partnership, WDFW, WDOE, and NOAA. Several other metrics may also be currently monitored by members of the Puget Sound Partnership or other agencies. For example, land-cover change is currently tracked in NOAA's C-CAP (which uses satellite data) and by Ken Pierce of WDFW (aerial photography data). We anticipate that most metrics that were selected in our review processes are already measured in the nearshore, and we will attempt to use existing data collection efforts where possible. For example, eelgrass and herring data are collected annually, and we are able to use those data to examine eelgrass trends throughout Puget Sound. We will also ground-truth several aerial photography metrics in the large river, floodplain, and delta habitats. We will initially focus on bank armoring and levees in floodplain channels, and wetlands and tidal complex channels in delta habitats.

Begin to develop fish–habitat relationships for all habitat types

The primary objective of this project element is to examine the relationship between habitat status and trend data to salmon population size or productivity. This may require a literature review, targeted study in basins where we have reliable adult and smolt data, and modeling to estimate the change in population size for a given suite of restoration options. We will first collaborate with WDFW to identify salmon datasets that can be used for this task, and examine adult and smolt data by watershed to identify trends and intrinsic productivity for Chinook salmon and steelhead at the watershed scale. A secondary task is to examine how fish abundance and productivity vary by land-cover stratum at the reach scale. We anticipate using correlation analyses to examine relationships between habitat data and fish data by MPG and by land-cover stratum, and to examine fish–habitat relationships across a gradient of land uses at the habitat and reach scales.

Develop pilot projects with local watershed groups

Identification of specific data gaps such as the length of armored banks has become more evident as we have developed the initial year of status data. As we have presented the work to various groups across Puget Sound, several groups have identified the need to develop mutually beneficial information. For example, several watersheds in the North Puget Sound region, an area with a relatively larger proportion of habitat in the floodplain, have identified the need to quantify the amount and quality of floodplain habitat in the field. We are currently in the process of developing proposals to implement several of our remote sensing and field protocols in coordination with local watershed groups. We would like to continue to expand this effort. Specifically, we would like to implement a project that helps us quantify floodplain channel habitat which is not identifiable using aerial photography or other remote sensing products.

Retrospective analysis of metrics to determine sensitivity to land use

One question we have not been able to answer in the first year of the project is, How sensitive are the metrics to changes in land use? In order to answer this question, we will initiate a retrospective analysis on a subset of sites in the large river and floodplain habitats in order to distinguish between anthropogenic change and natural change for each metric. At each site, we will measure each metric for a designated time period and compare the change between time periods to determine if we can use the metric to quantify a signal due to anthropogenic change.

Role and contribution of small independent watersheds to steelhead abundance and productivity

This is a basic question that needs to be addressed not only from a status and trends perspective, but also from a broader steelhead recovery perspective. While we do not have a specific plan in place, we have identified this as an important next step. Our hierarchical monitoring approach should work well for this task, although one major challenge is that most of the streams are far too small for remote sensing metrics to be of value. Therefore, this task would likely require additional funding or cooperation from other entities to conduct field surveys to monitor these habitats.

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Appendix A: Summary of Expert Panel Meetings

In the process of developing our monitoring program, we enlisted the help of many experts who have worked on similar issues and were in a position to help us avoid common pitfalls and take advantage of previous experience. In this appendix, we briefly describe three key expert panel meetings convened for 1) general lessons learned from previous habitat status assessments and trend monitoring programs, 2) identification of potential delta and nearshore metrics, and 3) identification of potential large river and floodplain monitoring metrics.

Expert Panel Meeting 1: Lessons Learned from Other Monitoring Programs

Before developing our sample design, we convened a meeting of experts in Portland, Oregon, on 12 June 2014, at which groups engaged in similar efforts were invited to share with us their lessons learned. We invited six scientists who have led large habitat monitoring or assessment programs in Oregon, California, the Columbia River basin, Puget Sound, and across the Pacific Rim (Table A-1). Each presented important results from their research or monitoring programs, and discussed aspects of their programs that either worked well or were challenging. A few key take-home points from that meeting were:

1. A key advantage of the hierarchical approach is that coarse-resolution datasets can be used to expand high-resolution habitat and fish data into regional or watershed-wide estimates of salmon production potential.
2. There are tradeoffs between spatially balanced and imbalanced designs. A balanced design allows comparisons among strata, while an imbalanced design can focus data collection on more relevant areas. Trends can be evaluated with either design, but the statistical approaches vary.

Table A-1. Expert panel members, affiliations, and expertise for the status and trends monitoring Lessons Learned meeting in Portland, Oregon, 12 June 2014.

Panel member(s)	Affiliation	Expertise
Sean Gallagher	California Department of Fish and Wildlife	Developed and leads fish status and trend monitoring in northern California.
Chris Jordan	NOAA Fisheries	Leads the Columbia Habitat Monitoring Program (CHaMP).
Kara Anlauf-Dunn, Kim Jones	Oregon Department of Fish and Wildlife	Codeveloped habitat status and trend monitoring in Coastal Oregon.
Bruce Crawford	Puget Sound Partnership	Performance analysis.
Diane Whited	University of Montana	Use of hierarchical sampling design to assess status of salmon habitat across the Pacific Rim using satellite data to field data.

3. Detecting improvements from restoration projects is difficult because the number of restoration sites is small compared to the number of reaches not restored.
4. Having an oversample in the pool of potential sample sites is important so that surveyors can move to the next site if access is not granted. (Field data collection is often dependent on landowner permission to access sites, and access is not always allowed.)
5. Measurement of key covariates at each site is important even with stratification, because monitored attributes vary with channel slope, size, etc., within strata.
6. Variables with a signal-to-noise ratio less than 2 should be abandoned, and those with signal-to-noise ratios greater than 10 are good metrics from a statistical point of view (but they still must be relevant to the goals of the monitoring program).

Expert Panel Meeting 2: Development of Delta and Nearshore Metrics

Before developing our delta and nearshore monitoring protocols, we convened a meeting of experts in Seattle, Washington, on 7 July 2014, to brainstorm lists of potential metrics and begin evaluating them for inclusion in our monitoring program. We invited ten scientists who have experience monitoring delta and nearshore habitats in Puget Sound, and eight were able to attend (Table A-2). At this first meeting, we were able to evaluate very few metrics due to the length of time spent discussing the evaluation process, and brainstorming the table of potential metrics was a more fruitful exercise for this meeting.

Table A-2. Expert panel members, affiliations, and expertise for the status and trends monitoring delta and nearshore metrics identification meeting in Seattle, Washington, 7 July 2014. Additional attendees: Tim Beechie, Kurt Fresh, George Pess, Mindy Rowse, Mindi Sheer, Alison Agnes (NOAA Fisheries), Leska Fore (Puget Sound Partnership), and Ken Currens (Northwest Indian Fisheries Commission).

Panel member	Affiliation	Expertise
Kelly Andrews	NOAA Fisheries	Habitat indicator selection for California Current Integrated Ecosystem Assessment.
Correigh Greene	NOAA Fisheries	Delta habitat capacity and tide gate monitoring.
Casey Rice	NOAA Fisheries	Published research on nearshore habitats and developed habitat monitoring program for delta habitat restoration.
Paul Cereghino	NOAA Restoration Center	Nearshore and delta restoration; Puget Sound Partnership lead for tidal wetlands indicator.
Greg Hood	Skagit River System Cooperative	Published research on delta habitat monitoring and tidal channel allometry.
Eric Grossman	U.S. Geological Survey	Research on sediment transport and nearshore habitat change.
Hugh Shipman	Washington Department of Ecology	Geomorphic classification of shore types.
Randy Carman	Washington Department of Fish and Wildlife	Research and monitoring of shoreline armoring in Puget Sound.

Expert Panel Meeting 3: Development of Large River and Floodplain Metrics

Before developing our large river and floodplain monitoring protocols, we convened a meeting of experts in Seattle, Washington, on 8 July 2014, to brainstorm lists of potential metrics and begin evaluating them for inclusion in our monitoring program. We invited nine scientists who have experience assessing or monitoring large river and floodplain habitats, and six were able to attend (Table A-3). At this second metrics meeting, we focused on brainstorming potential metrics with little regard to their feasibility for the Puget Sound Habitat Status and Trends monitoring effort. Evaluation of potential metrics and selection of final monitoring metrics were subsequently conducted by Northwest Fisheries Science Center staff, and then reviewed by the expert panel. Results of the metrics identification and evaluation are summarized in Overview of Selected Metrics and Protocols and in Appendix C.

Table A-3. Expert panel members, affiliations, and expertise for the status and trends monitoring large river and floodplain metrics identification meeting in Seattle, Washington, 8 July 2014. Additional attendees: Tim Beechie, Kurt Fresh, George Pess, Mindy Rowse, Mindi Sheer, Alison Agnes (NOAA Fisheries), Leska Fore (Puget Sound Partnership), and Ken Currens (Northwest Indian Fisheries Commission).

Panel member(s)	Affiliation	Expertise
Gino Lucchetti, Sara McArthy	King County	Land-cover change analysis (Lucchetti) and habitat survey protocols (McArthy).
Treva Coe	Nooksack Tribe	Large river and floodplain habitat restoration, monitoring.
Diane Whited	University of Montana	Remote sensing metrics and protocols for assessing status of salmon habitat across the Pacific Rim.
Eric Grossman	U.S. Geological Survey	Research on sediment transport, nearshore habitat change.
Chris Konrad	U.S. Geological Survey	Developed floodplain, large river data layers for Floodplains by Design project in Puget Sound; published research on river and floodplain geomorphology, restoration.

Appendix B: GIS Methods for Creating Strata

Large River and Floodplain Strata

We used the attributed hydrography layer from Davies et al. (2007) as our base hydrography dataset. This layer includes the channel slope and bankfull width attributes, which we used in our reach delineation procedure. We first clipped the stream layer with a layer of valley bottom polygons used to identify multibenefit floodplain restoration projects in Puget Sound (Konrad 2015). The floodplain polygons extend up all Puget Sound river networks to a drainage area of 50 km^2. That is, streams with drainage area <50 km^2 were excluded from the hydrography dataset.

We recalculated confinement ratios (valley width:bankfull width) for all reaches, and then classified reaches with ratios of ≥4.0 as unconfined and <4.0 as confined (Hall et al. 2007, Beechie and Imaki 2014). To measure valley width, we generated transect lines perpendicular to the stream line at 50-m intervals and then clipped the transect lines (maximum transect length, 15 km) using the high floodplain polygon derived from the National Elevation Dataset (NED) by Konrad (2015). The length of each transect was calculated and then used to calculate confinement based on average floodplain width divided by bankfull width. No connection filter was used for this process. These lines were converted to single-part features and intersected with the stream layer to remove erroneous segments.

We created geomorphic reach breaks based on a modification of the method of Beechie and Imaki (2014). We first generated start and end nodes for each segment in the hydrography layer, and then spatially joined the start and end nodes. The percent difference in gradient and bankfull widths were then calculated between reaches. End nodes were then classified as geomorphic reach breaks where there was a significant change in any one of four attributes: a gradient change of ≥1%, a bankfull width change of ≥10%, a confinement class change (confined to unconfined or vice versa), or a land-cover class change. The reach breaks were then used to segment the hydrography layer into reaches with relatively uniform geomorphic and land-cover characteristics. Finally, we averaged attribute values from all of the original reaches contained within each of the new aggregated reaches, and assigned those values to the aggregated reach (bankfull width, wetted width, channel slope, drainage area, 2-year flood discharge, stream power, floodplain width, confinement ratio, and proportion of each land-cover class).

We removed all reaches that fell within reservoirs or lakes to avoid their inclusion in the sample of floodplain and large river reaches. We also omitted segments that were less than 100 meters in length because we wanted to avoid selecting reaches that would be much smaller than the length of habitat surveys we anticipate in the field effort (minimum 300 m). Reaches <100-m long were relatively evenly distributed across basins and channel sizes (i.e., they were as likely to occur on very large channels as they were on small channels), so we do not expect these omissions to bias the sample.

Geomorphic strata were assigned by intersecting the aggregated reaches with Geographic Information System (GIS) maps of valley process domains from Collins and Montgomery (2011), which delineated glacial valleys and post-glacial valleys. For reaches that were not within one of the two process domains, we classified the remaining unconfined reaches as mountain valleys, and all confined reaches as canyons.

Land cover was attributed to the cross-section lines using the 2010 Coastal Change Analysis Program (C-CAP) dataset reclassified into forest/wetland, agriculture, and developed (Figure B-1). Stratifications of land cover (forest/wetland, agriculture, developed, or mixed) for each reach were assigned by averaging the proportions of each land-cover stratum across all floodplain transects in each stream segment (totals did not equal 100%). As described in the main report (Table 2), forest/wetland sites are >50% forest, agriculture sites are >50% agriculture, developed sites are >50% developed, and mixed sites are <50% any type. Because the cross-section lines were oriented perpendicular to the stream line (Figure B-1a), this method produced errors due to the meandering nature of some streams in Puget Sound. On the inside of meander bends, the coverage of some land-cover strata was overestimated where multiple transects crossed the same land-cover cells. By contrast, coverage was underestimated along the outside of meander bends where lines diverged from each other. Therefore, after sample sites were selected and floodplain polygons delineated, the land-cover stratum for each polygon was corrected (Figure B-1b).

To correct the land-cover stratification within each polygon, zonal statistics were extracted using C-CAP land-cover 2011 data in ArcGIS 10.2 using the Spatial Analyst Zonal Tool. Cells of forest/wetland, agriculture, or developed were then counted, and the proportion of each cover class was calculated. For both field and aerial sites, error matrices comparing the original transect classification to the corrected polygon-based classification indicated that one-third of sites were reclassified (Tables B-1 and B-2). That is, the accuracy of the land-cover stratification at the 124 aerial sites and 21 field sites sampled was 67%. The mixed cover class was least accurately classified, with approximately 50% of aerial photography sites misclassified. Hence, the most common corrections were reassignment of mixed sites to forest/wetland, agriculture, or developed, or reassignment of forest/wetland or urban sites to mixed. In subsequent years, we will alleviate this problem by delineating all floodplain polygons in Puget Sound prior to assigning land-cover strata (i.e., we will no longer use the transect method to assign land-cover strata).

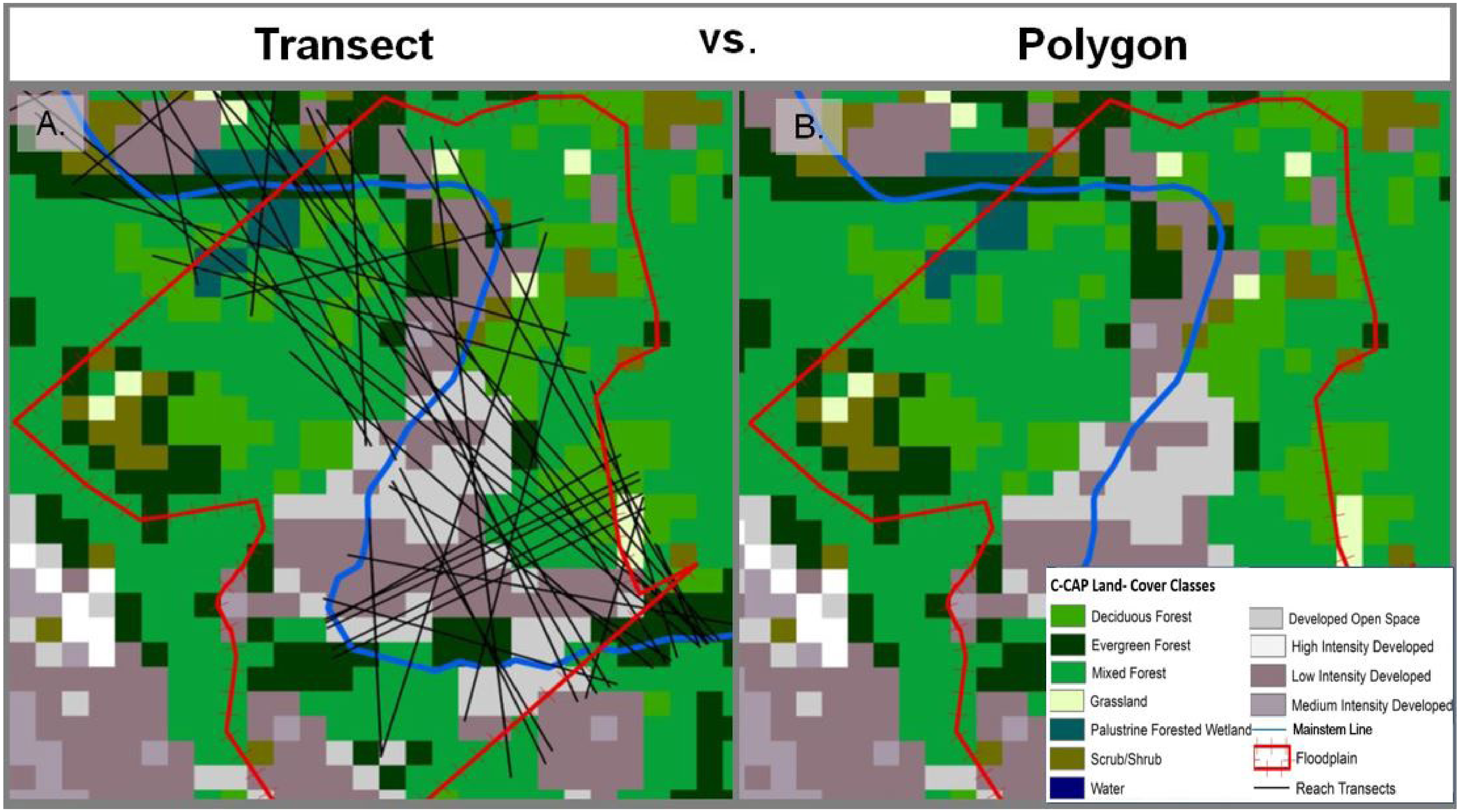

Figure B-1. Methods for a) assigning land-cover strata using the transect method, and b) obtaining the corrected land-cover stratification once the reach polygon was delineated.

Table B-1. Error matrix of C-CAP 2011 land-cover classification at the 21 field sites using original classification method of transects vs. floodplain polygons. Overall land classification accuracy was 67%. *Key*: F/W = forest/wetland, Agr = agriculture, Dev = developed, Mix = mixed.

		Polygon						
		F/W	Agr	Dev	Mix	Total	% Correct	% Commission
Transect	F/W	4	1			5	80	20
	Agr		6		1	7	86	14
	Dev	1		2	3	6	33	67
	Mix	1			2	3	67	33
	Total	6	7	2	6	21		
	% Correct	67	86	100	33		67	
	% Omission	33	14	0	67			

Table B-2. Error matrix of C-CAP 2011 land-cover classification at the 124 aerial photography sites using original classification method of transects vs. floodplain polygons. Overall land classification accuracy was 67%. *Key*: F/W = forest/wetland, Agr = agriculture, Dev = developed, Mix = mixed.

		Polygon						
		F/W	Agr	Dev	Mix	Total	% Correct	% Commission
Transect	F/W	31	4		5	40	78	23
	Agr	5	21		2	28	75	25
	Dev	3	1	16	6	26	62	38
	Mix	3	5	7	15	30	50	50
	Total	42	31	23	28	124		
	% Correct	74	68	70	54		67	
	% Omission	26	32	30	46			

Table B-3. Cross-validation table of classification accuracy for regrouped C-CAP land-cover classes (modified from Washington Department of Ecology, unpublished report). Overall classification accuracy of the grouped data is 94%. *Key*: F/W = forest/wetland, Agr = agriculture, Dev = developed, Mix = mixed.

	F/W	Agr	Dev	Water	Mix	Accuracy
F/W	493	9	3	10	3	95%
Agr	7	100				93%
Dev	13	4	85	1		83%
Water				61		100%
Mix					6	100%
Accuracy	96%	88%	97%	85%	67%	94%

Delta Strata

Each delta was manually assigned a geomorphic type based on Shipman (2008), because there are only 16 major deltas in Puget Sound. Most of the deltas are river-dominated. Only the Hamma Hamma, Dosewallips, Duckabush, and Big Quilcene deltas were classified as fan-shaped, and there were no wave-dominated deltas. The Elwha was classified as wave-dominated by Shipman (2008), but since removal of the two Elwha dams, there has been significant building of a river-dominated delta. Land cover was summarized for each delta using the Puget Sound Nearshore Ecosystem Restoration Project (PSNERP) delta polygons and C-CAP 2011 land-cover data (Landsat) grouped into forest/wetland, agriculture, and developed land-cover types. The delta polygons used for these summaries do not consider connectivity, and include areas that are not connected to tidal flooding. Given that all deltas were sampled, percent cover by type was summarized without statistical comparisons by delta, Chinook salmon (*Oncorhynchus tshawytscha*) major population group (MPG), or steelhead (*O. mykiss*) MPG.

Classification Accuracy of the Original Land-Cover Data

Overall classification accuracy of the land-cover types was 82% across 23 land-cover classes (Washington Department of Ecology,[1] unpublished report). After aggregating the 23 classes into five simpler classes, classification accuracy was 94% (Table B-3). This error is embedded within the classification and cannot be corrected.

References: Appendix B

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[1] http://www.ecy.wa.gov/programs/sea/wetlands/pdf/C-CAPWetlandAssessmentReport.pdf

Appendix C:
Details of Selecting Monitoring Metrics

This appendix provides a set of summary tables for metric scoring and supporting references for the large river, floodplain, delta, and nearshore metrics. Scores are: 0 (no, criterion not met), 0.5 (moderate or context-dependent), or 1 (yes, criterion met). Tables C-1, C-3, C-5, and C-7 summarize the scores for, respectively, large rivers, floodplains, deltas, and the nearshore. Tables C-2, C-4, C-6, and C-8 show citations that support the assigned scores.

Table C-1. Score sheet for large river metrics. Metrics in bold are those that scored 4.5 or higher and were selected for monitoring.

Data resolution	Type	Metric	Link to salmon VSP	Sensitive to land use	Link across scales	Cost-effective	Signal-to-noise ratio	Total
Satellite	Habitat quantity	Stream type at the network scale	1	0.5	1	1	0.5	4
	Habitat quality	Hydrologic condition index (flashiness)	0.5	1	1	0.5	0.5	3.5
	Pressure/process	**Percent natural, agricultural, developed land cover**	1	1	1	1	0.5	4.5
Aerial photography/lidar	Habitat quantity	Channel or water surface area	1	0.5	1	1	0.5	4
		Hydrology (monthly mean, peak flows, etc.)	1	1	0.5	1	0.5	4
		Pool spacing	1	1	1	1	0	4
		Edge habitat length by type	1	1	1	1	0	4
		Passable river miles	1	1	0.5	0	0.5	3
	Habitat quality	**Sinuosity (L_{main}/L_{valley})**	1	1	0.5	1	1	4.5
		Wood jam area	1	1	1	1	0.5	4.5
		Riparian forest providing direct shade	0.5	1	1	1	0.5	4
	Pressure/process	**Riparian buffer width and type**	1	1	1	1	1	5
		Percent of large river disconnected from floodplain	1	1	1	0.5	0.5	4
		Levee length	1	1	1	0.5	0.5	4
		Bank armoring	1	1	1	0.5	0.5	4
		Channel migration rate	1	1	1	1	0	4
Field	Habitat quantity	Levee length	1	1	0.5	0.5	1	4
		Wood abundance	1	1	1	1	0.5	4.5
		Edge habitat area by type (shallow shore)	1	1	1	1	0.5	4.5
		Hydraulic complexity	1	0.5	1	0	0	2.5
		Pool spacing	1	1	0.5	1	0.5	4
		Coefficient of variation of thalweg depth	1	1	1	0	0.5	3.5
		Hydrology (monthly mean, peak flows, etc.)	1	1	0.5	1	0.5	4
	Habitat quality	B-IBI	1	1	1	0.5	0.5	4
		Invertebrate drift	1	1	1	0.5	0.5	4
		Temperature	1	1	1	0.5	0	3.5
		Dissolved oxygen	1	1	1	0.5	0	3.5
		Nutrients	1	1	1	0.5	0	3.5
		Turbidity	1	1	1	0.5	0.5	4
		Conductivity	1	1	0.5	1	0.5	4
	Pressure/process	**Length of human-modified bank**	1	1	1	0.5	1	4.5
		Contaminants	1	1	0.5	0.5	0.5	3.5
		Entrenchment ratio	0.5	0.5	1	1	0.5	3.5
		Riparian buffer width and type	1	1	1	1	1	5
		Percent of large river disconnected from floodplain	1	1	1	0	0.5	3.5

Table C-2. References supporting scores for large river metrics. Metrics in bold are those that scored 4.5 or higher and were selected for monitoring.

Data resolution	Metric	Link to salmon VSP	Sensitive to land use	Link across scales	Cost-effective	Signal-to-noise ratio (S:N)
Satellite	Stream type at the network scale	Yes	Benda et al. 2004	Benda et al. 2004	Moderate. Processing of remote sensing data is not trivial.	—
	Hydrologic condition index (flashiness)	—	Lucchetti et al. 2014	Lucchetti et al. 2014	Moderate. Processing of remote sensing data is not trivial.	—
	Percent natural, agriculture, and developed land cover	Booth 1990, Booth and Reinelt 1993, Booth and Jackson 1997, Feist et al. 2011, Scholz et al. 2011, Spromberg and Scholz 2011	Booth and Reinelt 1993, Booth et al. 2002	Booth and Reinelt 1993	—	—
Aerial photography/ lidar	Channel or water surface area	Bisson et al. 1988	Bisson et al. 1988	Whited et al. 2011	Whited et al. 2011	—
	Hydrology (monthly mean, peak flows, etc.)	Bisson et al. 1988, Connor and Pflug 2004, Golden and Houston 2010	Connor and Pflug 2004	Hall et al. 2015	Yes, at USGS gages.	Depends on location, but is not well known.
	Pool spacing	Beechie and Sibley 1997	Montgomery et al. 1995, Beechie and Sibley 1997, Collins et al. 2002	Beechie and Sibley 1997	—	Montgomery et al. 1995 (S:N across streams = 8.2), Kauffmann et al. 1999
	Edge habitat area by type	Whited et al. 2011	Whited et al. 2011	Whited et al. 2011	Whited et al. 2011	—
	Passable river miles	Golden and Houston 2010	Steel et al. 2004	—	For large dams (but not culverts).	For large dams (but not culverts).
	Sinuosity (L_{main}/L_{valley})	Beechie and Imaki 2014, Beechie et al. 2015	Collins et al. 2002, Doering et al. 2012	Arscott et al. 2002	Beechie and Imaki 2014, Beechie et al. 2015	Friend and Sinha 1993, Kauffmann et al. 1999 (S:N across streams = 1.1)
	Wood jam area	Montgomery et al. 1995, Abbe and Montgomery 1996 (via pool creation), Beechie and Sibley 1997	Montgomery et al. 1995, Abbe and Montgomery 1996 (via pool creation), Beechie and Sibley 1997	Abbe and Montgomery 1996, Naiman et al. 2002a, Abbe and Montgomery 2003	Beechie and Sibley 1997, Montgomery et al. 1999	Beechie and Sibley 1997, Kauffmann et al. 1999 (S:N across streams = 7.0)
	Riparian forest providing direct shade	Meehan 1970, Torgersen et al. 1999	Steinblums et al. 1984	Steinblums et al. 1984	Yes	—

Table C-2 (continued). References supporting scores for large river metrics. Bold metrics scored 4.5 or higher and were selected for monitoring.

Data resolution	Metric	Link to salmon VSP	Sensitive to land use	Link across scales	Cost-effective	Signal-to-noise ratio (S:N)
Aerial photography/ lidar	**Riparian buffer width**	Bisson et al. 1988, Bilby and Ward 1989, Hyatt et al. 2004	Beechie et al. 2003, Fullerton et al. 2006	Beechie et al. 2003, Fullerton et al. 2006	Hyatt et al. 2004, Fullerton et al. 2006	Kauffmann et al. 1999 (proportion of riparian across-stream S:N = 0–37, avg. 4.6), Fullerton et al. 2006
	Percent of large river disconnected from floodplain	Jeffres et al. 2008, Golden and Houston 2010	Beechie et al. 1994, Hohensinner et al. 2004, Jeffres et al. 2008	Jeffres et al. 2008	Moderate. Requires repeat lidar.	—
	Levee length	Beechie et al. 1994, Beamer et al. 2005	Yes	Yes	Where data are available, but not over wide areas.	Low accuracy from aerial photography.
	Bank armoring	Beamer and Henderson 1998	Yes	Yes	Where data are available, but not over wide areas.	Low accuracy from aerial photography.
	Channel migration rate	Yes	Latterell et al. 2006	Latterell et al. 2006	Latterell et al. 2006	Variable (likely high when migration rate is high).
Field	Levee length	Beechie et al. 1994, Beamer et al. 2005	Yes	Spatial: yes; temporal: no.	Where data are available, but not over wide areas.	Yes
	Wood abundance	Montgomery et al. 1995 (via pool creation), Beechie and Sibley 1997	Montgomery et al. 1995, Beechie and Sibley 1997	Naiman et al. 2002a	Beechie and Sibley 1997, Montgomery et al. 1999	Beechie and Sibley 1997, Kauffmann et al. 1999 (S:N across streams = 7.0)
	Edge habitat area by type (shallow shore)	Bisson et al. 1988, Murphy et al. 1989, Beamer and Henderson 1998, Beechie et al. 2005, Latterell et al. 2006	Bisson et al. 1988, Murphy et al. 1989, Beamer and Henderson 1998	Bisson et al. 1988, Murphy et al. 1989, Whited et al. 2011	—	Varies with discharge.
	Hydraulic complexity	Bisson et al. 1988, Jeffres et al. 2008	Woessner 2000	Woessner 2000	—	—
	Pool spacing	Beechie and Sibley 1997	Montgomery et al. 1995, Beechie and Sibley 1997, Collins et al. 2002	Beechie and Sibley 1997	—	Montgomery et al. 1995 (S:N across streams = 8.2 [RPGT75], Kauffmann et al. 1999

Table C-2 (continued). References supporting scores for large river metrics. Bold metrics scored 4.5 or higher and were selected for monitoring.

Data resolution	Metric	Link to salmon VSP	Sensitive to land use	Link across scales	Cost-effective	Signal-to-noise ratio (S:N)
Field	Coefficient of variation of thalweg depth	Mossop and Bradford 2006	Mossop and Bradford 2006	Mossop and Bradford 2006	—	Kauffmann et al. 1999 (S:N across streams = 6.9 [thalweg mean depth])
	Hydrology (monthly mean, peak flows, etc.)	Bisson et al. 1988, Connor and Pflug 2004, Golden and Houston 2010	Connor and Pflug 2004	Hall et al. 2015	Yes, at USGS gages.	Depends on location, but not well known.
	B-IBI	Morley and Karr 2002	Karr 1991, Morley and Karr 2002, Karr 2006	Morley and Karr 2002	Karr 1981	Moderate
	Invertebrate drift	OPSW 1999	Herringshaw et al. 2011	Herringshaw et al. 2011	—	—
	Temperature	Brett 1971, Ward 1985, Bjornn and Reiser 1991, Pankhurst 1997, McCullough 1999, OPSW 1999, Torgersen et al. 1999, Poole and Berman 2001, Caissie 2006, Van der Kraak and Pankhurst 1997, Webb et al. 2008, McCullough et al. 2009, Mayer 2012, Tan and Cherkauer 2013	Torgersen et al. 1999, Arrigoni et al. 2008, Farrell et al. 2008 (aerobic scope of migrations), Isaak et al. 2010, Arismendi et al. 2012, Isaak et al. 2012 (climate change, wildfire), Arismendi et al. 2013a, 2013b	Torgersen et al. 1999	Spatial: empirical data expensive, models (i.e., from NorWeST[a]) inexpensive; temporal: yes.	Van der Kraak and Pankhurst 1997, Torgersen et al. 1999
	Dissolved oxygen	OPSW 1999	Inkpen and Embrey 1998	Inkpen and Embrey 1998, OPSW 1999	—	—
	Nutrients	OPSW 1999, Naiman et al. 2002b	Inkpen and Embrey 1998	Inkpen and Embrey 1998	—	—
	Turbidity	Murphy et al. 1989, Gregory and Levings 1998, OPSW 1999	Opperman et al. 2005	Opperman et al. 2005	—	Murphy et al. 1989
	Conductivity	OPSW 1999	Gardi 2001	OPSW 1999	—	—
	Length of human-modified bank	Beamer and Henderson 1998	Yes	Spatial: yes; temporal: no.	Where data are available, but not over wide areas.	Yes

[a] https://www.fs.fed.us/rm/boise/AWAE/projects/NorWeST.html

Table C-2 (continued). References supporting scores for large river metrics. Bold metrics scored 4.5 or higher and were selected for monitoring.

Data resolution	Metric	Link to salmon VSP	Sensitive to land use	Link across scales	Cost-effective	Signal-to-noise ratio (S:N)
Field	Contaminants	Feist et al. 2011, Spromberg and Scholz 2011	Booth and Reinelt 1993, Feist et al. 2011, Spromberg and Scholz 2011	Booth and Reinelt 1993, Feist et al. 2011, Spromberg and Scholz 2011, Jones et al. 2015	—	Booth and Reinelt 1993
	Entrenchment ratio	—	Beechie et al. 2008	—	—	Rosgen 1994
	Riparian buffer width and type	Bisson et al. 1988, Bilby and Ward 1989, Hyatt et al. 2004	Beechie et al. 2003, Fullerton et al. 2006	Beechie et al. 2003, Fullerton et al. 2006	Hyatt et al. 2004, Fullerton et al. 2006	Kauffmann et al. 1999 (proportion of riparian across-stream S:N = 0–37, avg. 4.6), Fullerton et al. 2006
	Percent of mainstem disconnected from floodplain	Jeffres et al. 2008	Beechie et al. 1994, Hohensinner et al. 2004, Jeffres et al. 2008	Jeffres et al. 2008	—	—

Table C-3. Score sheet for floodplain metrics. Metrics in bold are those that scored 4.5 or higher and were selected for monitoring.

Data resolution	Type	Metric	Link to salmon VSP	Sensitive to land use	Link across scales	Cost-effective	Signal-to-noise ratio	Total
Satellite	Habitat quantity	Fragmentation by roads, levees, etc.	0	1	0.5	1	1	3.5
		Wetland area	1	1	1	0.5	0.5	4
	Habitat quality	Hydrologic condition index (flashiness)	0.5	1	1	0.5	0.5	3.5
	Pressure/process	**Percent natural, agricultural, and developed land cover**	1	1	1	1	0.5	4.5
Aerial photography/ lidar	Habitat quantity	**Length of side channel**	1	1	1	1	1	5
		Area of side channel	1	1	1	1	0	4
		Area of connected floodplain	1	1	1	0.5	1	4.5
		Area of ponded habitat	1	1	1	1	0	4
		Percent side channel disconnected by levees	1	1	1	0.5	0	3.5
	Habitat quality	**Braid ratio (L_{br}/L_{main})**	1	1	1	1	0.5	4.5
		Side channel ratio (L_{sc}/L_{main})	1	1	1	1	0.5	4.5
		Braid node density	1	1	1	1	1	5
		Side channel node density	1	1	1	1	1	5
	Pressure/process	**Percent disconnected floodplain**	1	1	1	1	1	5
		Length of human-modified bank	1	1	1	0.5	0.5	4
		Turnover rate of floodplain surfaces	0	1	1	1	0.5	3.5
Field	Habitat quantity	**Pool frequency or spacing**	1	1	1	1	0.5	4.5
		Percent pool area	1	1	0.5	1	0.5	4
		Wood abundance	1	1	1	1	0.5	4.5
		Area of side channel	1	1	1	1	1	5
	Habitat quality	**Residual pool depth (d_{max}–d_{tail})**	1	1	1	1	0.5	4.5
		B-IBI	1	1	1	0.5	0.5	4
		Invertebrate drift	1	1	1	0.5	0.5	4
		Temperature	1	1	1	0.5	0	3.5
		Dissolved oxygen	1	1	1	0.5	0	3.5
		Nutrients	1	1	1	0.5	0	3.5
		Conductivity	1	1	0.5	1	0.5	4
	Pressure/process	Riparian species composition and buffer width	1	1	1	0	1	4
		Length of human-modified bank	1	1	1	1	1	5
		Contaminants	1	1	0.5	0	0.5	3

Table C-4. References supporting scores for floodplain metrics. Metrics in bold are those that scored 4.5 or higher and were selected for monitoring.

Data resolution	Metric	Link to salmon VSP	Sensitive to land use	Link across scales	Cost-effective	Signal-to-noise ratio (S:N)
Satellite	Fragmentation by roads, levees, etc.	—	Yes	Jeffres et al. 2008	—	Yes
	Wetland area	Yes	Poff 2002	Yes	—	—
	Hydrologic condition index (flashiness)	—	Lucchetti et al. 2014	Lucchetti et al. 2014	Moderate. Processing of remote sensing data is not trivial.	—
	Percent natural, agricultural, and developed land cover	Sommer et al. 2005, Konrad et al. 2008	Booth and Reinelt 1993, Collins et al. 2002	Booth and Reinelt 1993, Konrad et al. 2008	Konrad et al. 2008	Wickam et al. 2013
Aerial photography/ lidar	**Length of side channel**	Beechie et al. 1994, Whited et al. 2012	Beechie et al. 1994, Hohensinner et al. 2004, Whited et al. 2011, 2012	Hall et al. 2007, Whited et al. 2012	Whited et al. 2011, 2012	Whited et al. 2012
	Area of side channel	Beechie et al. 1994, Whited et al. 2012	Beechie et al. 1994, Hohensinner et al. 2004, Whited et al. 2011, 2012	Hall et al. 2007, Whited et al. 2012	Whited et al. 2011, 2012	Whited et al. 2012: forest canopy will reduce accuracy.
	Area of connected floodplain	Jeffres et al. 2008	Beechie et al. 1994, Hohensinner et al. 2004, Whited et al. 2011, 2012	Hall et al. 2007, Whited et al. 2012	Whited et al. 2011, 2012, Konrad 2015	Whited et al. 2012, Konrad 2015
	Area of ponded habitat	Beechie et al. 1994, 2001, Jeffres et al. 2008, Malison et al. 2014	Beechie et al. 1994, Hohensinner et al. 2004	Whited et al. 2011, 2012	Whited et al. 2011, 2012, Malison et al. 2014	Whited et al. 2012: forest canopy issues in Puget Sound?
	Percent side channel disconnected by levees	Beechie et al. 1994, Whited et al. 2012	Beechie et al. 1994, Whited et al. 2011, 2012	Hall et al. 2007, Whited et al. 2012	Whited et al. 2011, 2012	Whited et al. 2012
	Braid ratio (L_{br}/L_{main})	Beechie and Imaki 2014, Beechie et al. 2015	Collins et al. 2002, Doering et al. 2012	Arscott et al. 2002	Beechie et al. 2006a	—
	Side channel ratio (L_{sc}/L_{main})	Beechie and Imaki 2014, Beechie et al. 2015	Collins et al. 2002, Doering et al. 2012	Arscott et al. 2002	Beechie et al. 2006a	—
	Braid node density	Luck et al. 2010, Whited et al. 2012	Whited et al. 2011, 2012	Benda et al. 2004	Whited et al. 2011, 2012	Whited et al. 2012
	Side channel node density	Luck et al. 2010, Whited et al. 2012	Whited et al. 2011, 2012	Benda et al. 2004	Whited et al. 2011, 2012	Whited et al. 2012

Table C-4 (continued). References supporting scores for floodplain metrics. Bold metrics scored 4.5 or higher and were selected for monitoring.

Data resolution	Metric	Link to salmon VSP	Sensitive to land use	Link across scales	Cost-effective	Signal-to-noise ratio (S:N)
Aerial photography/ lidar	**Percent disconnected floodplain**	Jeffres et al. 2008	Beechie et al. 1994, Hohensinner et al. 2004, Whited et al. 2011, 2012	Hall et al. 2007, Whited et al. 2012	Whited et al. 2011, 2012	Whited et al. 2012
	Length of human-modified bank	Beamer and Henderson 1998	Yes	Yes, via link to land cover.	Requires field validation.	Probably low from aerial photography.
	Turnover rate of floodplain surfaces	Beechie et al. 2006a, Latterell et al. 2006	—	Beechie et al. 2006a, Latterell et al. 2006	Latterell et al. 2006	Variable.
Field	**Pool frequency or spacing**	Beechie and Sibley 1997, Montgomery et al. 1999	Montgomery et al. 1995, Beechie and Sibley 1997, Collins et al. 2002	Beechie and Sibley 1997	Beechie and Sibley 1997, Montgomery et al. 1999	Montgomery et al. 1995, Kauffmann et al. 1999 (S:N across streams = 8.2)
	Percent pool area	Beechie and Sibley 1997	Montgomery et al. 1995, Beechie and Sibley 1997, Collins et al. 2002	Beechie and Sibley 1997	Beechie and Sibley 1997	Kauffmann et al. 1999 (S:N across streams = 7.5 [pools + glides ÷ reach length])
	Residual pool depth (d_{max}–d_{tail})	Lisle 1987, Mossop and Bradford 2006	Lisle 1987	Yes, via link to land cover and riparian functions.	Mossop and Bradford 2006	Kauffmann et al. 1999 (S:N across streams = 9.0)
	Wood abundance	Montgomery et al. 1995 (via pool creation), Beechie and Sibley 1997	Montgomery et al. 1995, Beechie and Sibley 1997	Naiman et al. 2002a	Beechie and Sibley 1997, Montgomery et al. 1999	Beechie and Sibley 1997, Kauffmann et al. 1999 (S:N across streams = 7.0)
	Area of side channel	Beechie et al. 1994, Whited et al. 2012	Beechie et al. 1994, Hohensinner et al. 2004, Whited et al. 2011, 2012	Hall et al. 2007, Whited et al. 2012	Whited et al. 2011, 2012	Whited et al. 2012
	B-IBI	Morley and Karr 2002	Karr 1991, Morley and Karr 2002, Karr 2006	Morley and Karr 2002	—	Moderate.
	Invertebrate drift	OPSW 1999	Herringshaw et al. 2011	Herringshaw et al. 2011	Karr 1981	—

Table C-4 (continued). References supporting scores for floodplain metrics. Bold metrics scored 4.5 or higher and were selected for monitoring.

Data resolution	Metric	Link to salmon VSP	Sensitive to land use	Link across scales	Cost-effective	Signal-to-noise ratio (S:N)
Field	Temperature	Brett 1971, Ward 1985, Bjornn and Reiser 1991, Van der Kraak and Pankhurst 1997, McCullough 1999, OPSW 1999, Torgersen et al. 1999, Poole and Berman 2001, Caissie 2006, McCullough et al. 2009, Mayer 2012, Tan and Cherkauer 2013	Torgersen et al. 1999, Arrigoni et al. 2008, Farrell et al. 2008 (aerobic scope of migrations), Isaak et al. 2010, Arismendi et al. 2012, Isaak et al. 2012 (climate change, wildfire), Arismendi et al. 2013a,b	Torgersen et al. 1999	Spatial: empirical data expensive, models (i.e., from NorWeST[a]) inexpensive; temporal: yes.	Van der Kraak and Pankhurst 1997, Torgersen et al. 1999
	Dissolved oxygen	OPSW 1999	Inkpen and Embrey 1998	Inkpen and Embrey 1998, OPSW 1999	—	—
	Nutrients	OPSW 1999, Naiman et al. 2002b	Inkpen and Embrey 1998	Inkpen and Embrey 1998	—	—
	Conductivity	OPSW 1999	Gardi 2001	OPSW 1999	—	—
	Riparian species composition and buffer width	Bisson et al 1988, Bilby and Ward 1989, Hyatt et al. 2004	Beechie et al. 2003, Fullerton et al. 2006	Beechie et al. 2003, Fullerton et al. 2006	Hyatt et al. 2004, Fullerton et al. 2006	Kauffmann et al. 1999 (proportion of riparian across-stream S:N = 0–37, avg. 4.6), Fullerton et al. 2006
	Length of human-modified bank	Beamer and Henderson 1998	Beamer and Henderson 1998	Yes, via link to land cover.	Beamer and Henderson 1998	Should be high.
	Contaminants	Feist et al. 2011, Spromberg and Scholz 2011	Booth and Reinelt 1993, Inkpen and Embrey 1998, Feist et al. 2011, Spromberg and Scholz 2011	Booth and Reinelt 1993, Inkpen and Embrey 1998, Feist et al. 2011, Spromberg and Scholz 2011, Jones et al. 2015	—	Booth and Reinelt 1993

[a] https://www.fs.fed.us/rm/boise/AWAE/projects/NorWeST.html

Table C-5. Score sheet for delta metrics. Metrics in bold are those that scored 4.5 or higher and were selected for monitoring.

Data resolution	Type	Metric	Link to salmon VSP	Sensitive to land use	Link across scales	Cost-effective	Signal-to-noise ratio	Total
Satellite	Habitat quantity	Estuary surface area/drainage area	1	0	1	1	1	4
		Wetland area	1	1	1	1	0.5	4.5
		Elevation (sediment accretion)	1	1	0.5	0.5	0.5	3.5
	Pressure/process	**Percent natural, agricultural, and developed land cover**	1	1	1	1	1	5
		Length of tidal barriers/levees	1	1	1	1	0	4
Aerial photography/ lidar	Habitat quantity	**Tidal channel area**	1	1	1	1	0.5	4.5
		Tidally influenced area	1	1	1	0	0.5	3.5
	Habitat quality	**Node density**	1	1	1	1	0.5	4.5
		Wetland area by type	1	1	1	1	0.5	4.5
		Infrared intensity	0.5	1	1	1	0.5	4
		Aerial extent of salinity zones	1	1	1	0.5	0	3.5
	Pressure/process	**Proportion of delta behind levees (connectivity)**	1	1	1	1	0.5	4.5
		Length of levees and dikes along distributaries	1	1	1	1	0.5	4.5
Field	Habitat quality	Plant species diversity and composition	0.5	1	1	1	0.5	4
		Proportion of nonnative species	0.5	1	1	1	0.5	4
		Wetland type	1	1	1	0.5	0.5	4
		Temperature	1	1	1	0.5	0.5	4
		Dissolved oxygen	1	0.5	0.5	0.5	0.5	3
		Extent of salinity zones	1	1	1	0.5	0.5	4
	Pressure/process	**Length of armoring**	1	1	1	1	0.5	4.5
		Location of barriers and culverts blocking access	1	1	1	1	0.5	4.5
		Contaminants	1	1	0.5	0	0.5	3
		Nutrients	1	1	0.5	0	0.5	3
		Bay fringe erosion rate	0.5	1	0	0	0.5	2
		Sediment accretion rate	0.5	1	0.5	0	0.5	2.5

Table C-6. References supporting scores for delta metrics. Metrics in bold are those that scored 4.5 or higher and were selected for monitoring.

Data resolution	Metric	Link to salmon VSP	Sensitive to land use	Link across scales	Cost-effective	Signal-to-noise ratio (S:N)
Satellite	Estuary surface area/ drainage area	Bottom and Jones 1990, Visintainer et al. 2006, Engle et al. 2007, Lee and Brown 2009	Bottom and Jones 1990, Engle et al. 2007, Hood 2007a, Lee and Brown 2009	Bottom and Jones 1990, Lee and Brown 2009, Edmonds and Slingerland 2010	Engle et al. 2007, Lee and Brown 2009	Relatively insensitive to variations.
	Wetland area	—	Hood 2007b	Hood 2007b	—	Hood 2007b
	Elevation (sediment accretion)	—	French and Stoddart 1992	—	—	—
	Percent natural, agricultural, and developed land cover	—	Hood 2004, Kennedy et al. 2010, Vanderhoof 2011	Hood 2004, Kennedy et al. 2010, Vanderhoof 2011	—	—
	Length of tidal barriers/levees	Toft et al. 2007, Fresh et al. 2011, Greene et al. 2012, Morley et al. 2012	Toft et al. 2007, Greene et al. 2012	Fresh et al. 2011, Greene et al. 2012	Fresh et al. 2011, Greene et al. 2012	Fresh et al. 2012
Aerial photography/ lidar	**Tidal channel area**	Simenstad and Cordell 2000, Howe and Simenstad 2014, Hood 2015	Coleman 1988, Makaske 2001, Pasternack et al. 2001, Slingerland and Smith 2004, Syvitski et al. 2005, Edmonds and Slingerland 2007, Hood 2007a, Stouthamer and Berendsen 2007, Syvitski and Saito 2007, Syvitski 2008	Collins et al. 2003	—	—
	Tidally influenced area	Levy and Northcote 1982, Halpin 1997, Williams and Zedler 1999, Hood 2002	Simenstad 1983, Odum 1984, Rozas et al. 1988, French and Stoddart 1992, Pethick 1992, French and Spencer 1993	—	—	—

Table C-6 (continued). References supporting scores for delta metrics. Bold metrics scored 4.5 or higher and were selected for monitoring.

Data resolution	Metric	Link to salmon VSP	Sensitive to land use	Link across scales	Cost-effective	Signal-to-noise ratio (S:N)
Aerial photography/ lidar	**Node density**	Visintainer et al. 2006, Krentz 2007, Luck et al. 2010, Simenstad et al. 2011, Whited et al. 2011, Beamish et al. 2013	Visintainer et al. 2006, Krentz 2007, Luck et al. 2010, Simenstad et al. 2011, Whited et al. 2011, Beamish et al. 2013	—	Visintainer et al. 2006 (historical mapping for many areas), Luck et al. 2010, Whited et al. 2011	Natural variation on longer time scales, but not defined. Variation attainable through historical analysis. Natural features should be stable for short time scales.
	Wetland area by type	Lunetta et al. 1997, Good 2000, Magnusson and Hilborn 2003, Bottom et al. 2005a, Bottom et al. 2005b, Van Dyke and Wasson 2005, Hood 2007a, Maier and Simenstad 2009, Barbier et al. 2011, Greene and Beamer 2012, Beamer et al. 2013, Jones et al. 2014	Lunetta et al. 1997, Good 2000, Magnusson and Hilborn 2003, Bottom et al. 2005a, Bottom et al. 2005b, Van Dyke and Wasson 2005, Hood 2007a, Maier and Simenstad 2009, Barbier et al. 2011, Greene and Beamer 2012, Beamer et al. 2013, Jones et al. 2014	Collins and Sheik 2005, Simenstad et al. 2011, Marcoe and Pilson 2013; See also: National Wetlands Inventory[a]	Thomas 1983, Good 2000, Borde et al. 2003, Collins and Sheik 2005, Van Dyke and Wasson 2005, Marcoe and Pilson 2013	Spatial variations well captured by remote sensing and GIS mapping. S:N is high, but may require ground-truthing of wetland classes mapped from imagery.
	Infrared intensity	Ausseil et al. 2007	Chust et al. 2008	Chust et al. 2008	Ausseil et al. 2007	Chust et al. 2008
	Aerial extent of salinity zones	Bottom and Jones 1990	Jay and Naik 2011, Cloern and Jassby 2012	Cowardin et al. 1979, Monaco et al. 1990, Emmett et al. 1991	Moore et al. 2008a, Moore et al. 2008b	Moore et al. 2008a,b, Cloern and Jassby 2012
	Proportion of delta behind levees (connectivity)	Magnusson and Hilborn 2003, Bottom et al. 2005a, Bottom et al. 2005b, Greene et al. 2012	Collins et al 2003, Greene et al. 2012	Collins et al 2003, Greene et al. 2012	Greene et al. 2012	—
	Length of levees and dikes along distributaries	Quinn 2005, Toft et al. 2007, Fresh et al. 2011, Greene et al. 2012, Morley et al. 2012, Woodson et al. 2013	Collins et al. 2003, Toft et al. 2007, Greene et al. 2012	Fresh et al. 2011, Greene et al. 2012	Fresh et al. 2011, Greene et al. 2012	Fresh et al. 2012

[a] http://www.fws.gov/wetlands/

Table C-6 (continued). References supporting scores for delta metrics. Bold metrics scored 4.5 or higher and were selected for monitoring.

Data resolution	Metric	Link to salmon VSP	Sensitive to land use	Link across scales	Cost-effective	Signal-to-noise ratio (S:N)
Field	Plant species diversity and composition	Good 2000	Mack and Kentula 2010, Kentula et al. 2011	Mack and Kentula 2010, Kentula et al. 2011	Mack and Kentula 2010, Kentula et al. 2011	—
	Proportion of nonnative species	Good 2000	Karr and Chu 1999, Mack and Kentula 2010	Mack and Kentula 2010, Kentula et al. 2011	Mack and Kentula 2010, Kentula et al. 2011	—
	Wetland type diversity	Lott 2004	Karr and Chu 1999, Mack and Kentula 2010	Mack and Kentula 2010, Kentula et al. 2011	Mack and Kentula 2010, Kentula et al. 2011	—
	Temperature	Baker 1995, Good 2000	Howarth et al. 1991, Bilkovic et al. 2006, Hayslip et al. 2006	Bilkovic et al. 2006, Hayslip et al. 2006	—	—
	Dissolved oxygen	Good 2000	Howarth et al. 1991, Bilkovic et al. 2006, Hayslip et al. 2006	Bilkovic et al. 2006, Hayslip et al. 2006	—	—
	Extent of salinity zones	Iwata and Komatsu 1984, Morgan and Iwama 1991, Good 2000	Howarth et al. 1991, Bilkovic et al. 2006, Hayslip et al. 2006	Bilkovic et al. 2006, Hayslip et al. 2006	—	—
	Length of armoring	Quinn 2005, Toft et al. 2007, Fresh et al. 2011, Greene et al. 2012, Morley et al. 2012, Woodson et al. 2013	Collins et al 2003, Toft et al. 2007, Greene et al. 2012	Fresh et al. 2011, Greene et al. 2012	Fresh et al. 2011, Greene et al. 2012	—
	Location of barriers and culverts blocking access	Quinn 2005, Toft et al. 2007, Fresh et al. 2011, Greene et al. 2012, Morley et al. 2012, Woodson et al. 2013	Collins et al 2003, Toft et al. 2007, Greene et al. 2012	Fresh et al. 2011, Greene et al. 2012	Fresh et al. 2011, Greene et al. 2012	—
	Contaminants	Stein et al. 1995, Arkoosh et al. 1998	Stein et al. 1995, Arkoosh et al. 1998, Hayslip et al. 2006	Stein et al. 1995, Arkoosh et al. 1998	Field collection, lab analysis.	Arkoosh et al. 1998
	Nutrients	—	Hayslip et al. 2006	Hayslip et al. 2006	—	—
	Bay fringe erosion rate	—	Edmonds and Slingerland 2007, Edmonds et al. 2011	Edmonds and Slingerland 2007, Edmonds et al. 2011	Edmonds and Slingerland 2007, Edmonds et al. 2011	—
	Sediment accretion rate	—	Edmonds and Slingerland 2007, Edmonds et al. 2011	Edmonds and Slingerland 2007, Edmonds et al. 2011	Edmonds and Slingerland 2007, Edmonds et al. 2011	—

Table C-7. Score sheet for nearshore metrics. Metrics in bold are those that scored 4.5 or higher and were selected for monitoring.

Data resolution	Type	Metric	Link to salmon VSP	Sensitive to land use	Link across scales	Cost-effective	Signal-to-noise ratio	Total
Satellite	Pressure/process	**Percent natural, agricultural, and developed land cover**	1	1	1	1	0.5	4.5
Aerial photography/ lidar	Habitat quantity	Length of unarmored feeder bluffs	0.5	1	0.5	1	0.5	3.5
		Area of eelgrass	1	1	1	1	0.5	4.5
		Area of kelp	1	1	1	1	0.5	4.5
		Embayment area	1	1	1	1	0.5	4.5
		Beach width	0.5	1	1	1	0.5	4
	Habitat quality	**Connectivity of embayment to nearshore (width of opening)**	1	1	1	1	0.5	4.5
		Length of forested shoreline	1	1	1	1	1	5
	Pressure/process	**Shoreline armoring**	1	1	1	1	0.5	4.5
		Percent impervious (in 200-m buffer)	1	1	1	1	0.5	4.5
		Percent forest (in 200-m buffer)	1	1	1	1	0.5	4.5
		Area of overwater structures	1	1	0.5	1	1	4.5
Field	Habitat quantity	Elevation of bulkhead toe	1	1	0.5	0.5	0.5	3.5
		Small stream/pocket estuary connectivity	1	1	0.5	1	0.5	4
	Habitat quality	Beach composition (shells)	0	0	0	0	0.5	0.5
		Epibenthic taxa richness	1	1	0.5	0	0.5	3
		Grain size	0.5	0.5	0.5	0.5	0.5	2.5
		Area of wood and rack	1	1	1	0.5	0.5	4
		Temperature	1	1	1	0.5	0.5	4
		Dissolved oxygen	1	1	1	0.5	0.5	4
		Turbidity	1	1	1	0.5	0.5	4
		Condition of pocket estuary and small stream mouth/estuary	1	1	1	0.5	0.5	4
	Pressure/process	**Shoreline armoring**	1	1	1	1	0.5	4.5
		Location of culverts/tide gates blocking access	1	1	1	1	0.5	4.5
		Contaminants	1	1	1	0	0.5	3.5
		Nutrients	0.5	1	1	0	0.5	3

Table C-8. References supporting scores for nearshore metrics. Metrics in bold are those that scored 4.5 or higher and were selected for monitoring.

Data resolution	Metric	Link to salmon VSP	Sensitive to land use	Link across scales	Cost-effective	Signal-to-noise ratio (S:N)
Satellite	**Percent natural, agricultural, and developed land cover**	—	Hood 2004, Kennedy et al. 2010, Vanderhoof 2011	Hood 2004, Kennedy et al. 2010, Vanderhoof 2011	—	—
Aerial photography/ lidar	Length of unarmored feeder bluffs	Whitman and Hawkins 2014	Keuler 1988, Finlayson 2006, Johannessen and MacLennan 2007, Shipman 2008	Fresh et al. 2011	—	—
	Area of eelgrass	Dayton 1985, Simenstad and Wissmar 1985, Duggins et al. 1988, Simenstad et al. 1988, Bottom and Jones 1990, Irlandi 1994, McMillan et al. 1995, Simenstad and Fresh 1995, Short and Burdick 1996, Norris et al. 1997, Robbins 1997, Graham 2004, Krentz 2007, Penttila 2007	Duggins 1980, Foster and Schiel 1985, Carr 1991, Jones 1992, Bustamante and Branch 1996, Steneck et al. 2002, Mumford 2007	Bernstein et al. 2011, Gaeckle et al. 2011	Bernstein et al. 2011	Thom et al. 2012
	Area of kelp	Dayton 1985, Simenstad and Wissmar 1985, Duggins et al. 1988, Simenstad et al. 1988, Bottom and Jones 1990, Irlandi 1994, McMillan et al. 1995, Simenstad and Fresh 1995, Short and Burdick 1996, Norris et al. 1997, Robbins 1997, Graham 2004, Krentz 2007, Penttila 2007	Duggins 1980, Foster and Schiel 1985, Carr 1991, Jones 1992, Bustamante and Branch 1996, Babcock et al. 1999, Steneck et al. 2002, Mumford 2007	Bernstein et al. 2011, Gaeckle et al. 2011	Bernstein et al. 2011	Thom et al. 2012

Table C-8 (continued). References supporting scores for nearshore metrics. Bold metrics scored 4.5 or higher and were selected for monitoring.

Data resolution	Metric	Link to salmon VSP	Sensitive to land use	Link across scales	Cost-effective	Signal-to-noise ratio (S:N)
Aerial photography/lidar	**Embayment area**	Levy and Northcote 1982, Simenstad and Cordell 2000, Beamer et al. 2005, McBride et al. 2005	Shipman 2008, Fresh et al. 2011, Simenstad et al. 2011	—	—	Beamer et al. 2003
	Beach width	—	—	—	—	—
	Connectivity of embayment to nearshore (width of opening)	Simenstad and Cordell 2000, Beamer et al. 2003, 2005	Clancy et al. 2009	Clancy et al. 2009	—	—
	Length of forested shoreline	MacLennan and Johannessen 2008	Brennan et al. 2009	—	—	—
	Shoreline armoring	Toft et al. 2007, Morely et al. 2012, Heerhartz et al. 2014	Toft et al. 2007, Fresh et al. 2011, Greene et al. 2012, Morely et al. 2012, Heerhartz et al. 2014	Fresh et al. 2011, Greene et al. 2012	Greene et al. 2012	—
	Percent impervious cover (in 200-m buffer)	—	Richey 1982, Booth 1991, Arnold and Gibbons 1996, May 1996, May et al. 1997, Moscrip and Montgomery 1997, Morley and Karr 2002, Matzen and Berge 2008, Brennan et al. 2009	Brennan et al. 2009	—	—
	Percent forest (in 200-m buffer)	—	Richey 1982, Booth 1991, Arnold and Gibbons 1996, May 1996, May et al. 1997, Moscrip and Montgomery 1997, Morley and Karr 2002, Matzen and Berge 2008, Brennan et al. 2009	Brennan et al. 2009	—	—
	Area of overwater structures	Toft et al. 2007, 2013	Higgins 2014	Higgins 2014	—	—
Field	Elevation of bulkhead toe	—	—	—	—	—

Table C-8 (continued). References supporting scores for nearshore metrics. Bold metrics scored 4.5 or higher and were selected for monitoring.

Data resolution	Metric	Link to salmon VSP	Sensitive to land use	Link across scales	Cost-effective	Signal-to-noise ratio (S:N)
Field	Small stream/pocket estuary connectivity	—	—	—	—	—
	Beach composition (shells)	—	—	—	—	—
	Epibenthic taxa rischness	—	—	—	—	—
	Grain size	—	—	—	—	—
	Area of wood and rack	Heerhartz et al. 2013	—	—	—	—
	Temperature	National Research Council 2000, Young and Sanzone 2002, Heinz Center 2008, Krembs 2012	National Research Council 2000, Young and Sanzone 2002, Heinz Center 2008, Krembs 2012	Yes	Yes	Yes
	Dissolved oxygen	Diaz and Rosenberg 1995, National Research Council 2000, Young and Sanzone 2002, Heinz Center 2008, Krembs 2012	National Research Council 2000, Young and Sanzone 2002, Heinz Center 2008, Krembs 2012	Yes	Yes	Yes
	Turbidity	—	—	—	—	—
	Condition of pocket estuary and small stream mouth/ estuary	—	—	—	—	—
	Shoreline armoring	Rice 2006, National Research Council 2007, Toft et al. 2007, Halpern et al. 2009, Shipman et al. 2010, Sobocinski et al. 2010, Morley et al. 2012, Heerhartz et al. 2014	Fletcher et al. 1997, Woodroffe 2002, Griggs 2005, Toft et al. 2007, Shipman et al. 2010	Yes	—	Storlazzi and Griggs 2000, Storlazzi et al. 2000, Simenstad et al. 2011
	Location of culverts/ tide gates blocking access	Greene et al. 2012	Collins et al. 2003	—	—	—
	Contaminants	West et al. 2001, 2011, unpublished data[a]	—	—	—	—
	Nutrients	—	—	—	—	—

[a] J. E. West, S. M. O'Neil, J. Lanksbury, G. M. Ylitalo, and S. Redman, Washington State Department of Fish and Wildlife and Puget Sound Partnership, unpublished data.

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Appendix D: Monitoring Protocols

Our monitoring protocols are designed to efficiently measure the suite of selected metrics at each sample site. Here we describe the sampling protocols for each data type (satellite, aerial photography/lidar, or field) in each habitat area. Our aim is to have a suite of metrics that can be measured quickly at each site, so that we can achieve a large sample size within each stratum. In general, we anticipate that we will have complete (yet low-resolution) coverage of the landscape with satellite data, large, mid-resolution sample sizes for the aerial photography data, and small, high-resolution sample sizes for field metrics.

Satellite Protocols

Large River and Floodplain Satellite Protocols

We selected two satellite metrics for large rivers and floodplains, percent forest area on the floodplain and percent developed area on the floodplain. For this analysis there were four land-cover data sets available (Table D-1).

Table D-1. List of available land-cover data sets used in the Puget Sound Habitat Status and Trends Monitoring Program (PSHSTM).

Data set specifications and availability					
Data set	**Pixel size**	**Year**	**Coverage**	**Number of land-cover classes**	**Availability status**
C-CAP (NLCD Landsat, aerial photography, field data)	30 m	1992, 1996, 2001, 2006, 2011	Puget Sound	25	available
NLCD (Landsat, 5-year cycle)	30 m	2001, 2006, 2011	United States	16	available
LandTrendr (USGS and NASA Landsat)	30 m	1986–2008	Puget Sound	7	available (through 2010 in spring 2015)
NAIP (satellite/aerial photography)	1 m	2011	Puget Sound	8	available (other years may be added in the future)

Percent forest and percent developed land cover in the ESU

Two layers were required for this analysis: 1) a floodplain polygon layer for all of Puget Sound, and 2) Landsat data from NOAA's Coastal Change Analysis Program (C-CAP). The protocols for calculating percent forested floodplain and percent developed floodplain in each sampled floodplain site are:

1. In GIS, convert all layers to the same projection as the land-cover raster file (C-CAP).
2. Add the layers required to the data frame within ArcMap.
3. Using the reclass or extract tools, group and extract C-CAP's 25 land-cover layers into separate raster layers of forest, agriculture, and developed (see Table 2 for the classification system).
4. Run *Zonal Statistics as Table* for each land-class raster layer using the floodplain polygon layer as your input feature zone data and a Reach ID as the zone field. The input value raster will be the land-cover raster layer.
5. When you have run zonal statistics for all land-cover types, join the tables to the original polygon layer (be sure to keep all records) and extract the table to Excel (Conversion Tools).
6. Evaluate sites within Excel and calculate the percentage of each land-cover class within all floodplain polygons in the ESU:

$$\text{\% forest area in ESU} = \frac{\text{sum of forest area in ESU}}{\text{total area of floodplain in ESU}}$$

$$\text{\% developed area in ESU} = \frac{\text{sum of developed area in ESU}}{\text{total area of floodplain in ESU}}$$

Percent forest and percent developed land cover by major population group (MPG)

Four layers were required for this analysis: 1) 2011 C-CAP Landsat data, 2) 2011 National Agriculture Imagery Program (NAIP) data, 3) a floodplain polygon layer for all of Puget Sound, and 4) a map of the MPGs. The attributes necessary for C-CAP and NAIP data are the land-cover class and a unique land-cover code or value. The Puget Sound-wide floodplain polygon layer will need a unique identifier ID and area. The attribute necessary for the MPG layer is the MPG name.

The protocols for calculating land-cover status are:

1. In GIS, convert all layers to the same projection as the land-cover raster file (start with C-CAP, then do the same for a separate analysis with NAIP). Note: Skip step 4 for the C-CAP dataset.
2. Add the appropriate layers to the data frame within ArcMap.
3. Spatially join the MPG layer with the floodplain layer, so that each floodplain polygon has an assigned MPG name.
4. For the NAIP dataset, first clip the full NAIP layer by the floodplain layer:
    a. Add a field to the floodplain polygon layer and assign all values to 1:
        i. Open the attribute table and select *Add Field.*
        ii. Using *Field Calculator*, assign all entries a value of 1.
    b. *Select Convert Feature to Raster*:
        i. Use the floodplain polygon layer with the added field as the input.
        ii. Select the new *Field* where all entries are 1.
        iii. Input the NAIP raster layer for *Output Cell Size.*

Table D-2. NAIP land-cover classifications.

NAIP land-cover class	PSHSTM land-cover class	NAIP land-cover code	Group number
1. Shadow/Water	water	1	1
2. Indeterminate	other	2	2
3. Built/Gray	impervious	3	3
4. Bare ground	other	4	2
5. Veg shadow/Tree	other/forest	5	2 or 4
6. Herbaceous/Grass	other	6	2
7. Shrub OR Tree	other/forest	7	2 or 4
8. Tree	forest	8	4

iv. Within *Environments*, set *Processing Extent* to *Same as layer* (the NAIP land-cover layer).

c. Open the *Raster Calculator*:

i. Multiply the newly created raster layer of floodplain polygons by the original full-extent NAIP land-cover layer.

d. Use the output land-cover raster to follow steps 5 and 6.

5. Reclass (or Extract) the land-cover classes of interest from the C-CAP data as separate raster layers. In this case, we were interested in forest and developed land cover. See Table 2 and Table D-2 for the groupings of C-CAP and NAIP land-cover classes.
6. Run *Zonal Statistics as Table* for each land-cover raster layer using the floodplain polygon layer as your input feature zone data and a Reach ID as the zone field. The Input value raster will be the land-cover raster layer.
7. When you have run zonal statistics for all your land-cover types, join the tables to the original polygon layer (so you are sure to keep all records) and extract the table to Excel (Conversion Tools) for analysis by area of floodplain and area of land-cover class (in this case, the forest and developed land-cover classes):

$$\%\text{ forest by MPG} = \frac{\text{sum of forest area in MPG}}{\text{total area of floodplains in MPG}}$$

$$\%\text{ developed area by MPG} = \frac{\text{sum of developed area in MPG}}{\text{total area of floodplains in MPG}}$$

Percent forest and percent developed land cover by land-cover class

Three layers were required for this analysis: 1) C-CAP Landsat data for Puget Sound; 2) NAIP data for Puget Sound; 3) a floodplain polygon layer of sample sites. The attributes necessary within the land-cover datasets (C-CAP and NAIP) are the land-cover class and unique land-cover code or value. The floodplain polygon layer will need the Reach ID or Site ID to link the land-cover class to the site, and the area of the polygon.

The protocols for percent forest and percent developed land cover by land-cover class are:

1. In GIS, convert all layers to the same projection as the land-cover raster file (start with C-CAP, then do the same for a separate analysis with NAIP). Note: Skip step 3 for the C-CAP dataset.
2. Add the appropriate layers to the data frame within ArcMap.
3. For the NAIP dataset, first clip the full NAIP layer by the floodplain layer:
    a. Add a field to the floodplain polygon layer and assign all values to 1:
        i. Open the attribute table and select *Add Field.*
        ii. Using *Field Calculator,* assign all entries a value of 1.
    b. *Select Convert Feature to Raster*:
        i. Use the floodplain polygon layer with the added field as an input.
        ii. Select the new *Field* where all entries are 1.
        iii. Input the NAIP raster layer for *Output Cell Size.*
        iv. Within *Environments*, set *Processing Extent* to *Same as layer* (the NAIP land-cover layer).
    c. Open the *Raster Calculator*:
        i. Multiply the newly created raster layer of floodplain polygons by the original full-extent NAIP land-cover layer.
    d. Use the output land-cover raster to follow steps 4–6.
4. Reclass (or Extract) land-cover classes of interest from Landsat data as separate raster layers. In this case, we were interested in forest and developed land cover. See Table 2 and Table D-2 for the groupings of C-CAP and NAIP land-cover classes.
5. Run *Zonal Statistics as Table* for each land-class raster layer using the floodplain polygon layer as your input feature zone data and a Reach ID as zone field. The input value raster will be the land-cover raster layer.
6. When you have run zonal statistics for all your land-cover types, join the tables to the original polygon layer (so you are sure to keep all records) and extract the table to Excel (Conversion Tools) for analysis by area of floodplain and area of land-cover class (in this case, the forest and developed land-cover classes):

$$\text{\% forest area in sample site} = \frac{\text{forest area in sample site}}{\text{area of floodplain sample site polygon}}$$

$$\text{\% developed area in sample site} = \frac{\text{developed area in sample site}}{\text{area of floodplain sample site polygon}}$$

Delta and Nearshore Satellite Protocols

Land cover was summarized for each delta using PSNERP delta polygons and C-CAP 2011 land-cover data (Landsat) grouped into forest, agriculture, and developed land-cover types (see Table 2 for a reclassification of C-CAP land-cover classes). The delta polygons used for these summaries do not consider connectivity, but do include areas that are not connected to tidal flooding. Given that all deltas were sampled, percent cover by type was summarized without statistical comparisons by delta, Chinook salmon (*Oncorhynchus tshawytscha*) MPG, or steelhead (*O. mykiss*) MPG. From these data, we calculated percent forest and percent developed land-cover metrics for each delta, and data were summarized by MPG and delta land-cover class.

Aerial Photography Protocols

Large River and Floodplain Aerial Photography Protocols

We based our aerial photography protocols for large river and floodplain areas on several sources, including WFPB (2011), Beechie et al. (2006a), and Fullerton et al. (2006). These sources described general methods of measuring channel and riparian characteristics, but our protocols required much greater specificity in order to create a repeatable methodology for monitoring trends over time. We developed these protocols over several iterations of aerial photography trials, and used interobserver comparisons to help identify and correct errors or omissions in the protocols (i.e., to identify where increased specificity in the protocols could reduce interobserver variation).

Land cover

The sampling area for floodplain land cover is the high floodplain polygon from Konrad (2015), which is based on analysis of the 10-m National Elevation Dataset (NED). Land-cover data are available from C-CAP, and change analyses have been completed for five years from 1992 to 2011 (Table D-1). Future analyses of land-cover change can be obtained directly from C-CAP. Data are also available from the National Land Cover Dataset (NLCD), but only for the years 2001, 2006, and 2011. NOAA has also generated an annual time series (1986 to 2008) of land cover from satellite data (LandTrendr, Kennedy et al. 2010). Finally, the Washington Department of Fish and Wildlife (WDFW) has developed land-cover data for Puget Sound based on NAIP (K. Pierce, Washington Department of Fish and Wildlife, unpublished data). Each dataset uses a slightly different land-cover classification system (Table D-3).

Six GIS layers are required for the land-cover accuracy assessment: 1) C-CAP Landsat data for Puget Sound, 2) NAIP data for Puget Sound, 3) the GIS aerial photography base map, 4) a polygon layer of designated floodplain sites, 5) bankfull lines for each site, and 6) a grid point layer (created using ET GeoWizards [ET SpatialTechniques, Pretoria, South Africa]; see step 2, below).

Table D-3. Comparison of land-cover classification systems across data sets used in the Puget Sound Habitat Status and Trends Monitoring Program.

C-CAP	NLCD	LandTrendr	NAIP
Evergreen forest	Evergreen forest	Evergreen forest	Trees
Deciduous forest	Deciduous forest	Deciduous forest	
Mixed forest	Mixed forest		
Scrub/shrub	Shrub/scrub		Shrub/tree
Grassland	Grassland/herbaceous	Herbaceous	Herbaceous/grass
Palustrine forested wetland	Woody wetlands	NA	NA
Palustrine scrub/shrub wetland			
Palustrine emergent wetland			
Delta forest wetland			
Estuarine scrub/shrub wetland			
Estuarine emergent wetland			
Unconsolidated shore	Herbaceous wetlands		
Cultivated land	Cultivated crops	NA	NA
Pasture/hay	Hay/pasture		
High-intensity developed	Dev. – high intensity	Developed – medium-high intensity	Built/gray
Medium-intensity developed	Dev. – med. intensity		
Low-intensity developed	Dev. – low intensity		
Developed open space	Dev. – open space		
Open water	Open water	Open water	Water/shadow
Palustrine aquatic bed			
Delta aquatic bed			
Unclassified	Perennial ice/snow	Barren land	Bare ground
Bare land	Barren land	Perennial snow/ice	Indeterminate
Tundra			
Snow/ice			

The attributes necessary within the land-cover datasets (C-CAP and NAIP) are the land-cover class and unique code or value. The floodplain polygon layer will need the Reach ID or Site ID within the attribute table, as will the bankfull line polyline layer. The grid point layer will need the Site ID and/or Reach ID as well as a unique ID.

1. Prepare the floodplain polygon for the point grid layer:
    a. Create a polygon of the large river using bankfull lines and the floodplain polygon:
        i. Convert the bankfull line feature to a polygon.
    b. Use this layer to extract the large river from the floodplain polygon, resulting in a floodplain polygon layer that excludes the large river.
    c. Perform a *Spatial Join* to make sure that all floodplain polygons have Reach and Site IDs:
        i. Delete the Site and Reach ID fields in the polygon layer that excludes large rivers, join 1 to 1, and select the closest as your *Match Option*.
    d. *Dissolve* the new polygon layer so that each floodplain site containing two or more polygons is combined into one feature (for creating the grid points).
        i. Dissolve by Site and Reach ID, using the default settings.

2. Use the dissolved floodplain polygon layer minus the large river layer to create grid points for analysis:
    a. Generate grid points with the *Uniform Points in Polygon* tool in ET GeoWizard (set 100 points per site or reach).
3. Process individual NAIP Water Resource Inventory Areas (WRIAs) for analysis:
    a. Reclass the WRIAs and eliminate 0 values with no data (using a mix of Reclass and Set Null within the spatial analyst).
    b. On WRIA files that won't reclass, use SetNull (*Spatial Analyst Tool* → *Conditional*):
        i. For the Expression Field, set VALUE equal to 0.
        ii. Build an attribute table with the output.
        iii. If that doesn't work, convert the file to a tiff and then build the attribute table.
    c. Select *Mosaic to New Raster* in the Data Management Toolbox:
        i. Within the *Environment Setting*, set *Processing Extent* to *Union of Inputs*.
4. Manually classify points using the basemaps in ArcGIS and the classification in Table 2, supplemented with Google Earth aerial imagery.
5. Extract land-cover values from Landsat (C-CAP) and digitized aerial imagery (NAIP) data at the grid points:
    a. Create a table with land-cover class codes and summarize using the numeric *Value* attribute:
        i. Within the attribute table drop-down menu, go to *Export*.
    b. Convert the grid point layer to raster:
        i. If it is not already there, add a Point_ID column to the attribute table:
            1. Set the field type to *long integer*.
            2. Using the field calculator, type "Point_ID=FID+1".
        ii. *Select Feature to Raster* in the Conversion Toolbox.
        iii. Set the field to a unique point ID.
        iv. Set the grid output cell size to the land-cover data layer.
        v. In Environments, set the process extent to be the same as the LC layer.
6. Run zonal statistics using the grid point raster layer:
    a. Make sure each point has a unique ID Value.
    b. Set the statistics type to Mean.
7. Join the zstats table (using whatever statistic type was selected in the zstats tool, in this case MEAN) with the class code table (using VALUE).
8. Summarize in Excel.

Channels and habitat

The GIS layers needed to begin the aerial photography measurements are: 1) the aerial imagery layer, 2) the sample location points, 3) a new polyline layer to contain all of the feature lines, 4) a new polygon layer to contain all of the feature polygons, and 5) the floodplain polygon layer derived from lidar (or the 10-m Digital Elevation Model [DEM] where lidar is not available).

For the polyline layer, the attribute table includes:

- Imagery Date: Extracted from the aerial imagery layer.
- River Name: The name of the river being measured.

- Site ID: Associated with the site location.
- Reach ID: Associated with the site location.
- Sample Type: The category of metric being measured (Large River, Bank, or Edge Habitat).
- Line Type: The category of line being measured within a Sample Type (see lists of line types for each Sample Type below).
- Confidence: A categorical line confidence designation.
- Bank: The bank designation (left or right bank, facing downstream).
- Classification: The side channel and braid classification.
- Length: The calculated line length.
- Cover Classification: The dominant land-cover classification for the reach (forested, agriculture, developed).
- Valley Type: A designation of the valley type (glacial, post-glacial, canyon, mountain valley).
- Observer: The name of the observer performing the measurements.
- Comment: A field where observers can enter comments.

All of these attributes should be included for each line created in the polyline layer. Metrics that are classified in the polyline layer under the Sample Type attribute (Large River, Bank, and Edge Habitat) each have their own line types, which are listed below. Note that the Bank Types describe conditions at the edge of the bankfull channel (i.e., outside the water), whereas the Edge Habitat Types describe aquatic habitat conditions experienced by fish.

The Large River line types include:

- Main channel: Contains a majority of the river discharge.
- Braid: Contains less than half of the discharge and is separated from the main channel by an unvegetated bar.
- Side channel: Contains less than half of the discharge and is separated from the main channel by a vegetated island.
- Valley Center Line (VCL): Line located equidistant between the floodplain edges.

The Bank line types include:

- Armored: The bank is protected with rip-rap, concrete, or other material to prevent erosion.
- Levee: The bank is a levee.
- Natural: The bank is in a natural condition (no armor or levee).
- No bank unit (NBU): Where the bank line crosses a side channel or braid, the line is labeled NBU to indicate that there is no bank present.

The Edge Habitat line types (examples of which appear in Figure D-1) include:

- Natural bank: A slow-water unit located where the channel meets a deep, nearly vertical shore, with no rip-rap or revetment (usually at the outside of meander bends or in straight segments).
- Modified bank: A slow-water unit located where the channel meets a deep, nearly vertical shore, and the bank is protected with rip-rap or other revetment.

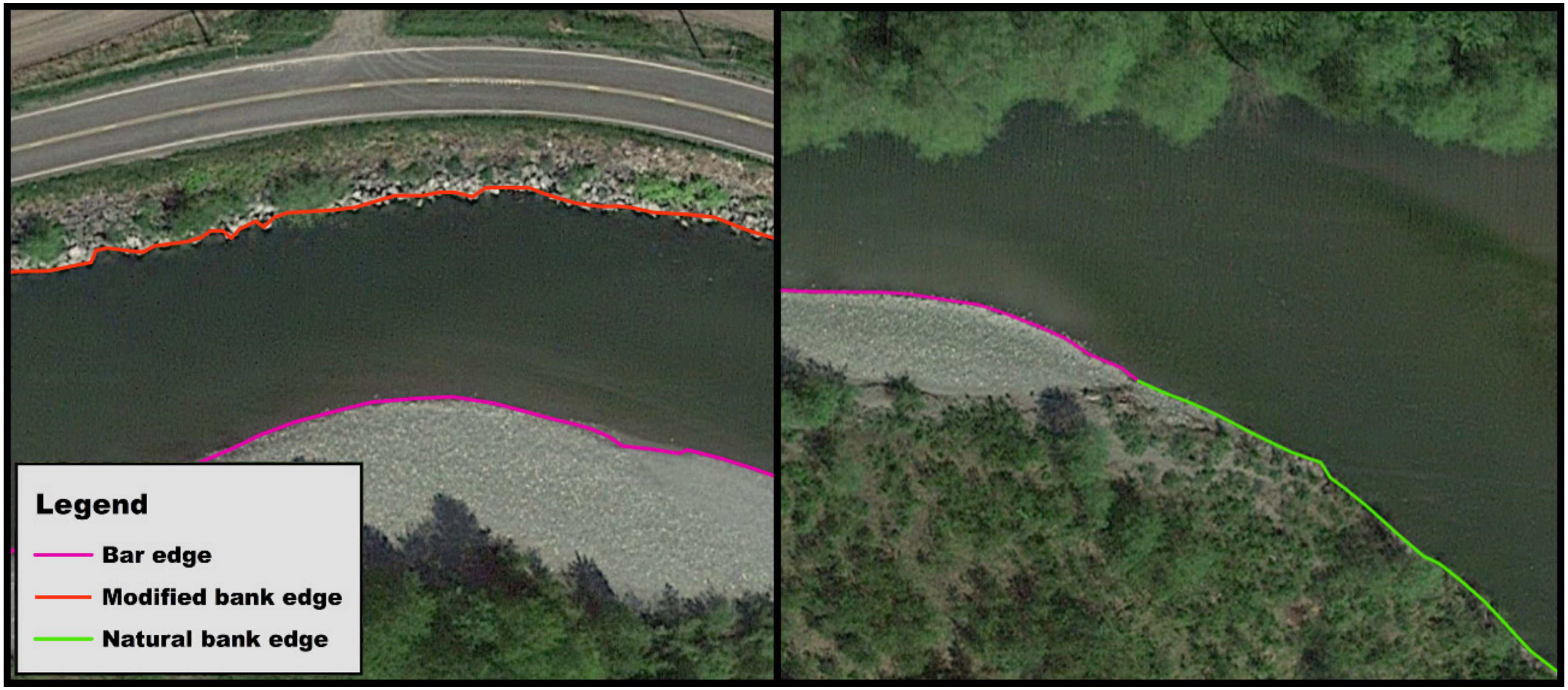

Figure D-1. Example of digitized habitat edge features using the large river aerial photography protocol.

- Bar edge: A slow-water unit located where the channel meets a shallow, gently-sloping shore (usually on the inside of a meander bend).
- No edge unit (NEU): Where the main channel crosses a side channel or braid.

The Confidence attribute designates the observer's categorical confidence in the correct identification of a feature that is being measured. There are three levels of confidence for this attribute:

- High: The entire feature is visible.
- Moderate: Parts of the feature are visible.
- Low: The feature is not visible, but is likely present at the location in question.

In addition, a high confidence call could be utilized if a supporting feature layer is available for that location, even if the feature is not visible. For example, when a leveed bank is suspected to be present but is not clearly visible, but an existing levee layer is available that confirms the presence of a levee at that location, it is appropriate to designate the confidence call as high. Line confidence designations are not required for these line types: main channel, VCL, NBU, and NEU.

The Bank attribute is used to designate which side of a channel a feature is on. Here, designations are Left or Right (when facing downstream) and NA (not applicable). The channel side designation is only required for Bank and Edge Habitat line types. Mainstem lines do not require channel side designations and should be marked with NA.

The Classification attribute is used to classify the type of side channel or braid. There are four types of classifications for this attribute:

- Surface water: The channel is connected at both ends, with water present.
- Groundwater: The channel is only connected at a lower end, with water present.
- Dry: An overflow or flood channel, with water partially present or not present.
- Unknown: Observer is unable to classify the channel.

In order for a feature to be considered a side channel or a braid, at least half of its length should be visible to the observer. In addition, this attribute is only used when side channels or braids are measured. If a line type other than side channel or braid is measured, this attribute should be designated NA in the attribute table.

Similarly to the polyline layer, there are several key attributes that should be incorporated in the attribute table for the polygon layer:

- Imagery Date: Extracted from the aerial imagery layer.
- River Name: The name of the river being measured.
- Site ID: Associated with the site location.
- Reach ID: Associated with the site location.
- Polygon Type: The type of feature being measured.
- Area: The calculated polygon area.

- Cover Classification: The land-cover classification.
- Valley Type: A designation of the valley type.
- Observer: Name of the observer performing the measurements.
- Comment: A field where observers can enter comments.

All of these attributes should be included for each polygon created in the polygon layer. There are three categories in the Polygon Type attribute:

- Backwater: An area of still water within a main channel, side channel, braid, or tributary.
- Wood jam: Wood jam comprising stacked pieces of wood in water, on the bank, or on an island.
- Floodplain: A floodplain polygon created from a floodplain layer.

The backwater and wood jam polygon categories contain a minimum area limit that affects their consideration for metric measurement. The minimum area required for a backwater polygon is 50 m^2 and the minimum area required for a wood jam polygon is 50 m^2. Furthermore, both polygon types should only be measured along their clearly visible and contiguous area. For example, if individual pieces of wood are adjacent to but not connected to a wood jam, they should not be included in the measurement of the wood jam area.

The protocols for aerial photography channel and habitat measurements are:

1. In GIS, add the appropriate layers to the data frame.
2. Measure the bankfull channel width at five equally spaced transects and calculate the average channel width. Calculate the reach length by multiplying the average bankfull channel width by 20, and then digitize the large river line along the thalweg.
3. In the polygon layer, create a floodplain polygon for the reach using the lidar (or 10-m DEM) floodplain layer to delineate the floodplain edges, and create lines across the floodplain at the ends of the large river line. Merge the edges and end lines to create the floodplain polygon. Once this polygon is created, any feature in the polyline layer or the polygon layer should not extend outside of its boundaries.
4. Digitize the valley center line for the reach by creating points at the center of the lower and upper floodplain polygon boundaries and then tracing a smooth line along the center of the valley. This line should be as straight as possible, but where the valley orientation curves, the valley center line should accommodate that curvature.
5. Digitize bank type lines along the bankfull edge on each side of the main channel. In some cases, vegetated islands will be present in the reach. In those cases, the bankfull edge for the main channel will be along the vegetated islands. Bank type lines crossing side channels should be digitized across the side channel between the bank and the vegetated island and should be designated NBU. Each bank line should also be assigned a confidence rating.
6. Digitize edge habitat lines along the main channel edges (not in side channels or braids). Where the main channel edge crosses a side channel, the NEU designation should be used.
7. Digitize each braid and side channel using the following criteria: 1) only digitize a channel if more than half of its length is clearly visible; 2) braids and side channels can be connected within the floodplain, but should not extend past the edge habitat line and should not be connected to the large river line (i.e., they should end at the edge of the main channel);

3) where the floodplain has been disconnected and water does not flow regularly, side channels or braids should not be measured; 4) if a channel is separated from the large river by a vegetated island, designate it as a side channel, and if it is separated by an unvegetated island, designate it as a braid; and 5) if it is unclear whether a feature can be classified as an island within a channel, imagery during different flow conditions should be referred to.

8. In the polygon layer, digitize each wood jam that is visible within the main channel, side channels, braids, and/or functional floodplain (example in Figure D-2). Wood jams should only be measured when 1) the wood jam includes key and racked wood pieces, 2) the wood jam's visible and contiguous area is at least 50 m^2, and 3) only adjoining and visible pieces of wood are included in the wood jam area measurement.
9. Digitize each backwater area. Only backwaters adjoining the main channel or braids should be measured, including backwaters that are at the downstream end of a side channel, braid, or tributary that connects to the main channel. Measurements should be limited to the visible areas of backwaters, and isolated pools or ponds within a floodplain are not considered backwaters.

Riparian buffer width

Riparian buffer width was digitized at a 0.3-m resolution with 2010 aerial photography in ArcMap GIS at a scale of 1:2,000. Methods were modified from Fullerton et al. 2006. During protocol development, we first measured the width of the forested area at ten points along each bankfull channel edge to calculate the average forested buffer width. However, we encountered a number of cases in the riparian buffer analysis that led to a transect not being digitized or being digitized improperly: 1) natural land cover upland of the bankfull line was not forested (no buffer was digitized); 2) the point landed on a side channel inlet or outlet (no buffer was digitized); 3) a side channel >15 m wide ran through the forested buffer, stopping the buffer transect short of 100 m; or 4) elevation was not accounted for in transect length, meaning that buffer widths on hill slopes may be longer than our horizontal measurements indicated.

A total of 50 sites, or 40% of the 124 total sites, had one or more of these issues. Table D-4 illustrates the proportion of sites with issues by type. These results led us to investigate the difference between digitizing forested buffers versus natural buffers (not impacted by humans). The mean buffer width was reevaluated at 32 sites (eight in each land-cover stratum: forest/wetland, agriculture, developed, and mixed), and transects were created or redrawn to include natural buffers. By following this protocol, the issue of a transect not being digitized because a point landed where there was natural land cover or a side channel was eliminated, reducing the proportion of sites with potential issues to only 7% (those due to elevation). Mean buffer width at the 32 sites was calculated and the results are reported in Table D-5.

Within sites classified as predominantly agriculture, we found that there was an 8% difference in mean transect width when digitizing transects based on "forest only" land cover versus "natural" (forest + other natural land cover; Table D-5). However, for forest/wetland, developed, and mixed sites, there was no more than a 2% difference in mean buffer width between methods. Based on these results, our final protocols include modifications to improve consistency of measurements, and we will reevaluate buffer width in the future.

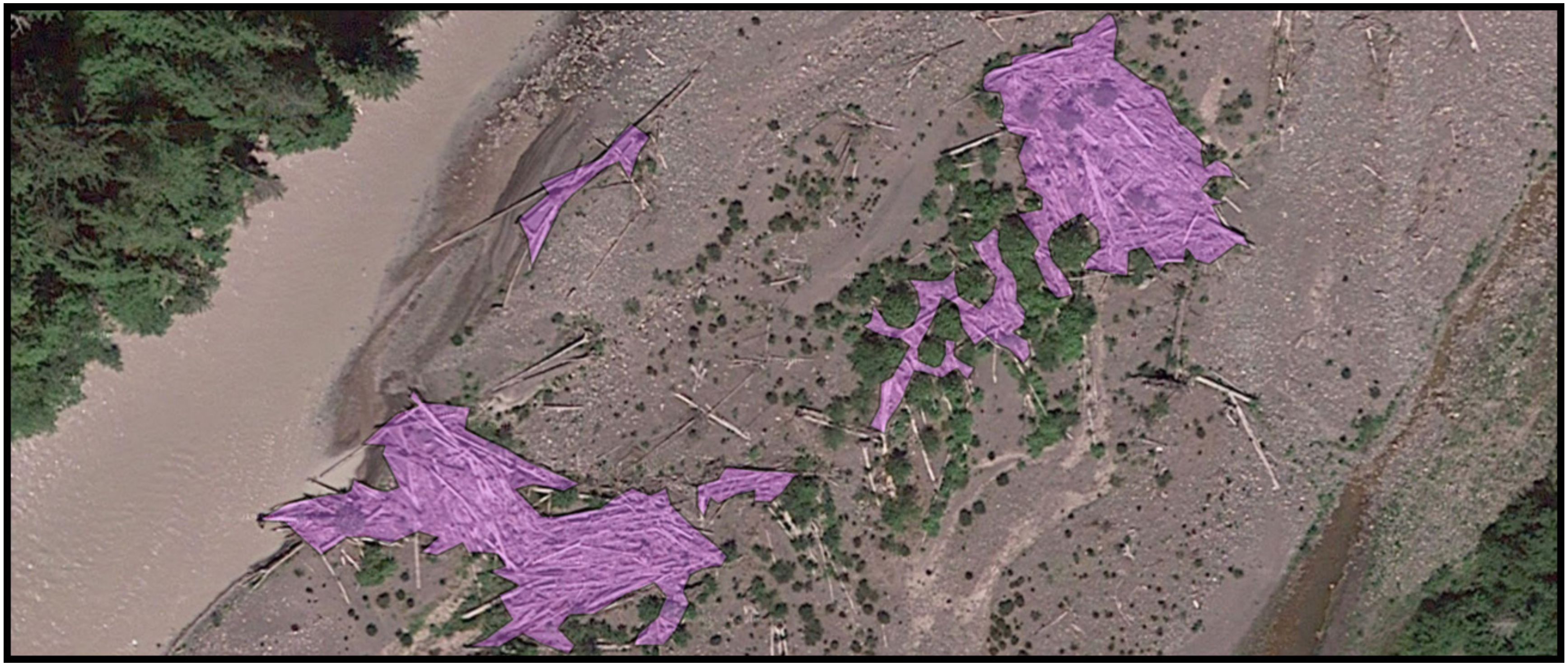

Figure D-2. Example of digitized wood jam area using the protocol. Wood jam area is marked in pink. Excluded wood pieces were not digitized, as they did not meet the requirement of minimum area >50 m².

Table D-4. Proportion of sites by issue type (note: one site may have more than one issue).

Issue encountered	Proportion of total sites
Natural land cover not forested (buffer not digitized)	28%
Side channel issues (buffer not digitized)	14%
Elevation not accounted for (buffer may be measured incorrectly)	7%

Table D-5. Comparison of average buffer widths at 32 sites (eight in each land-cover stratum), drawn using criteria of forest vs. "natural" (not impacted by humans) buffers.

Land-cover stratum	Natural buffer (m)	Forested buffer (m)	Percent difference
Forest/wetland	95	93	+2%
Agriculture	67	62	+8%
Developed	39	39	none
Mixed	56	55	+2%

The final riparian buffer width protocols are:

1. Obtain the right and left bankfull lines that were digitized for the large river habitat analysis.
2. Along each of these lines, create ten equidistant points for a total of 20 points per site.
3. At each point, digitize a buffer transect perpendicular to the bankfull edge, if forested land cover is present at the point.
4. The maximum length of a transect is 100 m. If forest cover ends before 100 m is reached, the transect ends at that point and its length is recorded.
   a. Where the bankfull line is drawn along a vegetated gravel bar with forest upland, digitize the transect until the forest ends or 100 m is reached (Figure D-3).
   b. Where the transect crosses a side channel or gap of other natural land-cover <15 m wide, continue extending the transect until the forest ends or 100 m is reached (Figure D-3).

We also considered classifying different land-cover strata within the 100 m buffer, but found that our classification of land-cover types from aerial photography was not accurate enough to warrant continuing that analysis. However, we report the accuracy assessment for that analysis, and therefore include the protocols here. The protocols for riparian classification from aerial photography were:

1. Using GIS, generate the midpoints of each land-cover segment from field-surveyed riparian transects. Remove all attributed values to mask data being collected from aerial images.
2. Load the midpoint shapefile into ArcMap.
3. Load the base map of aerial imagery into the new map.
4. For each point, classify the vegetation type, size class, density, image date (MM/DD/YYYY), and any comments in the shapefile attribute table. Note: The image date should be the same for each transect and within each site, but image dates should be checked when moving to new sites. Vegetation types (modified from Hyatt et al. 2004 and Lucchetti et al. 2014) are:
   - Conifer dominated: Forested, more than 70% of trees are conifers.
   - Hardwood dominated: Forested, more than 70% of trees are hardwood.
   - Mixed forest: No dominance greater than 70%.
   - Grass/shrub: Grass or small woody vegetation.

Figure D-3. Examples of digitized buffer widths using the riparian buffer width protocols: a) example of exception a) under step 4, b) example of exception b) under step 4. The side channel is >15 m wide.

- Bare ground: Gravel bars, or bare soil not in the agriculture or disturbed pervious vegetation types.
- Water: Open water (rivers, side channels, wetlands, etc.).
- Wetland: Includes open-water wetlands.
- Agriculture: Pasture or row crops.
- Disturbed impervious: Pavement, rooftops, etc.
- Disturbed pervious: Lawns, golf courses, etc.

Size classes for trees (from data in Beechie et al. 2006b and T. J. Beechie, unpublished data) are:

- Crowns not distinguishable (classify as shrub).
- Forest with crown diameter <9 m (<0.3 m mean diameter at breast height [dbh]).
- Forest with crown diameter 9–12 m (0.3–0.5 m mean dbh).
- Forest with crown diameter >12 m (>0.5 m mean dbh).
- NA if the cover class is not forested (e.g., grass/shrub, large river channel, agriculture, disturbed impervious, etc.).

Density classes (from WFPB 2011) are:

- Sparse: >33% of the area is bare ground.
- Dense: <33% of the area is bare ground.
- NA if the cover class is not forested (e.g., grass/shrub, large river channel, agriculture, disturbed impervious, etc.).

Delta and Nearshore Aerial Photography Protocols

We based aerial photography protocols for delta and nearshore areas on several sources, including Beamer et al. (2005) and Hood (2005, 2015). These sources described general methods of delineating functionally distinct tidally influenced channel and marsh features from aerial photography, but our protocols required much greater specificity in order to create a repeatable methodology for monitoring trends over time at the scale of Puget Sound. We developed these protocols over several iterations of aerial photography trials.

Delta channels

Juvenile Chinook salmon utilize specific habitats in deltas where low water velocities and shallow water depths create favorable habitats for rearing. These favorable habitats occur primarily along the margins of distributary channels and blind tidal channels in delta estuaries (Beamer et al. 2005). However, the number of such habitats within Puget Sound is not known given that tidal channel features have not been consistently mapped and quantified across Puget Sound. Mapping of tidal channel features throughout Puget Sound's major deltas would provide the necessary first step toward quantifying the amount of tidal channel habitat while also providing a base layer from which numerous habitat quantity and quality metrics can be derived.

We digitized delta channel features for all 16 major Puget Sound deltas to begin developing status and trends metrics for delta habitat by MPG. From this effort, we developed polygon features of channel networks in all major deltas that were used to calculate habitat area and perimeter estimates. Tidal channel features were digitized within PSNERP delta polygons for all 16 major Puget Sound deltas. Channel features were digitized from 0.3-m resolution Microsoft imagery in ArcMap GIS at a scale of 1:2,000. Aerial images used to digitize channel features in this analysis were acquired on 9 July 2010 (for the Nooksack, Skagit, Samish, Stillaguamish, Dosewallips, Duckabush, Big Quilcene, Dungeness, and Elwha deltas), 24 July 2010 (for the Skokomish and Hamma Hamma deltas), 1 August 2011 (for the Snohomish, Duwamish, Puyallup, and Nisqually deltas), and 20 August 2011 (for the Deschutes delta). We digitized six tidal channel feature types as polygons within each delta unit: 1) primary distributary, 2) distributaries, 3) tidal channels, 4) tidal channel complexes, 5) tidal flats, and 6) industrial waterways (Figure D-4). Each type is functionally different with respect to fish habitat, and requires different protocols to ensure consistent delineation and measurement of channel features within deltas.

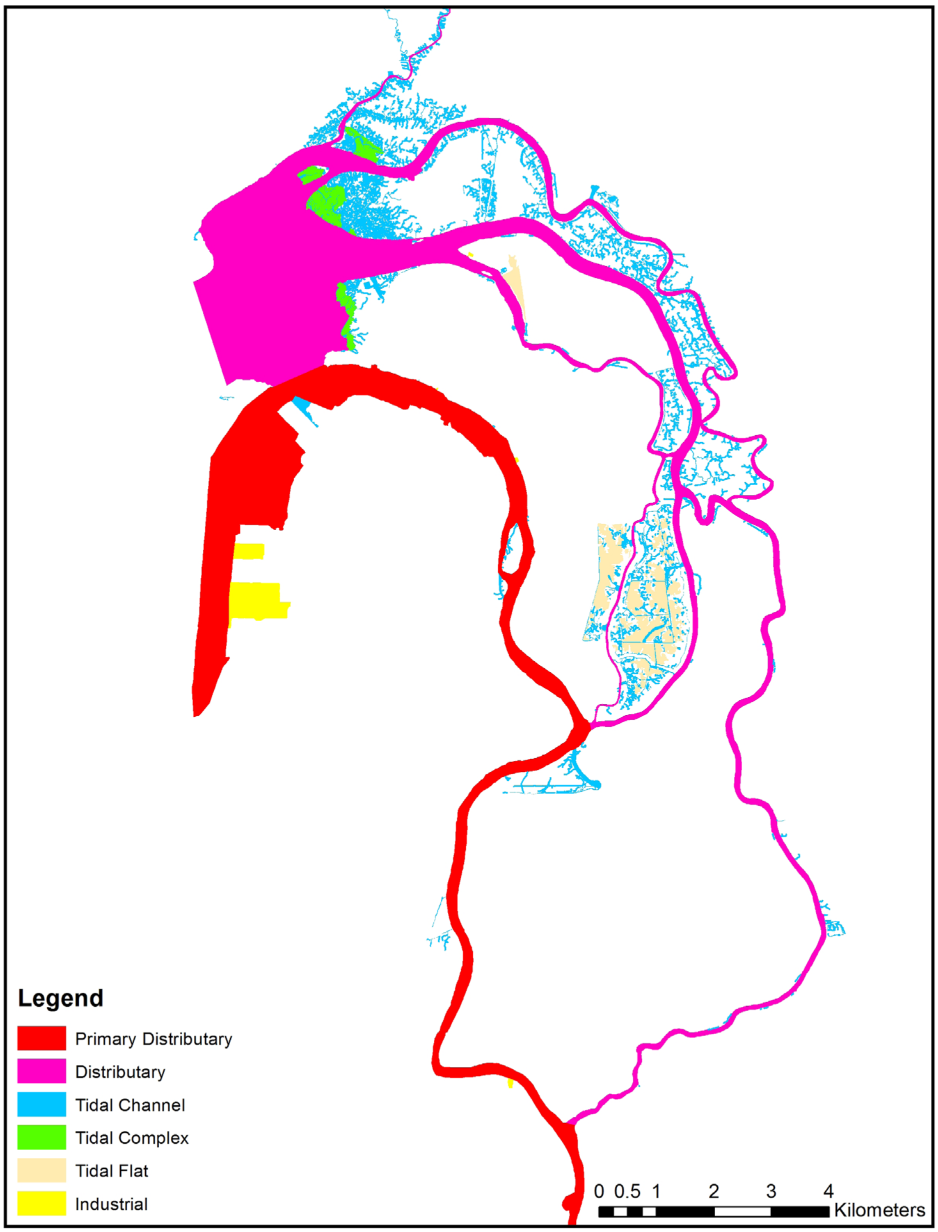

Figure D-4. Example of digitized tidal channel features in the south fork Skagit River delta illustrating the six feature types.

The protocols for aerial photography channel and habitat measurements are:

1. Digitize distributary polygons for channels that a) are formed from bifurcations of the river network and convey river discharge through the delta to saltwater, and b) are at least 5 m wide. Digitize distributaries to bankfull width, except in the lower delta, where tidal flats can greatly extend the bankfull width. Where tidal flats extend >50 m from the primary distributary flow path, digitize the edge of the primary flow path instead of the bankfull width.
2. Digitize tidal channel polygons for blind tidal channels and tidal channels connected to other tidal channels or distributaries (but not those that bifurcate the flow of river water as distributaries). Digitize polygons for all tidal channels that are at least 5 m wide and at least 50 m long, or connected on both ends to other tidal channel or distributary features if <50 m.
3. For tidal channels smaller than 5 m wide and <50 m long, digitize polylines along the flow path and then buffer the polylines by 1 m to create a polygon feature. While all other features can be reasonably delineated within a variety of land-cover types, tidal channel features are most likely to be obscured in areas with forested cover, given that tidal channels are the smallest features to be digitized. Therefore, tidal channels are most likely to be underrepresented in areas with the mature forested cover that makes visual detection and delineation of smaller tidal channels difficult.
4. Digitize tidal complex polygons where complex tidal channel networks within mostly vegetated marshes prevent accurate delineation of channel flow paths and connections within the tidal complex (Figure D-5). These features typically occur in the lower delta, although some maturing restoration projects—where vegetation has become mostly established, but channels have not yet fully formed—can also be digitized as tidal complexes. Channels in these areas account for at least 50% of the polygon area by visual estimation.

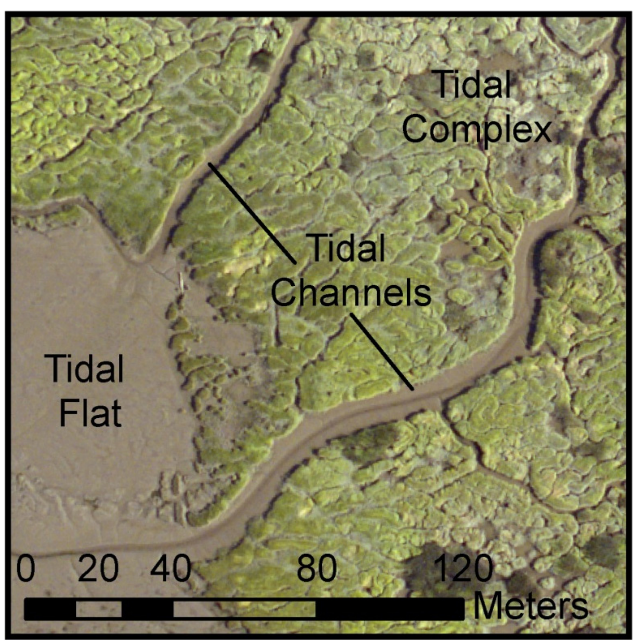

Figure D-5. Example of a tidal complex bordering a tidal flat with numerous tidal channels <5 m wide that were digitized as a tidal complex. Tidal channels that were >5 meters wide within these tidal complexes were still digitized as tidal channels.

5. Digitize tidal flats within the delta polygons where complex channel networks occur within largely unvegetated, tidally flooded areas. However, restricted delineation of tidal flats to the seaward extent of vegetated marsh within the deltas, and exclude mud flat habitats that occur at the delta terminus. While most tide flat habitats do occur within the lower delta, these features also occur in the delta interior, where new restoration projects have restored tidal connectivity but channel formation and vegetation establishment have not progressed enough to develop clearly defined channel networks between vegetated substrate.
6. Digitize industrial waterways as separate polygons where waterways are constructed for human purposes (e.g., marinas, ports, launches, etc.). Connect these industrial channel features to other delta channel network features. Where necessary, digitize to connect other natural channel features within the delta unit (e.g., a tidal channel may connect to a marina basin, but is not directly connected with the distributary that connects to the marina basin).

For all features, areas above culverts or tidegates were not digitized at this time, as the type of structure cannot be accurately determined from aerial imagery. While this approach may omit some delta channel features that have tidal connectivity to the delta network, this was the only way to develop a consistent inventory of delta features in the absence of a comprehensive spatial database of tidegates and culverts in Puget Sound deltas. We did, however, digitize above what appeared to be bridges (but not tidegates or culverts), as tidal connectivity in these areas was less likely to be impacted.

Tidal Channel Edge Habitat Length: Given that we digitized channel polygons, and that juvenile fish are known to primarily use the edges of distributary and tidal channels (Beamer et al. 2005), we also calculated channel perimeters from channel polygons to derive an estimate of edge habitat within each delta. To do this, we dissolved all tidal channel features by channel feature type and created single-part features such that only the perimeter of an individual feature was derived. This dissolve operation removes segments of polygon edges where the same channel types connect (e.g., bifurcations in a blind tidal channel), but does not remove the segment lengths of polygon edges where two different feature types converge (e.g., tidal channel bifurcation from a distributary). Therefore, perimeter estimates represent the edge length within clusters of similar tidal channel features.

Tidal Channel Length: Center flow paths were generated from the polygons of tidal channel features within each delta. These center lines were only generated for distributary and tidal channel features, and were not developed for tidal flats or tidal complexes given that polygon shapes for these features do not have a clear path of flow as compared to a tidal channel or distributary feature. However, we did digitize larger tidal channel features in tidal flats and tidal complexes with widths of at least 5 m (an arbitrary threshold). Therefore, tidal channel lengths are only biased against smaller tidal channel features in tidal flats and tidal complexes as derived in this analysis.

Node Density: From the center flow paths derived above, we also converted feature intersections to nodes. The center flow paths were derived from primary distributary, distributary, and tidal channel features only, and therefore did not represent channel connection nodes in tidal complexes and tidal flats (with the noted exception of channels that were at least 5 m wide, as described above). The density of nodes was then calculated based on the total length of primary distributary channel within each delta, much like a side channel node density calculation for large rivers. Connections with industrial waterway features were excluded from the node density calculations.

Delta habitats

These protocols have not yet been developed.

Nearshore habitats

These protocols have not yet been developed.

Field Protocols

Large River Field Protocols

Field protocols for large rivers include surveys of 1) instream edge habitats important to juvenile salmonids, 2) bank type and wood count, and 3) riparian vegetation transects. The edge habitat unit survey is a continuous survey in either the upstream or downstream direction (whichever is more convenient). On the return, bank type and wood count are continuously surveyed, and the riparian transects are surveyed at three roughly equally spaced intervals. The edge habitat survey is not a ground-truthing survey; rather, it is intended to describe habitat conditions within the survey reach. Our aim is to be able to quantify differences in habitat conditions, both among strata and over time. The bank type and wood count survey is intended to measure lengths of each bank type and record locations of bank type changes in GPS. It also records all wood within the survey reach up to bankfull edge. The riparian transects are ground-truth surveys, and our purpose is to locate stand-type transitions and measure the width of each stand. Transects should be located at 0.25, 0.50, and 0.75 of the reach length.

Large river habitats

Habitat unit areas will be measured on one bank in each study reach (these channels are non-wadable, so we can only access one side efficiently). The length of the survey reach is 10 times the bankfull channel width along the water's edge. Habitat units are classified as natural bank, modified bank, bar edge, backwater, or no edge unit using the following definitions (from Beamer and Henderson 1998, Beechie et al. 2005, and J. Latterell, King County Department of Natural Resources, unpublished data):

- Natural bank: A slow-water (<0.45 m/s, <1 m deep) unit located where the channel meets a deep, nearly vertical shore; no rip-rap or revetment.
- Rip-rap bank: A slow-water (<0.45 m/s, <1 m deep) unit located where the channel meets a deep, nearly vertical shore; bank is rip-rap or other revetment.
- Bar: A slow-water (<0.45 m/s, <1 m deep) unit located where the channel meets a shallow, gently-sloping shore.
- Backwater: A partially enclosed slow-water (<0.45 m/s, no depth limit) unit along the large river, often at the downstream or sometimes upstream end of a side channel or braid.
- No edge unit (NEU): Where the width of the edge unit is less than 0.5 m, we measure the length but do not record width, depth, or other data; may also occur when crossing a side channel during bank survey.

The protocols for habitat surveys are:

1. In the office, measure five bankfull widths equally spaced along the reach in Google Earth, average them, and multiply the average bankfull width by ten to determine the reach length to survey. From the center point of the survey reach (the point used for sample site selection), measure half the reach length downstream and record the end-point coordinates (GPS), then measure half the reach length upstream and record the other end-point coordinates. These are the reach boundaries for the field survey.
2. Use a coin flip or random number generator to determine which side of the channel to survey.
3. At the site, record all header information at the start point, including direction of survey (upstream or downstream).
4. At the first survey point, record channel type (M = main, B = braid) and bank (L = left, R = right). (Note that side channels are included in the floodplain survey protocols rather than the large river protocol.) Also record GPS point for the header field *Lat/Long begin*, and a unit number (begin with 1 at each site). The channel type may change throughout the survey reach as you move along the bank edge.
5. Within each unit, choose a representative point to measure edge habitat width from the bank edge toward the channel to the point at which velocity exceeds 0.45 m/s or depth exceeds 1 m (adapted from Bjornn and Reiser 1991, Beechie et al. 2005). To do this, position the monopod with the laser range finder at the point at which velocity exceeds 0.45 m/s or depth exceeds 1 m and measure distance from the stadia rod to the water edge. Obtain an average in-stream depth along the width transect. If depth is beyond wadeable, record NM (not measureable). Finally, record dominant substrate within the unit. Substrate classes are:
   - O: Organic.
   - Si: Silt.
   - Sa: Sand (<2 mm).
   - G: Gravel (2–64 mm).
   - C: Cobble (64–256 mm).
   - B: Boulder (>256 mm).
   - Bed: Bedrock.
6. Factors determining a change in unit would be change in bank edge type or *Unit Type*. Intermediate points may need to be taken within a single unit. Factors determining the need to measure intermediate points include distance (if the unit is too long), a change in the bank contour (in order to get a more accurate distance measurement), or a change in the representative habitat unit width and depth. If more than one point and representative habitat sample is taken within a unit, give them the same *Unit #*.
7. Measure the distance from the start point to the next unit or segment break with the laser range finder, and record the distance. Then move the laser range finder up to the stadia rod point.
8. Continue steps 5–7 for each point within the habitat unit. On long units, more intermediate points or segment breaks may be necessary.
9. Each line entry for *Length* represents the length of the unit or segment being measured. By choosing a point within a unit to measure a representative width, substrate, and average depth, we are capturing the characteristics representative of the unit or segment. See Figure D-6 for an example of a completed large river habitat survey form.
10. Repeat steps 5–9 until the end of the survey segment is reached (as located using the GPS coordinates from step 1).
11. Record GPS location at the end of the survey for the header field *Lat/Long end*.

Puget Sound Habitat Status and Trend Monitoring

Large Channel Habitat Survey Data Sheet

(≥ 20m BFW)

Crew:_________Smith, Jones____________________________________ Date:___08/14/2014_

River & Reach ID: _____Example River, reach 31xx__________ Downstream/Upstream:____DS_____

Lat/Long begin: N47°27.742', W122°5.468'_______Lat/Long end: N47°27.746', W122°5.599'_______

Channel Type (M,B)	Bank (L/R)	Unit #	Unit type (Bar,BW,Bank, RR,SC,NEU)	Length (m)	Width (m)	Max Depth or NM (m)	Substrate (O,SI,SA, G,C,B,Bed)	Comments (photo #'s)
M	L	1	Pool	55.61	22.96	0.53	G	
		2	Bank	46.56	1.7	0.57	G	
		3	Pool	39.88	1.7	0.53	G	
		4	Bar	15.51	0.8	0.30	G	
		4	Bar	43.33	7.56	.20	C	
		4	Bar	111.78	7.32	.38	SA	
		5	BW	15.14	0.8	0.16	G	
		6	Pool	23.7	0.8	0.23	G	
		7	Bank	31.0	1.3	0.32	G	
		8	NEU	22.2	NA	NA	NA	
		9	RR	12.3	1.5	0.26	G	

NM = not measurable

Return to George.pess@noaa.gov Entered by & date_____________________________

Figure D-6. Completed large river habitat survey form.

Large river bank type and wood count

From the end point of the habitat survey, begin the bank type and wood count survey in the opposite direction. This is a continuous survey, measuring distances along the bankfull edge and recording whether bank type is natural, rip-rap, or levee, and counting wood abundance or wood jam dimensions between the bankfull channel edge and the center of the main channel within each bank segment (i.e., between measurement points). Note that the bank types describe conditions at the edge of the bankfull channel (i.e., outside the water), whereas the edge habitat types describe aquatic habitat conditions experienced by fish.

The large river bank type and wood count protocols are:

1. At the site, record all header information at the start point, including direction of survey (upstream or downstream). Also record GPS coordinates for the header field *Lat/Long begin*. These should be nearly the same as the end point coordinates of the habitat survey, though they may not be identical if the water edge is not against the bankfull channel edge.
2. Record channel type (M, B) and bank (L or R). Also record the bank type:
   - N: Natural.
   - RR: Rip-rap.
   - L: Levee.
3. For the first bank segment, measure length along the bankfull channel edge, using the laser range finder and sighting on the stadia rod held at the end of the first bank segment. Record the bank type for the segment in between the two points.
4. Count any wood pieces in the survey segment that are between the bankfull channel edge and the center of the bankfull channel, or measure the dimensions of the wood jam if the accumulation exceeds 30 pieces. Wood counts will be in three size classes:
   - Small (length >2 m and midpoint diameter 0.1–0.2 m).
   - Medium (length >3 m and midpoint diameter 0.2–0.5 m).
   - Large (length >5 m and midpoint diameter >0.5 m).
5. A wood piece must meet both size criteria to be assigned to that class (e.g., a 0.3-m diameter piece that is 4 m long is a medium piece, whereas a 0.3-m diameter piece that is 1.5 m long is small; Beechie and Sibley 1997). When we encounter wood jams with more than 30 pieces, we will not count individual pieces and instead measure the length, width, and height of the wood accumulation with the laser range finder. Also, record the wood type as natural or placed (N or P).
6. Repeat steps 2–4 until the start point of the habitat survey is reached. Record GPS coordinates at the end point of the survey, and enter them in the header field *Lat/Long end*.

Large river riparian transects

Within each survey segment, we will survey three riparian transects for crossvalidation of the aerial photography classification of riparian conditions. Transects should be placed at 0.25, 0.50, and 0.75 of the reach length, unless there are unusually complex or unique features that should be captured for crossvalidation. Transects extend 52 m from the bankfull edge (a typical site potential tree height for conifer species in the region; McArdle et al. 1961, Beechie et al. 2000). Complex riparian zones might include a large number of stand type changes within each transect, and unique features might include cover types that are rare within the crossvalidation sample.

The riparian condition survey protocols are:

1. At the site, record all header information at the start point. Also record GPS coordinates for the header field *Lat/Long begin*.
2. Locate the start point of the transect at the inner edge of the vegetation as it will be viewed in aerial photography (e.g., the inner edge of tree crowns). Record channel type, transect number, bank (L or R), and bankfull width. These data remain the same for all survey points in this transect. Record station = 0, distance = 0, and NA for vegetation type, size class, and density. If the Real Time Kinematic (RTK) GPS unit is not able to record points, record GPS coordinates and azimuth of the transect with a hand-held GPS unit and hand-held compass.
3. If there is vegetation within the bankfull channel, be sure that a transect station is placed at the bankfull edge and the location of the bankfull edge is noted in the comments. The 52-m width of the transect is from the bankfull edge, and does not include the width of any vegetation within the bankfull channel.
4. Moving perpendicular to the bank, measure the distance to the first cover class change using the laser range finder or stadia rod (the stadia rod may work better in dense young trees or shrub). Record the distance, cover type, size class, and density within the first segment of the riparian transect (i.e., the area between stations 0 and 1). Riparian vegetation/cover classes are modified from Hyatt et al. (2004) and Lucchetti et al. (2014):
    - Conifer dominated: Forested, more than 70% of trees are conifers.
    - Hardwood dominated: Forested, more than 70% of trees are hardwood.
    - Mixed forest: No dominance greater than 70%.
    - Grass/shrub: Grass or small woody vegetation.
    - Bare ground: Gravel bars, or bare soil not in the agriculture or disturbed pervious vegetation types.
    - Water: Open water (rivers, side channels, wetlands, etc.).
    - Wetland: Includes open water wetlands.
    - Agriculture: Pasture or row crops.
    - Disturbed impervious: Pavement, rooftops, etc.
    - Disturbed pervious: Lawns, golf courses, etc.

    Size classes for trees are (from WFPB 2011):
    - 0–0.03 m dbh (1.5 m above the ground).
    - 0.03–0.3 m dbh.
    - 0.3–0.5 m dbh.
    - >0.5 m dbh.
    - NA if the cover class is not forested.

    Density classes are (from WFPB 2011):
    - Sparse: >33% of the area is bare ground.
    - Dense: <33% of the area is bare ground.
    - NA if the cover class is not forested.
5. Continue measuring the widths of cover types perpendicular to the channel to a distance of 52 m.
6. If impervious surface is present under tree canopy, start and end the transect according to the impervious surface. This is one key difference from the aerial photography approach, in which we only record what is visible from the air (i.e., we would start at the edge of the tree in aerial photography, but at the edge of the impervious surface in the field survey).

Floodplain Channel Field Protocols

Field protocols for floodplain channels include surveys of 1) instream habitat important to juvenile salmonids, 2) bank type and wood abudance, and 3) riparian vegetation transects. The habitat survey is a continuous survey in either the upstream or downstream direction (whichever is more convenient). On the return, bank type and wood abundance are continuously surveyed, and the riparian transects are surveyed at three roughly equally spaced intervals. The habitat survey is not a ground-truthing survey; rather, it is intended to describe habitat conditions within the survey reach. Our aim is to be able to quantify differences in habitat conditions, both among strata and over time. The bank type survey is intended to measure lengths of each bank type and record locations of bank type changes in GPS or with a laser range finder. The riparian transects are ground-truth surveys, and our purpose is to locate cover-type transitions and measure width of each type. Transects should extend away from the side channel on both banks at roughly 0.25, 0.50, and 0.75 of the reach length (a total of six transects, three on the right bank and three on the left). Transect locations can be shifted somewhat to capture transitions or vegetation types that may be difficult to identify in the field.

Floodplain channel habitats

We will survey at least one side channel or braid in each study reach selected in the sample frame. The surveyed side channel will be classified as a braid or side channel using the following definitions:

- Braid: Contains less than half the discharge and is separated from the main channel by an unvegetated bar.
- Side channel: Contains less than half the discharge and is separated from the main channel by a vegetated island.

Within the channel selected for sampling, we will measure habitat areas, pool spacing, maximum and tail crest depths of pools (to calculate residual depths), wetted area of habitat, and wood abundance, using a continuous long-profile survey. We will survey three 100-m long reaches, located at roughly 0.25, 0.50, and 0.75 of the side channel length. The survey protocol is modified from long-profile field protocols used to monitor side channels in the Elwha dam removal monitoring project (East et al. 2015). A long-profile survey is a continuous survey that measures distance and elevations along the thalweg so that the bed and water surface profiles can be constructed from the data.

The protocols for the habitat surveys are:

1. In the office, using a random number generator, randomly select the channel to survey from among the side channels on the same side of the river as the large river survey (if there is more than one side channel within the reach).
2. In Google Earth, locate the three 100-m reaches at roughly 0.25, 0.50, and 0.75 of the side channel length, and record start-point coordinates to identify reach locations in the field. If the reach is less than 300 m long, survey the entire reach.
3. At the site, record all header information at the start point, including direction of survey (upstream or downstream).

4. Locate the first of the three reaches, begin the survey at either end, and record GPS coordinates in the header field *Lat/Long begin*. Surveys should begin and end at riffle crests (the location in a riffle with the highest elevation) for streams with a pool–riffle structure, or be measured at midriffle for streams lacking pool–riffle morphology.
5. At the first survey point, record the river name, Site ID, channel type (braid or side channel), and sub-reach (lower, middle, or upper). These will remain the same for all survey records for the sub-reach survey. Record *station = 0*, *length = 0*, and *elevation = 0* at the first point.
6. Also at the first survey point, measure water depth to the nearest centimeter with the stadia rod, and wetted width to the nearest 0.1 m. Record dominant substrate and habitat unit type. Substrate classes are:
   - O: Organic.
   - Si: Silt.
   - Sa: Sand (<2 mm).
   - G: Gravel (2–64 mm).
   - C: Cobble (64–256 mm).
   - B: Boulder (>256 mm).
   - Bed: Bedrock.

   Habitat types are:
   - Riffle: Fast water with a rough surface.
   - Glide: Fast or slow water with a relatively flat bed form and a smooth surface.
   - Pool: Deep, slow water that exceeds the minimum residual depth (Table D-6).
   - Pond: Large beaver pond or oxbow pond, very low velocity, with a smooth surface.
7. To survey the next point, position a laser range finder monopod at the 0 station and position the stadia rod at a midpoint along the thalweg within the first habitat unit (to ensure at least one wetted width measurement in each unit). Measure distance and elevation with the laser range finder, and record them in the data row for station 1. Also measure water depth to the nearest centimeter with the stadia rod. If the depth measurement is at the top, tail crest, or maximum depth in a pool, record the measurement type in the *Max/Tail/Top* column of the data form. Measure wetted width to the nearest 0.1 m, and record dominant substrate and unit type. If there is a dry area (i.e., a midchannel gravel bar) within the wetted width, measure the wetted width of each channel and sum to get the total width; enter the total width in the *Wetted Width* column.
8. For the next survey point, move the laser range finder to station 1 (the position of the range finder target).
9. Continue repeating steps 7 and 8 for 100 meters along the thalweg (making sure that each habitat unit has at least one point in the middle of each unit), at the top end of each unit, and at all pool tail-crests and maximum depths.
10. Record the GPS coordinates at the end of the survey for the header field *Lat/Long end*.
11. Repeat steps 1–10 for the remaining two subreaches.

Table D-6. Minimum residual depth requirements for pools, by channel width (from WDNR 1995). (Note: We will switch to the large river habitat survey protocol if bankfull channel width exceeds 20 m and edge units are present.)

Bankfull channel width	Minimum residual pool depth
0–2.5 m	0.10 m
2.5–5 m	0.20 m
5–10 m	0.25 m
10–15 m	0.30 m
15–20 m	0.35 m
>20 m	0.40 m

Floodplain channel bank type and wood count

We will measure the length of rip-rap and leveed bank in the field, using either a laser range finder or RTK GPS survey. Both survey methods are accurate to within centimeters, and should provide reliable data on the lengths of modified banks.

The floodplain channel bank type protocols are:

1. At the site, record all header information at the start point of the survey, including the direction of the survey (upstream or downstream). Also record a GPS point for the header field *Lat/Long begin*. This should be nearly the same as the end location of the habitat survey, but the distance measurements will be along the channel center line in this case.
2. At each point, record bank type for both the left and right banks (two rows for each point). In the first row, Site ID, channel type, and distance are all *0*. Record bank (*L* or *R*) for the first survey point. In the second row, the Site ID, channel type, and distance remain the same, but the opposite bank is recorded (i.e., record *R* in the second row if *L* was recorded in the first row). Record the bank type for each side of the channel:
   - N: Natural.
   - RR: Rip-rap.
   - L: Levee.
3. For the first segment, measure length along the channel center to the point at which the bank type changes on either bank. Record the distance and bank type for the length of bank between the two points, using one row for each bank. The distance will be the same for both rows, but one row is the left bank and the other row is the right bank.
4. Count the number of wood pieces in the survey segment that are within the bankfull channel, or measure the dimensions of the wood jam if the accumulation exceeds 30 pieces. Record the totals in only one row (*L* or *R*), and record *0* for all wood fields in the second row. Wood counts will be in three size classes:
   - Small (length >2 m and midpoint diameter 0.1–0.2 m).
   - Medium (length >3 m and midpoint diameter 0.2–0.5 m).
   - Large (length >5 m and midpoint diameter >0.5 m).

   A wood piece must meet both size criteria to be assigned to that class (e.g., a 0.3-m diameter piece that is 4 m long is a medium piece, whereas a 0.3-m diameter piece that is 1.5 m long is small; Beechie and Sibley 1997). When we encounter wood jams with more than 30 pieces, we will not count individual pieces, but instead measure the length, width, and height of the wood accumulation with the laser range finder.

5. Repeat steps 3 and 4 until you reach the start point of the habitat survey. Record the GPS coordinates at the end point and enter them in the header field *Lat/Long end*.

Floodplain channel riparian transects

Within each subreach of a side channel, we will survey two riparian transects for crossvalidation of the aerial photography classification of riparian conditions (Beechie et al. 2003). Transects will be placed in the center of each reach, with one transect on each bank. If there are unusually complex or unique features that should be captured for crossvalidation, the transect location can be shifted to capture those features. Complex features might include a large number of stand type changes within each transect, and unique features might include cover types that are rare within the crossvalidation sample. At each transect, we will measure the distance from the vegetation edge as it will be viewed from aerial photography to the first change in riparian vegetation, and then the distance to each vegetation change thereafter out to a distance of 52 m (one site potential tree height for conifer species in the region; McArdle et al. 1961, Beechie et al. 2000).

The riparian condition survey protocols are:

1. At the site, record all header information at the start point of the survey. Also record a GPS point for the header field *Lat/Long begin*.
2. Locate the start point of the transect at the inner edge of the vegetation as it will be viewed in aerial photography (e.g., the inner edges of tree crowns). Record channel type, transect number, bank (L or R), and bankfull width. These data remain the same for all survey points in this transect. Record *station = 0*, *distance = 0*, and *NA* for veg type, size class, and density. If the RTK is not able to record points, record the GPS coordinates and azimuth of the transect with a hand-held GPS unit and a hand-held compass.
3. If there is vegetation within the bankfull channel, be sure that a transect station is placed at the bankfull edge and that the location of the bankfull edge is noted in the comments. The 52-m width of the transect is from the bankfull edge, and does not include the width of any vegetation within the bankfull channel.
4. Moving perpendicular to the bank, measure the distance to the first cover class change using the laser range finder or stadia rod (the stadia rod may work better in dense young trees or shrub). Record the distance, cover type, size class, and density within the first segment of the riparian transect (i.e., the area between stations 0 and 1). Riparian vegetation/cover classes are modified from Hyatt et al. (2004) and Lucchetti et al (2014):
    - Conifer dominated: Forested, more than 70% of trees are conifers.
    - Hardwood dominated: Forested, more than 70% of trees are hardwood.
    - Mixed forest: No dominance greater than 70%.
    - Grass/shrub: Grass or small woody vegetation.
    - Bare ground: Gravel bars, or bare soil not in the agriculture or disturbed pervious vegetation types.
    - Water: Open water (rivers, side channels, wetlands, etc.).
    - Wetland: Includes open water wetlands.
    - Agriculture: Pasture or row crops.
    - Disturbed impervious: Pavement, rooftops, etc.

- Disturbed pervious: Lawns, golf courses, etc.

Size classes for trees are (from WFPB 2011):

- 0–0.03 m dbh (1.5 m above the ground).
- 0.03–0.3 m dbh.
- 0.3–0.5 m dbh.
- >0.5 m dbh.
- NA if the cover class is not forested.

Density classes are (from WFPB 2011):

- Sparse: >33% of the area is bare ground.
- Dense: <33% of the area is bare ground.
- NA if the cover class is not forested.

5. Continue measuring the widths of cover types perpendicular to the channel to a distance of 52 m.
6. Record the GPS coordinates at the last point of the transect and enter them in the *Lat/Long end* header field. If the point cannot be reached, record *NM* (not measureable).
7. Begin the second transect on the opposite bank, and repeat steps 1–5 for the second transect.

Delta and Nearshore Field Protocols

Delta and nearshore field protocols will be developed in 2015 and 2016.

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Appendix E: Evaluation of Forest Land-Cover Classes

Both the Coastal Change Analysis Program (C-CAP) and the National Agriculture Imagery Program (NAIP) datasets contain multiple classes that might be considered forested, and it is not obvious which combination(s) of those classes will best represent forest land cover and provide the most accurate estimate of percent forest cover in floodplain polygons. For the C-CAP data, we compared two alternative groupings of land-cover classes reclassified as forest. C-CAP Landsat data contains 25 land-cover classifications, of which we first grouped evergreen forest, deciduous forest, and mixed forest as a single forest cover class (Table E-1). However, preliminary comparisons of the C-CAP data to aerial photography indicated that a significant proportion of floodplain forests were classified as forested wetland in the C-CAP data. Therefore, we also combined C-CAP's two forested wetland land-cover classes with evergreen forest, deciduous forest, and mixed forest to create a broader forest class (Table E-2).

Table E-1. First reclassification of C-CAP Landsat data into forest, wetland, agriculture, developed, water, and other classes.

C-CAP land-cover class	PSHSTM riparian class	C-CAP land-cover code
evergreen forest	forest	10
deciduous forest	forest	9
mixed forest	forest	11
estuarine emergent wetland	wetland	18
estuarine scrub/shrub wetland	wetland	17
estuarine forested wetland	wetland	16
palustrine emergent wetland	wetland	15
palustrine scrub/shrub wetland	wetland	14
palustrine forested wetland	wetland	13
unconsolidated shore	wetland	19
cultivated land	agriculture	6
pasture/hay	agriculture	7
high intensity development	developed	2
medium intensity development	developed	3
low intensity development	developed	4
water	water	21
palustrine aquatic bed	water	22
delta aquatic bed	water	23
developed open space	other	5
grassland	other	8
scrub/shrub	other	12
bare ground	other	20
tundra	other	24
snow/ice	other	25
unclassified	other	1

Table E-2. Alternate reclassification of C-CAP land-cover classes with forested wetlands grouped in the forest cover class instead of the wetland class. Bold rows are reclassed.

C-CAP land-cover class	PSHSTM riparian class	C-CAP land-cover code
evergreen forest	forest	10
deciduous forest	forest	9
mixed forest	forest	11
estuarine forested wetland	**forest**	**16**
palustrine forested wetland	**forest**	**13**
estuarine emergent wetland	wetland	18
estuarine scrub/shrub wetland	wetland	17
palustrine emergent wetland	wetland	15
palustrine scrub/shrub wetland	wetland	14
unconsolidated shore	wetland	19
cultivated land	agriculture	6
pasture/hay	agriculture	7
high intensity development	developed	2
medium intensity development	developed	3
low intensity development	developed	4
water	water	21
palustrine aquatic bed	water	22
delta aquatic bed	water	23
developed open space	other	5
grassland	other	8
scrub/shrub	other	12
bare ground	other	20
tundra	other	24
snow/ice	other	25
unclassified	other	1

Table E-3. First reclassification of NAIP land-cover classes into water, developed, forest, and other classes.

NAIP land-cover class	PSHSTM land-cover class	NAIP land-cover code
Shadow/water	water	1
Built/gray	developed	3
Tree	forest	8
Veg/shadow/tree	other	5
Shrub/tree	other	7
Indeterminate	other	2
Herbaceous/grass	other	6
Bare ground	other	4

Land-cover data classified from NAIP were acquired from the Washington Department of Fish and Wildlife (K. Pierce, Washington Department of Fish and Wildlife, unpublished data). Land cover was classified into eight different categories, three of which contained the word tree (Table E-3). Therefore, we compared four alternative groupings of land-cover classes to evaluate which combination most accurately represented forest cover: *tree*, *tree + Veg/shadow/tree*, *tree + Shrub or tree*, and *tree + Veg/shadow/tree + Shrub or tree* (Table E-4).

Table E-4. Alternate reclassification of NAIP land-cover classes into water, developed, forest, and other classes. Bold rows are NAIP classes that we regrouped from *other* to *forest* to determine whether this improved the accuracy of the percent forested metric.

NAIP land-cover class	PSHSTM land-cover class	NAIP land-cover code
Shadow/water	water	1
Built/gray	developed	3
Tree	forest	8
Veg/shadow/tree	**forest**	**5**
Shrub/tree	**forest**	**7**
Indeterminate	other	2
Herbaceous/grass	other	6
Bare ground	other	4

To determine which combination(s) of land-cover classes in C-CAP and NAIP would provide the best estimates of percent forest cover, we selected 32 floodplain sample sites from the 124 aerial photography sites. The 32 sites were evenly distributed across eight different strata (forest/wetland, agriculture, developed, and mixed, in both the glacial and post-glacial valley types). We created a grid of 100 points within each of 32 floodplain polygons using the *Uniform Points in Polygon* tool in ET Geowizards (ET SpatialTechniques, Pretoria, South Africa), manually classified the land-cover type at each point (see Figure E-1 for an example), and calculated percent forest cover. We also calculated the percent forest cover within the floodplain polygon from each combination of forest land-cover classes in the C-CAP and NAIP datasets. Finally, we used regression analysis of the manually classified percent forest area against both the C-CAP- and NAIP-derived percent forest areas for each combination of land-cover classes. Regressions with slope nearest 1 and intercept nearest 0 are considered the most accurate, and the highest r^2 value is considered the most precise.

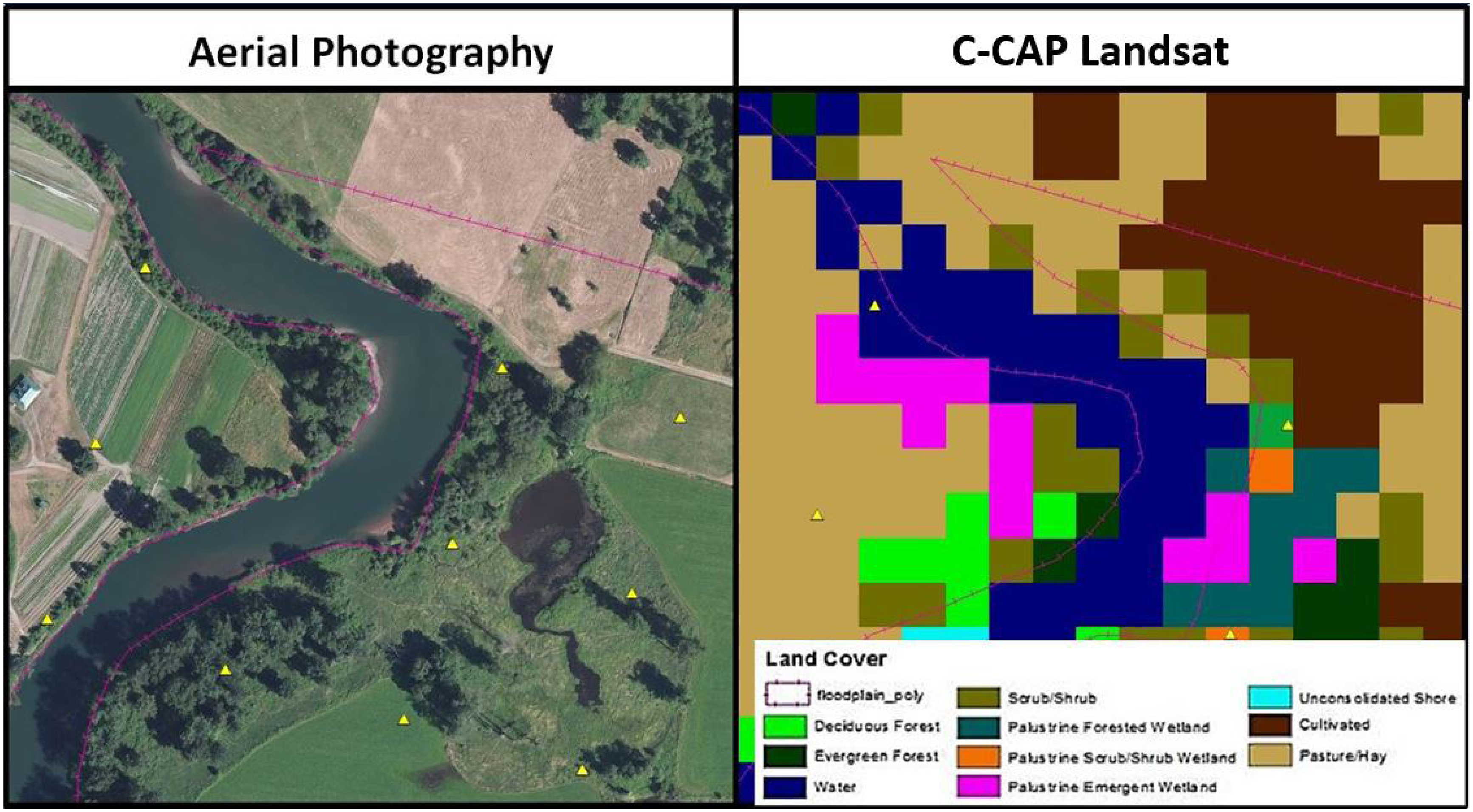

Figure E-1. Image of grid points overlaid on C-CAP land-cover data, and aerial photography.

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