Monitoring habitat status and trends in Puget Sound: development of sample designs, monitoring metrics, and sampling protocols for nearshore, delta, large river, and floodplain environments

Timothy J. Beechie, Oleksandr Stefankiv, Britta Timpane-Padgham, Jason Hall, George R. Pess, Mindy Rowse, Martin Liermann, Kurt Fresh, Mike Ford

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Introduction

In 1999, the Puget Sound Chinook salmon (*Oncorhynchus tshawytscha*) and the Hood Canal summer chum salmon (*Oncorhynchus keta*) Evolutionary Significant Units (ESU) were listed as “Threatened” under the Endangered Species Act (ESA). In 2007 Puget Sound Steelhead (*Oncorhynchus mykiss*) were also listed as “threatened” under the ESA. It is the statutory responsibility of the National Marine Fisheries Service (NMFS) to evaluate progress towards 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 that determine Viable Salmon Populations (VSP; abundance, productivity, spatial structure, and diversity), as well 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 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 element to any five-year status review. This was effectively demonstrated in the recent five-year status review for Oregon Coastal Coho salmon (*Oncorhynchus kisutch*), where consistent data on habitat trends was essential for determining species status (Stout et al 2012). Consistent habitat data across the entire ESU is not currently available for the Puget Sound. A 2011 report commissioned by the NMFS entitled “Implementation status assessment final report – A qualitative assessment of implementation of the Puget Sound Chinook salmon recovery plan” stated “Habitat status and trends monitoring at the population, major population group and ESU (Evolutionary Significant Unit) 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 is there a program established to collect those data for assessing status and trends of salmon habitats in the 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 have five objectives for the first year of this monitoring effort: (1) develop a hierarchical sampling design to monitor habitat status and trends, (2) identify habitat metrics that are cost-effective and related to Viable Salmon Population (VSP) parameters (growth, survival, abundance, productivity), (3) develop protocols to measure these metrics, (4) test the satellite, aerial photograph, and field methods for repeatability and reliability, and (5) evaluate habitat status to assess the ability of each metric to detect habitat differences among land cover classes. We have organized this report as follows:

1. Hierarchical monitoring approach

2. Sample design (stratification and sample selection process)
3. Selection of monitoring metrics
4. Sampling protocols for satellite, aerial photograph, and field metrics
5. Analysis methods
6. Results (metric evaluation and habitat status by MPG and landcover class)
7. Discussion (key findings and next steps)

We also include information on key meetings at which we convened expert panels to assist us in developing our sample design and selecting monitoring metrics (Appendix A).

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 (Figure 1). The Olympic and Cascade Mountains commonly exceed 1,800 m, and several volcanic peaks exceed 3,000 m in elevation. Mean annual precipitation ranges from less than 50 cm/yr on the northeast Olympic Peninsula to more than 450 cm/year on Mount Baker (PRISM Climate Group 2014). Hydrologic regimes are classified as snowmelt-dominated, rainfall dominated, or transitional (Beechie et al. 2006). The snowmelt regime is at higher elevations (mean basin elevation >1300 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 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 (Heller, 1979; 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. 2006). Floodplains are wider in low elevation valleys (<600 m elevation) bounded by erodible glacial terraces (e.g., Beechie 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 comprise floodplain, shoreline, and delta vegetation in the study area, which is part of the Pacific Coastal Forest extending from Northern California to Alaska. 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*) (Franklin and Dyrness, 1973). 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 either 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 (Williams et al., 1975; 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 sub-yearlings 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).

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 2 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 2 years for winter run steelhead, but almost exclusively 1 year for the Deer Creek summer run steelhead (Busby et al. 1996).

Monitoring Approach: A Hierarchical Monitoring Strategy

We evaluate habitat status and trends in four salmon and steelhead spawning and rearing environments: large rivers, floodplains, deltas, and the nearshore (Bartz et al. 2015) (Figure 1). We defined large rivers as stream channels with 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 drainage area of 50km^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 nearshore environment extended 200 m inland from the ordinary high water mark of the marine shoreline (Simenstad et al. 2011). 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 (Anchor QEA, LLC 2009).

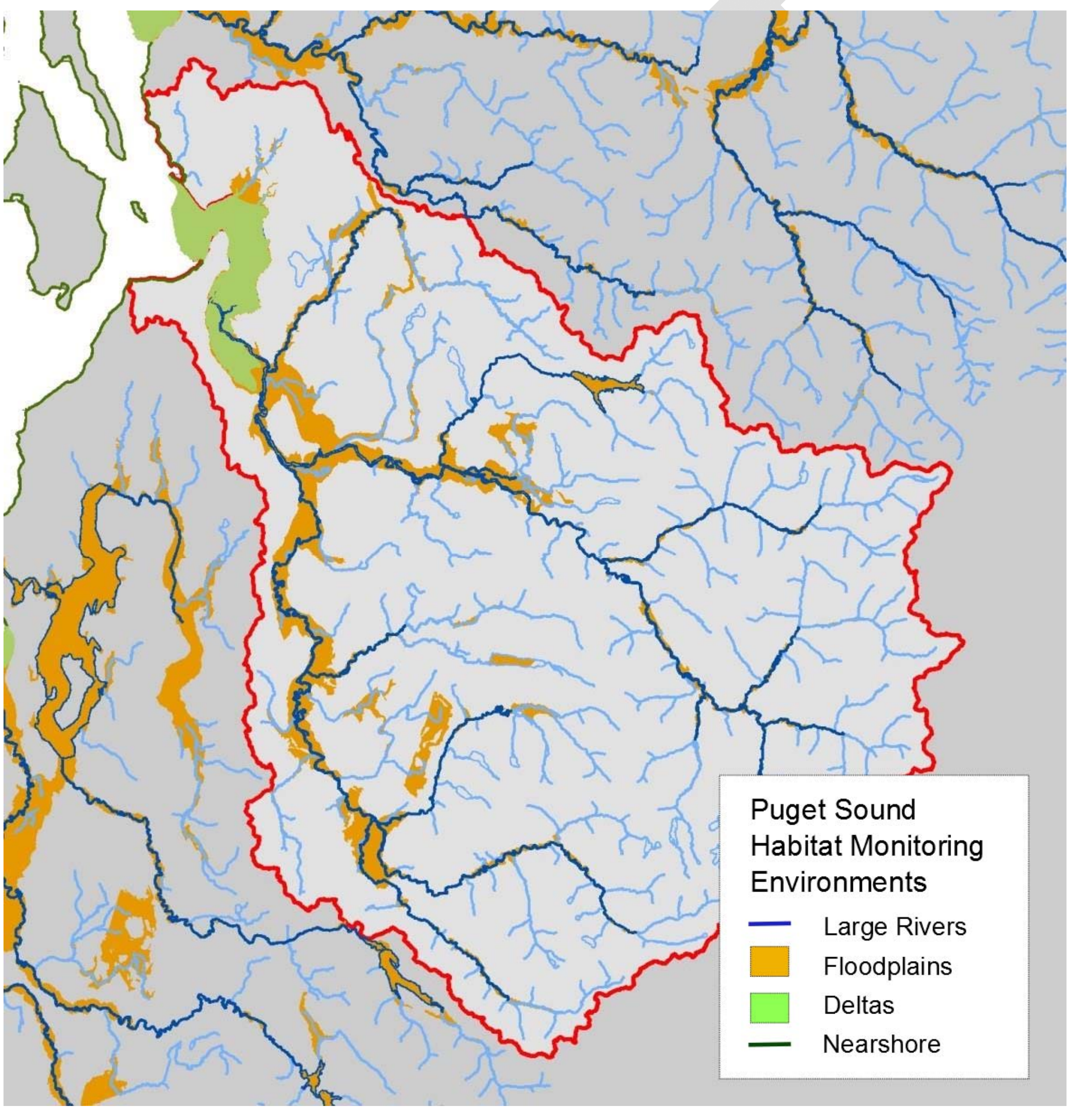


Figure 1. The four key salmonid spawning and rearing environments that will be sampled as part of the Puget Sound habitat status and trends monitoring effort. Map highlights the Snohomish River basin in Puget Sound.

In each of the four monitoring environments, the distribution of geomorphic features and physical habitats are 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 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 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 photograph 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 with aerial photograph data, and lower sample site density with 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).

Satellite measures
(coarse resolution, complete coverage)

Purpose:
Assess status and trend in land use

Example metrics:
Percent forest cover on floodplain
Percent impervoius cover on floodplain

Aerial photograph/LIDAR measures
(moderate resolution)

Purpose:
Assess reach-scale habitat condition

Example metrics:
Forested buffer width
Side-channel/mainstem length ratio
Wood jm area

Field measures
(fine resolution)

Purpose:
Quantify habitat area and quality

Example metrics:
Pool-riffle areas
Residual pool depth
Wood abundance

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

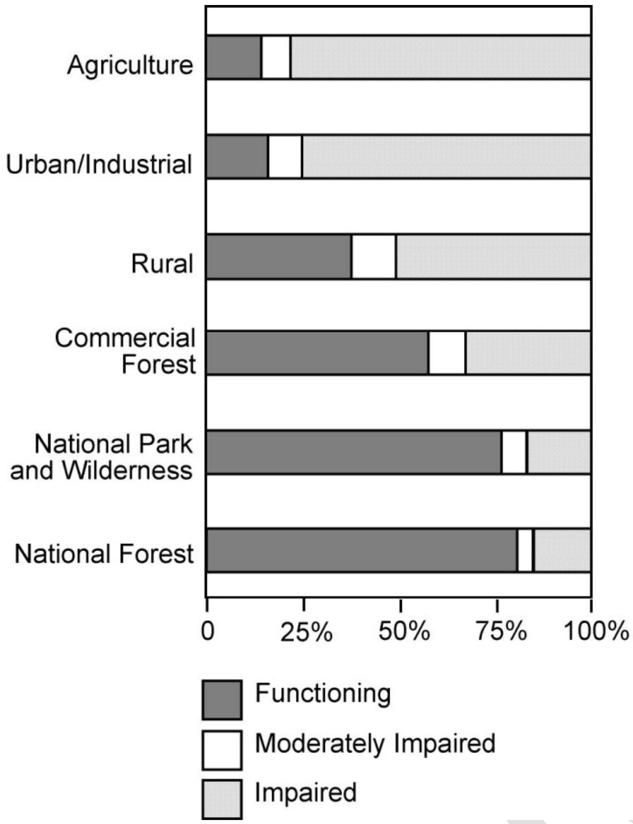


Figure 3. Example of riparian conditions as a function of land cover or ownership in the Skagit River basin. From Beechie et al. 2003.

Sample Design

Key steps in developing the sample design include (1) stratifying large rivers, floodplains, deltas and the nearshore by geomorphic type, land cover, and major population group (2) development of a site selection process that is statistically robust but also considers accessibility of sites for field data collection, (3) power analysis to determine 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 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 stratified 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 stratification was intended to group sites based on degree of human influence. Detailed methods for stratification of the landscape are 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, biological), were not used for stratification because they are sensitive to land use (i.e., they are mutable). Rather, those feature types, as well as other geomorphic attributes, are included 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 includes 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 (Collins and Montgomery 2011). 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 (Collins and Montgomery 2011). The canyons are typically a short and steep transition zone between the mountain valleys and post-glacial valleys (Collins and Montgomery 2011). Because the canyons do not have floodplains associated with them, we initially 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 (Bottom et al. 2005, Simenstad 1983). 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) (Figure 5). Most rivers flowing from the Cascades have river-dominated deltas, whereas Hood Canal deltas are predominantly fan-shaped. The remaining

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 based on NMFS (2010) and PSSTRT (2013).

Habitat area	Geomorphic strata	Land cover strata	Chinook MPG strata	Steelhead MPG strata
Large river/	Mountain valley	Forest/wetland	Georgia Straight	Northern Cascades
floodplain	Canyon	Agriculture/rural	North Sound	South Central Cascades
	Glacial (aggrading)	Urban	South Sound	Olympic
	Post-glacial (incising)		Hood Canal	
			Juan de Fuca	
Delta	River-dominated	Forest/wetland	Georgia Straight	Northern Cascades
	Wave-dominated	Agriculture/rural	North Sound	South Central Cascades
	Fan-shaped	Urban	South Sound	Olympic
			Hood Canal	
			Juan de Fuca	
Nearshore	Open shore - rocky	Forest/wetland	Georgia Straight	Northern Cascades
	Open shore - beach	Agriculture/rural	North Sound	South Central Cascades
	Embayment - lagoon	Urban	South Sound	Olympic
	Embayment – beach		Hood Canal	
	Modified		Juan de Fuca	

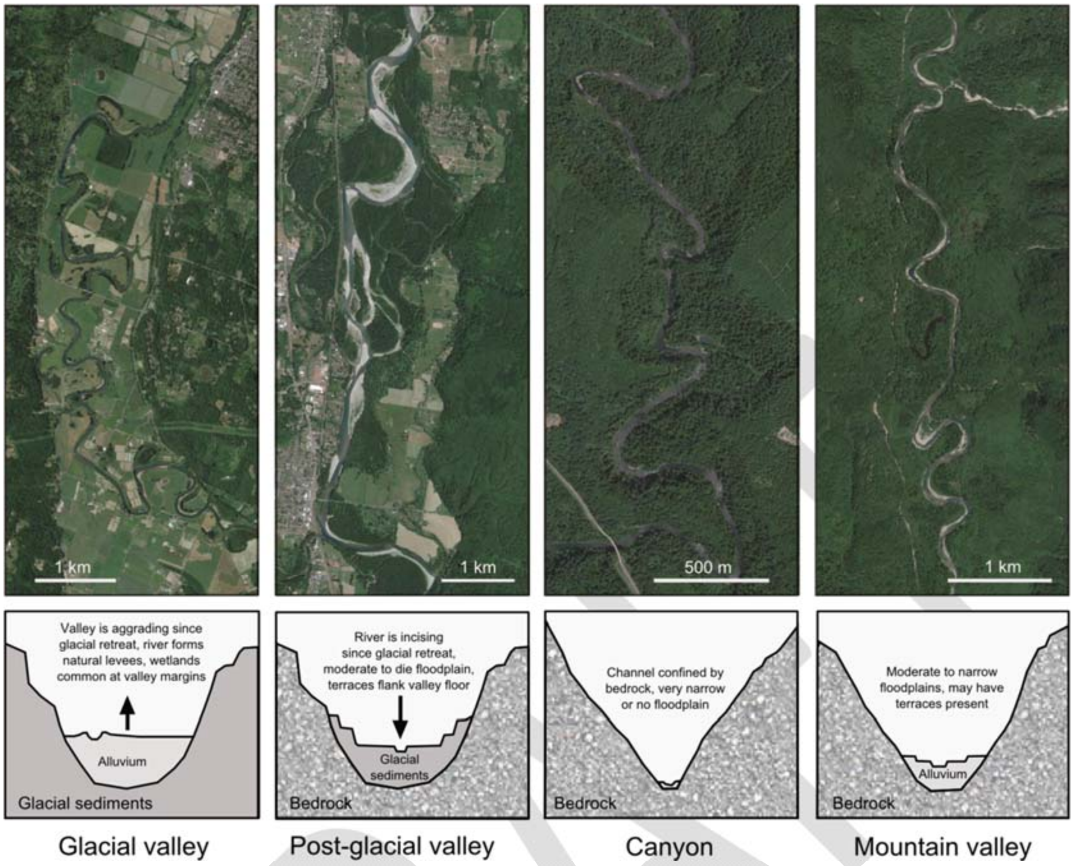


Figure 4. Geomorphic process domains for large river and floodplain strata (based on Collins and Montgomery 2011).

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

(non-delta) shoreline was stratified into open shores and embayments, with open shore subdivided into beaches and rocky shores and embayments subdivided into beaches and lagoons as defined by Shipman (2008) and McBride et al. (2009) (Figure 6). In addition to these four shore types, heavily developed shorelines are classified as "modified", and any shore type may be armored by rip-rap, levees or bulkheads (see for example the armored beach in Figure 6).

Land Cover Strata

In each habitat area, we also stratified by land cover class using NOAA's Coastal Change Analysis Program (C-CAP) 2010 data, which classifies land cover into 25 different types. We simplified the classification by aggregating like classes into 5 main classes: developed, agriculture, forest/wetland, water, and other (Table 2). The 'forest/wetland' class was intended to capture all relatively natural land cover types, 'developed' captured developed lands, and 'agriculture' captured cultivated and grazing lands. In floodplain areas the dominant natural cover will likely be forest, whereas shoreline areas (especially deltas and embayments) may naturally be dominated by wetlands. For each sample unit (e.g., river reach, delta, or shore segment), we classified land cover as predominantly forested/wetland if more than 50% of the area was forested and/or wetland, developed if more than 50% of the area was developed, agriculture if more than 50% of the area was cultivated and/or pasture, or mixed if no land cover class exceeded 50% (Figure 7).

Major Population Group Strata

The Chinook salmon ESU is divided into five major population groups: Georgia Strait, Central Puget Sound, South Sound, Hood Canal, and the Strait of Juan de Fuca (Figure 8). For this ESU to be removed from the Endangered Species list several biological criteria must be met including (1) the viability of all populations is improved, (2) 2-4 populations in each MPG are viable, (3) at least one population from each genetic and life-history group historically present within each MPG is viable, and (4) habitat condition and Chinook salmon production from independent tributary that are not part of one of the 22 populations are healthy enough to support recovery (NMFS 2010). In addition to meeting the biological criteria, habitat conditions in each MPG must be sufficient to support sustained recovery of Chinook salmon.

The steelhead ESU is divided into 3 major population groups: northern Puget Sound, South-Central Puget Sound, and the Olympic Peninsula. For the steelhead ESU to be removed from the Endangered Species the biological criteria are (1) the majority of populations in each MPG improve in viability, (2) at least 40% of populations in each MPG are 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 is sufficient to support recovery of the ESU. As with Chinook salmon, habitat conditions in each MPG must be also sufficient to support sustained recovery of steelhead.

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

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

PSHSTM cover class	Original C-CAP cover class
Forest/Wetland	Grassland (8)
	Deciduous forest (9)
	Evergreen forest (10)
	Mixed forest (11)
	Scrub/shrub (12)
	Palustrine forested wetland (13)
	Palustrine scrub/shrub wetland (14)
	Palustrine emergent wetland (15)
	Delta forest wetland (16)
	Delta scrub/shrub wetland (17)
	Delta emergent wetland (18)
	Unconsolidated shore (19)
Agriculture	Cultivated land (6)
	Pasture/hay (7)
Developed	High intensity developed (2)
	Medium intensity developed (3)
	Low intensity developed (4)
	Developed open space (5)
Water	Open water (21)
	Palustrine aquatic bed (22)
	Delta aquatic bed (23)
Other	Unclassified (1)
	Bare land (20)
	Tundra (24)
	Snow/ice (25)

Figure 7. Examples of each of the four land cover classes used to stratify sample sites 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.

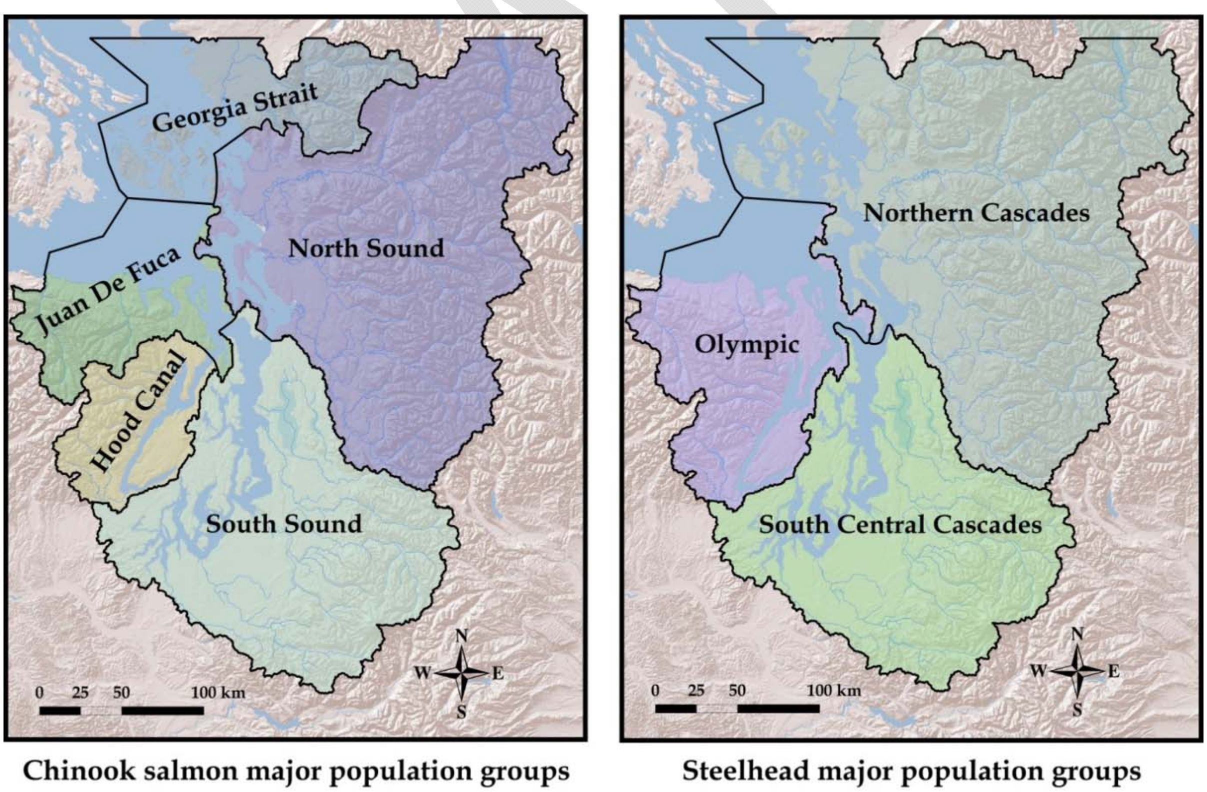


Figure 8. Major population groups for Chinook salmon and steelhead in Puget Sound.

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 assure that sites are distributed evenly across Puget Sound and within designated major population groups (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 photograph metrics (mid-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.

We sampled 124 aerial photograph 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 each direction from the sample point). Sites 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. The sample site distribution across all 36 strata is shown in Figure 10. Sample distribution by land cover class included 31 sample sites within agriculture, 42 within forest, 28 within mixed, and 24 within urban. Sample distribution by geomorphic valley type included 48 sample sites within the glacial valley type (GL), 61 within the post-glacial valley type (PGL), and 15 within mountain valley type (MNT). Among the Chinook salmon MPGs, 10 sample sites were in Georgia Strait, 46 in North Sound, 50 in South Sound, 11 in Hood Canal, and 7 in Juan de Fuca. Among the three Puget Sound Steelhead (*O. mykiss*) MPGs, 56 sample sites were in the Northern Cascades, 18 in the Olympic, and 50 in the South Central Cascades MPGs.

Field sites were also selected from the GRTS design, with a total of 21 sites sampled in the pilot year of 2014. We sampled 3 sites in each land cover class in the post-glacial valley type (12 sites), and 3 sites in the forested, agriculture and urban classes in the glacial valley type (9 sites) (Table 3, Figure 11). Sample site lengths ranged from 233 to 845 m. Land cover class distribution included seven sites in agriculture, six in forest, six in mixed, and two in the urban land cover class, respectively. Out of the 21 sites, 9 sites were located in the glacial valley type, and the remaining 12 sites in the post-glacial valley type.

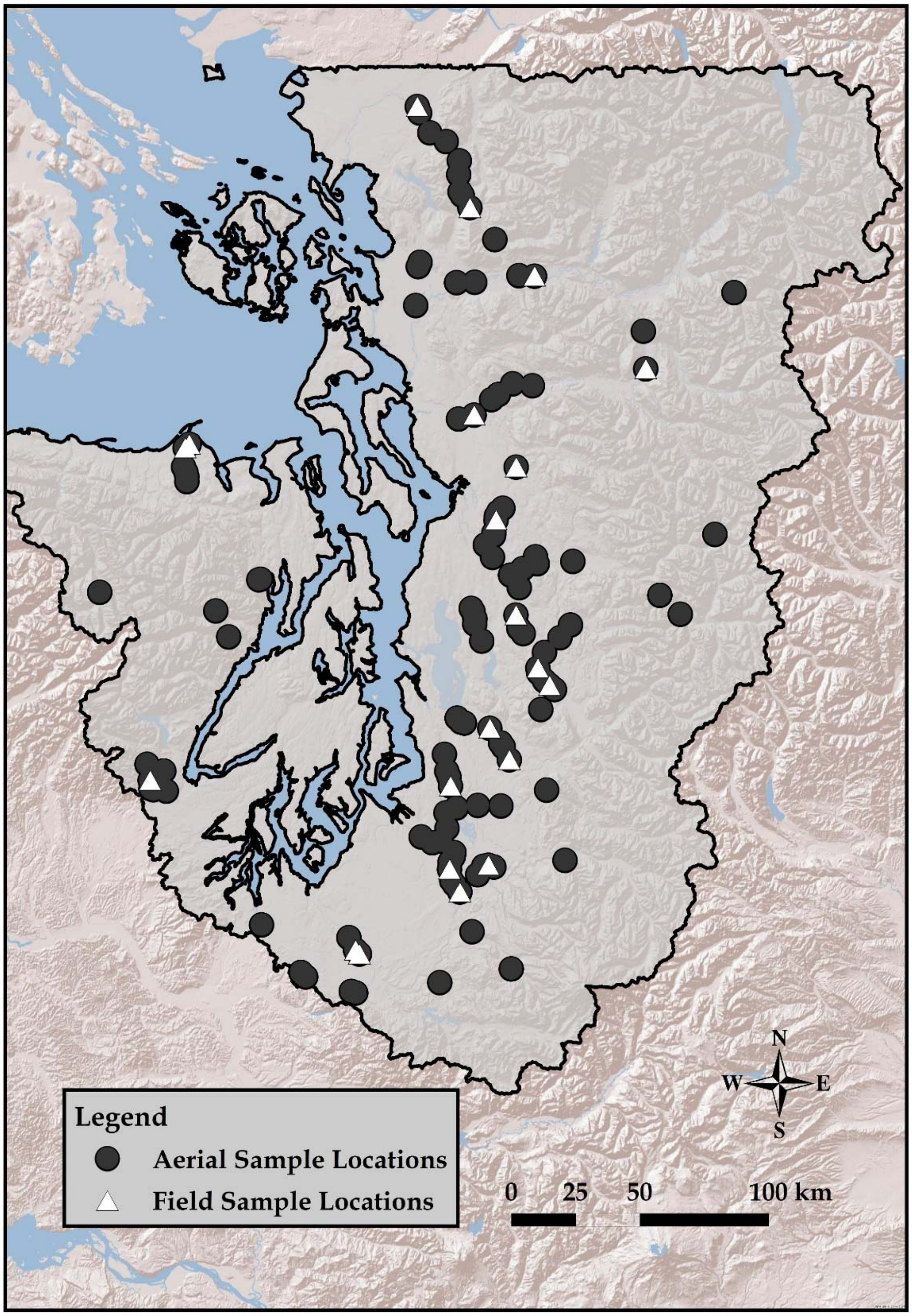


Figure 9. Sample site locations for aerial photography and field sampling of large river and floodplain habitats in Puget Sound.

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

Habitat area	Geomorphic Stratum	Land cover class: Urban	Agriculture	Forest	Mixed
Large river and flood-plain (aerial photo)	Glacial	12	16	9	11
	Post-glacial	11	15	18	17
	Mountain			15	
	Confined				
Large river and flood-plain (field)	Glacial	3	3	3	
	Post-glacial	3	3	3	3
	Mountain				
	Confined				
Nearshore	Open shore - rocky	Nearshore sample sites are not yet selected			
	Open shore - beach				
	Embayment - lagoon				
	Embayment - beach				
Delta (aerial photo)	River-dominated	3		5	3
	Wave-dominated			1	
	Fan shaped			4	

Table 4. Number of aerial photograph sites sampled in each habitat area and stratum. LR-FP indicates large river and floodplain sites.

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

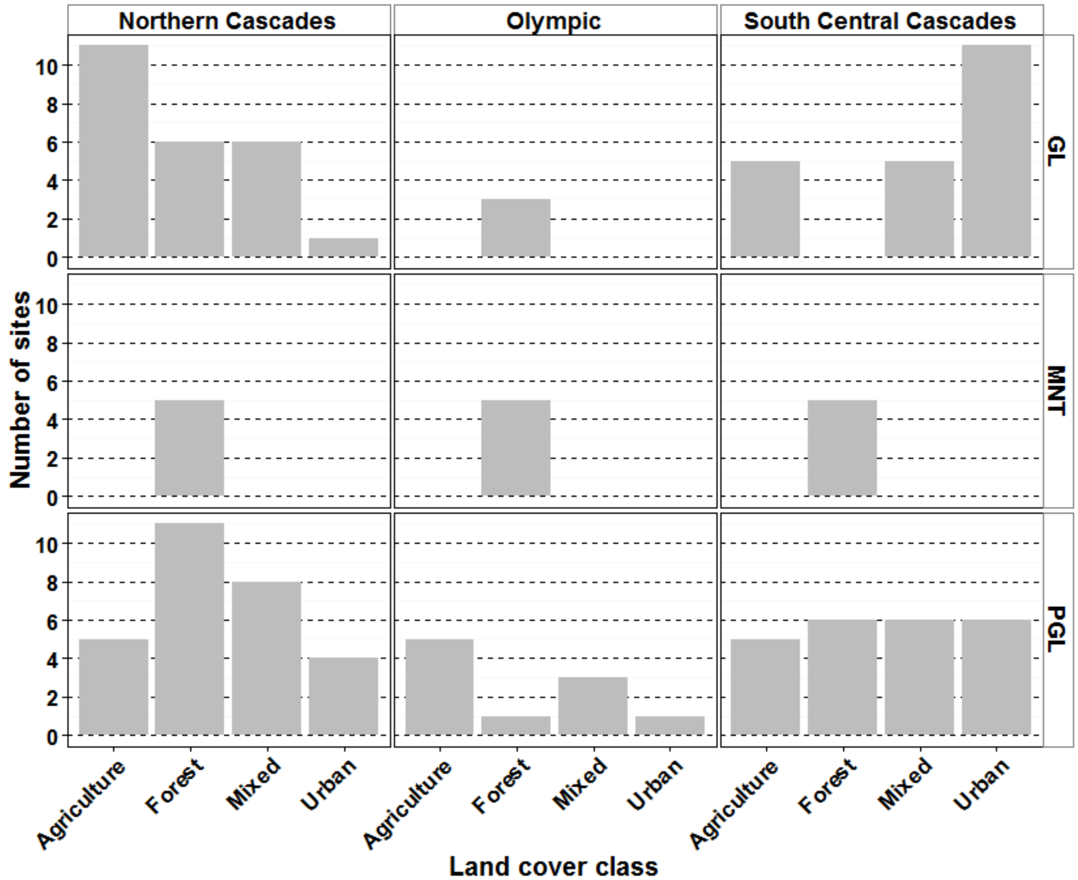


Figure 10: Distribution of aerial photography sample sites within agriculture, forest, mixed, or urban land cover class aggregated by Northern Cascades, Olympic, and South Central Cascades Steelhead MPG, and by glacial (GL), mountain (MNT), and post-glacial (PGL) geomorphic valley types.

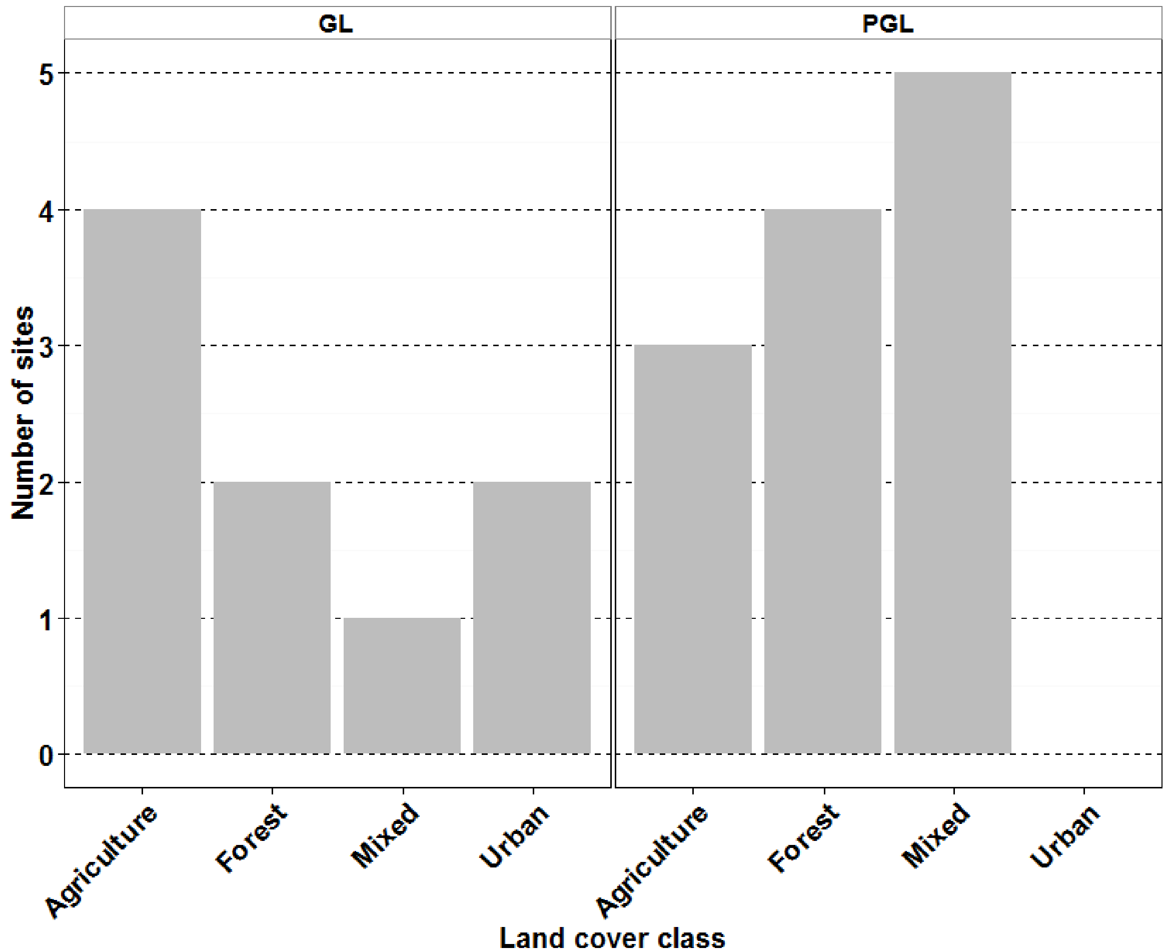


Figure 11: Distribution of field sample sites within agriculture, forest, mixed, or urban land cover class aggregated by glacial (GL) or post-glacial (PGL) geomorphic valley type.

Delta Sample Sites

We measured habitat metrics on all 16 major deltas identified by Simenstad et al. (2011) (Figure 12). That is, there is no sample design since we evaluated every major delta in Puget Sound). These deltas are: 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. Historically the Sammamish and Cedar Rivers flowed into the Duwamish delta, but now are connected to Lake Union and flow to the Puget Sound through the Ballard Locks. Sample sites in nearshore habitat areas will also be selected using the GRTS design in 2015.

The 16 river deltas in Puget Sound were predominantly river-dominated (11 of 16) and forested (10 of 16) (Table 3, Figure 13). Only one delta (Elwha) was classified as wave-dominated, and none were classified as predominantly agriculture. The Deschutes, Puyallup, and Duwamish were predominantly urban.

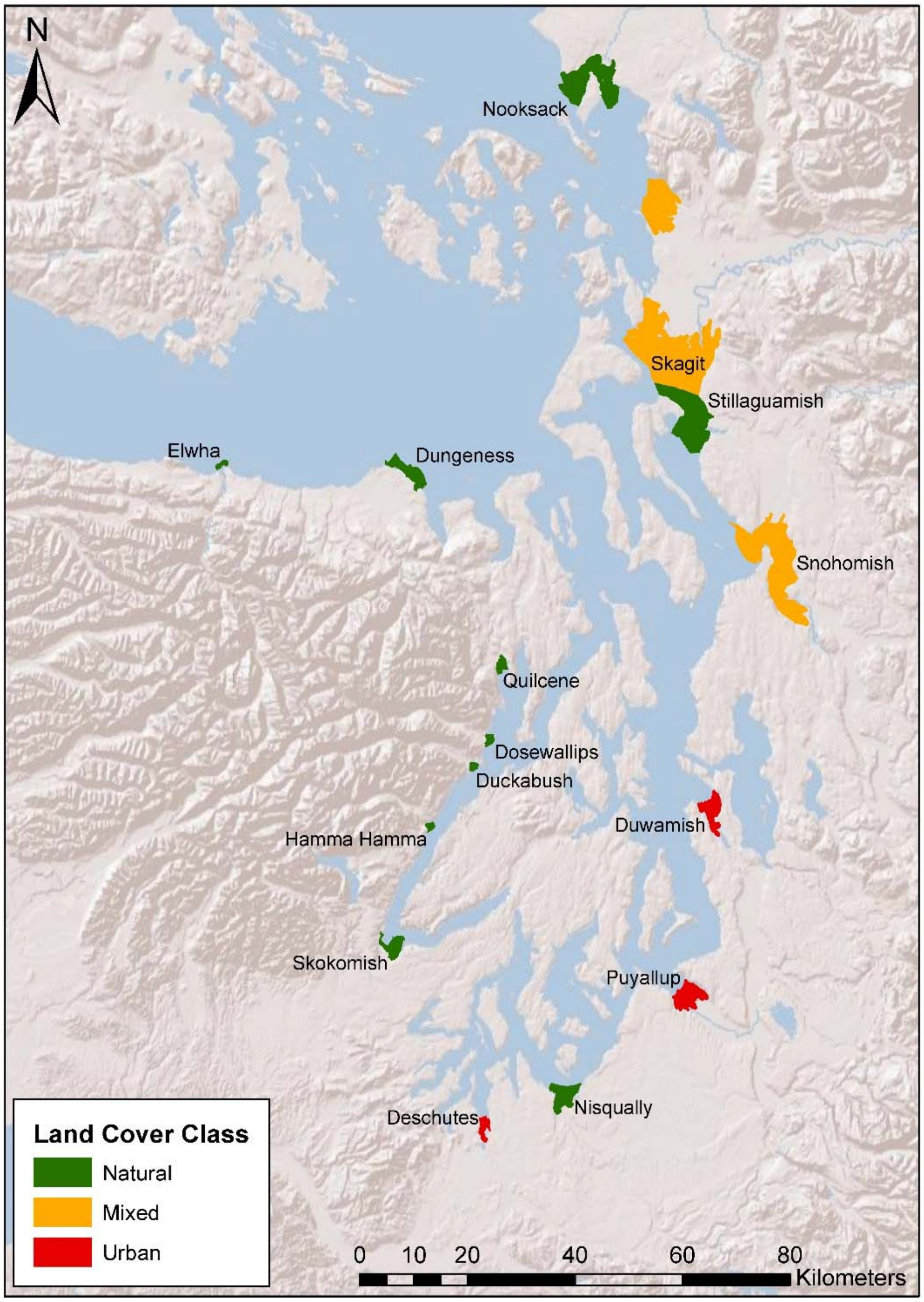


Figure 12. Location of the 16 major deltas in Puget Sound, color coded by land cover class.

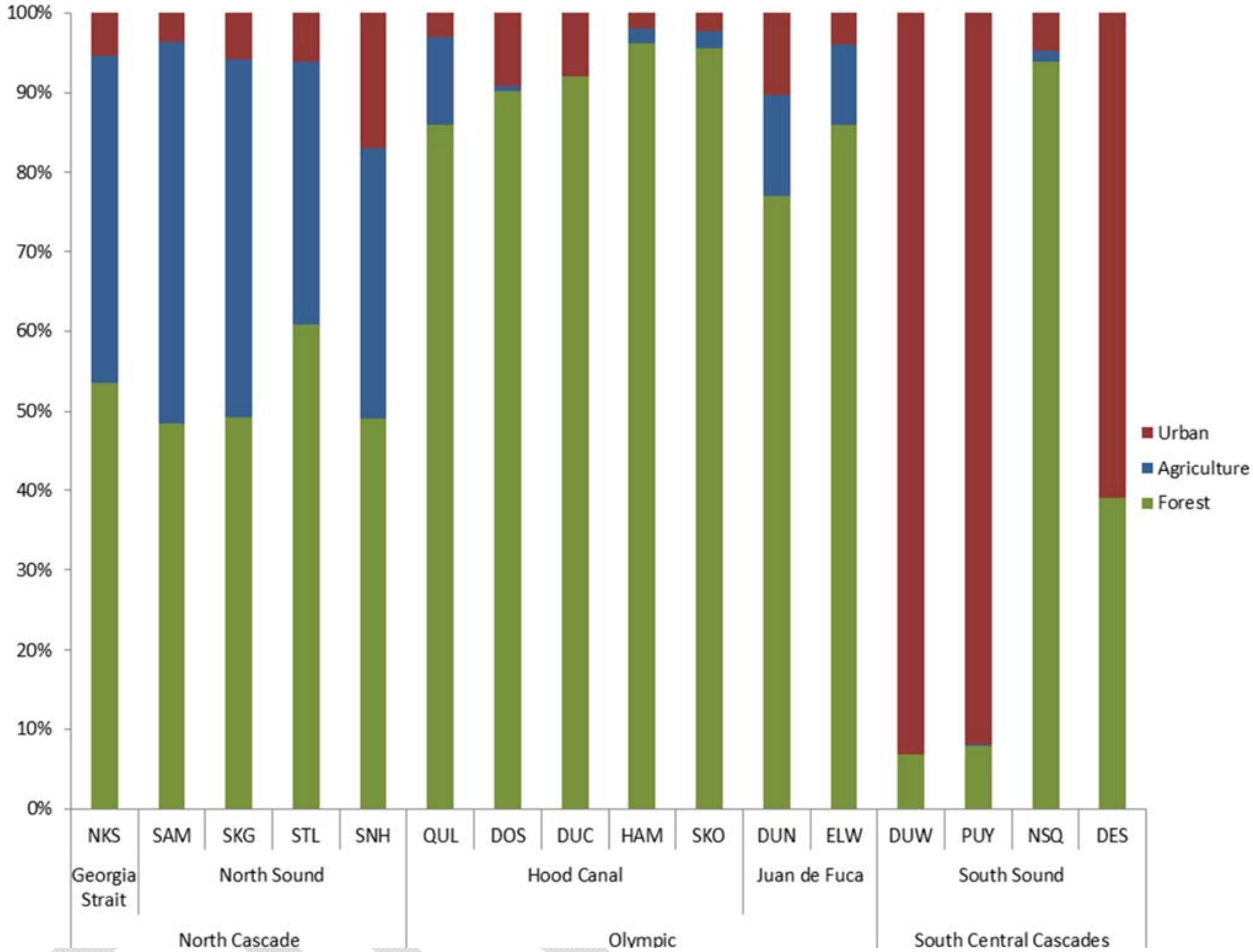


Figure 13. Land cover distribution for each of the 16 major river deltas in Puget Sound. Labels indicate river names: NKS – Nooksack, SAM – Samish, SKG – Skagit, STL – Stillaguamish, SNH – Snohomish, DUW – Duwamish, PUY – Puyallup, NSQ – Nisqually, DES – Deschutes, SKO – Skokomish, HAM – Hamma Hamma, DUC – Duckabush, DOS – Dosewallips, QUL – Quilcene, DUN – Dungeness, ELW – Elwha.

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 estuary/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 three levels of data resolution described previously in the hierarchical sampling approach (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) (See evaluation tables in Appendix C). Once we completed scoring, we selected metrics that scored 4.5 or higher for our monitoring program. We chose the arbitrary threshold value of 4.5 to give us reasonable small number of metrics (i.e., a small set of metrics that we could monitor with our limited budget), yet 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 using fewer evaluation criteria. Our five evaluation criteria were:

1. Is the metric related to at least one of the salmon Viable Salmon Population (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 metrics are based on Analauf et al. (2011a), 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 salmon VSP parameters?

Metrics should be related to at least one of the four VSP parameters (abundance, productivity, diversity, and spatial structure). Habitat quantity and quality metrics are generally related to salmon abundance or productivity, whereas metrics of habitat diversity are more likely related to life history diversity or spatial structure. Pressure/process metrics should influence habitat quantity or quality. The majority of metrics selected for this monitoring program are related to abundance and productivity because they mostly reflect the quantity or quality of habitat available to salmon populations. Diversity metrics that affect spatial structure or diversity within populations 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 resolution, 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 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 classes), 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 S/N ratios are generally lowest in that case.

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

Large River Metrics

We evaluated 34 potential metrics for monitoring status and trends of large river habitats. Only seven 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 pressure/process metrics at all three data resolutions, but suitable habitat quantity metrics were identified only at the aerial photography and field resolutions, and habitat quality metrics only at the aerial photography resolution.

The only satellite data metric that scored 4.5 or higher was the percent of large river riparian forest in various land cover types. This metric met all five criteria, 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 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

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.

Data Resolution	**Metrics (by indicator type)**		
	Pressure/process	**Habitat quantity**	**Habitat quality**
Satellite	• **Percent natural, agriculture, and developed landcover**	• Stream type at network scale	• Hydrologic condition index (flashiness)
Aerial photography/LIDAR	• **Riparian buffer width and type** • Percent of large river disconnected from floodplain • Levee length • Bank armoring • Channel migration rate	• Channel or water surface area • Hydrology • Pool spacing • Edge habitat area by type • Passable river miles	• **Sinuosity** • **Wood jam area** • Riparian forest providing direct shade
Field	• **Length of human modified bank** • Contaminants • Entrenchment ratio • **Riparian buffer width and type** • Percent of large river disconnected from floodplain	• Levee length • **Wood abundance** • **Edge habitat area by type (shallow shore)** • Hydraulic complexity • Pool spacing • CV of thalweg depth • Hydrology (mean, peak flows, ect.)	• B-IBI • Invertebrate drift • Temperature • DO • Nutrients • Turbidity • Conductivity

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 photograph metrics for all three data types (pressure/process, habitat quantity, habitat quality). The aerial photograph metric for pressures is riparian buffer width and type along the main channel. This metric meets all five criteria, and has been used in large scale hierarchical analyses such ours (Fullerton et al. 2006, Konrad 2015). The one aerial photograph metric that scored well for habitat quantity was water surface area, and the suitable habitat quality metric from aerial photography was riparian forest area providing direct shade. 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 S/N ratio scores. The habitat quantity and quality metrics also scored low primarily because all had low S/N ratios.

Suitable field metrics included riparian buffer width/type length of human modified bank (levee, rip-rap) for pressure/process, and wood abundance and habitat area for habitat quantity. 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 salmon VSP were low. Habitat quantity metrics that scored low (hydraulic complexity, pool spacing, CV of thalweg), scored low mainly because signal to noise ratios were low.

None of the field metrics for habitat quality scored 4.5 or higher, primarily because they were expensive to implement or have 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., 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 status and trends of floodplain habitats, and 15 scored 4.5 or higher and were selected for use in the first year of the monitoring program (Table 6). We identified suitable pressure/process metrics at all three data resolutions, but suitable habitat quantity metrics were identified only at the aerial photography and field resolutions, and habitat quality metrics only at the aerial photography resolution.

The only satellite data metric that scored 4.5 or higher was the percent of floodplain in various land cover types. This metric met all five criteria, and was selected as the primary pressure metric for floodplain habitats. The National Land Cover Dataset (NLCD) is produced at approximately 5-year intervals and can be used to track land cover change with

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.

Data Resolution	**Metrics (by indicator type)**		
	Pressure/process	**Habitat quantity**	**Habitat quality**
Satellite	• **Percent natural, agriculture, and developed landcover**	• Fragmentation by roads levees, etc. • Wetland area	• Hydrologic condition index (flashiness)
Aerial photography/LIDAR	• **Percent of floodplain disconnected** • Length of human modified bank • Turnover rate of floodplain surfaces	• **Length of side channel** • Area of side channel • **Area of connected floodplain** • Area ponded habitat • Percent of side channel disconnected by levees	• **Braid-channel ratio (L_{bc}/L_{main})** • **Side-channel ratio (Lsc/Lmain)** • **Braided-channel node density** • **Side-channel node density**
Field	• **Riparian species composition and buffer width** • **Length of human modified bank** • Contaminants	• **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 • DO • Nutrients • Conductivity

reasonable accuracy (Wickham et al. 2013). The fragmentation metric and hydrologic condition index scored low mainly because they were difficult to link to salmon 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 photograph metrics for all three data types (pressure/process, habitat quantity, habitat quality). Aerial photograph metrics for pressures included riparian buffer width and type 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 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.

Aerial photograph metrics that scored well for habitat quantity included length of side channel (Beechie et al. 2006) 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 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 from Quickbird imagery scored low primarily because of the anticipated low accuracy of measurements in forested areas (Whited et al. 2013). Suitable habitat quality metrics from aerial photography included the braid/channel ratio (or the ratio of side-channel length to main channel length), sinuosity (channel length divided by valley length), and 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. 2013, Beechie et al. 2015).

We also identified two suitable field metrics for pressure/process and four field metrics for habitat quantity. For pressures we will monitor 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). 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.

None of the habitat quality metrics scored 4.5 or higher, primarily because they were expensive to implement or have 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., 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.

Delta Metrics

Delta habitats encompass the transitional area between marine waters and freshwater in Puget Sound (Fresh et al. 2011). 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 (average of the lower low water height of each tidal day over the National Tidal Datum Epoch, https://tidesandcurrents.noaa.gov/datum_options.html).

We evaluated 25 potential metrics for monitoring status and trends of delta habitats, and 12 scored 4.5 or higher and were selected for use in the monitoring program (Table 7). We identified suitable pressure/process metrics at all 3 data resolutions, but suitable habitat quantity and habitat quality metrics were identified only at 2 data resolutions, no metrics were identified for habitat quantity at the field resolution, and no habitat quality metrics were identified at the satellite resolution.

At the satellite resolution, three metrics scored 4.5 or higher: percent forest or developed land cover, estuary surface area/drainage area, and wetland area. Each of these metrics met all five criteria with high scores. The National Land Cover Dataset (NLCD) is produced at approximately 5-year intervals and can be used to track land cover change with reasonable accuracy (Wickham et al. 2013). The estuary surface area/drainage area metric facilitates comparison of delta area among river systems, while wetland area is an indicator of rearing habitat availability. Connectivity is measured as distance and pathways between various delta marsh and distributary habitats and is strongly correlated to salmon VSP (Beamer et al. 2005).

We identified 7 aerial photograph (or LIDAR) metrics, and consider 6 to be suitable, for all three indicator types (pressure/process, habitat quantity, habitat quality). Two aerial photograph metrics for pressures are proportion of delta behind levees and length of human modified bank along distributary channels. Three metrics for habitat quantity are tidal channel area, wetland area, and node density. Two metrics related to habitat quality are node density (again) and wetland type. Infrared intensity did not score high enough for links to salmon VSP or signal to noise ratio.

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.

Data Resolution	Metrics (by indicator type)		
	Pressure/process	Habitat quantity	Habitat quality
Satellite	• **Percent natural, agriculture, and developed landcover** • Length of Tidal barriers/levees	• Estuary surface area/drainage area • **Wetland Area** • Elevation	
Aerial photography /LIDAR	• **Proportion of delta behind levees** • **Length of levees and dikes along distributaries**	• **Tidal channel area** • Tidally influenced area	• **Node density** • **Wetland area by type** • Infrared intensity • Aerial extent of salinity zones
Field	• **Length of armoring, location of barriers, and culverts** • Contaminants • Nutrients • Bay fringe erosion rate • Sediment accretion rate		• Plant species diversity and composition • Proportion of non-native species • Wetland type • Temperature • DO • Extent of salinity zones

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

Nearshore Metrics

Nearshore habitats are habitats along the shoreline (Fresh et al. 2011), 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 (https://tidesandcurrents.noaa.gov/datum_options.html). Adjacent land use can have a significant influence on this wetted habitat (Simenstad et al. 2006). We include a buffer strip of 200 m width along the delta and nearshore shoreline to represent this land/water interface (Fresh et al. 2011; Simenstad et al. 2011).

We evaluated 26 potential metrics for monitoring status and trends of nearshore habitats, and 11 scored 4.5 or higher and were selected for use in the first year of the monitoring program (Table 8). We identified suitable pressure/process metrics at 3 data resolutions, but suitable habitat quantity metrics were identified at only 2 data resolutions, and habitat quality metrics only at 2 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 thus measure the percent of various land cover types of nearshore in the adjacent 200 m buffer zone. The National Land Cover Dataset (NLCD) is produced at approximately 5-year intervals and can be used to track land cover change with reasonable accuracy (Wickham et al. 2013).

Ten metrics using aerial photography analysis were considered, and 7 were found suitable. These metrics fit all three data types (pressure/process, habitat quantity, habitat quality). Pressure/process metrics included shoreline armoring, percent developed, rate of forest clearing, and area of agriculture. Two habitat quantity metrics were selected (wetland area by type, area of eelgrass and kelp beds), and one habitat quality metric was selected (length of forested shoreline). The metric "number of overwater structures" scored low in linkage to salmon VSP, sensitivity to land use, link across scales, and signal:noise ratio. Two metrics, length of unarmored feeder bluffs and beach width scored low in link to salmon VSP and signal:noise ratio.

Fifteen field metrics were proposed, and 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 low for signal:noise ratio. Nutrients also scored low for link to salmon VSP. Two metrics for habitat quantity were identified and 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:noise ratio. Small stream and pocket estuary connectivity scored low for the linkage across scales and signal: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.

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.

Data Resolution	**Metrics (by indicator type)**		
	Pressure/process	**Habitat quantity**	**Habitat quality**
Satellite	• **Percent natural, agriculture, and developed landcover**		
Aerial photography	• **Shoreline armoring** • **Percent impervious (in 200m buffer)** • **Percent forest (in 200m buffer)** • **Area of overwater structures**	• Length of unarmored feeder bluffs • **Area of eelgrass and kelp** • **Embayment Area (total, wetted, veg)** • Beach width	• **Connectivity of embayment to nearshore (width of opening)** • **Length of forested shorelines**
Field	• **Shoreline armoring** • **Location of culverts/tide gates blocking access** • Contaminants • Nutrients	• Elevation of bulkhead toe • Small stream/pocket estuary connectivity	• Beach composition (shells) • Epibenthic taxa richness • Grain size • Area of wood and rack • Temperature (microclimate and water) • DO • Turbidity • Condition of pocket estuary and small stream mouth/estuary

Overview of selected metrics and protocols

Our monitoring protocols were designed to efficiently measure the suite of selected metrics at each sample site. Our aim was 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 each monitoring environment. In general, we anticipated that we would have complete coverage of the landscape with satellite data (low resolution), large sample sizes for aerial photograph 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 the delta and nearshore metrics separately because sample sites do not overlap and protocols differ between the two environments.

Large River and Floodplain Metrics

Percent natural, agriculture, or developed land cover (satellite, aerial photo)

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. 2010b). 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 with our first year of data collection.

In this first year of sampling we measured land cover from two different data sets: satellite data from NOAA's Costal Change Analysis Program (C-CAP, 30-m grid cell resolution) and WDFW's digitally processed aerial imagery from the National Agriculture Imagery Program (NAIP, 1-m grid cell resolution) (Ken Pierce, unpublished data). In both cases we simply extracted the desired metrics from the landcover data sets in each floodplain polygon using zonal statistics in GIS. Sampling intervals for these metrics are dependent on intervals for which each data set is available. At present the C-CAP data is available every five years, and the NAIP data processed by WDFW is 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 be consistently defined and mapped among reaches, and that there are consistent rules for determining whether portions of that 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 metric that ultimately influences salmon abundance and productivity through via changes in habitat quantity and quality.

This metric has been estimated from analysis of LIDAR data for the major floodplains of Puget Sound by Konrad (2015). 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 not 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, Collins et al. 2012, Naiman et al. 2010b). 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. 2010a), 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 straight forward (Hyatt et al. 2004, Fullerton et al. 2006), and the S/N 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 are 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, the main channel, and the valley center line 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., 2006). 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 edge of the channel (velocity <0.45 m/s, < 1 m deep; 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 S/N 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 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 urban 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 the large river and its floodplain. We included wood that was visible in the water, on gravel bars, and in young vegetation on islands or the floodplain, 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 3 size classes, large (length>5m and diameter >0.5 m), medium, (length >2m and diameter >0.2m), and small (length >1 m and diameter >0.1 m).

Length of human modified bank (field)

Length of 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 2003, 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 (Naiman et al. 2010a, Beamer and Henderson 1998). 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 length of human modified banks from aerial photography, but had low confidence in the results. We digitized visible levees and armored banks, and 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 photograph metric in the future. In the field, the length of human modified bank was measured using 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 channels: pool spacing, residual depth, wood abundance (field)

Habitat metrics for smaller floodplain channels include pool area (an indicator of habitat abundance), wood abundance, pool spacing, and residual pool depth (indicators of habitat diversity) (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). Wood abundance, pool spacing, and residual pool depth have higher signal to noise ratio because they are not flow dependent and pools can be identified consistently using residual depth thresholds (Lisle 1987).

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>5m and diameter >0.5 m), medium, (length >2m and diameter >0.2m), and small (length >1 m and diameter >0.1 m). From the survey data we then calculate pool spacing, residual depths of pools, and wood abundance in 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

Percent natural, agriculture, or developed land cover (satellite)

In a previous study, wetland area in Puget Sound deltas is inversely related to percent developed land cover (Fresh et al. 2011). 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 NOAA's Costal Change Analysis Program (C-CAP, 30-m grid cell resolution) For each delta polygon we simply extracted the desired metrics from the landcover data sets using zonal statistics in GIS. Sampling intervals for these metrics is dependent on intervals for which the C-CAP data is available (~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)

Wetland type refers to the vegetation type and tidal inundation of wetlands (e.g., emergent marsh, estuary-forest transition, and forested-riverine tidal) (Cowardin et al. 1979). 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 marsh and blind tidal channels are linked to greater life history diversity, delta rearing capacity and survival of juvenile Chinook (Fresh 2006, Magnusson and Hilborn 2003, Beamer et al. 2005, Beamer et al 2014). Large losses of wetland area across many watershed delta areas 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.

Proportion of delta behind levees (aerial photography/LIDAR)

The proportion of delta area that is behind levees is a measure of capacity of fish habitat, both historically and currently. Tidal marsh and blind tidal channel networks are typically lost from diking and draining of wetlands, and fish rearing capacity is diminished (Magnusson and Hilborn 2003, Bottom et al. 2005). This parameter is effectively measured using aerial photography. Tidal marsh restoration, dike setbacks, tide gate 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)

Connectivity of delta and nearshore marine habitats is critically important for juvenile salmonids migrating from upstream freshwater natal habitats into the Puget Sound (Quinn 2005). Rearing and feeding of juvenile fishes in these habitats is critical to 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, as well as fish densities (Toft et al. 2007, Greene et al. 2012, Morley et al. 2012, and Fresh et al. 2011). Changes in mean substrate temperatures, epibenthic invertebrate densities, epibenthic taxa richness and fish densities were also evident at armored sites (Morley et al. 2012, Greene et al. 2012). Fish use is limited in distributary channels with tidegates, even if there are fish passage mechanisms used (Greene et al 2012). We have not yet developed a protocol for this metric.

Length of armoring

The cumulative impacts of shoreline armoring have resulted 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. 2011). Determining the extent of shoreline armoring in delta and nearshore habitats and monitoring the change in the amount of structures over time is thus important to assessing salmon habitat quality and is directly related to habitat connectivity (PS RITT 2015). We have not yet developed a protocol for this metric.

Location of barriers and culverts

One of the most obvious changes to the nearshore of Puget Sound is the loss of connectivity between land, 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 typically are located at streams and embayments and restrict 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 and so they are closed by an incoming tide and open when the tide begins to ebb. Where tidegate inventories do not exist, we may using both aerial photography and field verification to identify the number of tidegates/culverts and assess extent of blockage. We have not yet developed a protocol for this metric. The level of effort put towards this metric will depend on staffing levels.

Tidal channel area (aerial photography)

Tidal channel area is an important measure of habitat capacity for juvenile salmonids in deltas (Hood 2015). The extent of both distributary channels and blind tidal channels provide corridors for migration as well as access to intertidal marshes (Howe and Simenstad 2014). The edge habitat of tidal channels provides vegetative cover from predation, lower velocity refugia, and is the primary area in which they feed (Simenstad and Cordell 2000). Therefore a 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 greater than 5 m wide 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 smaller than 5 meters in width, we digitized polylines along the flow path and then buffered the polylines by 1 m to create a polygon feature. The area 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 smaller than 5-m wide. 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 (Whitehead et al. 2013). In estuary habitats, marsh-channel confluences with large river/distributary channels are primary rearing habitats for coastal cutthroat (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 (described previously), and node density calculated as the number of nodes per km of main distributary (nodes/km).

Nearshore Metrics

In 2014 we completed the selection of nearshore metrics, but did not have time to develop protocols for any of these metrics. Here we describe each of the selected metrics; protocols will be developed in 2015.

Percent natural, agriculture, or developed landcover (satellite)

As with floodplains and deltas, land cover in the nearshore is correlated with habitat degradation (Rice 2006, 2007, Fresh et al. 2011). Therefore we will monitor land cover change in the nearshore as causal factor for habitat degradation. We will monitor land cover change within 200-m of the shoreline using data from NOAA's Costal Change Analysis Program (C-CAP, 30-m grid cell resolution). For each shoreline segment we will extract the desired metrics from the landcover data sets using zonal statistics in GIS.

Percent impervious (aerial photography)

Developed land cover is a quantifiable and commonly used land use indicator in stream ecosystems that correlates closely with a variety of biophysical and chemical changes to aquatic ecosystems. While it is not clear whether impervious surface coverage in the 200 m marine riparian buffer has the same sort of impacts as in stream systems, it is known that changes in shoreline land cover affect bird species composition and spawning and incubation habitats for surf smelt (Rice 2006, 2007). Therefore, we hypothesize that increases in the amount of impervious surface in the nearshore will also be correlated with degradation of other aspects of nearshore ecosystems. And, as the amount of impervious surface increases, a variety of chemical, physical, and biological changes can occur.

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 IBI) and fish communities in stream ecosystems (Richery 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, abundance) in the nearshore.

Land cover/land use in the 200m buffer along the nearshore will be analyzed using NOAA's Coastal Change Analysis Program (C-CAP) data that is 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 what PSNERP reported (Simenstad 2011). In addition, several other metrics will be generated in the 200 m marine riparian buffer using aerial photography. These are described below.

Percent forested (satellite, aerial photography)

One of the dominant features of Puget Sound is its long shoreline that in pre-settlement condition was heavily forested (Collins et al 2003). Emerging science suggests that 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 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.

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. 2013). Shoreline armoring refers to the construction of structures along the shoreline, for erosion control and protection of property and infrastructures 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 (MHHW)).

Armoring directly impacts the beach where it is constructed. It affects access to the beach, loss of terrestrial sediment supply and transport, and localized beach erosion or changes to sediment transport caused by wave interaction with structures (Woodroffe 2002, Griggs 2005). 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 the encroachment in the intertidal zone, changes in groundwater flow, and disruption of detritus and large wood import and export (M. Dethier, Univ. Wash., Pers. Comm., Shipman et al. 2010). 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 data set. There are a variety of different data sets that vary in temporal and spatial extent. The Puget Sound Nearshore Ecosystem Research Project (PSNERP) developed a shoreline armoring dataset for an analysis of nearshore changes that occurred from circa 1850 to the 2010. This analysis determined that 26% of the shoreline of Puget Sound was armored (Fresh et al. 2011, Simenstad et al. 2011). Currently, a new armoring data set is being developed with support from PSP, NOAA, WDFW, and WDOE. This new data set will provide a spatially explicit analysis of presence/absence of armoring, and is being developed from aerial photo analysis and field verification.

Length of forested shorelines (aerial photography)

We will also measure the length of forested shoreline, as obtained from aerial photographs, 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) ns. Eelgrass is well-recognized as an indicator of ecosystem health. In shallow subtidal and intertidal areas, it functions as rearing habitat for Dungeness crab (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), spawning substrate for Pacific herring (Penttila 2007), and rearing habitats for a variety of coastal species including cutthroat trout, and juvenile coho and Chinook salmon (Krentz 2007, Bottom and Jones 1990). Eelgrass also can 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 to commercial and sport fish, invertebrates, marine mammals and marine birds (Dayton 1985, Duggins et al. 1989). 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 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, with greatest abundance 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). WADNR mapped the extent of kelp in Puget Sound as part of the Puget Sound Shore Zone survey in approximately 2000, and conduct annual surveys in the Strait of Juan de Fuca and outer coast (Gaeckle et al. 2011). Protocols for these metrics are currently being developed.

Area of overwater structures

Overwater structures typically include docks, piers, floats, ramps, wharfs, ferry terminals, marinas, structural or supporting pilings, and other structures that are supported above or float on the water. Overwater structures in nearshore marine environments cause impacts to fish habitat as a result of shading, change in littoral vegetation and littoral drift, change in riparian and shoreline vegetation, decreased water quality, increased noise from vessel activities, increase in artificial light, and substrate modifications (WDFW 2006). The impacts may be temporary 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 causing altered migration routes, behavior, growth, prey availability, and ultimately survival (Nigingale 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 sub types, 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 are non-natal rearing habitats for Chinook salmon (often called "pocket estuaries", Beamer et al 2005, McBride et al. 2005). That is, no Chinook spawning occurs within them and 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 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. 2011; 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. 2011). 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. 2011). Protocols for this metric are currently being developed.

Culverts/tidegates blocking access (field)

One of the most obvious changes to the nearshore of Puget Sound is the loss of connectivity between land, 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 typically are located at streams and embayments and restrict 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 and so they are closed by an incoming tide and open when the tide begins to ebb. Where tidegate inventories do not exist, we may using both aerial photography and field verification to identify the number of tidegates/culverts and assess extent of blockage. The level of effort put towards this metric will depend on staffing levels.

Analysis Methods

1. Accuracy of Land Cover Classification

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

Land cover metrics were summarized by land cover class (forest, urban, agriculture, or mixed). Sample sites were created using USGS floodplain polygons (Konrad 2015) and reach breaks delineated in aerial photography. Forest and developed land cover classes were extracted and zonal statistics was run in ArcGIS 10.2 using the floodplain polygon layer, C-CAP 2011 Landsat data, and 2011NAIP 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 data base (30-m resolution) and the land cover classification developed by Ken Pierce of WDFW using aerial photography from NAIP (1-m resolution) in three 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. Finally, we created error matrices of the C-CAP and NAIP classifications to examine which land cover classes were likely creating confusion in the classification of forested or developed areas.

To assess the accuracy of the percent forest and percent developed land cover metrics from C-CAP and NAIP, we used regression analyses of 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 created error matrices of the two land cover classifications to evaluate overall accuracy of the classification system. In the error matrix, a low commission error indicates that the land cover data set rarely assigns a land cover type that is incorrect. For example, a low commission error for the forest land cover class would indicate that when the land cover data set identifies a cell as forest, there is a high likelihood that the land cover in that cell is in fact forest. By contrast, omission error indicates the frequency of missed land cover types. For example, if there is high omission error for the forest land cover, that indicates that many cells that should have been identified as forest cover were not.

We also evaluated the accuracy of manually classified land cover from aerial photography by comparing aerial photograph 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 photograph land cover classification.

2. Observer Variability in Aerial Photograph Metrics

One important task in developing our new aerial photograph monitoring protocols was determining how much inter-observer variation there is in the measurement of each feature from aerial photography. For example, if two observers use slightly different criteria 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 the methods for analyzing observer variation for the large river and floodplain habitat metrics.

Using GIS software and previously defined aerial photography sampling protocol, 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), and reach sample length and area were defined for each location before sampling took place. Sample locations ranged in length from 497 m to 5606 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. Positive percentages indicate greater feature measurements by the first observer, while negative percentages indicate greater feature measurements by the second observer. Where there were large differences among observers, we examined individual habitat feature to determine the causes of differences and refine protocols.

3. Status of Habitat and Riparian Areas by MPG

We summarized the current status of each of the large river and floodplain metrics by Steelhead Major Population Group (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 (*Oncorhynchus mykiss*) MPG within all sample-able 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, agriculture, or urban land cover (Konrad 2015). Zonal statistics was used to extract landcover 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 (Landsat) grouped into forest, agriculture, and urban 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 Class

We summarized the current status of each of the large river metrics across our floodplain sample sites by land cover class. 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 class. Metrics were un-weighted in this case because we are interested in differences among land cover classes (urban, agriculture, forest, mixed), regardless of the aerial extent of each land cover class. We did not summarize the delta metrics by land cover class because we sampled all deltas and there was an uneven distribution of land cover classes (only 3 urban deltas and no deltas in the agriculture class).

Results

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

In this section we present the results of three separate analyses. The first analysis examined which land cover classes in either C-CAP or NAIP produced the most accurate representation 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. We may review overall accuracy of both the C-CAP and NAIP land cover classification products in the future, although such a re-analysis is arguably less important than our second analysis presented here, which directly examined the accuracy of our selected land cover metrics (percent forest and percent developed land cover).

Evaluation of forest land cover classes

An important first step in developing our landcover 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 classification accuracy assessments for C-CAP forest land cover classification and the NAIP forest land cover classification.

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 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, mixed), and found that percent forest was significantly 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, but 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, delta forested wetland) to calculate percent forest in floodplains.

NAIP Forest Land Cover Classification

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 ($r^2 = 0.84$) (Figure 15). However, several other classes also contained the word “tree”, so we examined all combinations of variables with the word tree 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, and precision was the same or reduced. Therefore all subsequent analyses we estimated percent forest from the NAIP data using only the “tree” class.

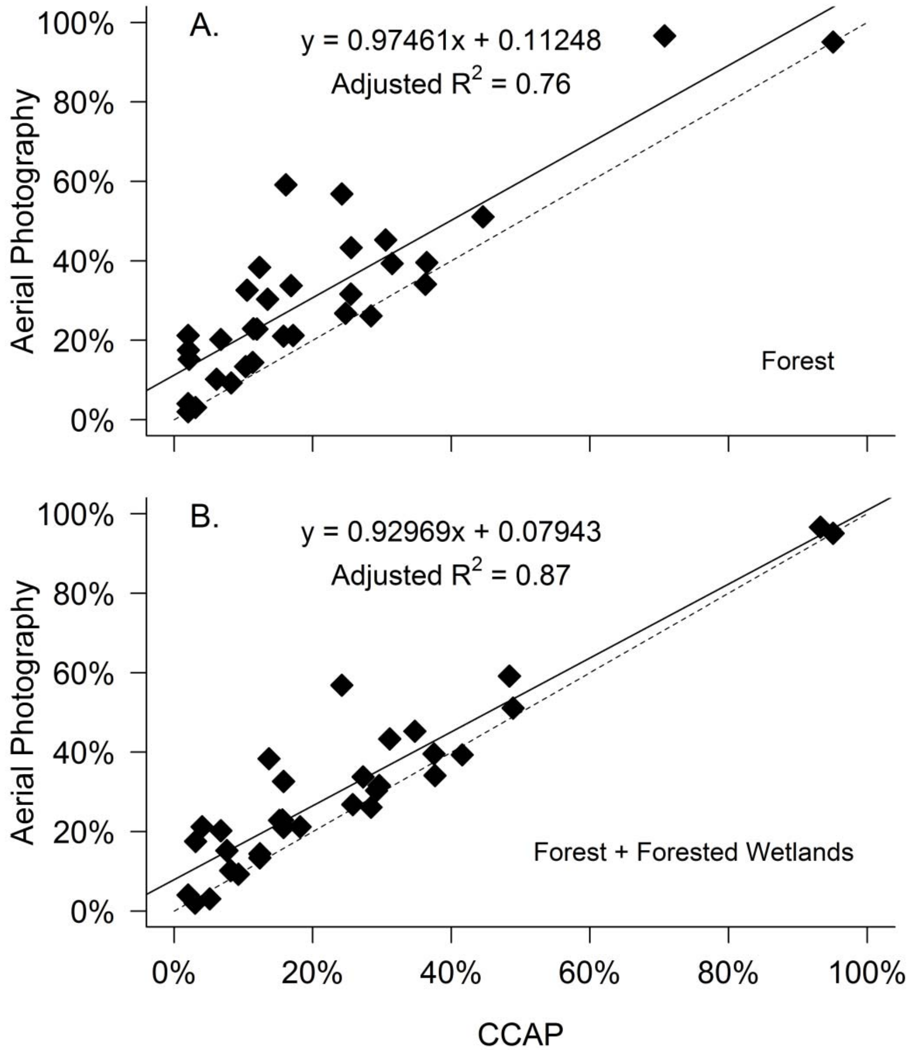


Figure 14. Regression plots for two different groupings of forest land cover of C-CAP data at 32 floodplain sites (points). Percent *forest* and percent *forest + forested wetlands* is plotted against observed land cover from aerial photography.

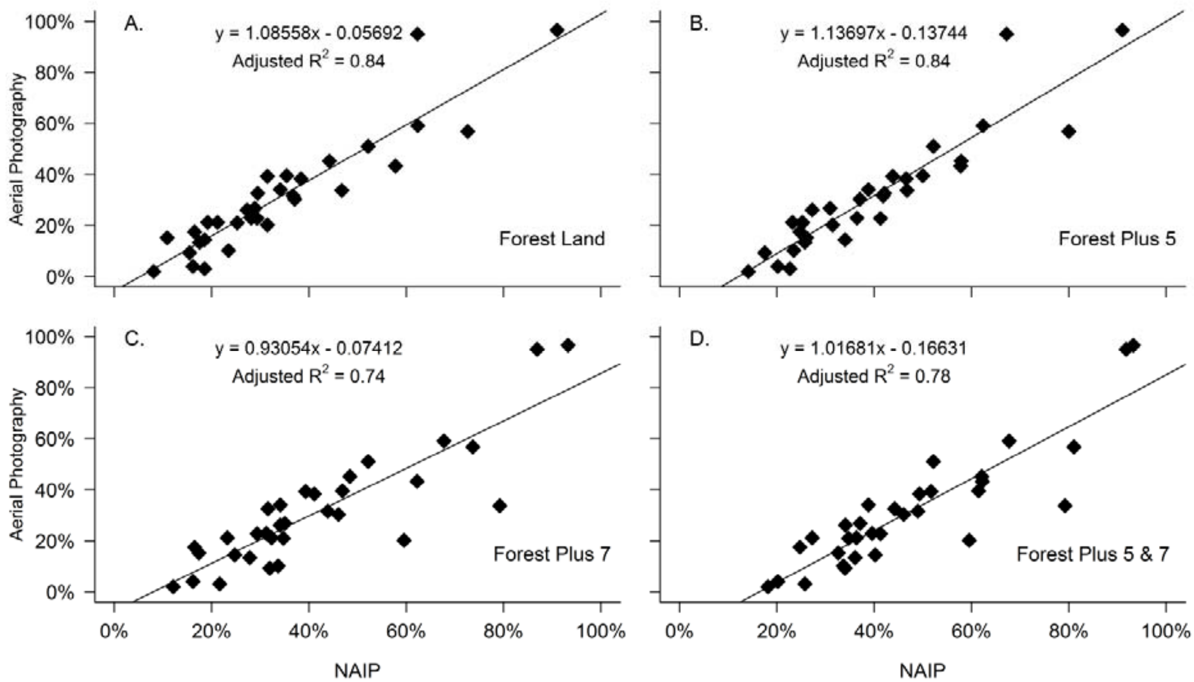


Figure 15. Regression plots depicting the accuracy of four different possible groupings for forest land cover of NAIP data at 32 floodplain sites (points). Based on the closeness of fit with the x-intercept and the adjusted R^2 value there is not a significant benefit to adding other land classes to *Forest Land* (class 8).

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 accuracy of the two metrics from each data set (Figure 16). Each metric from each data set 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 overestimate percent developed, while NAIP tends to overestimate percent forest and underestimate percent developed. Recent improvements in the NAIP photo interpretation process may increase its accuracy over that of the C-CAP data in future. We will reevaluate the NAIP imagery within the next two years. We report our land cover metrics by MPG and LCC using both NAIP and C-CAP since the result of this accuracy assessment demonstrated that there was no significant difference between the data sets.

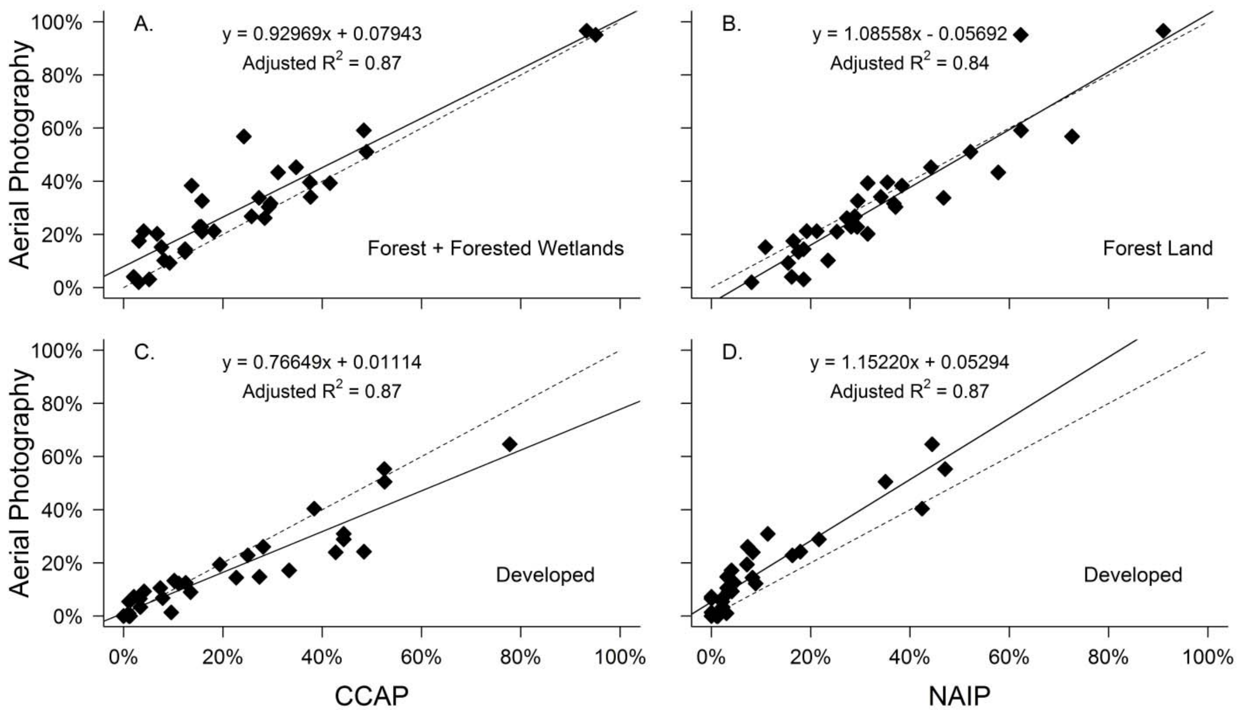


Figure 16. Regression plots with percent forest and percent developed of C-CAP and NAIP data by Aerial Imagery at 32 sites (dots).

Accuracy of aerial photograph 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 and we opted not to use manual land cover classification for our monitoring program. Our analysis started with accuracy evaluation for eight 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 occurred between the image date and field survey dates. The error associated with changes on the ground that occurred between the image date and ground survey dates 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 interpretation of aerial photos (Table 11 and Table 12).

Another major source of error was incorrect classification of tree community type in the aerial image, 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 differentiation of tree community types appears to be difficult from aerial image analysis, we grouped all forest community types (C, D, and M) into one forest category (F) and revaluated the classification accuracy (Table 13 and Table 14).

With tree community types 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 was the misclassification of grass/shrub (G/B) as tree community cover types and tree community types as grass/shrub. This represents 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 classification of shrub communities as tree cover types or 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 which prevents further segregation of the error matrix using our current field data.

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

Photo \ Ground	BG	C	D	DI	DP	G/B	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). BG=bare ground, C=conifer, D=deciduous, DI=disturbed impervious, DP=disturbed impervious, G/B=grass/brush, M=mixed forest, W=water.

Photo \ Ground	BG	C	D	DI	DP	G/B	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	13		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 that excludes sites where changes occurring between the image date and survey dates caused misclassifications. Overall classification accuracy was 70% (118/168). BG=bare ground, C=conifer, D=deciduous, DI=disturbed impervious, DP=disturbed impervious, G/B=grass/brush, M=mixed forest, W=water.

Photo \ Ground	BG	C	D	DI	DP	G/B	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 that excludes sites where changes occurring between the image date and survey dates caused misclassifications. Overall classification accuracy was 65% (108/167). BG=bare ground, C=conifer, D=deciduous, DI=disturbed impervious, DP=disturbed impervious, G/B=grass/brush, M=mixed forest, W=water.

Photo \ Ground	BG	C	D	DI	DP	G/B	M	W	Total	%Correct	%Commission
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	96%	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). BG=bare ground, F=forest, DI=disturbed impervious, DP=disturbed impervious, G/B=grass/brush, W=water.

Ground

Photo	BG	DI	DP	F	G/B	W	Total	%Correct	%Commission
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	84%	17%
G/B			3	3	5		11	46%	55%
W						2	2	100%	0%
Total	6	24	35	84	17	2	168		
%Correct	100%	79%	80%	91%	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). BG=bare ground, F=forest, DI=disturbed impervious, DP=disturbed impervious, G/B=grass/brush, W=water.

Ground

Photo	BG	DI	DP	F	G/B	W	Total	%Correct	%Commission
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	46%	55%
W						1	1	100%	0%
Total	4	22	32	82	17	1	158		
%Correct	100%	86%	84%	81%	59%	100%		80%	
%Omission	0%	14%	16%	20%	41%	0%			

2. Observer Variability in Aerial Photograph Metrics

A second important task in developing our new aerial photograph monitoring protocols was determining the magnitude of inter-observer 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. Later in this report we discuss how this error analysis contributed to refining our protocols to reduce observer variation in measurements (see Question 4 in the Discussion section).

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

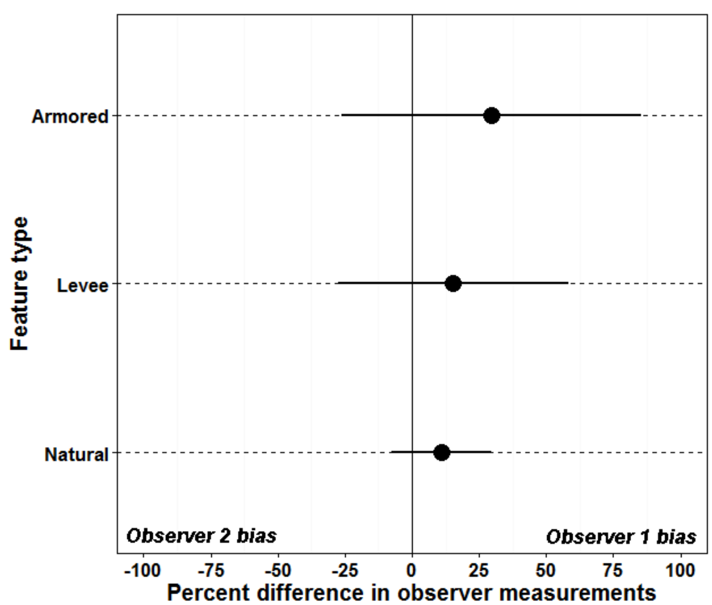


Figure 17. Mean percent difference and 95% confidence interval for armored bank, levee bank, and natural bank.

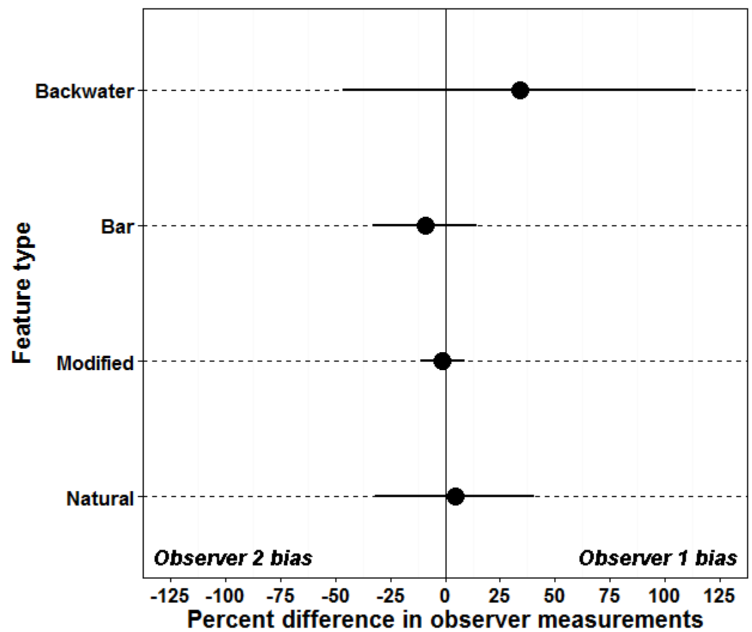


Figure 18. Mean percent difference and 95% confidence interval for backwater area, bar edge length, modified bank edge length, and natural bank edge length.

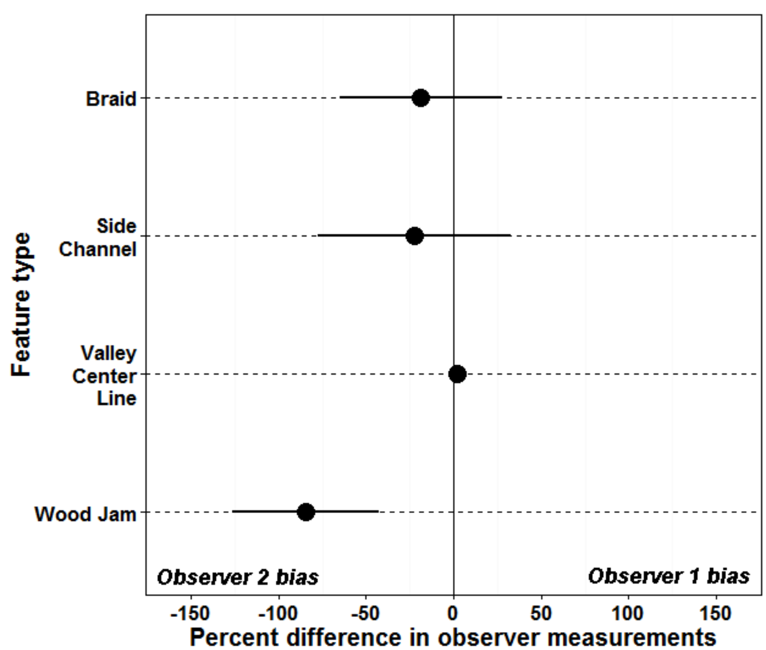


Figure 19. Mean percent difference and 95% confidence interval for braid length, side channel length, valley center line length, and wood jam area.

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 changes to protocols that could reduce those differences. For example, within the armored bank length analysis, the largest differences between the two observers were observed at three sample sites (98, 116, and 287) (Figure 20). At sample site 98 both observers recognized the bank as modified, but the first observer identified a portion of a bank type as armored (marked in light blue) while the second observer identified it as levee (marked in light green) creating a difference in feature length of 170 m km^{-1} (Figure 21a). At sample site 116 the first observer identified portion of a bank as armored (marked in light blue), while the second identified it as levee (marked in light green) creating a difference in feature length of 120 m km^{-1} (Figure 21b). Lastly, at sample site 287, the first observer identified portion of a 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^{-1} in length (Figure 21c).

Differences between observers in armored bank length at the three sample sites also account for the differences in levee bank, as either classification was used for the same portion of the bank by different observers (Figure 22). Subsequently, a significant difference in levee bank length of 273 m km^{-1} was observed at sample site 262. The source of inconsistency at this sample location was the classification of portion of a bank as natural (marked in light blue) by the first observer and classification of the same portion of a bank 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).

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 “guess” at the identification of the habitat feature. To improve the accuracy and repeatability of these metrics, we revised the protocols to include use of reference data sets (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 re-evaluate observer variability when the revised protocols are implemented.

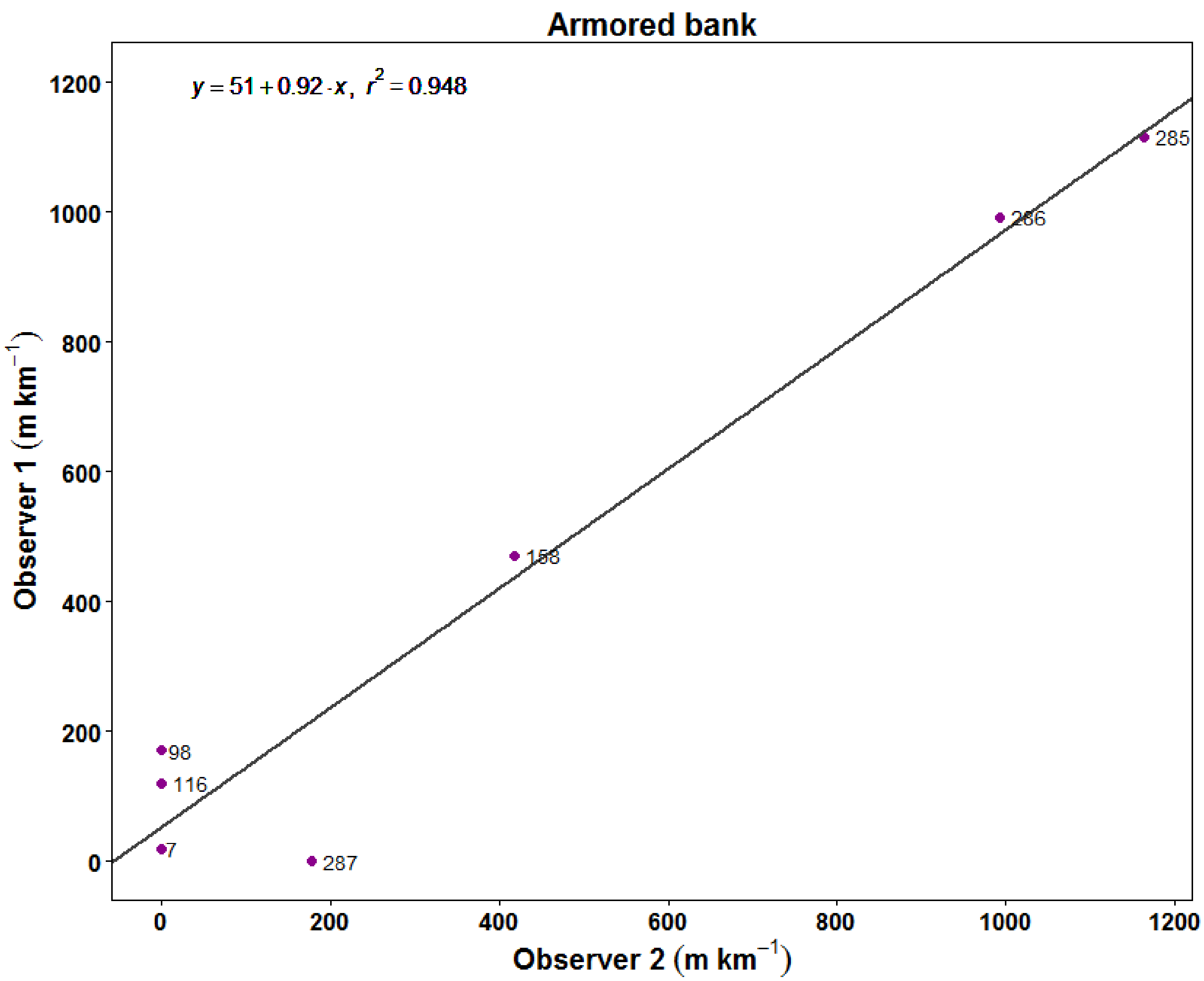


Figure 19. Normalized armored bank length in each sample location between two observers.

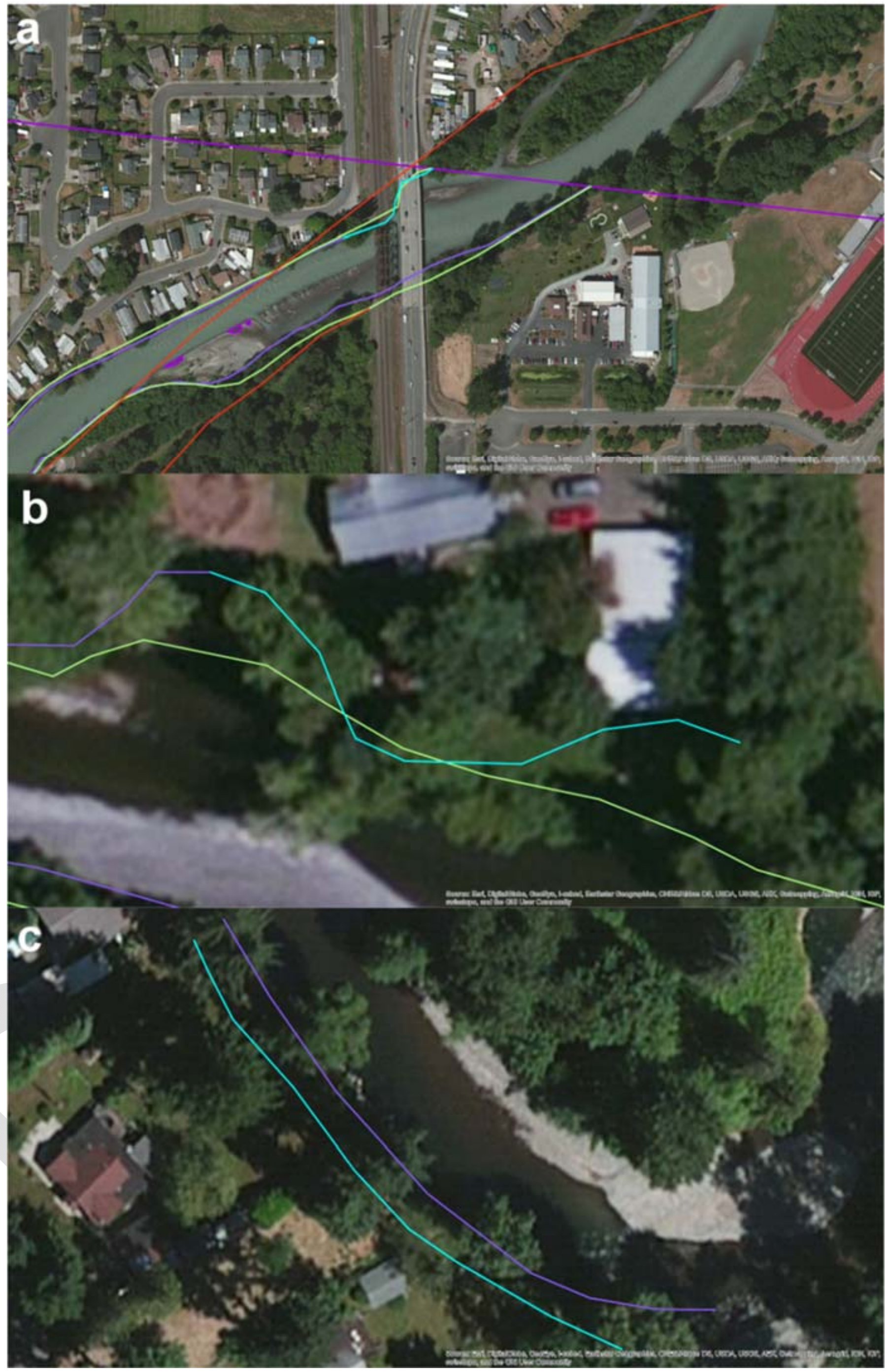


Figure 21. (a) Armored bank length differences between observers within sample site 98. Armored bank marked in light blue, natural bank marked in light green. (b) Armored bank length differences between observers within sample site 116. Armored bank marked in light blue, levee bank marked in light green. (c) Armored bank length differences between observers within sample site 287. Armored bank marked in light blue, levee bank marked in purple.

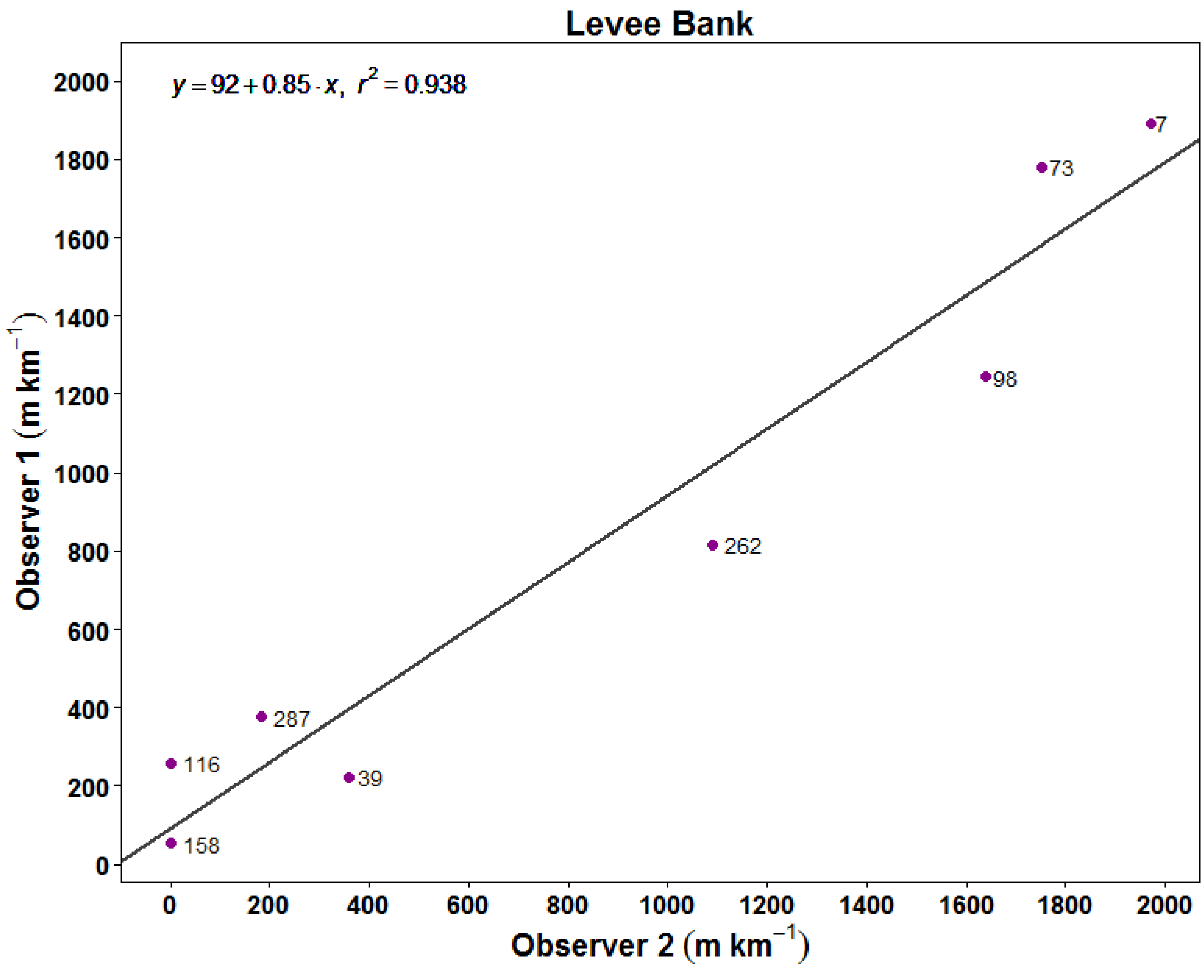


Figure 22. Normalized levee bank length within sample location between two observers.

Figure 23. Levee and natural bank length differences between observers within sample site 262. Natural bank marked in light blue, while levee bank marked in red.

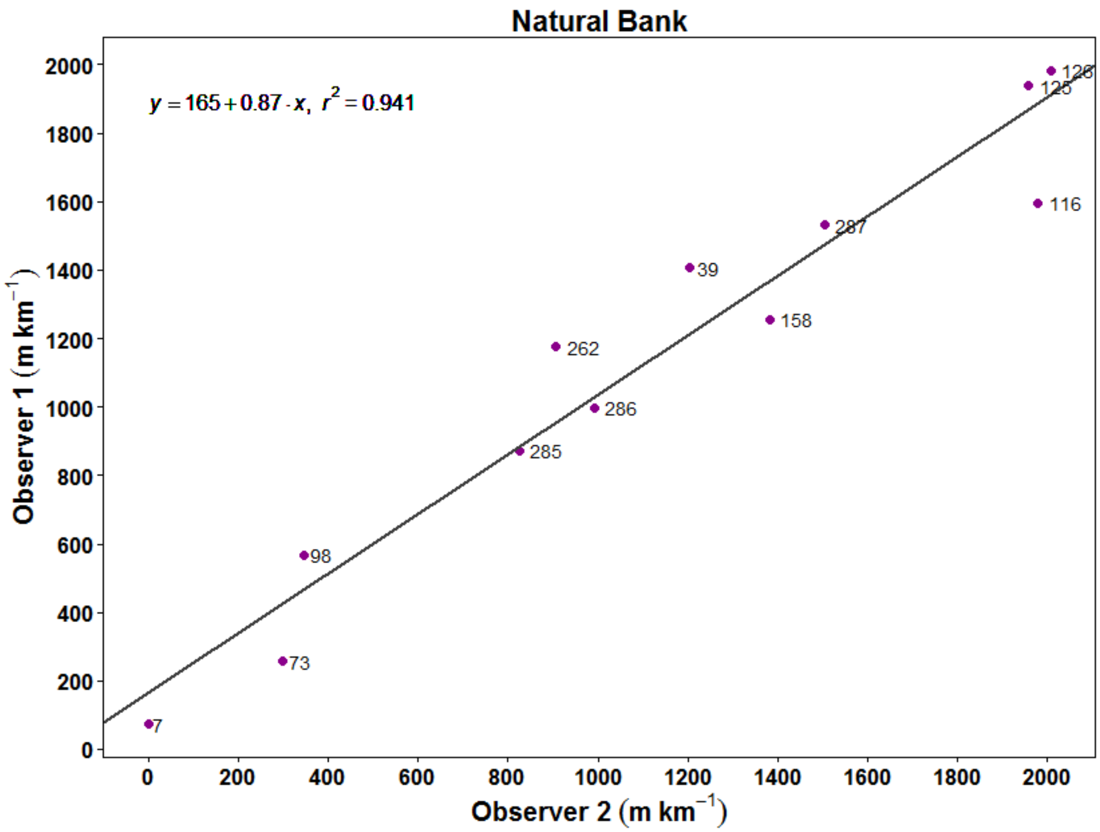


Figure 24: Normalized natural bank length within sample location between two observers.

There were significant differences in backwater area classification at sample sites 116, 158, and 287 (Figure 25). A difference of 1343 $m^2 km^{-2}$ in backwater area within sample site 116 can be attributed to inconsistent measurements between the two observers of the same feature. Here the first observer digitized a larger area of the backwater feature (marked in red), while the second observer digitized a smaller area of the backwater (marked in light blue) (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 (marked in light blue) (Figure 26b). By contrast, in sample site 287 the second observer misidentified the feature, resulting in a difference of 894 $m^2 km^{-2}$ in backwater area (marked in red) (Figure 26c).

We anticipate that more detailed instruction on 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 have more detailed instruction guiding observers to digitize only visible portions of the backwater unit and not to include estimated areas beneath tree canopy. The revised protocols are in Appendix D; this metric will be tested for repeatability again in 2016 using these revised protocols. If repeatability is not improved, we will eliminate this metric from our protocols.

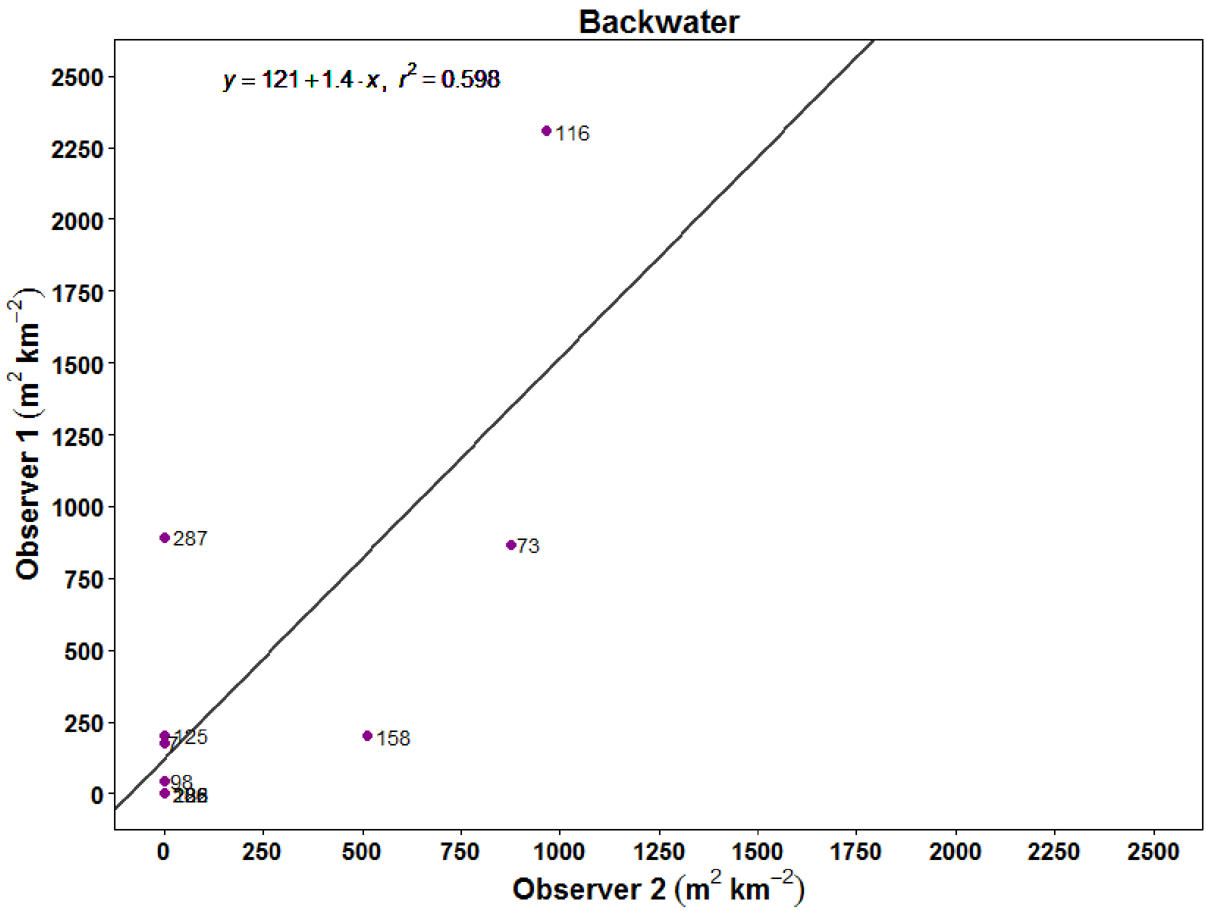


Figure 25: Normalized backwater area within sample location between two observers.

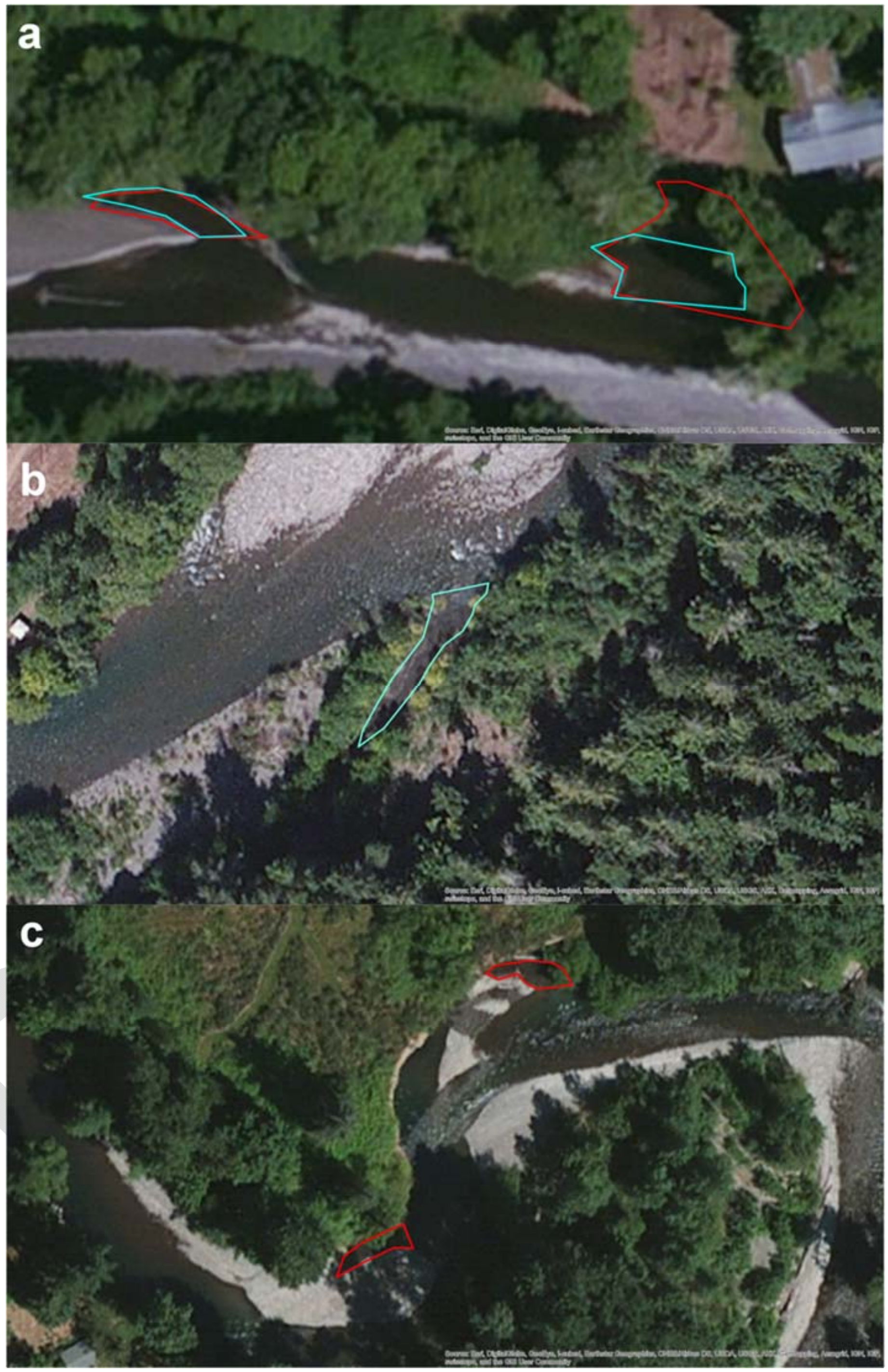


Figure 26. (a) Backwater area differences between observers within sample site 116. First observer is marked in red, while second observer is marked in light blue. (b) Backwater area differences between observers within sample site 158. First observer is marked in red, while second observer is marked in light blue. (c) Backwater area differences between observers within sample site 287. First observer is marked in red, while second observer is marked in light blue.

There were also differences between observers in braid length (Figure 27). A difference of 178 m km^{-1} was observed within sample site 39, where the first observer identified the feature as a braid (marked in light green) (Figure 28a). Within sample site 73, the second observer identified the feature as a braid (marked in light blue) while the first observer did not, resulting in a difference of 140 m km^{-1} in length (Figure 28b). Similarly, only the first observer identified the feature as a braid (marked in light blue) creating a difference of 200 m km^{-1} (Figure 28c).

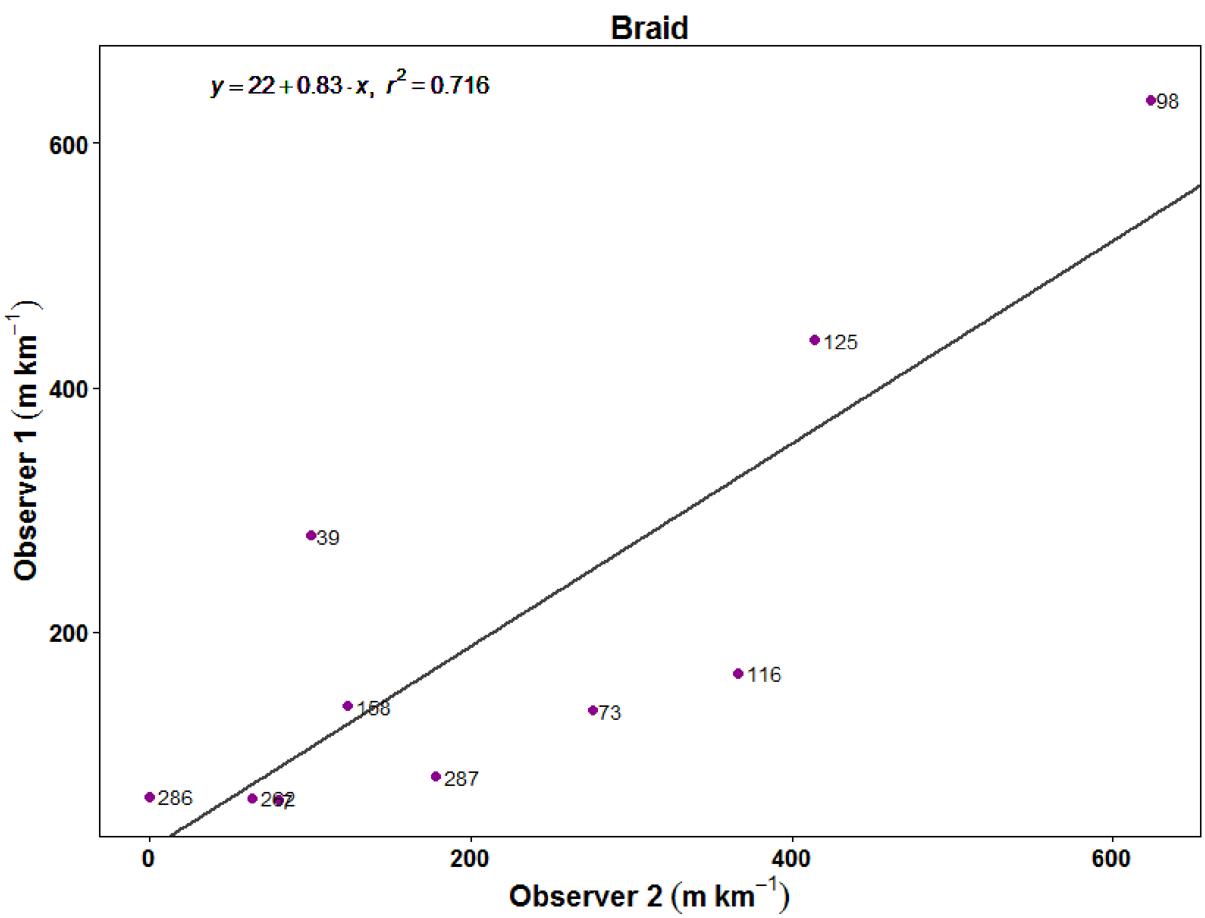


Figure 27. Normalized braid length within sample location between two observers.

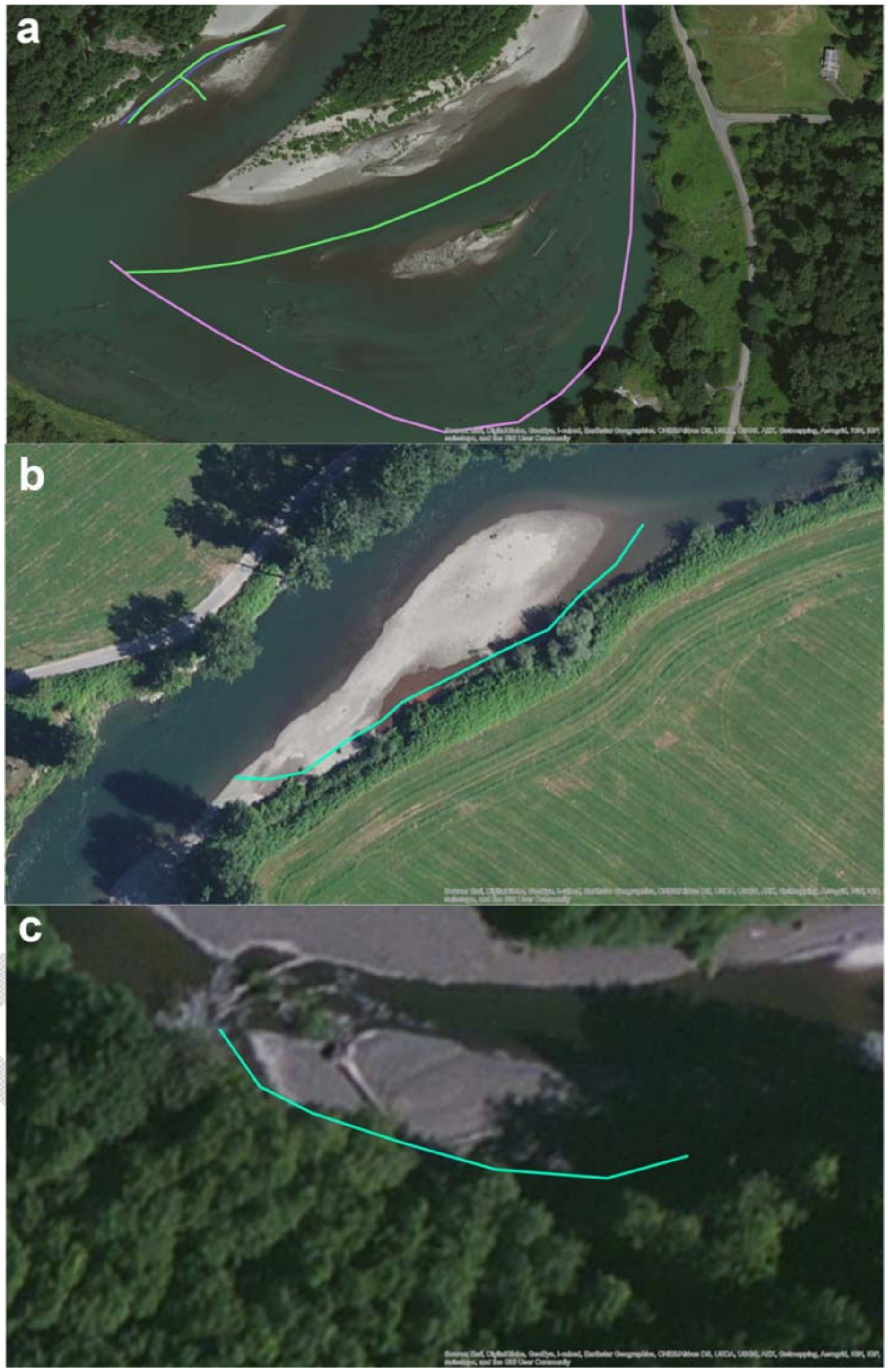


Figure 28. (a) Braid length differences between observers within sample site 39. First observer is marked in light green. (b) Braid length differences between observers within sample site 73. Second observer is marked in light blue. (c) Braid length differences between observers within sample site 116. Second observer 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 identified the feature as a side channel (marked in light blue), while the second observer did not, creating a difference of 477 m km^{-1} (Figure 30a). Within sample site 158, the first observer identified all of the features as a side channel (marked in light blue), while the second observer identified different set of features as a side channel (marked in red), thus a difference of 224 m km^{-1} was generated (Figure 30b). A difference of 175 m km^{-1} is the result of misidentification of a side channel by one of the observers within sample sites 287 (Figure 30c). Here, the second observer identified the features in question as a side channel (marked in red) while the first did not (Figure 30c).

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 (included in Appendix D: Sampling protocols). For example, we added a 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 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. In FY 2016 we plan to re-evaluate observer variability for this metric using the revised protocol.

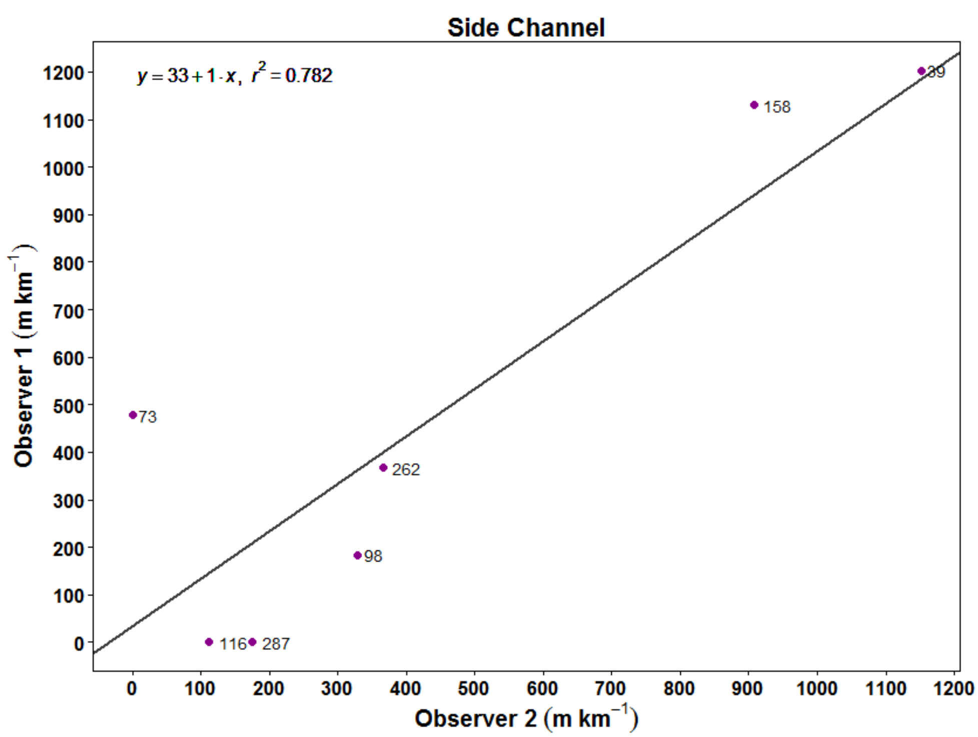


Figure 29. Normalized side channel length within sample location between two observers.

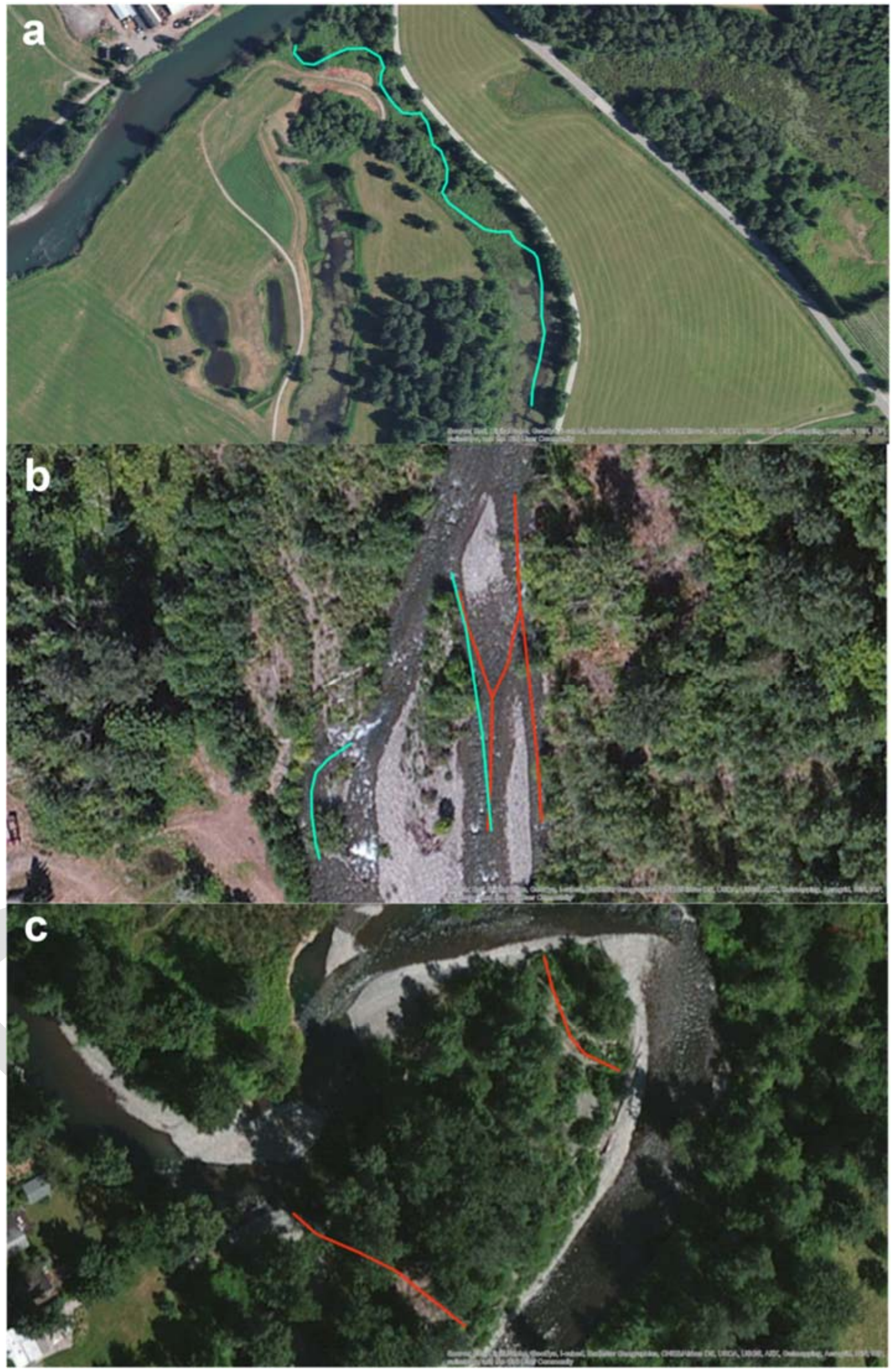


Figure 30. (a) Side channel length differences between observers within sample site 73. First observer is marked in light blue, second observer is marked in red. (b) Side channel length differences between observers within sample site 158. Second observer is marked in light blue. (c) Side channel length differences between observers within sample site 287. Second observer is marked in red.

The two observers frequently measured wood jams differently in our initial trials (Figure 31). The most common difference in wood jam area between observers was that one observer consistently measured a much larger feature area than the other observer. That is, in many cases the second observer (marked in yellow) estimated a much larger area for each wood jam than the first observer (marked in red) (Figure 32). To correct this problem, we revised the protocols to include a minimum jam area (100 m^2) for inclusion in the wood jam area measurement, and to specify the level of detail with 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 photograph images. Moreover, while we expect edits to past digital records to be rare, the archived information also allows for corrections to mapped polygons for prior years (e.g., if a wood jam is missed in the past, it can be added to the data record for that photo year).

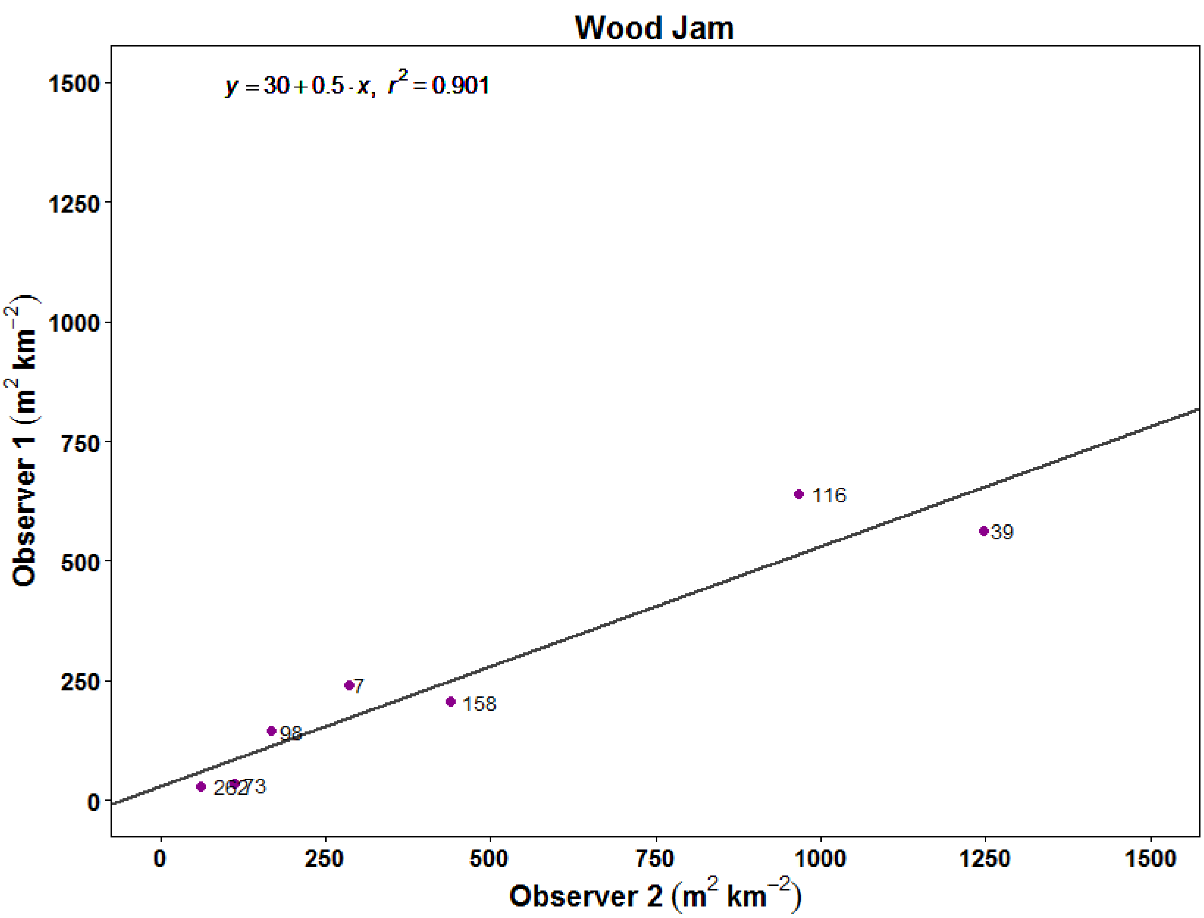


Figure 31. Normalized wood jam area within sample location between two observers.

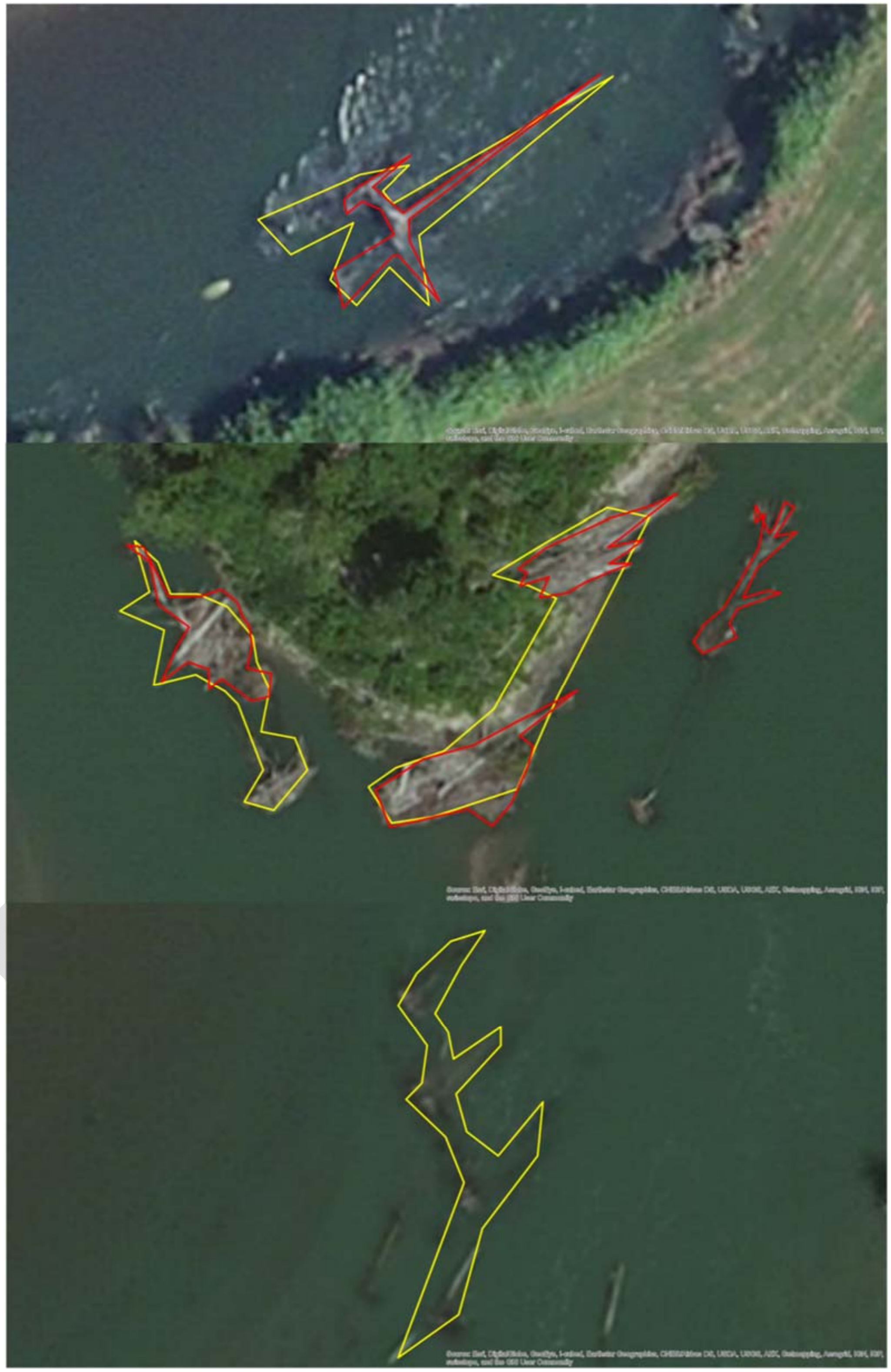


Figure 32. Wood jam measurement differences between observers. First observer is marked in red, while second observer is marked in yellow.

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, only one observer measured all sites, so observer variation will not affect the results of this analysis. Here we first report on our large river and floodplain metrics collected from satellite or aerial photograph data, followed by the large river and floodplain metrics from field data. We then report the delta metrics collected from satellite or aerial photograph 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 results for land cover status, percent forest and percent developed land cover, riparian buffer width, edge habitat length by type, proportion of disconnected floodplain, sinuosity, braid and side-channel lengths, braid and side-channel node densities, backwater area, and wood jam area.

Land cover Status on Floodplains by MPG

The South Central Cascades MPG has the greatest percentage of lands classified as urban (28%) and the lowest percentage of agriculture lands (10%) (Figure 33). The greatest proportion of lands classified as forest is within the Olympic MPG (51%). The Northern Cascades MPG contains the lowest percentage of urban land cover (10%) and the highest of agriculture lands (39%).

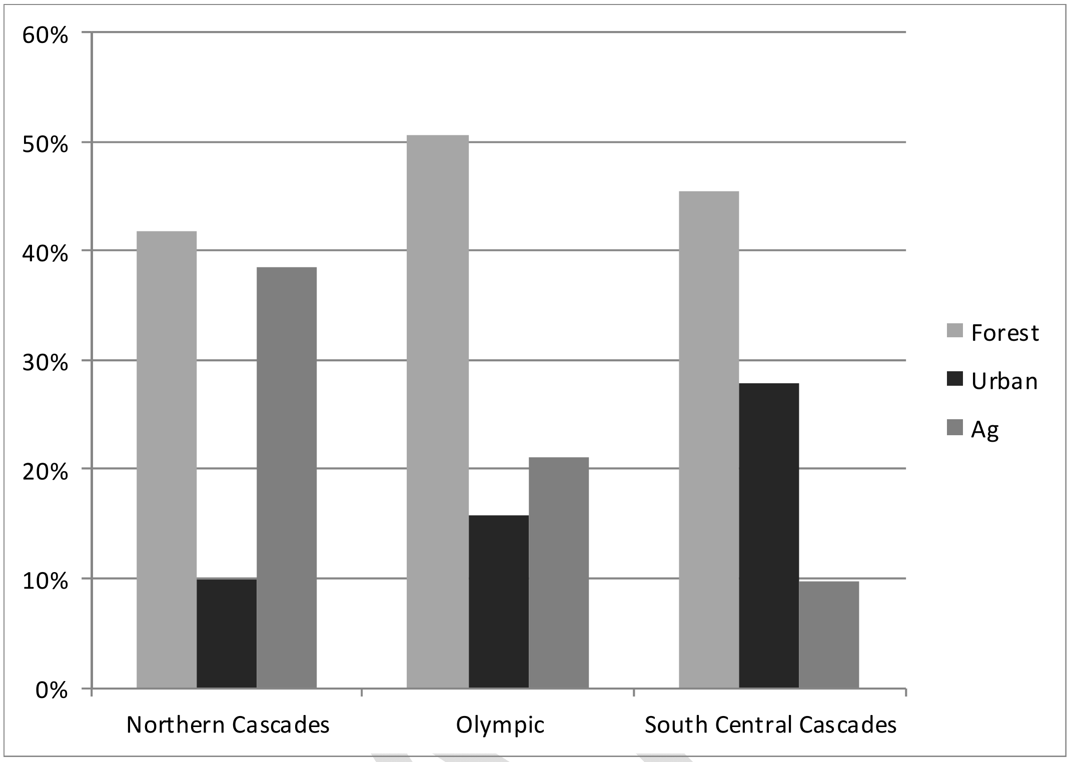


Figure 33. Proportion of land cover type by MPG in all sample-able floodplains in Puget Sound

Percent forest and percent developed land cover on floodplains

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

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

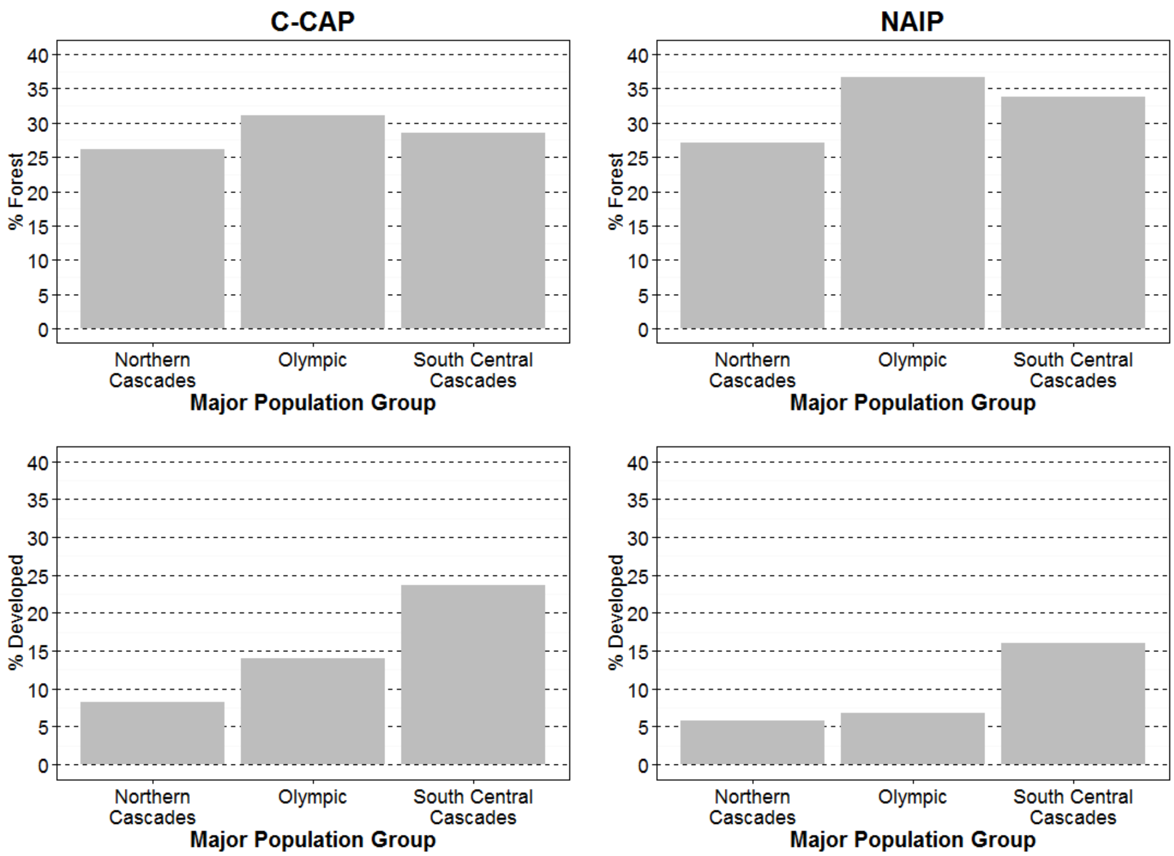


Figure 34. Percent forest and percent developed land cover in Puget Sound floodplains by Steelhead MPG.

Riparian buffer width

The average buffer width was the greatest in the Olympic MPG (85m) where there are more forested sites (± 11.7m 95% C.I.). Conversely, in the South Central Cascades MPG where there are more urban sites, the average buffer width was the lowest at 51m (± 12m 95% C.I.) (Figure 35). The average buffer width within the Northern Cascades MPG is 72m (± 7.6m 95% C.I.).

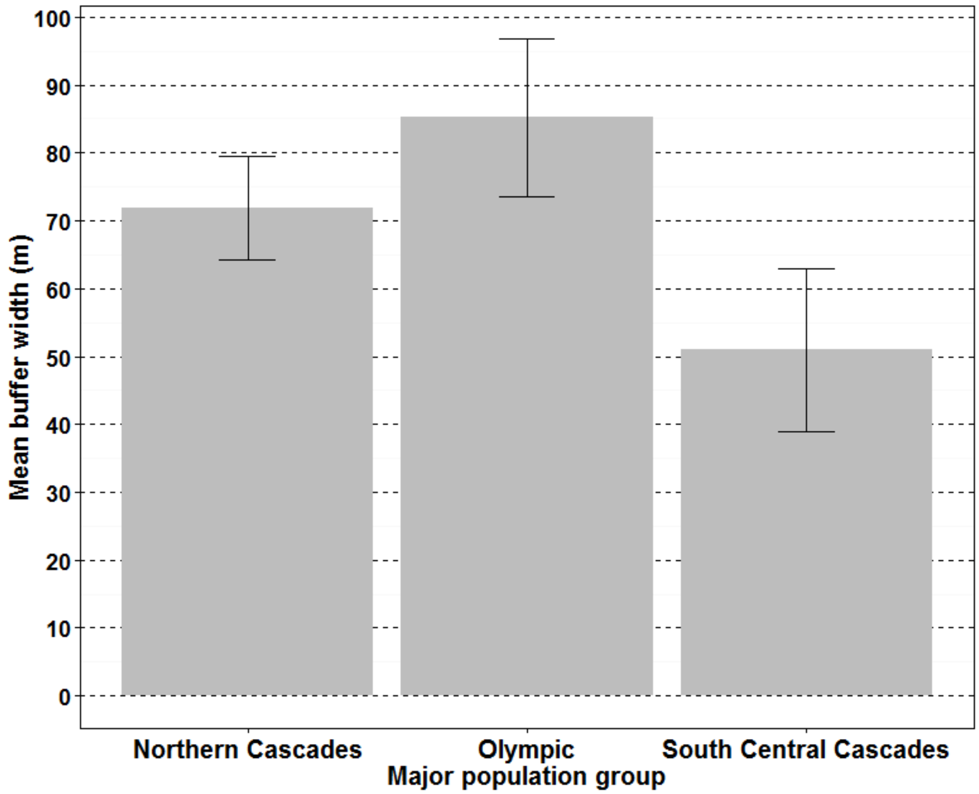


Figure 35. Mean forested buffer width along PS large river rivers at 124 sites by Steelhead (*Oncorhynchus mykiss*) MPG. 95% confidence intervals are depicted by error bars.

Edge habitat length by type

Habitat edge length by bank type varied considerably among Steelhead MPGs and among sample sites within MPGs (Figure 36). The mean proportion of natural bank edge length was the greatest in the Olympic MPG at 68% (± 22% 95% C.I.) and least in the South Central Cascades MPG (37%, ± 17% 95% C.I.). Conversely, the mean proportion of modified bank edge length ranged from 2% (± 3%, 95% C.I.) in the Olympic MPG, to 35% (± 18% 95% C.I.) in the South Central Cascades MPG. The mean proportion of bar edge habitat was similar between all MPGs, ranging between 26% (± 17% 95% C.I.) in South Central Cascades MPG and 33% (± 9% 95% C.I.) in Northern Cascades MPG.

Within the Northern Cascades MPG, the proportion of modified bank edge was highest in urban areas (70%-79%), and lowest in forested areas (4%-15%) (Figure 37). The highest mean proportion of modified bank edge length was observed in urban land cover class and PGL valley type (79%, ± 36% 95% C.I.) and the lowest occurred in the forest land cover class and MNT valley type (4%, ± 6% 95% C.I.). The highest mean proportion of bar edge was observed in forest land cover class and GL valley type (49%, ± 11% 95% C.I.), while the lowest was observed in urban land cover class and PGL valley type (6%, ± 7% 95% C.I.) (Figure 37). The highest mean proportion of natural bank edge length occurred in the forest land cover class and MNT valley type (68%, ± 25% 95% C.I.).

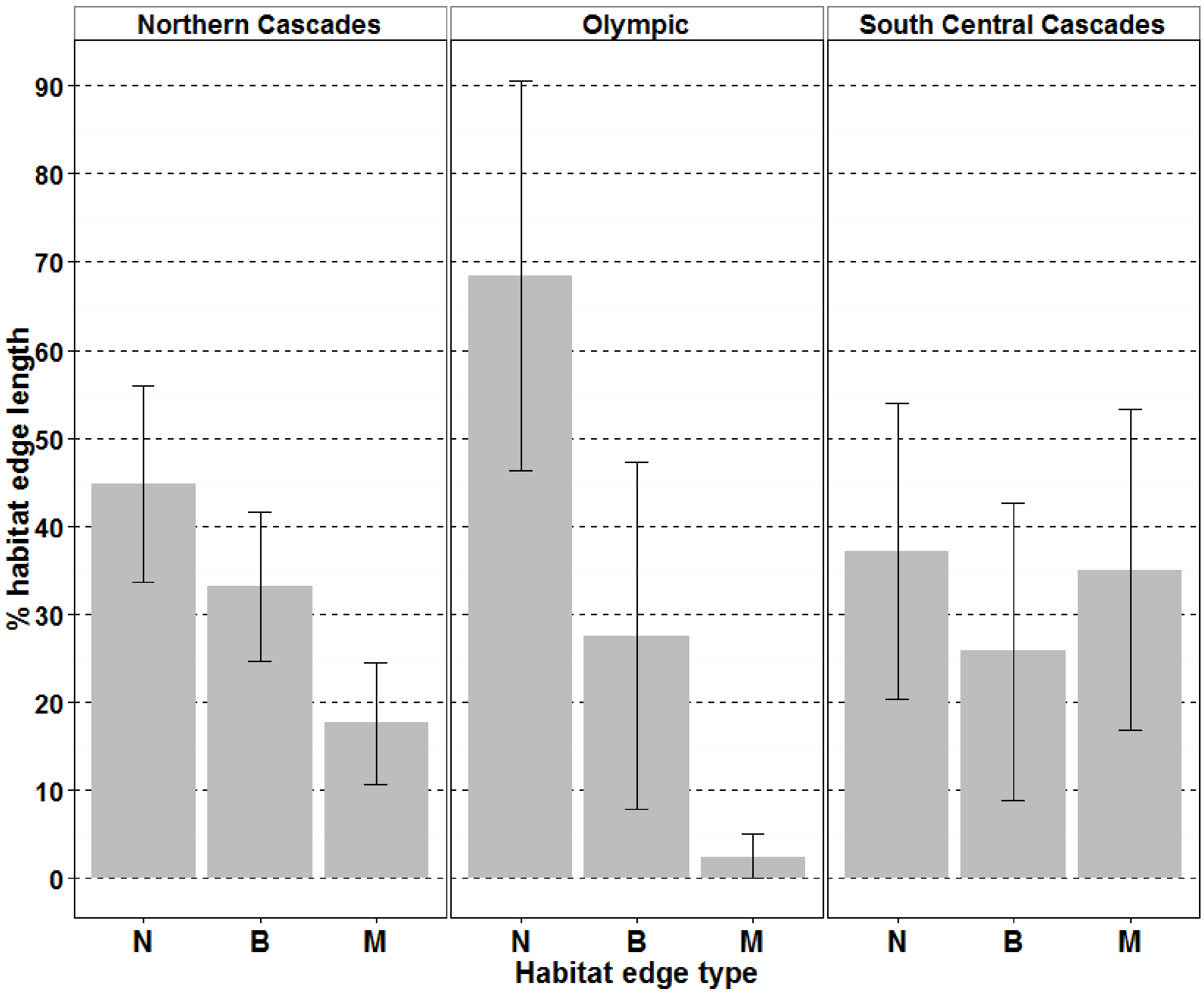


Figure 36: Mean proportion of natural bank (N), bar (B), or modified bank (M) edge length and 95% confidence interval aggregated by Northern Cascades, Olympic, and South Central Cascades Steelhead MPGs. Error bars indicate 95% confidence interval.

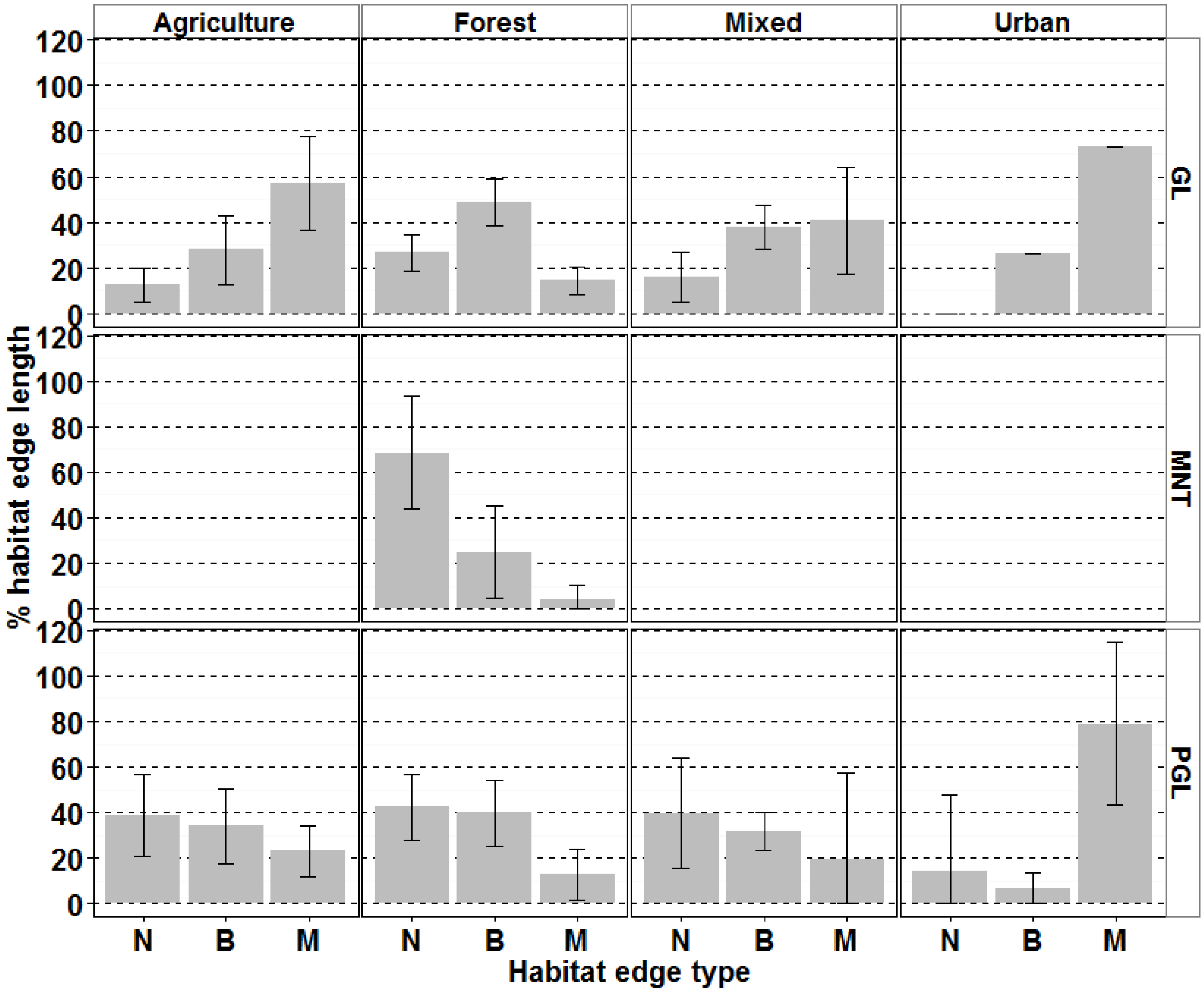


Figure 37: Mean proportion of natural bank (N), bar (B), or modified bank (M) edge length and 95% confidence interval within Northern Cascades MPG aggregated by agriculture, forest, mixed, and urban land cover classes, and by glacial, mountain, and post-glacial geomorphic valley types. Error bars indicate 95% confidence interval. Very small (or zero) samples sizes are strata for which sample sites were few or did not exist. For example, there were no urban-glacial sites in this MPG.

Within Olympic MPG the proportion of modified bank edge was consistently low (0-14%). The highest mean proportion of modified bank edge length was in the agriculture land cover class and PGL valley type (14%, ± 51% 95% C.I.), whereas the lowest was in the forest land cover class and MNT valley type (0%). The highest mean proportion of bar edge was observed in mixed land cover class and PGL valley type (59%, ± 49% 95% C.I.), while the lowest was observed in forest land cover class and MNT valley type (20%, ± 25% 95% C.I.) (Figure 38). The highest mean proportion of natural bank edge length occurred in the forest land cover class and MNT valley type (79%, ± 27% 95% C.I.) while the lowest was found in the in mixed land cover class and PGL valley type (32%, ± 10% 95% C.I.).

Within South Central Cascades MPG, modified bank edge length was consistently high in urban, agricultural, and mixed land cover sites (58%-83%), but relatively low in forested landcover sites (0-27%). The highest mean proportion of modified bank edge length was observed in urban land cover class and GL valley type (85%, ± 12% 95% C.I.), and the lowest mean proportion of modified bank edge length was observed in forest land cover class and MNT valley type (2%, ± 5% 95% C.I.). The highest mean proportion of bar edge was observed in forest land cover class and MNT valley type (42%, ± 40% 95% C.I.), while the lowest was observed in agriculture land cover class and PGL valley type (1%, ± 11% 95% C.I.) (Figure 39). The highest mean proportion of natural bank edge length was again in forest land cover class but occurred in the PGL valley type (52%, ± 6% 95% C.I.) and lowest in the mixed land cover class and GL valley type (1%, ± 1% 95% C.I.).

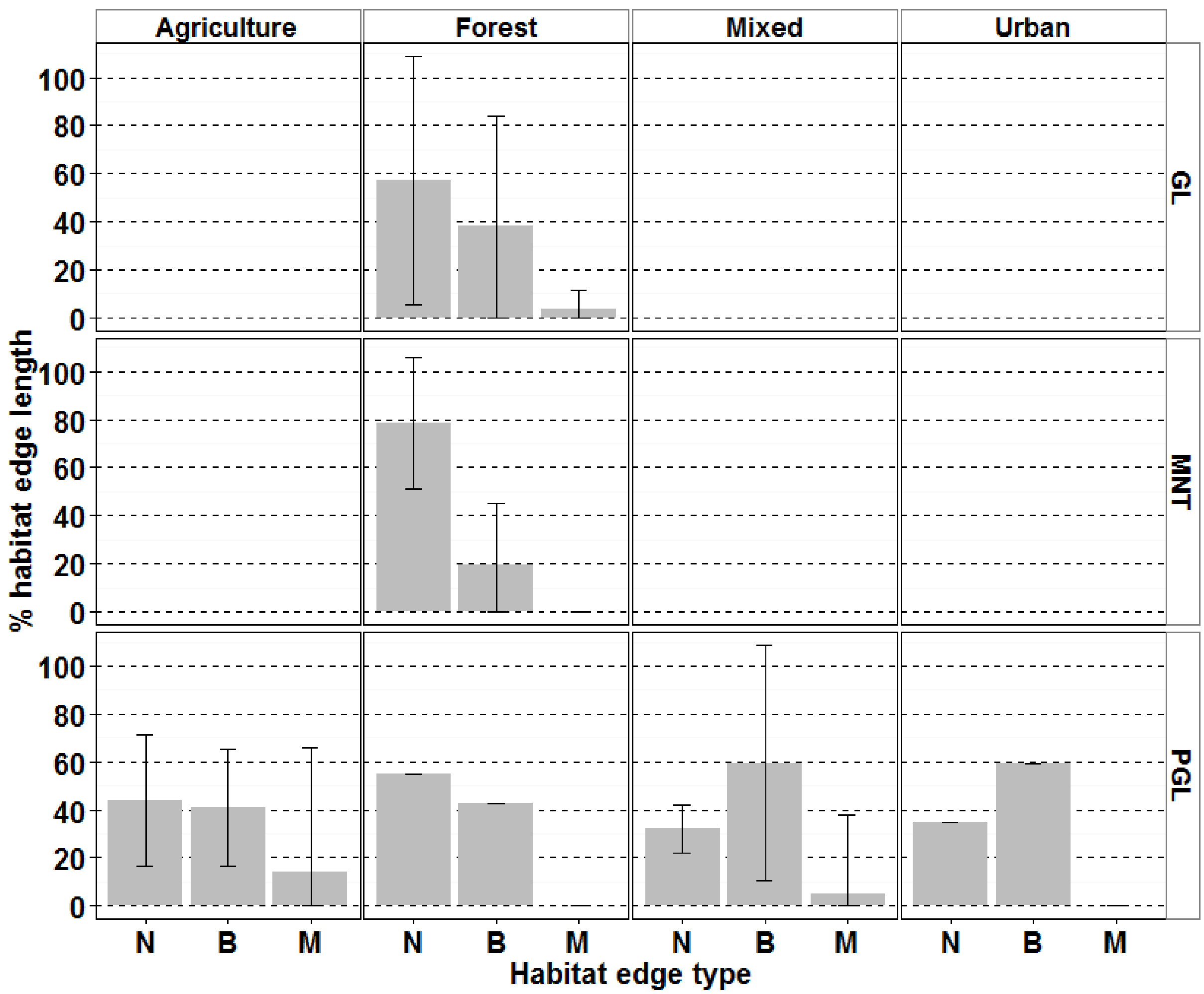


Figure 38: Mean proportion of bar (B), modified bank (M), or natural bank (N) edge length and 95% confidence interval within Olympic MPG aggregated by agriculture, forest, mixed, and urban land cover classes, and by glacial, mountain, and post-glacial geomorphic valley types. Error bars indicate 95% confidence interval.

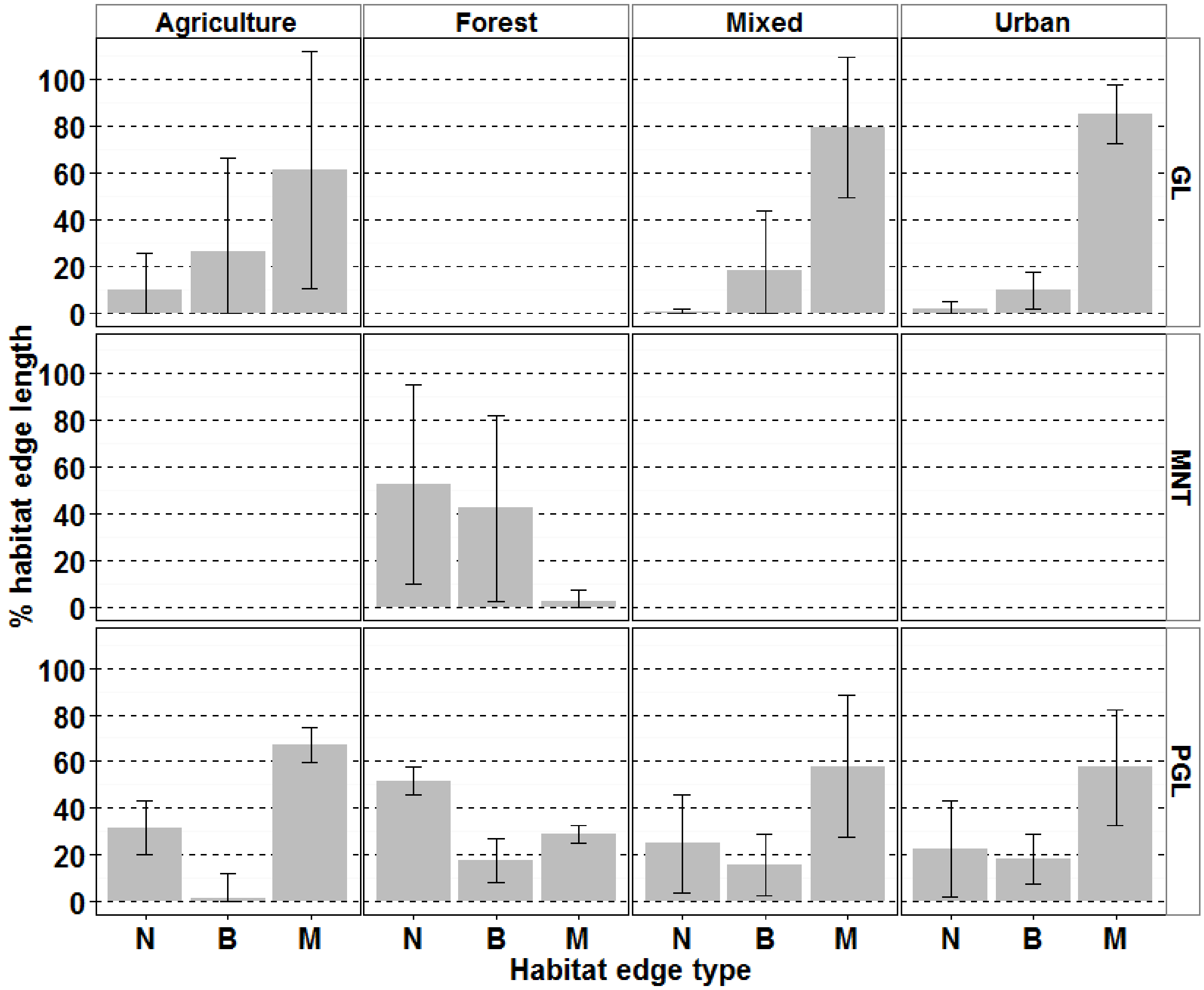


Figure 39: Mean proportion of bar (B), modified bank (M), or natural bank (N) edge length and 95% confidence interval within South Central Cascades MPG aggregated by agriculture, forest, mixed, and urban land cover classes, and by glacial, mountain, and post-glacial geomorphic valley types. Error bars indicate 95% confidence interval.

Sinuosity

Sinuosity varied little among MPGs, especially in mountain valleys where sinuosities were consistently near 1.0 (Figure 40). Mean sinuosity was around 1.5 in some landcover classes within the glacial and post-glacial valley types. However, landcover classes with high sinuosity were not consistent among valley types or MPGs.

Braid length

The mean braid length was similar across MPGs, although there was considerable variation among valley types and land cover classes within MPGs (Figure 41). However, no land cover class or valley type was consistently high or low relative to the others.

Braid node density

The mean braid node density was similar among all MPGs, ranging from 2.2 nodes km^{-1} (± 1.3 nodes km^{-1} 95% C.I.) in Northern Cascades to 2.4 nodes km^{-1} (± 1.9 nodes km^{-1} 95% C.I.) in South Central Cascades (Figure 42a). Within North Cascades major population group, the highest mean braid density was observed in forest land cover class and PGL valley type (3.9 nodes km^{-1}, ± 2.6 nodes km^{-1} 95% C.I.), while the lowest occurred in urban land cover class and PGL valley type (0 nodes km^{-1}) (Figure 42b). Mean braid density ranged in the South Central Cascades MPG from 0.3 nodes km^{-1} (± 0.6 nodes km^{-1} 95% C.I.) in urban land cover class and post-glacial geomorphic valley type, to 6.2 nodes km^{-1} (± 13.3 nodes km^{-1} 95% C.I.) in agriculture land cover class and glacial geomorphic valley type (Figure 42b).

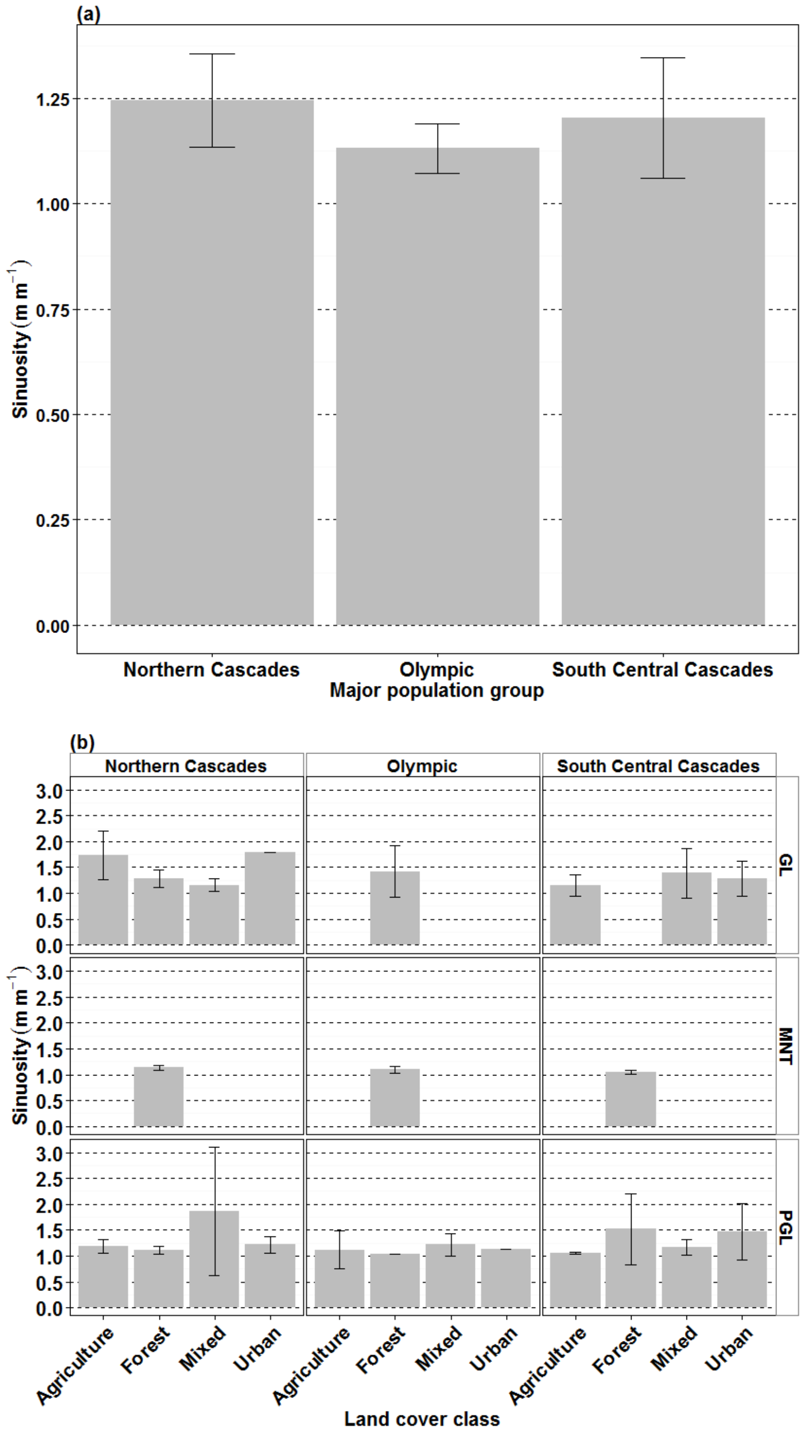


Figure 40. Mean sinuosity and 95% confidence interval aggregated by Northern Cascades, Olympic, and South Central Cascades Steelhead MPGs. (b) Mean sinuosity and 95% confidence interval within Steelhead major population groups, aggregated by glacial, mountain, and post-glacial geomorphic valley types, and by agriculture, forest, mixed, and urban land cover classes. Error bars indicate 95% confidence interval.

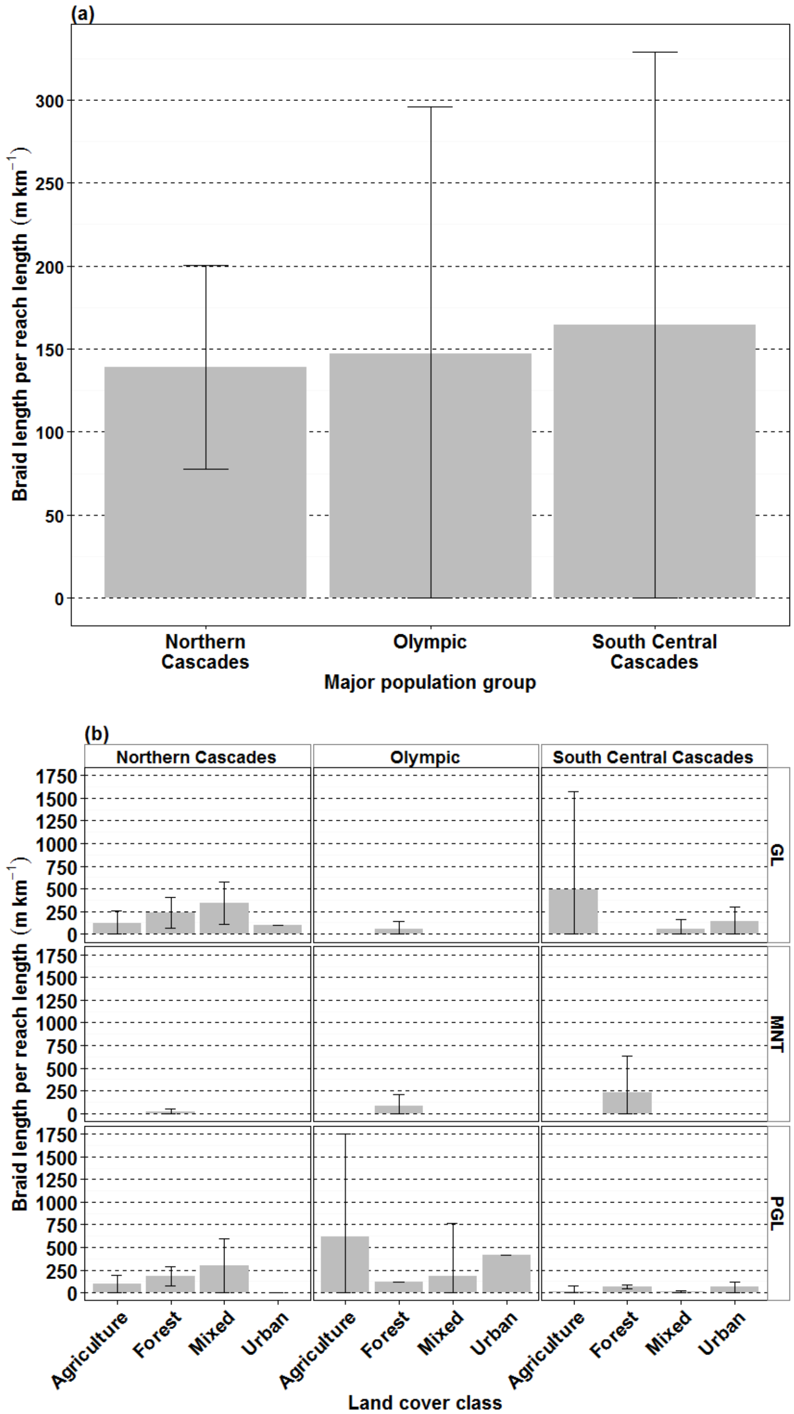


Figure 41: (a) Mean braid length ratio and 95% confidence interval aggregated by Northern Cascades, Olympic, and South Central Cascades Steelhead MPGs. (b) Mean braid length ratio and 95% confidence interval within Steelhead major population groups, aggregated by glacial, mountain, and post-glacial geomorphic valley types, and by agriculture, forest, mixed, and urban land cover classes. Error bars indicate 95% confidence interval.

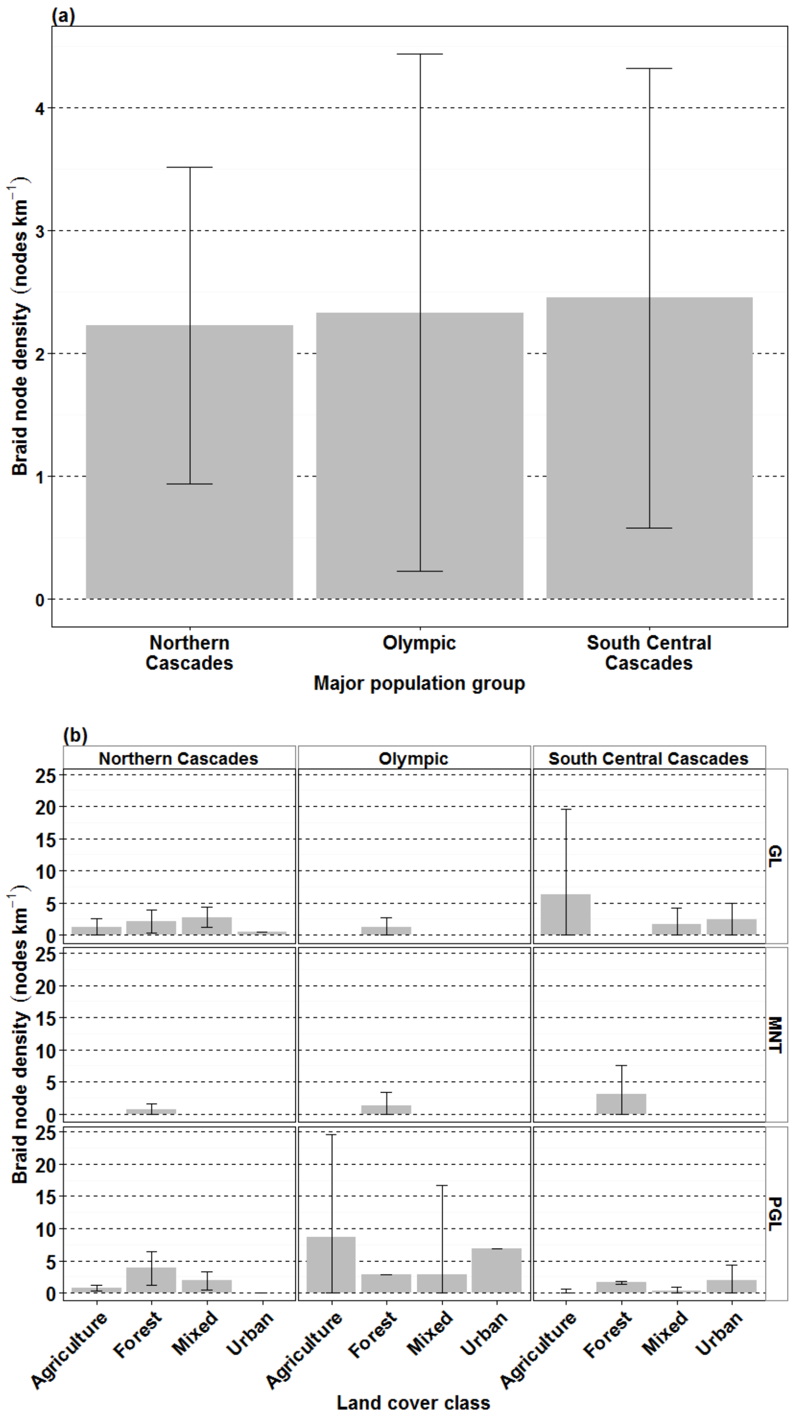


Figure 42: (a) Mean braid node density and 95% confidence interval aggregated by Northern Cascades, Olympic, and South Central Cascades Steelhead MPGs. (b) Mean braid node density and 95% confidence interval within Steelhead major population groups, aggregated by glacial, mountain, and post-glacial geomorphic valley types, and by agriculture, forest, mixed, and urban land cover classes. Error bars indicate 95% confidence interval.

Proportion of disconnected floodplain

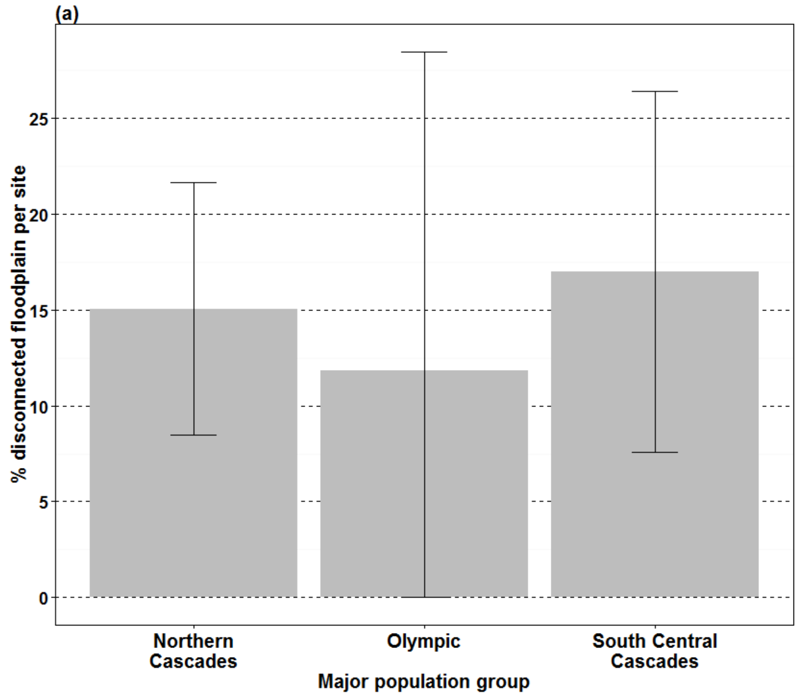
The mean proportion of disconnected floodplain was similar among MPGs but variable among sample sites within MPGs (Figure 43a). The highest mean proportion of disconnected floodplain was observed in South Central Cascades MPG (17%, ± 9% 95% C.I.), while the lowest was observed in Olympic MPG (12%, ± 17% 95% C.I.). Within South Central Cascades MPG, the highest mean proportion of disconnected floodplain was observed in urban land cover class and GL valley type (67%, ± 18% 95% C.I.), while the lowest occurred again in forest land cover class and MNT valley type (0%). The highest mean proportion of disconnected floodplain in the Olympic MPG was observed in agriculture land cover class and PGL valley type (80%, ± 57% 95% C.I.) (Figure 43b). In contrast, the lowest mean proportion of disconnected floodplain was observed in forest land cover class and MNT valley type (0%).

Side channel node density

Mean side channel node density varied both among MPGs and among sample sites within MPGs (Figure 44). The lowest density occurred in the South Central Cascades MPG (0.7 nodes km^{-1}, ± 0.5 nodes km^{-1} 95% C.I.) while the highest occurred in the North Cascades MPG (2.1 nodes km^{-1}, ± 1.7 nodes km^{-1} 95% C.I.) (Figure 44a). Within the South Central Cascades MPG, the highest mean side channel node density was observed in forest land cover class and mountain geomorphic valley type (1.1 nodes km^{-1}, ± 1.1 nodes km^{-1} 95% C.I.), while the lowest in urban land cover class and post-glacial geomorphic valley type (0 nodes km^{-1}) (Figure 44b). Conversely, within North Cascades MPG, mean side channel node density ranged from 0 nodes km^{-1} in urban land cover class and post-glacial geomorphic valley type, to 3.3 nodes km^{-1} (± 5.4 nodes km^{-1} 95% C.I.) in forest land cover class and mountain geomorphic valley type. Further, within Olympic MPG, the highest mean side channel node density was observed in agriculture land cover class and post-glacial geomorphic valley type (8.69 nodes km^{-1}, ± 15.9 nodes km^{-1} 95% C.I.), while the lowest in forest land cover class and glacial geomorphic valley type (1.2 nodes km^{-1}, ± 1.5 nodes km^{-1} 95% C.I.).

Side Channel Length

Mean side channel length per sample reach area varied considerably between MPGs, and among sample sites within MPGs (Figure 45a). Mean side channel length ranged from a low of 126 m km^{-2} (± 163 m km^{-2} 95% C.I.) in the Olympic MPG to a high of 555 m km^{-2} (± 549 m km^{-2} 95% C.I.) in the Northern Cascades MPG. Within the Olympic MPG the highest mean side channel length was observed in the mixed land cover class and PGL valley type (746 m km^{-2}, ± 442 m km^{-2} 95% C.I.), while the lowest in the forest land cover class and GL valley type (0 m km^{-2}) (Figure 45b). The Northern Cascades MPG had its highest mean side channel length in the forest land cover class in mountain valleys (1088 m km^{-2}, ± 1819 m km^{-2} 95% C.I.) and the lowest in the urban land cover class within the PGL valley type.



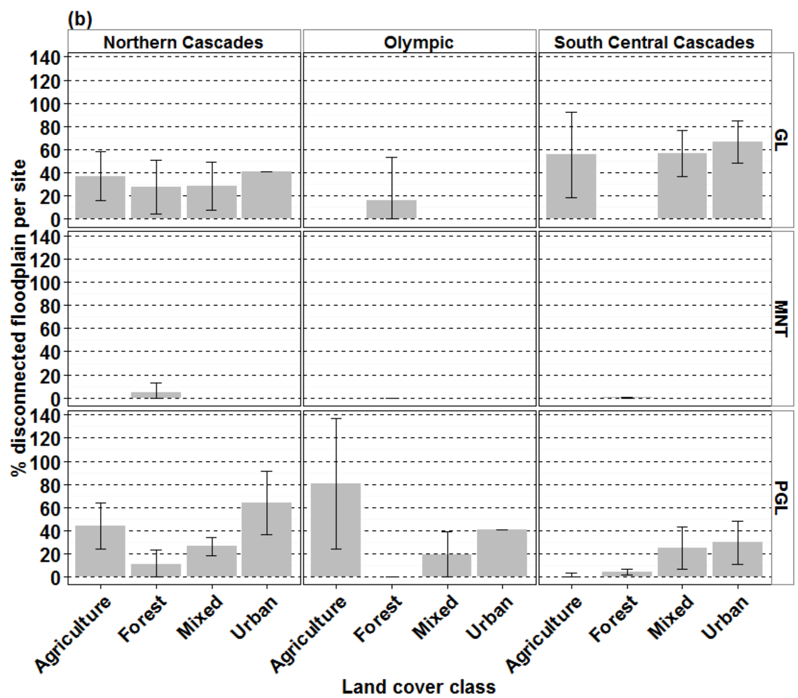
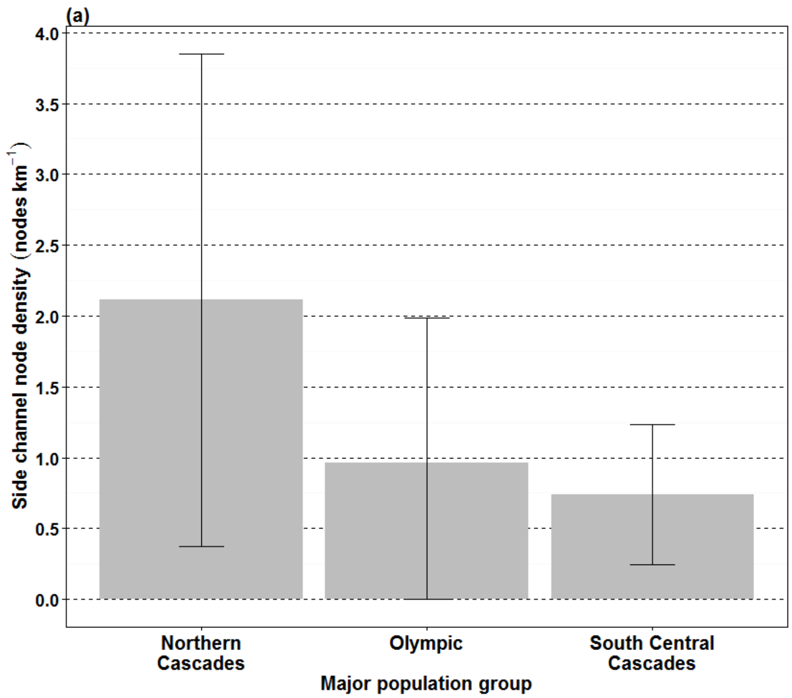


Figure 43: (a) Mean proportion of disconnected floodplain and 95% confidence interval aggregated by Northern Cascades, Olympic, and South Central Cascades Steelhead MPGs. (b) Mean proportion of disconnected floodplain and 95% confidence interval within Steelhead MPGs, aggregated by glacial, mountain, and post-glacial geomorphic valley types, and by agriculture, forest, mixed, and urban land cover classes.



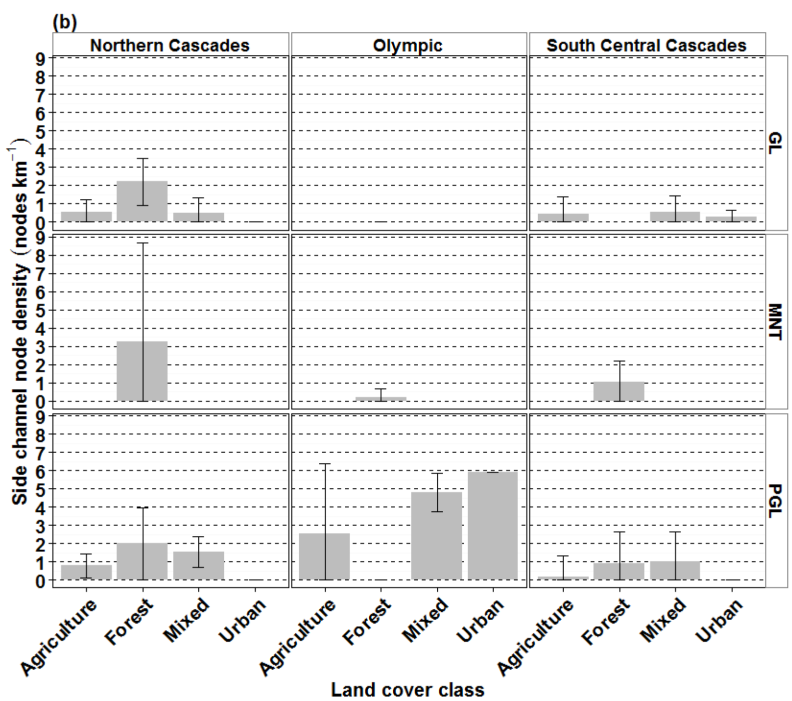
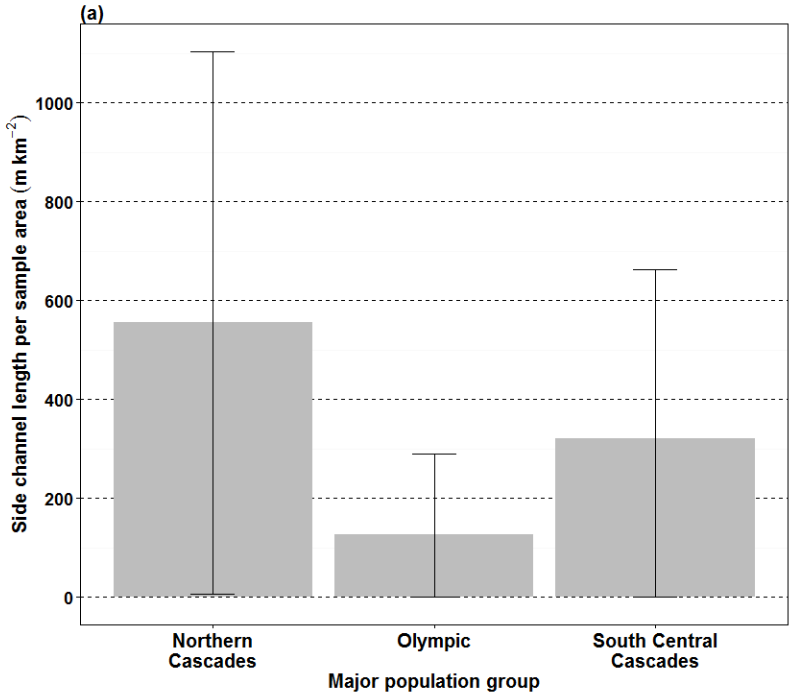


Figure 44: (a) Mean side channel node density and 95% confidence interval aggregated by Northern Cascades, Olympic, and South Central Cascades Steelhead MPGs. (b) Mean side channel node density and 95% confidence interval within Steelhead MPGs, aggregated by glacial, mountain, and post-glacial geomorphic valley types, and by agriculture, forest, mixed, and urban land cover classes. Error bars indicate 95% confidence interval.



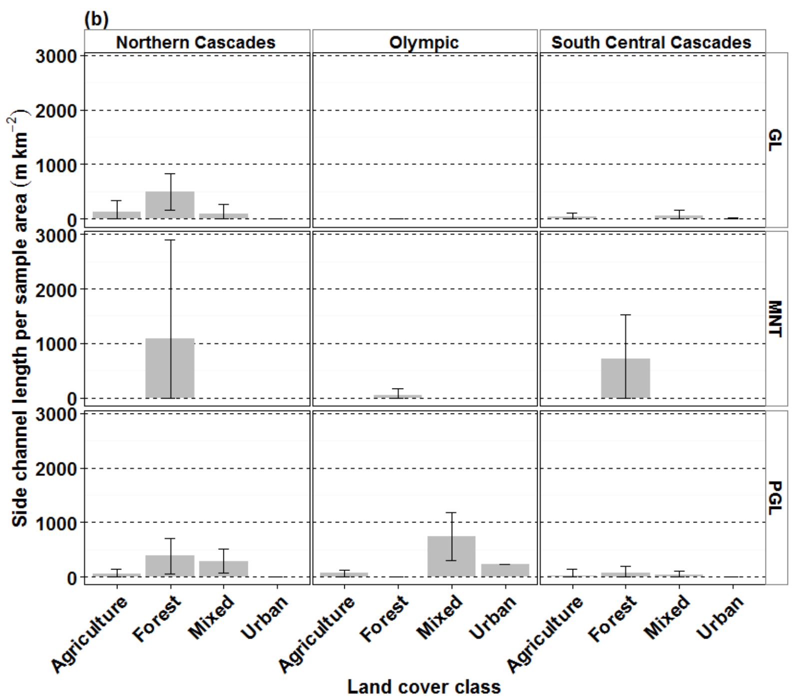


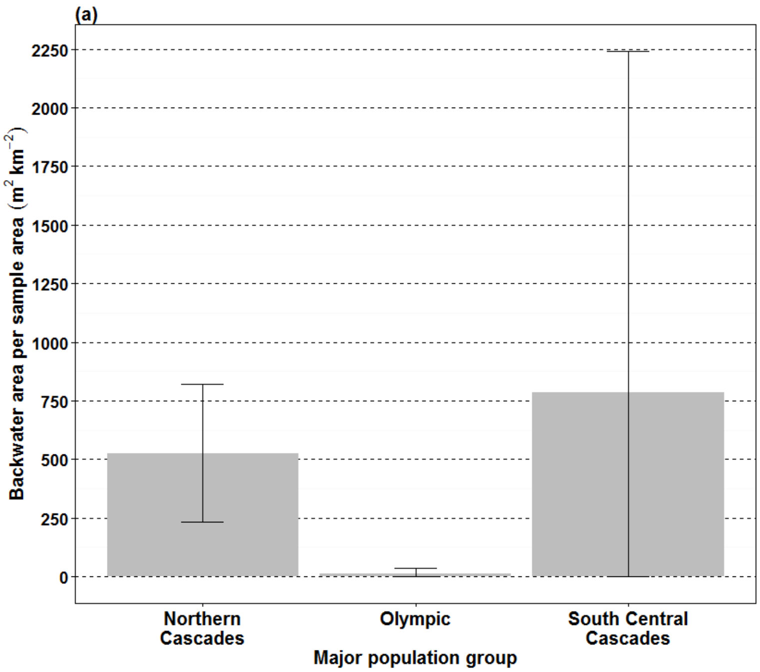
Figure 45: (a) Mean side channel length and 95% confidence interval aggregated by Northern Cascades, Olympic, and South Central Cascades Steelhead MPGs. (b) Mean side channel length and 95% confidence interval within Steelhead MPGs, aggregated by glacial, mountain, and post-glacial geomorphic valley types, and by agriculture, forest, mixed, and urban land cover classes. Error bars indicate 95% confidence interval.

Backwater Area

Backwater area was very low in the Olympic MPG (near zero) relative to the Northern Cascades and South Central Cascades, which had approximately 500 and 750 m^2 of backwater per km^2 of active channel, respectively (Figure 46). The highest mean backwater area was in forested glacial valleys in the Northern Cascades (2000 m^2/km^2), and most of the other valley-type/landcover combinations with high backwater areas were also in the Northern Cascades MPG. In the South Central Cascades, all valley-type/landcover combinations had low backwater areas with the exception of forested post-glacial valleys (~1800 m^2/km^2).

Wood jam area

The highest mean wood jam area per sample reach was observed in the Olympic MPG (4152 m^2km^{-2}, ± 7879 $m^2\,km^{-2}$ 95% C.I.), while the lowest occurred in the Northern Cascades MPG (1509 m^2km^{-2}, ± 1252 $m^2\,km^{-2}$ 95% C.I.) (Figure 47a). Within the Northern Cascades MPG, the highest mean wood jam area per sample reach area was observed in the forest land cover class in mountain valleys (1989 m^2km^{-2}, ± 3493 $m^2\,km^{-2}$ 95% C.I.), while the lowest was measured in the urban land cover class in the PGL valley type (99 m^2km^{-2}, ± 232 $m^2\,km^{-2}$ 95% C.I.) (Figure 47b). In all three MPGs, the highest wood jam area was in the forest land cover class in mountain valleys.



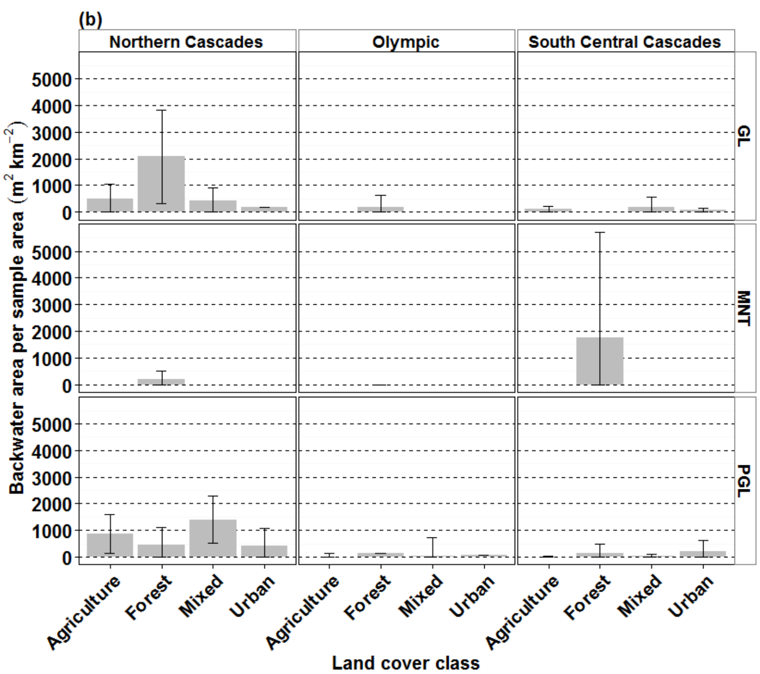


Figure 46: (a) Mean normalized backwater area and 95% confidence interval aggregated by Northern Cascades, Olympic, and South Central Cascades Steelhead MPGs. (b) Mean normalized backwater area and 95% confidence interval within Steelhead MPGs, aggregated by glacial, mountain, and post-glacial geomorphic valley types, and by agriculture, forest, mixed, and urban land cover classes.

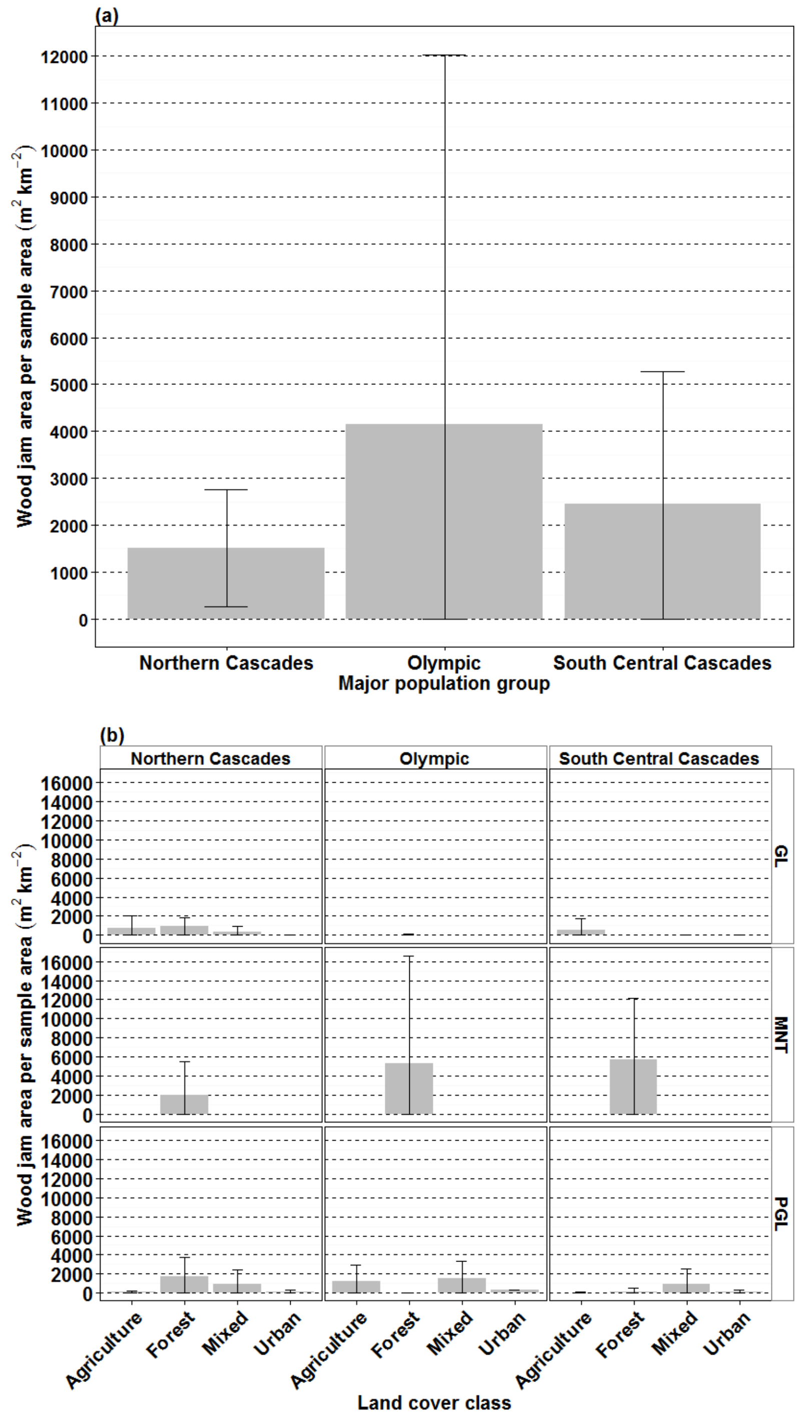


Figure 47: (a) Mean normalized wood jam area and 95% confidence interval aggregated by Northern Cascades, Olympic, and South Central Cascades Steelhead MPGs. Mean normalized wood jam area and 95% confidence interval within Steelhead MPGs, aggregated by glacial, mountain, and post-glacial geomorphic valley types, and by agriculture, forest, mixed, and urban land cover classes.

Delta Metrics

Percent developed and percent forest land cover

The South Central Sound Chinook and Steelhead MPGs have the most urbanized deltas in the Puget Sound (Table 15 and Figure 48), with the Puyallup and Duwamish deltas being over 90% urban. All other Chinook and Steelhead MPGs are primarily forested, with the Olympic Steelhead MPG and nested Juan De Fuca and Hood Canal Chinook MPGs having over 75% forested land cover. Agricultural land cover is most prevalent in the North Cascade Steelhead MPG and nested Georgia Strait and North Sound Chinook MPGs, with about 40% agricultural land cover occurring within the North Cascade 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 the South Central Cascades, and 15 times more than the Olympic MPGs (Table 16 and Figure 49). In the 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 only account for 18% and 33.9% of tidal channel habitat area in the Olympic and South Central Cascades deltas, respectively. Tidal channels and tidal complex habitat account for a majority of the tidal channel habitat area in the Olympic deltas, with 58% of tidal channel habitat being tidal channels and tidal complex habitat. In the 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 (Table 16 and Figure 49). Tidal flats in the South Central Cascades are noticeably inflated however by the Nisqually delta, where large recent restoration projects have created large areas of tidally flooded habitat where channel features and vegetation have not developed sufficiently to delineate channel flow paths within the delta.

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

Steelhead MPG, Chinook MPG, Delta	% Forested	% Agricultural	% Urban
Northern Cascades	**51.5%**	**40.0%**	**8.5%**
Georgia Strait	**53.6%**	**41.1%**	**5.4%**
NKS	53.6%	41.1%	5.4%
North Sound	**51.2%**	**39.9%**	**9.0%**
SAM	48.4%	47.9%	3.6%
SKG	49.3%	45.0%	5.8%
STL	60.9%	33.0%	6.1%
SNH	49.2%	33.9%	16.9%
Olympic	**89.1%**	**5.7%**	**5.3%**
Hood Canal	**92.7%**	**3.5%**	**3.8%**
QUL	86.0%	10.9%	3.1%
DOS	90.2%	0.6%	9.2%
DUC	92.0%	0.0%	8.0%
HAM	96.2%	1.8%	2.0%
SKO	95.6%	2.2%	2.2%
Juan de Fuca	**78.0%**	**12.4%**	**9.6%**
DUN	77.0%	12.7%	10.2%
ELW	86.0%	10.1%	3.9%
South Central Cascades	**33.5%**	**0.4%**	**66.1%**
South Sound	**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%
Total	**51.6%**	**32.5%**	**15.9%**

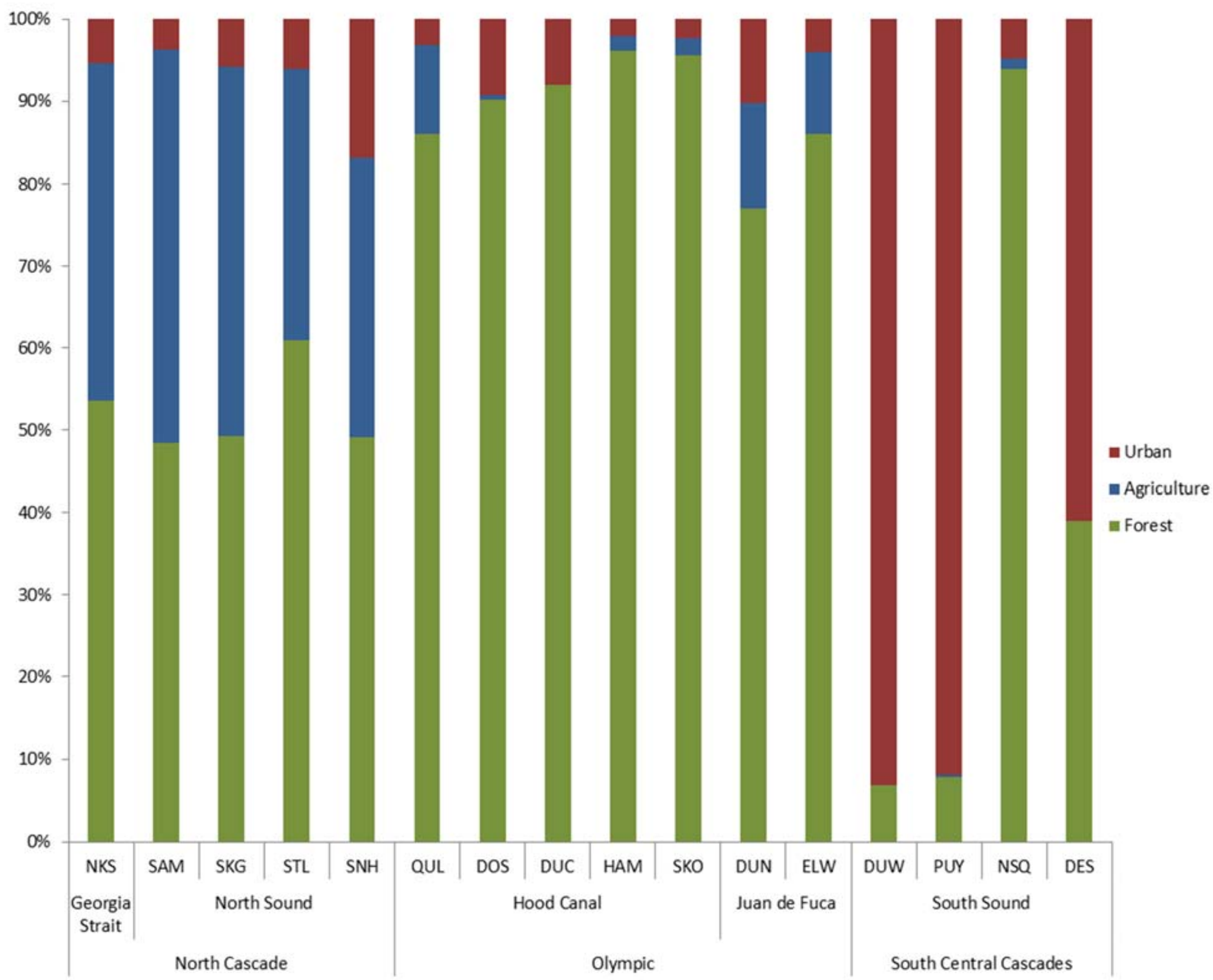


Figure 48. Percent forest, agriculture, and urban land cover by delta and MPG (Steelhead MPGs = North Cascades, Olympic, and South Central Cascades; Chinook MPGs = Georgia Strait, North Sound, Hood Canal, Juan de Fuca, and South Sound) for all 16 major Puget Sound deltas (NKS = Nooksack, SAM = Samish,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

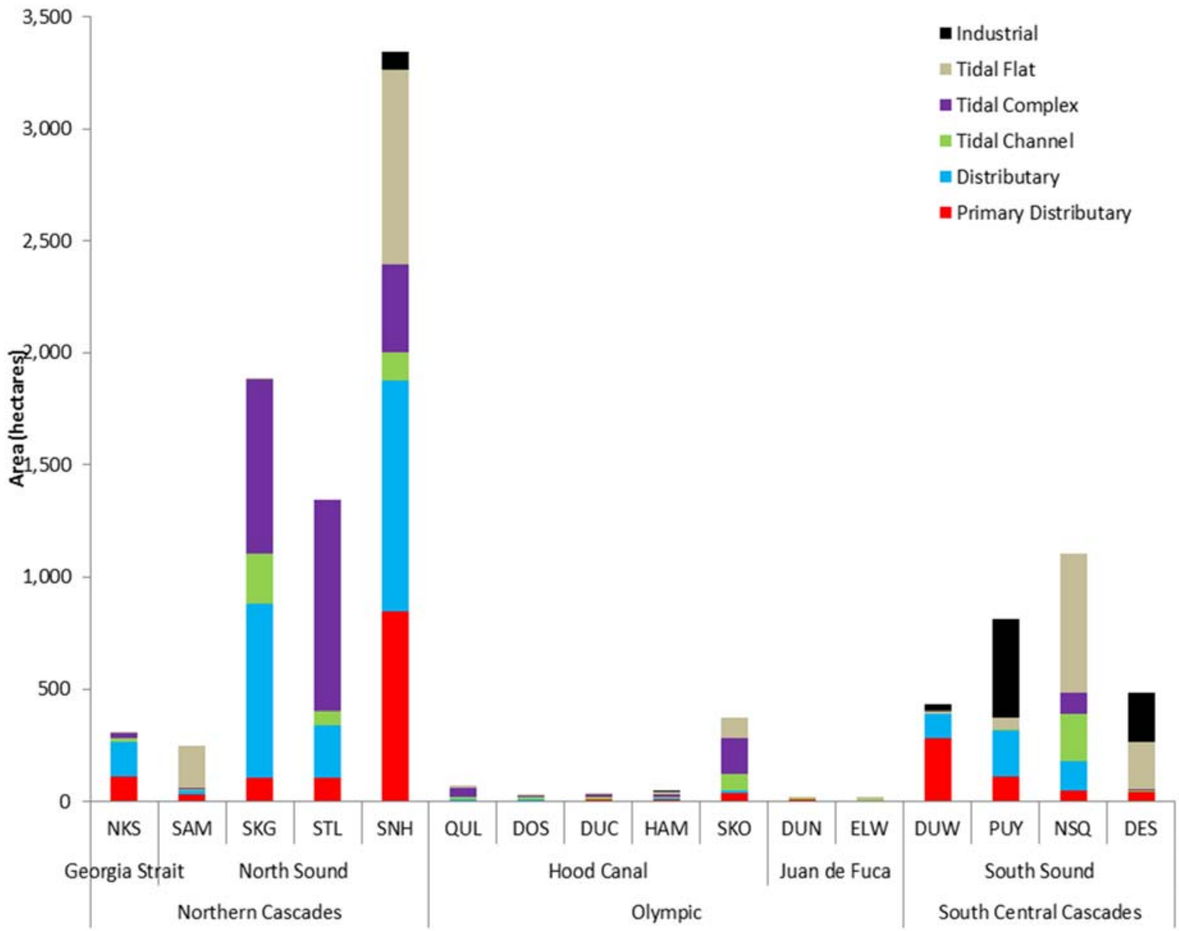


Figure 49. Area (hectares) of channel features by delta and MPG (Steelhead MPGs = North Cascades, Olympic, and South Central Cascades; Chinook MPGs = Georgia Strait, North Sound, Hood Canal, Juan de Fuca, and South Sound) for all 16 major Puget Sound deltas (NKS = Nooksack, SAM = Samish, SKG = Skagit, STL = Stillaguamish, SNH = Snohomish, QUL = Big Quilcene, DOS = Dosewallips, DUC = Duckabush, HAM = Hamma Hamma, SKO = Skokomish, DUN = Dungeness, ELW = Elwha, DUW = Duwamish, PUY = Puyallup, NSQ = Nisqually, and DES = Deschutes). Areas digitized 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 smaller than 5 meters wide occurring within the feature.

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 relative to distributary channel habitat, while deltas with more than 60% forested cover had more tidal channel habitat by length relative to distributary channel length. This suggests that conversion of forest land to urban or agricultural is accompanied by lost tidal channel habitat.

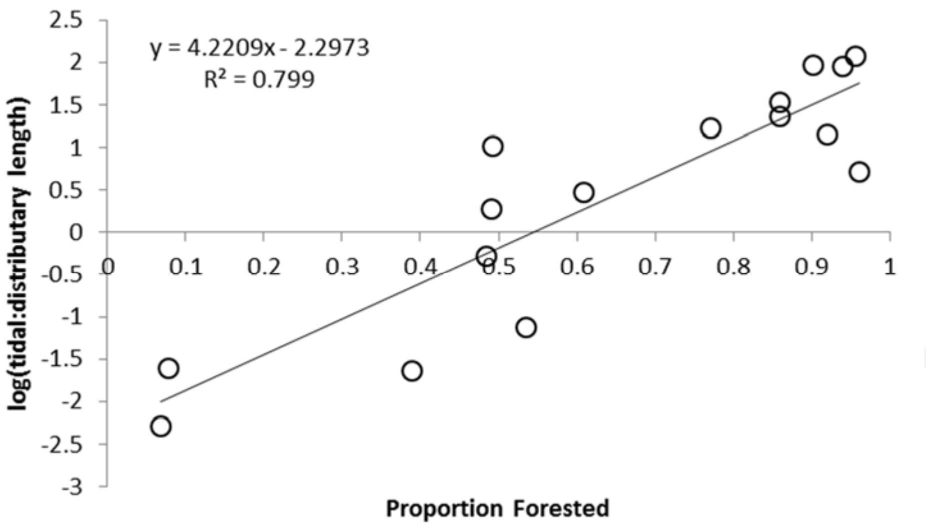


Figure 50. Proportion forested land cover within a delta and the log transformed ratio of tidal channel length to distributary length (primary distributary + distributary) and linear regression trend line. Log transformed ratios of more than 0 represent deltas with more tidal channel length than distributary length, while deltas with 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 and 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 as compared to the Skagit delta, but the Skagit delta has more edge habitat. This indicates that there are more small channel networks in the Skagit delta compared to fewer larger channels in the Snohomish. Given that juvenile salmonids are more likely to use the edges of tidal channel features as opposed to the middle 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 6 times greater in the North Cascades MPG than in the Olympic MPG, and over 4 times as much as the South Central Cascades MPG (Table 18 and Figure 52). Channel lengths are dominated by tidal channels in all MPGs, with tidal channels representing 62% of channel length in the Northern Cascades MPG, 84% in the Olympic MPG, and 70% in the South Central Cascades MPG (Table 18 and Figure 52). However, this comparison is biased given that the Nisqually delta is the only South Central Cascades delta that 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 to 17% tidal channels. After removing the Nisqually delta, the South Central Cascades MPG delta channel length are dominated by distributaries (71 to 91%) (Table 18 and Figure 52).

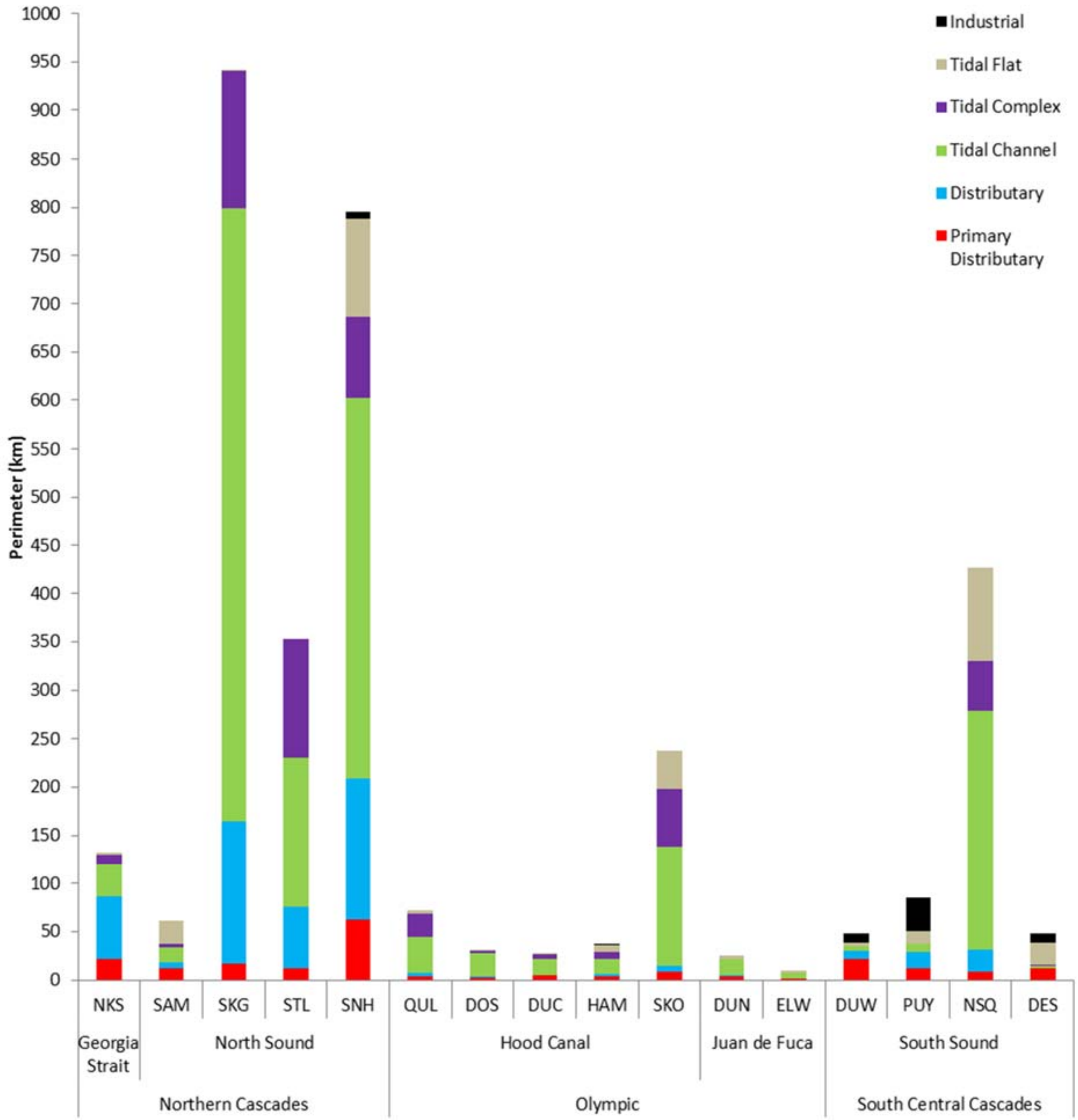


Figure 51. Perimeter of channel features by delta and MPG (Steelhead MPGs = North Cascades, Olympic, and South Central Cascades; Chinook MPGs = Georgia Strait, North Sound, Hood Canal, Juan de Fuca, and South Sound) for all 16 major Puget Sound deltas (NKS = Nooksack, SAM = Samish, SKG = Skagit, STL = Stillaguamish, SNH = Snohomish, QUL = Big Quilcene, DOS = Dosewallips, DUC = Duckabush, HAM = Hamma Hamma, SKO = Skokomish, DUN = Dungeness, ELW = Elwha, DUW = Duwamish, PUY = Puyallup, NSQ = Nisqually, and DES = Deschutes). Areas digitized 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 smaller than 5 meters wide occurring within the feature.

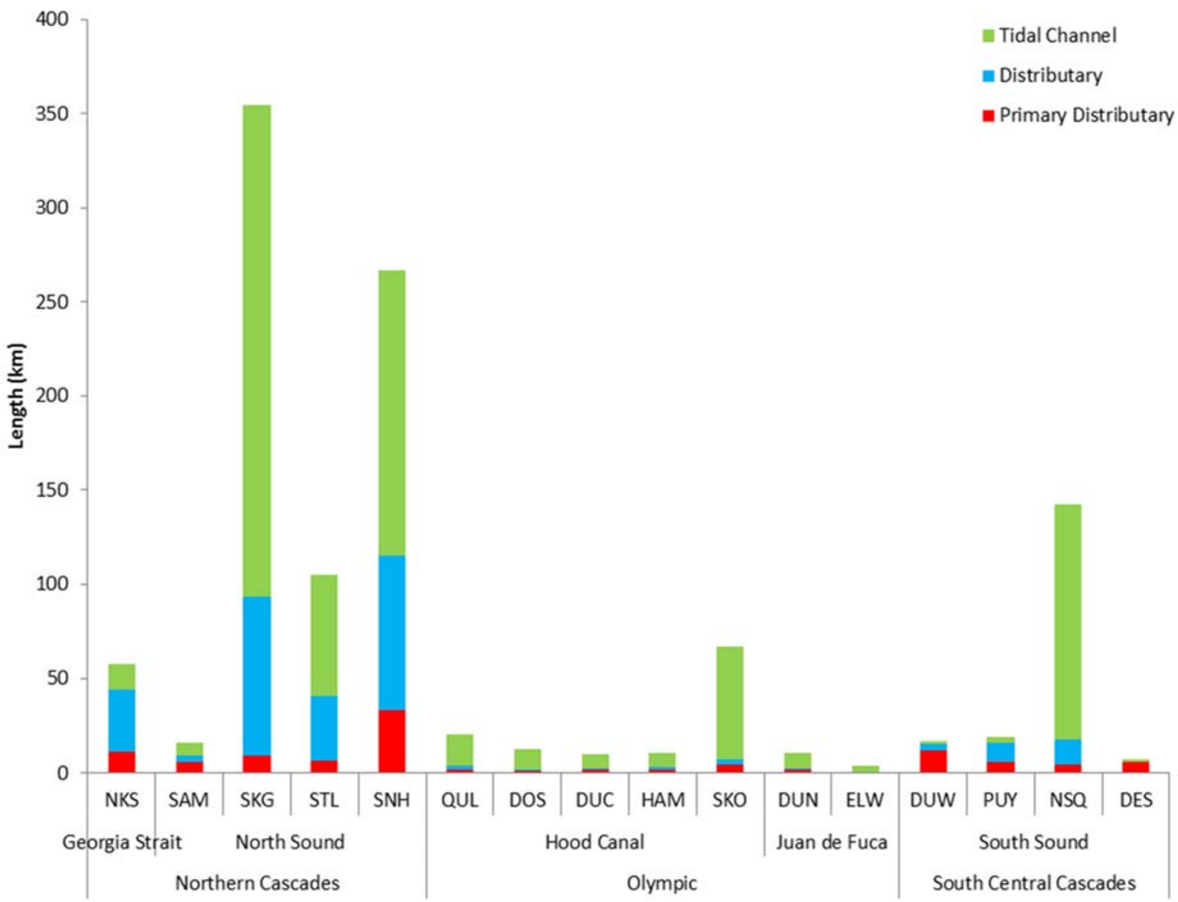


Figure 52. Length of channel features by delta and MPG (Steelhead MPGs = North Cascades, Olympic, and South Central Cascades; Chinook MPGs = Georgia Strait, North Sound, Hood Canal, Juan de Fuca, and South Sound) for all 16 major Puget Sound deltas (NKS = Nooksack, SAM = Samish, SKG = Skagit, STL = Stillaguamish,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

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 provide large contributions to habitat area but numerous small tidal channels provide more linear edge and channel length compared to distributaries.

Node density

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

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

Steelhead MPG, Chinook 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	**1210.6**	**2202.4**	**435.4**	**2143.2**	**1065.9**	**78.8**	**7136.4**
Georgia Strait	**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
North Sound	**1097.7**	**2049.3**	**419.2**	**2118.5**	**1061.0**	**78.8**	**6824.4**
SAM	33.1	15.4	6.9	3.8	192.7	0.0	252.0
SKG	106.7	777.6	220.4	780.3	0.1	0.0	1885.1
STL	107.1	231.1	65.5	939.7	0.0	0.0	1343.4
SNH	850.9	1025.1	126.4	394.7	868.1	78.8	3344.0
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**
QUL	4.2	2.7	11.8	43.7	9.3	0.0	71.7
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
HAM	10.2	5.4	6.5	9.1	13.8	0.5	45.6
SKO	35.5	15.0	72.5	161.0	90.2	0.0	374.2
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
South Central Cascades	**489.7**	**442.8**	**222.2**	**99.8**	**890.8**	**687.2**	**2832.5**
South Sound	**489.7**	**442.8**	**222.2**	**99.8**	**890.8**	**687.2**	**2832.5**
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	1103.6
DES	46.3	0.0	2.1	4.5	212.9	218.3	484.1
Total	**1781.1**	**2670.9**	**785.5**	**2470.3**	**2088.2**	**766.5**	**10562.4**

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

Steelhead MPG, Chinook 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**	**1231.9**	**361.8**	**127.6**	**7.5**	**2281.5**
Georgia Strait	**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
North Sound	**103.3**	**362.9**	**1198.7**	**352.2**	**125.3**	**7.5**	**2150.0**
SAM	11.9	6.5	15.3	3.0	23.9	0.0	60.7
SKG	17.1	146.8	634.7	142.3	0.2	0.0	941.1
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
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**
QUL	3.4	4.3	36.3	24.5	3.5	0.0	72.0
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
HAM	3.6	3.0	15.3	6.3	8.3	0.5	37.0
SKO	8.7	6.1	122.9	59.9	40.3	0.0	237.9
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
South Central Cascades	**53.6**	**47.5**	**262.6**	**52.9**	**138.1**	**53.2**	**607.9**
South Sound	**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
Total	**207.0**	**490.8**	**1732.2**	**513.2**	**324.4**	**61.2**	**3328.8**

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

Steelhead MPG, Chinook 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**	**6068**	**90.9**
Georgia Strait	**11.1**	**32.5**	**14.2**	**57.9**	**224**	20.1
NKS	11.1	32.5	14.2	57.9	224	20.1
North Sound	**55.6**	**203.0**	**483.8**	**742.4**	**5844**	**105.1**
SAM	6.0	3.2	6.9	16.0	105	17.6
SKG	9.5	84.2	260.7	354.4	2971	312.7
STL	6.9	33.7	64.8	105.4	661	95.6
SNH	33.2	81.9	151.4	266.6	2107	63.4
Olympic	**14.2**	**7.6**	**113.5**	**135.3**	**1132**	**79.7**
Hood Canal	**11.5**	**7.1**	**102.4**	**121.0**	**1047**	**91.0**
QUL	1.7	1.9	16.8	20.4	212	122.3
DOS	1.2	0.4	11.2	12.8	135	116.0
DUC	2.0	0.4	7.8	10.2	100	49.0
HAM	1.8	1.6	7.1	10.6	104	56.3
SKO	4.7	2.8	59.5	67.0	496	105.1
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
South Central Cascades	**27.8**	**26.9**	**130.7**	**185.4**	**1738**	**62.6**
South Sound	**27.8**	**26.9**	**130.7**	**185.4**	**1738**	**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	1617	347.0
DES	5.9	0.0	1.1	7.0	24	4.1
Total	**108.7**	**270.1**	**742.2**	**1121.0**	**8938**	**82.2**

4. Status of Habitat and Riparian Areas by Land Cover Class

We also summarized the status of each of the metrics by land cover class. We first report the large river and floodplain metrics collected from satellite, aerial photograph, and field data. We then report the delta metrics collected from satellite or aerial photograph 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 percent forest and percent developed land cover, riparian buffer width, sinuosity, edge habitat length by type, proportion of disconnected floodplain, 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 classified as forest (44%), with agricultural lands being the next most represented (28%), and urban land cover with the lowest proportion (16%) (Figure

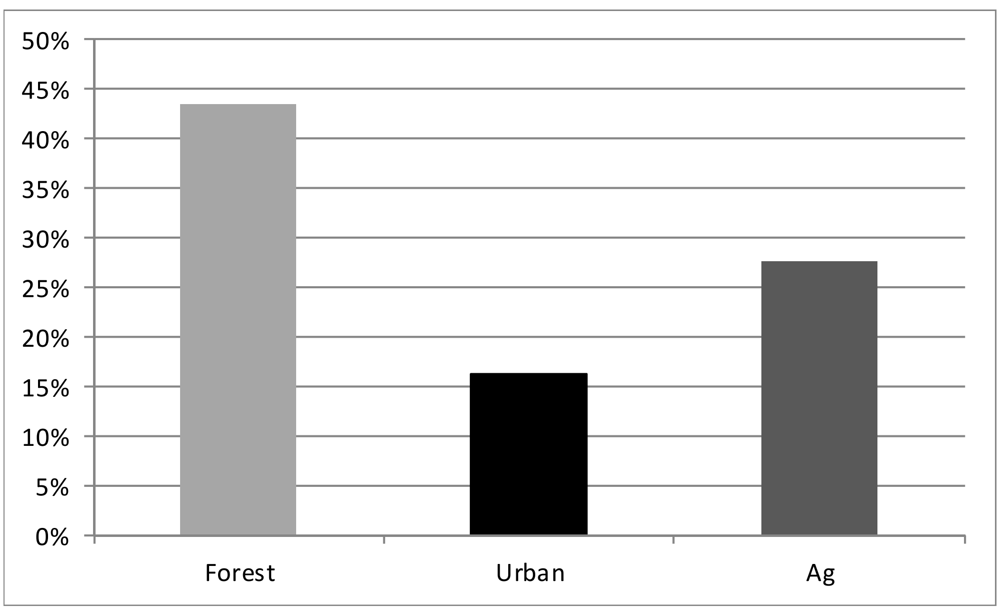


Figure 53. Proportion of land cover type by land cover class (Forest, Urban, Ag) in all sample-able floodplains in Puget Sound.

53). Within Puget Sound's floodplains, forest, urban, and agriculture lands represent 88% of the land cover. The remaining 12% consists of bare land, water, and snow/ ice.

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 dominantly forest and lowest at sites with dominantly agriculture land cover (12% for C-CAP and 19% for NAIP) (Figure 54). Percent developed is greatest in urban sights for both data sets however there is a significant difference between the data sets at urban sites (Figure 54). C-CAP's estimate across sites is at 50% whereas NAIP estimates percent developed land at just over 20% at urban sites. These findings are consistent with the riparian validation results (See Results Section 1, Figure 16), which show that C-CAP tends to overestimate developed land cover and NAIP to underestimate developed land cover.

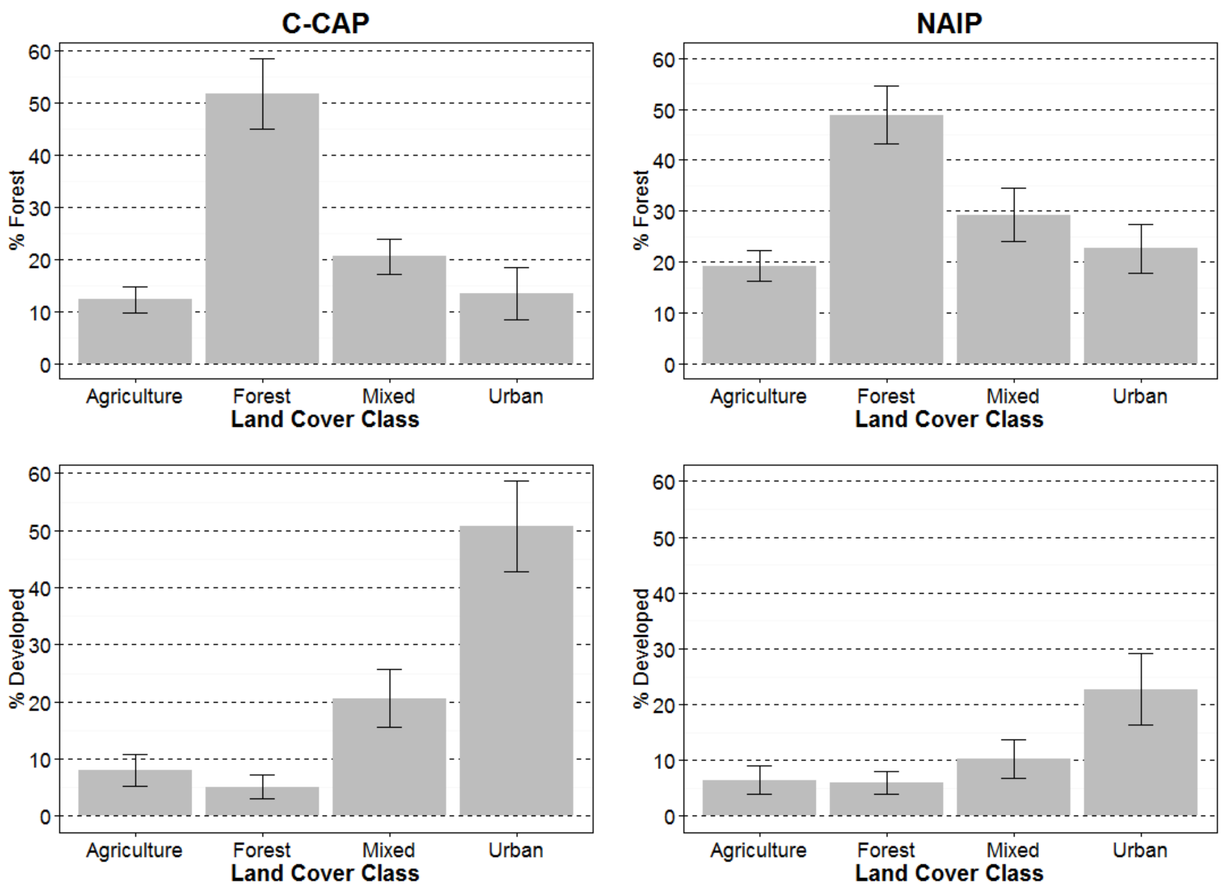


Figure 54. Percent forest and percent developed land cover at 124 sites across Puget Sound by land cover class (agriculture, forest, mixed, urban).

Riparian buffer width

The median of mean riparian buffer widths by land cover class is greatest at sites classified as Forest (72 m) and lowest at urban sites (15 m) (Figure 55). Median buffer widths at forested sites is roughly 30 meters wider than the median width at sites classified as Agriculture and Mixed (40m and 42 m, respectfully), and more than 50 meters wider than median widths at urban sites. Error bars indicate 95% confidence interval.

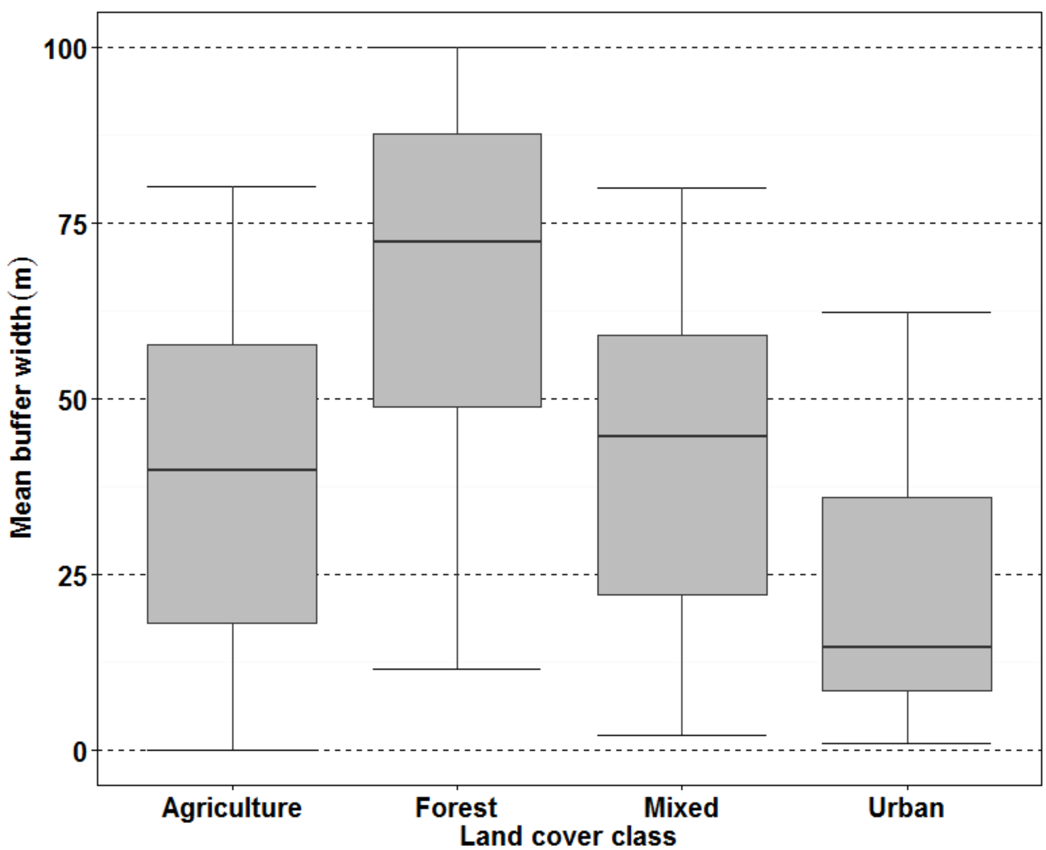


Figure 55. Box plots indicating median (line), upper (75%) and lower (25%) quartiles (box edges), and upper and lower limits (whiskers) of mean forested buffer width along large rivers in Puget Sound by land cover class (agriculture, forest, mixed, or urban). Each data point represents one sample reach and mean buffer width is the mean of 20 width measurements for that sample reach.

Edge habitat length by type

The highest mean proportion of bar edge length was in forest-dominated sites (33%, ± 7% 95% C.I.), while the lowest was in urban sites (16%, ± 7% 95% C.I.) (Figure 56). The mean proportion of natural bank edge length ranged from 13% (± 10% 95% C.I.) in urban sites to 50% (± 9% 95% C.I.) in the forest-dominated sites. The highest mean proportion of modified bank edge length was observed in the urban land cover class (69%, ± 13% 95% C.I.) and the lowest in forested sites (14%, ± 6% 95% C.I.).

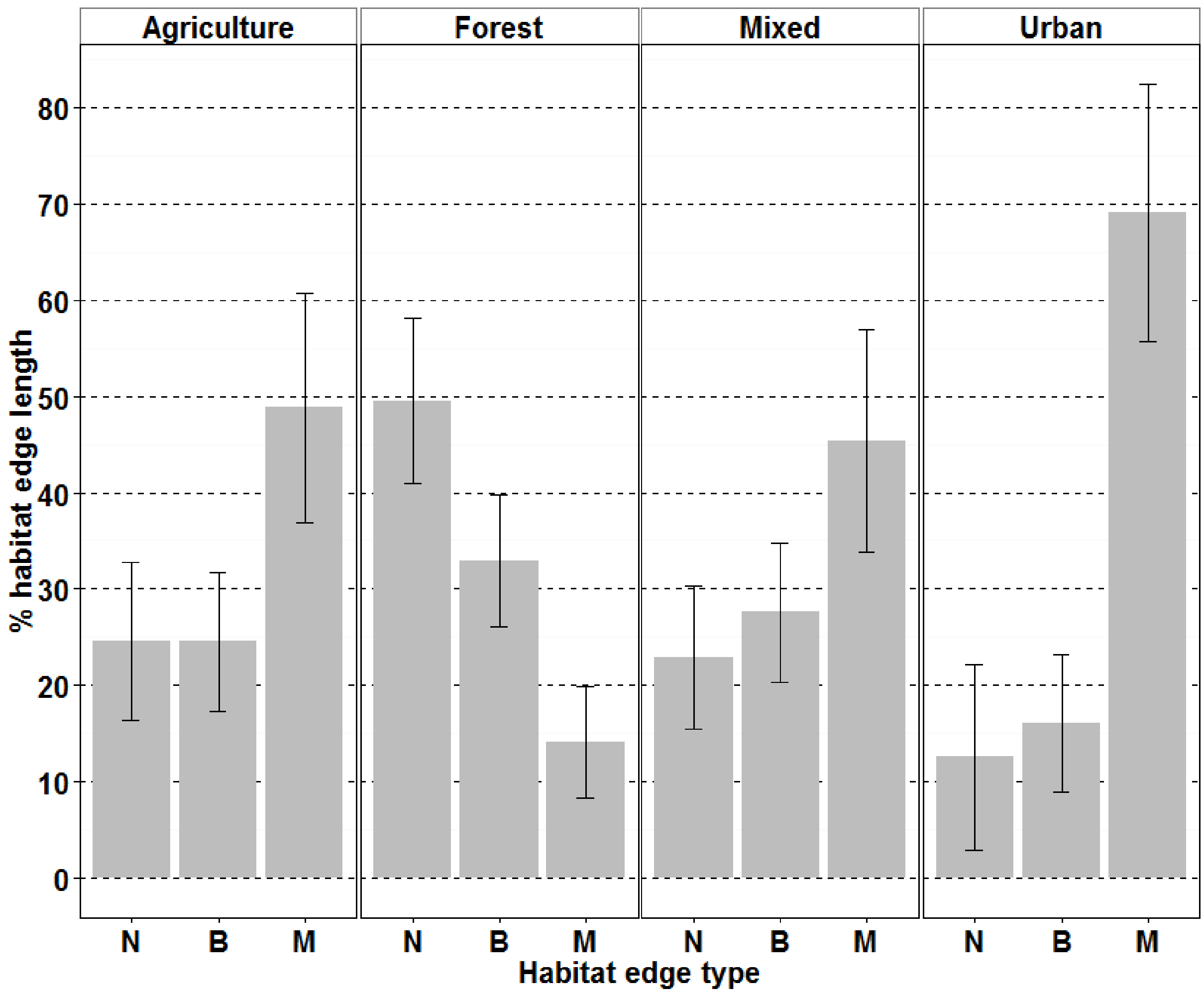


Figure 56. Mean proportion of bar (B), modified bank (M), or natural bank (N) edge length and 95% confidence interval within agriculture, forest, mixed, and urban land cover class. Error bars indicate 95% confidence interval.

Sinuosity

Mean channel sinuosity did not vary significantly between land cover classes, and variation among sites within each land cover class was relatively low (Figure 57).

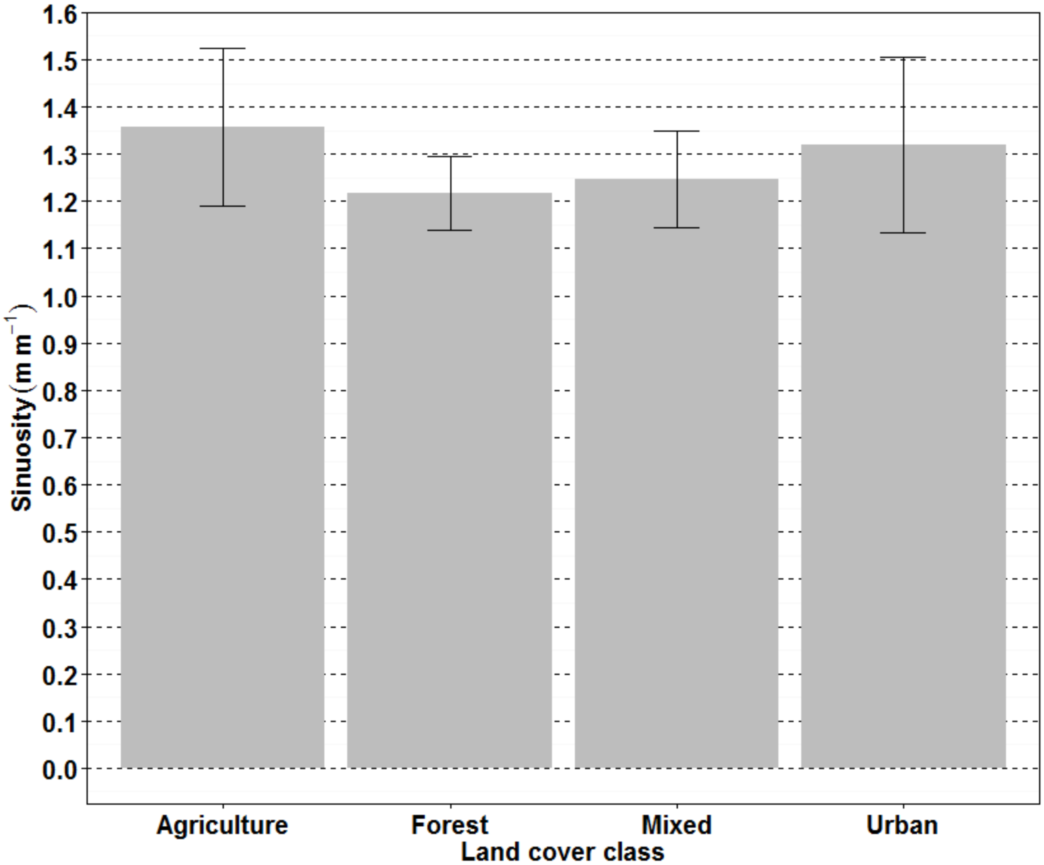


Figure 57. Mean sinuosity and 95% confidence interval (depicted by error bars) within agriculture, forest, mixed, and urban land cover class.

Braid node density and braid channel length

The mean braid node density was similar among land cover classes, with only a slightly higher density in the urban land cover class (2.2 nodes km^{-1}, ± 1.4 nodes km^{-1} 95% C.I.) and a slightly lower density in the agriculture land cover class (1.6 nodes km^{-1}, ± 1.3 nodes km^{-1} 95% C.I.). However, variation around the mean was high and the differences were not statistically significant (Figure 58a). Mean braid node density was similar between forest and mixed land cover class at ~2 nodes km^{-1}. Perhaps surprisingly, the mean braid-channel ratio was not correlated with mean braid node density. Mean braid main channel ratio ranged from 0.12 m m^{-1}(± 0.08 nodes km^{-1} 95% C.I.) in the urban land cover class to 0.16 m m^{-1}(± 0.08 nodes km^{-1} 95% C.I.) in the mixed land cover class (Figure 58b).

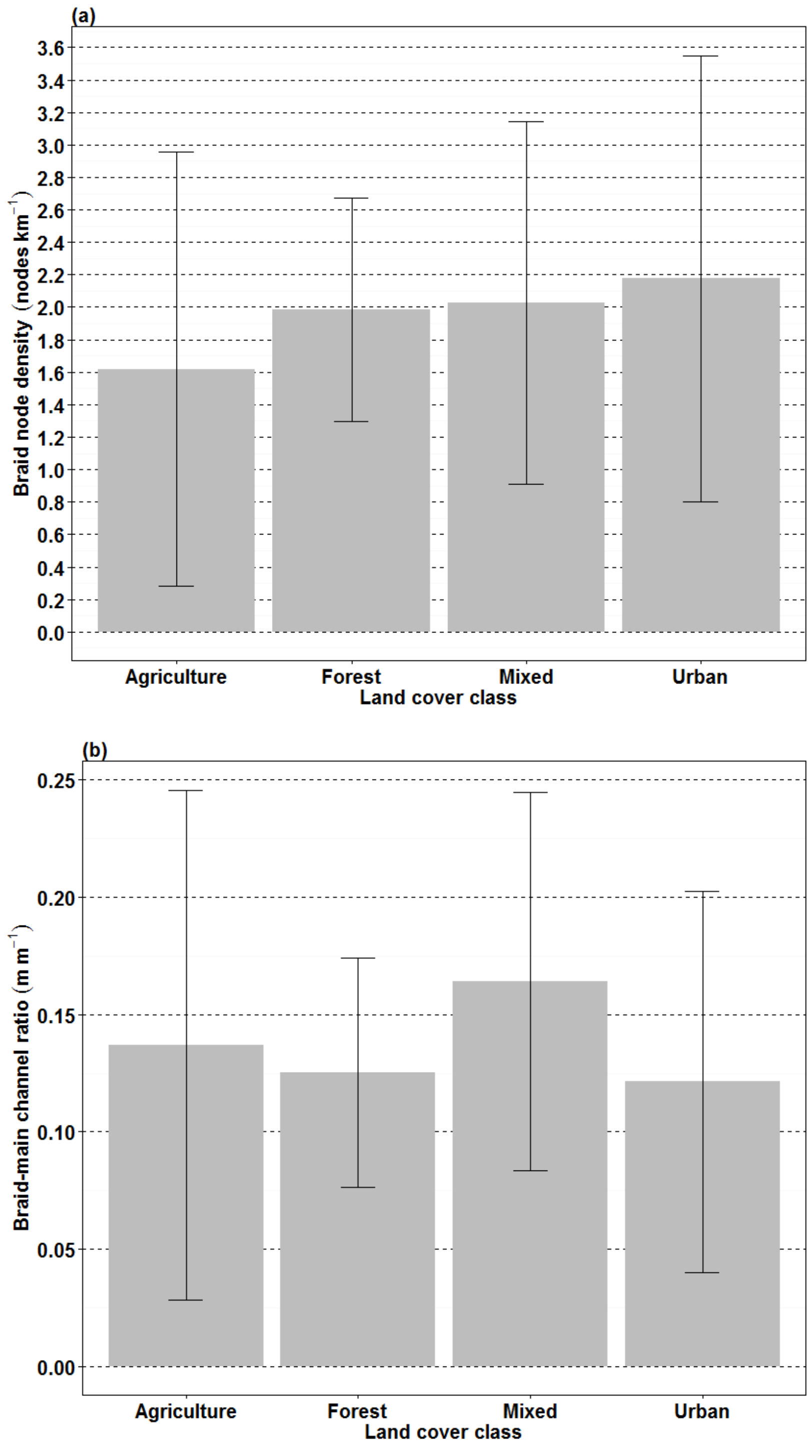


Figure 58. (a) Mean braid node density and 95% confidence interval (depicted by error bars) within agriculture, forest, mixed, and urban land cover class. (b) Mean braid-main channel ratio and 95% confidence interval within agriculture, forest, mixed, and urban land cover class.

Percent disconnected floodplain

The mean proportion of disconnected floodplain varied greatly between land cover classes (Figure 59). The highest mean proportion of disconnected floodplain was observed in urban land cover class where over 50% of the sites have disconnected floodplains (± 11% 95% C.I.), while the lowest mean proportion of disconnected floodplain was observed in the forest land cover class (11%, ± 6% 95% C.I.).

Side channel node density and side channel-main channel ratio

The mean side channel node density differed among land cover classes, but also exhibited high variability among sites within the land cover classes (Figure 60a). Mean side channel node density ranged from 0.4 nodes km^{-1}in the urban land cover class to 1.4 nodes km^{-1} in forest land cover class. 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 forest land cover class (0.32 m m^{-1}, ± 0.19 m m^{-1} 95% C.I.) and lowest in the urban cover class (0.05 m m^{-1}, ± 0.08 m m^{-1} 95% C.I.).

Backwater area

Not surprisingly, backwater area was highest in forested sites and lowest in urban sites (Figure 61). Mean backwater area was nearly 750 m^2km^{-2} of active channel in forested sites, and only about 200 m^2km^{-2} in urban sites.

Wood Jam Area

The mean wood jam area per km^2 of active channel varied among land cover classes and among the sites within land cover classes (Figure 62). The highest mean wood jam area per km^2 of active channel was in the forest land cover class (1913 m^2km^{-2}, ± 1440 m^2km^{-2} 95% C.I.), while the lowest was in urban land cover class (74 m^2km^{-2}, ± 64 m^2km^{-2} 95% C.I.).

Length of human modified bank (field)

Bank type composition varied considerably both among and within land cover classes (Figure 63). Natural banks dominated the forest and mixed land cover classes, while modified banks dominated the agriculture and urban land cover classes. The lowest mean proportion of modified bank length was observed in the forest land cover class (32%, ± 11% 95% C.I.). Conversely, the highest mean proportion of modified bank length was observed in the urban land cover class at 100% (Figure 63). There were no natural banks present in any of the urban sample sites, but sample size was limited to two sites. The highest mean proportion of natural bank length was in the forest land cover class (84%, ± 15% 95% C.I.). Over two-thirds of the sites contained modified bank, while over three-quarters of the sites contained natural bank.

Wood abundance (field)

The highest mean abundance of wood was observed within agriculture land cover class at 84 wood pieces km^{-1} (± 42 wood pieces km^{-1} 95% C.I.), while the lowest mean abundance within urban at 52 wood pieces km^{-1} (± 38 wood pieces km^{-1} 95% C.I.) (Figure 64). However, differences among all classes were small compared to the variation within classes, and sample sizes were small for all land cover classes (n=6 for urban, forest and agriculture; n=3 for mixed).

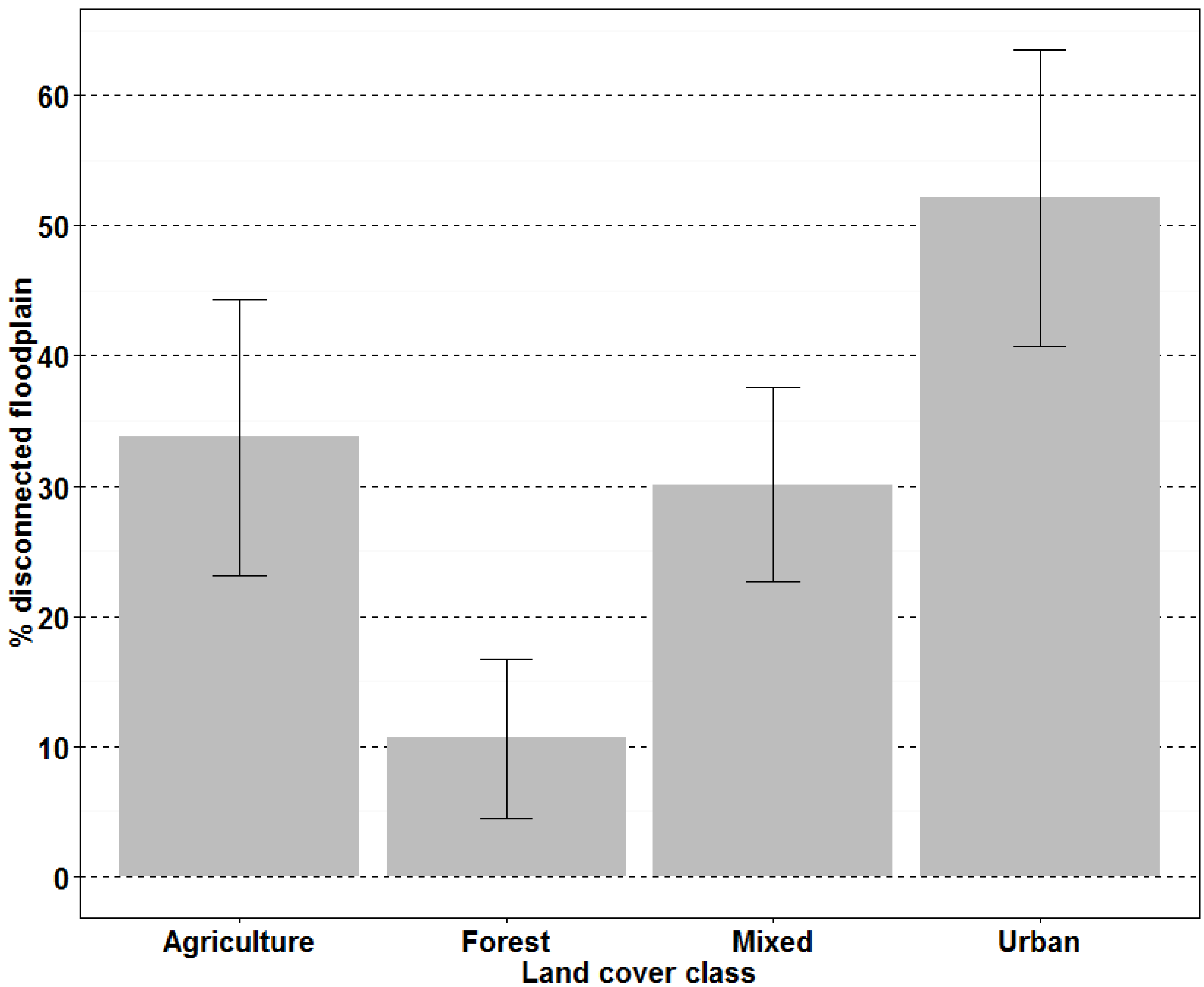


Figure 59. Mean proportion of disconnected floodplain and 95% confidence interval (depicted by error bars) aggregated by agriculture, forest, mixed, and urban land cover class.

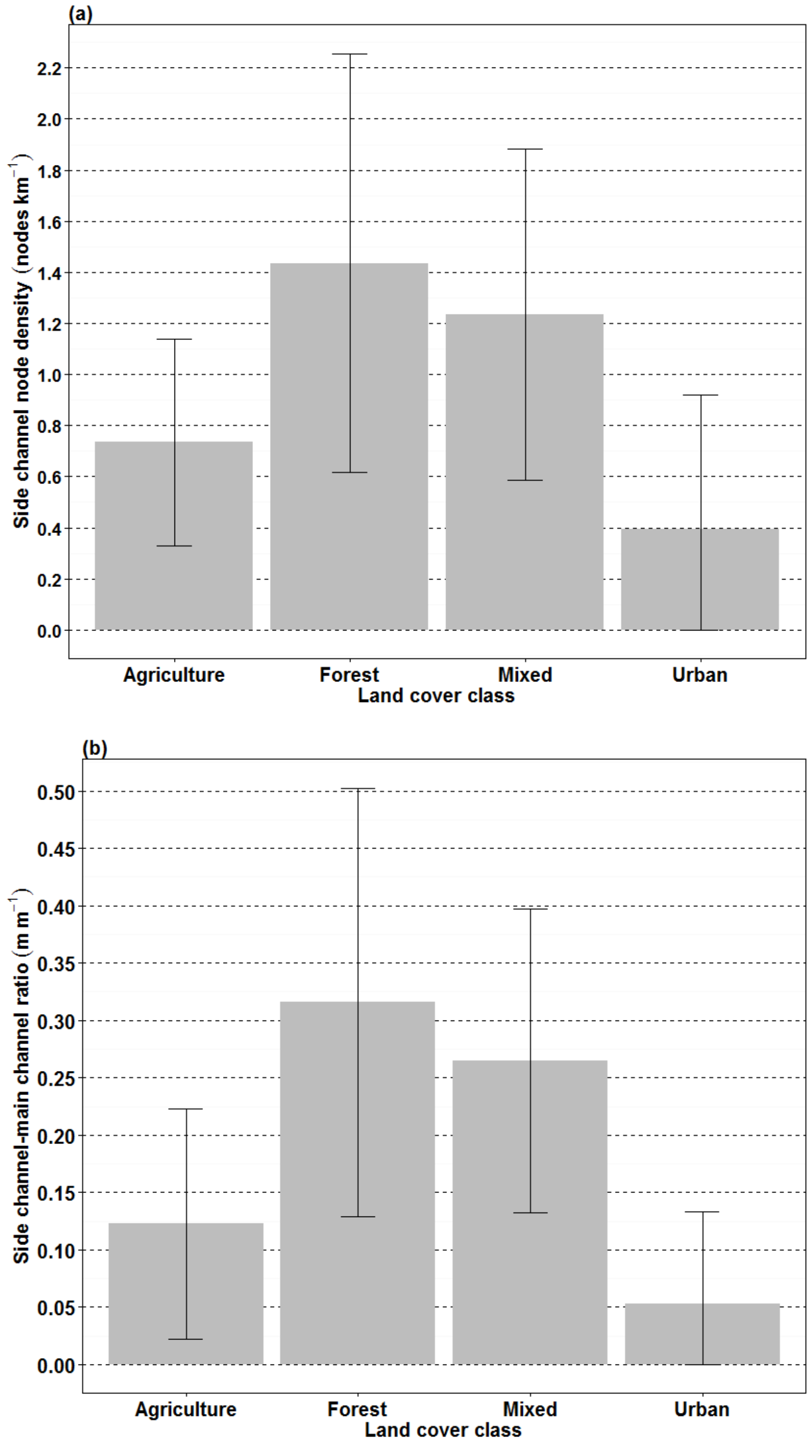


Figure 60. (a) Mean side channel node density and 95% confidence interval within agriculture, forest, mixed, and urban land cover class. (b) Mean side channel-main channel ratio and 95% confidence interval within agriculture, forest, mixed, and urban land cover class. Error bars indicate 95% confidence interval.

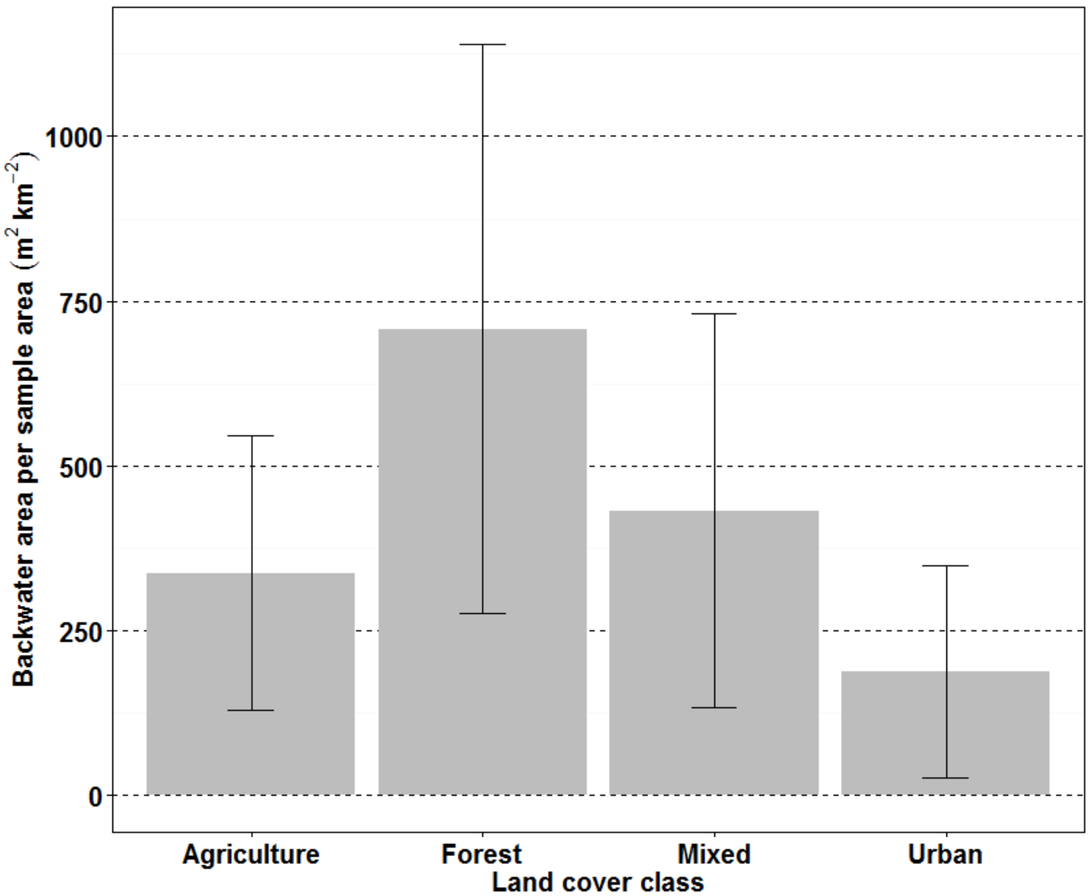


Figure 61. Mean backwater area per sample reach area and 95% confidence interval aggregated by agriculture, forest, mixed, and urban land cover class. Error bars indicate 95% confidence interval.

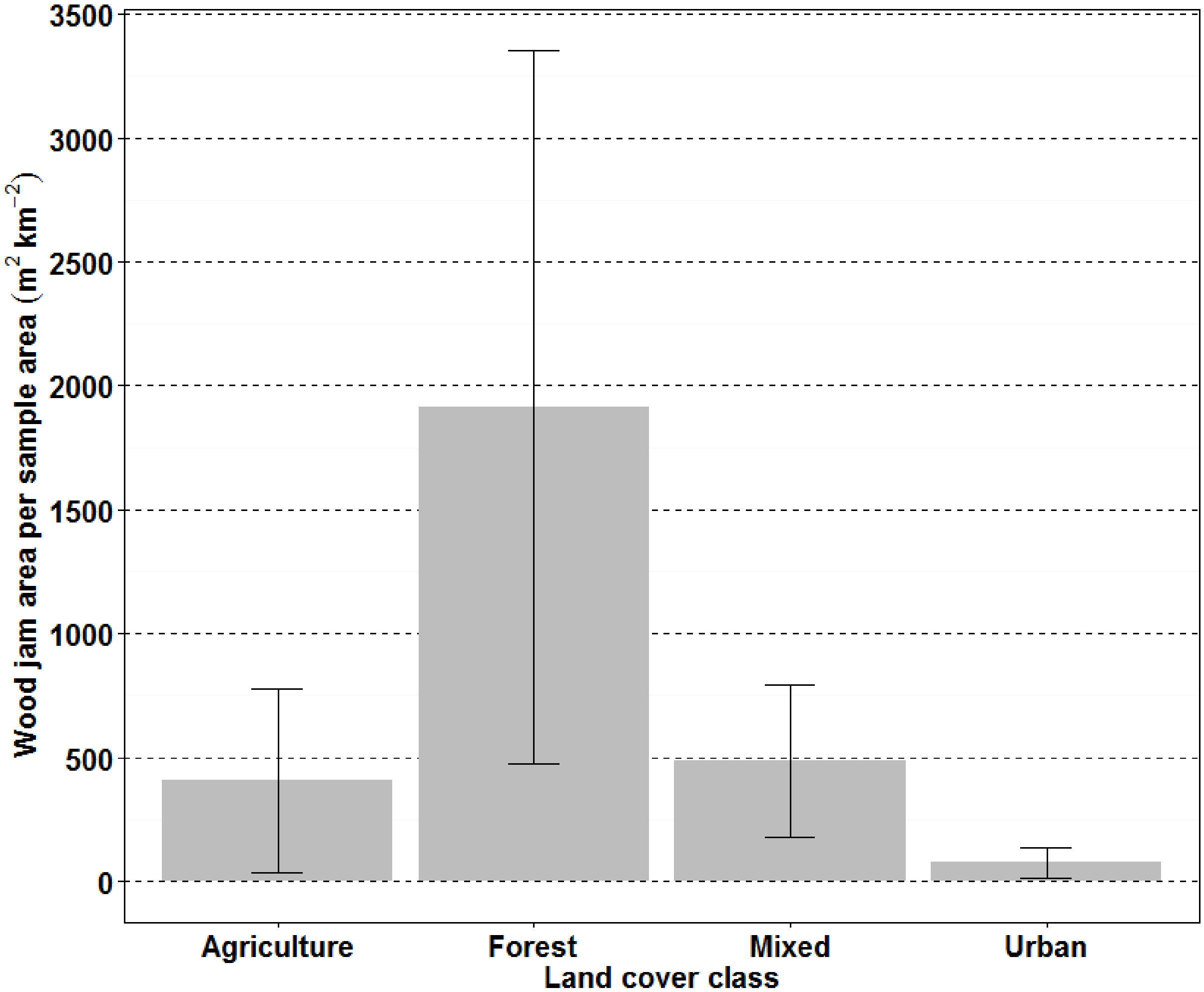


Figure 62. Mean wood jam area per sample reach area and 95% confidence interval aggregated by agriculture, forest, mixed, and urban land cover class. Error bars indicate 95% confidence interval.

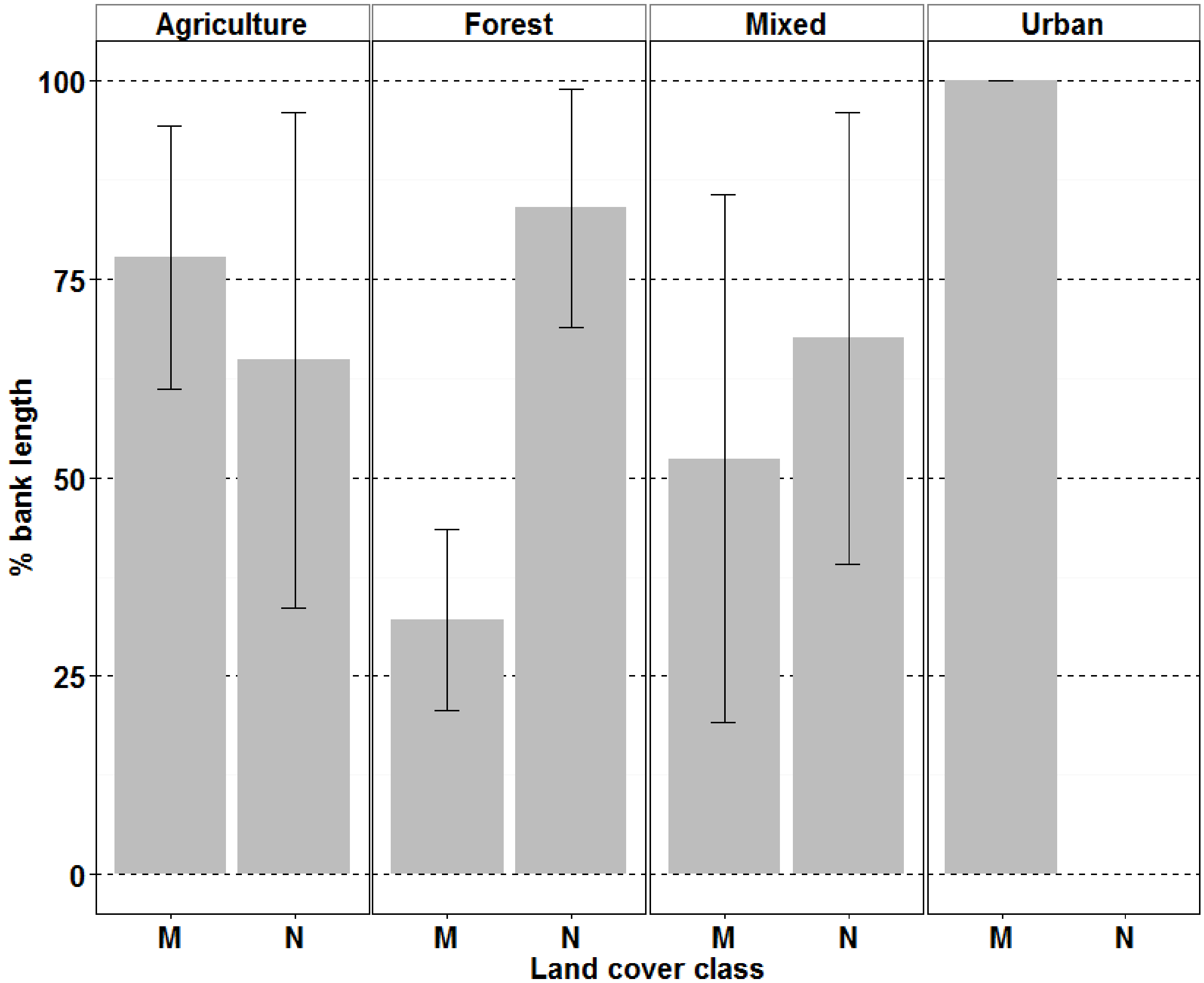


Figure 63. Mean proportion of modified (M) or natural (N) bank length and 95% confidence interval aggregated by agriculture, forest, mixed, or urban land cover class. Error bars indicate 95% confidence interval.

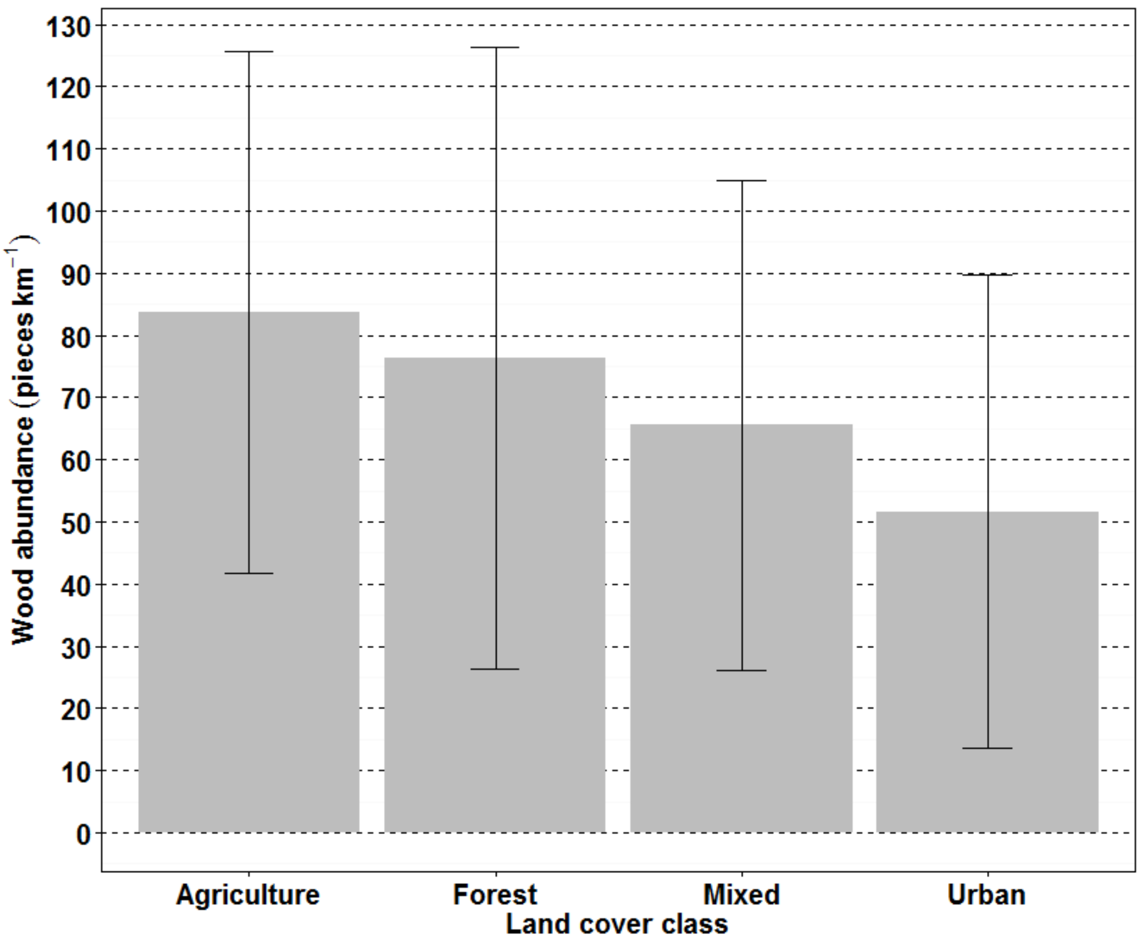


Figure 64. Mean number of wood pieces per reach length and 95% confidence interval within agriculture, forest, mixed, or urban land cover class. Error bars indicate 95% confidence interval.

Habitat edge area by type (field)

The mean percentage of bar edge area was highest in the forest, urban, and agriculture classes, but not in the mixed land cover class (Figure 65). The highest mean percentage of bar edge was in the urban land cover class (75%, ± 0.5% 95% C.I.) while the lowest mean proportion was observed in mixed land cover class (37%, ± 25% 95% C.I.). Natural bank edge was observed in the agriculture, forest, and mixed land cover classes but not urban. The highest mean proportion of natural bank edge was observed in the mixed land cover class at 43% (± 27% 95% C.I.). Backwater was observed within all land cover classes. The highest mean proportion of backwater edge was present within mixed land cover class at 17% (± 15% 95% C.I.). In contrast, the lowest mean proportion of backwater edge was seen within the urban land cover class at 2% (± 1% 95% C.I.). Modified bank edge was observed in all land cover classes with the highest mean proportion in the forest land cover class at 32% (± 26% 95% C.I.) and the lowest proportion in mixed land cover class at 18% (± 10% 95% C.I.).

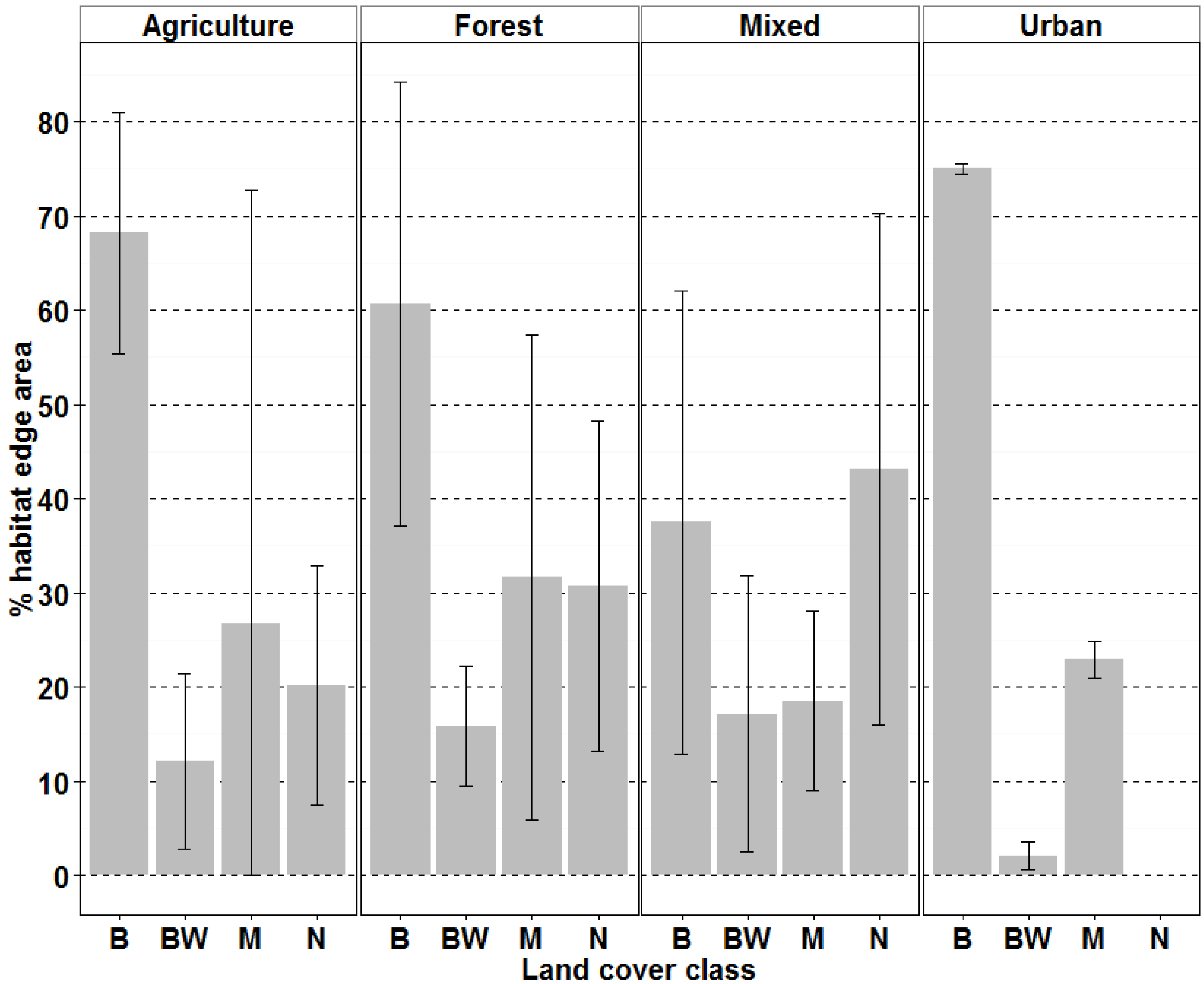


Figure 65. (a) Mean proportion of bar (B), backwater (BW), modified bank (M), or natural bank (N) edge area and 95% confidence interval aggregated by agriculture, forest, mixed, or urban land cover classes. Error bars indicate 95% confidence interval.

Discussion

We first discuss two important accuracy assessments of our sample design and metrics development for landcover and large river aerial photograph 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 the nearshore by MPG and land cover class. Finally, we summarize our lessons learned and next steps for the Puget Sound Habitat Status and Trends Monitoring Program.

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-data used for C-CAP, revealed that tree canopy cover and impervious cover were underestimated by 9.7% and 5.7% respectively (Nowak and Greenfield, 2010). Similarly, an accuracy assessment of NCLD near Baltimore Maryland showed that percent forest and percent impervious were underestimated in the 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 overestimated by the NLCD.

Forest cover is probably underestimated by the NLCD because it does not detect small patches of trees within a grid cell dominated by another land use. For example, a 30m grid cell that is predominantly developed may contain individual trees (Nowak and Greenfield, 2010), and the grid cell is classified as developed. 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, leading to higher percent forest cover in the aerial photo data set. The contrasting results for developed or impervious area likely result from differences in the NLCD data sets used. 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 underestimate 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). However, in our study we manually classified a point as developed when the point landed on an impervious surface, yet the developed cell in NLCD may include other cover types. Hence, percent developed is overestimated relative to impervious areas.

Percent forest measured with NAIP is the most accurate of all the landcover metrics (slope near 1 and intercept near 0), with only a slight tendency to overestimate percent forest. One potential cause of the overestimation of forest in the NAIP data could be that for single trees in the middle of 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 was classified as impervious in manual observations but as tree in the NAIP data set. By contrast, NAIP underestimates developed area, possibly because some developed areas are in the shadow of trees or structures and not included in the developed area calculation. Because the resolution of the NAIP data is much finer than NLCD (1-m grid cells compared to 30-m grid cells), missed features are not likely a cause of underestimating impervious area as it may be with the NLCD. In future analyses we will re-examine accuracy of the NAIP data because improvements to the landcover classification have been made recently, and we will examine use of the NLCD impervious surface coverage instead of the developed land cover classifications that were derived from the original impervious surface classification.

Accuracy of aerial photograph land cover classification

We encountered two main sources of error in aerial photograph classification that significantly reduced apparent accuracy of manual classification. The first major source of error was related to channel movement or vegetation growth that occurred between the image date and 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 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 a forest and forest as grass/shrub. These errors are most likely associated with classification of shrub communities as tree cover types or 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 image analysis and distinguishing them in the field would help improve classification accuracy. And 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 landcover classification is not required.

2. Observer Variability in Aerial Photograph 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 in shadows created by the canopy. This issue can only be alleviated by field verification, or by use of field-verified data on features such as levees or riprap. However, there or no complete feature 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 vary 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 would be measured exactly along the edges of all contiguous and stacked pieces of wood. Similarly, we specified that at least half a side channel must be visible to include it in the side-channel to main channel length ratio.

3. Status of Habitat and Riparian Areas by MPG

Most of our metrics indicate that habitat in the South Central Cascades Steelhead MPG is most impaired, likely because 78% of its sample sites were in the urban, mixed, and agriculture land cover classes. The Olympic Steelhead MPG is least impaired, largely because 50% of sample sites were in the forest land cover class, which tends to be less altered. However, the Olympic MPG 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 the Olympic MPG, although 39% of the sites were in the forest land cover class.

Forested riparian buffer widths were greatest in the Olympic MPG, and lowest in the South Central Cascades. While the Olympic MPG has the least floodplain area (176 km^2), proportionately it has more forested land cover within the floodplain boundaries (Figure 9). The small average forested buffer width in the South Central Cascades was anticipated because that MPG contains the most urban area and the highest percent developed land cover. Percent forested floodplain was slightly higher in the Olympic MPG 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 the Olympic MPG, which has the highest area of forested floodplain. Hence, the Olympic MPG may have fewer roads and levees artificially disconnecting the floodplain from the channel. By contrast, percent disconnected floodplain was highest in the South Central Cascades MPG, 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 the side-channel node density and side channel length was highest in the Northern Cascades MPG and low in both the Olympic and South Central Cascades MPG. Side channel length is also highest in the Northern Cascades MPG and lowest in the Olympic MPG. While it may seem counterintuitive that the Olympic MPG has less side channel length and node density, we found that it has considerably more naturally confined valleys than the South Central and North Cascades MPGs. The Olympic MPG consists mostly of post-glacial and mountain valleys. These valley types tend to be smaller and more confined which limits the formation of side channels. The majority of sample sites within the South Central Cascades MPG 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 urban. The low amount of natural bank edge, moderate amount of bar edge, and high amount of modified bank edge in South Central Cascades MPG is indicative of habitat areas with high anthropogenic effect 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 the Olympic MPG are likely due to the dominance of forest land cover, which contains more natural habitat. The Northern Cascades MPG is a mix of both forested and anthropogenically altered land cover classes, and habitat conditions are intermediate between those of the Olympics and South Central Cascades Steelhead MPGs.

The area of wood jams in large rivers is highest in the Olympic Steelhead MPG, but variation among sample sites is also much greater. Despite having the most urban floodplains, the South Central Cascades MPG did not have the lowest wood jam area. Rather, the Northern Cascades MPG 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 historic landscape practices. The lack of wood jam area in Northern Cascades MPG is likely a result of the high percentage of floodplains in agriculture and 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 the Northern Cascade MPG has the most tidal wetland habitat, with the Olympic MPG having the second most, and South Central Cascades having the least amount of tidal wetland habitat (Collins and Sheikh 2005). By contrast, our metrics show that the South Central Cascades MPG has more tidal channel area than the Olympic MPG (Table 16 and Figure 49) (but also that the Northern Cascade MPG 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 is larger in the Snohomish delta than in the Skagit delta (Table 16 and Figure 49). This difference may be due the fact that the Snohomish delta is a much longer and lower gradient delta, which allowed formation of multiple large distributaries in the lower river compared to Skagit delta.

4. Status of Habitat and Riparian Areas by Land Cover Class

Land cover status within floodplains by LCC was generally as expected for both the NLCD and NAIP data sets. For example, sites in the forest stratum had a higher proportion of forest in the NLCD and in the NAIP data sets, which is unsurprising (in fact nearly guaranteed) because forested sites by definition had more than 50% forest in the 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 urban sites, suggesting that there is greater tree retention in urban areas than in agricultural lands even.

Differences among land cover classes for both the aerial photography and field habitat metrics were also largely consistent with our expectations. For example, average forested buffer width along large rivers was highest in forest sites and lowest in urban sites, and variability was very high in all land cover classes because most sites contain a mix of narrow and wide buffer segments. Forested sites also had the highest average proportion of bar edge and natural bank edge (measured from aerial photography), while the urban land cover sites contained the most modified bank edge 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 forested land cover class and more disturbed habit edge area within the urban land cover class, 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.

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

While the braid node density and braid channel ratio were similar across land cover classes, the side-channel node density and side-channel length ratio were highest in forested and mixed land cover classes and lowest in urban and agriculture sites. We hypothesize that the restricted lateral channel movement by levees in the urban and agriculture 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. 2006), leading to much higher side-channel lengths and side-channel node densities in forested sites.

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

Finally, forested sites on average contained a much greater wood jam area than urban sites. Within forest sites, natural floodplain erosion allows for recruitment of wood, while locations with 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 urban sites and highest in agriculture sites, but the 95% confidence intervals encompassed the means for all land cover classes. The main reason for the difference between the aerial photograph 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 protocol does 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 retain it as a monitoring metric.

Most of the differences among land cover classes for the large river and floodplain habitat metrics are attributable to the degree of channel confinement by dikes and levees. River bank 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).

Channel confinement is a key factor that controls the rate of sediment exchange between the large river and floodplain, which ultimately creates the mosaic of aquatic and riparian habitats in floodplains (Beechie et al, 2006). Specifically, the processes of lateral migration, channel avulsion, meander cutoffs, and channel switching result in the creation and maintenance of floodplain channels and associated habitats (Beechie et al. 2006). 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 more transient features such as gravel bars where historically side channels were created and maintained (Beechie et al. 2001, 2006). Further, the artificial reduction in the floodplain to channel width ratio can lead to an overall reduction in key habitat features such as side channels, gravel bars, oxbows, and log jams (Chone & Brion 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 2011). Large wood (> 10 cm diameter and 1> m in length) creates pools (Bisson et al. 1987, Beechie and Sibley 1997, Montgomery et al. 1995), promotes sediment storage (Naiman and Sedell 1980), increases channel complexity (Abbe and Montgomery 1996), and provides vital habitats for fish and invertebrates by (Bisson et al. 1987). Habitat formed by LWD has large impacts on invertebrate production and diversity (Naiman et al. 2002, Pilotto et al. 2014), food availability and refuge and cover for salmonids, and habitat complexity (Naiman et al. 2002). The abundance of large wood is influenced by the adjoining riparian forest, channel type, and channel substrate (Gregory et al 1991). The distribution of LWD is dependent on channel size, because larger channels have greater capacity to promote large woody debris transport (Bilby and Ward 1989, Beechie and Sibley 1997, Beechie et al. 2000). LWD input is dependent upon several processes including live tree addition from bank erosion, tree mortality from stand development and succession, debris flow, wind-throw, and flooding (Gurnell et al. 2001).

In order to maintain the unique ecological characteristics of riparian corridors and habitat diversity, active natural disturbance through lateral channel movement and connectivity with floodplains is necessary (Naiman et al. 1993). Floodplain forest age diversity is linked to the floodplain turnover rate, which results in an impact on the distribution of biological diversity (Hauer and Lorang 2004, Beechie et al. 2006). Despite the knowledge on the importance of lateral channel connectivity, floodplains are often disconnected by channel confining features such as levees, road beds, or railroad grades. Channel floodplain disconnection can result in truncated meanders, lower channel sinuosity, reduced habitat complexity, decreased amount of large woody debris, reduced side channel habitat, and diminished riparian forest cover (Blanton and Marcus 2013).

Summary 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 lessons learned from our initial results, as well as other next steps we will take in the future. Future work on this monitoring program will first focus on a few key next steps, including (1) developing a floodplain reach map that accurately reflects geomorphic and land cover strata, (2) developing nearshore protocols, (3) revising existing protocols as needed, and (4) exploring the relationship of the habitat metrics to salmon population metrics. Additional next steps include examining sensitivity of metrics to land use with a retrospective aerial photograph analysis, developing ground-truthing protocols for aerial photograph metrics, and developing pilot studies with collaborators to fill in data gaps. In the following paragraphs we describe each of these steps in more detail.

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 were drawn in our GRTS design, and ultimately contributed to an unbalanced distribution of sample sites among strata. We also did not include MPGs as strata because we expected that the GRTS design would distribute sample sites relatively equally across MPGs. This also contributed to some MPGs (especially for Chinook) having too few sample sites and unbalanced distributions of sample sites among strata. However, it is also important to note that the unbalanced distribution of sample sites within MPGs was the result of natural features and land use patterns driving the distribution of sample sites among strata. 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. And in part because of the lack of large glacial and post-glacial floodplains, most of the landscape remains forested and there are very few sample sites in the agriculture and urban land cover classes. 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 class.

This result also influences our approach to the nearshore analysis, because we anticipate similar problems selecting sample sites in the nearshore if the shore types and land cover classes are not accurately assigned to segments. Therefore, we will establish nearshore polygons and assign land cover classes prior to selecting sample sites. We do not have the same issue with delta habitats because we are measuring habitats in all 16 major deltas.

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 photograph 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 photograph metrics, we developed protocols for the large river, nearshore and delta areas. Two remaining tasks are to resolve whether to use % impervious area or % developed area as a landcover metric, and re-evaluate the landcover class groupings we used in the analysis. We have also completed aerial photograph 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 also 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. It’s possible that acquisition or creation of reference feature layers along large river rivers would 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 completion of the analysis comparing the accuracy of C-CAP and NAIP data (we found little difference in accuracy between the two), updates to land classification 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 data set and use this to test percent forest and percent developed by LCC and Steelhead MPG’s. If accuracy does not improve with the revised data set, we will simply rely on C-CAP, which is a well-known program 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 additionally tidally influenced channel habitat. Furthermore, the current analysis did not consider habitat behind tide gates and converted dikes and levees. Developing regional layers of tide gate 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 use of higher resolution imagery and elevation data to determine flow paths. Development of plans to acquire high resolution imagery over the full spatial extent of the Puget Sound that can be acquired in a relatively short time period (e.g., within the same year) would provide a valuable data set 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 through implementation of field validations in targeted areas or consultation with individuals that 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, deriving mean channel widths and widths at channel bifurcations can 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 and by Chinook and steelhead major population group. A shoreline armoring protocol and GIS layer are currently under development by the Puget Sound Partnership, WDFW, DOE, 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 photograph 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 photograph metrics in the floodplain, large river, and delta habitats. We will initially focus on floodplain channels bank armoring and levees, wetlands in delta habitat, 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 determine how to scale up habitat status and trend data to estimate its influence on 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 class at the reach scale. We anticipate using correlation analyses to examine relationships between habitat data and fish data by MPG, by landcover class, and examine fish-habitat relationships across a gradient of land uses at the habitat and reach scale.

Develop pilot projects with local watershed groups: Identification of specific data gaps such as the quantity and quality of floodplain channels 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. We are currently in the process of developing proposals to implement several of our remote sensing and field protocol in coordination with local watershed groups. We would like to continue and 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 a change 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 of small independent watersheds and their contribution to steelhead abundance and productivity: This is a basic question that needs to be addressed not only from a status and trends perspective but 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 remoting 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 other 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 described 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 June 12, 2014 at which groups engaged in similar efforts were invited to share their "lessons learned" with us. 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 data sets 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 unbalanced designs. A balanced design is good for comparisons among strata, while an unbalanced design can focus data collection on more relevant areas. Trends can be evaluated with either design, but the statistical approaches vary.
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 land owner 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 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).

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

Panel member	Affiliation	Expertise
Diane Whited	Flathead Biological Station, University of Montana	Use of hierarchical sampling design to assess status of salmon habitat across the Pacific Rim using satellite data to field data
Kara Anlauf-Dunn, Kim Jones	Oregon Department of Fish and Wildlife	Developed and leads habitat status and trend monitoring in Coastal Oregon
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)
Bruce Crawford	Puget Sound Partnership	Performance Analyst

Expert panel meeting 2: Delta and nearshore metrics development

Before developing our delta and nearshore monitoring protocols we convened a meeting of experts in Seattle, Washington on July 7, 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 trend monitoring delta and nearshore metrics identification meeting in Seattle, Washington on July 7, 2014. Additional attendees were Tim Beechie, Kurt Fresh, George Pess, Mindy Rowse, Mindi Sheer, Alison Agnes (All of NOAA Fisheries), Leska Fore (Puget Sound Partnership), and Ken Currens (Northwest Indian Fisheries Commission).

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

Expert panel meeting 3: Large river and floodplain metrics development

Before developing our large river and floodplain monitoring protocols we convened a meeting of experts in Seattle, Washington on July 8, 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 five 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 Trend 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 earlier in this report and in Appendix C.

Table A-3. Expert panel members, affiliations, and expertise for the status and trend monitoring large river and floodplain metrics identification meeting in Seattle, Washington on July 7, 2014. Additional attendees were Tim Beechie, Kurt Fresh, George Pess, Mindy Rowse, Mindi Sheer, Alison Agnes (All of NOAA Fisheries), Leska Fore (Puget Sound Partnership), and Ken Currens (Northwest Indian Fisheries Commission).

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

Appendix B. GIS methods for creating strata

GIS Methods for Creating Large River/Floodplain Strata

We used the attributed hydrography layer from Davies et al. (2006) as our base hydrography data set. This layer includes the attributes channel slope and bankfull width, which we used in our reach delineation procedure. We first clipped the stream layer with a layer of valley bottom polygons used to identify multi-benefit 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 less than 50 km^2 were excluded from the hydrography data set.

We recalculated confinement ratios (valley width/bankfull width) for all reaches, and then classified reaches width ratios of ≥ 4.0 as unconfined and ratios of < 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 meter intervals and then clipped the transect lines using the high floodplain polygon derived from the National Elevation Dataset (NED) by Konrad (2015) (maximum transect length was 15 km). 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-yr 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 selection of reaches that would be much smaller than the length of habitat surveys we anticipate in the field effort (minimum 300 m). Reaches less than 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 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 C-CAP data set reclassified into forest, urban, and agriculture (Figure B-1). Classifications of land cover (forest, agriculture, urban or mixed) for each reach were assigned by averaging the proportions of each land cover class across all floodplain transects in each stream segment (totals will not equal 100%). As described in the main report (Table 2), forested sites are >50% forest, developed sites are >50% developed, agriculture sites are >50% agriculture, and mixed sites are <50% of all classes. 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 the Puget Sound. On the inside of meander bends the coverage of some land cover classes was overestimated where multiple transects cross the same land cover cells. By contrast, coverage was underestimated along the outside of meander bends where lines diverge from each other. Therefore, after sample sites were selected and floodplain polygons delineated, the land cover class for each polygon was corrected (Figure B-1b).

To correct the land cover classification 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, urban, or agriculture 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 (Table B-1 and Table B-2). That is, accuracy of the land cover classification 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 photograph sites misclassified. Hence, the most common corrections were reassignment of mixed sites to agriculture, urban or forest, or reassignment of urban or forest sites to mixed. In subsequent years we will alleviate this problem by delineating all floodplain polygons in Puget Sound prior to assigning land cover classes (i.e., we will no longer use the transect method to assign land cover classes).

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

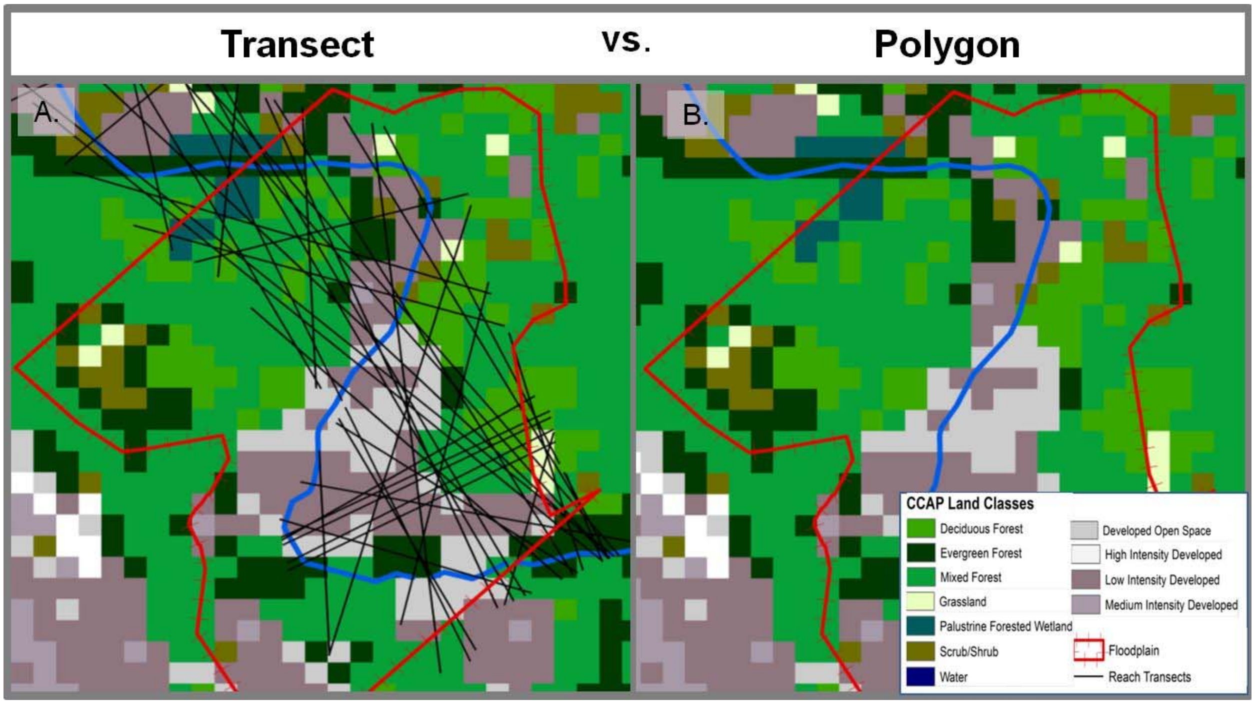

Table B-1. Error matrix of C-CAP 2011 land cover classification at the 21 field sites using original classification method of transects vs. floodplain polygons. Overall land classification accuracy was 67%.

Polygon

Transect	Mixed	Agriculture	Urban	Forest	total	% polygon acc	% comission
Mixed	2			1	3	67%	33%
Agriculture	1	6			7	86%	14%
Urban	3		2	1	6	33%	67%
Forest		1		4	5	80%	20%
total	6	7	2	6	21		
% transect acc	33%	86%	100%	67%		67%	
% omission	67%	14%	0%	33%			

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%.

Transect \ Polygon	Mixed	Agriculture	Urban	Forest	total	% polygon acc	% commission
Mixed	15	5	7	3	30	50%	50%
Agriculture	2	21		5	28	75%	25%
Urban	6	1	16	3	26	62%	38%
Forest	5	4		31	40	78%	23%
total	28	31	23	42	124		
% transect acc	54%	68%	70%	74%		67%	
% omission	46%	32%	30%	26%			

GIS methods for creating delta strata

Each delta was manually assigned a geomorphic type based on Shipman (2008) because there are only 16 major deltas in the Puget Sound. Most of the deltas are river dominated. Only the Dosewallips, Duckabush, Big Quilcene, and Hamma Hamma 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 PSNERP delta polygons and C-CAP 2011 land cover data (Landsat) grouped into forest, agriculture, and urban 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, Steelhead MPG, and Chinook MPG.

Classification accuracy of the original landcover data

Overall classification accuracy of the land cover types was 82% across 23 land cover classes (Washington Department of Ecology, unpublished report, http://www.ecy.wa.gov/programs/sea/wetlands/pdf/C-CAPWetlandAssessmentReport.pdf). After aggregating the 23 classes into 5 simpler strata, classification accuracy was 94% (Table B-3). This error is embedded within the stratification and cannot be corrected.

Table B-3. Cross-validation table of classification accuracy for regrouped C-CAP land cover classes (modified from DOE unpublished report). Overall classification accuracy of the grouped data is 94%.

	Photo-interpreted point classification						
C-CAP classification		Urban	Agric.	Forest/ wetland	Water	Other	Accuracy
	Urban	85	4	13	1		83%
	Agriculture		100	7			93%
	Forest/wetland	3	9	493	10	3	95%
	Water				61		100%
	Other					6	100%
	Accuracy	97%	88%	96%	85%	67%	94%

Appendix C: Details of monitoring metric selection

A suite of potential metrics for each habitat area was identified by a small group of experts in river-floodplain assessment and monitoring or estuary/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 ecosystem 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 three levels of data resolution described previously in the hierarchical sampling approach (satellite, aerial photography/LIDAR, and field). We then evaluated each of the metrics using a method similar to that used in the California Current Integrated Ecosystem Assessment (Greene et al. 2014) (see Selection of Monitoring Metrics section for complete list), and scored each criterion with a value of 0 (no, criterion not met), 0.5 (moderate or context dependent), or 1 (yes, criterion met) (Tables C-1, C-3, C-5, C-7). Once we completed scoring, we selected metrics that scored 4.5 or higher for our monitoring program. We chose the arbitrary threshold value of 4.5 to give us reasonable small number of metrics (i.e., a small set of metrics that we could monitor with our limited budget), yet still encompass a comprehensive suite of habitat attributes. We also provided citations to support each score where possible (Tables C-2, C-4, C-6, C-8). Citations were generally available for the first three criteria, but only sometimes available for the last two.

Scale/resolution	Type	Metric	Link to salmon VSP?	Sensitive to land use?	Link across scales?	Cost-effective ?	Signal/ noise ratio	Total	Comments
Satellite	Pressure/process	**Percent natural, agriculture, and developed landcover**	1	1	1	1	0.5	4.5	
	Habitat quantity	Stream type at 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	
Aerial/LIDAR	Pressure/process	**Riparian buffer width**	1	1	1	1	1	5	
	Pressure/process	Percent of mainstem disconnected from floodplain	1	1	1	0.5	0.5	4	
	Pressure/process	Levee length	1	1	1	0.5	0.5	4	
	Pressure/process	Bank armoring	1	1	1	0.5	0.5	4	
	Pressure/process	Channel migration rate	1	1	1	1	0	4	
	Habitat quantity	Channel or water surface area	1	0.5	1	1	0.5	4	
	Habitat quantity	Hydrology (monthly mean and peak flows, ect)	1	1	0.5	1	0.5	4	
	Habitat quantity	Pool spacing	1	1	1	1	0	4	Couldn't identify pools in AI
	Habitat quantity	**Edge habitat length by type**	1	1	1	1	0	4	Trials indicated low S/N ratio
	Habitat quantity	Passable river miles	1	1	0.5	0	0.5	3	
	Habitat quality	**Sinuosity (Lc/Lv)**	1	1	0.5	1	1	4.5	
	Habitat quality	**Wood Jam Area**	1	1	1	1	0.5	4.5	
	Habitat quality	Riparian forest providing direct shade	0.5	1	1	1	0.5	4	covered by buffer width and type
Field	Pressure/process	**Length of human modified bank**	1	1	1	0.5	1	4.5	
	Pressure/process	Contaminants	1	1	0.5	0.5	0.5	3.5	
	Pressure/process	Entrenchment ratio	0.5	0.5	1	1	0.5	3.5	Should this be a tributary method?
	Pressure/process	**Riparian buffer width and type**	1	1	1	1	1	5	
	Pressure/process	Percent of mainstem disconnected from floodplain	1	1	1	0	0.5	3.5	
	Habitat quantity	Levee length	1	1	0.5	0.5	1	4	
	Habitat quantity	**Wood abundance**	1	1	1	1	0.5	4.5	
	Habitat quantity	**Edge habitat area by type**	1	1	1	1	0.5	4.5	Skagit or Elwha method
	Habitat quantity	Hydraulic complexity	1	0.5	1	0	0	2.5	tracer dye method
	Habitat quantity	Pool spacing	1	1	0.5	1	0.5	4	
	Habitat quantity	CV of thalweg depth	1	1	1	0	0.5	3.5	
	Habitat quantity	Hydrology (monthly mean and peak flows, ect)	1	1	0.5	1	0.5	4	
	Habitat quality	B-IBI	1	1	1	0.5	0.5	4	
	Habitat quality	Invertebrate drift	1	1	1	0.5	0.5	4	
	Habitat quality	Temperature	1	1	1	0.5	0	3.5	
	Habitat quality	DO	1	1	1	0.5	0	3.5	
	Habitat quality	Nutrients	1	1	1	0.5	0	3.5	
	Habitat quality	Turbidity	1	1	1	0.5	0.5	4	
	Habitat quality	Conductivity	1	1	0.5	1	0.5	4	

Table C-1. Score sheet for large river metrics.

Scale/resolution	Metric	Link to salmon VSP?	Sensitive to land use?	Link across scales?	Cost-effective?	Signal/ noise ratio
Satellite	**Percent natural, agriculture, and developed landcover**	Land use indicator is sound, Booth 1990; Booth and Jackson 1997; Booth and Reinelt 1993; Feist et al. 2011; Scholz et al. 2011; Spromberg & Scholz 2011;	Booth and Reinelt 1993; Booth et al. 2002	Booth and Reinelt 1993		
	Stream type at 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	
Aerial/LIDAR	**Riparian buffer width**	Bilby and Ward 1989; Bisson et al 1988; Hyatt et al. 2004	Beechie et al. 2003; Fullerton et al. 2006	Beechie et al. 2003; Fullerton et al. 2006	Fullerton et al. 2006; Hyatt et al. 2004	Fullerton et al. 2006; Kauffmann et al. 1999 (proportion of riparian across streams S/N = 0-37, Av. 4.6)
	Percent of large river disconnected from floodplain	Jeffres et al. 2008; Golden and Houston 2010	Beechie et al. 1994; Jeffres et al. 2008; Hohensinner et al. 2004	Jeffres et al. 2008	Moderate. Requires repeat LIDAR	
	Levee length	Beamer et al. 2005 App. D; Beechie et al. 1994	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)
	Chanel or water surface area	Bisson et al. 1988	Bisson et al. 1988	Whited et al. 2013	Whited et al. 2013	
	Hydrology (monthly mean and peak flows, ect)	Bisson et al. 1988; Connor and Pflug 2004; Golden and Houston 2010	Connor and Pflug 2004	Hall et al. in press	yes, at USGS gages	Depends on location, but not well known.
	Pool spacing	Beechie and Sibly 1997	Beechie and Sibly 1997; Collins et al. 2002b; Montgomery et al. 1995	Beechie and Sibly 1997		Kauffmann et al. 1999; Montgomery et al. 1995 (S/N across streams = 8.2 (RPGT75)
	Edge hatitat area by type	Whited et al. 2013	Whited et al. 2013	Whited et al. 2013	Whited et al. 2013	
	Passable river miles	Golden and Houston 2010	Steele et al. 2004		for large dams (but not culverts)	for large dams (but not culverts)
	Sinuosity (Lc/Lv)	Beechie and Imaki 2014; Beechie et al. 2014	Collins et al. 2002b; Doering et al 2012	Arscott et al. 2002	Beechie and Imaki 2014; Beechie et al. 2014	Friend and Sinha 1993; Kauffmann et al. 1999 (S/N across streams =1.1)
	Wood Jam Area	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; Montgomery et al. 1995	Abbe and Montgomery 1996, 2003; Naiman et al. 2002a	Beechie and Sibly 1997; Montgomery et al. 1999	Beechie and Sibly 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	

Field	**Length of human modified bank**	Beamer and Henderson 1998	yes	Spatial - yes, temporal - no	Where data are available, but not over wide areas	yes
	Contaminants	Fiest et al. 2011; Spromberg and Scholz 2011	Booth and Reinelt 1993; Fiest et al. 2011; Spromberg and Scholz 2011	Booth and Reinelt 1993; Fiest et al. 2011; Jones et al. 2015; Spromberg and Scholz 2011		Booth and Reinelt 1993
	Entrenchment ratio		Beechie 2006			Rosgen 1994
	Riparian buffer width and type	Bilby and Ward 1989; Bisson et al 1988; Hyatt et al. 2004	Beechie et al. 2003; Fullerton et al. 2006	Beechie et al. 2003; Fullerton et al. 2006	Fullerton et al. 2006; Hyatt et al. 2004	Fullerton et al. 2006; Kauffmann et al. 1999 (proportion of riparian across streams S/N = 0-37, Av. 4.6)
	Percent of mainstem disconnected from floodplain	Jeffres et al. 2008	Beechie et al. 1994; Jeffres et al. 2008; Hohensinner et al. 2004	Jeffres et al. 2008		
	Levee length	Beamer et al. 2005; Beechie et al. 1994	yes	Spatial - yes, temporal - no	Where data are available, but not over wide areas	yes
	Wood abundance	Beechie and Sibley 1997; Montgomery et al. 1995 (via pool creation)	Beechie and Sibly 1997; Montgomery et al. 1995	Naiman et al. 2002a	Beechie and Sibly 1997; Montgomery et al. 1999	Beechie and Sibly 1997; Kauffmann et al. 1999 (S/N (across streams) = 7.0)
	Edge habitat area by type	Beamer and Henderson 1998; Beechie et al. 2005; Bisson et al. 1988; Latterell et a. 2006; Murphy et al. 1989	Beamer and Henderson 1998; Bisson et al. 1988; Murphy et al. 1989	Bisson et al. 1988; Murphy et al. 1989; Whited et al. 2013		varries with discharge
	Hydraulic complexity	Bisson et al. 1988; Jeffres et al. 2008	Woessner 2000	Woessner 2000		
	Pool spacing	Beechie and Sibly 1997	Beechie and Sibly 1997; Collins et al. 2002b; Montgomery et al. 1995	Beechie and Sibly 1997		Kauffmann et al. 1999; Montgomery et al. 1995 (S/N across streams = 8.2 (RPGT75)
	CV 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 and peak flows, ect)	Bisson et al. 1988; Connor and Pflug 2004; Golden and Houston 2010	Connor and Pflug 2004	Hall et al. in press	yes, at USGS gages	Depends on location, but not well known.
	B-IBI	Yes. Morely and Karr 2002	Yes. Karr 1991, 2006; Morley and Karr 2002	Morley and Karr 2002	Karr 1981	Moderate
	Invertebrate drift sample	OPSW 1999	Herringshaw et al. 2011	Herringshaw et al. 2011		
	Temperature	Temporally: Bjornn et al. 1991; Brett 1971; Caissie 2006; McCullough et al. 1999, 2009; Poole and Berman 2001; Ward 1985; Webb et al. 2008 Spatially: Caissie 2006; Mayer 2012; McCullough et al. 2012; OPSW 1999; Tan and Cherkauer 2013; Torgersen et al. 1999; Van der Kraak and Pankhurst 1997; Webb et al. 2008	Arismendi et al. 2012, 2013a,b; Arrigoni et al. 2008; Farrell et al. 2008 (aerobic scope of migrations); Isaak et al. 2010, 2012 (climate change; wildfire); Torgersen et al. 1999;	Torgersen et al. 1999	Temporally: yes, Spatially: empirical data expensive; models (ie from NorWeST) inexpensive	Torgersen et al. 1999; Van der Kraak an Pankhurst 1997
	DO	OPSW 1999	Inkpen and Embrey 1998	Inkpen and Embrey 1998; OPSW 1999		
	Nutrients	Naiman et al. 2002b; OPSW 1999	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		

Table C-2. Reference sheet for large river metrics

Scale/resolution	Type	Metric	Link to salmon VSP?	Sensitive to land use?	Link across scales?	Cost-effective?	Signal/noise ratio	Total	Comments
Satellite	Pressure/process, Habitat quality	**Percent natural, agriculture, and developed landcover**	1	1	1	1	0.5	4.5	
	Habitat quantity	Fragmentation	0	1	0.5	1	1	3.5	overlay road, levee, railroad over floodplains, size of fragments
	Habitat quantity	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	
Aerial/LIDAR	Pressure/process	**Percent of floodplain disconnected**	1	1	1	1	1	5	
	Pressure/process	Length of human modified bank	1	1	1	0.5	0.5	4	Inlcude type of modification (levee, revetment, rip-
	Pressure/process	Turnover rate of floodplain surfaces, half-life of floodplain surfaces	0	1	1	1	0.5	3.5	This is related to floodplain channel length and area, but hard to link to fish in a clear mechanistic way.
	Habitat quantity	**Length of side channel**	1	1	1	1	1	5	
	Habitat quantity	Area of side channel	1	1	1	1	0	4	Rated low on S/N because much of the habitat is under canopy
	Habitat quantity	**Area of connected floodplain**	1	1	1	0.5	1	4.5	
	Habitat quantity	Area of ponded habitat from quickbird	1	1	1	1	0	4	Rated low on S/N because much of the habitat is under canopy
	Habitat quantity	Percent of side channel disconnected by levees	1	1	1	0.5	0	3.5	In urban areas we can't identify disconnected
	Habitat quality	**Braid-channel ratio (Lbc/Lmain)**	1	1	1	1	0.5	4.5	
	Habitat quality	**Side-channel ratio (Lsc/Lmain)**	1	1	1	1	0.5	4.5	
	Habitat quality	**Braided channel node density**	1	1	1	1	1	5	
	Habitat quality	**Side channel node density**	1	1	1	1	1	5	# nodes per length of channel
Field	Pressure/process	**Riparian species composition and buffer width**	1	1	1	1	1	5	
	Pressure/process	**Length of human modified bank**	1	1	1	1	1	5	Include type of modification (levee, revetment, rip-
	Pressure/process	Contaminants (need specific metrics)	1	1	0.5	0	0.5	3	
	Habitat quantity	**Pool frequency or spacing**	1	1	1	1	0.5	4.5	
	Habitat quantity	Percent pool area	1	1	0.5	1	0.5	4	
	Habitat quality	**Residual pool depth (d_{max}/d_{tai}l)**	1	1	1	1	0.5	4.5	
	Habitat quantity	**Wood abundance**	1	1	1	1	0.5	4.5	
	Habitat quantity	**Area of side shannel**	1	1	1	1	1	5	
	Habitat quality	B-IBI	1	1	1	0.5	0.5	4	
	Habitat quality	Invertebrate drift	1	1	1	0.5	0.5	4	
	Habitat quality	Temperature	1	1	1	0.5	0	3.5	Continuous, variability is high.
	Habitat quality	DO	1	1	1	0.5	0	3.5	
	Habitat quality	Nutrients	1	1	1	0.5	0	3.5	
	Habitat quality	Conductivity	1	1	0.5	1	0.5	4	

Table C-3. Score sheet for floodplain metrics.

Scale/resolution	Metric	Link to salmon VSP?	Sensitive to land use?	Link across scales?	Cost-effective?	Signal/ noise ratio
Satellite	**Percent natural, agriculture, and developed landcover**	Konrad et al. 2008; Sommer et al. 2005	Collins et al. 2002b; Booth and Reinelt 1993	Konrad et al. 2008; Booth and Reinelt 1993	Konrad et al. 2008	WDOE unpublished; Wickam et al. 2013
	Fragmentation		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	
Aerial/LIDAR	**Percent of floodplain disconnected**	Jeffres et al. 2008	Beechie et al. 1994; Hohensinner et al. 2004; Whited et al. 2012, 2013	Hall et al. 2007; Whited et al. 2013	Whited et al. 2012, 2013	Whited et al. 2013
	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, half-life of floodplain surfaces	Latterell et al. 2006; Beechie et al. 2006 (diverse biotic assemb.)		Beechie et al. 2006; Latterell et al. 2006	Latterell et al. 2006	variable
	Length of side channel	Beechie et al. 1994; Whited et al. 2013	Beechie et al. 1994; Hohensinner et al. 2004; Whited et al. 2012, 2013	Hall et al. 2007; Whited et al. 2013	Whited et al. 2013; 2012	Whited et al. 2013
	Area of side channel	Beechie et al. 1994; Whited et al. 2013	Beechie et al. 1994; Hohensinner et al. 2004; Whited et al. 2012, 2013	Hall et al. 2007; Whited et al. 2013	Whited et al. 2012, 2013	Whited et al. 2013; forest canopy will reduce accuracy
	Area of connected floodplain	Jeffres et al 2008	Beechie et al. 1994; Hohensinner et al. 2004; Whited et al. 2012, 2013	Hall et al. 2007; Whited et al. 2013	Whited et al. 2012, 2013; Konrad (in press(	Whited et al. 2013; Konrad (in press)
	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. 2012, 2013	Whited et al. 2012, 2013; Malison et al. 2014	Whited et al. 2013; Forest canopy issues in PS?
	Percent of side channel disconnected by levees	Beechie et al. 1994; Whited et al. 2013	Beechie et al. 1994; Whited et al. 2012, 2013	Hall et al. 2007; Whited et al. 2013	Whited et al. 2012, 2013	Whited et al. 2013
	Braid-channel ratio (Lbc/Lmain)	Beechie and Imaki 2014; Beechie et al. 2014	Collins et al. 2002b; Doering et al 2012	Arscott et al. 2002	Beechie et al. 2006	
	Side-channel ratio (Lsc/Lmain)	Beechie and Imaki 2014; Beechie et al. 2014	Collins et al. 2002b; Doering et al 2012	Arscott et al. 2002	Beechie et al. 2006	
	Braided channel node density	Luck et al. 2010; Whited et al. 2013	Whited et al. 2012, 2013	Benda et al. 2004	Whited et al. 2012, 2013	Whited et al. 2013
	Side channel node density	Luck et al. 2010; Whited et al. 2013	Whited et al. 2012, 2013	Benda et al. 2004	Whited et al. 2012, 2013	Whited et al. 2013

Field	**Riparian species composition and buffer width**	Hyatt et al. 2004; Bilby and Ward 1989; Bisson et al 1988	Beechie et al. 2003; Fullerton et al. 2006	Beechie et al. 2003; Fullerton et al. 2006	Fullerton et al. 2006; Hyatt et al. 2004	Fullerton et al. 2006; Kauffmann et al. 1999 (proportion of riparian across streams S/N = 0-37, Av. 4.6)
	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 (need specific metrics)	Fiest et al. 2011; Spromberg and Scholz 2011	Booth and Reinelt 1993; Fiest et al. 2011; Inkpen and Embrey 1998; Spromberg and Scholz 2011	Booth and Reinelt 1993; Fiest et al. 2011; Inkpen and Embrey 1998; Jones et al. 2015; Spromberg and Scholz 2011		Booth and Reinelt 1993
	Pool frequency or spacing	Beechie and Sibly 1997; Montgomery et al. 1999	Montgomery et al. 1995; Collins et al. 2002b; Beechie and Sibly 1997	Beechie and Sibly 1997	Beechie and Sibly 1997; Montgomery et al. 1999	Montgomery et al. 1995; Kauffmann et al. 1999 (S/N across streams = 8.2 (RPGT75)
	Percent pool area	Beechie and Sibly 1997	Montgomery et al. 1995; Collins et al. 2002b; Beechie and Sibly 1997	Beechie and Sibly 1997	Beechie and Sibly 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 (RP100))
	Wood abundance	Montgomery et al. 1995 (via pool creation); Beechie and Sibley 1997	Montgomery et al. 1995; Beechie and Sibly 1997	Naiman et al. 2002a	Beechie and Sibly 1997; Montgomery et al. 1999	Beechie and Sibly 1997; Kauffmann et al. 1999 (S/N (across streams) = 7.0)
	Area of Side Channel	Beechie et al. 1994; Whited et al. 2013	Beechie et al. 1994; Hohensinner et al. 2004; Whited et al. 2012, 2013	Hall et al. 2007; Whited et al. 2013	Whited et al. 2012, 2013	Whited et al. 2013
	B-IBI	Yes. Morely and Karr 2002	Yes. Karr 1991, 2006; Morley and Karr 2002	Morley and Karr 2002		Moderate
	Invertebrate drift	OPSW 1999	Herringshaw et al. 2011	Herringshaw et al. 2011	Karr 1981	
	Temperature	Temporally: Brett 1971; Bjornn et al. 1991; Ward 1985; Poole and Berman 2001; McCullough et al. 1999, 2009; Caissie 2006; Webb et al. 2008 Spatially: Torgersen et al. 1999; Van der Kraak and Pankhurst 1997; Webb et al. 2008; McCullough et al. 2009a; Caissie 2006; Mayer 2012; Tan and Cherkauer 2013; OPSW 1999	Arrigoni et al. 2008; Torgersen et al. 1999; Arismendi et al. 2012, 2013a,b; Isaak et al. 2010, 2012 (climate change; wildfire); Farrell et al. 2008 (aerobic scope of migrations)	Torgersen et al. 1999	Temporally: yes, Spatially: empirical data expensive; models (ie from NorWeST) inexpensive	Torgersen et al. 1999, Van der Kraak an Pankhurst 1997, Wootton 1990
	DO	OPSW 1999	Inkpen and Embrey 1998	OPSW 1999; Inkpen and Embrey 1998		
	Nutrients	Naiman et al. 2002b; OPSW 1999	Inkpen and Embrey 1998	Inkpen and Embrey 1998		
	Conductivity	OPSW 1999	Gardi 2001	OPSW 1999		

Table C-4. Reference sheet for Floodplain metrics.

Scale/resolution	Type	Metric	Link to salmon VSP?	Sensitive to land use?	Link across scales?	Cost-effective?	Signal/ noise ratio	Total	Comments
Satellite	Pressure/process	**Percent natural, agriculture, and developed landcover**	1	1	1	1	1	5	
	Pressure/process	Length of Tidal barriers/levees	1	1	1	1	0	4	
	Habitat quantity	Estuary surface area/drainage area	1	0	1	1	1	4	
	Habitat quantity	**Wetland area**	1	1	1	1	0.5	4.5	
	Habitat quantity	Elevation (sediment accretion)	1	1	0.5	0.5	0.5	3.5	
Aerial/LIDAR	Pressure/process	**Proportion of delta behind levees (connectivity)**	1	1	1	1	0.5	4.5	
	Pressure/process	**Length of levees and dikes along distributaries**	1	1	1	1	0.5	4.5	
	Habitat quantity	**Tidal channel area**	1	1	1	1	0.5	4.5	tidal channel feature area, length, and perimeter
	Habitat quantity	Tidally influenced area	1	1	1	0	0.5	3.5	
	Habitat quantity, habitat quality	**Node density**	1	1	1	1	0.5	4.5	
	Habitat quantity, habitat quality	**Wetland area by type**	1	1	1	1	0.5	4.5	Beamer et al 2005 App D. IEA: Areal wetland coverage is an important measure of habitat quantity for all species that are resident in estuaries. Can be measured using remote sensing, but extent of FW tidal zones need groundtruthing.
	Habitat quality	Infrared intensity	0.5	1	1	1	0.5	4	
	Habiat quality	Aerial extent of salinity zones	1	1	1	0.5	0	3.5	
Field	Pressure/process	**Length of armoring, location of barriers, and culverts**	1	1	1	1	0.5	4.5	
	Pressure/process	Contaminants	1	1	0.5	0	0.5	3	
	Pressure/process	Nutrients	1	1	0.5	0	0.5	3	
	Pressure/process	Bay fringe erosion rate	0.5	1	0	0	0.5	2	
	Pressure/process	Sediment accretion rate	0.5	1	0.5	0	0.5	2.5	
	Habitat quality	Plant species diversity and composition	0.5	1	1	1	0.5	4	
	Habitat quality	Proportion non native species	0.5	1	1	1	0.5	4	
	Habitat quality	Wetland type	1	1	1	0.5	0.5	4	
	Habitat quality	Temperature	1	1	1	0.5	0.5	4	
	Habitat quality	DO	1	0.5	0.5	0.5	0.5	3	
	Habitat quality	Extent of salinity zones. (CTD profile)	1	1	1	0.5	0.5	4	

Table C-5. Score sheet for Delta metrics.

Scale/ resolution	Metric	Link to salmon VSP?	Sensitive to land use?	Link across scales?	Cost-effective?	Signal/ noise ratio
Satellite	**Percent natural, agriculture, and developed landcover**		Hood 2004; Pierce 2011; Robert Kennedy et al. 2010; Vanderhoof 2011	Hood 2004; Pierce 2011; Robert Kennedy et al. 2010; Vanderhoof 2011		
	Length of Tidal barriers/levees	Greene et al. 2012; Fresh et al. 2011; Morley et al. 2012; Toft et al. 2007	Greene et al. 2012; Toft et al. 2007	Fresh et al. 2011; Greene et al. 2012	Fresh et al. 2011; Greene et al. 2012	Fresh et al. 2012
	Estuary surface area/drainage area	Bottom and Jones 1990; Engle et al. 2007; Lee and Brown 2009; Visintainer 2006	Bottom and Jones 1990; Engle et al. 2007; Lee and Brown 2009; Engel et al. 2007; Lee and Brown 2009; Hood 2007	Bottom and Jones 1990; Edmonds and Slingerland 2011; Lee and Brown 2009	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			
Aerial/LIDAR	**Proportion of delta behind levees (connectivity)**	Bottom et al. 2005; Greene et al. 2012; Haas and Collins 2001; Magnusson and Hilborn 2003	Collins et al 2003; Greene et al. 2012; Haas and Collins 2001	Collins et al 2003; Greene et al. 2012;	Greene et al. 2012;	
	Length of levees and dikes along distributaries	Fresh et al. 2011; Greene et al. 2012; Morley et al. 2012; PS RITT InPress; Quinn 2005; Toft et al. 2007; Woodson et al. 2013	Collins et al. 2003; Greene et al. 2012; Toft et al. 2007; Haas and Collins 2001	Fresh et al. 2011; Greene et al. 2012	Fresh et al. 2011; Greene et al. 2012	Fresh et al. 2012
	Tidal channel area	Hood 2015; Howe and Simenstad 2014; Simenstad and Cordell 2000	Coleman 1988; Edmonds and Slingerland 2007; Hood 2007a; Makaske 2001; Pasternack et al. 2001; Slingerland and Smith 2004; Stouthamer and Berendsen 2007; Syvitski et al. 2005; 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	French and Spencer 1993; French and Stoddart 1992; Odum 1984; Pethick 1992; Rozas et al. 1988; Simenstad 1983			
	Node density	Beamish et al. 2013; Krentz 2007; Luck et al. 2010; Simenstad et al. 2011; Visintainer et al. 2006; Whited et al. 2011	Beamish et al. 2013; Krentz 2007; Luck et al. 2010; Simenstad et al. 2011; Visintainer et al. 2006; Whited et al. 2011	yes, using imagery	Luck et al. 2010; Whited et al. 2011; Visintainer 2006; Historical mapping for many areas	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	Barbier et al. 2011; Beamer et al. 2013; Bottom et al. 2005; Gray et al. 2002; Greene and Beamer 2012; Good 2000; Hood 2007a; Jones et al. (In Press); Lunettaet al. 1997; Magnusson and Hilborn 2003; Maier and Simenstad 2009; Van dyke and Wasson 2005	Barbier et al. 2011; Beamer et al. 2013; Bottom et al. 2005; Greene and Beamer 2012; Good 2000; Hood 2007a; Jones et al. (In Press); Magnusson and Hilborn 2003; Maier and Simenstad 2009; Sanderson et al. 2000; Stralberg et al. 2011; Van Dyke and Wasson 2005	Collins and Sheik 2005; Marcoe and Pilson 2013; National Wetlands Inventory (http://www.fws.gov/wetlands/Data/); Simenstad et al. 2011	Borde et al. 2003; Collins and Sheik 2005; Good 2000; Marcoe and Pilson 2013; Thomas 1983; Van Dyke and Wasson 2005	Spatial variations well captured by remote sensing and GIS mapping; high signal to noise ratio 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	Cloern and Jassby 2013 ; Jay and Naik 2011	Cowardin et al. 1979; Emmett et al. 1991; Monaco et al. 1990	Yes. NOAA GIS coverage for Atl., Gulf, and Pacific coasts; Moore et al. 2008a,b	Cloern and Jassby 2012; Moore et al. 2008a,b

Field	**Length of armoring, location of barriers, and culverts**	Greene et al. 2012; Fresh et al. 2011; Morley et al. 2012; Quinn 2005; PS RITT InPress; Toft et al. 2007; Woodson et al. 2013	Collins et al 2003, Greene et al. 2012; Haas and Collins 2001; Toft et al. 2007	Greene et al. 2012; Fresh et al. 2011	Greene et al. 2012; Fresh et al. 2011	
	Contaminants	Arkoosh et al. 1998; Stein et al. 1995	Arkoosh et al. 1998; Hayslip et al. 2006; Stein et al. 1995	Arkoosh et al. 1998; Stein et al. 1995	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	
	Plant species diversity and composition	Good 2000	Kentula et al. 2011; Mack and Kentula 2010	Kentula et al. 2011; Mack and Kentula 2010	Kentula et al. 2011; Mack and Kentula 2010	
	Proportion non native species	Good 2000	Karr and Chu 1999; Mack and Kentula 2010	Kentula et al. 2011; Mack and Kentula 2010	Kentula et al. 2011; Mack and Kentula 2010	
	Wetland type diversity	Lott 2004	Karr and Chu 1999; Mack and Kentula 2010	Kentula et al. 2011; Mack and Kentula 2010	Mack and Kentula 2010; Kentula et al. 2011	
	Temperature	Baker 1995, Good 2000	Bilkovic et al. 2006; Hayslip et al. 2006; Howarth et al. 1991	Bilkovic et al. 2006; Hayslip et al. 2006		
	DO	Good 2000	Bilkovic et al. 2006; Hayslip et al. 2006; Howarth et al. 1991	Bilkovic et al. 2006; Hayslip et al. 2006		
	Areal extent of salinity zones (CTD profile)	Iwata and Komatsu 1984; Morgan and Iwama 1991; Good 2000	Bilkovic et al. 2006; Hayslip et al. 2006; Howarth et al. 1991	Bilkovic et al. 2006; Hayslip et al. 2006		

Table C-6. Reference sheet for Delta metrics.

Scale/resolution	Type	Metric	Link to salmon VSP?	Sensitive to land use?	Link across scales ?	Cost-effective?	Signal/ noise ratio	Total	Comments
Satellite	Pressure/process	**Percent natural, agriculture, and developed landcover**	1	1	1	1	0.5	4.5	
Aerial/LIDAR	Pressure/process	**Shoreline armoring**	1	1	1	1	0.5	4.5	
	Pressure/process	**Percent developed surface and percent forest in 200m shoreline buffer**	1	1	1	1	0.5	4.5	Rate of forest clearing, NAIP
	Pressure/process	**Area of overwater stuctures**	1	1	0.5	1	1	4.5	
	Habitat quantity	Length of unarmored feeder bluffs	0.5	1	0.5	1	0.5	3.5	
	Habitat quantity	**Area of kelp**	1	1	1	1	0.5	4.5	
	Habitat quantity	**Area of eelgrass**	1	1	1	1	0.5	4.5	should also consider density
	Habitat quantity	**Embayment Area (total, wetland, veg)**	1	1	1	1	0.5	4.5	
	Habitat quantity	Beach width	0.5	1	1	1	0.5	4	
	Habitat quality	**Connectivity of embayment to nearshore (width of embayment opening)**	1	1	1	1	0.5	4.5	
	Habitat quality	**Length of forested shoreline**	1	1	1	1	1	5	
Field	Pressure/process	**Shoreline armoring**	1	1	1	1	0.5	4.5	
	Pressure/process	**Location of culverts & tide gates blocking access**	1	1	1	1	0.5	4.5	
	Pressure/process	Contaminants	1	1	1	0	0.5	3.5	Sandie O'neill
	Pressure/process	Nutrients	0.5	1	1	0	0.5	3	
	Habitat quantity	Elevation of bulkhead toe	1	1	0.5	0.5	0.5	3.5	
	Habitat quantity	Small stream and pocket estuary connectivity	1	1	0.5	1	0.5	4	
	Habitat quality	Beach composition (shells)	0	0	0	0	0.5	0.5	
	Habitat quality	Epibenthic taxa richness	1	1	0.5	0	0.5	3	
	Habitat quality	Grain size	0.5	0.5	0.5	0.5	0.5	2.5	
	Habitat quality	Area of wood and rack	1	1	1	0.5	0.5	4	
	Habitat quality	Temperature	1	1	1	0.5	0.5	4	microclimate and water
	Habitat quality	DO	1	1	1	0.5	0.5	4	
	Habitat quality	Turbidity	1	1	1	0.5	0.5	4	
	Habitat quality	Condition of pocket estuaries and small stream mouth/estuary	1	1	1	0.5	0.5	4	

Table C-7. Score sheet for Nearshore metrics.

Scale/resolution	Metric	Link to salmon VSP?	Sensitive to land use?	Link across scales?	Cost-effective?	Signal/ noise ratio
Satellite	Percent natural, agriculture, and developed landcover		Kennedy et al. 2010; Hood 2004; Pierce 2011; Vanderhoof 2011;	Kennedy et al. 2010; Hood 2004; Pierce 2011; Vanderhoof 2011;		
Aerial/LIDAR	Shoreline armoring	Heerhartz et al. 2014; Morely et al. 2012; Toft et al. 2011;	Fresh et al 2012; Greene et al. 2012; Heerhartz et al. 2014; Morely et al. 2012; Toft et al. 2011;	Fresh et al. 2012; Greene et al. 2012	Greene et al. 2012	
	Percent Impervious surface and percent forest coverage in 200m buffer		Arnold and Gibbons 1996; Brennan et al. 2009; Booth 1991; Matzen and Berge 2008; May 1996; May et al. 1997; Morley and Karr 2002; Moscrip and Montgomery 1997; Richery 1982	Brennan et al. 2009		
	Overwater stuctures	Toft et al. 2007, 2013	Higgins et al. 2014	Higgins et al. 2014		
	Length of unarmored feeder bluffs	Whitman and Hawkins 2014	Finlayson 2006; Johannessen and MacLennan 2007; Keuler 1988; Shipman 2008	Fresh et al. 2012		
	Area of kelp	Bottom and Jones 1990; Dayton 1985; Duggins et al. 1989; Graham 2004; Irlandi 1994; Kendrick et al. 2002; Krentz 2007; McMillan et al. 1995; Norris et al. 1997; Penttila 2007; Robbins 1997; Simenstad et al. 1988; Simenstad and Fresh 1995; Simenstad and Wissmar 1985; Short & Burdick 1996	Babcock et al. 1999; Bustamante & Branch 1996; Carr 1991; Duggins 1980; Foster and Schiel 1985; Jones 1992; Steneck et al 2002; Mumford 2007	Bernstein et al. 2011; Friends of the san Juans et al. 2004; Gaeckle et al. 2011	Bernstein et al. 2011; Cavanaugh et al. 2010; Deysher 1993; Hessing-Lewis 2011; Olyarnik & Stachowicz 2012	Kamer et al. 2001; Kairis & Rybczyk 2010; Teichberg et al. 2010; Thom et al. 2012
	Area of eelgrass	Bottom and Jones 1990; Dayton 1985; Duggins et al. 1989; Graham 2004; Irlandi 1994; Kendrick et al. 2002; Krentz 2007; McMillan et al. 1995; Norris et al. 1997; Penttila 2007; Robbins 1997; Simenstad et al. 1988; Simenstad and Fresh 1995; Simenstad and Wissmar 1985; Short & Burdick 1996	Babcock et al. 1999; Bustamante & Branch 1996; Carr 1991; Duggins 1980; Foster and Schiel 1985; Jones 1992; Steneck et al 2002; Mumford 2007	Bernstein et al. 2011; Friends of the san Juans et al. 2004; Gaeckle et al. 2011	Bernstein et al. 2011; Cavanaugh et al. 2010; Deysher 1993; Hessing-Lewis 2011; Olyarnik & Stachowicz 2012	Kamer et al. 2001; Kairis & Rybczyk 2010; Teichberg et al. 2010; Thom et al. 2012
	Embayment Area (total, wetland, veg)	Beamer et al 2005; Levy and Northcote 1982; McBride et al. 2005; Simenstad and Cordell 2000	Fresh et al. 2011; Shipman 2008; Simenstad et al. 2011			Beamer et al. 2003
	Beach width					
	Connectivity of embayment to nearshore	Beamer et al. 2003, 2005; Puget Sound Recovery	Clancy et al. 2009	Clancy et al. 2009		
	Lenth of forested shorelines	MacLennan and Johannessen 2008	Brennan et al. 2009			

Field	**Shoreline armoring**	Bulleri and Chapman 2010; Ferdaña et al. 2006; Halpern et al. 2009, 2009b; Heerhartz et al. 2013; Morley et al. 2012; National Research Council 2007; Rice 2006; Shipman et al. 2010; Sococinski et al. 2010; Toft et al. 2007; Williams and Thom 2001	Fletcher et al. 1997; Griggs 2005; Shipman et al. 2010; Toft et al. 2007; Williams and Thom 2001; Woodroffe 2002;	yes		Simenstad et al. 2011; Storlazzi et al. 2000
	Location of culverts & tide gates blocking access	Greene et al. 2012	Collins et al. 2003			
	Contaminants	West et al. 2001, 2011a, 2011b				
	Nutrients					
	Elevation of bulkhead toe					
	Small stream and pocket estuary connectivity					
	Beach composition (shells)					
	Epibenthic taxa rischness					
	Grain size					
	Area of wood and rack	Heerhartz et al. 2013				
	Temperature	EPA 2002, 2008; Heinz Center 2008; Krembs 2012; National Research Council 2000; Rogers & Greenaway 2005; SWAMP 2007	EPA 2002; Heinz Center 2008; Krembs 2012; National Research Council 2000	yes	yes	yes
	DO	Diaz and Rosenberg 1995; EPA 2002a,b; Heinz Center 2008; Krembs 2012; National Research Council 2000; Rogers & Greenaway 2005	EPA 2002; Heinz Center 2008; Krembs 2012; National Research Council 2000	yes	yes	yes
	Turbidity					
	Condition of pocket estuaries and small stream mouth/estuary					

Table C-8. Reference sheet for Nearshore metrics.

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 photo, 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 coverage of the landscape with satellite data (low resolution), large sample sizes for aerial photograph metrics (mid-resolution), and small sample sizes for field metrics (high resolution).

Satellite Protocols

Large River and Floodplain Satellite Protocols

We selected two satellite metrics for large rivers and floodplains, percent forested area on the floodplain and percent developed area on the floodplain.

Large river and floodplain satellite protocols: Percent natural and percent developed landcover in the ESU

Layers required for this analysis are: (1) Floodplain polygon for all Puget Sound, (2) C-CAP Landsat data. 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 land cover raster file (C-CAP).
2. Add the layers required to the data frame within ArcMap.
3. Using the re-class or extract tool, group and extract C-CAP's 25 land cover into separate raster layers of Forest, Urban, and Agriculture (see Table 2 for 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 zone field. The Input value raster will be the landcover raster layer.
5. When you have run zonal statistics for all your landcover types join the tables to the original polygon layer (so you are sure to keep all records) and extract table to excel (Conversion Tools)
6. Evaluate sites within excel, calculate % of each cover class within all floodplain polygons in the ESU

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

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

Large river and floodplain satellite protocols: Percent natural and percent developed by major population group (MPG)

GIS layers required are: (1) 2011 C-CAP Landsat data; (2) 2011 NAIP data; (3) Floodplain polygon layer of all Puget Sound; (4) Map of MPG's. The attributes necessary for C-CAP and NAIP data are the land cover class and 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 land cover status are:

1. In GIS, convert all layers to the same projection as land cover raster file (start with C-CAP).
2. Add the appropriate layers to the data frame within in 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 data set there are a few extra steps necessary since it is a very big file:
    a. Clip the full NAIP layer by the floodplain layer
        i. Add a field to the floodplain polygon layer and assign all values "1"
            1. Open the attribute table and select *Add Field*
            2. Using *Field Calculator* assign all entries with a value of 1
        ii. *Convert Feature to Raster* (Conversion)
            1. Use floodplain polygon layer with added field as input
            2. Select the new field with "1's" for *Field*
            3. Input NAIP raster layer for *output cell size*
            4. Within *Environments* – set *Processing Extent* to: *Same as layer*: the NAIP land cover layer
        iii. Open Raster Calculator
            1. Multiply newly created raster layer of floodplain polygons and the original full extent NAIP land cover layer
        iv. Use the output land cover raster to follow steps 5 & 6
5. Re-class (or extract) land cover classes of interest from C-CAP and NAIP data as separate raster layers. In this case we were interested in forest and developed land cover. See Tables 8 and 9 for grouping of land cover classes.
6. 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 landcover raster layer.
7. When you have run zonal statistics for all your landcover types join the tables to the original polygon layer (so you are sure to keep all records) and extract table to excel (Conversion Tools) for analysis by area of floodplain and area of land cover class (in this case forest and developed land cover classes):

$$\% \, natural \, by \, MPG = \frac{sum \, of \, natural \, area \, in \, MPG}{total \, area \, of \, floodplains \, in \, MPG}$$

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

Large river and floodplain satellite protocols: Percent natural and percent developed land cover by land cover class

GIS layers required are: (1) C-CAP Landsat data for Puget Sound; (2) NAIP data for Puget Sound; (3) polygon layer of floodplain sample sites. The attributes necessary within the land cover data sets (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 LCC to the site, and the area of the polygon.

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

1. In GIS, convert all layers to the same projection as land cover raster file (start with C-CAP).
2. Add the appropriate layers to the data frame within in ArcMap.
3. For the NAIP data set there are a few extra steps necessary since it is a very big file:
    a. Clip the full NAIP layer by the floodplain sites
        i. Add a field to the floodplain polygon layer and assign all values "1"
            1. Open the attribute table and select *Add Field*
            2. Using *Field Calculator* assign all entries with a value of 1
        ii. *Convert Feature to Raster* (Conversion)
            1. Use floodplain polygon layer with added field as input
            2. Select the new field with "1's" for *Field*
            3. Input NAIP raster layer for *output cell size*
            4. Within *Environments* – set *Processing Extent* to: *Same as layer*: the NAIP land cover layer
        iii. Open Raster Calculator
            1. Multiply newly created raster layer of floodplain polygons and the original full extent NAIP land cover layer
        iv. Use the output raster to follow steps 4-6
4. Re-class (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 Tables 8 and 9 for grouping of 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 landcover raster layer.

6. When you have run zonal statistics for all your landcover types join the tables to the original polygon layer (so you are sure to keep all records) and extract table to excel (Conversion Tools) for analysis by area of floodplain and area of land cover class (in this case forest and developed land cover classes):

$$\%\, natural\ area\ in\ sample\ site\ = \frac{natural\ area\ in\ sample\ site}{area\ of\ floodplain\ sample\ site\ polygon}$$

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

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 urban land cover types (see Table E-1 for 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, Steelhead MPG, and Chinook MPG. From these data we calculated percent natural and percent developed land cover metrics for each delta, and data were summarized by MPG and delta land cover class.

Aerial Photograph Protocols

Large River and Floodplain Aerial Photograph Protocols

We based aerial photograph protocols for large river and floodplain areas on several sources, including WDNR (1995), Beechie et al. (2006), 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 photograph trials, and used inter-observer comparisons to help identify and correct errors or omissions in the protocols (i.e., to identify where increased specificity in the protocols could reduce inter-observer variation).

Large river and floodplain aerial photograph protocols: landcover

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 NOAA’s Coastal Change Analysis Program (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 NOAA’s C-CAP. Data are also available from the National Land Cover Data Set (NCLD), 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, WDFW has developed land cover data for the Puget Sound based on the National Agriculture Imagery Program (NAIP) (Pierce 2011). Each data set uses a slightly different land cover classification system (Table D-2)

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

Available Data Sets					
Data Set	**Pixel Size**	**Year**	**Coverage**	**Land cover**	**Availability Status**
NLCD (Landsat, 5-year cycle)	30m	2001, 2006, 2011	US wide	16 classes	available
C-CAP (NLCD Landsat, aerial photography, field data)	30m	1992, 1996, 2001, 2006, 2011	PS wide	25 classes	available
LandTrendr (USGS & NASA Landsat)	30m	1986-2008	PS wide	7 classes	available, - 2010 in spring 2015
NAIP (satellite/aerial imagery)	1 m	2011	PS wide	8 classes	available, other years possibly in the future
PSHSTM Aerial Photography	0.3 m	2010 & 2011	PS wide	5-9 classes	available

Table D-2. Comparison of land cover classification systems across data sets used in the Puget Sound Habitat Status and Trends Monitoring Program.

Land Cover Classes of Available Data				
C-CAP	**NAIP**	**LandTrendr**	**PSM**	**NLCD**
Evergreen forest	Trees	Evergreen forest	Conifer	Evergreen forest
Deciduous forest		Deciduous forest	Hardwood	Deciduous forest
Mixed forest			Mixed forest	Mixed forest
Scrub/shrub	Shrub/Tree		Shrub	Shrub/Scrub
Grassland	Herbaceous/Grass	Herbaceous	Grass	Grassland/herbaceous
Palustrine forested wetland				Woody wetlands
Palustrine scrub/shrub wetland				
Palustrine emergent wetland				
Delta forest wetland				Herbaceous wetlands
Delta scrub/shrub wetland				
Delta emergent wetland				
Unconsolidated shore				
Cultivated land	NA	NA	Agriculture	Cultivated Crops
Pasture/hay				Hay/Pasture
High intensity developed	Built/Gray	Developed – Medium High Intensity	Dist. Impervious	Dev. – High Intensity
			Dist. Pervious	Dev. – Med. Intensity

Medium intensity developed Low intensity developed Developed open space				Dev. – Low Intensity Dev. – Open Space
Open water Palustrine aquatic bed Delta aquatic bed	Water/Shadow	Open Water	Water	Open Water
Unclassified Bare land Tundra Snow/ice	Bare Ground Indeterminate	Barren Land Perennial Snow/Ice	Bare Ground	Perennial Ice/Snow Barren Land

GIS layers required for the land cover accuracy assessment are: (1) C-CAP Landsat data for Puget Sound; (2) NAIP data for Puget Sound; (3) GIS Aerial photography base map; (4) polygon layer of designated floodplain sites; (5) bankfull lines for each site; (6) grid point layer (created using ET GeoWizard – see step 1 first).

The attributes necessary within the land cover data sets (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 floodplain polygon for point grid layer
    a. Create polygon of the large river using bankfull lines and floodplain polygon
        i. Convert bankfull line feature to polygon
    b. Use this layer to extract the large river from the floodplain polygon to have 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 ID
        i. Delete site and Reach ID fields in the polygon layer that excludes large rivers, join 1 to 1, and select closest as your *Match Option*
    d. *Dissolve* the new polygon layer so that each floodplain site containing two or more polygons are combined into one feature (for creating the grid points)
        i. Dissolve by Site & Reach ID, Use default settings

2. Use dissolved floodplain polygon layer minus large river to create grid points for analysis
    a. Generated with the *Uniform Points in Polygon* tool in ET Geowizard
        i. 100 points per site/reach
3. Process individual NAIP WRIA's for analysis
    a. Reclass WRIA's and eliminate 0 value with no data (used mix of reclass and Set Null w/in spatial analyst).
    b. On WRIA files that won't reclass use SetNull (*Spatial Analyst Tool > Conditional*)
        i. Expression Field="VALUE"=0
        ii. Built attribute table with output
        iii. If that doesn't work convert file to a tiff then build attribute table
    c. Mosaic to New Raster
        i. Within *Environment Setting* set *Processing Extent* to *Union of Inputs*
4. Manually classify points using basemaps in ArcGIS and 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 grid points:
    a. Create table with land cover class code – summarize using numeric *value* attribute
        i. Within the attribute table drop down menu go to *export*
    b. Convert grid point layer to raster
        i. If not already there add a Point_ID column to attribute table
            1. Make as long integer
            2. Field calculator Point_ID=FID+1
        ii. Feature to Raster (Conversion)
        iii. Set field to unique point ID
        iv. Set grid output cell size to land cover data layer
        v. In environments set process extent to same as the LC layer
6. Run zonal statistics using grid point raster layer
    a. make sure point has unique ID – VALUE
    b. set statistics type to MEAN
7. Join zstats table (using whatever statistic type was selected in zstats tool -MEAN) with class code table (using VALUE)
8. Summarize in excel

Large river and floodplain aerial photograph protocols: channels and habitat

GIS layers that are required to start aerial photography measurements are: (1) the aerial imagery layer; (2) 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 DEM where LIDAR is not available).

For the polyline layer, the attribute table includes: (1) Imagery Date – extracted from aerial imagery layer; (2) River Name – name of the river being measured (3) Site Id - associated with site location; (4) Reach Id – associated with site location; (5) Sample Type – the category of metric being measured; (6) Line Type – the category of line being measured; (7) Confidence – a categorical line confidence designation; (8) Bank – bank designation; (9) Classification – side channel and braid classification; (10) Length – calculated line length; (11) Cover Classification – land cover classification; (12) Valley Type – designation of valley type; (13) Observer – name of observer performing the measurements; and (14) Comment – comment section. 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 in include 3 categories of line types: the Large River line type, the Bank Type, and Edge Habitat type. The Large River line types include:

1. Main channel - Contains a majority of the river discharge,
2. Braid - Contains less than half the discharge and is separated from the main channel by an unvegetated bar,
3. Side channel - Contains less than half the discharge and is separated from the main channel by a vegetated island, and
4. Valley Center Line (VCL).

The Bank Type line types include:

1. Armored—bank armored with rip-rap, concrete, or other material for prevention of erosion,
2. Levee—the bank is a levee,
3. Natural—the bank is in a natural condition (no armor or levee), and
4. No bank unit (NBU)—where the bank line crosses a side channel the line is labeled NBU to indicate that there is no bank present.

The Edge Habitat line types include (see example in Figure D-1):

1. Natural bank—Slow-water unit located where the channel meets a deep, nearly vertical shore; no rip-rap or revetment (usually at the outside of meander bends or in straight segments,
2. Modified bank—Slow-water unit located where the channel meets a deep, nearly vertical shore; bank is rip-rap or other revetment,
3. Bar edge—Slow-water unit located where the channel meets a shallow, gently-sloping shore (usually on the inside of a meander bend), and
4. No edge unit (NEU)—where the main channel crosses a side channel or braid.

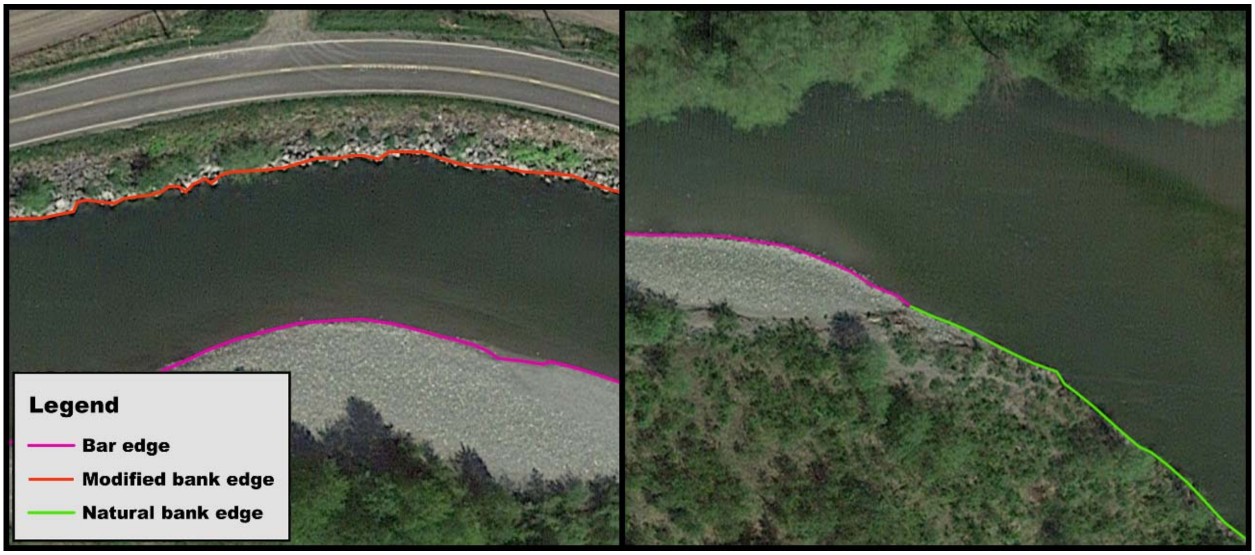

Figure D-1. Example of digitized habitat edge features using the protocol.

The confidence attribute is used to designate the observer's categorical confidence in correct identification of a feature that is being measured. There are three levels of confidence for this attribute; (1) High – entire feature is visible; (2) Moderate – parts of the feature are visible; and (3) 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, and if an existing levee layer is available that confirms 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 (facing downstream), Right, or NA (not applicable). The channel side designation is only required for Bank Type and Edge Habitat lines. Mainstem lines do not require channel side designation and should be marked with NA.

The classification attribute is used to classify the type of side channel and/or braid. There are four types of classifications for this attribute; (1) Surface Water – channel is connected at both ends, with water present; (2) Groundwater – channel is only connected at a lower end, with water present; (3) Dry – overflow or flood channel, with water partially present or not present; and (4) 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 with NA (not applicable) in the attribute table.

In a similar manner to the polyline layer, there are several key attributes that should be incorporated in the attribute table for the polygon layer; (1) Imagery Date – extracted from aerial imagery layer; (2) River Name – name of the river being measured (3) Site Id - associated with site location; (4) Reach Id –associated with site location; (5) Polygon Type – type of feature being measured; (6) Area – calculated polygon area; (7) Cover Classification – land cover classification; (8) Valley Type – designation of valley type; (9) Observer – name of observer performing the measurements; and (10) Comment –comment section. All of these attributes should be included for each polygon created in the polygon layer.

There are three categories in the Polygon Type attribute; (1) Backwater – an area of still water within a main channel, side channel, braid, or tributary; (2) Wood Jam – wood jam comprised of stacked pieces of wood in the water, on the bank, or on the island; and (3) Floodplain –a floodplain polygon created from a floodplain layer. The Wood Jam and Backwater 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 100 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 photograph channel and habitat measurements are:

1. In GIS, add the appropriate layers to the data frame.
2. Measure bankfull channel width at five equally spaced transects and calculate the average channel width. Calculate the reach length by multiplying the average of 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 No bank unit (NBU). Each bank line should also be assigned a confidence rating. High confidence should be used when a bankfull edge is clearly visible or an additional feature layer is able to confirm the identification of a bank type. If the bankfull edge is not visible at a level to produce at least a moderate confidence call, adjacent land cover is taken into account. For example, if housing developments are in close proximity to the bankfull edge, it is likely that the bank has been modified and the bank is considered armored but with low confidence.
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 No Edge Unit (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) in order for a channel to be considered a Side Channel designation, it has to be separated from the large river by a vegetated island, if a channel is separated from the large river by unvegetated island, it should be classified as a braid; and (5) if it is unclear whether a feature can be classified as an island within channel, imagery during different flow conditions should be referred to.
8. In the polygon layer, digitize each wood jam that is visible within main channel, side channels, braids, 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 should be at least 100 square meters; and (3) only adjoining and visible pieces of wood should be included in the wood jam area measurement.
9. Digitize each backwater area. Only backwaters adjoining to 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 area of a backwater, and isolated pools or ponds within a floodplain should not be considered a backwater.

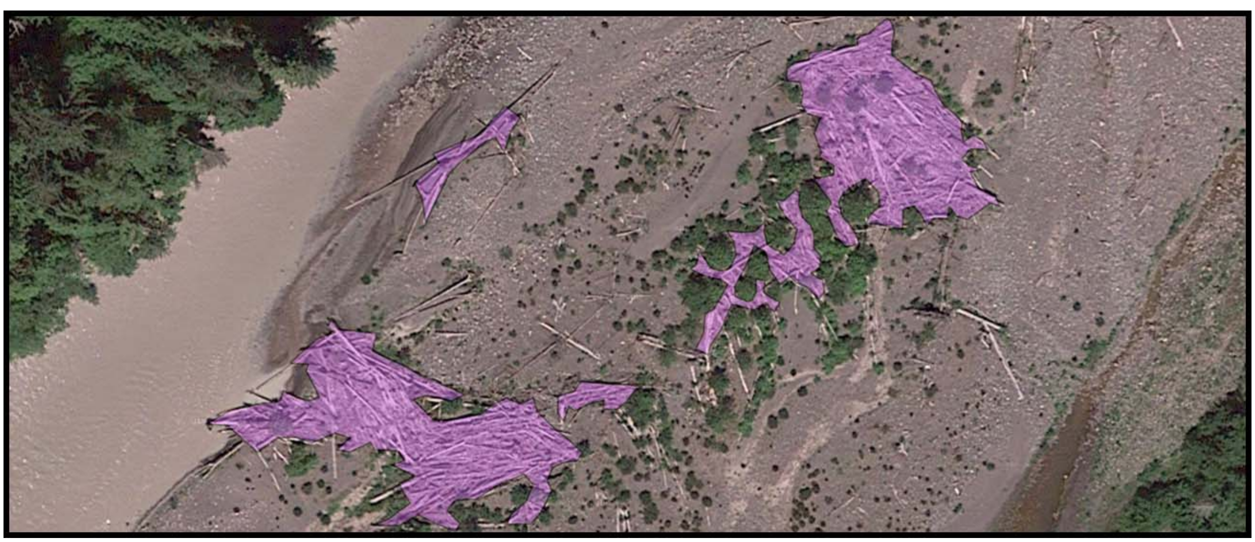

Figure D-2: Example of digitized wood jam area using the protocol. Wood jam area is marked in pink. Excluded wood pieces were not digitized as they did not meet the requirement of minimum area of 100 m^2.

Large river and floodplain aerial photograph protocols: 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 10 points along at each bankfull channel edge, and calculated 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 digitized improperly: (1) natural land cover is upland of the bankfull line but is not forest (no buffer digitized), (2) the point lands on a side-channel inlet, outlet (no buffer digitized), (3) a side-channel > 15m runs through forested buffer (stopping the buffer transect short of 100m), and (4) elevation is not accounted for in transect length, which means that buffer widths on hillslopes may be longer than our horizontal measurements indicate.

A total of 50 sites had one or more of these issues or 40% of the 124 sites. Table D-3 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 re-evaluated at 32 sites (eight in each land cover class; forest, urban, agriculture, and mixed) and transects were created or re-drawn to include natural buffers. By following this protocol the issues of a transect not being digitized because a point landed where there was natural land cover or a side-channel was eliminated and reduced the proportion of sites to have potential issues to only 7% (elevation). Mean buffer width at the 32 sites was calculated and the results reported in Table D-4.

Table D-3. Proportion of sites by issue type (note: one site may have more than one issue).

Issue Encountered	Proportion of Total Sites
Natural Land Cover	28%
Side-Channel	14%
Elevation	7%

Table D-4. A comparison of average buffer widths at 32 sites (8 in each LCC), drawn using criteria of forest vs. "natural" or non-human impacted buffers.

Land Cover Class	Natural buffer (m)	Forested buffer (m)	Percent difference
Agriculture	67	62	+8%
Forest	95	93	+2%
Mixed	56	55	+2%
Urban	39	39	No difference

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 "forest + other natural land cover" (Table D-4). However, for forest, mixed and urban 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 re-evaluate buffer width in the future.

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 was present at the point.
4. The maximum length for a transect is 100 m. If forest cover ends before 100 m is reached, the transect is ended at that point and its length recorded.
    a. Where the bankfull line was 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).

Figure D-3: Example of digitized buffer widths using the protocol; (a) example of exception *a* under step 4, (b) example of exception *b* under step 4. The side channel is >15m wide.

We also considered classifying different land cover classes 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 aerial photograph riparian classification were:

1. Midpoints of each land cover segment from field-surveyed riparian transects were generated using GIS. All attributed values were removed to mask data being collected from aerial images.
2. Load the midpoint shapefile into ArcMap (2014_Riparian_Transect_Validation_Points_20141022A.shp).
3. Load base map of ESRI aerial imagery into map.
4. For each point, classify the veg type, size class, density, image date (MM/DD/YYYY), and any comments in the shapefile attribute table. Note: image date should be the same for each transect and within each site, but image dates should be checked when moving to new sites.
    - Conifer dominated: Forested, more than 70% of trees are conifer
    - 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, bare soil not in agriculture or disturbed pervious
    - 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 data in Beechie et al., 2006 and unpublished data):
    - Crowns not distinguishable (classify as brush)
    - Forest with crown diameter less than 9m (<30cm mean dbh)
    - Forest with crown diameter 9m-12m (30-50 cm mean dbh)
    - Forest with crown diameter >12m (>50 cm dbh)
    - NA if the cover class is not forested (e.g., grass/shrub, large river channel, agriculture, disturbed impervious)

    Density classes are (from Washington DNR Watershed Analysis Manual, 1995):
    - Sparse: >1/3 of the area is bare ground
    - Dense: <1/3 of the area is bare ground
    - NA if the cover class is not forested (e.g., grass/shrub, large river channel, agriculture, disturbed impervious)

Delta and Nearshore Aerial Photograph Protocols

We based aerial photograph protocols for delta and nearshore areas on several sources, including Hood (2015), Beamer et al. (2005), and Hood (2005). 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 photograph trials.

Delta aerial photograph protocols: channels and habitat

Juvenile Chinook salmon utilize specific habitats in deltas where low water velocities and shallow water depths create favorable habitat 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 amount of such habitats is not known within Puget Sound 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 of 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 7/9/2010 (Nooksack, Samish, Skagit, Stillaguamish, Duckabush, Dosewallips, Big Quilcene, Dungeness, and Elwha deltas), 7/24/2010 (Skokomish and Hamma Hamma deltas), 8/1/2011 (Snohomish, Duwamish, Puyallup, and Nisqually deltas), and 8/20/2011 (Deschutes delta). We digitized six tidal channel feature types as polygons within each delta unit; (1) distributaries, (2) tidal channels, (3) tidal channel complexes, (4) tidal flats, and (5) industrial waterways (Figure D-5). Each type is functionally different with respect to fish habitat, and requires different protocols to assure consistent delineation and measurement of channel features within deltas.

The protocols for aerial photograph channel and habitat measurements are:

1. Distributary polygons were digitized for channels that were formed from bifurcations of the river network that convey river discharge through the delta to saltwater, and that were at least 5 meters wide. Distributaries were digitized to bankfull width except in the lower delta where tidal flats greatly extended the bankfull width. Where tide flats extended more than 50 meters from the primary distributary flow path, the edge of the primary flow path was digitized instead of the bankfull width.
2. Tidal channel polygons were digitized for blind tidal channels and tidal channels connected to other tidal channels or distributaries but do not bifurcate flow of river water as distributaries. Polygons were digitized for all tidal channels that were at least 5 meters wide and at least 50 meters long, or connected on both ends to other tidal channel or distributary features if less than 50 meters long.

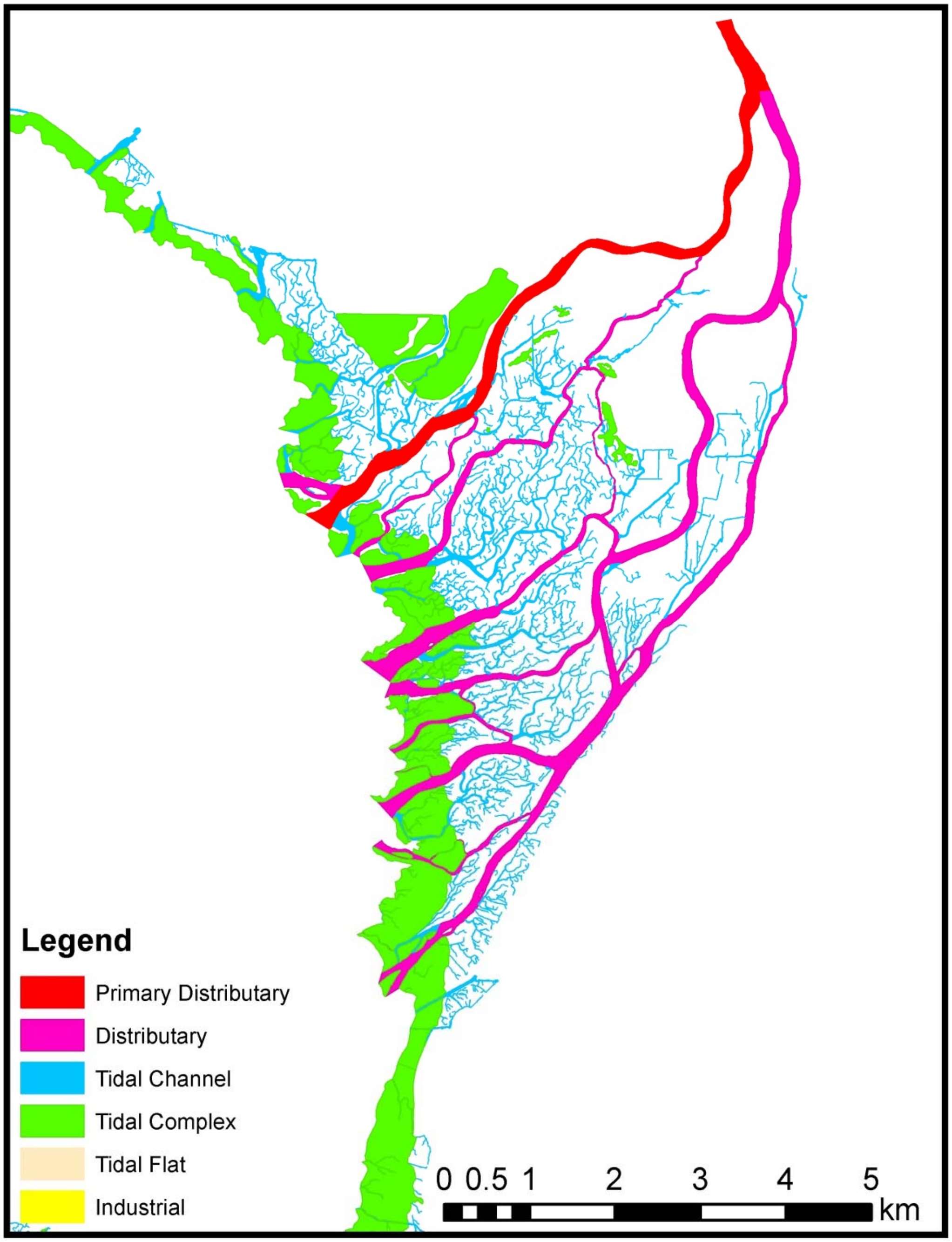

Figure D-5. Example of digitized tidal channel features in the South Fork Skagit River delta illustrating the five feature types (the primary distributary is coded as a sixth feature type for calculating metrics, but is included in the distributary feature type).

3. For tidal channels smaller than 5 meters in width and at least 50 meters long, we digitized polylines along the flow path and then buffered the polylines by 1 m to create a polygon feature. While all other features could be reasonably delineated within a variety of land cover types, tidal channel features were most likely to be obscured in areas with forested

cover given that tidal channels were the smallest features digitized. Therefore, tidal channels are most likely to be underrepresented in areas with mature forested cover that make visual detection and delineation of smaller tidal channels difficult.

4. Tidal complex polygons were digitized where complex tidal channel networks within mostly vegetated marshes prevented accurate delineation of channel flow paths and connections within the tidal complex (Figure D-6). These features typically occurred in the lower delta, although some maturing restoration projects where vegetation has become mostly established but channels have not fully formed were also digitized as tidal complexes. Channels in these areas account for at least 50% of the polygon area by visual estimation.
5. Tidal flats were digitized within the delta polygons where complex channel networks occurred within largely unvegetated tidally flooded areas. However, we restricted delineation of tidal flats to the seaward extent of vegetated marsh within the deltas to exclude mud flat habitats that occur at the delta terminus. While most tide flat habitats digitized did 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. Industrial waterways were also digitized as separate polygons where waterways were constructed for human purposes (e.g., marinas, ports, launches, etc…). These industrial channel features were connected to other delta channel network features, and in some cases, were necessary to 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).
7. For all features, areas above culverts or tide gates were not digitized at this time given that the type of structure cannot be accurately determined from aerial imagery. While this approach likely omits 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 tide gate and culverts in Puget Sound deltas. We did however digitize above what appeared to be bridges and not tide gates or culverts given that tidal connectivity in these areas are 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 create single part features such that only the perimeter of individual features 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 also 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 at this point, 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 meters (an arbitrary threshold). Therefore, tidal channel lengths are only biased against smaller tidal channel features in tidal flat and tidal complex features 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 does not represent channel connection nodes in tidal complexes and tidal flats (with the noted exception of channels that were at least 5 meters 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 river rivers. Connections with industrial waterway features were excluded from the node density calculations.

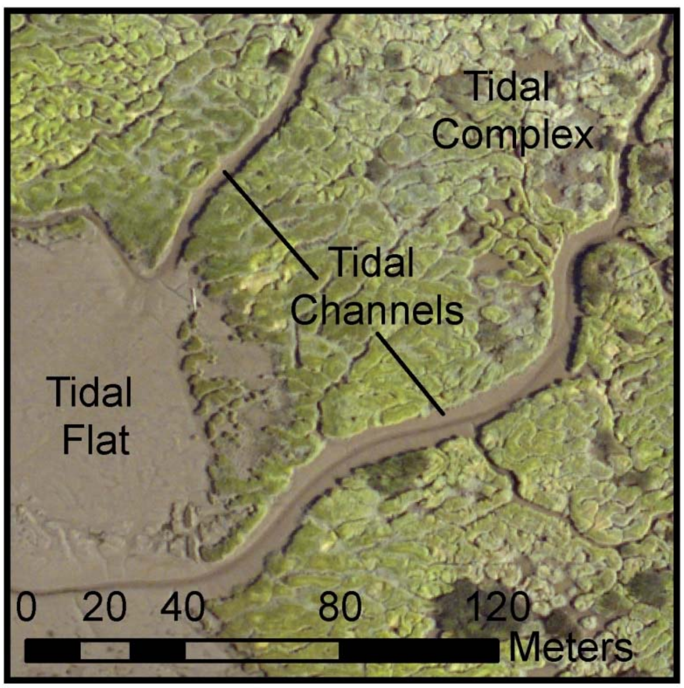

Figure D-6. Example photo showing a tidal complex boarding a tidal flat with numerous tidal channels less than 5 meters wide that were digitized as a tidal complex. Tidal channels that were at least 5 meters wide within these tidal complexes were still digitized as tidal channels.

Nearshore habitat: aerial photograph protocols

Protocols not yet developed.

Delta and Nearshore habitats: riparian aerial photograph protocols

Protocols not yet developed.

Field Protocols

Large River Field Protocols

Field protocols include surveys of (1) instream edge habitat 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 (a matter of convenience). 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 between 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 width of each stand. Transects should be located at 0.25, 0.50, and 0.75 of the reach length.

Large river habitat survey

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 and be efficient) (See Habitat survey form LR-1, Appendix A). The length of the survey reach will be 10x the bankfull channel width along the water's edge. Habitat units will be classified as natural bank edge, rip-rap bank edge, bar edge, or backwater using the following definitions (from Beamer and Henderson 1998, Beechie et al. 2005, and Josh Latterell unpublished large river monitoring protocols):

- Natural bank—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
- Riprap bank—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—Slow-water (<0.45 m/s, <1 m deep) unit located where the channel meets a shallow, gently-sloping shore
- Backwater—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
- NUE—no edge unit; where width of the edge unit is less than 0.5 m wide 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 office, measure five bankfull widths equally spaced along the reach in Google Earth, average them, and multiply the average bankfull width by 10 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 start-point coordinates, then measure half the reach length upstream and record 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 start of survey, including direction of survey (upstream or downstream).
4. At the first survey point, record channel type (M, B) and bank (L, R). Also record GPS point for header field "Lat/Long begin" and 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 1m (adapted from Bjornn and Reiser 1991, Beechie et al. 2005). To do this, position the monopod with laser range finder at the point at which velocity exceeds 0.45 m/s or depth exceeds 1m 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 a wadeable depth, 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 taking an intermediate point would be distance if unit is too long, change in bank contour (in order to get a more accurate distance measurement), or a change in 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 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 a 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-7 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 (located using the GPS coordinates from step 1).
11. Record GPS location at the end of the survey for 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-7. Example of completed Large River habitat survey form.

Large river bank type and wood count

From the end of the habitat survey, begin the bank condition and wood count in the opposite direction. This is a continuous survey, measuring distances along the bankfull edge and recording whether it 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).

The large river bank type and wood count protocols are:

1. At the site, record all header information at start of survey, including direction of survey (upstream or downstream). Also record GPS point for the header field "Lat/Long begin". This should be nearly the same as the end location of the habitat survey, though it may not be identical if the water edge is not against the bankfull channel edge.
2. Record channel type (M, B), 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 and of the first bank segment. Record the bank type for the segment in between the two points.
4. Count 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 (10-20 cm midpoint diameter and >2 m in length),
    - medium (20-50 cm midpoint diameter and > 3 m in length), and
    - large (>50 cm midpoint diameter and > 5 m in length).

    A wood piece must meet both size criteria to be assigned to that class (e.g., a 30 cm piece that is 4 m long is a medium piece, whereas a 30 cm piece that is 2.5 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).
5. Repeat steps 2 - 4 until the start point of the habitat survey is reached. Record GPS coordinates at the end of the survey and enter in the header field "Lat/Long end".

Large river riparian transects

Within each survey segment, we will survey three 3 riparian transects for cross validation of the aerial photograph classification of riparian conditions. Transects should be placed at 25%, 50%, and 75% of length of the reach, unless there are unusually complex or unique features that should be captured for cross validation. Transects extend 52 m from the bankfull edge (a typical site potential tree height for conifer species in the region) (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 cross validation sample.

The riparian condition survey protocols are:

1. At the site, record all header information at start of 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 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 veg 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 brush). 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 conifer
    - Hardwood dominated: Forested, more than 70% of trees are hardwood
    - Mixed Forest: no dominance greater than 70%
    - Shrub: small woody vegetation
    - Grass: natural grasslands
    - Water: any standing or moving water that is not wetland
    - 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 Washington DNR Watershed Analysis Manual, 1995):
    - 0-3 cm dbh (1.5 m above the ground)
    - 3-30 cm dbh
    - 30-50 cm dbh
    - >50 cm dbh
    - NA if the cover class is not forested

    Density classes are (from Washington DNR Watershed Analysis Manual, 1995):
    - Sparse: >1/3 of the area is bare ground
    - Dense: <1/3 of the area is bare ground
    - NA if the cover class is not forested
5. Continue measuring widths of cover types perpendicular to the channel out 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 the one exception from the aerial photography point of view approach.

Floodplain Channel Field Protocols

Field protocols for floodplain habitats include surveys of (1) instream habitat important to juvenile salmonids and wood count, (2) bank type, and (3) riparian vegetation transects. The habitat survey and wood count is a continuous survey in either the upstream or downstream direction (a matter of convenience). On the return, bank type is continuously surveyed, and the riparian transects are surveyed at three roughly equally spaced intervals. The habitat survey and wood count is not a ground truthing survey; rather, it is intended to describe habitat conditions within the survey reach. Our aim is be able to quantify differences in habitat conditions between 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 be 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 habitat survey

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 (from Elwha large river sampling protocols):

- 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 one hundred meter 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. 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 habitat surveys are:

1. In 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 start of survey, including direction of survey (upstream or downstream).

4. Locate the first of the three reaches, and begin the survey at the downstream end, and record GPS co-ordinates 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 measured at mid-riffle for streams lacking pool–riffle morphology.
5. At the first survey point, record 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, rough surface
    - Glide: fast or slow with a relatively flat bed form, smooth surface
    - Pool: deep, slow unit that exceeds the minimum residual depth (Table D-5).
    - Pond: large beaver pond or ox-bow pond, very low velocity, smooth surface
7. To survey the next point, position laser range finder monopod at the 0 station and position the stadia rod at a mid-point along the thalweg within the first habitat unit (to assure 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. mid-channel 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 range finder target), and repeat steps 7 and 8.
9. Continue steps 7-8 for 100 meters along the thalweg, making sure that each habitat unit has at least one point in the middle of each unit, the top end of each unit, and at all pool tail-crests and maximum depths.
10. Record GPS location at the end of the survey for header field "Lat/Long end".
11. Repeat steps 1-10 for the remaining two sub-reaches.

Table D-5. Minimum residual depth requirements for pools, by channel width (from WDNR 1995, Standard Methodology for Conducting Watershed Analysis). (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 length of modified banks.

The floodplain channel bank type protocols are:

1. At the site, record all header information at start of survey, including direction of survey (upstream or downstream). Also record 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, distance = 0, 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 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 will be left bank and the other row 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 (10-20 cm midpoint diameter and >2 m in length),
- medium (20-50 cm midpoint diameter and > 3 m in length), and
- large (>50 cm midpoint diameter and > 5 m in length).

A wood piece must meet both size criteria to be assigned to that class (e.g., a 30 cm piece that is 4 m long is a medium piece, whereas a 30 cm piece that is 2.5 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.

12. Once the habitat unit measurements are complete, count wood pieces between the two survey points and within the bankfull channel, or measure the dimensions of the wood jam if a wood accumulation exceeds 30 pieces. Wood counts for single pieces or in jams <30 pieces, record S (single) in the wood accumulation type column and count wood in each of three size classes:
    - small (10-20 cm midpoint diameter and >2 m in length),
    - medium (20-50 cm midpoint diameter and > 3 m in length), and
    - large (>50 cm midpoint diameter and > 5 m in length).

    A wood piece must meet both size criteria to be assigned to that class (e.g., a 30 cm piece that is 4 m long is a medium piece, whereas a 30 cm piece that is 2.5 m long is small) (Beechie and Sibley 1997). For wood jams with more than 30 pieces, record J (jam) in the wood accumulation type column and measure the length, width, and height of the wood accumulation with the laser range finder.
5. Repeat steps 3 and 4 until the start point of the habitat survey is reached. Record GPS coordinates at the end of the survey and enter in the header field “Lat/Long end”.

Floodplain channel riparian transects

Within each sub-reach of a side channel, we will survey two riparian transects for cross validation of the aerial photograph 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 cross validation, 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 cross validation 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 Douglas fir in much of western Washington) (e.g., McArdle et al. 1961).

The riparian condition survey protocols are:

1. At the site, record all header information at start of 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 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 veg type, size class, and density. If the RTK 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 brush). 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 conifer
    - Hardwood dominated: Forested, more than 70% of trees are hardwood
    - Mixed Forest: no dominance greater than 70%
    - Shrub: Small woody vegetation
    - Grass: natural grasslands
    - 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 Washington DNR Watershed Analysis Manual, 1995):
    - 0-3 cm dbh (1.5 m above the ground)
    - 3-30 cm dbh
    - 30-50 cm dbh
    - >50 cm dbh
    - NA if the cover class is not forested (e.g., grass/shrub, large river channel, agriculture, disturbed impervious)

    Density classes are (from Washington DNR Watershed Analysis Manual, 1995):
    - Sparse: >1/3 of the area is bare ground
    - Dense: <1/3 of the area is bare ground
    - NA if the cover class is not forested (e.g., grass/shrub, large river channel, agriculture, disturbed impervious)
5. Continue measuring widths of cover types perpendicular to the channel out to a distance of 52 m.
6. Record the GPS coordinates at the last point of the transect and enter in the "Lat/Long end" header field. If the point cannot be reached, record NM (not measureable) in the "Lat/Long end" header field.
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.

Appendix E: Evaluation of forest land cover classes

Both C-CAP and NAIP data sets contain multiple classes that might be considered forested, and it is not obvious which combination(s) of those class 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).

Land cover data classified from the National Agriculture Imagery Program (NAIP) was acquired from the Washington Department of Fish & Wildlife (Ken Pierce). 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).

To determine which combination 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 photograph sites. The 32 sites were evenly distributed across 8 different strata (forest, agriculture, mixed, and urban in the GL and PGL valley types). We created a grid of 100 points within each of 32 floodplain polygons using the *Uniform Points in Polygon Tool in ET Geowizard*, manually classified the land cover type at each point (see Figure E-1 for 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 data sets. 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.

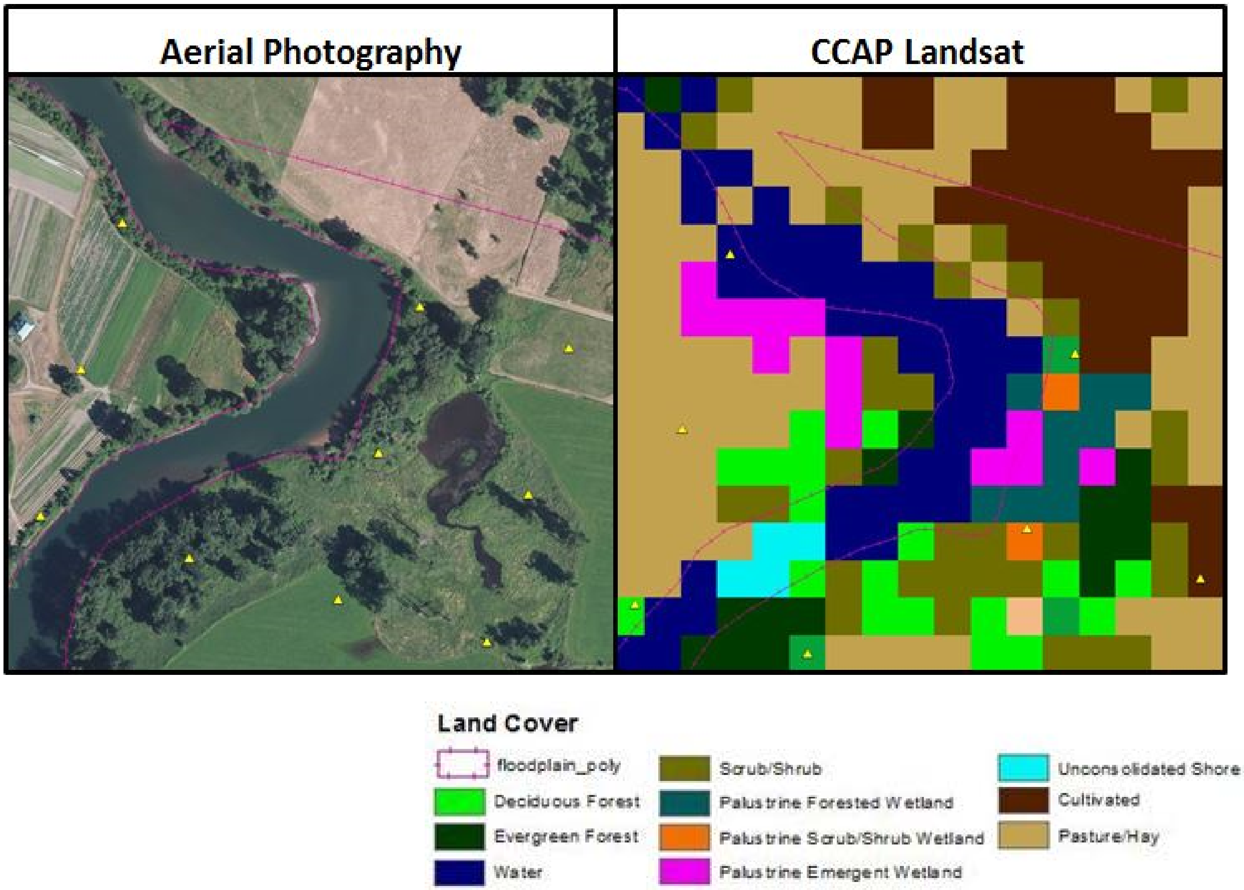

Figure E-1. Image of grid points overlaid on C-CAP Landsat land cover data and Aerial Photography downloaded from ArcGIS online.

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

C-CAP Land Cover Classes	**PSM Riparian Classes**	**C-CAP Land Cover Code**
evergreen forest	forest	10
deciduous forest	forest	9
mixed forest	forest	11
delta emergent wetland	wetland	18
delta scrub/shrub wetland	wetland	17
delta forested wetland	wetland	16
palustrine emergent wetland	wetland	15
palustrine scrub/shrub wetland	wetland	14
palustrine forested wetland	wetland	13
unconsolidated shore	wetland	19
high intensity development	developed	2
medium intensity development	developed	3
low intensity development	developed	4
cultivated land	ag	6
pasture/hay	ag	7
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 re-classification of C-CAP land cover classes with forested wetlands grouped in the forest cover class instead of the wetland class. Gray shaded rows are the re-classed forested wetlands into the forest class.

C-CAP Land Cover Classes	**PSM Riparian Classes**	**C-CAP Land Cover Code**
evergreen forest	forest	10
deciduous forest	forest	9
mixed forest	forest	11
delta forested wetland	forest	16
palustrine forested wetland	forest	13
delta emergent wetland	wetland	18
delta scrub/shrub wetland	wetland	17
palustrine emergent wetland	wetland	15
palustrine scrub/shrub wetland	wetland	14
unconsolidated shore	wetland	19
high intensity development	developed	2
medium intensity development	developed	3
low intensity development	developed	4
cultivated land	ag	6
pasture/hay	ag	7
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 re-classification of NAIP land cover classes into water, developed, forest, and other classes.

NAIP Land Cover Class	PSM Land Classes	NAIP Land cover code
Shadow/Water	water	**1**
Built/Gray	impervious	**3**
Tree	forest	**8**
Veg shadow/Tree	other	**5**
Shrub OR Tree	other	**7**
Indeterminate	other	**2**
Herbaceous/Grass	other	**6**
Bare ground	other	**4**

Table E-4. Alternate re-classification of NAIP land cover classes into water, developed, forest, and other classes. Gray shaded rows are NAIP classes that we re-grouped from other to "forest" to determine whether their inclusion as forest improved the accuracy of the percent forested metric.

NAIP Land Cover Class	PSM Land Classes	NAIP Land cover code
Shadow/Water	water	**1**
Built/Gray	impervious	**3**
Tree	forest	**8**
Veg shadow/Tree	forest	**5**
Shrub OR Tree	forest	**7**
Indeterminate	other	**2**
Herbaceous/Grass	other	**6**
Bare ground	other	**4**