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Influences of valley form and land use on large river and floodplain habitats in Puget Sound

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Abstract

In this paper, we use a system-wide census of large river and floodplain habitat features to evaluate influences of valley form and land use on salmon habitats along 2,237 km of river in the Puget Sound region of Washington State, USA. We classified the study area by geomorphic process domains to examine differences in natural potential to form floodplain habitats among valley types, and by dominant land cover to examine land use influences on habitat abundance and complexity. We evaluated differences in aquatic habitat among strata in terms of metrics that quantify the length of main channels, side channels, braid channels, and area of wood jams. Among geomorphic process domains, habitat metrics standardized by main channel length were lowest in canyons where there is limited channel migration and less potential to create side channels or braids, and highest in post-glacial and mountain valleys where island-braided channels tend to form. Habitat complexity was lower in glacial valleys (generally meandering channels) than in post-glacial valleys. Habitat abundance and complexity decreased with increasing degree of human influence, with all metrics being highest in areas classified as forested and lowest in areas classified as developed. Using multiple-year aerial photography, we assessed the ability of our methods to measure habitat changes through time in the Cedar and Elwha Rivers, both of which have recent habitat restoration activity. We were able to parse out sources of habitat improvement or degradation through time, including natural processes, restoration, or development. Our investigation indicates that aerial photography can be an effective and practical method for regional monitoring of status and trends in numerous habitats.

KEYWORDS: habitat assessment; floodplains; aerial photograph; remote sensing; monitoring

Introduction

Floodplains and floodplain channels have a disproportionately high habitat value for many species, and they have high species diversity (e.g., Beechie *et al.*, 1994; Ward *et al.*, 1999; Naiman *et al.*, 2010; Bellmore and Baxter, 2014). Floodplains are also some of the most degraded environments in the world because agricultural and urban development have often been concentrated in these flat, low elevation areas (Beechie *et al.*, 2001; Hohensinner *et al.*, 2004, Burnett *et al.*, 2007; Hall *et al.*, 2007).

Despite the widespread alteration of floodplains, there is surprisingly little data describing how land uses have affected floodplain habitats and what types of larger river channels are most severely impacted. Several studies have examined the influence of land use changes at individual sites over time (e.g., Collins and Montgomery, 2002; Hohensinner, 2004; Chone and Biron, 2015), and others have examined pairs of confined and unconfined sites to evaluate the influence of floodplain width (Blanton and Marcus, 2013). Other studies have examined the influence of land use on habitats at the river basin scale (Beechie et al. 1994), and Collins and Montgomery (2011) examined the influence of geomorphic process domains on channel morphology. However, we are not aware of any study examining the combined influences of valley form and land use on large river and floodplain habitats.

In this paper, we evaluate influences of valley form and land use on river and floodplain habitat features in the Puget Sound region of Washington State, USA. We used habitat metrics from a regional census of salmon habitat, developed as part of an effort to evaluate the status of habitat condition for populations of Chinook salmon (*Oncorhynchus tshawytscha*) and Steelhead (*O. mykiss*) listed under the Endangered Species Act. We measured main channel, side channel, and braid channel lengths, as well as wood jam areas across all large rivers and floodplains in the study area. We classified the study area by geomorphic process domains to examine differences in natural potential to form floodplain habitats, and by dominant land cover to examine the influence of land use on habitat abundance and complexity. Finally, we assessed the ability of our methods to measure temporal habitat changes in Cedar and Elwha Rivers, two major rivers in Puget Sound that have been the focus of recent restoration activity.

Puget Sound

The Puget Sound basin encompasses 16 major 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/yr on Mount Baker (PRISM Climate Group, 2014). Hydrologic regimes are classified as snowmelt-dominated (mean basin elevation >1300 m), rainfall dominated (mean basin elevation <800 m), or transitional (Beechie *et al.*, 2006).

The Cascade and Olympic Mountains are composed of diverse lithologies, ranging from relatively erosion resistant igneous and high-grade metamorphic rocks to more easily eroded marine sedimentary rocks and low-grade metamorphic rocks. 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).

Prior to Euro-American settlement the region was primarily forested (Ayers, 1898), with a mix of hardwood and conifer species on floodplains (Ayers, 1898; Franklin and Dyrness, 1973). Since the late 1800s, urban and agricultural land uses have removed significant areas of floodplain forest and reduced the extent of floodplain habitats for fishes (e.g., Beechie *et al.*, 2001; Konrad, 2015). Habitat complexity and wood cover in river and floodplain habitats are important spawning and rearing habitats for both Chinook salmon and steelhead (Beechie *et al*., 2005; Pess *et al.*, 2012; Whited *et al*., 2013; Hall *et al.*, 2018).

Methods

Data sources

We used the Arc2Earth extension (Arc2Earth, 2017) to access the most recently acquired high-resolution Google aerial and satellite imagery in ArcMap GIS (Version 10.3) for Puget Sound's large river and floodplain habitats. Photographs were less than 0.5-meter in spatial resolution with dates ranging from 2013 to 2016, and all generated under summer leaf-on conditions.

We obtained three sets of aerial images for both the Cedar River and Elwha River to test the ability of our remote sensing methods to detect changes in habitat metrics from restoration. In the Cedar River watershed, we surveyed habitats below the Landsburg Diversion Dam using aerial images acquired from King County for May 2009 (leaf-on), April 2012 (leaf-off), and March 2015 (leaf-off). In the Elwha River, we surveyed habitats below the former Elwha Dam using aerial imagery acquired from the U.S. Geological Survey and National Park Service for August 2008, September 2013, and September 2016. These aerial images represent pre, during, and post dam removal (the Elwha Dam was removed in 2012) and were all flown during leaf-on conditions.

We also utilized lidar digital elevation models (DEMs) with a spatial resolution ranging from 0.9 to 1.8 meters and a vertical resolution of 30 cm or less to delineate floodplain extent (Puget Sound Lidar Consortium, http://www.pugetsoundlidar.org).

Floodplain delineation

We manually digitized all floodplains in Puget Sound in ArcGIS, using lidar DEM data and aerial photography to guide location of floodplain boundaries (Beechie *et al.*, 2017). Manual digitizing allowed us to exclude low terraces that had little potential for development of salmon habitat (often 5 m or more above the channel elevation), and include important floodplain habitat features missed by automated methods (especially where lidar was unavailable). Within each river, the digitized floodplain extent was restricted to habitat upstream of delta boundaries and included all rivers and streams with drainage areas greater than 50 km^2 (Figure 1). In Puget Sound, rivers with a drainage area of 50 km^2 or greater have a bankfull width of at least 15-20 m, which is the threshold size range at which rivers begin to exhibit floodplain habitat features such as braids and side channels (Beechie *et al.*, 2006). Because the purpose of this monitoring effort is to track changes in salmon and steelhead habitat over time, we excluded river sections that were above natural and man-made salmon migration barriers and therefore not accessible to salmon or steelhead (StreamNet Project, 2012).

Floodplain stratification

We stratified large rivers and floodplains by valley type to examine the natural potential of floodplain habitats by geomorphic setting, and by land use to examine the influence of land use on habitat features (Beechie *et al.*, 2017). To stratify by valley type we used geomorphic process domains defined by Collins and Montgomery (2011), which includes glacial valleys, post-glacial valleys, canyons, and mountain valleys (Figure 2). The geomorphic process domain sets the range of potential conditions and therefore dictates possible channel patterns (i.e., the geomorphic process domain is independent of land use, whereas channel pattern is sensitive to land use). Glacial valleys are aggrading as they gradually fill deep glacial troughs carved by sub-glacial melt under the Puget lobe of the continental ice sheet (Collins and Montgomery, 2011), which retreated from Puget Sound approximately 16,500 years ago (Porter and Swanson, 1998). Post-glacial valleys are incising into glacial sediments deposited in river valleys blocked by the Puget lobe during the last continental glaciation (Collins and Montgomery, 2011). Mountain valleys are generally above a bedrock canyon transition from the lowland glacial fill to higher elevation bedrock mountains, and have relatively smaller floodplains (Collins and Montgomery, 2011). Canyons are confined sections of river with little or no floodplain (valley width to channel width ratio <4, Beechie et al. 2017), usually in a relatively short transition zone between mountain valleys and glacial or post-glacial valleys (Collins and Montgomery, 2011; Beechie *et al.*, 2017). To map valley types, we first used the published map of valley types from Collins and Montgomery (2011), and then filled in missing valley type designations using the above definitions.

We stratified by land cover using NOAA's Coastal Change Analysis Program (C-CAP) 2010 data, which we aggregated into five main classes: forest, agriculture, developed, water, and other (NOAA Coastal Services Center, 2014; Beechie *et al.*, 2017). We stratified each contiguous floodplain area by visually marking changes in land cover within a valley type, and then classifying by dominant land cover within each segment (i.e., the highest proportion of forested, agriculture, or developed land cover, excluding the water and other cover types; Appendix Figure A1).

Habitat measurements and metrics

We digitized habitat features following the protocols in Beechie *et al.* (2017), including the main channel, side channels, braids, and wood jams (Figure 3). The main channel was the flow path carrying the most water, braids were secondary wetted flow paths separated from other flow paths by gravel bars, and side channels were secondary wetted flow paths separated by vegetated islands (Beechie *et al.*, 2017). Both braids and side channels contain important salmon and steelhead habitats, and strongly influence production of juvenile salmonids from rivers (Beechie *et al.*, 1994; Whited *et al.*, 2013; Hall *et al.*, 2018). The number of side channel or braid channel nodes was the number of channels multiplied by two (one node where the side channel or braid separates from another flow path and a second where it rejoins). The number or density of nodes (nodes/km) has been used as an indicator of habitat complexity and is correlated with floodplain habitat area (Whited *et al.*, 2013). Finally, we digitized all wood jams with area >20 m^2. Wood is important for maintaining habitat diversity and high habitat quality for juvenile salmonids in large rivers (Beechie *et al.*, 2005; Latterell *et al.*, 2006; Collins *et al.*, 2012; Pess *et al.*, 2012). A single observer performed all measurements to reduce observer error.

We standardized side-channel and braid length, number of side-channel and braid nodes, and wood jam area to the main stem length to facilitate comparisons among groups with unequal spatial extent (e.g., to compare among land cover strata, where the total length of main channel in developed areas is much less than length of main channel in forested areas). In each case, we divided the total length, number, or area of features within a group by the total length of main channel in the group. The final large river and floodplain habitat metrics were braid length ratio, side-channel length ratio, braid node density, side-channel node density, and wood jam area per main channel length (definitions and measurement methods in Appendix Table A1).

Habitat analyses

We addressed three questions with our habitat analyses:

1. Do habitat metrics vary among geomorphic valley types?
2. Do habitat metrics vary among land cover strata?

3. Can we measure change in habitat metrics through time?

To address question 1, we selected only river segments in the forest land-cover stratum to reduce influence of land use, and compared values of each metric among valley types. We note, however, that the forest land cover stratum includes sites that range from 50% to 100% forested (the remainder is agriculture or developed). Therefore, these sites are less impacted by land use than sites in the other strata, but they are not true reference sites. The distributions of main-channel length, number of sites, and average main-channel length within a site by land-cover and valley type are provided in the Appendix (Table A2). We did not account for the influence of dams upstream of study segments, which are most often located in mountain valleys or canyons. To address question 2, we used the full data set, summarizing habitat metrics by land cover strata. Further, to examine whether effects of land use varied by valley type, we also explored the patterns of habitat metrics by land cover strata within each valley type. Finally, we carried out a multiyear assessment of large river and floodplain habitat in sections of Cedar and Elwha Rivers to address question 3. For these assessments, we compared both the complexity metrics and total length or area of habitat features among years.

In the Cedar River, we evaluated our ability to measure habitat changes as a result of floodplain restoration actions. That is, were changes due to restoration actions significant enough to detect a signal amongst the noise of natural variability? In 2010, the Cedar River Spawning Channel project was constructed at river kilometer (rkm) 5.5, which created a groundwater fed side channel (City of Renton, 2017). In 2013 the Rainbow Bend Levee Removal and Floodplain Reconnection Project was completed at rkm 17.2 creating two new side channels (King County, 2016). In each photo year, we digitized all visible side channels throughout the Cedar River and eliminated others that were shortened by channel migration or became obscured by canopy cover. In some cases new channels had been created by restoration actions, and in other cases new channels were created naturally through channel migration or became visible in leaf-off conditions (i.e., the channel was not visible in the 2009 image with leaf-on conditions but was visible in the 2012 and 2015 images in leaf-off conditions). To distinguish among the potential causes of changes in metrics, each channel change was attributed to (1) restoration, (2) change in canopy cover, or (3) natural variation between years.

In the Elwha River, we examined whether we could detect changes in braids, side channels, and wood jam area due to removal of two dams upstream of the study section. In 1913, the 32-m high Elwha Dam was constructed at river kilometer 8, and in 1927, the 64-m high Glines Canyon Dam was constructed at river kilometer 22 (Draut and Ritchie, 2013). Dam removals were completed in April 2012 and October 2014, respectively. Collectively, The Elwha and Glines Canyon Dams impounded nearly 21 million m^3 of sediment and stored pre-dam woody debris within reservoirs (East *et al*., 2015). Their removal presented an opportunity to track changes in floodplain habitat due the rapid influx of new sediment and wood. For instance, during the first two years after dam removal, sediment release totaled nearly 7.1 million m^3 (East *et al*., 2015). As with the Cedar River example, we tracked feature changes due to natural variation, as well as the influence of individual large features that obscured underlying trends in habitat metrics through time (all photos were in leaf-on conditions for this site).

Results

Valley type influences on habitat metrics

Post-glacial valley types in Puget Sound have the highest braid and side-channel to main channel length ratios, as well as the highest wood jam area (Figure 4). Mountain valley types had the highest braid and side-channel node densities. However, post-glacial valleys also had relatively high node densities (Figure 4). Canyon valleys had the lowest values for each of the five metrics (Figure 4).

Land cover influences on habitat metrics

All five metrics were highest in the forested land cover stratum, and lowest in the developed stratum (Figure 5). In addition, the relative ranking of metrics among land-cover strata was similar for four of the five metrics. Only the side-channel length ratio had a different ranking, in which the agriculture stratum was equal to that of the forest stratum (0.21 and 0.23 km/km, respectively). Notably, the agriculture stratum had a relatively high mean side-channel length ratio but low side-channel node density, indicating that there were relatively fewer but longer side channels in that stratum relative to the other land cover strata. Wood jam area ranged from less than 50 m^2/km in the developed land cover stratum to over 500 m^2/km in the forested land cover stratum (Figure 5).

We observed a similar pattern in metrics among land cover strata within individual geomorphic valley types (Figure 6). The forested land cover stratum had the highest values for all metrics and valley types, while the developed land cover stratum had the lowest values for all metrics and valley types except one. The one exception was the post-glacial valley type, where the braid node density was higher in the developed land-cover stratum than in the agriculture land cover stratum (Figure 6).

Measuring habitat change through time

In the Cedar River, we observed a substantial change in habitat features from 2009 to 2012, and a much lesser change from 2012 to 2015. Much of 2009-2012 difference was due to the change from leaf-on conditions in the 2009 image to leaf-off conditions in the 2012 images. The braid length ratio, braid node density, and wood jam area increased each photo year from 2009 to 2015 (Table 1). The side-channel length ratio and side-channel node density increased dramatically between 2009 and 2012, but remained relatively stable between 2012 and 2015 (Table 1).

We measured an increase in total side-channel length of 3.40 km from 2009 to 2012 (4.34 km to 7.73 km) and an increase of 0.07 km from 2012 to 2015 (Figure 7). Of the 3.40 km increase, we attributed 0.37 km to restoration (the Cedar River Spawning Channel project), 2.17 km to the change in visibility between leaf-on and leaf-off conditions (Figure 8a and 8b), and the remaining 0.86 km to natural variation between years. Between 2012 and 2015, we identified a decrease in side-channel length of 0.14 km due to natural variation, and an increase of 0.58 km due to side channels created in the Rainbow Bend Levee Removal and Floodplain Reconnection project (Figure 8c and 8d).

In the Elwha River, the braid length ratio and braid node density increased from 2008 to 2013, and then decreased in 2016 (Table 1). There was a steady decrease in side-channel length ratio and side-channel node density from 2008 to 2013 and to 2016 (Table 1). Wood jam area decreased from 2008 to 2013, and subsequently increased in 2016 (Table 1, Figure 9). Of the 42,396 m^2 area measured in 2008, we attributed 20,444 m^2 to a single wood jam complex on the floodplain. By 2013, the jam complex was largely covered by vegetation, and we attributed only 3458 m^2 of wood jam area to that complex. In 2016, the wood jam complex was completely covered by vegetation. When we separated out the single wood jam complex, wood jam area in channels increased from 5782 m^2 in 2008, to 12,518 m^2 in 2013, and then to 21,952 m^2 in 2016.

Discussion

Our study revealed that natural physical potential and land use both profoundly influence the types and abundance of habitat features in large river and floodplain environments. Moreover, through a multiyear analysis of large river and floodplain habitats in Cedar and Elwha Rivers, we were able to demonstrate that our methods can serve as a simple and effective tool for monitoring habitat changes through time.

Valley type influences on habitat metrics

By comparing habitat metrics across valley types in only predominantly forested floodplain river sections, which we consider the least impacted among the land cover strata, we found that habitat metrics varied systematically among geomorphic settings. Not surprisingly, all of the habitat metrics were lowest in canyon river sections, which have little or no natural floodplain.

This is consistent with prior studies, which found that confined valleys (floodplain width < four times the bankfull channel width) have little potential to create side channels or braids, and limited channel migration and wood recruitment (Beechie *et al.*, 2006; Hall *et al.* 2007). Hence, canyon river sections have fewer and shorter braids and side channels, and reduced channel migration and wood recruitment results in low wood jam area (Chone and Biron, 2015). However, confined rivers have higher leaf litter input and invertebrate production, but rivers with floodplains have higher retentive capacity for such inputs as well as greater species richness (Bellmore and Baxter, 2014).

Braid node densities were approximately three times higher than side-channel node densities in unconfined valley types (glacial, post-glacial, and mountain valleys), while braid and side-channel length ratios were of roughly equal magnitude. This suggests that braids on average are roughly one-third the length of side channels in unconfined river sections, and that there are about three times as many braids as side channels.

Glacial valleys had less habitat complexity than post-glacial valleys, perhaps reflecting the natural tendency toward low-slope, meandering channels with lower potential for side channel development (Beechie *et al.*, 2006, Collins and Montgomery, 2011). Meandering channels naturally have combined side-channel and braid length ratios near 1, whereas island-braided channels (the dominant channel type in post-glacial valleys) can have combined side-channel and braid length ratios as high as 4.5 (Beechie *et al.*, 2006). While differences in length ratios between the two valley types were not as dramatic in this study, the difference we did observe likely reflects the greater natural potential for side channel development in island-braided channels.

Land use influences on habitat metrics

Habitat abundance and complexity decreased with increasing degree of human influence, with all metrics being highest in forested areas and lowest in developed areas. However, side-channel, braid-channel, and wood jam metrics can be altered independently by adjacent land uses. Thus, no single metric provides a comprehensive measure of habitat change. For example, in the absence of floodplain development or bank armor to restrict channel migration, erosion of floodplain surfaces recruits substantial amounts of wood to river channels and may create side-channels and braids (Latterell *et al.*, 2006; Collins *et al.*, 2012). However, increased channel confinement in developed areas restricts natural side-channel creation and wood recruitment, but channel braiding within the confined area may be maintained (Collins *et al.*, 2002; Chone and Biron, 2015). Similarly, wood can be removed from channels for flood conveyance without substantially altering side-channel or braid length. Because the combination of these metrics is related to salmon productivity in several watersheds (Hall *et al.*, 2018), quantifying all five metrics offers a more complete habitat assessment.

In general, post-glacial and mountain valleys tended to contain island-braided channels, whereas glacial valleys tended to contain meandering channels (Collins and Montgomery, 2011). In a study of braid and side-channel length ratios among channel patterns in relatively natural floodplain sites in western Washington, Beechie *et al.* (2006) found that the combined side-channel and braid length ratios of island-braided channels ranged from 0.4-4.7 km/km, whereas length ratios in meandering channels ranged from 0.1-1 km/km. By comparison, our combined braid and side-channel length ratios for post-glacial and mountain valleys ranged from only 0.5 to 0.7 km/km, which is at the low end of the published range for island-braided channels. However, the combined mean braid and side-channel length ratios for glacial valleys (0.44 km/km) are in the middle of the range for meandering channels. This is likely a consequence of the fact that study sites in the Beechie *et al.* (2006) study were nearly entirely forested, whereas our predominantly forested sites could have developed and agricultural land uses on as much as half of the floodplain area. Therefore, post-glacial or mountain valley sites that naturally would have high side-channel length ratios may have dramatically reduced length ratios when even a relatively small proportion of the floodplain is converted from forest to another land cover class. By contrast, the glacial valleys would naturally have low combined braid and side-channel length ratios, so even conversion of nearly half of the floodplain to non-forest land cover results in little reduction of braid and side-channel lengths. However, we also note that our data do not measure the changes to floodplain ponds and marshes, which may have been substantial in sections with meandering channels (Chone and Biron, 2015).

In natural floodplain systems in this region, island-braided channels have high riparian species diversity and wood recruitment (Collins and Montgomery, 2002; Latterell *et al.*, 2006; Naiman *et al.*, 2010). However, development of floodplains for agriculture or urban uses restricts the area available for channel migration. Past studies have shown that increasing development through time decreases the length and complexity of side channels (Beechie *et al.*, 1994; Hohensinner *et al.*, 2004), and that bank armoring or placement of roads and railroads to limit channel migration results in less diverse riparian vegetation, a simplified planform, and reduced habitat diversity (Blanton and Marcus, 2013; Chone and Biron, 2015). Such habitat changes result not only in local losses of habitat complexity, but at the river basin scale can result in population level changes in salmon production (Beechie *et al.*, 1994).

Detecting habitat change through time

Our aerial photography based monitoring approach has two key advantages that facilitated our ability to detect habitat change through time in river and floodplain habitats in the Cedar and Elwha Rivers. First, we conducted a complete census of all habitats in each river basin, so we were able to detect even small habitat changes. Second, by revisiting archived aerial photography we were able to identify and separate sources of variation in metrics, including natural variability, differences between leaf-on and leaf-off conditions, the influence of large and transient features, or changes due to restoration actions. Hence, we can track multiple sources of habitat change through time, which allows us to isolate and quantify habitat improvement or degradation from natural processes, restoration, or development.

In both of our test cases, there were large changes in habitat metrics that at first overwhelmed the signal from restoration. However, our method allowed us to parse out individual sources of variation, thereby improving our ability to detect underlying trends in habitat metrics due to restoration. In the Cedar River, the additional side channel length from the two restoration projects was 11% of the total length of side channels in 2015, while the additional side channel length attributed to leaf-off versus leaf-on conditions and natural variability were 28% and 6%, respectively. Therefore, we were able to detect a relatively small change due to restoration even when the influence of other sources of variation was 3 times larger. Similarly, in our test in the Elwha River, a single large wood jam obscured the underlying pattern of increasing wood jam area in channels after removal of an upstream dam. When we accounted for that single jam area separately, we found that wood jam area in channels increased dramatically, by 116% from 2009 to 2013 and another 75% from 2013 to 2016. This increase was likely due to the release of stored wood in the reservoir, as well as increased floodplain erosion resulting from increased sediment supply (East *et al*., 2015). Both examples indicate that being able to parse sources of change in the metrics allows us to distinguish effects of restoration even when other sources of change (e.g., season of photography, natural variation) are much larger.

Limitations

We utilized available leaf-on aerial photographs to map channel features because leaf-off photography is not widely available. Use of leaf-on photography likely introduces a detection bias as side-channel features are more easily identified in open areas (e.g., agriculture) and tend to be obscured by canopy in forested areas, which likely results in an underestimate of side-channels. Assuming this relative bias in side channel detection among land cover classes, our assessment likely underestimates the influence of land cover change on the side-channel length ratio and side-channel node density because our estimate of side-channel metrics is biased low in the forested land cover stratum. In addition to the bias imposed by leaf-on imagery, side channel length and size scale with channel width (Beechie et al. 2006), so side-channels in mountain valleys and canyons where rivers are smaller are more difficult to detect than side-channels in glacial and post-glacial valleys where rivers are larger. Nonetheless, our protocols were designed to maintain consistency of measurements among observers (Beechie et al. 2017), so change detection through time should be minimally affected by this bias.

We utilized aerial photographs acquired generally under low flow conditions. However, exact river stage information was difficult to ascertain because photograph acquisition may have occurred over a protracted period within one region. A recent study using aerial photography to assess riverine habitats found that braid channels could be obscured during high river stages as gravel bars are inundated (Konrad et al. 2018). Consequently, this may also result in underestimation of braid length when imagery was acquired during periods of higher flow. Future work should address these limitations by testing these detection biases using bare-earth lidar data and ground-truthing to delineate channel features in randomly chosen reaches, and then comparing those results with the results from the photographic analysis.

Conclusions

In this paper, we used a system-wide census of large river and floodplain habitat features to evaluate influences of valley form and land use along 2,237 km of river in the Puget Sound region of Washington State, USA. Using this unique large data set, we were able to quantify differences in abundance of habitat features among geomorphic valley types and among land cover classes. These results confirm the common expectation that increasing conversion of forested floodplains to agriculture and development reduces the abundance and complexity of large river and floodplain habitat features. Moreover, because we applied this methodology across diverse geomorphic settings and land cover types in a heavily forested area, we anticipate that our methodology should be broadly applicable in other physical and climatic settings.

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Tables

Table 1. Results from habitat survey of braid and side-channel length ratios (km/km main channel), braid and side-channel node density (nodes/km main channel), and wood jam density (area of wood jams/km main channel) in Cedar River between 2009, 2012, and 2015; and in Elwha River between 2008, 2013, and 2016.

River	**Year**	**Braid length ratio (km/km)**	**Braid node density (nodes/km)**	**Side-channel length ratio (km/km)**	**Side channel node density (nodes/km)**	**Wood jam area (m^2/km)**
Cedar	2009	0.08	2.24	0.12	1.42	123.12
	2012	0.10	2.86	0.21	2.31	166.93
	2015	0.11	3.18	0.21	2.25	186.88
Elwha	2008	0.17	4.39	0.71	2.82	4110.68
	2013	0.57	12.91	0.57	2.10	2398.75
	2016	0.28	7.22	0.42	1.67	3048.85

Figures

Figure 1. Map of Puget Sound study region, including all sampled large rivers in black.

Figure 2. Geomorphic process domains for large river and floodplain strata (adapted from Beechie *et al.*, 2017).

Figure 3. Illustration of digitized habitat features in one section of the Skagit River basin. Note that braids and side channels are digitized to the edge of the main channel rather than the centerline, which provides a more accurate and repeatable length measurement. Note that the number of nodes equals twice the number of braid and side channel features.

Figure 4. Census results summarized by glacial (GL), post-glacial (PGL), canyon (C), and mountain (MTN) geomorphic valley types within the forest land-cover stratum: (a) braid to main channel (MC) length ratio, (b) side-channel (SC) to main channel (MC) length ratio, (c) braid node density, (d) side-channel (SC) node density, and (e) wood jam area.

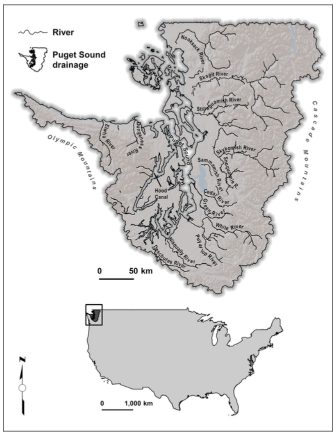
Figure 5. Census results summarized by forest, agriculture, and developed land cover stratum for (a) braid to main channel (MC) length ratio, (b) side-channel (SC) to main channel (MC) length ratio, (c) braid node density, (d) side-channel (SC) node density, and (e) wood jam area.

Figure 6. Census results summarized by forest/wetland (F), agriculture (A), and developed (D) land cover strata, within glacial (GL), post-glacial (PGL), canyon (C), and mountain (MTN) geomorphic valley types: (a) braid to main channel (MC) length ratio, (b) side-channel (SC) to main channel (MC) length ratio, (c) braid node density, (d) side-channel (SC) node density, and (e) wood jam area.

Figure 7. Side-channel length measurements summarized by year within Cedar River. “Restoration” is differences in measurements from side channel restoration projects; “Visibility” is differences in measurements from visibility between leaf-on and leaf-off conditions; “Natural variation” is differences in measurements from natural variation between years.

Figure 8. Illustration of side channel measurements (pictured in blue) between imagery from May of 2009 with full leaf-on canopy (A) and April of 2012 with leaf-off (B) canopy; and illustration of Rainbow Bend Levee Removal and Floodplain reconnection project side channel measurements before restoration outset in April of 2012 (C) and after project completion in March of 2015 (D).

Figure 9. Summarized results of wood jam area measurements by year within Elwha River.



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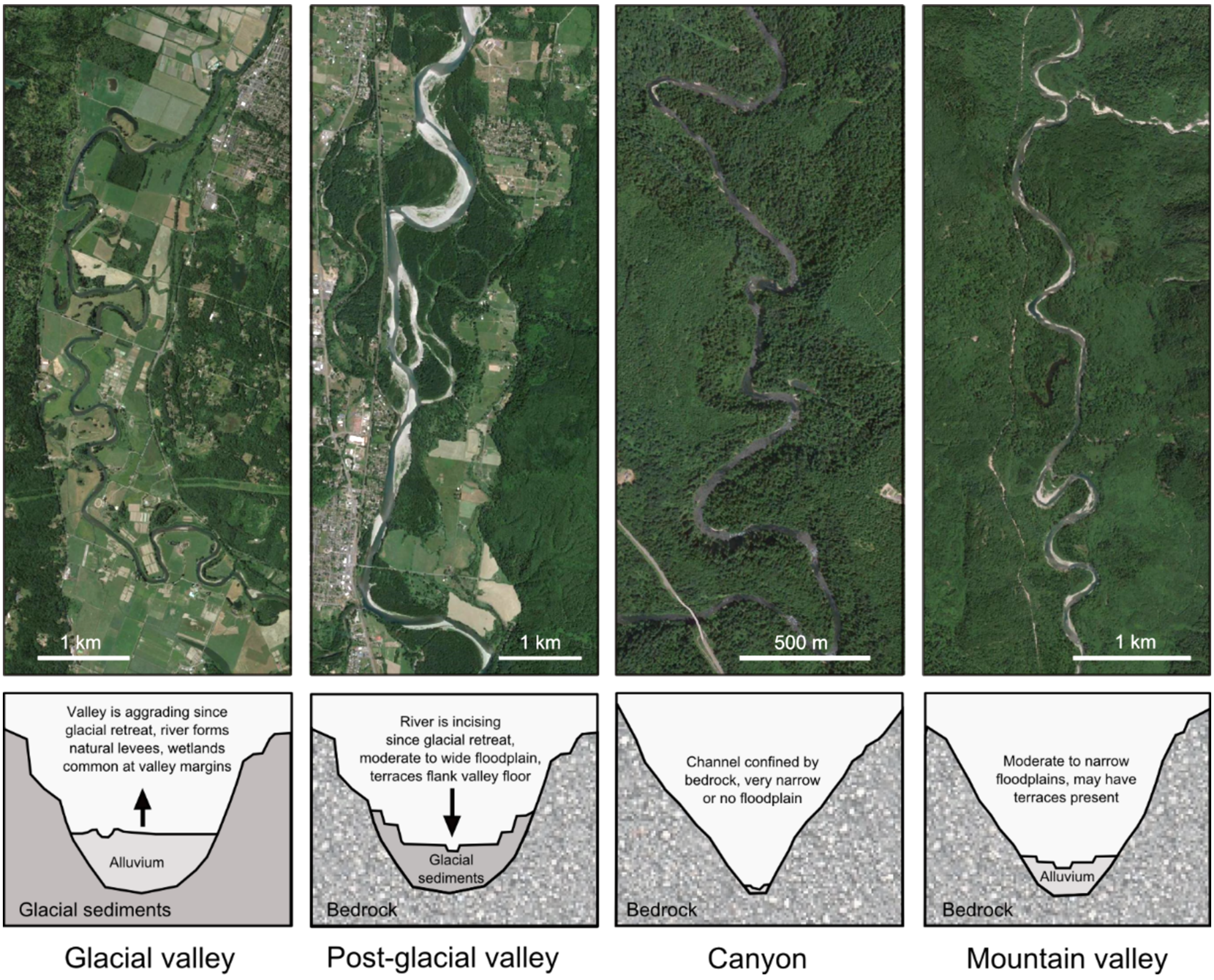

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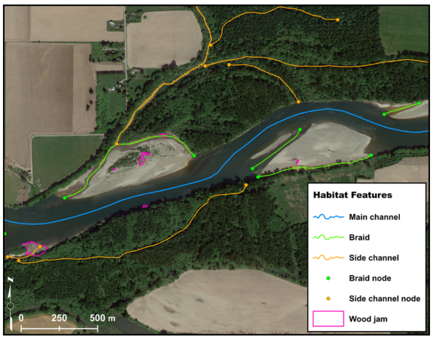

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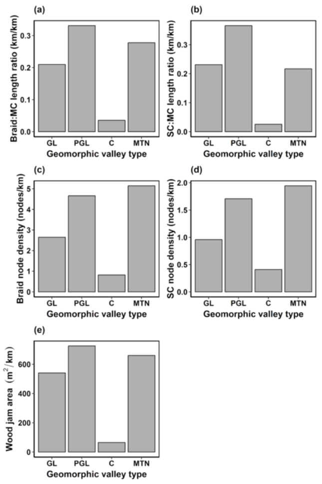

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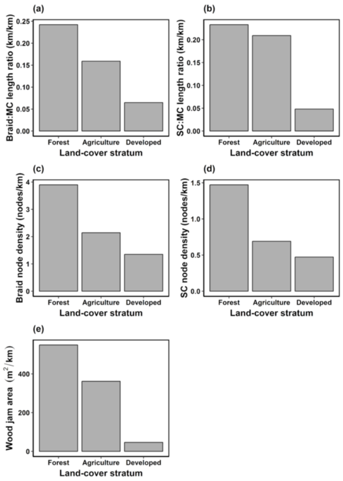

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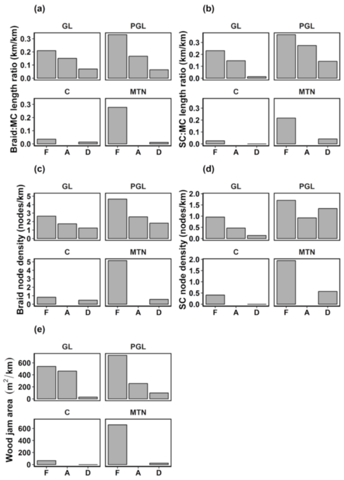

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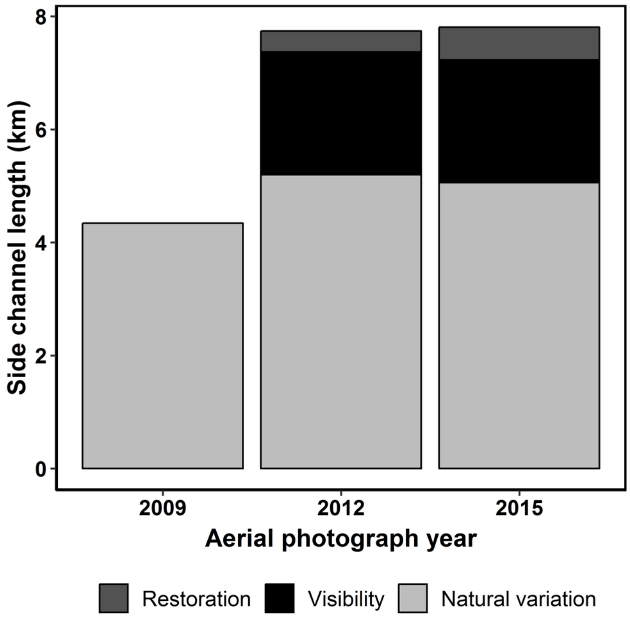

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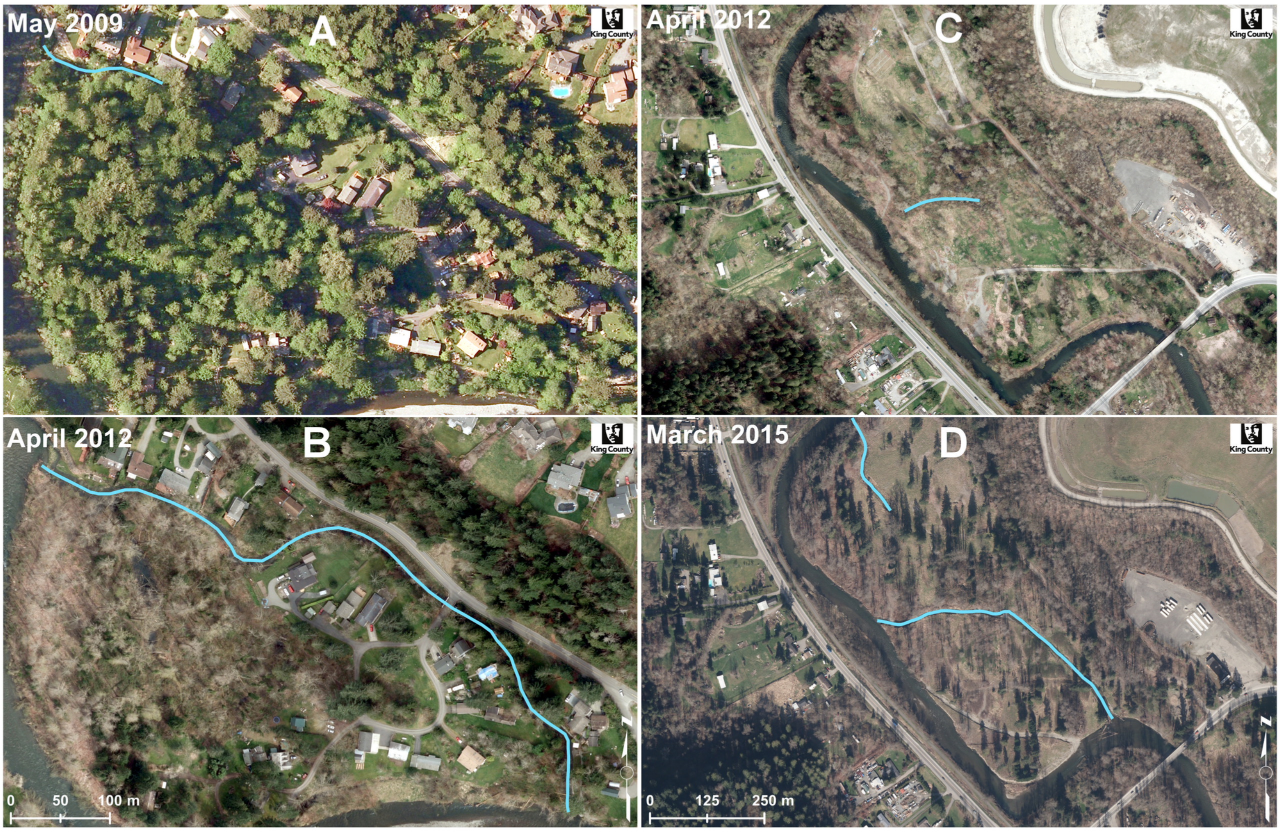

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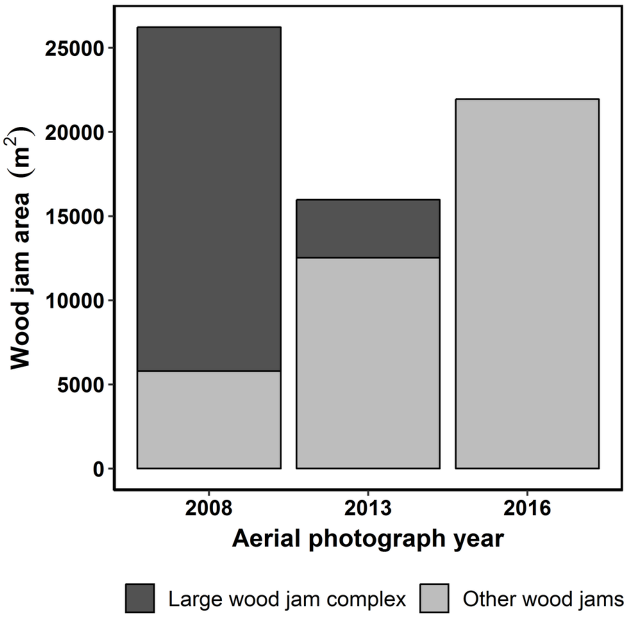

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