Hood Greg (Orcid ID: 0000-0001-6286-7935)
Thom Ronald (Orcid ID: 0000-0002-8639-6709)

Using Landscape Ecology Principles to Prioritize Habitat Restoration Projects Across the Columbia River Estuary

Running head: estuary landscape restoration assessment

Authors: W.G. Hood[a*], K. Blauvelt[b], D.L. Bottom[c], J.M. Castro[d], G.E. Johnson[e], K.K. Jones[f], K.L. Krueger[g], R.M. Thom[h], and A. Wilson[b].

[a]Skagit River System Cooperative, PO Box 368, LaConner, Washington 98257, USA, ghood@skagitcoop.org

[b]PC Trask and Associates, Inc. 1220 SW Morrison, Suite 1300. Portland, Oregon 97205, USA, katie@pctrask.com; andy@pctrask.com

[c]U.S. National Marine Fisheries Service National Oceanic and Atmospheric Administration (retired), USA, dan.bottom@gmail.com

[d]U.S. Fish and Wildlife Service, Columbia River Fish and Wildlife Conservation Office, 1211 SE Cardinal Court, Suite 100, Vancouver, Washington 98683, Janine_M_Castro@fws.gov

[e] Pacific Northwest National Laboratory (retired), 620 SW 5th Avenue, Portland, Oregon, 97204, USA, gary.johnson@bioanalysts.net

[f]Oregon Department of Fish and Wildlife (retired), 28655 Hwy 34, Corvallis, Oregon 97333, USA, k.jones.corvallis@gmail.com

[g]Washington Department of Fish and Wildlife, PO Box 43200, Olympia, Washington 98504-3200, USA, kirk.krueger@dfw.wa.gov

[h]Pacific Northwest National Laboratory (retired), 1529 W. Sequim Bay Road, Sequim, Washington, 98382, USA, thom.ronald@gmail.com

*Corresponding author

This is the author manuscript accepted for publication and has undergone full peer review but has not been through the copyediting, typesetting, pagination and proofreading process, which may lead to differences between this version and the Version of Record. Please cite this article as doi: 10.1111/rec.13519

This article is protected by copyright. All rights reserved.

Author Manuscript

Author Manuscript

Author contributions: All authors contributed to writing and editing the text; WGH provided final editing; KB, AW developed figures and tables, and wrote Supplement S1.

Abstract

To increase survival of diverse Columbia River salmon populations and life history types, we developed a landscape framework for habitat restoration to assess and reduce habitat fragmentation, and thereby improve habitat functions. For the last two decades, aquatic habitat has been restored in the Columbia River Estuary to aid salmon and steelhead (*Oncorhynchus* spp.) listed under the Endangered Species Act. The 234-km long estuary exhibits tidal to fluvial gradients in hydrology, sedimentology, and ecology, punctuated by large tributary rivers, cities, and land uses; it has lost two-thirds of its historical floodplains and wetlands to development. Since 2009, an expert panel has assessed potential benefits of proposed restoration projects based on habitat "opportunity" (accessibility to juvenile salmon) and "capacity" (attributes supporting salmon production). These criteria favored large restoration projects located near the mainstem river, but they were insufficient for assessing a project's benefits due to geographic location relative to existing habitat. Our landscape framework applies the concept of restoring and conserving habitat "stepping stones" of appropriate size and location to benefit juvenile salmon growth and survival throughout their estuary residency and migration. We also compared contemporary and historical landscape conditions to identify restoration priorities. We improved our restoration project assessments by evaluating each project's benefits to juvenile salmon according to its location in the estuary relative to other habitat. Our approach operationalizes landscape ecology-based decisions within the Columbia River Estuary for migratory salmon and is applicable to other large estuary systems with migratory aquatic species.

Author Manuscript

Key Words: juvenile salmon migration, river corridor restoration, stepping-stone habitat

Implications for Practice:

- Using a landscape framework to help assess restoration projects can improve large-scale, long-term restoration planning by identifying important knowledge gaps (uncertainties), landscape-scale variation in habitat loss, and previously underappreciated restoration opportunities.
- A landscape framework and stepping-stone model provide new information, and thereby complement, a site-specific evaluation process by providing a conceptual foundation, ecological criteria, and metrics to identify restoration priorities across a large and complicated landscape.
- Identification of landscape-scale restoration needs and priorities can allow long-term, proactive cultivation of strategic restoration projects with potential restoration partners, in addition to more common, relatively short-term reactive responses to opportunistic restoration projects.

Author Manuscript

Introduction

There are 874 species of migratory freshwater and diadromous fish that require laterally and longitudinally connected habitats to complete their life cycles (Bower et al. 2015). Diverse habitats from shallow streams to deep rivers, as well as associated lakes, floodplains, side channels, tidal, riparian, and lacustrine wetlands, and other associated habitats support spawning, rearing, and refuge from disturbance or predation (Bower et al. 2015). Disconnection, fragmentation, and loss of these habitats threatens the conservation of these migratory species and requires a landscape-scale perspective to guide habitat restoration. Here we present an example of a landscape framework for habitat restoration along a migratory corridor for threatened Pacific salmon in the 234 km-long Columbia River Estuary (CRE). This landscape framework can be tailored to conservation of other migratory fish species in other rivers according to the biological, geological, and sociological constraints of those systems.

Aquatic habitat restoration is a priority in the CRE because estuarine habitat loss, especially juvenile rearing habitat, reduces salmon survival, abundance, and life history diversity (Bottom et al. 2005a; Burke 2004). Since the late 1800s, nearly 70% of vegetated tidal wetlands in the CRE have been lost to development (Kukulka & Jay 2003; Marcoe & Pilson 2017), eliminating much rearing habitat for salmon and reducing wetland macrodetritus production that supports salmonid food webs (Simenstad et al. 1990; Maier & Simenstad 2009).

To mitigate impacts of the federal hydropower system on salmon, the Expert Regional Technical Group (ERTG) was asked by the Bonneville Power Administration and the U.S. Army Corps of Engineers to develop a scientifically-rigorous process for assessing juvenile salmon survival benefits of proposed habitat restoration projects (Krueger et al. 2017). Principal criteria of the ERTG's assessment process include the likelihood that a proposed restoration site will be

Author Manuscript

accessible to salmon (habitat opportunity), and the habitat attributes promoting juvenile salmon production (habitat capacity) (Simenstad & Cordell 2000). Salmon may access the site for refuge or prey, and also benefit indirectly through food web subsidies of exported prey and organic material. These criteria encourage restoration projects that are accessible to salmon from the estuary mainstem and sufficiently large to increase salmon-rearing capacity and persistence (Krueger et al. 2017).

Unfortunately, large restoration projects near the mainstem are not widely available, and the discontinuous geographic distribution of restoration opportunities raises questions about the relative benefits of other types of restoration projects. For example, would it be more beneficial for a restoration project to increase the size of an existing habitat, or to restore habitat where none exists? When restoration opportunities that improve access to wetlands are limited, what other actions might benefit juvenile salmon?

Here, we propose a landscape framework to address these questions in the CRE. Our objectives are to: (1) identify landscape metrics to define the geographic distribution of estuarine habitats for juvenile salmon; (2) apply these metrics to quantify historical changes in juvenile salmon habitat; (3) identify restoration priorities to address significant habitat deficits; and (4) evaluate the utility of the landscape framework by comparing the salmon benefits of selected restoration projects using site-scale (i.e., accessibility and capacity) and landscape-scale metrics.

Our landscape framework has been motivated by the management goals and challenges of the system in which we work, which likely resemble those of many other river systems used by migratory species. Every restoration program must address particular management goals (e.g., conservation of particular species), and operate within various natural and anthropic constraints (e.g., volcanic geology, hydropower systems), which vary from system to system. This requires

Author Manuscript

tailoring the restoration program for each system to these goals and constraints, and this can include adapting our landscape ideas to fit local circumstances. To understand how we have tailored our landscape ecology framework to the circumstances of the CRE, we provide a brief introduction to the natural history of juvenile salmon in the CRE landscape.

Juvenile salmon natural history

Historically, the large size and habitat diversity of the Columbia River basin (the size of France) and estuary (234 km long; Fig. 1) have provided ample scope for salmon life history expression. However, anthropogenic habitat loss has concomitantly reduced variation in salmon life histories (Rich 1920; Burke 2004; Bottom et al. 2005a; Jones et al. 2014).

Five species of Pacific Salmon composed of diverse genetic stocks, populations, and life history types are distributed across nearly 190,000 km^2 of spawning and rearing habitat in the Columbia River basin (Bottom et al. 2005a). In 2006 for example, an estimated 168 million hatchery and naturally produced juvenile salmon migrated through the estuary to the ocean (NMFS 2011). The migratory pathways of juvenile salmon and the habitats they encounter are functions of the geography (e.g., location of entry into the CRE) and life histories of each population. Salmon from different populations are not uniformly distributed across the tidal-freshwater gradient (Rich 1920; Bottom et al. 2011), but display distinct patterns of estuary use, including variations in migration timing and geographic distribution (Teel et al. 2014). Population-specific differences suggest it is important to have habitat available throughout the estuary to support the full range of potential migratory and rearing behaviors by salmon.

Habitat and life history diversity are important to salmon population resilience and productivity (Rogers & Schindler 2008; Schindler et al. 2010; Moore et al. 2010). Each life

Author Manuscript

history type represents an alternative survival pathway used by some population members. Salmon life history diversity can be recovered by reconnecting habitats in fragmented estuarine landscapes. In Oregon's Salmon River estuary, life history diversity of the local Chinook salmon (Bottom et al. 2005b) and coho salmon (Jones et al. 2014) populations increased substantially after dikes and tide gates were removed from over 60% of the estuary's tidal marshes. The additional juvenile life histories supported by the restored tidal marshes now account for up to 75% of the returning adult Chinook salmon and 20–35% of the returning adult coho salmon in the Salmon River basin. The Salmon River study was the first to demonstrate empirically that restoring an estuary landscape can rebuild life history diversity and enhance adult production in salmon populations.

Ecological support functions

Ecological support functions of estuaries benefiting juvenile salmon include: transitional habitats for gradual physiological and behavioral adjustments to saline and tidal environments; complex physical structure for refuge from predators and high-water velocities; habitat for the production and export of prey and organic matter that directly and indirectly, respectively, support juvenile salmon foraging; and dynamic landscapes that provide habitats that enable the expression of diverse salmonid life histories necessary for resilient populations (Thorpe 1994; Bottom et al. 2005a; b; Jones et al. 2014).

Ecological support functions can benefit all size classes of juvenile salmon (e.g., Johnson et al. 2015). Small juveniles (40-60 mm) are generally more abundant and have longer average residence times in tidal wetlands than larger juveniles, and therefore often benefit most directly from habitat restoration. However, yearlings (often > 120 mm) can occur in significant numbers

Author Manuscript

and reside for extended periods in the deeper channels of large tidal and floodplain wetlands (Johnson et al. 2015). Additionally, large juveniles that do not enter wetland habitats nevertheless benefit indirectly because tidal and floodplain wetlands export organic matter and prey resources to deeper waters (Ramirez 2008; Eaton 2010; Thom et al. 2018). Stable isotope analyses reveal that juvenile Chinook salmon are supported largely by macrodetrital food webs associated with marshes and other shallow habitats (Anderson 2006; Maier & Simenstad 2009; Maier et al. 2011), most likely by consuming estuarine detritivores (e.g., epibenthic crustaceans) and terrestrial insects (Maier & Simenstad 2009; Bottom et al. 2011).

Landscape and salmon diversity

Tidal and riverine processes create a diverse, dynamic, habitat mosaic along the 234-km gradient from near-coastal marine habitats at the river mouth to river-dominated habitats in the upper estuary. The physical and ecological complexity and discontinuities in process rates characterize eight distinct hydrogeomorphic reaches (Fig. 1, A–H) (Simenstad et al. 2011). Habitat structures and processes are not uniform, nor are they uniformly distributed along the estuary’s tidal-fluvial gradient. For example, the minimum floodplain area required to support a channel network likely varies with tide range along the freshwater-estuarine gradient (e.g., Hood 2007; 2015). In the upper estuary below Bonneville Dam (Reach H), where fluvial processes dominate and tidal range is < 0.3 m, relatively few peripheral floodplain habitats historically existed (Simenstad et al. 2011). Here, off-channel rearing opportunities are limited to a few large islands, wetlands below rocky projections, and the confluences of small tributaries that deliver cool water, food, and sediments to the mainstem. In contrast, extensive off-channel rearing and foraging opportunities are more widely distributed throughout Reaches B and C where the

Author Manuscript

estuary broadens, tidal range is > 3.0 m, and a series of shallow, productive peripheral bays, extensive tidal flats, emergent and forested wetlands, and mainstem island complexes have formed and are shaped by the dynamic interactions of tidal and fluvial forces.

Landscape framework

In the context of landscape ecology, CRE shorelines are composed of patch and matrix habitat. We define patch habitat as off-channel habitats that juvenile salmon can inhabit for many hours, days, or weeks, such as wetlands with blind tidal channels and seasonally inundated floodplains. Matrix habitat consists of the remaining shorelines, such as narrow, fringing wetlands; fringing, riparian forests; and armored or riprapped banks. Shoreline matrix habitats offer limited opportunity for juvenile salmon to avoid river currents, and generally are transitional areas for juvenile salmon, but they may provide important allochthonous subsidies to river food webs and areas of momentary refuge from predation, depending on habitat quality (cf. Garland et al. 2002).

Stepping-stone model

We adapted the concept of migratory corridor stepping-stone habitats (Gilpin 1980; Saura et al. 2014) to account for the spatial continuity of habitats necessary to support the diverse life histories of out-migrating juvenile salmon (Fig. 2). This concept acknowledges the disproportionate significance of small habitat patches in some locations. For example, where wetland rearing habitats are limited by steep bedrock shorelines, even small restoration projects could reduce vulnerability to predation and physiological stress during migration. This may be true where urban development constrains restoration project size, provided urban impacts on

Author Manuscript

water quality do not undermine potential benefits (Simenstad et al. 2005). Even small stepping-stone patches may be critical to sustain the migratory pathways of some rare but critical life history types (e.g., Saura et al. 2014). To apply this concept we defined habitat “patches” as shallow-water tidal channels and wetlands ≥ 2 ha that are regularly inundated, located along shorelines of the CRE mainstem, islands, or major tributaries, and fall within the modeled 2-year flood zone. We choose this size criterion because wetlands < 2 ha do not support complex channel networks (Hood 2007).

Patch spacing

Most wetland and floodplain rearing habitats in the CRE dewater during low river flow and low tides. This forces some rearing juvenile salmon to emigrate to deeper water where they can be exposed to strong currents. Because swimming speed scales with fish size (Bottom et al. 2005a), small salmon are most vulnerable to being carried downstream. Habitat patches should be located within a distance that the current could carry individuals before the tide reverses (about every 6 hours) so fish can reoccupy shallow tidal habitats. If the current averages 0.5 m/s during a tidal exchange, fish will be carried 11 km, 22 km if the current is 1.0 m/s, unless they encounter shoreline eddies. These are common current velocities along estuarine shorelines where juvenile salmon are typically found. These estimates of likely travel distance are in the range of 5 to 36 km/day estimated by recapturing marked juvenile salmon in the estuary (Dawley et al. 1986). We propose that habitats in the CRE be spaced < 5 km apart. Short travel distances likely benefit a greater diversity of juvenile size classes and life history types by providing greater opportunity for accessing diverse rearing habitats.

Author Manuscript

Transition areas

Transition habitats are important for juvenile salmon to adapt to abrupt physical and ecological changes in the estuarine environment. Key transitions include: the upper limits of tidal influence, e.g., below Bonneville Dam, which is the entry point for the many stocks of juvenile salmon originating east of the Cascade divide; near tributary junctions, which are entry points for the many stocks of juvenile salmon originating in large western tributaries such as the Willamette, Lewis, Cowlitz, Kalama, and Sandy rivers; the hydrological and geomorphological changes across estuary reach boundaries (Fig. 1); the upper extent of salinity intrusion; and the high-energy marine environment near the CRE outlet. Seasonal flow and tidal forces change the locations of physical and ecological transitions in what would otherwise be “fixed” hydrogeomorphic reaches. We have selected the areas 5 km upstream and downstream of each reach boundary to characterize habitat within each reach transition area (i.e., 10 km transition area). For context, mean reach length is about 40 km.

Shoreline matrix conditions

Complex physical structure along shorelines can benefit juvenile salmon growth and survival (Tanner 2006; Driscoll et al. 2013). Juvenile salmon found along riverine and lacustrine shorelines characterized by natural cover (e.g., undercut banks, overhanging vegetation, and large wood) are more abundant and better fed than those along engineered shorelines (Garland et al. 2002; Tabor et al. 2011; reviewed by Reid & Church 2015). Riprap, for example, disrupts natural processes that create and maintain refuge and foraging habitats for juvenile fish, including: bank erosion, which delivers sediments, recruits large wood, and creates complex shorelines with undercut banks; and riparian succession, which establishes overhanging

Author Manuscript

vegetation and produces and delivers detritus and insects to the estuary. Morley et al. (2012) reported a tenfold greater density of epibenthic invertebrates on unarmored versus armored shorelines of the industrialized Duwamish estuary in Puget Sound. Thus, restoration that improves shorelines along migration corridors can benefit juvenile salmon.

Priorities and rationale

Our conceptual framework (Fig. 2) suggests the following sequence of priorities for estuarine habitat restoration projects to benefit migrating juvenile salmon: (1) establish habitat patches near reach transitions and tributary junctions along both shorelines; (2) reduce travel distances between habitat patches, especially where distance exceeds 5 km; (3) increase opportunities for feeding and residency by increasing the number, size, condition, and access of habitat patches; and (4) improve the habitat quality of shorelines. These priorities provide for gradual physiological transition; increased access to habitat patches; opportunity for increased residence, growth, and survival; and reduced stress and mortality between habitat patches.

Methods

We evaluated the condition of estuarine landscapes for migrating juvenile salmon using GIS mapping techniques to characterize the distribution of shallow-water and shoreline habitats. The analysis used a series of geographical metrics to characterize habitat availability in key transition areas and to map the spatial distribution and proximity of habitats relative to the stepping-stone model. We quantified changes in these metrics by comparing contemporary and historical habitat distributions and identified restoration needs and priorities according to the objectives described above. Finally, we developed and applied a methodology for assessing the landscape-scale contributions of individual restoration projects that previously had been evaluated at the site-scale only.

Landscape priorities and metrics

We compared contemporary estuarine landscapes and the effects of restoration project proposals as the percent change relative to historical conditions along each shoreline (Oregon and Washington) and within each estuary reach (A-H). For these comparisons, we calculated the following landscape metrics: (a) total patch count, (b) total patch area, (c) nearest-patch distance, (d) total shoreline distance, (e) total number of gaps, (f) sum of gap lengths, (g) total patch area near reach transition, (h) total patch area near tributary, (i) total area of functional shoreline, and (j) total area of functional shoreline within 100 m of shore (Table 1; Supplementary Material). Functional shorelines included both matrix and patch habitat bordering the shoreline without levees, armoring, riprap, or other anthropogenic hardening. To summarize results across metrics and compare among reaches, we applied a landscape quality rank (LQ Rank) as the mean rank, from lowest (1) to highest (8) quality, of each landscape metric for each reach. A low LQ Rank suggests overall landscape conditions for salmon are poor compared to historical conditions (details in Supplementary Material).

Historical conditions were estimated from Simenstad et al. (2014) and Marcoe & Pilson (2017), General Land Office survey maps and Office of Coast topographic sheets (circa 1870-1890); contemporary conditions were compiled from Simenstad et al. (2014) and a 2009–2011 lidar surface model. We used GIS (ESRI ArcMap) to delineate habitats and calculate attributes and landscape metrics (Supplementary Material).

Author Manuscript

Author Manuscript

Project assessment and landscape criteria

We added a landscape assessment criterion (LAC) to the site-scale project review process described by Krueger et al. (2017). We defined seven attributes and associated ordinal scores to assess project benefits due to their landscape position (Table 2).

(1) Connectivity and access for salmon species, stocks, and life history types: This attribute considers the ease with which juvenile salmon from different source populations and with different life histories can access a habitat (e.g., site location relative to salmon stock distributions and distance from mainstem), and whether nutrients or salmon prey can be readily exported to the mainstem estuary. Besides travel distance, landscape connectivity can be influenced by variations in tidal velocities, tidal exchange, river flows and channel configurations that determine the travel distance and direction for fish to enter a habitat patch from the mainstem and for nutrients from a habitat patch to be transported to the mainstem.

(2) Presence in priority reach: We identified key estuary transitional areas—Reaches A, B, G, and H—as priorities for estuary restoration and highlighted particularly important areas within these reaches. All anadromous salmonids in the CRE encounter saltwater before entering the ocean in Reaches A and B. Reaches G and H constitute a transition area for upriver stocks entering the estuary from Bonneville Dam. Priority reaches are not ranked. Projects in priority reaches receive a score of 5; other projects receive a score of 1.

(3) Habitat gap size improvement: We score the smallest distance between the nearest upstream and downstream habitat patches remaining after project completion. For example, a project located 1 km from a habitat patch in a 10-km gap leaves a 1-km gap and a 9-km gap. The smaller gap is scored. However, if the project is in the center of the gap, leaving two 5-km gaps, it scores a 5. Projects adding to an existing habitat patch and not filling a gap are scored a 1.

Author Manuscript

(4) Proximity to a reach transition or tributary: We score the distances from the proposed project to large tributaries, reach transitions, Bonneville Dam (if in Reach H), and the ocean (if in Reach A). We score the distance to the Columbia River mainstem if a project is located on a tributary. If the proposed project is within 5 km of a large tributary and a reach transition, Bonneville Dam, or the ocean, the higher of the two scores is applied and the second score is recorded.

(5) Tributary size: Because large tributary confluences afford more transitional habitat for many local and upriver salmon stocks than do small tributaries, those with mean annual flow > 28 m^3/s receive the highest score, those < 0.3 m^3/s the lowest. Stream size scoring criteria reflect the range of tributary sizes found in the CRE and geometric scaling of landforms (e.g., Hood 2007).

(6) Stepping-stone patch size: Small, strategically positioned "stepping-stone" habitats may afford critical resting areas and refugia from predators, even if they are too small to retain individuals for long periods. However, large habitat patches of all types are more beneficial. We give the maximum score to large stepping-stone patches (> 12 ha). Patch size scoring criteria reflect our professional judgment, because there is little information on the effect of habitat size on juvenile salmon residence time, growth rates, etc., although relationships are likely non-linear (e.g., Hood 2007). These relationships also likely vary along the estuarine-fluvial gradient of the CRE.

(7) Synergy with adjacent or nearby habitats: We score synergy by considering the likely degree of interactions between the proposed project with nearby habitats. Strong beneficial interaction implies the project will yield disproportionate benefits, such as enhanced geomorphological dynamics, salmon residency potential, or nutrient export due to their

interaction. We give a score of 1 if the synergistic relationship is likely detrimental rather than beneficial.

Author Manuscript

Evaluating landscape assessment criteria

To evaluate our landscape framework and new landscape assessment criteria (LAC), we selected eight restoration projects that we had previously reviewed using only site-scale criteria (Krueger et al. 2017). Our objective was to better understand how the landscape framework and scoring criteria modified our project evaluation. Projects were selected from seven of the eight reaches (excepting E) to represent a range of circumstances. They ranged from < 0.4 ha to > 40 ha; three projects added to existing patches and filled no gaps; shoreline gap sizes for the remaining five projects ranged from ~1 km to 18 km; all but one of the projects was within 5 km of a tributary or reach transition. For each project, ERTG members scored each of the seven landscape attributes, individually weighted each attribute, assigned a final subjective rank (1-5), and provided summary comments.

Results

Habitat patch count and area

We delineated 629 contemporary habitat patches ranging from 0.004 ha to 1,798 ha; most were < 2 ha (Fig. 3), but totaled < 2% of patch area estuary-wide. Patches < 2 ha were categorized as shoreline matrix habitat for the CRE and its major tributaries. Few habitat patches were found in Reach G on either side of the river; habitat patches were more abundant on the Oregon than the Washington side in Reaches B, C, and F (Fig. 4). Habitat patch number and area have been reduced by 10-90% among reaches compared to historical conditions. The reduction is

Author Manuscript

less obvious in Reach H because patch opportunity has always been geomorphically constrained in this area, but the reduction to contemporary conditions is nevertheless substantial (90%).

Distances between habitat patches

The number and total length of large gaps (> 5 km) between habitat patches have increased in most reaches and the increases are heterogeneously distributed. Large gaps in reaches A, B, and C on the Oregon shoreline have increased by more than 100%, whereas there was no increase in Reach D on either shoreline (Fig. 5). The number of contemporary large gaps among reaches ranges from 3 to 10 (n = 39) on the Washington shoreline and 2 to 12 (n = 50) on the Oregon shoreline. The sum of large gap distances is about 490 km on the Washington shoreline and 620 km on the Oregon shoreline.

Reach and tributary transitions

Patch area in reach transitions was reduced by 50 to 90 percent relative to historical amounts in most reaches (Fig. 6). Patch area has not significantly changed from historical conditions near the ocean on the Washington side, at the Reach G/H transition, nor near Bonneville Dam on the Oregon side. These areas had very little habitat historically. Juvenile salmonids do not have proportionally more patch habitat available in transition zones than in the broader estuary.

No large tributaries enter the Columbia River in Reach H on either side of the river. In the other reaches, patch habitat in tributary transition areas is reduced by 30 to 90 percent from historical to contemporary conditions as a result of levee construction and development. Areas close to large tributaries on the Washington side have very little patch habitat available.

Shoreline condition

Except in geologically constrained reaches G and H, functional shoreline habitat has decreased in area by 50-90% (Fig. 7). Although the 100 m buffer metric is area-based (shoreline width varies significantly within the buffer zone), it serves as a proxy for shoreline length. As such, five reaches have experienced > 40% reduction in the length of available functional shoreline habitat.

Landscape quality rank

Ranking all landscape metrics relative to historical conditions revealed considerable fragmentation of salmon habitat across most estuary reaches (Table 3). Mean LQ Rank ranged from 3.1 to 6.1 (mean = 4.2) on the Washington shoreline and from 2.3 to 6.6 (mean = 4.2) on the Oregon shoreline. Values for the individual landscape metrics used to calculate the landscape quality rank often differed substantially among reaches with similar final ranks. However, even reaches with an intermediate LQ Rank have experienced considerable habitat loss. In Reaches B and F, for example, mean habitat gaps have increased 35-45% on the Oregon shore while historical habitat patch area has declined more than 50% along both shorelines.

Application of landscape metrics to example projects

Landscape metrics were used to evaluate selected restoration projects for prioritization based on their location and proximity to other salmon habitats. Projects located within a priority reach or area tended to receive high scores (e.g., projects 3, 7, and 8) (Table 4). Projects with the three lowest landscape scores (1, 4, and 5) ranked poorly for filling a habitat gap and for location

Author Manuscript

Author Manuscript

(i.e., outside a priority area) or connectivity, or both. We found no consistent relationship between the site-scale and the landscape-scale scores for projects (ERTG 2020). However, several small projects with moderately low site scores received higher landscape scores by providing habitat in priority reaches where off-channel rearing opportunities for salmon are otherwise limited (e.g., projects 2,7, and 8).

Discussion

We designed, operationalized, and applied a landscape-scale framework for evaluating benefits of habitat restoration projects for juvenile salmon in the CRE. The new framework compares contemporary and historical landscape conditions along the Washington and Oregon shorelines, and evaluates the contributions of proposed restoration projects based on their location relative to other habitats. We documented widespread fragmentation of contemporary estuarine landscapes—decreased availability of reach and tributary transition habitats, habitat patch area, and shoreline habitat, and increased gap lengths between habitat patches—that could limit the number and diversity of migratory pathways available to juvenile salmon. The landscape framework and stepping-stone model provide new, landscape-scale information, and thereby complement, the site-specific evaluation process of Krueger et al. (2017).

Identifying landscape priorities

Limited resources make identifying restoration priorities a common challenge for project proponents and for those who make funding decisions. The expert panel process of Krueger et al. (2017) provides guidance for the types, designs, and locations of restoration proposals, but it was not designed to establish a broad strategy for estuary restoration. Conceptual development of

Author Manuscript

landscape perspectives of habitat and populations has a long history in stream and river ecology, but generally exceeds empirical studies (Winemiller et al. 2010) and their application. Here we adapt a conceptual model based on habitat “stepping-stones”, a theory most commonly associated with island biogeography (e.g. Gilpin 1980) and terrestrial resource areas and corridors (Saura et al. 2014), to habitats within an estuary for a migratory species. Similarly, Hulse et al. (2007) proposed cold water refugia as stepping stones for adult salmonids during their return journey in the 215-km Willamette River. They accounted for effective travel distance of adult salmonids to suggest a spatial framework and priorities could be established to rebuild floodplain functions and connectivity where cold water refugia were distantly separated.

In developing our landscape framework, we synthesized information for juvenile salmon from different populations and with different life histories that might use distinct stepping-stone habitats depending upon where and when they enter the estuary. Teel et al. (2014) reported characteristic temporal and spatial patterns of estuary use among Chinook salmon genetic stock groups and life history types within these groups. We analyzed landscape metrics at the estuary reach scale to account for variations in habitat conditions along the estuarine gradient (i.e., tides and river flow, geomorphology, sediment type, etc.) and for reach-specific differences in habitat-use patterns of different genetic stocks and their associated populations (Teel et al. 2014). Our landscape framework provides context for quantitatively comparing landscape metrics to identify restoration priorities. For example, several stocks from the interior basin primarily occupy nearshore habitats in the uppermost reaches (G and H) of the estuary. Historical nearshore changes have been relatively minor where the upper estuary is naturally constrained, but the lack of large habitat patches in this region suggests even small stepping stones may provide critical support for interior basin migrants transitioning into a tidal environment.

Author Manuscript

Restoration often lacks clear connections to system or population needs (Barnas et al. 2015). We quantified changes in landscape metrics to facilitate comparisons among priority reaches, locations within reaches, and project types within each. For example, few habitat patches are present in Reach D and Reach E on either shoreline relative to other reaches, and the proportion of patches lost is high. This suggests habitat restoration in these reaches might be very beneficial. Similarly, the small area of most patches and the large distances between them suggest creating small stepping-stone habitats is a priority in many reaches, especially where large habitat patches cannot be restored or where they did not occur historically. Our summary LQ Rankings only provide coarse information on reaches with least and most change across all metrics. However, a high or intermediate LQ Rank does not ensure that one or more metrics are not substantially degraded.

Quantifying change required spatial information about contemporary and past conditions. Fortunately, information (Simenstad et al. 2014; Marco & Pilson 2017) was available to estimate historical habitat patch area and show a 39,610 ha difference between historical and contemporary patch area in the CRE. The accuracy of our calculated changes is difficult to assess, but because we used contemporary and historical data consistently across reaches our comparisons should reliably identify restoration priorities among reaches.

Information about historical conditions is not a prerequisite for using a conceptual framework to identify restoration priorities. Indeed, it will often not be possible to restore many habitats to historical conditions, because river regulation has fundamentally altered physical, habitat-forming processes. Where habitat restoration is constrained, habitat enhancement or creation of novel habitats might be beneficial.

Author Manuscript

Project assessment using landscape criteria

After identifying landscape priorities, assessing individual project benefits remains important. Landscape assessment criteria allow us to clearly and consistently assess juvenile salmon benefits of individual projects due to their geographic location and to incorporate this information into our project-scale assessments (Krueger et al. 2017).

Assessing the eight example projects allowed us to ensure that no single criterion or attribute was overly influential and that each could help differentiate projects. Five of the seven landscape criteria attributes are quantitative, which reduces variability amongst reviewer scores. The remaining variability reflects uncertainty in valuing subjective project attributes, specifically connectivity and synergy, and in the relative importance of each attribute under individual project circumstances. Synergy was difficult to evaluate because it is strongly affected by geographic proximity to other patches, which is the antithesis of filling a large gap along a shoreline; a high score for synergy often means a low score for gap filling, and vice versa. A large project located near other projects may interact synergistically to enhance ecological functioning of the combined habitat complex. In contrast, a remote site isolated from other habitat patches provides little synergy, but may afford a critical stepping-stone patch to reduce the habitat gap for migrating salmon. Even with some subjectivity in the scoring process, the explicit definition of values for each attribute improved our consistency.

Shoreline matrix, or riparian, habitat should be considered an integral component of the ecosystem (Prugh et al. 2008), particularly for migratory species and life history types that hug shorelines. Comparing salmon residence times might provide insight into the tradeoffs between restoring patch and shoreline matrix habitat. By this measure, restoration of small stepping-stone habitat might partially compensate for hardened shorelines. Further, patches in close proximity

Author Manuscript

are more likely to interact synergistically (e.g., by allowing re-colonization of native plants or producing and exporting a greater diversity of prey). Such determinations likely differ ecologically (e.g., species, life history), geographically (e.g., regions), and temporally (e.g., season, year). They also should be expected to change as the condition of the patch and matrix habitats change.

Project assessment can help project proponents by facilitating comparison of the benefits of different projects and, importantly, different designs of the same project. Attribute scores provide a useful starting point to explicitly evaluate the benefits of a project to fish, its distance from other patches and transitions, and the location within a priority reach or area with little remaining historical habitat. Attribute scores offer a useful pre-screening tool for project sponsors to evaluate the landscape-scale benefits of project proposals before developing a proposal. Discussions with project sponsors and internally among ERTG members highlights the key landscape features of each project and aids the assessment of each criterion's relative contribution to the overall score. The trial scoring of the eight restoration projects reinforced the LAC as a valuable addition to the existing ERTG project review process.

Validating the landscape framework

To develop our landscape approach to restoration we made several assumptions that should be investigated. The type of project (e.g., stepping stone, shoreline matrix habitat), location (e.g., reach transition, proximity to other habitat patches), and project area relative to historical condition (e.g., small stepping stone, long shoreline matrix habitat) address questions of what, where, and how much. The question of "why" assumes defragmentation and enhancement of native habitats in the estuary will result in enhanced growth and survival of out-

Author Manuscript

migrating salmonids. Using two sets of assessment criteria also facilitates project development order (i.e., addressing the question of when) through a comprehensive assessment of existing versus historical conditions, thereby identifying which projects may provide the greatest benefits by reach and throughout the estuary. However, we stress that both identifying landscape priorities and assessing project benefits using landscape criteria are necessarily iterative processes – results of both processes will change as CRE habitat conditions change naturally and due to restoration.

When developing the landscape framework we made several assumptions about system structure and fish usage for which there was qualitative, but limited quantitative information. The key scientific uncertainties include: [1] travel times and spatiotemporal patterns of fish use of the estuary; [2] relatively high value of transition (reach and tributary) areas; [3] minimum habitat size to benefit fish; [4] time spent in patches of various size; [4] value of patch size to feeding and refuge; and [5] value of shoreline matrix habitat. These scientific uncertainties are not unique to the estuary, but are applicable to similar systems regionally and globally. These uncertainties are not critical to proceeding with landscape-scale project assessment, because most restoration projects provide some benefits and have a positive trajectory. Nonetheless, reduced uncertainty and better knowledge of a project's relative importance would further justify the approach and help verify the cumulative benefits of projects to juvenile salmonid fitness and survival. Addressing uncertainties at technical and programmatic levels is ongoing in the CRE restoration effort (Littles et al. In Review).

Rather than tailoring restoration to particular life histories or stocks, our landscape approach emphasizes habitat reconnection to support basin-wide variation in estuary rearing pathways. The habitat needs of all stocks and life history types are only coarsely known, and in

Author Manuscript

recent years we have been repeatedly surprised by habitat assumptions shown to be false, e.g., yearlings using tidal marshes (Littles et al. In Review). Furthermore, habitat needs vary from year to year, depending on variable environmental conditions and disturbances (drought, floods, mass wasting events). Re-establishing habitat connections in each estuary reach will maximize opportunities for life history expression, including alternative life history pathways that are poorly recognized. We believe this approach is applicable to management of many different species and river systems. The details of its design and implementation can be adapted to the natural history and management constraints of each locale.

Acknowledgements

We appreciate the review and oversight provided by the Expert Regional Technical Group's Steering Committee, including Mark Bierman, Anne Creason, Jason Karnezis, Lynne Krasnow, Chanda Littles, Josie Thompson, and Phil Trask. We thank the restoration community for input during development of concepts and applications of the CRE landscape framework. The Bonneville Power Administration's Environment, Fish, and Wildlife organization funded this work through Contract No. BPA-21-C-86539 and No. 56065-Releases 26 and 30 (in part). The findings and conclusions in this manuscript are those of the authors and do not necessarily represent the views of the US Fish and Wildlife Service.

Author Manuscript

Literature Cited

Anderson GO (2006) Variations in Estuarine Life History Diversity of Juvenile Chinook Salmon Based on Stable Isotope Analysis of Food Web Linkages. MS Thesis, University of Washington, Seattle, Washington

Barnas KA, Katz SL, Hamm DE, Diaz MC, Jordan CE (2015) Is habitat restoration targeting relevant ecological needs for endangered species? Using Pacific Salmon as a case study. Ecosphere 6(7):110. http://dx.doi.org/10.1890/ES14-00466.1

Bottom DL, Baptista A, Burke J, Campbell L, Casillas E, Hinton S, Jay DA, Lott MA, McCabe G, McNatt R, Ramirez M, Roegner GC, Simenstad CA, Spilseth S, Stamatiou L, Teel D, Zamon JE (2011) Estuarine Habitat and Juvenile Salmon: Current and Historical Linkages in the Lower Columbia River and Estuary. Northwest Fisheries Science Center, U.S. National Marine Fisheries Service, Seattle, Washington

Bottom DL, Simenstad CA, Baptista AM, Jay DA, Burke J, Jones KK, Casillas E, Schiewe MH (2005a) Salmon at River's End: The Role of the Estuary in the Decline and Recovery of Columbia River Salmon [Memorandum]. NMFS-NWFSC-68. Seattle, Washington: U.S. Department of Commerce, NOAA National Marine Fisheries Service

Bottom DL, Jones KK, Cornwell TJ, Gray A, Simenstad CA (2005b) Patterns of Chinook Salmon Migration and Residency in the Salmon River Estuary (Oregon). Estuarine Coastal and Shelf Science 64:79-93

Bower SD, Lennox RJ, Cooke SJ (2015) Is there a role for freshwater protected areas in the conservation of migratory fish? Inland Waters 5:1-6.

Author Manuscript

Burke JL (2004) Life histories of juvenile Chinook salmon in the Columbia River estuary: 1916 to the present. MS thesis, Oregon State University, Corvalis, Oregon.

Dawley EM, Ledgerwood RD, Blahm TH, Sims CW, Durkin JT, Kirn RA, Rankis AE, Monan GE, Ossiander FJ (1986) Migrational Characteristics, Biological Observations, and Relative Survival of Juvenile Salmonids Entering the Columbia River Estuary. Prepared by the National Marine Fisheries Service for the Bonneville Power Administration, Seattle, Washington

Driscoll DA, Banks SC, Barton PS, Lindenmayer DB, Smith AL (2013) Conceptual domain of the matrix in fragmented landscapes. Trends in Ecology and Evolution 28:605-613

Eaton CD (2010) Resource Partitioning, Habitat Connectivity, and Resulting Variation Among Salmonids in the Estuarine Habitat Mosaic. MS Thesis, University of Washington, Seattle, Washington

ERTG (Expert Regional Technical Group) (2020) Landscape Scoring Exercise. ERTG #2020-03, prepared for the Bonneville Power Administration, National Marine Fisheries Service, and U.S. Army Corps of Engineers. Portland, Oregon. Available at: https://www.cbfish.org/EstuaryAction.mvc/Documents

Garland RD, Tiffan KF, Rondorf DW, Clark LO (2002) Comparison of subyearling fall Chinook salmon's use of riprap revetments and unaltered habitats in Lake Wallula of the Columbia River. North American Journal of Fisheries Management 22:1283-1289

Gilpin ME (1980) The role of stepping-stone islands. Theoretical Population Biology 17:247-253

Author Manuscript

Hood WG (2007) Scaling tidal channel geometry with marsh island area: A tool for habitat restoration, linked to channel formation process." Water Resources Research 43(3):W03409. https://doi.org/10.1029/2006WR005083

Hood WG (2015) Geographic variation in Puget Sound tidal channel planform geometry. Geomorphology 230:98-108

Hulse DW, Branscomb A, Enright C, Gregory SV, Wildman R (2007) Linking cold-water refuges into a biologically effective network in the southern Willamette River floodplain: Outlining key locations and knowledge gaps. Mid-Willamette Valley Council of Governments, Portland, Oregon

Johnson GE, Ploskey GR, Sather NK, Teel DJ (2015) Residence times of juvenile salmon and steelhead in off-channel tidal freshwater habitats, Columbia River, USA. Canadian Journal of Fisheries and Aquatic Sciences 72:684-696

Jones KK, Cornwell TJ, Bottom DL, Campbell LA, Stein S (2014) The contribution of estuary-resident life histories to the return of adult coho salmon, Oncorhynchus kisutch. Journal of Fish Biology 85:52-80

Krueger KL, Bottom DL, Hood WG, Johnson GE, Jones KK, Thom RM (2017) An expert panel process to evaluate habitat restoration actions in the Columbia River Estuary. Journal of Environmental Management 188:337-350

Kukulka T, Jay DA (2003) Impacts of Columbia River discharge on salmonid habitat: 2. Changes in shallow-water habitat. Journal of Geophysical Research 108(C9):3294

Author Manuscript

Littles C, Karnezis J, Blauvelt K, Creason A, Diefenderfer H, Johnson G, Krasnow L, Trask P (In Review) Adaptive management of large-scale ecosystem restoration: Increasing certainty of habitat outcomes in the Columbia River Estuary, USA. Restoration Ecology

Maier GO, Simenstad CA (2009) The role of marsh-derived macrodetritus to the food webs of juvenile Chinook salmon in a large, altered estuary. Estuaries and Coasts 32:984-998

Maier GO, Toft JD, Simenstad CA (2011) Variability in isotopic (δ13C, δ15N, δ34S) composition of organic matter contributing to detritus-based food webs of the Columbia River Estuary. Northwest Science 85:41-54

Marcoe K, Pilson S (2017) Habitat change in the lower Columbia River Estuary, 1870–2009. Journal of Coastal Conservation 21:505-525

Morley SA, Toft JD, Hanson KM (2012) Ecological effects of shoreline armoring on intertidal habitats of a Puget Sound urban estuary. Estuaries and Coasts 35:774-784

Moore JW, McClure M, Rogers LA, Schindler DE (2010) Synchronization and portfolio performance of threatened salmon. Conservation Letters 3:340-348

NMFS (National Marine Fisheries Service) (2011) Columbia River Estuary ESA Recovery Plan Module for Salmon and Steelhead. NMFS Northwest Region, Seattle, Washington. https://www.salmonrecovery.gov/Files/2011%20APR%20files/New%20Folder%203/NOAA_2011_CR_Estuary_Recov_Plan_Mod.pdf.

Prugh LR, Hodges KE, Sinclair RE, Brashares JS (2008) Effect of habitat area and isolation on fragmented animal populations. Proceedings of the National Academy of Sciences 105:20770-20775

Author Manuscript

Ramirez MF (2008) Emergent Aquatic Insects: Assemblage Structure and Patterns of Availability in Freshwater Wetlands of the Lower Columbia River Estuary. MS Thesis, University of Washington, Seattle, Washington

Reid D, Church M (2015) Geomorphic and ecological consequences of riprap placement in river systems. Journal of the American Water Resources Association 51:1043-1059

Rich WH (1920) Early history and seaward migration of Chinook salmon in the Columbia and Sacramento Rivers. Bulletin of the Bureau of Fisheries 37:1-74

Rogers LA, Schindler DE (2008) Asynchrony in population dynamics of sockeye salmon in Southwest Alaska. Oikos 117:1578-1586

Saura S, Bodin O, Fortin M (2014) Stepping stones are crucial for species' long-distance dispersal and range expansion through habitat networks. Journal of Applied Ecology 51:171-182

Schindler DE, Hilborn R, Chasco B, Boatright CP, Quinn TP, Rogers LA, Webster MS (2010) Population diversity and the portfolio effect in an exploited species. Nature 465:609-612

Simenstad CA, Cordell JR (2000) Ecological assessment criteria for restoring anadromous salmonid habitat in Pacific Northwest estuaries. Ecological Engineering 15:283-302

Simenstad CA, Small LF, McIntire CD (1990) Consumption processes and food web structure in the Columbia River Estuary. Progress in Oceanography 25:271-297

Simenstad C, Tanner C, Crandell LC, White J, Cordell J (2005) Challenges of habitat restoration in a heavily urbanized estuary: Evaluating the investment. Journal of Coastal Research SI(40), 6-23

Simenstad CA, Burke JL, O’Connor JE, Cannon C, Heatwole DW, Ramirez MF, Waite IR, Counihan TD, Jones KL (2011) Columbia River Estuary Ecosystem Classification—Concept and Application. 2011-1228. U.S. Department of the Interior, U.S. Geological Survey

Simenstad CA, Ramirez MF, Wagoner HM, Whiting AH, Trask PC (2014) A landscape approach to planning restoration and conservation of anadromous fish habitat across a complex estuarine mosaic: Applications to long-term monitoring and salmon recovery. Proceedings 9th European Conference on Ecological Restoration. Oulu, Finland, 3-8 August 2014

Tabor RA, Fresh KL, Piaskowski RM, Gearns HA, Hayes DB (2011) Habitat use by juvenile Chinook salmon in the nearshore areas of Lake Washington: Effects of depth, lakeshore development, substrate, and vegetation. North American Journal of Fisheries Management 31:700-713

Tanner JE (2006) Landscape ecology of interactions between seagrass and mobile epifauna: The matrix matters. Estuarine, Coastal and Shelf Science 68:404-412

Teel DJ, Bottom DL, Hinton SA, Kuligowski DR, McCabe GT, McNatt R, Roegner GC, Stamatiou LA, Simenstad CA (2014) Genetic identification of Chinook salmon in the Columbia River Estuary: Stock-specific distributions of juveniles in shallow tidal freshwater habitats. North American Journal of Fisheries Management 34:621-641

Thom RM, Breithaupt SA, Diefenderfer HL, Borde AB, Roegner GC, Johnson GE, Woodruff DL (2018) Storm-driven particulate organic matter flux connects a tidal tributary floodplain wetland, mainstem river, and estuary. Ecological Applications 28:1420-1434

Author Manuscript

Thorpe JE (1994) Salmonid fishes and the estuarine environment. Estuaries 17:76-93

Winemiller KO, Flecker AS, Hoeinghaus DJ (2010) Patch dynamics and environmental heterogeneity in lotic ecosystems. Journal of the North American Benthological Society 29:84-99

Author Manuscript

Author Manuscript

Tables

Table 1. Landscape metrics describing reaches on each shoreline of the CRE.

Landscape Metric	Definition
Patch Count	Total number of habitat patches
Patch Area	Total patch area
Nearest-patch distance	Mean distance between nearest habitat patches
Total-shoreline distance	Mean distance between habitat patch nodes along all shorelines
Number of Gaps > 5 km	Count of gaps greater than 5 km. Gaps bridging two reaches were accounted for within the primary reach
Sum of Gap Lengths > 5 km	Cumulative length of gaps greater than 5 km. Gaps bridging two reaches were split, with each segment accounted for in the respective reaches
Hydrogeomorphic Reach Transitions	Total patch area within 5 km upstream and downstream of each reach transition, summed (1) within a reach, and (2) across the reach transition
Tributary Transition	Total patch area within a 5 km radius of each large tributary confluence
Functional Full Shoreline Area	Total area of unarmored, non-leveed shoreline within the two-year flood elevation
Functional Buffered Shoreline Area	Total area of functional shoreline within 100 m of the shoreline

Author Manuscript

Table 2. Landscape assessment criteria attributes, values, and associated ordinal scores for restoration project assessment.

Score	Connectivity/access for most species and populations	Location re: priority reach or area	Location re: habitat gap size	Proximity to large tributary or reach transition	Tributary size (mean annual discharge)	Stepping-stone patch size	Synergy with nearby habitat or restoration project
5	High	Yes	> 5 km	< 0.5 km	> 28 m^3/s	> 12 ha	High
4	Intermediate to high	Yes	2.5 - 5 km	0.5 - 1 km	14 - 28 m^3/s	8 - 12 ha	Moderate
3	Intermediate	Yes	1 - 2.5 km	1 - 2.5 km	3 - 14 m^3/s	4 - 8 ha	None or weak positive
2	Intermediate to low	No	0.5 - 1 km	2.5 - 5 km	0.3 - 3 m^3/s	2 - 4 ha	None or weak negative
1	Low	No	< 0.5 km	> 5 km	< 0.3 m^3/s	< 2 ha	Negative

Author Manuscript

Table 3. Landscape metrics within each reach along the Washington and Oregon shorelines. Shaded cells highlight the poorest values among all reaches. Landscape quality rank (LQ Rank) is the mean rank from lowest (1) to highest (8) quality of each landscape metric for each reach. Reach-transition habitat was measured 5 km above the lower transition and 5 km below the upper transition in each reach. Increases in shoreline habitat gap distances are relative to the historical baseline.

Washington Reaches	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**
Transition Habitats								
Total Reach (% of historical)	88%	33%	12%	4%	6%	10%	1%	41%
Tributary (% of historical)	8%	30%	11%	11%	5%	11%	10%	100%
Gaps								
Shoreline (% increase)	6%	35%	11%	8%	20%	45%	7%	4%
Mean nearest patch (km)	2.58	2.25	2.54	6.02	2.47	5.01	8.31	3.91
# gaps ≥5 km	3	10	4	5	5	5	4	3
Total gap >5 km (% increase)	1%	29%	34%	0%	1%	27%	8%	33%
Patches								
Patch area (% of historical)	8%	28%	15%	8%	17%	45%	11%	71%
Functional Shoreline								
2Y flood (% of historical)	14%	34%	16%	10%	28%	30%	81%	99%
100 m buffer (% of historical)	92%	56%	44%	81%	84%	82%	94%	99%
LQ Rank	**4.6**	**4.2**	**3.3**	**3.0**	**3.9**	**3.7**	**3.9**	**6.0**

Oregon Reaches	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**
Transition Habitats								
Total Reach (% of historical)	15%	26%	26%	34%	17%	67%	8%	93%
Tributary (% of historical)	7%	49%	16%	34%	33%	71%	20%	100%
Gaps								
Shoreline (% increase)	56%	8%	49%	0%	29%	61%	28%	0%
Mean nearest patch (km)	1.81	0.86	1.69	6.46	2.10	4.56	6.47	10.41
# gaps ≥5 km	12	8	9	2	3	7	6	3
Total gap >5 km (% increase)	117%	119%	110%	0%	74%	15%	15%	0%
Patches								
Patch area (% of historical)	12%	49%	16%	34%	11%	30%	8%	95%
Functional Shoreline								
2Y flood (% of historical)	18%	52%	16%	13%	17%	37%	92%	95%
100 m buffer (% of historical)	41%	76%	47%	91%	87%	50%	82%	97%
LQ Rank	**2.3**	**5.0**	**3.2**	**5.2**	**4.2**	**4.4**	**3.8**	**6.5**

Author Manuscript

Table 4. Landscape scoring exercise for eight sample projects. Scoring criteria for the assigned values are defined in Table 2. The mean value is the average of assigned values across all criteria. The mean ERTG score is the average project score for the six ERTG members, which requires subjective judgement about the relative weighting of the criteria for each location. Mean ERTG site scores are the mean of all ERTG member scores for three site-scale criteria in Krueger et al. (2017): likelihood of success, accessibility to salmon from the mainstem, and habitat capacity.

Project	**Connectivity**	**Priority Reach or Area**	**Gap Size**	**Proximity to Transition**	**Tributary Size**	**Patch Size**	**Synergy**	**Mean of Landscape Metrics**	**Mean ERTG Landscape Score**	**Mean ERTG Site Score**
1 (Colewort)	1	5	1	2	4	3	4	2.9	2.5	3.8
2 (Megler)	5	5	5	3	n/a	1	2.5	3.6	3.8	3.2
3 (Kandoll)	2	5	3	1	5	5	5	3.7	3.9	4.3
4 (Dibblee)	3	1	1	2	n/a	3	3	2.2	2.1	2.8
5 (Ruby)	2	1	1	2	n/a	5	5	2.7	2.7	4.0
6 (S. Bachelor)	5	1	4	2	5	5	2.5	3.5	3.8	3.4
7 (Thousand Acres)	4	5	3	3	5	4	3	3.9	4.0	3.2
8 (The Shire)	5	5	4	1	n/a	3	2.5	3.4	4.0	3.3

Author Manuscript

Figure Captions

Figure 1. The eight hydrogeomorphic reaches of the 234-km long Columbia River Estuary (Simenstad et al. 2011).

Figure 2. Conceptual model of stepping-stone migratory corridor restoration for juvenile salmon. Dark gray circles are floodplain wetland habitat patches. Narrow gray rectangles are restored riparian shoreline matrix habitat, which supplements or substitutes for patch restoration (when it is not feasible). Arrows represent the direction of river flow and migration. Loops indicate temporary fish residency.

Figure 3. Distribution of patch sizes throughout the contemporary estuary.

Figure 4. Historical (a) and contemporary (b) patch area for each reach (A-H) and shoreline (Washington and Oregon). Contemporary patch area as a percentage of historical (red squares) is scaled to the right y-axis on the bar graph (c).

Figure 5. Average shoreline distance between patches (a) and cumulative length of shoreline gaps greater than 5 km (b) for each reach (A-H) and shore (Washington and Oregon). Red squares indicate the relative increase from historical to present conditions (right y-axis). An example of between-patch shoreline distances for (c) historical and (d) contemporary conditions, near the transition from Reach A to Reach B on the Oregon side of the river.

Author Manuscript

Figure 6. Comparison by reach (A-H) and shoreline (Washington and Oregon) of patch habitat area within 5 km of reach transitions (a). In Reach A, this includes patches within 5 km of the ocean; in Reach H, within 5 km of Bonneville Dam. (b) Patch area within a 5 km radius of major tributary confluences. Contemporary patch area as a percentage of historical (red squares) is scaled to the right y-axis.

Figure 7. Comparison by reach (A-H) and shoreline (Washington and Oregon) of (a) full two-year flood functional shoreline habitat and (b) functional shoreline habitat area standardized to a maximum 100 m wide buffer. Red squares indicate contemporary conditions as a percentage of historical (right y-axis). Overview of the (c) historical and (d) contemporary full two-year flood functional shoreline habitat.

Author Manuscript

Figures

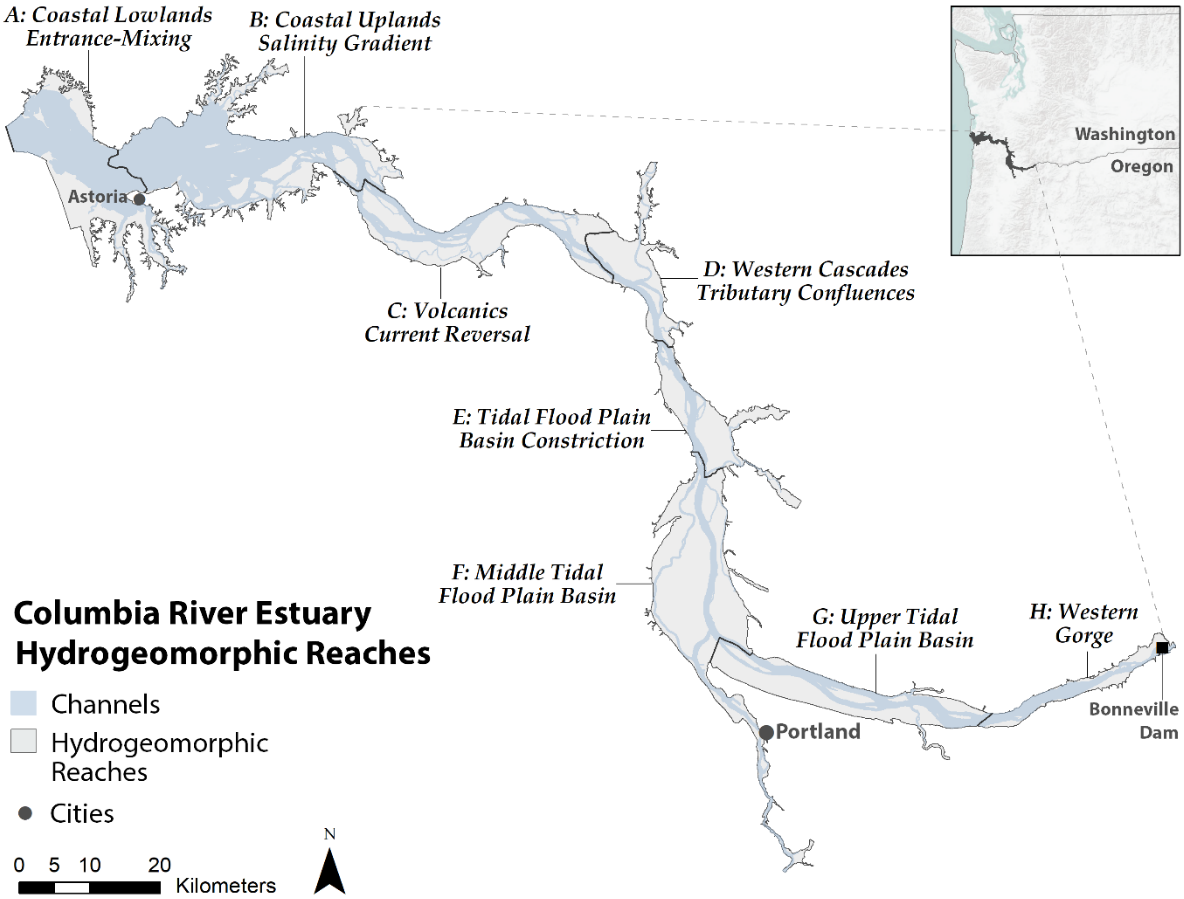
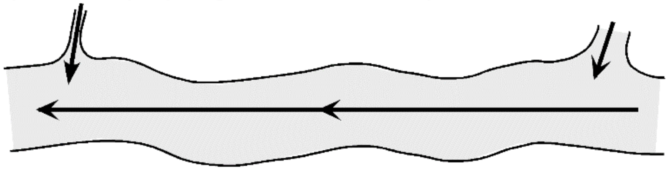


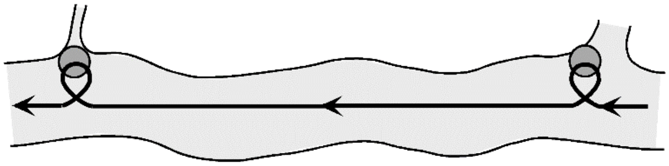
Figure 1

Author Manuscript

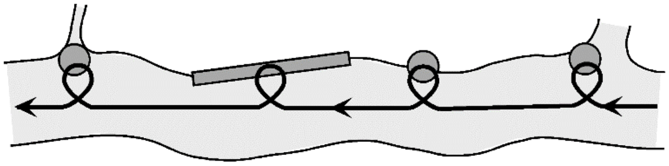
1. Initial condition--no habitat: short residence; low feeding opportunity; high predation, phsyiological stress, mortality.



2. Initial priority--restoration at tributary junctions: some habitat; some residence, feeding, refuge; use by multiple stocks; high fish density due to proximity to tributary population sources.



3. Stepping stone corridor: some residence, feeding, refuge in each stepping stone; long residence in system of stepping stones; reduced travel time and mortality risk between stepping stone refuges. Riparian shoreline matrix habitat restoration with comparable overall residence time to a patch can substitute for wetland floodplain stepping-stone habitat patch restoration.



4. Mature system restoration--large, well-connected habitat patches: long residence in large habitat patches, long residence in stepping stone corridor; low stress and mortality within and between large, well-connected habitat patches.

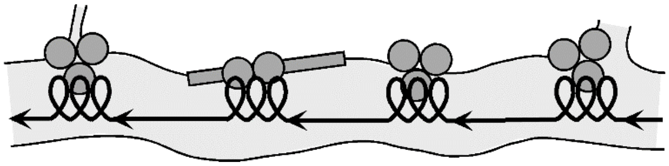


Figure 2

Author Manuscript

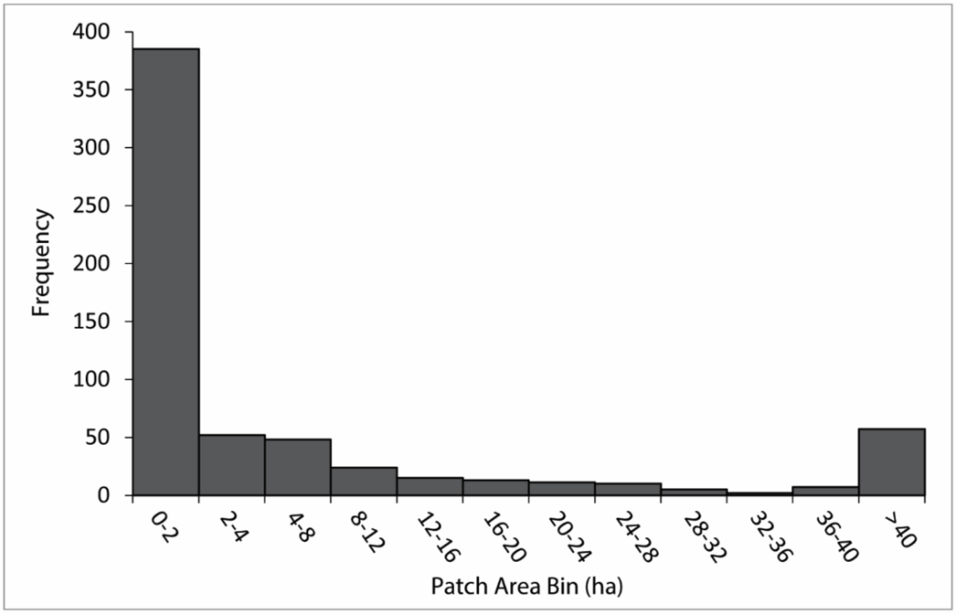


Figure 3

Author Manuscript

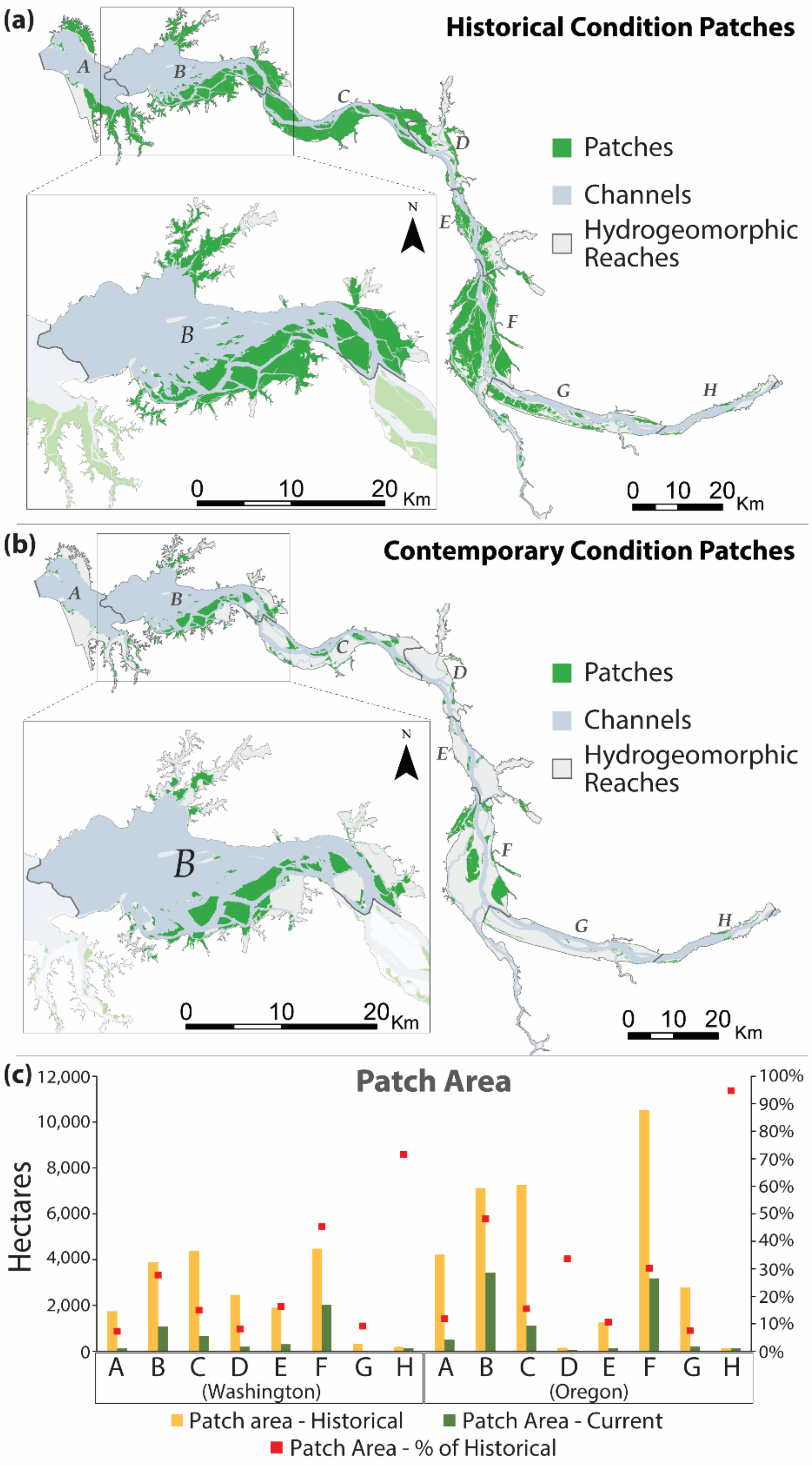


Figure 4

Author Manuscript

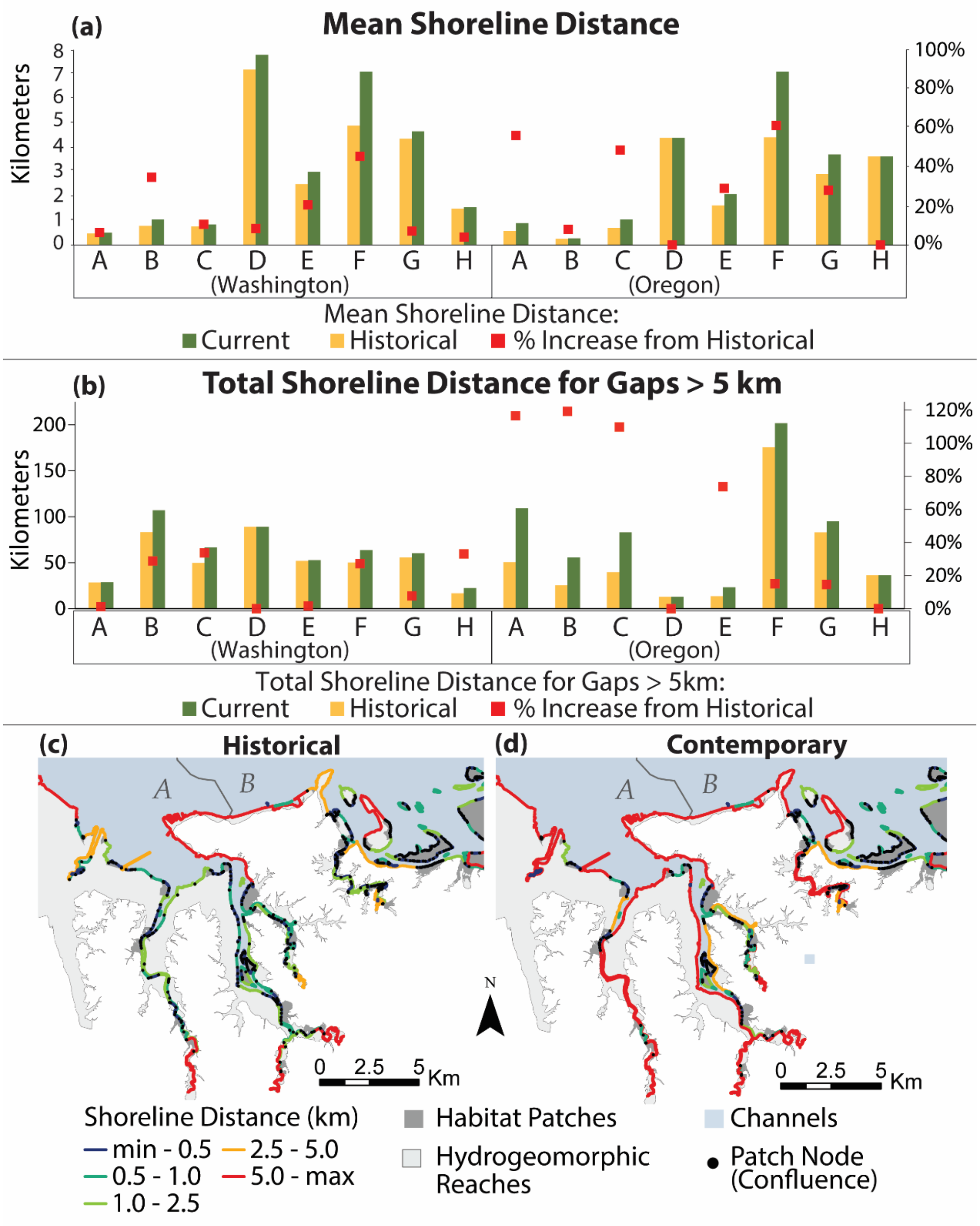


Figure 5

Author Manuscript

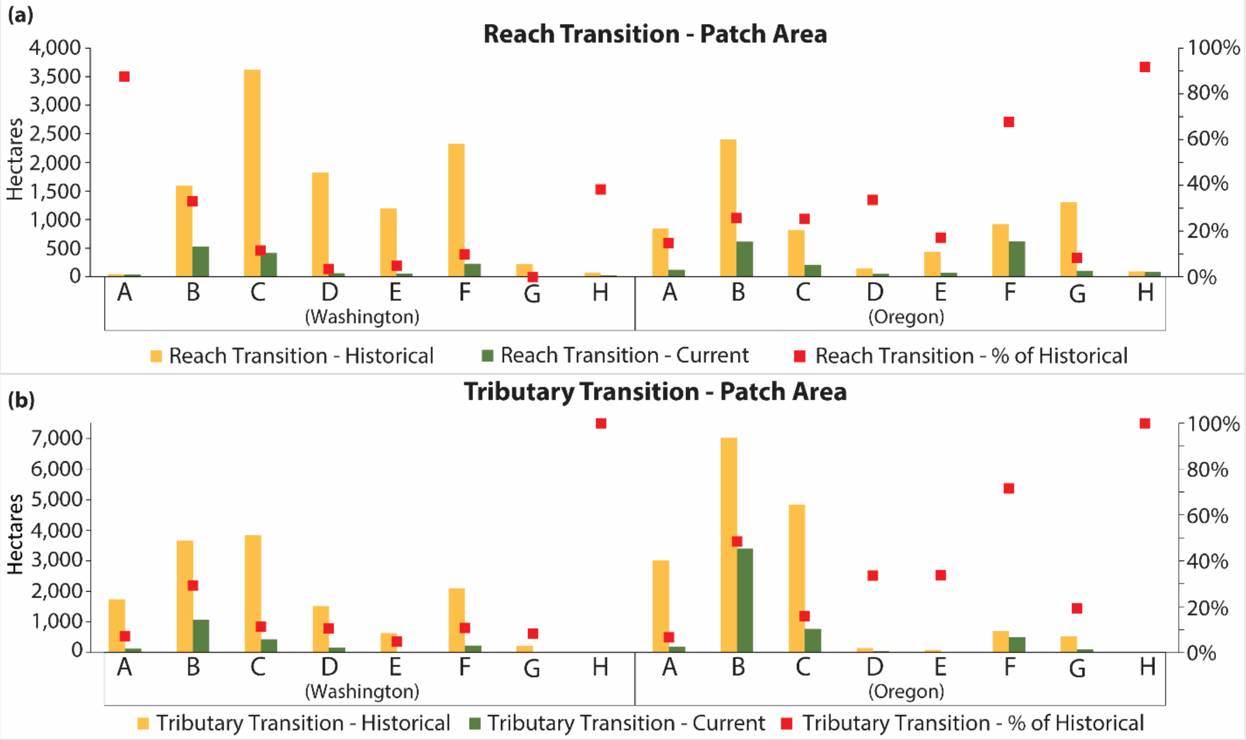


Figure 6

Author Manuscript

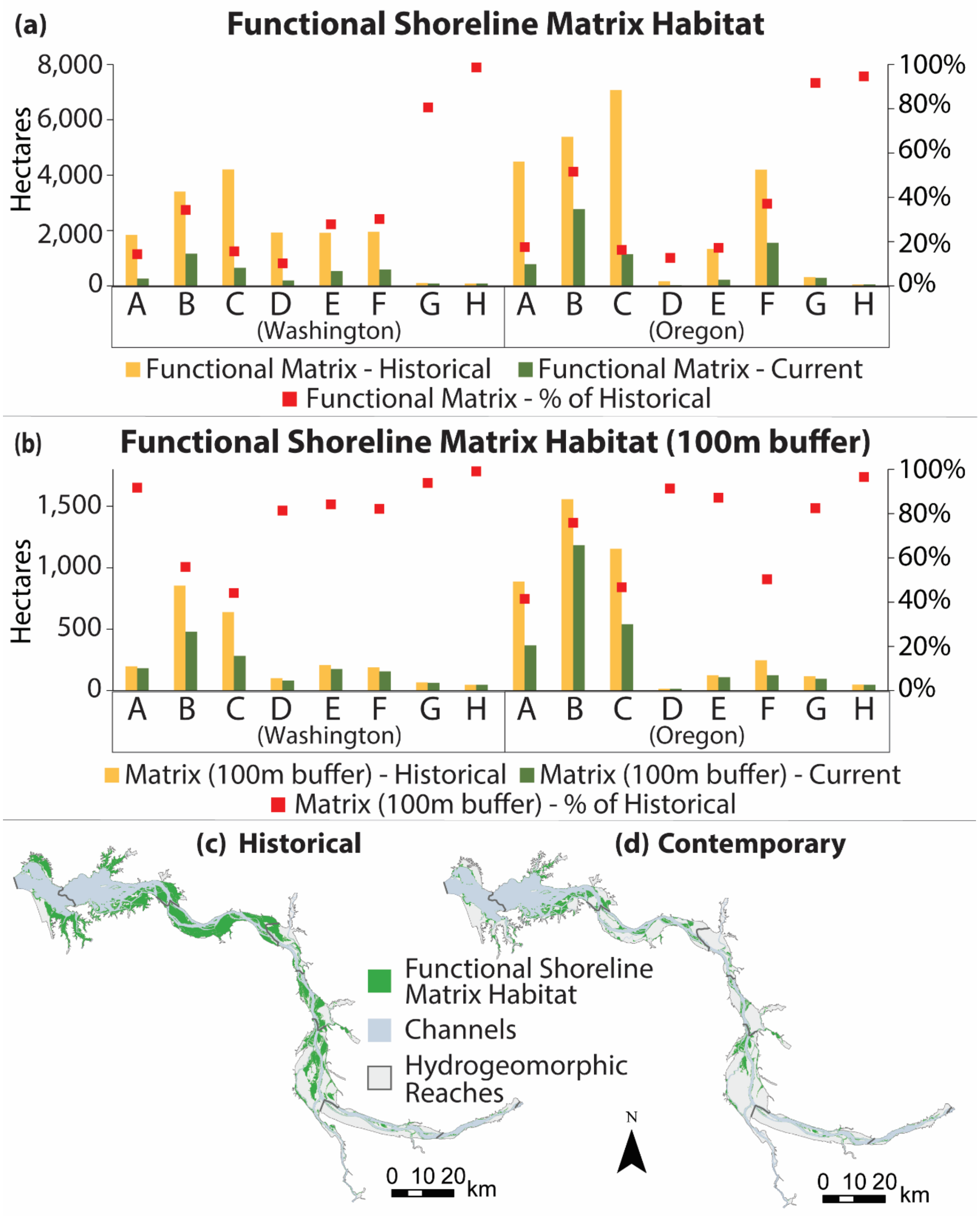


Figure 7

Author Manuscript

Supplement S1–Methodologies for Quantifying Landscape Elements

This supplement describes the underlying data sets and methodologies applied to derive the landscape elements metrics. For additional details see ERTG (2020). A landscape ecology perspective underlies the work. Thus, Columbia River Estuary (CRE) shallow water juvenile salmon habitats were conceived as either habitat patches or matrix habitat. Patch habitat consists of off-channel habitats that juvenile salmon can inhabit for many hours, days, or weeks, such as blind tidal channels or side channels, and their associated tidal wetlands or seasonally inundated floodplains. Matrix habitat consists of the remaining shorelines, such as narrow, fringing wetlands; fringing, riparian forests; and armored or riprapped banks. Shoreline matrix habitats offer limited opportunity for juvenile salmon to avoid fast river currents, and generally are transitional areas for juvenile salmon.

Data Sets Used

The data sets used in the GIS-based analysis included the following:

- Landscape Planning Framework (LPF), https://depts.washington.edu/wet/lpf.html (Simenstad et al. 2014)
- LCEP Historical Habitat Change in the Lower Columbia River, 1870-2010 (Marcoe and Pilson 2012)
- A packaged static geodatabase for Pacific coast estuary habitat that uses similar methods, https://psmfc.sharefile.com/ds5bf1b1efca24e7eb (Brophy et al. 2019)
- Columbia River Estuary Ecosystem Classification (CREEC) cultural features data set -- https://water.usgs.gov/GIS/dsdl/Columbia_River_Estuary_Ecosystem_Classification.zip -- Simenstad et al. (2011)
- LCEP 2009 High Resolution Land Cover data set,

http://s458607291.onlinehome.us/FTP/WebData/ep_2010_Landcover/data_VECTOR_format/ep0 20712_td_polygons.7z (LCEP 2010)

- Two-year flood elevations from USACE 50 percent annual exceedance probability model data set ERTG #2012-01, *ERTG Analysis of Water Levels for Site Delineation in Tidal Dominated Regions* https://www.cbfish.org/EstuaryAction.mvc/Documents

Contemporary Patches

The goal of patch delineation is to capture all areas in which juvenile fish could seek refuge from the mainstem of the Columbia River as they make their way through the estuary from Bonneville Dam to the ocean. Therefore, the basis of a patch is an open channel (primary channels, secondary channels, and tributary secondary channels) off of the migratory pathway. The wetland surrounding the channel is also considered to be part of a patch. The Landscape Planning Framework (LPF) provided an ideal data set for delineating patches in the CRE using GIS. The LPF geodatabase delineates all channels, and their associated floodplain habitat inundated at the two-year flood event, across the CRE. LPF also distinguishes between open and altered habitat, indicating what is currently accessible or inaccessible to fish.

For the purposes of this analysis, patches include any open channels (no levees, tide-gates or impassible culverts) that are accessible from the migration route and the adjacent area below the two-year flood elevation associated with each channel. Patches comprise the following "channel types" in the LPF: small channels, tidal channels, floodplain channels, minor tributaries, lakes and ponds, tertiary channels, tie channels, backwater embayments, floodplain sloughs, and tributary channels with mouth widths < 100 m. The LPF partitioned all areas under the two-year flood elevation into distinct polygons that are associated with individual channels

Author Manuscript

Author Manuscript

according to proximity (Euclidean distance). Each of these polygons was used to delineate patches. Therefore the patches reflect open channels rather than altered channels or low-elevation areas distant from any channel features. Contiguous patches were merged into a single patch. Across the entire estuary, 629 patches were delineated that range in size from 0.01 ac to 4,444 ac. However, patches smaller than 5 ac were ultimately considered to be shoreline habitat because smaller wetlands do not generally support complex channel networks (Hood 2007). Figures S1 and S2 illustrate and describe the LPF-based patch delineation.

Historical Patches

Patches were also delineated for a proxy-historical condition. The LPF geodatabase provided an ideal dataset to delineate historical patches, as it includes channels that are currently altered and inaccessible to fish, but historically would have likely been open to fish. For this analysis, the historical patches includes all contemporary patches and adds any channels classified as “altered” and their associated two-year flood polygons according to LPF. Because the LPF geodatabase two-year flood polygons are derived from the 2009–2011 lidar surface model, it does not account for areas that were historically below the two-year flood elevation, but were developed to an elevation above the two-year flood elevation prior to 2009.

To help account for this limitation, data from the Lower Columbia Estuary Partnership’s (LCEP) *Historical Habitat Change in the Lower Columbia River, 1870-2010* (Marcoe and Pilson 2012) were incorporated into historical patch delineation. This GIS dataset translated historical surveys of the CRE, conducted in the late 1800s, into habitat classes (e.g., coniferous upland

Author Manuscript

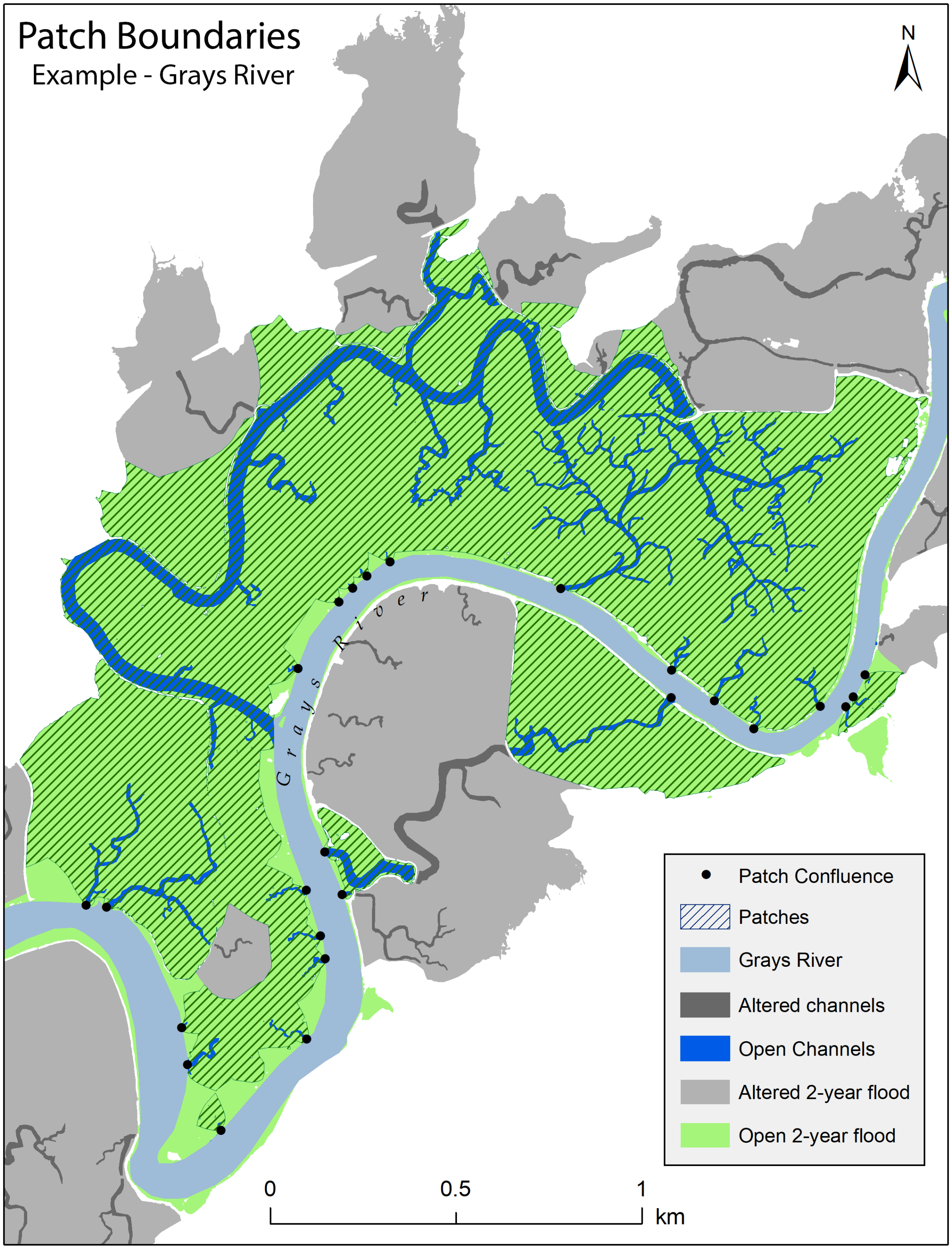


Figure A. Subset of Grays River (an estuarine tributary to the CRE) patch delineation. Patches include open channels and their associated 2-year flood polygons according to LPF. Patches exclude altered channels, or channels with tide gates or structures obstructing fish access (shown in dark gray), and their associated 2- year flood polygons (shown in light gray).

Author Manuscript

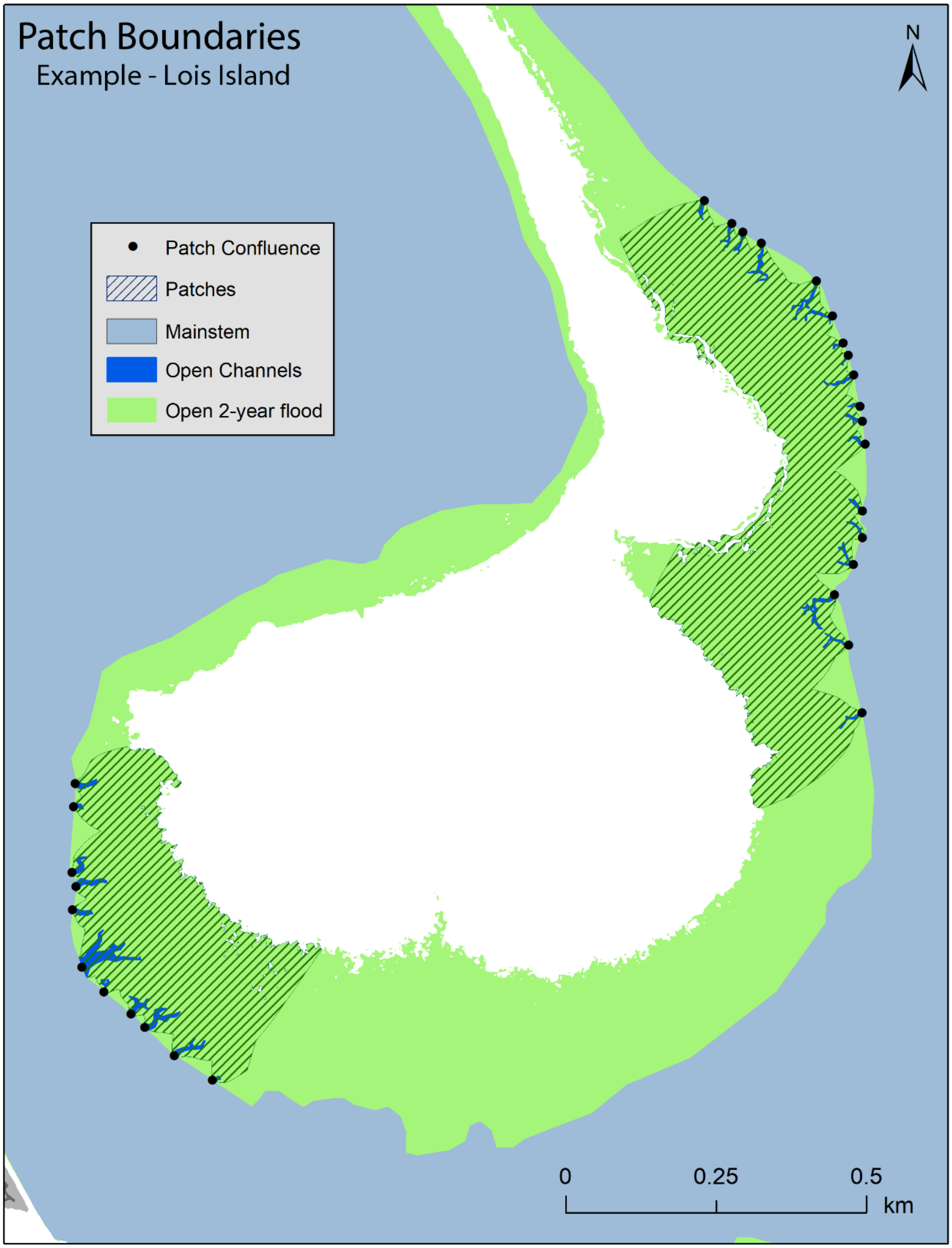


Figure B. Lois Island patch delineation. Areas under the two-year flood elevation classified as "open" are symbolized as light green and channels classified as "open" are symbolized as dark blue. Only the two-year flood polygons associated with the open channels are included in patch delineation. Contiguous polygons are merged into one discrete patch (shown in the hatched polygons).

Author Manuscript

forest, deciduous wetland forest, upland herbaceous) which provided evidence for delineating historical fish habitat patches that does not rely on contemporary terrain. All areas classified historically as “tidal wetland” (forested wetlands, herbaceous wetlands, and shrub scrub wetlands) were merged with LPF-derived historical patch areas. This increased the historical patch area across all reaches, most notably in urbanized areas like Astoria, Longview, and Portland, where infrastructure raised elevations above the two-year flood elevation. In total, historical patch area was increased by more than 6,880 ha by incorporating LCEP’s historical tidal wetlands. This yields an estimated 39,610 ha difference between historical and contemporary patch acreage across the estuary.

Shoreline and Nearest-Patch Distance

The CRE is spatially complex, with channel bifurcations, islands, and tributaries that do not fit neatly into the linear stepping-stone model outlined in the Landscape Principles document (ERTG 2020). Instead of just one linear route between the Bonneville Dam and the mouth of the estuary, there are infinite route possibilities. Therefore, two metrics were developed to quantify gaps between patches in the estuary to reflect the underlying concepts of the stepping-stone model. Each method was delineated separately on the Oregon and Washington side of the mainstem navigation channel.

“Total-shoreline distance” measures the gap length along all shorelines between patch nodes, i.e., the locations where patch channels intersect the mainstem migratory pathway (Fig. S3). Because this metric is measured along every shoreline, it identifies every potential shoreline gap in the estuary, reflecting the assumption that fish will generally hug the shoreline rather than cross a channel.

Author Manuscript

"Nearest-patch distance" measures the gap length from each patch in the estuary to its nearest patch (measured as node to node), whether that be across a channel (excluding the navigation channel) or along the same shoreline (Fig. S3). Thus, this method delineates a pathway from every patch in the estuary to the mouth of the Columbia River with the shortest travel distances between patches.

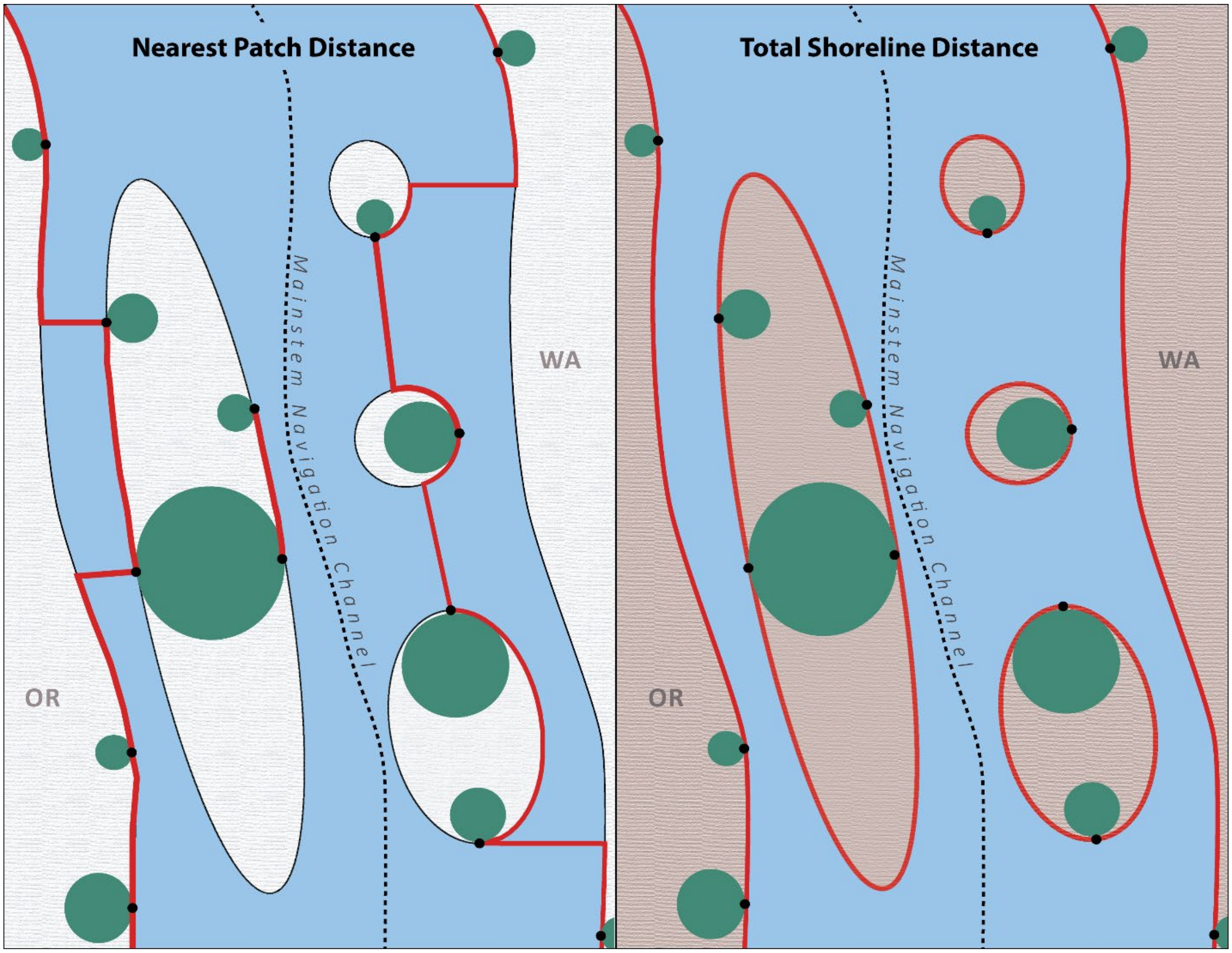


Figure C. Conceptual model illustrating the two distance metrics. The blue area is the mainstem river, textured white or brown areas are land, green circles are patches, and black dots are patch nodes. Red lines are the nearest-patch distances and total-shoreline distances on the left and right, respectively.

Author Manuscript

Historical Total-Shoreline Distance

The total-shoreline distance metric was also created for a proxy-historical condition. The historical condition was created by adding all “altered” patches and associated nodes from the LPF geodatabase. This yielded 396 more nodes in the historical condition than in the contemporary condition, each of which further reduces the average shoreline gap distance across the estuary. The nearest-patch distance metric was only created for the current condition because of data limitations. The boundaries and nodes of historical patches are somewhat ambiguous (no lidar visible or historically documented channels or nodes), which inhibits the ability to accurately measure patch-to-patch distances. Therefore, the nearest-patch distance metric is appropriate to compare across reaches for the contemporary condition, and the total-shoreline-distance metric is appropriate to compare within a reach relative to its historical condition.

Contemporary Functional Shoreline Habitat

For the purposes of this broad-scale analysis, functional shoreline habitat was defined as area below the two-year flood elevation, contiguous with the migratory route, and non-developed (e.g. excludes levees, roads, municipal). Functional shoreline includes both matrix and patch habitat that borders the shoreline. For the contemporary condition, the CREEC Cultural Features data set (Simenstad et al. 2011) and the 2009 High Resolution Land Cover data set (LCEP 2010) were used to remove impervious or developed areas. Within the Cultural Features layer, features labeled as railroad, road fill, levee, dam, jetty/groin, or wastewater treatment were removed. From the Land Cover layer, features labeled as urban-impervious or open space developed were removed. The remaining Cultural Features and Land Cover layers were then merged and clipped to the two-year-flood extent to create the intermediate functional shoreline habitat layer. The

Author Manuscript

mainstem migratory pathway and LPF channels were then removed so that all directly available channel habitat were excluded from shoreline calculations. Finally, all polygons that were non-contiguous with the mainstem channel (i.e., disconnected at the two-year flood event) were removed, resulting in the final functional shoreline habitat layer.

As an additional scenario, shoreline matrix habitat was limited to a 100 m buffer around the mainstem channel. The width of 100 m was selected as a conservative estimate of riparian habitat width required for various fish-related functions (e.g., nutrient and contaminant control, export of large wood and other organic matter) (USFS 2007; WDFW 2018).

The data used to characterize whether shoreline matrix habitat is functional or not (land cover and CREEC cultural features) do not capture all instances of shoreline riprap or development throughout the estuary. Some riprap or infrastructure is vegetated and thus not captured in these data sets. Depending on water levels when the data were acquired, armoring may be submerged and not captured. However, without an up-to-date and field-derived inventory of shoreline habitat quality across the entire estuary, these data sets are the best available information to characterize shoreline habitat quality in a GIS.

Historical Functional Shoreline Matrix Habitat

For the historical shoreline condition, all areas currently under the two-year flood elevation were assumed to historically have been functional (i.e., undeveloped). However, as stated previously, the two-year flood data are based on the 2009–2011 lidar surface model, which does not account for areas that were built above that elevation prior to 2009. Therefore, similar to historical patch delineation, all areas in LCEP’s historical habitat data set classified as “tidal wetland” were merged with the current two-year flood layer to achieve a more accurate historical

Author Manuscript

representation of areas below the two-year flood elevation. Similar to the contemporary shoreline methodology, the current mainstem migratory pathway and LPF channels were then removed. Lastly, any polygons that were non-contiguous with the mainstem migratory route were removed to create the historical functional shoreline layer. As with the contemporary shoreline, a 100 m buffer scenario of historical shoreline habitat was also created.

Four examples below illustrate how clipping shoreline habitat to the 100 m buffer would significantly alter the functional shoreline habitat acreage calculations for both current and historical conditions (Figs. S4 and S5). The first map on each page shows the historical shoreline extent. The light red reflects the full contiguous two-year flood shoreline area, while the dark red reflects the contiguous 100 m buffer shoreline habitat. The second map on each page shows the contemporary shoreline extent. Similarly, the light green indicates the full contiguous two-year flood shoreline area, while the dark green indicates the contiguous 100 m buffer shoreline habitat.

Landscape Elements

Each metric in the landscape elements table (Table S1) is derived from patch delineation, distances between patches, or shoreline habitat delineation. Each of the twelve landscape elements were quantified for each reach and shoreline combination (e.g., Reach A-OR, Reach A-WA, Reach B-OR, Reach B-WA, etc.). All landscape elements were quantified for contemporary conditions, and several elements were also quantified for historical conditions, depending on data limitations.

Author Manuscript

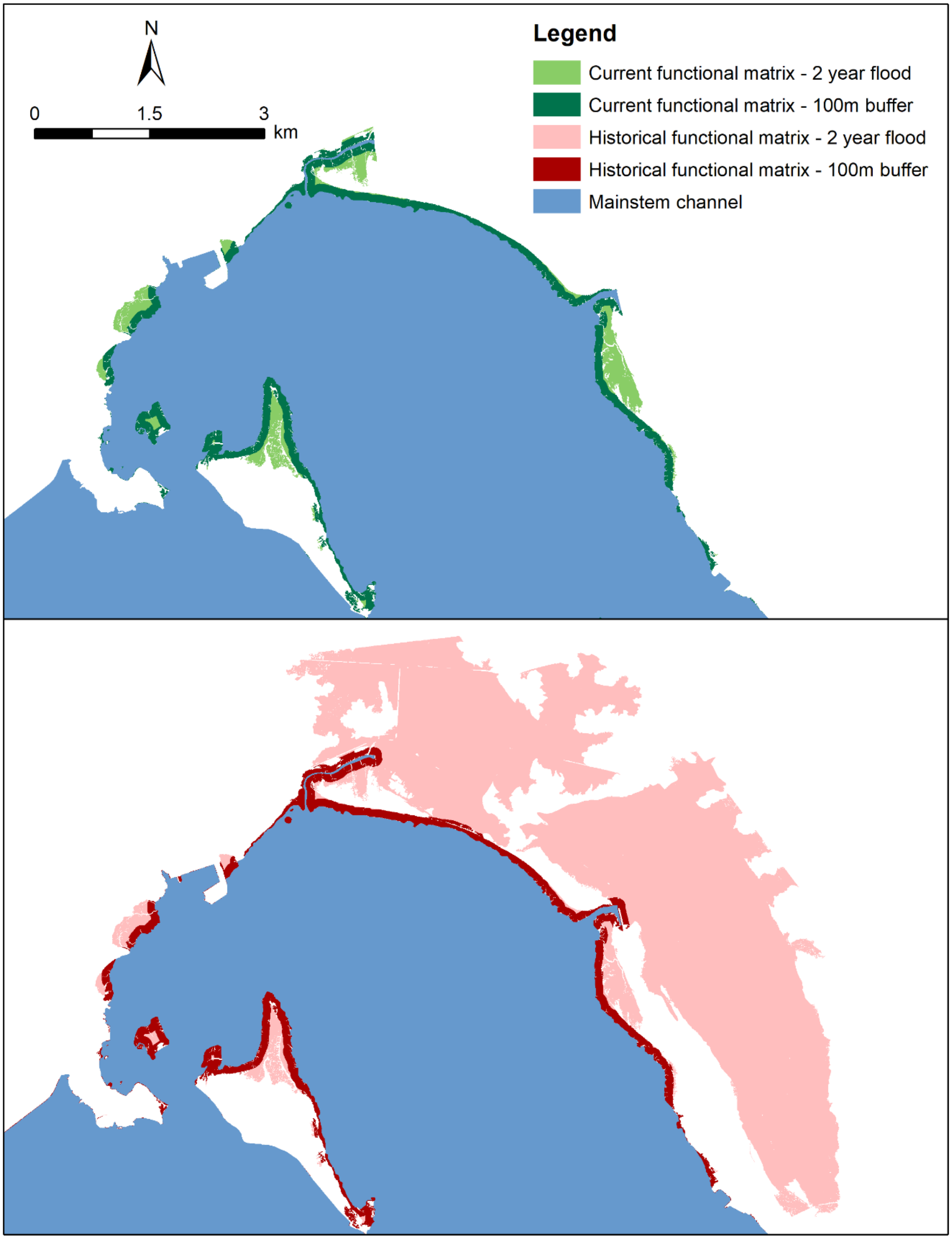


Figure D. Shoreline habitats for contemporary (top panel) and historical conditions (bottom panel) in Baker Bay.

Author Manuscript

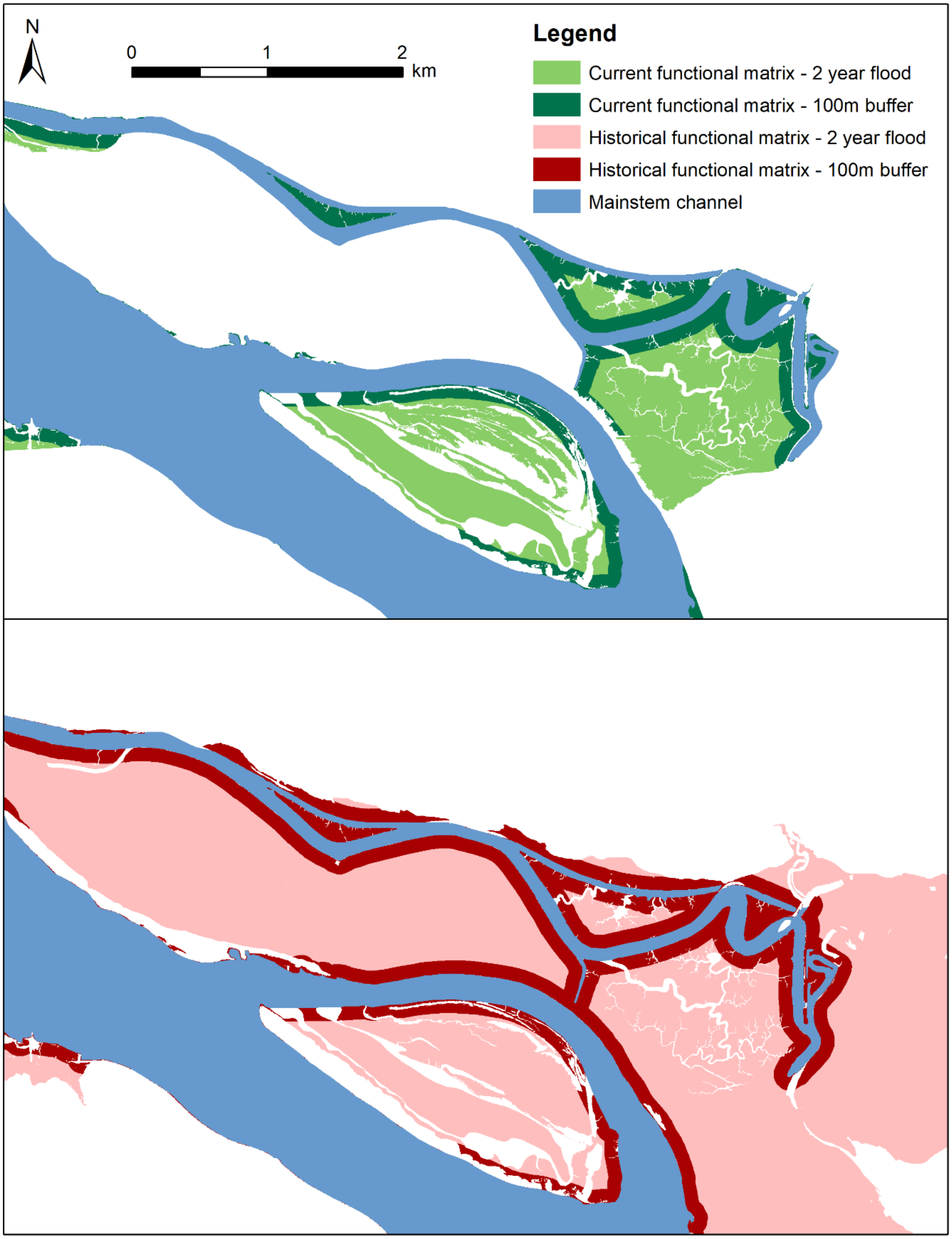


Figure E. Shoreline habitats for contemporary (top panel) and historical conditions (bottom panel) for Willow Grove area.

Author Manuscript

Table A. List of landscape elements. [(a)]

Landscape Element	**Definition**
*Patch Area	Total area (ha) of patches
*Reach Transition	Total patch area (ha) within a 5 km buffer zone around each hydrogeomorphic reach boundary[(b, c)]
*Tributary Transition	Total patch area (ha) within a 5 km buffer zone around tributary channel confluences[(c, d)]
*Total-Shoreline-Distance	Average distance (km)[(e, f)]
Nearest-Patch Distance	Average distance (km)[(f)]
*Number of Gaps > 5 km (total shoreline distance)	Count of distances > 5 km[(g)]
*Sum of Length of Gaps > 5 km (total shoreline distance)	Cumulative total of gap lengths > 5 km[(g)]
Number of Gaps > 5 km (nearest-patch distance)	Count of gaps > 5 km[(g)]
Sum of Length of Gaps > 5 km (nearest patch distance)	Cumulative total of gap lengths > 5 km[(g)]
Patch Count	Total number of patches
*Functional Shoreline	a) Total area (ha) of functional shoreline b) Total area (ha) of functional shoreline within a 100 m buffer

(a) An asterisk denotes when the landscape element was quantified for both the current and historical condition, and percentage of current relative to historical conditions.

(b) The boundaries at the mouth of the Columbia River and at Bonneville Dam were included as reach transitions.

(c) The intersect tool was used to determine patch acreage within the 5 km buffers. If a patch intersected the buffer but did not have a node within the buffer, it was excluded.

(d) Tributary channels were identified from the CREEC data set. The Chinook and Wallacut Rivers were not classified as tributary channels in the CREEC data, but were included as tributaries for this analysis.

(e) Island shorelines were excluded if the perimeter was <100m and there was no patch on the island.

(f) To quantify average distances within each reach-shoreline subset area, gap distances were split at hydrogeomorphic reach boundaries.

(g) Islands were included if the shoreline perimeter was >5 km. For gaps spanning a reach transition:
Count: full gap binned with majority reach (not split at reach boundaries).
Distance: Segment of gap within each reach binned separately (split at reach boundaries).

Author Manuscript

Literature Cited

Brophy LS, Greene CM, Hare VC, Holycross B, Lanier A, Heady WN, O’Connor K, Imaki, H, Haddad T, Dana R (2019) Insights into estuary habitat loss in the western United States using a new method for mapping maximum extent of tidal wetlands. PLoS ONE 14(8): e0218558. Available from https://doi.org/10.1371/journal.pone.0218558

ERTG (Expert Regional Technical Group) (2020) Landscape Principles: Applications and Operations for CEERP Restoration Strategy. ERTG #2019-01, prepared for the Bonneville Power Administration, U.S. Army Corps of Engineers, and NOAA Fisheries. Portland, Oregon. Available from https://www.cbfish.org/EstuaryAction.mvc/Documents

Hood WG (2007) Scaling tidal channel geometry with marsh island area: A tool for habitat restoration, linked to channel formation process.” Water Resources Research 43(3):W03409. https://doi.org/10.1029/2006WR005083

Lower Columbia Estuary Partnership (LCEP) (2010) LCEP 2009 High Resolution Land Cover data set, http://s458607291.onlinehome.us/FTP/WebData/ep_2010_Landcover/data_VECTOR_format/ep0 20712_td_polygons.7z

Marcoe K, Pilson S (2017) Habitat change in the lower Columbia River Estuary, 1870–2009. Journal of Coastal Conservation 21:505-525

Simenstad CA, Ramirez MF, Wagoner HM, Whiting AH, Trask PC (2014) A landscape approach to planning restoration and conservation of anadromous fish habitat across a complex estuarine mosaic: Applications to long-term monitoring and salmon recovery. Proceedings 9th European Conference on Ecological Restoration. Oulu, Finland, 3-8

August 2014

Simenstad CA, Burke JL, O'Connor JE, Cannon C, Heatwole DW, Ramirez MF, Waite IR, Counihan TD, Jones KL (2011) Columbia River Estuary Ecosystem Classification cultural features data set -- https://water.usgs.gov/GIS/dsdl/Columbia_River_Estuary_Ecosystem_Classification.zip

USFS (United State Forest Service) (2007) Riparian and Aquatic Habitats of the Pacific Northwest and Southeast Alaska: Ecology, Management History, and Potential Management Strategies

WDFW (Washington Department of Fish and Wildlife) (2018) Riparian Ecosystems, Volume 1: Science and Management Implications

Author Manuscript