ERTG 2017-02

Landscape Principles for CEERP Restoration Strategy

Prepared by the Expert Regional Technical Group of the Columbia Estuary Ecosystem Restoration Program

Prepared for the Bonneville Power Administration, U.S. Army Corps of Engineers, and NOAA Fisheries

FINAL

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Abstract

Habitat restoration actions have been proposed and implemented in the lower Columbia River and estuary (LCRE) for the last two decades in response to the National Marine Fisheries Service's Biological Opinions for operation of the Federal Columbia River Power System. Since 2010 proposed restoration projects are evaluated by an Expert Regional Technical Group (ERTG) that considers the potential benefits to juvenile salmon of each project based on its contributions to salmon rearing opportunity and capacity. These criteria generally favor large restoration projects located near the estuary mainstem but provide little guidance for the distribution of projects along the mainstem or the utility of alternative actions in areas where these priorities cannot be met. This ERTG report elaborates further on the topic of 'where' floodplain reconnections and alternative actions should occur by utilizing a landscape framework to support project review and selection for the Columbia Estuary Ecosystem Restoration Program. The framework offers guidance about the size, geographic distribution, and distance between restoration sites to restore ecological functions for salmon.

The landscape framework addresses four salmon-support functions of estuarine habitat: gradual transition through physical and chemical gradients, refuge from predators, production and export of prey and organic matter, and opportunities for salmon to express diverse juvenile life histories. The goal of the framework is to re-establish the continuity and complexity of the dynamic estuarine landscape in time and in space to satisfy the foraging and shelter requirements for diverse Columbia River salmon stocks and life history types. It is built on the concept of restoring and conserving habitat "stepping stones" of an appropriate size, proximity, and strategic location to ensure juvenile salmon growth and survival throughout their estuarine residency and migration. Historical conditions provide a useful template for defining restoration objectives consistent with the physical dynamics of particular estuarine regions (e.g., differences in tidal range, inundation frequencies, sediment transport rates) that create and maintain shallow-water habitats and determine their accessibility to salmon.

Under the landscape framework, we recommend the following priorities for choosing among habitat restoration and conservation alternatives in the LCRE: (1) ensure at least one large habitat complex is available within each of the eight hydrogeomorphic reaches near key transition zones (i.e., near the reach boundaries and at river confluences) along both estuary shores (Washington and Oregon); (2) minimize potential stress and predation risks to salmon by reducing travel distances (to < 5 km where possible) between existing large natural or restored habitat patches in each reach; and (3) restore small off-channel patches and/or improve the structure and function of the surrounding riparian and shoreline "matrix" habitat along the salmon migration route where shallow rearing habitats are naturally limited or impractical to recover (e.g., largely constrained by hardened shorelines and levees).

Habitat creation is sometimes proposed as another alternative to improve rearing opportunities for juvenile salmon. However, creating new habitat introduces additional risks and uncertainties and should not be undertaken without first assessing the possible tradeoffs in ecological function between the pre-existing and the newly created habitat. Habitat-creation projects should be considered only where the other restoration and conservation priorities above cannot be met, and the ecological tradeoffs of the novel habitat have been fully evaluated and are deemed acceptable.

Application of the landscape framework to past projects and future proposals may help determine whether the stepping-stone model provides a useful tool for setting restoration priorities. However,

empirical studies are also needed to validate assumptions of the model underlying the framework. Important areas of future research include the seasonal occupation of small patches and matrix habitats by salmon, the effects of distance from the mainstem on the use of small habitat patches by mainstem stocks, factors influencing salmon travel distances between habitats, and the prey and organic matter contributions of small and matrix habitats to the estuary. Additional research is also needed to understand potential ecological interactions with hatchery-reared salmon and whether these could undermine the presumed benefits of estuary restoration to naturally produced stocks.

Preface

The Expert Regional Technical Group (ERTG) was formed by the Action Agencies (Bonneville Power Administration [BPA] and U.S. Army Corps of Engineers [USACE]) in 2009 in response to the National Marine Fisheries Service's (NMFS's) 2008 Biological Opinion on the operation of the Federal Columbia River Power System. The ERTG reviews ecosystem restoration actions in the floodplain of the lower Columbia River and estuary proposed by the Action Agencies under the Columbia Estuary Ecosystem Restoration Program (CEERP). The ERTG's work is directed by a steering committee composed of representatives from BPA, NMFS, and USACE.

Landscape Principles for CEERP Restoration Strategy (ERTG 2017-02) offers landscape conservation concepts and principles that could support CEERP restoration strategy, help define restoration priorities, and provide metrics for assessing a given restoration project's contribution to estuary function and salmon conservation.

This document was prepared by the ERTG (Dan Bottom, Greg Hood, Kim Jones, Kirk Krueger, and Ron Thom). The ERTG Steering Committee, led by Anne Creason, Jason Karnezis, Lynne Krasnow, Cindy Studebaker, and Mike Turaski, oversaw the effort. Alex McManus and Katie Blauvelt (PC Trask and Associates) provided geographic information system analytics and discussions to help the ERTG formulate landscape principles. The ERTG appreciates review comments from the CEERP restoration community.

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Introduction

On June 30, 2017, the Expert Regional Technical Group (ERTG) was asked by their Steering Committee to develop a framework to guide future restoration for the Columbia Estuary Ecosystem Restoration Program (CEERP). The CEERP is a multi-agency effort to conserve and restore ecosystems of the lower Columbia River and estuary (LCRE). An important objective of CEERP is to restore and maintain shallow-water habitats necessary for the growth and survival of juvenile salmonids. The Steering Committee asked the ERTG to consider the geographic distribution of habitats across the estuary landscape and whether the collective array of conserved and restored habitats is sufficient to meet the diverse rearing and migratory requirements of Columbia River salmonids (hereafter referred to as “salmon”). Specifically, the ERTG was to propose and justify additional landscape conservation concepts and principles that might (1) support the CEERP strategy and define restoration priorities, and (2) provide metrics for assessing each project’s contribution to estuary function and salmon conservation. This report summarizes our response to this landscape framework request.

Restoration is a priority for the CEERP because loss of estuarine habitat, especially rearing habitat, is thought to reduce salmon survival, abundance, and life history diversity. Since the late 1800s, 68–70% of vegetated tidal wetlands of the LCRE have been lost to diking, filling, shoreline development, flow regulation, and other modifications (Kukulka and Jay 2003; Bottom et al. 2005b; Marcoe and Pilson 2017). Disconnection of wetlands and floodplains has eliminated much of the historical rearing habitat for salmon and reduced the production of wetland macrodetritus supporting salmonid food webs throughout the estuary (Simenstad et al. 1990; Maier and Simenstad 2009). Fewer rearing opportunities in the estuary may also have reduced salmon life history diversity. The diverse life histories of young salmon—including, for example, different rearing and migratory pathways through the estuary—are directly tied to the variety of habitats available (e.g., Bottom et al. 2005a; Jones et al. 2014). Diverse habitats offer alternative places for salmon to rear as environmental conditions change and as the suitability of particular estuarine locations varies through time.

Restoring diverse estuarine habitats, including their distinct locations, timing and accessibility, and capacities to deliver salmon prey, will be necessary to conserve salmon diversity and productivity (Bottom et al. 2005b; Fresh et al. 2005). The life history diversity of Columbia River salmon has been greatly simplified compared to that described when the first Chinook Salmon study was completed in the LCRE in 1913–14 (Rich 1920; Bottom et al. 2005b; Burke 2005). Estuary use by juvenile salmon has become narrowly focused during the spring and early summer; relatively few fish enter or remain in the estuary during mid-summer and fall. Recent survey results confirm this pattern, citing the effects of reduced estuarine rearing opportunities (i.e., from wetland loss, increased mainstem temperatures, spread of invasive species, etc.), upriver population losses (i.e., from the effects of dams, agriculture, and other development), and hatchery replacement of wild salmon production as contributing factors (Campbell 2010; Bottom et al. 2011). A principal strategy of LCRE restoration under CEERP is to expand off-channel rearing opportunities across the estuary to enable the fullest possible expression of juvenile life histories by all salmonid species and evolutionarily significant units (ESUs). Additionally, improvements in the quantity and quality of floodplain habitats should also benefit the growth and survival of all juvenile migrants by enhancing the production and delivery of wetland macrodetritus and preferred salmon prey to the mainstem estuary (Simenstad et al. 1990; Maier and Simenstad 2009).

The ERTG uses a systematic, collaborative process for reviewing project-specific habitat restoration proposals and quantifying their relative benefit to Columbia River salmon (Krueger et al. 2017). Principal criteria of the ERTG process include: (1) the likelihood that a proposed restoration site will be accessible to salmon (habitat opportunity), and (2) the estimated number of salmon that a proposed project might support directly by accessing the site and indirectly by exporting prey and organic material from the site (habitat capacity). These criteria encourage restoration projects that are located near the estuary mainstem to facilitate access by downstream migrants and are large in surface area to increase salmon-rearing capacity and persistence (Krueger et al. 2017). However, opportunities for large projects are limited and the relative benefits to juvenile salmon of alternative actions have been rarely explored. The discontinuous distribution of large, near-the-mainstem restoration opportunities raises questions about the landscape context of project proposals and the salmon-benefit tradeoffs between habitat size, location, and geographic distribution along the estuarine tidal-freshwater gradient:

- Is it best to increase the size of large, contiguous habitat wherever possible or to create “stepping stones” between large habitats?
- Can a particular landscape become saturated with restoration projects such that the benefits of continued restoration diminish?
- What beneficial actions besides hydrological reconnection can be taken to improve “matrix” areas between habitats?

We offer guidance about the size, geographic distribution, and distance between restoration sites to restore ecological functions for salmon. However, we do not propose an “optimal” design for the LCRE. Estuary habitats, salmon populations, and salmon life histories are diverse and dynamic such that no single habitat condition will be optimal for all salmon or for any salmon at all times. Similarly, we do not think that specific projects can be directed to benefit particular salmon populations. Instead, we define key ecological support functions for juvenile salmon so that the likely effects of restoration projects on these functions can be considered. We propose conservation principles to help identify important habitat types; restore life history diversity; and establish priorities based on habitat size, complexity, and geographic distribution. Our principles generally promote ecological resilience and reinforce recommendations that restoration projects should be robust to climate change (Krueger et al. 2017); however, we do not explicitly consider climate effects here. Finally, we present several conceptual models to facilitate understanding of the proposed conservation principles and offer recommendations for additional data and research to support them.

Ecological Support Functions

The LCRE must satisfy multiple habitat requirements of the diversity of salmon and life histories that can use estuary habitats at different time periods and locations. Ecological support functions of estuaries benefiting juvenile salmon include (Simenstad et al.1982; Healey 1991; Thorpe 1994; Bottom et al. 2005a, b; Jones et al. 2014):

- Transitional habitats for the gradual physiological and behavioral adjustment 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 and for juvenile salmon foraging and growth
- Dynamic landscapes that provide transitional, refuge, and foraging habitats and enable the expression of diverse salmonid life histories necessary for resilient populations.

Ecological support functions can benefit all juvenile salmon ages and sizes, including fry, parr, and yearlings (e.g., Johnson et al. 2015). Smaller juveniles 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, yearling salmonids can occur in significant numbers and reside for extended periods in the deeper channels of large tidal and floodplain wetlands (Johnson et al. 2015). Additionally, larger 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 and Simenstad 2009; Maier et al. 2011), most likely by consuming estuarine detritivores (e.g., epibenthic crustaceans) and terrestrial insects (Maier and Simenstad 2009; Bottom et al. 2011).

Recent research results reject the conventional view of the estuary as a simple corridor or “pipe” that rapidly conveys interior salmon stocks from Bonneville Dam to the ocean (Bottom et al. 2005b; McNatt et al. 2016). Tidal wetlands and their channels shelter lower basin and interior salmon stocks that enter the estuary below and above Bonneville Dam. In the upper portion of the tidal-fresh estuary (Rkm 221; Reach H; Simenstad et al. 2011), 100% of the PIT-tagged juvenile salmonids originated from above Bonneville Dam but at Rkm 52 and 47 (Reach B; Simenstad et al. 2011), 20–50% of the detected fish were interior stocks (McNatt and Hinton 2017). Similarly, at four other sites, interior stocks were detected but did not predominate. Of the interior stocks, 14–32% were stocks listed as threatened or endangered (McNatt and Hinton 2017).

Salmon Population Viability

The ecological support functions of the estuary contribute directly to salmon population viability as defined by abundance, productivity, diversity, and spatial structure (McElhaney et al. 2000; Fresh et al. 2005). Functions that promote growth and survival of juvenile salmon have been linked to the abundance and productivity of many Pacific salmon populations (e.g., Reimers 1973; MacDonald et al. 1988; Magnusson and Hilborn 2003; Jones et al. 2014). Direct estuary contributions to the growth and production of salmon from multiple Columbia River Chinook Salmon ESUs have been inferred using otolith chemistry to reconstruct the juvenile life histories of outmigrants (Campbell 2010) and returning adults (Roegner et al. 2014). Adult otolith analyses reveal that many Spring Chinook Salmon returning to spawn in the McKenzie River basin (Upper Willamette River ESU) spend extended periods of their juvenile life history feeding and growing in the tidal freshwater reaches of the LCRE (Rose 2015).

The number, geographic distribution, and connectivity of estuarine habitats contribute to the diversity and spatial structure of salmon populations by providing alternative survival opportunities (i.e., life history pathways) (Bottom et al. 2005a, b). Multiple habitat types within the estuary—deep channels, mudflats, emergent marshes, floodplain wetlands, etc.—are used by members of the same and different populations (Fresh et al. 2005; Teel et al. 2014). The cumulative population responses to these diverse rearing opportunities are reflected in the varied seasonal and spatial patterns of estuary use by fry, parr, and yearlings within and among Columbia River ESUs (Teel et al. 2014).

Habitat Template

We use the estuary definition of Simenstad et al. (2011), which encompasses the entire area of tidal influence from the Columbia River mouth to the base of Bonneville Dam (~Rkm 234), to account for the diversity of habitats potentially available to migrating salmon. Tidal and riverine processes interact in varying proportions to create a mosaic of habitats along the estuarine gradient from near-coastal marine conditions at the river mouth to river-dominated habitats in the upper estuary. The physical and ecological complexity and discontinuities in process rates are characterized by eight distinct hydrogeomorphic reaches (Figure 1, A–H) (Simenstad et al. 2011). The migratory pathways of juvenile salmon in the estuary—i.e., the sequence of reaches encountered between estuary entry and ocean entry—is a function of the geography of each source population and its point of estuary entry (e.g., above Bonneville Dam or confluence location in the lower estuary). Life histories within populations vary with the estuary entry times of individual population members and the diversity and distribution of habitat opportunities along each migration pathway at these times.

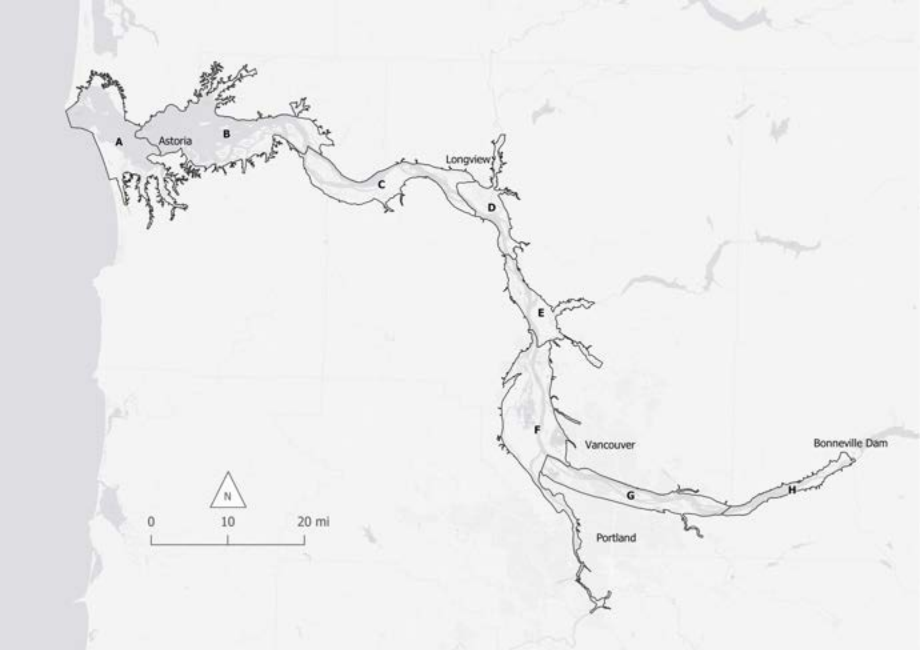


Figure 1. Classification of eight hydrogeomorphic reaches of the LCRE (from Simenstad et al. 2011).

Habitat structures and processes are not uniformly distributed along the estuarine tidal-freshwater gradient. For example, in the upper estuary below Bonneville Dam (Reach H), where fluvial processes dominate and tidal variations are <0.3 m, relatively few peripheral floodplain habitats exist (Simenstad et al. 2011). Here, off-channel rearing opportunities are limited to a few large islands, wetlands below rocky projections, and the junctions of small tributaries that deliver cool water, forage, and sediments to the mainstem. In contrast, extensive off-channel rearing opportunities are more widely distributed throughout Reaches B and C where the estuary broadens, 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.

Similarly, salmon from different genetic stocks are not uniformly distributed across the estuarine tidal-freshwater gradient but display distinct patterns of estuary use (Teel et al. 2014). For example, three lower Columbia River stocks (i.e., West Cascade Fall, West Cascade Spring, and Spring Creek Fall) accounted for most of the fish captured during a 2010-2012 beach-seine survey in the lower tidal freshwater reaches (B – D), whereas a more diverse mixture of Lower Columbia River Fall, Willamette River Spring, and Upper Columbia River Summer-Fall stocks frequented the shoreline habitats in Reaches E and F. In contrast, Reach H habitats were primarily used by upper Columbia River Summer/Fall and some interior stocks, including many fingerling migrants that entered the upper estuary during or after July. These stock-specific differences imply that having habitat in all reaches is important to enable expression of the full range of potential migratory and rearing behaviors by salmon from different Columbia River ESUs.

Recent studies have documented the importance of habitat and life history diversity to the resilience and productivity of salmon populations (Rogers and Schindler 2008; Schindler et al. 2010; Moore et al. 2010, 2014; Jones et al. 2014). In the Willamette River, Schroeder et al. (2016) identified a variety of subyearling and yearling life history types supporting the production and resilience of Spring Chinook Salmon. For example, extended juvenile rearing in the tidal-fluvial estuary provides alternative life history pathways for naturally produced yearlings, fingerlings, and fry from the Willamette's McKenzie River basin (Rose 2015). Overall, the rich diversity of subyearling and yearling migrant types in the Willamette River basin dampens the effects of varying freshwater and ocean conditions, providing greater stability to the native Spring Chinook Salmon populations (Schroeder et al. 2016).

Of particular significance to the CEERP is the finding that 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. 2005a) and Coho Salmon (Jones et al., 2014) populations increased substantially after dikes and tide gates were removed from 60% or more 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.

Conservation Principles

Based on the above ecological support functions for salmon, we propose the four principles presented below to assist restoration and protection efforts in the LCRE. These principles account for site- and landscape-scale factors that influence the growth and survival of juvenile salmon during estuarine residency. In this context a “habitat patch” is any suitable shallow-water, protected site, including tidal marsh channels and floodplain wetlands, that affords satisfactory foraging and sheltering opportunities for young salmon. Habitat “stepping stones” are defined as a sequence of habitat patches (small or large) located in near enough proximity for young salmon to migrate between them on successive tidal cycles (i.e., the next incoming tide). The term “matrix” refers to the adjacent riparian and shoreline areas between habitat patches along the salmon migration route.

1. Prioritize transition habitat.

System boundaries, particularly the mainstem hydrogeomorphic reaches immediately below Bonneville Dam and tributary confluences at the mainstem (network nodes), are transitional habitats where fish encounter and adjust to new conditions, such as tides and salinity. The oligohaline and brackish regions in estuary Reaches A and B are a chemical transition zone where salmon stocks first encounter and then must complete their adjustment to salt water. Network nodes at tributary junctions are generally characterized by increased habitat diversity and salmon productivity (Whited et al. 2011). Many estuary tributaries are also sources of cool water such that tributary nodes may also afford cool-water refugia for juvenile (and adult) salmon when mainstem temperatures reach stressful levels by late spring or summer.

Estuary restoration should account for daily, seasonal, and interannual access, movements, and residency of fish within a tidal and riverine landscape and their coarser-scale migrations through the estuary and to the ocean. Ensuring habitat access and capacity within each hydrogeomorphic reach, particularly near nodes and reach boundaries, should be a priority of estuary restoration efforts.

2. Prioritize large, complex habitats.

Large wetland and marsh habitats support disproportionately larger and more complex tidal channel networks than do small habitat patches; a non-linear relationship exists between marsh size and channel network size and complexity (Hood 2007, 2015, 2016). Large wetland sites have a greater variety of channel sizes and depths and afford rearing opportunities for a wider range of juvenile sizes and life history types than small, simple channels. Further, juvenile salmon may reside within large wetland complexes for long periods but only return infrequently and for brief periods to individual small channels within the larger complex (Hering 2010; McNatt et al. 2016). Additionally, we expect wetland area to be positively related to habitat maintenance and resilience in a dynamic estuarine environment (Thom et al. 2011).

The number of juvenile salmon a habitat can support—its capacity—is also a function of habitat size and complexity. Large habitat patches generally support more fish than small ones because competition for prey or space limits salmon density. Larger habitats can accommodate the same numbers of fish at lower densities, reducing competition and allowing fish to grow and emigrate from the habitat at larger sizes (Greene et al. 2016). Thus, reaches with few large habitat patches may require a larger total area of small habitat patches to provide the same benefit. A greater number of stepping-stone habitat patches may also provide more rearing opportunities, e.g., supporting the successive downstream movements of individuals with short residence times or ensuring some unoccupied habitat is available to new arrivals in all estuary reaches.

3. Promote habitat and life history diversity.

The estuary provides discontinuously distributed (patchy) rearing habitats along the migratory pathways of all anadromous salmon in the Columbia River basin (Bottom et al. 2005b). The specific rearing and migratory habitats benefiting juveniles vary with the time and location of estuary entry of each salmon stock. Interior stocks migrate through all estuary reaches (A–H); Lower Columbia River and Willamette River stocks primarily occupy habitats downstream from their respective tributary confluences.

A dynamic mosaic of estuarine habitats (i.e., patches and matrices) affords rearing opportunity for a diverse range of Columbia River salmon (Bottom et al. 2011; Teel et al. 2014; Roegner et al. 2014). The location, distribution, and juxtaposition of estuarine habitat patches and “stepping-stone” patches provide alternative rearing and migratory pathways through the estuary. Juvenile salmon that enter the estuary at different times, locations, sizes, and conditions benefit from different geographic and temporal arrangements of habitat to support their particular rearing and migratory pathways from estuary entry to ocean entry. For example, habitat preferences (e.g., water depths, velocities, etc.) of juvenile salmon tend to be size related (Bottom et al. 2005b, 2011). The particular rearing and migratory pathways of emergent fry, fingerlings, and yearlings thus may require or benefit from different geographic and temporal combinations of habitat.

The loss of stepping stones in the migratory corridor reduces opportunities for life history expression (e.g., Healey and Prince 1995) and could undermine salmon population resilience to future disturbance (Hilborn et al. 2003; Moore et al. 2014). A comprehensive estuary restoration strategy should seek to re-establish landscapes that support the full range of potential life history types within and among salmon ESUs as the suitability and accessibility of individual habitats change through time.

4. Use the physical template as a guide.

Natural processes create and maintain habitats, drive support functions, promote estuarine ecosystem resilience (minimizing the need for human intervention), and largely determine the habitat capacity that will likely result from conservation and restoration. Many processes that shape and maintain estuarine habitats vary along the estuarine tidal-freshwater gradient. These variations determine the structures and processes of habitats that might be successfully restored and maintained. Gradient discontinuities are depicted by the hydrogeomorphic reach classes (Figure 1) (Simenstad et al. 2011; Jay et al. 2016), where class boundaries usually coincide with abrupt changes in process rates. Natural disturbances affecting water and sediment transport rates are vital to estuarine habitat formation and maintenance (Simenstad et al. 2011). Geographic variations in disturbance frequency and intensity and in the rates of and capacities for physical recovery maintain diverse habitat conditions and rearing opportunities for juvenile salmon (Kukulka and Jay 2003; Rostaminia 2017).

Historical conditions provide a useful model to identify restoration needs based on the geographic distribution and size of habitat types that previously and currently exist within each estuary reach. Salmon have adapted to historical habitat conditions and disturbance regimes. For example, native salmon can effectively exploit and safely withdraw from seasonal floodplain wetlands during pulsed flooding events. Non-native fishes likely benefit from the muted flow regime managed by the Columbia River dams and may be less able to avoid stranding when floodwaters recede from floodplains (e.g., Sacramento River, Moyle et al. 2007). Optimal habitat conditions for salmon cannot be defined as a simple statistical average but rather as a dynamic mosaic of interconnected habitats in space and time (Reeves et al. 1995; Stanford et al. 2017). While it is generally impossible to re-establish historical conditions, especially in a shifting climate, pre-development habitat patterns can provide guidance regarding the types of habitat in greatest need of restoration (Marcoe and Pilson 2017).

Conceptual Framework

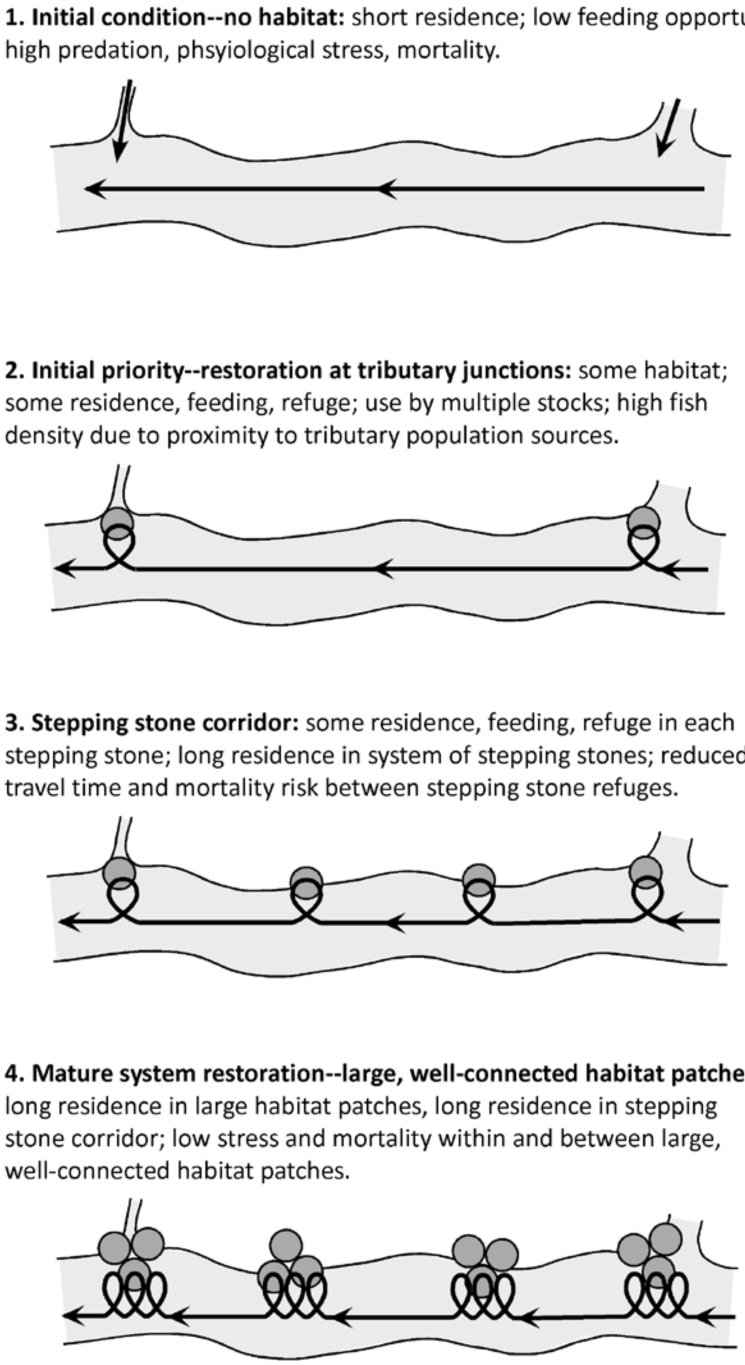
Restoration actions in the LCRE have prioritized large habitat patches to support juvenile salmon. However, some circumstances might justify restoring many small patches rather than fewer large ones. Even small habitat patches might be beneficial at strategic locations to enable fish to gradually adjust to tidal or saline environments or to provide refuge, feeding, or resting opportunities. For example, wetland rearing habitats may be limited in some estuary reaches by geological constraints, e.g., steep volcanic shorelines (Simenstad et al. 2011) such that small restoration projects could provide disproportionate benefits. The same may be true where urban development constrains the size of restored habitat patches, provided urban impacts on water quality do not undermine potential benefits. Determining the benefits of specific locations relative to the importance of site size is complex. The following section offers guidance for weighing restoration choices based on habitat patch size, geographic distribution, and proximity to other patch and matrix habitats.

Habitat Stepping Stones

The principal goals of habitat restoration for salmon under CEERP are to (1) provide physiological refuges for their transition to ocean conditions; (2) provide refuge from estuarine predators; and (3) maximize fish growth and condition to increase survival during the first months of ocean residency, a particularly vulnerable period (Pearcy 1992; Duffy and Beauchamp 2011). To support these goals, stepping-stone habitats (Figure 2) along the 234-km length of the Columbia River estuarine migratory corridor must provide foraging opportunities and shelter for a diversity of stocks and life history types. While growth and condition are maximized by high-quality habitat in large restoration sites, vulnerability to predation and physiological stress during migration could be improved by reducing distances between large patches by adding (small or large) stepping-stone habitats. Typical physiological stresses include thermal stress as seasonal water temperatures increase (salmon are cold-water fish), salinity stress in lower estuary reaches as the salt wedge moves with the tide, high water velocities during flood events, poor water quality in some locations and time periods, and lack of food in reaches with poor habitat.

Habitat patches and stepping-stone habitats for salmon include tidal channels and adjacent wetlands in the lower, tidally dominated estuary (Reaches A, B, and C), and floodplain channels, lakes, and wetlands accessible below mean higher high water in the upper, fluvial-dominated estuary (above Reach C). In Reaches G and H, creeks, alluvial fans, marshes, and sloughs may function as critical cold-water refugia and low-velocity rearing areas. Stepping-stone habitat should support channels or pools that are sufficiently deep to host yearling juvenile salmon during most of the daily tidal cycle. Tidal channels should contain or be linked to deeper pools or matrix habitat that provide suitable low-tide refugia (e.g., Hood 2012). Of course, small stepping stones will benefit relatively few juvenile salmon such that more habitats will be required to support migrating fish. The total area of habitat desired will depend on the distance between habitat patches, habitat patch sizes, habitat dynamics, and salmon abundance.

Habitats may function differently for fish (e.g., refuge, forage) depending on estuarine location and changing physical conditions (e.g., inundation timing). Restoration decisions must consider the effects of habitat type, location, and inundation timing (i.e., accessibility) on use by different salmon stocks and life histories. For example, the minimum floodplain area required to support a channel network varies along the estuarine-riverine tidal-freshwater gradient. Low in the estuary, where the tidal prism is great, relatively little area is required. High in the estuary, where tidal influence is reduced, large areas are likely required. The relationship between marsh area and tidal channel surface area or length has been well-documented in some tidal systems (Hood 2007, 2015). Such relationships have not been described in fluvially-dominated estuarine reaches with limited tidal exchange.



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.

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. Conceptual model of a stepping stone migratory corridor for juvenile salmon. Dark gray circles are habitat patches. Arrows represent the direction of river flow and general direction of migration. Loops indicate temporary fish residency in patches, analogous to nutrient spiraling.

Prioritizing restoration of a few large habitat patches versus several small stepping-stone habitats will depend on the sizes, geographic distributions, and accessibility of existing habitat as well as matrix conditions. We propose three principal objectives for selecting restoration sites and rebuilding an estuarine landscape that benefits juvenile salmon: (1) provide for gradual physiological transition of juvenile salmon during estuary and saltwater entry by establishing habitat opportunities in key transition zones along both estuary shores, (2) minimize stress and predation risks during estuary migration by reducing travel distances and improving matrix conditions between habitat patches, and (3) increase opportunities for estuary feeding and residency to improve growth and survival at ocean entry by increasing the size of available habitat patches.

An important question is how closely habitat patches should be spaced. Most floodplain rearing habitat in the LCRE is tidally influenced and drains on low tides or during low river flow. This forces at least some juvenile salmon rearing in those channels to emigrate to deeper water, where they are exposed to the currents of the mainstem river or large tributaries. Because swimming speed scales with fish size (Bottom et al. 2005b), salmon fry are at the mercy of river currents except where velocities are low. Fry and small fingerlings expelled from shallow, low-velocity habitat are most vulnerable to being carried downstream unless suitable low-tide refugia are available immediately adjacent to vacated wetland channels and confluences.

To accommodate fish swept downstream, the next available habitat patch should be located within a distance that the current could carry individuals for the next 6.2 hours, i.e., before the tide reverses and fish can reoccupy shallow tidal habitats. For example, 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. These are common current velocities along the shoreline, where salmon fry are typically found during migration, though fry can sometimes avoid high-velocity waters and travel shorter distances. This rough estimate of likely travel distance is similar to the range of 5 to 36 km/day estimated by recapturing marked salmon fry in the estuary (Dawley et al. 1986). As a conservative estimate, we propose that stepping-stone habitats in the LCRE be spaced <5 km apart, unless evidence for specific local conditions suggests otherwise. These estimates are based on existing data for small juveniles (fry). Larger juveniles (smolts) are more capable of swimming against stronger currents such that their dependence on stepping stones would be less compared to that of fry. Nevertheless, a high density of stepping stones would likely benefit smolts inclined to exploit them while providing rearing opportunities and shelter for a greater diversity of juvenile size classes and life history types.

A high-quality matrix can facilitate movement and survival between habitat patches (Tanner 2006; Driscoll et al. 2013). For example, juvenile salmon found along riverine and lacustrine shorelines characterized by natural cover (e.g., undercut banks, overhanging vegetation, and large woody debris) are more abundant and better fed than those distributed along shorelines armored by riprap (Garland et al. 2002; Tabor et al. 2011). Riprap creates habitat deserts for juvenile salmon (reviewed by Reid and Church (2015)). It disrupts the natural processes that create and maintain nearshore refuge and foraging habitats for juvenile fish, including (1) bank erosion, which delivers sediments, recruits woody debris, and creates complex shorelines with undercut banks; and (2) riparian succession, which establishes overhanging 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 relative to armored shorelines of the industrialized Duwamish River estuary in Puget Sound. Vegetated nearshore habitats produce terrestrial prey and epibenthic crustaceans favored by juvenile salmon and could provide other important prey-production sources for the estuary mainstem, particularly in constrained and urbanized reaches that have few opportunities to re-establish floodplain wetlands or large off-channel habitat patches. Thus, beyond reestablishing stepping-stone habitat patches, restoration should improve the adjacent matrix along the migration corridor, e.g., by removing riprap and other structures that disconnect channels from floodplain and riparian areas.

Determining the relative benefits and synergies of restoring patch and matrix habitats is challenging. However, matrix 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 matrix habitat. By this measure, restoration of small stepping-stone habitat might partially compensate for hardened shorelines. Further, patches in close proximity 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 habitats and matrix change.

Landscape Context and Site Recovery

Conservation of intact patch and matrix habitats facilitates habitat restoration once stressors are abated. The recovery rate and ecological functioning of a restoring habitat depends on multiple factors, including the sources and dispersal rates of plants and animals and the supply and delivery of sediments. Although not tested in the Columbia estuary, the principles of landscape ecology predict that isolated habitats will be colonized at a slower rate and have fewer species than those near relatively undisturbed landscapes (e.g., Forman and Godron 1986). Strategic conservation of patches and matrix habitat thus may strengthen the resilience of existing or newly restored estuarine habitat.

For example, recovery of habitat patches that are moderately disturbed by diking and channelization and located adjacent to an undisturbed matrix (e.g., the Cathlamet Bay region) should recover relatively quickly once the hydrological connections are restored because colonizing species and sediment sources will be readily accessible. In comparison, habitat patches may recover more slowly if extensive shoreline development and levee construction prevent transport of species and materials from adjacent matrix habitats (e.g., the Clatskanie region). Habitat patches in disconnected landscapes can be severely subsided because sediment input that would help maintain surface elevations has been restricted. The landscape context of habitats thus influences their recovery trajectories, including ecological support functions for juvenile salmon (Figure 3).

The diversity of vertical vegetation structure (i.e., the heights of species) within an assemblage is a metric of habitat complexity. By 2009, the restored habitat at Kandoll Farm was essentially a single layer of herbaceous vegetation, whereas the reference habitat was more vertically complex due to an overstory of spruce trees and an understory of shrubs and herbaceous species. The reference habitat also contained exposed and buried large wood debris and an array of incised tidal channels (Diefenderfer et al. 2008; Diefenderfer and Montgomery 2009). The transition from a restored herbaceous system to a fully mature spruce wetland—the condition of the Kandoll Farm habitat prior to human intervention—could take a century or more. Because recovery rates to historical conditions are protracted at sites like Kandoll Farm, interim functionality relative to restoration goals (e.g., juvenile salmonid access) should be considered an interim indicator of success (e.g., Zedler and Callaway 1999).

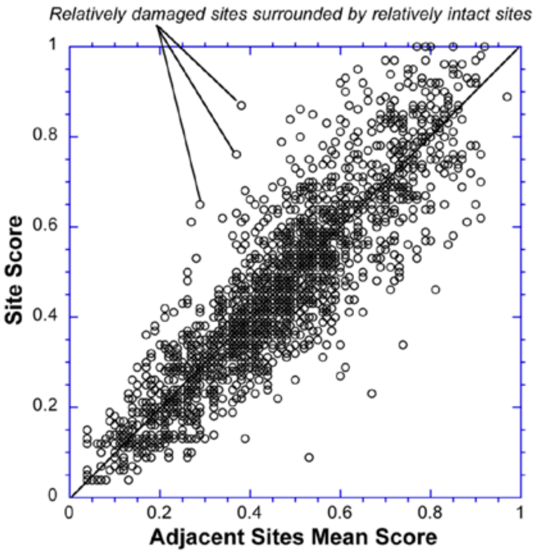


Figure 3. Plot of the condition of 2,072 hydrologically defined sites (ranging from 6 to 872 ha) in the Columbia estuary relative to the adjacent site conditions (Thom et al. 2011 [Figure 6]). Higher scores indicate greater disturbance levels. In general, disturbed sites surrounded by relatively undisturbed sites should recover more quickly than those surrounded by other highly disturbed sites.

The ecological responses in a recovering tidal wetland are typically non-linear. Early colonizing ("r-selected") species are later replaced by larger, longer-lived ("k-selected") species, and the number of species on a site declines. Although not studied in the LCRE, other ecological functions probably develop slowly during initial site recovery and then rapidly increase until the rate levels off at some sustainable maximum. Systems exhibiting these response dynamics include the Elk River marsh (Grays Harbor; Thom et al. 2002), Gog-li-Hi-Ti wetland (Tacoma, WA; Simenstad and Thom 1996), and the Salmon River (Oregon) tidal marshes (Gray et al. 2002; Gray 2005; Flitcroft et al. 2016). Diefenderfer et al. (2016) found that wetland systems within naturally breached levees in the LCRE develop their full/equilibrium structure, complexity, and function over several decades following the breaching event. Recently, Kidd (2017) showed that reconnecting the hydrology to former tidal wetlands in the LCRE resulted in protracted and varied changes in vegetation and soil conditions over at least five decades. Even after these extended periods, concordance between reference and reconnected sites was poor. It is clear that the trajectory and dynamics of the physical and physiological recovery are difficult to predict. Despite such varied and protracted ecological responses to restoration, juvenile salmon often benefit from renewed foraging and refuge opportunities soon after tidal wetlands have been reconnected (Gray et al. 2002; Bottom et al. 2005a; Roegner et al. 2010).

A common goal of ecological restoration is to strengthen and maintain the resilience of ecosystems to disturbance (Walker et al. 2004). Habitat resilience is largely a function of size and complexity. As noted above, large wetlands can develop and sustain larger and more complex tidal channel networks than small wetlands (Hood 2007, 2015, 2016). Such complex habitats can more effectively dissipate river flows and withstand disturbances than small, homogeneous sites. Physical complexity (i.e., elevations, sediment types, channels) also provides a greater variety of habitat opportunities (i.e., "niches") to support a larger number of plant and animal species. Importantly, a high-quality, continuous matrix can also improve habitat resiliency by facilitating rapid recovery and maintenance of habitat conditions by, for example, allowing frequent sediment deposition that maintains floodplain elevations and channel complexity.

The selection of habitats for restoration should consider their recovery potential and ecological function, as influenced by size and landscape context (i.e., proximity to intact habitats containing source materials and species, Figure 3). As illustrated in Figure 4, small habitat patches restored in poor locations currently offer minimal benefit to the broader ecosystem and its species, tend to be less complex, and are minimally resilient (see Figure 4, condition I). In contrast, large habitat patches located in minimally disturbed locations currently offer greater contributions to the ecosystem and are generally more complex and resilient (see Figure 4, condition VI). Thus, strategic improvement of matrix conditions or protection and conservation of nearby sources of materials and species may further aid the restoration of functional habitat patches.

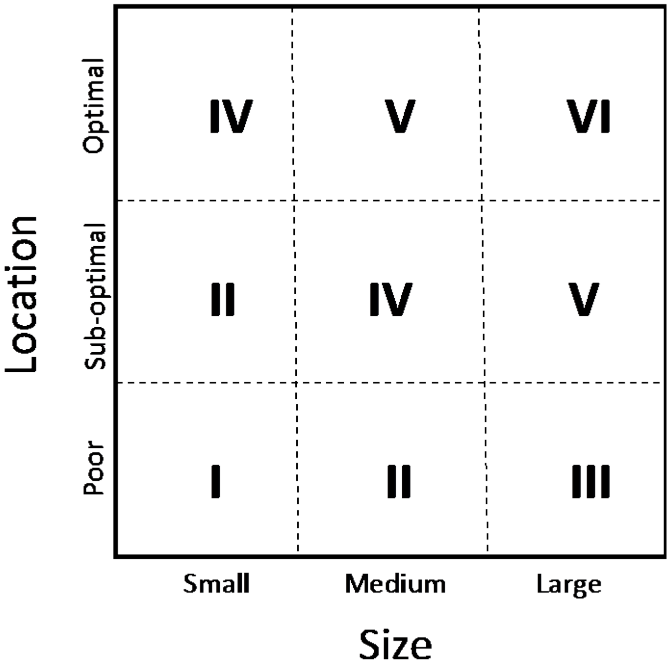


Figure 4. Matrix of restoration site size and landscape location. Size categories are roughly: small, <30 acres; medium, 30–100 acres; and large, >100 acres. Location describes connectivity with intact landscape (see Krueger et al. 2017).

Food Web Benefits of Wetland Restoration

The production of organic matter (OM) by tidal wetland plants is important to the food webs supporting juvenile salmon in the LCRE (Simenstad et al. 1990; Maier and Simenstad 2009; Bottom et al. 2011). Loss of wetland-derived OM due to diking of floodplain wetlands has shifted dominant estuarine food web sources from wetland-derived macrodetritus to pelagic (i.e., water-column-derived) microdetritus (e.g., plankton) produced in reservoirs (Sherwood et al. 1990; Small et al. 1990). Macrodetrital decomposition and entry into the estuarine food web supports several high-energy invertebrate species (e.g., amphipods) and provides the primary energy source for prey preferred by juvenile salmonids. By one estimate, wetland losses have accounted for an ~82% reduction in the historical macrodetrital production available to estuarine food webs (Sherwood et al. 1990). Despite a substantial shift toward pelagic OM sources, subyearling Chinook Salmon continue to select for foods that are linked to marsh detritus and benthic diatoms (Maier and Simenstad 2009). Anderson (2006) measured mean estuary residence times for subyearling Chinook Salmon in 2003 and 2004 by estimating the total periods that juveniles had interacted with emergent-marsh food webs in the lower 65 km of the estuary. On average, salmon "interaction times" with marsh-derived prey were ~65 d and ranged from 0 to 265 d (Anderson 2006; Maier and Simenstad 2009).

Reconnecting the floodplain and restoring the production of wetland-derived macrodetritus is an important step toward restoring the historical food web, which can benefit salmon growth and survival. Moreover, the food web benefits of marsh restoration are not confined to local wetland channels or those juvenile salmon that occupy them. Prey and OM produced in tidal wetlands are also food for salmon outside these habitats (Ramirez 2008; Eaton 2010; PNNL and NMFS 2018).

Figure 5 illustrates the effects of reconnecting a 65-ha former wetland to the Grays River approximately 7 km upstream from Grays Bay. This research (Thom et al. 2018) determined that ~9% of the peak above-ground marsh biomass produced in Kandoll Farm was deposited in the floodplain and Grays River downstream from the site, and ~10% reached the mainstem estuary in Grays Bay. Further, the bulk of the OM leaving the site was mobilized by peak flood events in November. The results demonstrate that pulsed hydrological events are important in the transport to the river of OM produced in floodplain wetlands. Although additional verification is needed, the results suggest that larger sites closer to the mainstem and with a greater degree of hydrological connection may contribute proportionally greater amounts of OM to the estuary. We speculate that the contribution of OM to the estuary decreases with distance upstream in tributaries, but this would depend on the size, connectivity, and marsh macrodetrital production in those sites. Additionally, sites with native marsh vegetation may provide greater amounts of OM compared to sites dominated by reed canary grass (Thom et al. 2018). Juvenile salmon gut contents and stable isotope analyses (Maier and Simenstad 2009; Maier et al. 2011) indicate that marsh OM is processed in the estuary and made available to various epibenthic prey (particularly amphipods and insects) that in turn are consumed by juvenile salmon (Bottom et al. 2011).

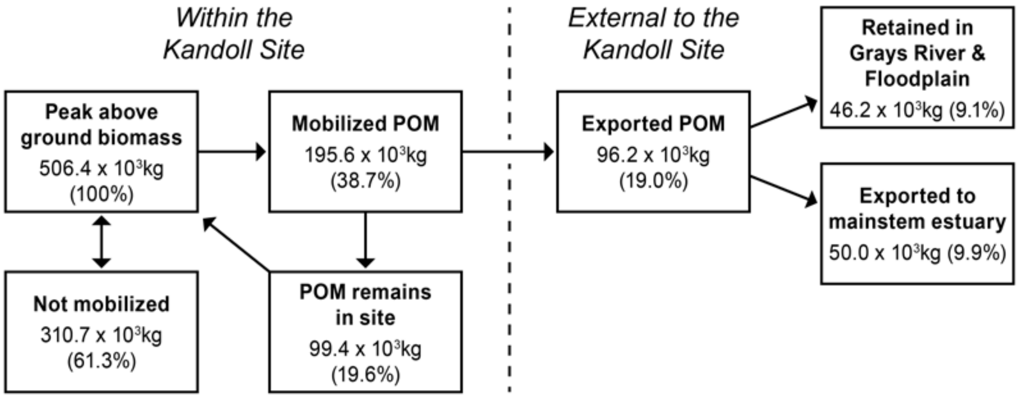


Figure 5. Example of the processing and export of marsh-derived OM from the Kandoll Farm restored site to the mainstem of the LCRE. (Reproduced from Thom et al. 2018.)

Amount of Restoration Needed

Benefits of habitat restoration are apparent; juvenile salmon from above Bonneville Dam use intact and reconnected estuary wetlands and the OM and prey exported from them (Johnson et al. [eds.] 2018). However, the amount of restoration required to have a measurable "signal" is not known. Several studies provide hints as to how much restoration may be needed to produce a significant population or ecosystem response.

A comparison of study results from nine Northwest estuaries (including the Columbia) concluded that fish density could constrain salmon foraging performance where large proportions of the historical wetland habitat have been lost (David et al. 2016). In this case, juvenile Chinook Salmon density had no effect on foraging performance (i.e., instantaneous ration and energy ration) where <50% of historical wetland area had been removed but had a negative influence in estuaries where wetland losses exceeded 50%. The results suggest that protecting or recovering more than half of the historical wetland area might mitigate the effects of fish density on foraging performance and thereby improve salmon fitness (i.e., through increased growth and size).

The results of population studies in Oregon's Salmon River suggest that restoring 60–70% of lost tidal wetlands can directly benefit adult salmon returns through the survival of juveniles with estuary-resident life histories (Jones et al. 2014; Flitcroft et al. 2016). For example, Jones et al. (2014) evaluated estuarine habitat use, life history composition, growth, and survival of four successive broods of Coho Salmon in the Salmon River, where approximately 70% (i.e., 175 ha) of the original wetland area (i.e., 254 ha) had been restored since 1978. Emergent fry, subyearling, and yearling Coho that used the restored wetland habitats for extended periods accounted for 20–35% of the adults returning to spawn in the four brood years. These juvenile life histories were rare or absent in the population when most of the estuary wetlands had been diked. Estuary restoration increased juvenile life history diversity in the population, revealing greater phenotypic plasticity (e.g., behavioral flexibility in timing and size at estuary entry, duration of residency, and habitat use) of this species in the US Pacific Northwest than previously recognized. The results of this study indicate that a 40-year effort to restore 70% of the historical wetland area had a measurable effect on Coho salmon returns.

Historical Template

Historical maps offer useful guidance for understanding wetland habitat changes and identifying recovery goals for different regions of the estuary. Detailed maps of historical conditions in the LCRE produced by the Coast Survey in the late 1800s (T-sheets) (Figure 6) depict land cover complexity and estuarine habitats that were available to juvenile salmon more than a century ago. Land cover classes in the LCRE have been identified and tracked through time by Marcoe and Pilson (2017) (Figure 6). The results can be used to quantify restoration trajectories based on the trends and similarities of current land cover types to the historical conditions.

The structure and scale of the estuarine landscapes and landforms in the Columbia estuary ecosystem have been classified by Simenstad et al. (2011) based on system hydrology and geology. This work delineates: "*(1) eight hydrogeomorphic reaches that embody the formative geologic and tectonic processes that created the existing estuarine landscape and encompass the influence of the resulting physiography on interactions between fluvial and tidal hydrology and geomorphology across 230 kilometers (km) of estuary, (2) more than 15 ecosystem complexes composed of broad landforms created* *predominantly by geologic processes during the Holocene, and (3) more than 25 geomorphic catenae embedded within ecosystem complexes that represent distinct geomorphic landforms, structures, ecosystems, and habitats, and components of the estuarine landscape most likely to change over short time periods.*"

The classification system provides insight into the geological and hydrological processes that have shaped historical estuarine habitats and landscapes and will influence the trajectory of future ecological responses to disturbance. Jay et al. (2014, 2016) also analyzed the hydrology, hydrodynamics, and elevation of the LCRE to determine the major controlling factors affecting the present distribution of vegetation in the undiked portion of the floodplain system. They then applied a model of vegetation hydrological requirements to classify zones of floodplain wetland assemblages along the estuarine gradient.

Collectively, the hydrogeomorphic classifications and historical landscape data described above as well as new research on habitat connectivity, OM production and export, and fish prey resources and growth (Johnson et al. [eds.] 2018) provide a powerful set of models and data to guide restoration. These tools will allow evaluation of habitat and ecosystem resilience in the context of primary forcing factors; restoration progress toward historical conditions (given current constraints, e.g., floodplain development, hydrosystem management, etc.); and future response to disturbances, including floods, sea-level rise, and climate warming.

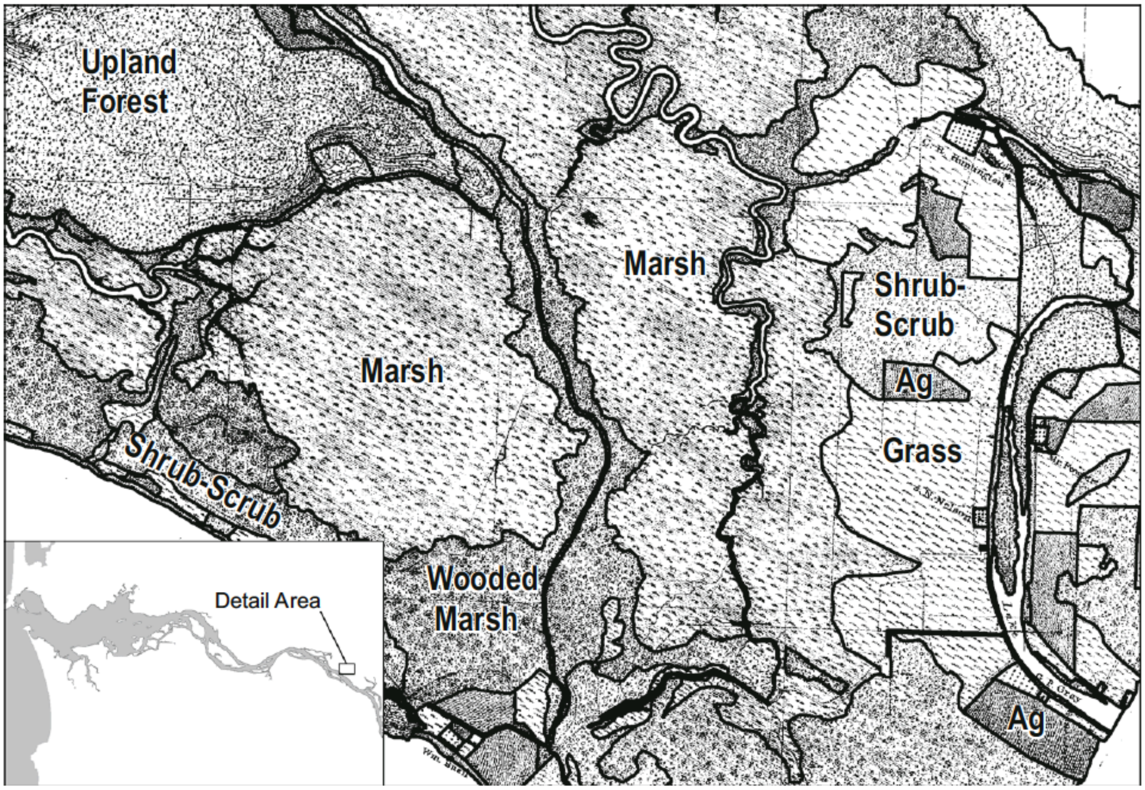


Figure 6. Land cover classes from the late 1800s Office of Coast Survey T-sheet, with an overlay of the University of Washington Wetland Ecosystem Team polygon interpretations of land cover based on T-sheet symbols (UWWET 2010). (Figure reproduced from Marcoe and Pilson 2017 [Figure 3]).

Habitat Creation

Where opportunities to restore historical habitat functions are limited, habitat creation is sometimes proposed to speed ecosystem processes and establish favorable conditions for juvenile salmon by emulating preferred habitat types that exist in a natural landscape. In restoration ecology, creation is defined variously as the development of a system or habitat type (e.g., emergent marsh) in a place where it did not exist historically or where that type has been irreversibly diminished or modified. In the LCRE we have reviewed at least three types of proposed habitat-creation actions since 2009: (1) using dredged material to fill (i.e., supplement) a former subsided marsh and increase its elevation to a level that will enable marsh development; (2) infilling an existing channel with material to create a sloping shoreline and higher riparian zone; and (3) creating terraces along shorelines for riparian vegetation planting and development.

We expect created habitats to have an initial period of relatively rapid physical and biotic change that later slows considerably. However, development trajectories would likely vary among created habitat types and locations (Figure 7b – d) and may not achieve the optimal reference conditions or functions expected from breaching a naturally occurring marsh habitat (Figure 7a). Through time, natural erosion and deposition processes may change the composition, structure, and function of created habitats, requiring frequent intervention and maintenance to maintain the intended ecological function for the new habitat. Creation projects using dredged material to increase the elevation of a former low-velocity marsh habitat may develop ecological functions more rapidly and require less maintenance than some other project types, as this approach recreates a historical habitat in type and location (Figure 7b). In contrast, efforts to build artificial riparian terraces could be hampered by hydrological processes (e.g., erosion and scour) that slow establishment of riparian vegetation and limit long-term recovery (Figure 7d). Further, created habitats will become a part of the landscape context for existing and proposed habitats and could undermine their benefits and resilience.

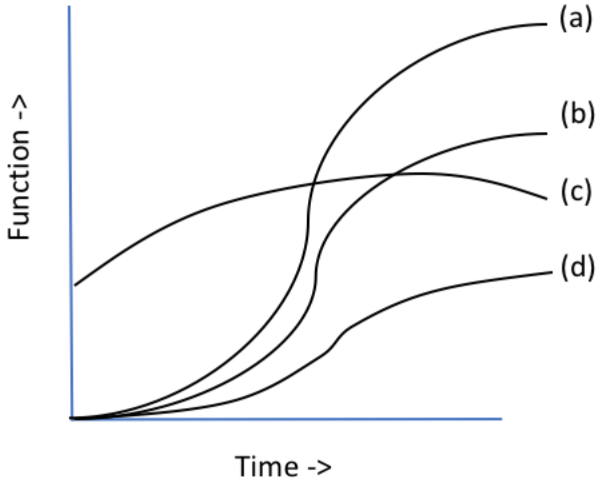


Figure 7. Relationship of increased ecological function with time of potential restoration actions: (a) breach levee of a former tidal wetland to reactivate channel network and wetlands; (b) place dredge material to fill a subsided former marsh to grade, breach levees, and excavate channel network; (c) infill a secondary channel of the Columbia River with dredge material to enhance the backwater and riparian characteristics of the area behind existing islands; (d) create terraces along the shore with riparian plantings.

One recent habitat-creation proposal in the LCRE would fill portions of an existing secondary channel with an associated embayment that is currently accessible to salmon and provides some refuge and food-producing habitat. Although these functions would likely continue, the proposed infilling to create additional edge and riparian area would eliminate some existing subtidal habitat and provide a short-term increase in shallow-water habitat. Access would not change but the net capacity benefit to juvenile salmon is less certain (e.g., Figure 7c). Sedimentation and erosion within created habitat in the primary and secondary channels of the Columbia River may not occur in a linear or unidirectional fashion. The ecological tradeoffs of removing one functional habitat to create another adds uncertainty that makes it difficult to anticipate the net outcome of creation projects. Engineered habitats that mimic natural wetland functions typically do not afford maximum ecological benefits, as “created habitats rarely perform the same functions or house the same biodiversity” as naturally occurring sites (Millenium Ecosystem Project 2005). Habitat creation, therefore, is not a substitute for protection or restoration of tidal wetlands.

Our approach generally assumes that restoration projects that restore historical environmental conditions reliably benefit salmon and system function; projects that emulate historical conditions to which salmon have adapted presumably provide substantial and predictable benefits (Krueger et al. 2017). Habitat-creation projects that create novel habitat-location combinations are potentially beneficial but introduce additional risks and uncertainties that must be fully assessed before a project is undertaken. Of particular concern are the potential ecological tradeoffs involved when replacing a previously existing habitat with a newly created one. Each creation project in a new location constitutes a unique experimental treatment that requires an initial assessment of the ecological costs and benefits and a subsequent monitoring program (Before-After-Control-Impact design) to measure the ecological response.

Guidelines and Uncertainties

Fragmentation of the LCRE and the patchy geographic distribution of large near-the-mainstem restoration opportunities raises specific questions about the landscape context of proposed projects and the salmon-benefit tradeoffs between their type, size, location, and geographic distribution along the estuarine tidal gradient. Our principles and conceptual models provide a general framework for evaluating individual projects and for developing a long-term strategy and options for reconnecting estuarine landscapes. Based on these models and principles, we return to the three questions posed at the beginning of this report:

1. Is it best to increase the size of large contiguous habitat wherever possible or to create "stepping stones" between habitats?

Restoration site selection and design should attempt to restore historical conditions while following the general approach described below, as possible, to expand the number, geographic distribution, accessibility, and ecological functions of habitat. Tagging studies and experimental releases have been designed to estimate salmon-mortality rates, identify presumed "limiting factors," and infer apparent "bottlenecks" in time or space to salmon survival and production (e.g., Dawley et al. 1986; Solazzi et al. 1991; Ryan et al. 2003; Bottom et al. 2005b; Good et al. 2005). However, we are increasingly aware that a dynamic mosaic of habitats and their ecological functions affect salmon migrating through the estuary, and no single "bottleneck" can be identified and controlled to ensure maximum survival of every stock. A better strategy than collecting data to predict and eliminate each presumed salmon "threat" is to expand the variety of habitat opportunities available to young salmon migrating through the estuary.

Restoration project selection and landscape design should prioritize at least one large habitat patch near the key transition zones within each hydrogeomorphic reach on both sides of the river. Transitional areas include the reach boundaries (Figure 1) and tributary confluences. Then, between the large, complex habitats, additional habitats (preferably large ones) should be established. Geomorphic considerations, as indicated by the historic habitats and geological template, will necessarily constrain opportunities within some of the reaches, such as Reaches C, G, and H. In more developed reaches (e.g., Reach D), where opportunities may be limited by levees or hardened banks, small off-channel patches become more important. Restoration of matrix composition, structure and function should be pursued when large and small patch restoration options are not available. The goal is a largely contiguous, complex, and dynamic habitat landscape as similar to historical conditions as feasible. Flow regulation, diking, and other changes clearly have modified estuarine hydrology from historical conditions. However, the historical template nonetheless depicts important spatial variations in water levels and inundation frequencies that have created and maintained salmon habitats and controlled the distributions of wetland vegetation (Jay et al. 2016). The historical template thus provides a useful model of the habitats and rearing conditions to which juvenile salmon have adapted that can help to define restoration objectives within the constraints set by the current hydrological regime (Krueger et al. 2011).

The stepping-stone strategy is intended to expand salmon rearing and migration opportunities in time (week, season, year) and space (reach and habitat type) by reestablishing a complex habitat landscape capable of supporting a diversity of stocks and life history types. Temporal variability in the estuary and the diversity of life histories within and among salmon stocks implies that no single, optimum habitat configuration exists. Some estuarine-resident life history types require weeks or months of rearing and growth in shallow, off-channel habitats. Some riverine-smolt life histories involve relatively rapid migration through the mainstem estuary channel. Expression of life history variation by multiple salmon species and stocks requires a complex estuarine landscape capable of supporting both small and large juveniles that may occupy the estuary during the same or different periods. Maximizing the diversity of habitat opportunities within and among hydrogeomorphic reaches is a useful objective. Recent survey data summarizing the temporal and spatial distributions of Chinook Salmon stocks in the estuary offer guidance regarding potential stock and life history beneficiaries of proposed restoration strategies (Teel et al. 2014).

Reestablishing complex habitat along the shoreline between patches (matrix habitat) will maintain continuity of opportunities for all juvenile fish as they move between small and large patches or migrate quickly to the ocean. Some of the shorelines are naturally constrained by geomorphology, such as in the Columbia River Gorge between Portland and Bonneville Dam or along the north shoreline in the lower estuary. Elsewhere, high levees protect industrial, residential, or agricultural infrastructure. Some of the small tributaries in these developed sites are redirected, channelized, confined to culverts, or tunneled under the development. In addition to preventing access to beneficial off-channel habitat or prey, the highly developed shorelines may be associated with poor water quality, toxic sediments, or increased concentrations of predators. It is challenging in these highly developed or leveed sections to provide opportunities for fish to find off-channel refuge, low velocity, shallow shelter, or access to benthic or terrestrial prey. Even in the absence of off-channel opportunity, the shorelines of the main channel, when functioning properly, can provide productive feeding areas for downstream migrating salmon of all life history types in the spring (Sather et al. 2016).

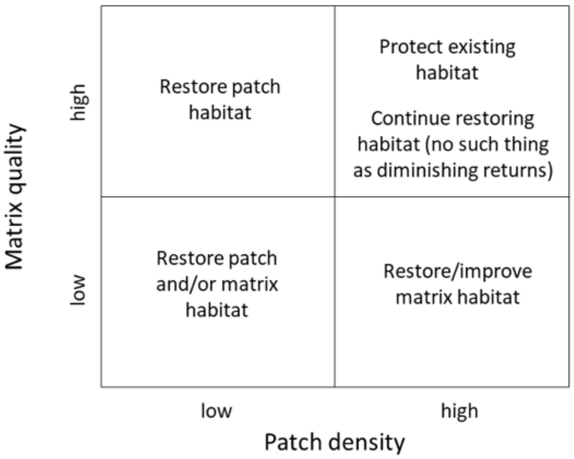
Restoration of developed shorelines is challenging but ignoring these areas is not beneficial. A first step is to restore shorelines upstream and downstream of developed areas to provide habitat for fish prior to encountering the area and shortly after passing through. Opportunities for restoration may be easier to locate and implement than in the developed areas and may avoid creating an attractive nuisance if poor water quality, toxic sediments, or non-native predators are present. Riparian or shoreline restoration in highly urbanized waterfronts may therefore be a lower priority than creating naturally functioning, self-maintaining habitats outside of the area.

If local water quality is acceptable, small, localized habitat opportunities may afford temporary residency, food, and growth opportunities for migrating fish. Quality may be more important than quantity in developed landscapes. For example, restoration actions could include planting riparian vegetation, enhancing benches (low-velocity areas along existing levees), adding large wood, developing tidal channels or sloughs, or connecting small streams directly to the river (Simenstad et al. 2005; Toft et al. 2010). Where constrained by levees and industrial development, restoration opportunities may be limited to habitat-creation projects such as the creation of benches or small beaches with riparian plantings (Toft et al. 2010) or “softened” shorelines (Chesapeake Bay Program 2018). Above all, potentially important habitats should be identified before development eliminates options for their restoration. Small stepping stones or migratory corridors may also provide important habitat for other fish and wildlife, create aesthetic natural areas, provide opportunities for education in an urban setting, and may better protect these shorelines in the long term.

2. Can a particular landscape become saturated with restoration projects such that the benefits of continued restoration diminish?

Evidence from other systems indicates that benefits increase as more historical habitat is restored (Bottom et al. 2005a; Jones et al. 2014; David et al. 2016; Flitcroft et al. 2016). Conceptually, the benefits of restoration projects could diminish (or increase) as a landscape or portion of a landscape becomes saturated with restored and relatively intact habitat. That is, as the landscape approaches historical structure and function, the benefit of each new project might decrease or increase relative to previous projects. However, in the small Salmon River system that has 70% of the historic estuary restored (Flitcroft et al. 2016), juvenile salmon are using all restored habitats, suggesting that benefits are not decreasing. Saturation and diminishing returns are unlikely even if habitats function independently and fish density is not limiting but additive (Hering 2010). Even greater benefits are likely if habitats interact synergistically. Similarly, the benefits of restoring "stepping stones" and shorelines in a landscape might increase to some asymptotic level. However, saturating the LCRE landscape with restored sites is unlikely because the estuary is highly altered (two-thirds of historic wetlands lost), landscapes are heterogeneous, and similar projects in similar landscapes can have very different salmon benefits based on their potential interactions with other sites. For example, relatively small projects may improve access to large areas and thereby improve the function of other restored sites.

We suspect that adjacent habitat conditions and ecological processes have important implications for the benefits, recovery rates, and persistence of restoration actions. Conceptually, very similar sites will function similarly for fish, but synergistic (and antagonistic) effects might differ in magnitude and direction due to the conditions of the surrounding habitats and matrix. Generally, we believe that restoration sites are more likely to achieve their intended function and persist through time if the surrounding landscape is relatively intact and provides sources of, for example, clean water, sediment, energy, nutrients, seeds, and native species for the restored habitat. Similarly, restoration sites may be more effective where the surrounding habitats and matrix are in good condition, while improvements to hardened shorelines or other poor-quality matrices might enhance the salmon-support functions of existing habitat patches or the recovery and resilience of restored sites. Restoration proposals for different estuary locations thus must weigh the relative benefits of restoring (or protecting) additional habitat patches and/or improving the quality of the surrounding matrix (Figure 8).



Matrix quality	Patch density: low	Patch density: high
high	Restore patch habitat	Protect existing habitat Continue restoring habitat (no such thing as diminishing returns)
low	Restore patch and/or matrix habitat	Restore/improve matrix habitat

Figure 8. Effects of patch habitat density and matrix quality on restoration priorities in different estuary locations.

In highly developed areas with few restoration opportunities, saturation of restoration sites is not a concern and the potential added benefit of the restored site might be great despite uncertainties about habitat recovery and maintenance (assuming water quality concerns are minimal, and the site does not pose an attractive nuisance). When support functions are limited regionally, even a small improvement might have an important benefit; that is, location can be more important than the project size or type. Accounting for the potential location benefits of a proposed project requires a more generalized assessment of restoration needs and priorities at a coarse scale, for example, the scale of each hydrogeomorphic reach.

The realized benefit of a specific habitat will likely change. Although restoring additional habitat and improving ecological function is expected to provide a net benefit (e.g., David et al. 2016; Flitcroft et al. 2016), the added value of each proposed project may vary depending on the combined effects of other improvements nearby. Similar to the ERTG scoring process, the current and anticipated effects of each project must be evaluated (or scored). As conditions change naturally and restored habitats and matrices evolve, the individual and cumulative benefit of habitat projects can be expected to change.

3. What beneficial actions besides hydrological reconnection can be taken to improve “matrix” areas between habitats?

The ERTG conceptual model identifies elements of a habitat that benefit juvenile salmon survival based on the assumption that opportunities for salmon life history expression most reliably benefit from historical habitat conditions (Krueger et al. 2017). Using this model, some subactions from the Estuary Module, such as habitat creation, could have detrimental effects (e.g., burial of currently functioning salmonid foraging habitat or providing habitat for piscivorous bird colonies), but still provide other useful functions (e.g., shading via riparian vegetation). Creating novel habitats within a reach or at a tributary confluence might best occur when no reasonable alternatives exist to restore historical conditions and where negative effects on adjacent habitat patches or matrices appear unlikely. We note that not all habitat types or conditions historically occurred in every reach due to differences in the processes that create and maintain habitats. Damage to adjacent natural or restored habitats and processes should be avoided.

To date, the CEERP has primarily focused on hydrological reconnection of floodplain habitats to provide transition, refuge, and feeding opportunities for juvenile salmon. This recognizes that floodplain habitats afford some of the most direct support functions for growth, predator avoidance, and survival of juvenile salmonids. However, opportunities for hydrological reconnection are limited. Viable restoration opportunities are becoming less available, and portions of shoreline are so altered in some industrial or urbanized areas that reconnection and restoration would be inordinately disruptive and expensive. In these areas, other types of restoration still may be useful to improve matrix habitats or environmental conditions between accessible floodplain habitats or to improve other ecosystem functions that benefit young salmon.

Palmer (2009) recommends that restoration emphasize ecological processes rather than structures and single species. Defragmenting the landscape can also enhance processes that form and maintain habitat and strengthen ecological resilience. A landscape-based approach suggests restoration actions such as those listed below can be beneficial.

- Improve the function of restored habitats (e.g., maintenance to ensure succession).

- Improve the function of floodplains by restoring habitats in the tributary watersheds; that is, further reintegrate ecosystem processes in watersheds (e.g., cooling of water temperature) to support functions near the mainstem.
- Enhance upland riparian ecosystems that may improve the quality of the restored wetland system.
- Restore and enhance the complexity of already connected habitats.
- Protect, restore, enhance, or create habitat features or attributes that address key ecological needs.
- Restore and enhance novel or rare elements of the system (e.g., cold-water refuges). Such elements provide a small “stepping stone” where few habitat opportunities exist.
- Protect and restore ecotonal habitats that affect habitat-creation processes and maintain habitat benefits (e.g., riparian reconnection and restoration of historical conditions).
- Protect and enhance narrow, fine-sediment beaches along the mainstem to minimize ship wake disturbances and maximize prey resource (e.g., amphipod) production for salmonids.
- In places where space is limited, create or enhance small habitats such as “pocket” embayments along corridors used by fish.
- Protect natural sources of sediment (e.g., floodplain tributaries and mainstem sources) for restoring wetlands.
- Modify land-use practices in watersheds that would introduce unnatural loads of sediment to restoring areas in the estuary.
- Restore salmon runs in local estuary tributaries (e.g., Youngs Bay).
- Refill dredged sites (e.g., abandoned boat basins and log storage sites) to historical shallow-water elevations; enhance habitat quality surrounding these sites as needed.
- Consider strategic fill placement to develop marsh-flat-channel complexes (e.g., Woodland Islands), especially where restoration to historical conditions is not possible.
- Eliminate or reduce sources of harmful pollutants to the estuary.
- Remove causes of enhanced predation opportunities by fish or birds.
- Clean up shallow, contaminated areas that could kill salmon, slow their growth, or introduce disease.
- Remove unnatural debris (e.g., derelict gear or Styrofoam floats) that could impede salmonid access to feeding and rearing habitat or entangle fish.
- Reduce or eliminate sources of introduced species or disease.

Research Needs for a Landscape Approach to Restoration

Understanding the ecological interactions and processes that benefit juvenile salmon in the LCRE is improved by research from this and other ecosystems both small (e.g., Salmon River) and large (e.g., Sacramento-San Joaquin and Fraser Rivers). The current CEERP process primarily evaluates the benefits of individual project proposals to salmon growth and survival, which may not describe the habitat needs or restoration benefits during an individual's entire estuarine residency. In a highly fragmented estuary, benefits accrued at a site may or may not predict subsequent performance or survival, regardless of the duration of estuary residence. The stepping-stone strategy would benefit from a better understanding of the effects of geographic distribution and size of patches on juvenile salmon survival until ocean entry. Primary questions include the population and life history diversity of fish using the habitats; salmonid response to wetland and floodplain restoration (e.g., use, timing, growth, survival); effects of location and juxtaposition of sites within and distant from the estuary mainstem (e.g., access, export of food); and influence of restoration on ecological processes in the mainstem.

Many interior basin stocks use floodplain wetlands in the estuary (e.g., McNatt and Hinton 2017) but few studies have investigated whether subyearling and yearling fish access habitats far from the mainstem. Salmon occupancy likely declines (linearly or geometrically) with distance from the mainstem Columbia River but studies have not addressed this question. With the exception of the large Willamette River confluence, Teel et al. (2014) reported few non-natal stocks of Columbia River salmon occupying the lower ends of estuary tributaries. Restoration within a tributary may directly benefit local populations but may not support fish migrating down the Columbia River. Similarly, restoration within an island complex (e.g., Sauvie Island) may produce prey resources and detritus, but river flows and water elevations could limit fish access from (and prey export to) the mainstem estuary. The relative timing of high flows and salmon migrations may determine which stocks and life history types can access floodplain habitats (Roegner et al. 2012). Sampling is needed to confirm the presence and frequency of occurrence for juvenile salmonids as well as for the factors (e.g., water level, river flows, etc.) that may influence dispersal of mainstem fish into back-channel areas. For example, tidal forces in Reaches A, B, and C may promote the movement of mainstem fish into the interior of island complexes and into tidally influenced tributary confluences, whereas salmon movement in fluvially dominated reaches may be constrained by regulated flows that limit fish dispersal into backwater areas and access to floodplain habitats. Lateral movement into wetland sites also will vary with life history type and source population. Directed sampling and passive integrated transponder detection could help answer some of these questions.

A bioenergetics study of juvenile salmon and their use of energy supported by the estuary might help tie restoration actions to outcomes (e.g., see Bieber 2005; Gray 2005; Klopfenstein 2016). Recent research has confirmed that juvenile salmon feed and grow between Bonneville Dam and the river mouth (McNatt and Hinton 2017; Sather et al. 2017; Weitkamp et al. 2017; PNNL and NMFS 2018). Wetland and floodplain restoration may provide prey resources that support upriver and local salmon stocks. Reliance on wetland-derived food resources and indications of improved growth provide strong evidence that the system is enhancing the fitness of juvenile salmon.

Data from the much smaller Salmon River (Jones et al. 2014) has provided the most direct evidence that restoring significant areas of wetland habitat can benefit adult salmon returns. These results demonstrate the importance of population-level studies to tie estuarine life histories and performance of juvenile outmigrants to the survival and return of adults. Otolith studies for selected Columbia River populations have demonstrated estuary linkages to returning adults (Roegner et al. 2014; Rose 2015). However, consistent monitoring of populations is needed to collect adult otoliths and document variations in the contributions of estuarine life histories as climate changes and the restoration program progresses. Long-term monitoring of juvenile life history contributions to selected spawning populations could provide a key indicator of salmon resilience to environmental change and the effectiveness of estuary restoration.

Eighty-two federal, state, and tribal hatcheries now release ~140 million salmon (*Oncorhynchus* spp.) and steelhead (*O. mykiss*) annually into the Columbia River basin totaling 3,700 to 6,000 metric tons (Flagg 2015). Hatchery releases are concentrated during the peak spring salmon migration period, when a diversity of all Columbia River salmon stocks congregate in and migrate through the estuary (Teel et al. 2014). An unstated assumption of the CEERP is that interactions between hatchery and naturally produced salmon are limited or benign and thereby will not undermine the presumed benefits of estuary restoration. Estuary habitat use by juvenile salmon is generally size related and could minimize interactions between hatchery and wild fish. For example, large hatchery juveniles frequent deep channel areas whereas many smaller, naturally produced fry and fingerlings congregate in shallow, nearshore, and wetland habitats (Bottom et al. 2011; Roegner et al. 2012; Weitkamp et al. 2015). Despite these general patterns, the distributions of hatchery and wild fish overlap considerably even in shallow, nearshore areas, such that the total biomass of hatchery Chinook often equals or exceeds that of naturally produced juveniles (NOAA Fisheries, unpublished data). New research is needed to determine the extent of behavioral and ecological interaction in the LCRE between hatchery and wild salmon and the implications for the CEERP.

Summary and Conclusions

Nearly two-thirds of the historical wetland habitats of the LCRE formerly available for salmon have been lost. We propose a framework for improving landscape connectivity: restoring ecological support functions and the dynamic mosaic of estuary habitats to enable the full expression of Columbia River salmon life history variation. The conservation principles and conceptual models supporting this framework are consistent with the general principles previously proposed by the Independent Scientific Group for the Columbia River Basin Fish Wildlife Program (Liss et al. 2006):

1. *Restoration of Columbia River salmonids must address the entire ecosystem, which encompasses the continuum of freshwater, estuarine, and ocean habitats where salmonid fishes complete their life cycles. . . .*
2. *Sustained salmonid productivity requires a network of complex and interconnected habitats, which are created, altered, and maintained by natural physical processes in freshwater, the estuary, and the ocean. . . .*
3. *Genetic diversity, life history, and population diversity are ways salmonids respond to their complex and connected habitats. These factors are the basis of salmonid productivity and contribute to the ability of salmonids to cope with environmental variation. . . .*

The ERTG review process for restoration projects is largely opportunistic and rarely considers the variety of habitats necessary to maintain a diversity of Columbia River salmon populations and life histories. Restoration of large sites is a clear priority for maximizing potential benefits to juvenile salmon, but the ERTG review process provides little guidance about restoration alternatives where options are naturally or anthropogenically limited. Based on our analysis and review, we offer the following conclusions and recommendations to incorporate a landscape approach in the CEERP:

Largely connected, complex, and dynamic habitat conditions that occurred historically offer a useful template for identifying "ideal" habitats for Columbia River salmon. While returning to historical conditions and dynamics is impossible, they provide useful insight into the habitats, geographic distributions, and dynamics that are underrepresented and may therefore be restoration priorities.

A stepping-stone conceptual model for juvenile salmon offers guidance for identifying circumstances when small estuarine restoration sites may yield disproportionate benefits. The stepping-stone approach restores and protects large habitats for maximum benefit to juvenile salmon residency and growth; creates stepping stones (small, beneficial habitats) to improve connectivity of large habitats and minimize migratory and predation stress; and restores shoreline habitats (matrix) along both sides of the estuary to promote the recovery and resilience of habitats.

Habitat stepping stones should be located strategically to maintain ecological support functions for all salmon populations and life histories:

- Position habitat stepping stones to support the gradual transition of fish to the estuary, including sites in estuary tributary junctions and brackish-water zones.
- Add stepping stones as needed to minimize potential stress, disturbance, and predation risks by reducing travel distances between existing large (natural or restored) habitats.

- Restore large stepping-stone habitats by expanding the size of existing habitat patches and adding new ones, thereby enhancing salmon residency and growth within the estuary.

The stepping-stone model provides direction for establishing habitat priorities and choosing among restoration alternatives for the LCRE. Application to actual project proposals and CEERP strategic planning will provide a true test of the model. However, we recommend the following steps to further evaluate the model and to incorporate a landscape perspective into the existing ERTG project-review process.

Apply the stepping-stone model to the existing LCRE habitat conditions and compare the results of alternative scenarios for restoring fragmented estuarine landscapes.

- Map key transition zone habitats and confluences in the LCRE from Bonneville Dam to the outlet.
- Map the current geographic distribution of restored and natural habitat patches and the distribution of other potential (i.e., “restorable”) estuarine habitat patches.
- Estimate the spacing of existing salmon-habitat patches and the potential spacing if some or all “restorable” sites are recovered.
- Compare restoration alternatives in one or more LCRE hydrogeomorphic reaches to evaluate the proposed design and priorities of the stepping-stone model, including, for example, potential tradeoffs between salmon-habitat patch size and location and improved matrix conditions.

Establish a consistent and repeatable method for incorporating landscape- and reach-scale criteria into the ERTG process for scoring restoration proposals. The ERTG should review the existing scoring approach and propose modifications for evaluating the contributions of individual restoration proposals to the habitat continuity of estuarine landscapes and/or hydrogeomorphic reaches.

Incorporate research and monitoring to validate or modify the stepping-stone model. The ERTG should review the assumptions inherent in the model using empirical research.

- Sample the occupancy and seasonal timing of juvenile salmonids in small and matrix habitats.
- Evaluate the relation of distance (connectivity) from the mainstem estuary with occupancy of small habitats by mainstem stocks of salmon.
- Measure travel distances and the factors affecting travel distances for juvenile salmon.
- Estimate the contribution of prey resources and particulate OM from small and matrix habitats to the estuary.

Evaluate interactions between hatchery and naturally produced salmon in the estuary. The effectiveness of the CEERP to improve survival of naturally produced salmon could be undermined by interactions with the larger juveniles released from scores of salmon hatcheries throughout the basin. New research is needed to determine whether behavioral and ecological interactions with hatchery fish reduce the foraging success, growth, or survival of naturally produced juveniles in the estuary.

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