Benefits of Habitat Improvements in the Lower Columbia River and Estuary: Results of Research, Monitoring and Evaluation

Seining in the Lower Columbia River Estuary as part of research into salmon and steelhead use of estuary habitat. NOAA Fisheries photo.

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U.S. Army Corps of Engineers
Bonneville Power Administration

Introduction

This paper is an overview of research on the role and benefits of estuary habitat improvements for juvenile salmon and steelhead in the Columbia River estuary[1] . It also includes some results of studies in other estuaries that, while different from the Columbia, may help readers understand the potential relationships between salmonids and estuarine habitats documented elsewhere. However, because this document is intended as a high-level overview, it is should not be considered a technical document and the reader should refer to the cited studies for full technical details.

In general, this paper primarily discusses research assessing the benefits of habitat improvements the Action Agencies[2] have undertaken in the Columbia River estuary for salmon and steelhead. Citations are included for the primary purpose of leading readers to the reports and papers describing the research so they can learn more. Online links are included in the list of references (where available) for ease of access. More information on the Action Agencies' estuary habitat program can be found in the Columbia Estuary Ecosystem Restoration Program (CEERP) documents. In some cases, synthesis reports are cited that are based on multiple other studies and represent important steps in advancing knowledge of the role and benefits of estuary habitat.

This paper begins with a general description of the estuary landscape and early research into the use of the estuary by salmon and steelhead. It then outlines how development has changed the estuary and describes increasing efforts to improve habitat and the biological rationale behind those efforts. It concludes with a brief description of primary habitat improvement strategies and initial assessments of their effectiveness. In summary, research thus far has determined that habitat improvement actions can increase access by fish to beneficial habitat that can contribute to the survival of juvenile salmon and steelhead migrating to the ocean.

[1] For simplicity, the Columbia River estuary is defined in this paper as the area of tidal influence that extends from the mouth of the Columbia River upstream to Bonneville dam (see Figure XX). It is also often referred to as the Lower Columbia River and Estuary (LCRE).

[2] The Action Agencies are the U.S. Army Corps of Engineers, Bonneville Power Administration and Bureau of Reclamation, although only the first two actively undertake habitat projects in the estuary.

Figure 1: The Lower Columbia River and estuary (with floodplain shaded in blue), defined as the area of tidal influence (i.e. both freshwater and saline tidal areas). The extent of salinity intrusion varies based on a number of factors, but typically extends no farther than 50 miles upstream from the Pacific Ocean.

1. Background

Habitat improvements for Columbia Basin salmon and steelhead have long been a cornerstone of regional efforts to mitigate the impacts of hydroelectric dams and other regional development. For many years, habitat actions focused on degraded reaches of tributaries where anadromous salmonids spawn and rear. In the last decade, the habitat improvements have increasingly included the Columbia River estuary. As described in this document, the Columbia River estuary refers to the roughly the 150 miles (240 kilometers) of the Columbia River below Bonneville Dam that is subject to tidal influence, including both freshwater and salinity-influenced areas. Columbia Basin salmon and steelhead spend anywhere from days to months in the estuary before entering the ocean. The rising attention to the lower river and estuary has been supported by an expanding body of research demonstrating the ecological importance of these habitats to salmon and steelhead, which has increasingly informed federal biological opinions that outline protections for fish listed under the Endangered Species Act and mitigation for the impacts of federal dams.

Strategy for improving juvenile salmon survival

Habitat is just one component of the 2008/2010 Biological Opinion (BiOp), which pursues an "All-H" strategy of improvements at hydroelectric dams, hatcheries and in harvest, as well as habitat and management of predators. The strategy recognizes that salmon and steelhead rely on many environments as they grow and mature – from spawning streams to the ocean, each with its own survival challenges. Improvements at dams are a core component of the BiOp, which sets performance standards for the percentage of juvenile fish that pass each dam safely. The BiOp, however, recognizes the importance of habitat and other actions to increase survival and promote recovery of salmon and steelhead populations. Habitat actions and other "all-H" strategies such as predation management also include performance standards and targets.

Habitat actions in the tributaries of the Columbia River above Bonneville Dam focus on (but are not limited to) 18 "priority" populations of salmon and steelhead, where habitat emphasize key factors limiting their growth and survival. A smaller scale program of targeted habitat improvements in the lower Columbia River and estuary complements the tributary effort, with the goal of benefiting all populations of Columbia salmon and steelhead on their migration to the ocean.

The Columbia River estuary: A changing view

Fish managers initially considered estuary habitat primarily for its risks to fish rather than its benefits and sought to increase the number of fish reaching the ocean through fast transit of the estuary. The tools for doing so included releasing numerous hatchery fish that were often larger than their wild counterparts and likely migrate through the estuary more quickly (Levings et al.

About life history types

Columbia River Chinook salmon are often broadly categorized as either "stream-type" which reside in freshwater streams for extended periods before migrating to the ocean and generally perform extensive offshore migrations during their ocean residency, or "ocean-type," which typically migrate to the ocean during their first three months as subyearlings, but may spend up to a year in freshwater first. Ocean-type fish generally use estuary and coastal habitats more extensively than other pacific salmon. Steelhead and sockeye generally display a stream-type life history.

The divisions simplify a complex picture, however, as research has shown that salmon and steelhead include a continuum of life histories with varied behavior and dependence on estuary habitat (Brannon et al. 2002). Although stream-type fish typically travel through the estuary in a few days, interior basin stocks (including Snake River fish) have been found in shallow estuarine habitats, indicating they also make use of the type of estuary wetlands habitats that are the focus of improvement (Bottom et al. 2005; Diefenderfer et al. 2012). The finding demonstrates that contrary to earlier thinking, a range of populations and life histories use estuary habitat, and the habitat must be accessible and have sufficient capacity for the populations to express their full range of diversity and productivity.

1986, Carter et al. 2009), as well as minimize risks such as predation. Some researchers experimented with transporting fish through the estuary to avoid dangers and releasing them at sea.

Over time, research changed the picture. Managers began to recognize that salmon and steelhead in the estuary are in fact complex combinations of distinct populations that each rely on certain habitat niches from birth through their migration to the ocean (Bottom et al. 2005a). These were described as various "life history" types that had each developed survival strategies that included use of estuary habitat. Some of the most important research on the topic (Rich 1920, Rich 1939) took place in the Columbia River system in the early 1900s, although its significance was not widely recognized until decades later. Willis Rich's studies of Chinook salmon found juvenile fish traveling through and feeding in the estuary throughout the year, leading him to conclude that the fish represented many populations, each evolved to somewhat different habitat and environmental conditions. He also found that their scale patterns showed significant growth in the estuary, indicating that they use the estuary more than once thought. A more recent study of life histories of juvenile Chinook salmon in the estuary was provided by Burke (2004).

Rich's continued research demonstrated that Columbia Basin salmon return to their home streams as adults to spawn (Bottom et al. 2005), providing further evidence that salmon species are composed of many local populations, each shaped by their spawning and rearing habitat. The populations spread out and use different parts of the estuary, in different ways, at different times, allowing for millions of fish to benefit from its diverse habitats.

Similar research by Reimers (1973) in the Sixes River, Oregon, identified five life history types among juvenile fall Chinook salmon, based on variation of residence times in the river and estuary. Fish remaining in freshwater until early summer and then undergoing improved growth in the estuary represented about 90 percent of returning spawners.

An important nursery

The indication that salmon and steelhead comprise various populations with different life histories gained ground over many decades, underscoring the ecological importance of estuary habitat for salmon and steelhead. Further research indicated that time spent in the estuary promoted survival; experimental releases of fish along different parts of their migratory paths demonstrated that those that spent time in the estuary generally survived at a higher rate than those that did not (Levings 1997).

> Higher proportions of intact estuary habitat were found to be associated with higher returns of adult salmon, indicating that estuary habitat confers an important advantage in terms of survival.

Research has since added further detail and definition to the benefits of estuary habitat for fish. A 2003 analysis (Magnusson and Hilborn, 2003) found that hatchery Chinook salmon passing through estuaries with larger proportions of intact habitat survived to adulthood at higher rates than those that transit degraded estuaries with less pristine

habitat. The study examined the survival to adulthood of millions of fall Chinook salmon smolts released from 27 hatcheries that passed through 20 different estuaries in Washington, Oregon and northern California. (The analysis did not include hatcheries in the Columbia River system or other large and heavily developed rivers such as the Sacramento because of the potential that other sources of mortality could confound the results; however, its general conclusions are informative.) It found nearly three times higher survival of adult Chinook salmon that transited estuaries in more natural condition than those from estuaries where pristine habitat was absent. The authors suggested that the differential could help predict the increase in fish survival related to preservation or restoration of estuary habitat.

The authors concluded that the study "demonstrates for the first time a direct link between estuarine conditions and survival of salmon through their entire life history" and "adds considerable strength to the arguments for preservation and restoration of estuarine habitat." As Fresh et al. (2005) explained, "The estuary has come to be regarded as part of the continuum of ecosystems that salmon need to utilize to complete their life cycle, rather than a place that salmon need to avoid." However, estuaries are by no means risk-free and includes some of the same hazards as the ocean. Rechisky et al. (2013) noted that while about one in two Chinook salmon survive their migration through the FCRPS dams, only about one in 50 of those survivors return from the ocean to spawn.

Loss of estuary habitat

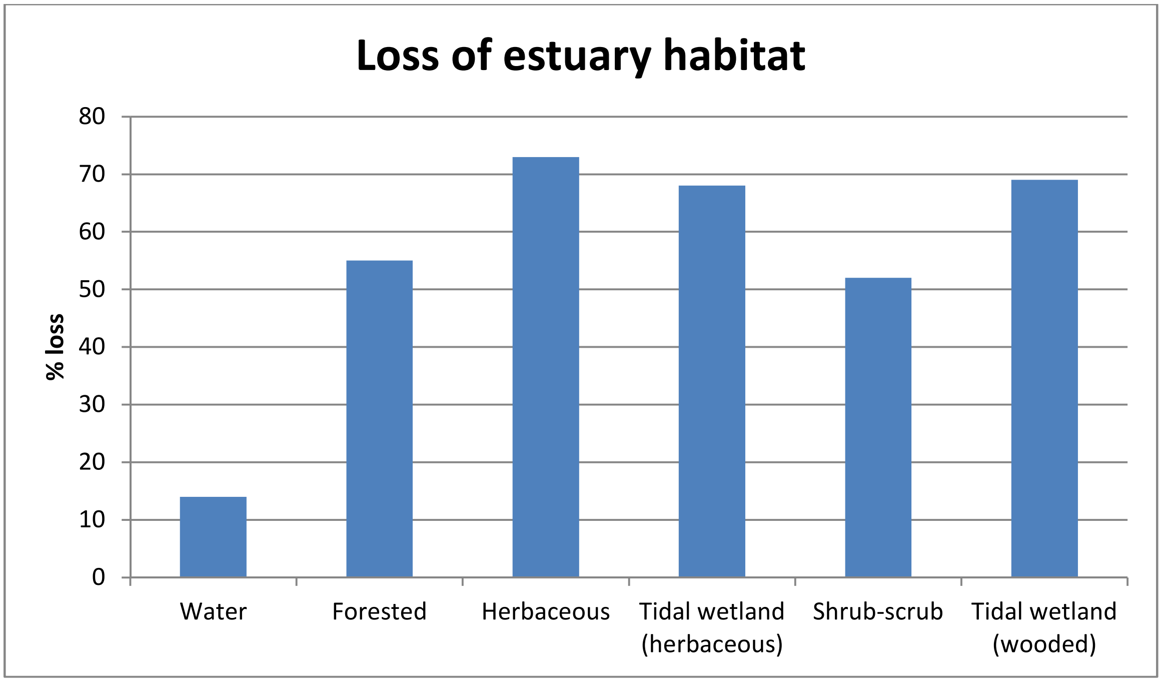
While the estuary is unique among Columbia River basin habitats in being transited by all salmon and steelhead species, including their various life history types, it is also among the most heavily modified sections of the basin. Dike construction, filling of historic wetlands and other forms of development over the last century have reduced some Columbia River estuary wetland habitats by nearly 70 percent from historical levels (Marcoe 2013), cutting juvenile fish off from productive habitat they would encounter on their way to the ocean. The decline of wetlands and changes in water management also reduces the export of food material from the wetlands into the rest of the estuary, where it could otherwise benefit a wider variety of salmon and steelhead. The loss of habitat and reduced access to food and refuge and has been identified as a limiting factor in salmon and steelhead recovery (Bottom et al. 2005). The Mainstem Lower Columbia River and Columbia River Estuary Subbasin Plan (2004) emphasized the consequences of estuary habitat loss, hypothesizing that changes in the estuary and lower mainstem decreased the ecosystem's productivity and contributed to the imperiled status of salmon and steelhead.

> About two-thirds of historical estuary wetland habitat has been lost to development, reducing shelter and food resources available to fish.

Tidal exchange through the estuary has also changed along with development of dams for flood control, irrigation, hydropower and other actions to manage flow.

The decline in estuary productivity associated with the loss of wetland habitat has been substantial, eliminating approximately 84 percent of macrodetritus that once provided the foundation for estuarine

food webs that salmon and steelhead utilize (Sherwood et al. 1990). The detritus historically came from vascular plants produced within estuary wetlands. More recently food webs are thought to be based on microdetritus from phytoplankton in upriver reservoirs that is less beneficial to juvenile salmon (Bottom and Jones 1990, Sherwood, et al. 1990, Simenstad et al. 1990). This has likely decreased the quality of estuary food webs and reduced its ability to support juvenile salmon and steelhead (Maier and Simenstad 2009).



Diking and other development has removed large amounts of the estuary's most productive historical habitat, especially tidal wetlands. From Marcoe (2013).

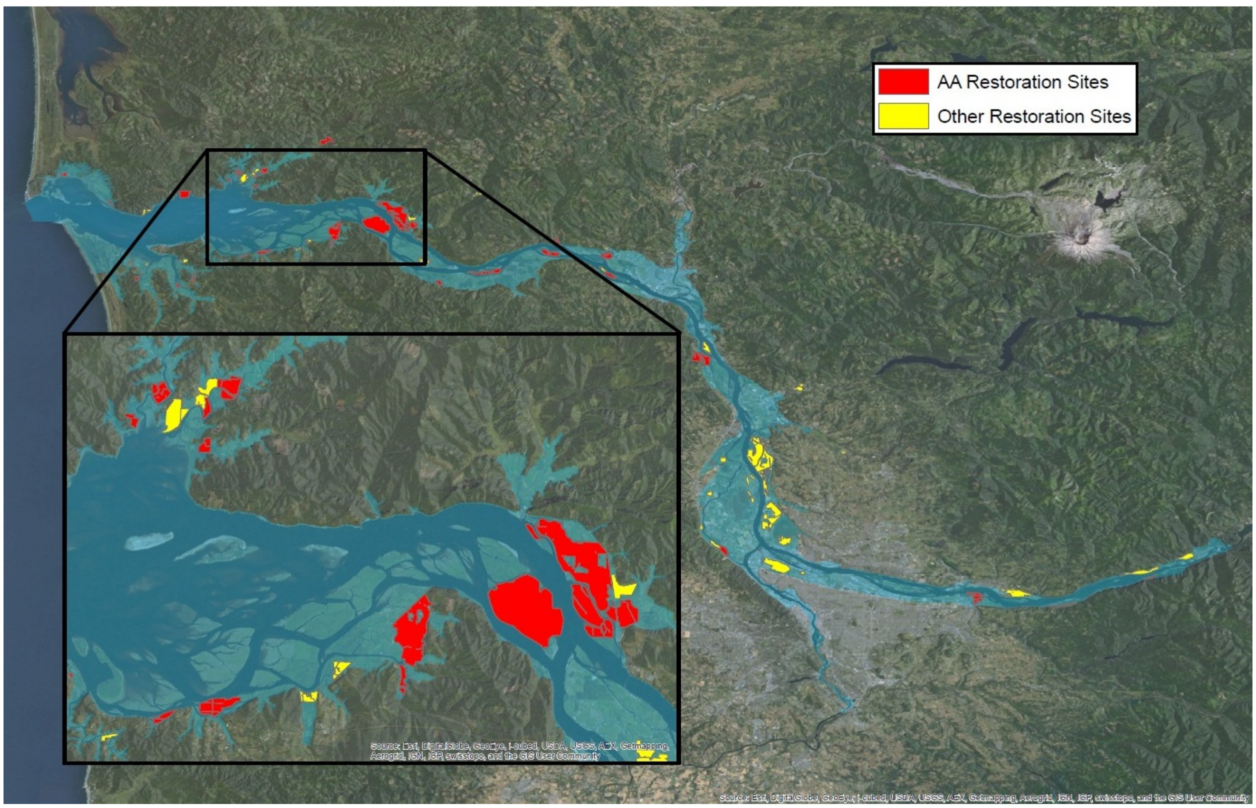
Improving estuary habitat

Recognizing research results on the role of the estuary, the Northwest Power and Conservation Council's Fish and Wildlife Program and biological opinions for the operation of the Federal Columbia River Power System have called on the federal Action Agencies to pursue habitat improvements in the estuary for salmon and steelhead listed under the Endangered Species Act. The Action Agencies are the U.S. Army Corps of Engineers, Bureau of Reclamation and Bonneville Power Administration, although the Corps and BPA have taken the lead on estuary actions. Since 2000, habitat improvement programs developed with estuarine recovery experts have taken an ecosystem approach to restoration, seeking to improve not only the physical habitat but also ecosystem processes that create and sustain habitat types and functions important to salmon and steelhead (Johnson et al. 2003). In 2011 the Action Agencies formalized the Columbia Estuary Ecosystem Restoration Program (CEERP), under development for

nearly a decade (see Johnson et al. 2003; 2008), to understand, conserve and restore estuary ecosystems, with three main objectives:

- Increase access by aquatic organisms to shallow-water habitat.
- Increase the capacity and quality of estuarine and tidal-fluvial ecosystems.
- Measurably improve ecosystem benefits for fish through improved diet, residency and growth and related factors.

The CEERP includes a program of research, monitoring and evaluation (RME) to inform, guide and assess habitat improvement actions (Johnson et al. 2008; 2013).



Areas of completed estuary habitat improvements as of 2012. Red shaded areas indicate habitat improved by the Action Agencies, while yellow shaded areas reflect improvements by other organizations. This does not reflect actions such as tide gate replacements that did not involve land acquisition.

Habitat restoration efforts in the LCRE have expanded in terms of the magnitude of investment and type of habitat actions pursued. The early years were developmental, with limited habitat improvements. This was followed by a transition period from 2010 to 2012, characterized by a more strategic approach based on additional scientific input, improved research and coordination and better planning tools. The program has since entered a period of more aggressive project implementation with a mature pipeline of projects prioritized according to scientific criteria. The criteria, for example, indicated that among the

most beneficial projects are those that reconnect tidal wetlands to the greatest degree possible. The criteria reflect the advice of the Expert Regional Technical Group (ERTG), a panel of restoration scientists that evaluate the anticipated benefits of proposed habitat projects.

Action Agency habitat achievements in the Lower Columbia River Estuary from 2008 to 2012 include:

- Reopening 162 acres to tidal influence through dike breaching or modification.
- Reconnecting 303 acres to tidal influence through improved tide gates or culverts.
- Improving 151 acres of degraded off-channel habitat.
- Planting or maintaining 1,070 acres of native vegetation and removed invasive plants.
- Acquisition and protection of 2,070 acres of intact habitat.

2. How habitat improvements benefit fish

Research and monitoring under the CEERP and other initiatives have evaluated the potential ecological benefits of habitat restoration in the estuary. Most recently, an assessment of the evidence surrounding estuarine habitat improvement concluded that “all lines of evidence from the LCRE indicated positive habitat-based and salmonid-based responses,” to habitat actions prioritized by the Action Agencies (Diefenderfer et al. 2012). “On this basis, we concluded that the habitat restoration activities in the LCRE are likely having a cumulative beneficial effect on juvenile salmonids that access restored shallow-water areas or actively transit main-stem river habitats as they migrate from the hydrosystem and lower-river tributaries to the ocean.” The authors assessed both the data on juvenile salmon response to restoration in the lower Columbia River and estuary and a review of literature from other regions.

Salmon accessing reopened habitat

One of the simplest and most basic indicators of whether restored habitat benefits salmon and steelhead is how quickly and to what degree fish access reopened habitat. A 2009 assessment of monitoring data from the LCRE found that at four of five improvement sites in the lower Columbia River and estuary, juvenile salmon either arrived where they had been absent or greatly increased in number; the only exception was a site where fish presence was depressed because it appeared few fish tended to migrate into the vicinity of the restoration site (Johnson and Diefenderfer, 2010). The review noted that researchers found wild and hatchery-reared Chinook salmon at all dike breaches and created habitat. Generally the more complete the reconnection of the habitat to natural hydrologic influences, the more positive the response from fish (Diefenderfer et al. 2012). In the Grays River, a tributary to the LCRE, Roegner et al. (2010) found that juvenile salmon quickly expanded into newly available habitat following the removal of tide gates from diked pastureland. Roegner et al. (2010) concluded that based on salmon

size and the timing of hatchery releases, most salmon sampled in the restored site were the progeny of natural spawners. The authors concluded that restoration of tidal wetlands in the Columbia River estuary improves ecosystem connectivity and reduces fragmentation and may therefore increase survival of a variety of Pacific salmon stocks during their migration.

> Thousands of subyearling Chinook salmon that returned to 94 acres of reopened wetland were larger, in better condition and feeding more intensively compared to those in an unrestored comparison area.

Haskell and Tiffan (2011) monitored a habitat project that reestablished about 94 acres of wetland and channel habitats at Crims Island and estimated 11,000 to 13,000 subyearling Chinook salmon used the site following restoration. Although they were unable to estimate numbers prior to restoration, they concluded that a "95 percent increase in available habitat coupled with the large numbers of subyearlings with high condition factors collected post-restoration indicate that the project was largely a success in creating suitable rearing habitat for subyearlings." Subyearlings using the restored habitat were larger and in better condition than those in an unrestored comparison area (Haskell and Tiffan, 2011). Catch data also indicated that more subyearlings per hour were accessing restored habitat and feeding more intensively compared to unrestored habitat. The overall abundance of chironomids (midges), a favored salmon food, increased following the restoration action.

Habitat improvements at Crims Island included excavating surface material to remove invasive reed canary grass and promote reestablish of tidal marsh vegetation and enlarging channels to improve habitat complexity and tidal exchange. Subyearling Chinook in the restored habitat were larger and in better condition than in unrestored areas.

Water temperatures can influence salmon presence (Roegner et al. 2010), with peak abundances when temperatures remain below 19 degrees C/66 degrees F. Reviewed restoration actions have generally improved water temperatures for fish, except tide gate installations at small sloughs (Johnson and Diefenderfer 2010; Diefenderfer et al. 2012). At the Kandoll Farm habitat improvement site on the Grays River, for instance, water temperatures declined following restoration. Prior to the habitat improvement project, 80 percent of temperatures were at or below 20°C while afterwards, 80 percent of temperatures were at or below 18 degrees C, likely because of improved water exchange.

PIT tag monitoring stations established at a few locations across the estuary indicate that some interior stocks of salmon and steelhead enter shallow wetland channels. Use of off-channel habitats by even a few individuals may be significant because the total abundance of threatened and endangered stocks is low, the channel area monitored is quite small, and the area potentially available to salmon is large (Dan Bottom, NOAA Fisheries, personal communication).

Productivity of improved habitat

> Rehabilitated estuary wetlands are highly productive, producing large amounts of organic matter and insect prey for salmon. Much of the material is exported beyond the wetlands into the mainstem river, where it benefits other juvenile salmon that are actively feeding while migrating downstream.

Monitoring has shown that sediment is actively accumulating in restoration sites, evidence that an important process for rebuilding tidal marshes has been restored or improved (Thom et al. 2012). Sediment accretion rates were consistently greater – in some cases two to three times higher – in restored areas than reference comparison sites. Habitat attributes have recovered to the point that areas behind three historically breached dikes (Haven Island, Fort Clatsop and Karlson Island) have transitioned to emergent marshes with little resemblance to the diked pastures that formerly occupied the areas (Diefenderfer et al. 2012).

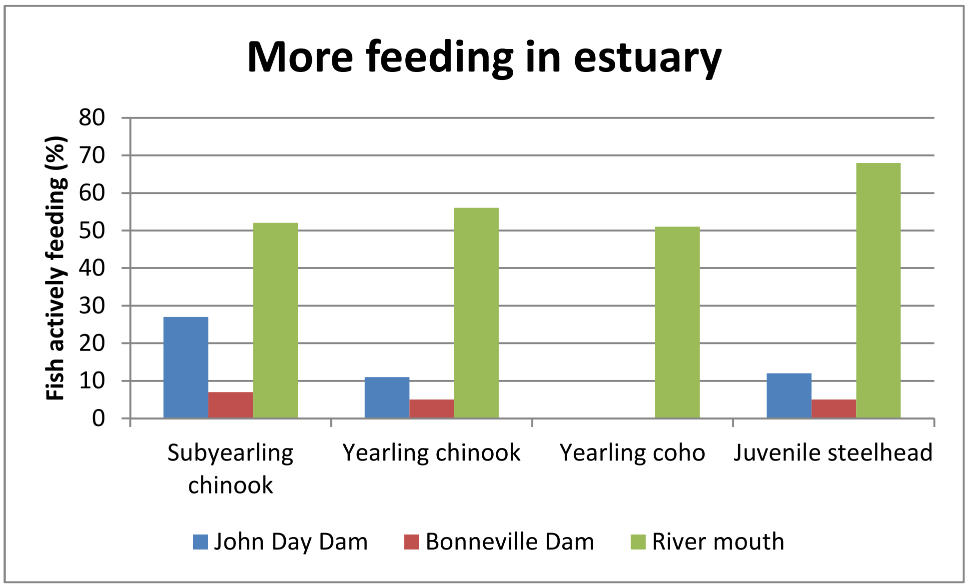
Rehabilitation of wetlands in the estuary of the Salmon River in Oregon preceded large-scale habitat improvements in the Columbia estuary. While the Salmon River is much smaller than the Columbia and therefore not directly comparable, findings from the Salmon provide general information about the potential pace of recovery. Monitoring by Gray et al. (2002) of rehabilitated wetlands in the Salmon River estuary documented rapid improvements that benefit fish, including an initial pulse of productivity in the first two to three years following restoration. The productivity was demonstrated by a surge in insects that provide prey for juvenile salmon and a corresponding influx of fish.

A later study by Hering (2009) in the Salmon River estuary compared growth rates and residence times of juvenile Chinook salmon in two intertidal marsh channels – one of them a natural channel and the other one a recently restored site that had previously been disconnected from the estuary by dikes and tide gates. The study found that marked and recaptured salmon in both channels showed similar mean growth rates and spent similar amounts of time in the channels. Hering concluded that rehabilitated estuarine marshes can recover to where they provide salmon with the same kind of habitat benefits as natural, undisturbed marshes.

Improved habitat can produce significant amounts of food resources for fish. Diptera are typically the primary insect prey of juvenile salmon in the estuary (Storch and Sather 2011). The results of numerous studies including several in the LCRE demonstrate that estuarine marsh and other wetlands are highly productive ecosystems that generate a wealth of insect prey. Models indicate that prey can be carried beyond the original wetland site into other parts of the estuary and river. An additive model of the dipteran insects present in marshes restored to date, based on data collected in the months of April through June, indicates numbers may be in the billions (Diefenderfer et al. 2012). The authors emphasized, however, that the estimates are based on extrapolation from small sampling areas and do not fully consider heterogeneity, or patchiness, in the environment.

Benefits of food from restored habitat

Sampling of the stomach contents of fish provides evidence of the food resources provided by wetland and shallow water habitats in the estuary. The stomach contents of fish sampled at John Day and Bonneville dams indicated that only a small proportion were actively feeding at those points of their downstream migrations. However, sampling of other fish in the lower estuary at rkm 15 (approximately 10 miles from the mouth of the river) found higher levels of active feeding (Diefenderfer et al. 2012) that included significant amounts of insects associated with floodplain wetlands. Given that food remains in the stomachs of fish for close to a day, depending on temperature (Brodeur and Pearcy 1987; Benkwitt et al. 2009), and even the fastest juvenile salmonids take several days to pass through the estuary (McMichael et al. 2011), the emerging data indicate that salmon and steelhead actively consume food resources produced in the type of estuary environments targeted for improvement.



Sampling of stomach contents of juvenile salmon and steelhead at three sites on their downstream migration indicated that their stomachs were substantially more full after transiting the estuary. Data from Diefenderfer et al. 2012

Stomach weights of fish at the mouth of the river contained about 1/3 to 1/2 *Americorophium* amphipod crustaceans and 1/3 to ½ insects, primarily dipterans (midges). Diefenderfer et al. (2012) presumed that the dipteran insects were produced in floodplain wetlands and commonly consumed in the mainstem river. This suggests that salmon select food from food webs linked to marsh detritus and benthic diatoms related to wetland habitats (Maier and Simenstad 2009; Sagar et al 2013). Model results indicate that organic matter produced at habitat improvement sites can be exported up to about four miles (7 kilometers)in the case of the Grays River, far enough to reach the mainstem river (Thom et al. 2012). Evidence in the literature indicates that tidal freshwater and estuarine habitats provide important forage for juvenile salmon, even those that do not use or reside in the marshes (Diefenderfer et al. 2012). This indicates that improvements to estuary habitat can increase the food available to both ocean and stream-type fish, promoting their survival.

Estuary growth and improved survival

Increased feeding by salmon and steelhead in the estuary can fuel rapid growth, in some cases exceeding 1 millimeter per day, as fish gain size quickly before entering the ocean (Bottom et al. 2011). Given those connections, the additional feeding and growth opportunities provided by estuary habitat improvements can confer an important survival advantage on fish that have an opportunity to make use of them (Beamer et al 2005).

> Additional feeding and growth opportunities supported by estuary habitat improvements can provide an important survival advantage for fish that make use of them.

Studies of yearling spring Chinook salmon have shown that growth prior to marine entry improves the adaptability of smolts to seawater (Wagner et al. 1969; Beckman et al. 1999). Bilton (1984) found that larger sub-yearling Chinook salmon survived to adulthood at a much higher rate than smaller fish as measured at release from a hatchery on Vancouver Island. Clarke and Shelbourn (1985) showed that larger subyearling Chinook have greater seawater tolerance than smaller fish and Parker (1971) found that smaller fish in juvenile salmon populations were consumed by predators more frequently than larger fish. Average body size and early marine growth in yearling Chinook and steelhead is also positively correlated with adult returns (Tomaro et al. 2012).

Such studies indicate that faster growing and larger juvenile Chinook salmon are better positioned to survive the first year in the ocean, when most salmon are believed to perish. Jacobson et al. 2012 found that winter mortality in the ocean "can be substantial (80-90%)" and is size selective at northern latitudes. Beamish and Mahnken (2001) found evidence for the view "that growth-related mortality occurs late in the first marine year and may be important in determining the strength of the year class." That conclusion generally supports the view that the food resources juvenile salmon consume in the estuary and resulting growth can improve the odds of marine survival, although the degree of improvement can vary based on different migration behavior and locations.

Life histories and the benefits of diversity

> Estuary habitat improvements that expand available habitat can support increased diversity of salmon life histories that, in turn, can support the productivity and resilience of salmon and steelhead populations.

The variety of salmon and steelhead life histories was historically a key to the success of Columbia River salmon and steelhead, spreading fish across many habitat niches across thousands of river miles throughout the Columbia Basin. Fish with various life histories use habitats at various times and for different periods. In the estuary, fish with different life histories also make wide use of habitats as they are available, rather than converging at once and overwhelming the habitats. The dispersal of fish has the corresponding benefit of spreading the risk associated with changing conditions, so that species

or populations do not depend solely on a slice of habitat at a point in time when conditions might prove unfavorable for fish in a given year. A range of migration strategies that vary across space and time provides some strategies that will likely perform better than others depending on the year, with all contributing to overall performance. This "spread the risk" approach buffers fish against vulnerabilities at different life stages as long as diverse habitat is available (Bottom et al. 2005).

Loss of estuary habitat can disadvantage fish with life histories associated with that habitat, reducing the viability of fish populations "by diminishing productivity, spatial structure and diversity" (Fresh et al. 2005). The fish cannot be generically replaced by hatchery fish or others that do not have the same life history connection with habitat. "For a population to use diverse habitats, the habitats must be available and the right fish must be available to use these habitats" (Fresh et al. 2005).

In their review of Rich's (1920) survey of Chinook salmon and their scale patterns, Bottom et al. (2005) found evidence for at least five types of ocean-type juveniles, in addition to stream-type juveniles. That range has narrowed, however, with the loss of habitat and dominance of hatchery fish. Yet PIT-tag and scale analysis have found that even now Snake River fall Chinook salmon currently display a range of life history strategies, with some migrating as subyearlings, some remaining in reservoirs their first year and migrating as yearlings and a significant number of transported fish from various lower and upper river stocks overwintering in the estuary below Bonneville Dam (Connor et al. 2005; Johnson et al. 2011).

Research in the Salmon River estuary found that the restoration of wetlands led to the reemergence of juvenile life histories that rear for extended periods in the estuary, with fry and fingerlings distributed through a greater proportion of the estuary and migrating into the ocean over a broader range of sizes and times (Bottom et al. 2005b). The authors suggested that the increased diversity may increase the prospects for fish survival in the unpredictable ocean environment.

3. Evaluation of Action Agency habitat improvement actions, 2007-2012

> Habitat actions such as dike breaches that provide the greatest hydrologic reconnection generally produce the greatest benefits for fish.

Available action effectiveness studies indicate that habitat improvement projects in the Lower Columbia River estuary can benefit juvenile salmon in terms of habitat access, capacity and measurable indicators such as growth and abundance (Thom et al. 2013). Some benefits such as improved access, floodplain reconnection and renewed tidal influence may be immediate, while others such as the recovery of wetland habitats and restoration of ecosystem processes may take more time. Most estuary habitat actions undertaken by the Action Agencies focus on reconnecting or reopening wetlands, often with accompanying habitat improvement measures such as restoration of tidal channels and planting of native riparian and wetland vegetation. Evaluation of different habitat actions in and beyond the Columbia has revealed that some are more

effective than others, with those that provide the most complete hydrologic reconnections generally demonstrating the greatest benefits to fish and environment (Greene *et al.* 2012; Thom *et al.* 2013).

A global literature review found that studies consistently documented increased salmon presence, residence time, prey availability and improved diet after floodplain reconnections.

Other scientific literature reinforces initial findings from the Columbia. A global literature review by Diefenderfer et al. (2012) found that studies consistently documented increased salmon presence, residence time and prey availability and improved diet after floodplain reconnections. Many studies from regions outside the Columbia reviewed by Diefenderfer et al. (2012) also found that juvenile salmon growth responded positively to habitat actions. At recent restoration sites in the Lower Columbia River estuary, variables known to respond quickly such as water surface dynamics and sediment accretion rates indicate that restorative ecosystem processes have begun. The following sections describe examples of the primary habitat improvement strategies employed in the estuary and initial results.

Dike breaching

Extensive construction of dikes throughout the estuary over the past century or more converted historic marsh and wetlands for agricultural use or other development and to prevent flooding (Giannico and Souder 2005). Tide gates were often included in dikes to allow upland water from rivers and streams to flow out at low tide while preventing the influx of brackish estuarine water at high tide. Dikes have impacts beyond the loss of wetlands: dikes reduce tidal flushing in undiked areas, leading to the deterioration of tidal channels (Hood 2004). Breaching or removing dikes addresses such impacts and restores natural wetland functions.

Tides flows back into reopened wetlands at Otter Point (west of Astoria) for the first time in more than 50 years, following opening of a dike to improve fish habitat.

Although dike breaches can be complex undertakings, requiring equally complex regulatory approvals, they are also the type of estuary habitat improvement with the clearest benefits (Diefenderfer et al. 2012). In the Skagit River estuary, juvenile Chinook salmon occupied reopened habitat in the first year after a dike breach. Higher densities

of juvenile salmon were often found in treatment areas than in reference areas, although with significant variability (Beamer et al. 2005). Similarly, fish rapidly accessed newly opened habitat following dike openings in the Lower Columbia River estuary (Roegner et al. 2010).

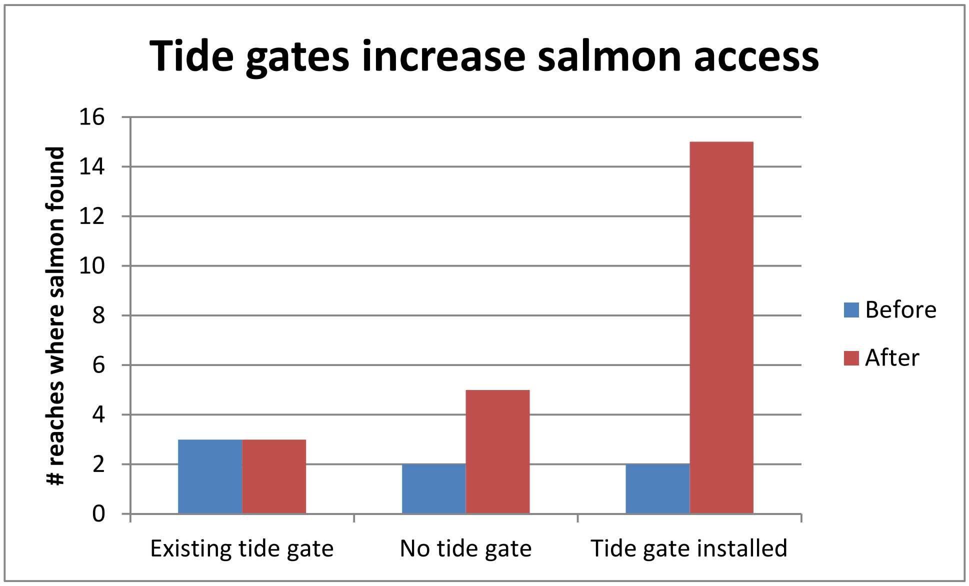
Relative benefits of three major types of habitat improvement actions in the estuary, indicating that more complete reconnections provide greater benefits for fish. Adapted from Thom et al. 2012.

Habitat attribute	Tide gate retrofit (Vera Slough)	Full dike breach (Kandoll Farm)	Elevation modification and dike breach (Crims Island)
Hydrology	Restricted tidal dynamics; no flooding	Natural tidal dynamics and flooding	Natural tidal dynamics and flooding
Water Quality	Altered temperatures	Favorable temperatures in most channels	Favorable temperatures
Topography	Small change; improved accretion compared to reference site	Small change; improved accretion compared to reference site	Large change in topography; improved accretion
Landscape	Detectable change in vegetation across site	Detectable change in vegetation across site	NA
Vegetation	Major loss; restricted colonization by new assemblage	Major shift; rapid colonization by new assemblage	Major shift; rapid colonization by new assemblage
Habitat availability	Greatly restricted	Greatly enhanced	Greatly enhanced
Material flux	Restricted	Natural exchange	Natural exchange
Fish use	Greatly restricted	Proven enhancement	Proven enhancement

Tide gate and culvert retrofits and installations

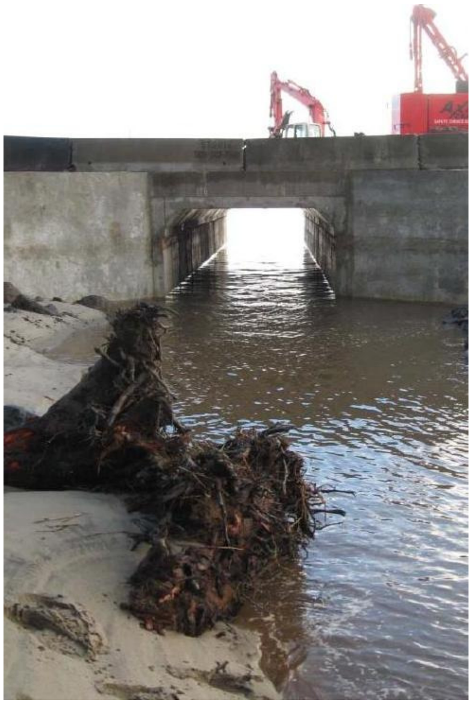
Among the most expedient habitat actions for improving tidal connectivity are the installation or retrofit of tidegates and culverts. Given their ease of implementation, these were initially among the most common habitat improvements the Action Agencies pursued in the Columbia River estuary. Where neighboring properties or local infrastructure may not permit a full dike opening, the installation of tide gates that allow exchange of water can partially reconnect floodplain

hydrology and increase the habitat available to salmon and steelhead. For example, construction in 2009 installed improved tide gates and culverts to open two previously closed sloughs at Julia Butler Hansen National Wildlife Refuge near Cathlamet, Washington and replaced another tide gate with a new design. Monitoring following the installation found juvenile salmon in all reaches where they had been present and several reaches where they had not previously been present, leading researchers to conclude that the tide gate installations had provided juvenile salmon increased access to habitat in the sloughs (Johnson and Whitesel, 2011).



Monitoring before and after the installation and retrofit of tide gates at Julia Butler Hansen National Wildlife Refuge found substantially more reaches with salmon after tide gate installations. Other comparison reaches with existing tide gates or no tide gates, but where no improvements were made, showed little change. From Johnson and Whitesel, 2011.

Other assessments of tide gates have found differences between traditional "flap" tide gates that block tidal flows into gated areas but allow runoff to drain out of the area and more fish-friendly self-regulating tide gates. Self-regulating tide gates vary in design but generally provide more flexibility to allow some inflow of water. Greene et al. (2012) examined several tide gate sites from the Columbia River estuary north to Samish Bay in northern Puget Sound and found that juvenile Chinook salmon densities increased an average of six times where self-regulating tide gates replaced the passive flap designs, indicating improved habitat use by salmon. However, salmon densities behind tide gates still did not approach the densities measured in unimpeded reference channels. This indicates that the improved tide gates can increase connectivity and quality of rearing habitat where more effective but complex dike breaches are not practical. Greene et al. emphasized that tide gates may be most beneficial where site selection focuses on reconnecting large amounts of habitat and where tide gates are designed and operated to maximize connectivity.



Tides flow through a new culvert installed at Fort Columbia State Park, reopening nearly 100 acres of wetlands to salmon.

The installation or replacement of culverts, either with or without associated tide gates, can also restore or improve tidal connectivity. For example, a large culvert installed at Fort Columbia State Park on the Washington side of the Columbia River estuary in early 2011 restored tidal influence to nearly 100 acres of wetlands along the Chinook River that had been cut off from the estuary by highway construction. No fish were previously found in the area of the wetland adjacent to where the culvert was installed and fewer than five salmon were caught along the shore of the estuary near the culvert site prior to its installation (CREST 2011). Sampling the month after the culvert installation found 20 chinook and one coho salmon in the wetland and exponentially more juvenile salmon in the estuary just outside the newly installed culvert, indicating more fish were drawn to the site. While culvert installations or replacements may not provide the same degree of connectivity as dike breaches, they can reopen or improve tidal influence and fish access to habitat. Careful culvert design and site selection are important to the success of such projects.

Land acquisition and protection

Many habitat improvement projects in the estuary include acquisition of property or conservation easements to allow habitat rehabilitation activities to move forward and protect the acquired habitat from development in the future. Protection of functioning habitat is also an important habitat element of habitat improvement programs , notably for the Columbia Land Trust (CLT) and Columbia River Estuary Task Force (CREST). The trends toward urbanization and deforestation indicated by land cover analysis have the potential to negatively impact restoration (Ke et al. 2013) and can be mitigated by land acquisition and protection. This is particularly true for the estuary, where the diversity of habitat conditions supports the diversity of life histories.

Roni and Beechie (2013) describe habitat protection as “a critical watershed conservation and restoration strategy that should not be overlooked.” They describe it as “a type of passive restoration that allows ecosystems to recover following disturbance.”

4. Improving benefits through RM&E and adaptive management

Research has greatly expanded scientific knowledge of juvenile salmon and steelhead ecology in the Columbia River estuary and other estuarine systems in the last 30 years. Accordingly, the Action Agencies' Columbia Estuary Ecosystem Restoration Program (CEERP) and the FCRPS BiOp both call for an adaptive management approach to estuary habitat improvement that applies the results of the latest research and best available science to adjust and refine strategies and actions to maximize the benefits for fish and the overall resilience of the estuarine ecosystem. Increased monitoring and evaluation of habitat improvements has in recent years provided new insight into how fish use and rely on estuary habitat and how they respond to habitat improvements, including:

- Rehabilitated estuary wetlands are highly productive, exporting insect prey that is consumed by migrating salmon and steelhead that do not directly use the wetlands.
- Additional feeding and growth opportunities supported by estuary habitat improvements can provide an important survival advantage for fish that make use of them.
- Thousands of subyearling Chinook salmon using a newly restored site in the Columbia estuary were found to be larger and in better condition than those in unrestored areas.
- Habitat actions such as dike breaches that provide the greatest hydrologic reconnection generally also produce the greatest benefits for fish.
- A global literature review that looked beyond the Columbia estuary found that studies consistently documented increased salmon presence, residence time, prey availability and improved diet following floodplain reconnections.
- Higher proportions of intact estuary habitat were associated with higher returns of adult fish, indicating a link between estuarine conditions and salmon life-cycle survival.

Increasingly, these and related findings have been reflected in the selection and design of projects, particularly evaluations by the Expert Regional Technical Group (ERTG). The ERTG is a panel of experts in restoration and estuarine science that objectively assesses prospective habitat projects in the estuary for their benefits to fish, based on physical and biological metrics, professional scientific judgment and the most recent science. Based on the best available scientific information, the Action Agencies have applied several restoration principles to project selection:

- Geographically larger projects provide more benefits for fish and for the estuarine environment as a whole.
- Projects closer to the Columbia's main stem and more accessible to fish provide more benefits than those farther away.
- Restoring remnant channels is preferred to excavating new ones.
- Projects should take advantage of natural processes where possible.
- More complete hydrologic reconnections provide greater benefits for fish and for the estuarine environment as a whole.

The principles are considered in the development and selection of projects. For example, the Corps and BPA have shifted away from tide gate replacements and placed a higher priority on dike breaches or modification, based on RM&E results indicating greater benefits for fish and more complete restoration of natural processes resulting from dike breaches or modification. Additional RM&E findings will assist BPA and the Corps in reducing uncertainties and refining and tailoring estuary habitat strategies to focus resources on projects and in areas that yield the most benefits for fish. Based on the cumulative evidence of RM&E examining habitat improvement approaches in the estuary, Diefenderfer et al. (2012) concluded that, “In summary, tidal wetlands in the LCRE currently support juvenile salmonids, including interior basin salmonids, and this effect would be expected to increase over time as existing restoration projects mature and new ones are implemented.”

5. Cited sources for further reference

Beamer et al., 2005. Delta and Nearshore Restoration for the Recovery of Wild Skagit River Chinook Salmon: Linking Estuary Restoration to Wild Chinook Salmon Populations.

Beamish, R.J., and C. Mahnken. 2001. A critical size and period hypothesis to explain natural regulation of salmon abundance and the linkage to climate and climate change. Prog. Oceanogr. 49: 423–437.

Beckman, Brian R., Walton W. Dickhoff, Waldo S. Zaugg, Cameron Sharpe, Steve Hirtzel, Robin Schrock, Donald A. Larsen et al. 1999. "Growth, smoltification, and smolt-to-adult return of spring Chinook salmon from hatcheries on the Deschutes River, Oregon." *Transactions of the American Fisheries Society* 128, no. 6 (1999): 1125-1150. ftp://ftp.pcouncil.org/pub/Salmon%20EFH/325_Beckman_et_al_1999.pdf

Benkwitt, C., Brodeur, R., Hurst, T. & Daly, E. 2009. Diel Feeding Chronology, Gastric Evacuation, and Daily Food Consumption of Juvenile Chinook Salmon in Oregon Coastal Waters. *Transactions of the American Fisheries Society*, *138*(1), 111-120. http://scholarsarchive.library.oregonstate.edu/xmlui/bitstream/handle/1957/23409/DielFeedingChronologyGastric.pdf?sequence=1

Bilton, H. T. 1984. Returns of Chinook salmon in relation to juvenile size at release. Canadian Technical Report of Fisheries and Aquatic Sciences 1245. http://www.dfo-mpo.gc.ca/Library/21739.pdf

Bottom, D.L., C.A. Simenstad, J. Burke, A.M Baptista, D.A. Jay, K.K. Jones, E. Casillas, and M.H. Schiewe. 2005a. *Salmon at River's End: The Role of the Estuary in Decline and Recovery of Columbia River Salmon*. U.S. Dept. Commerce, NOAA technical memorandum. NMFS/NWFSC- 68, 246 p.

Bottom, D.L., K.K. Jones, T.J. Cornwell, A. Gray and C.A. Simenstad. 2005b. Patterns of Chinook salmon migration and residency in the Salmon River estuary (Oregon). Estuarine, Coastal and Shelf Science 64.

Bottom, D. L., and K. K. Jones. 1990. Species composition, distribution, and invertebrate prey of fish assemblages in the Columbia River estuary. Prog. Oceanogr. 25:243–270.

Bottom, D.L., et al. 2011. *Estuarine Habitat and Juvenile Salmon: Current and Historical Linkages in the Lower Columbia River and Estuary, Final Report 2002-2008.*Report of research by Fish Ecology Division, Northwest Fisheries Science Center, U.S. National Marine Fisheries Service. http://www.nwfsc.noaa.gov/assets/26/8092_04122012_110540_Bottom.et.al.2011-rev.pdf

Brodeur, R. D., & Pearcy, W. G. (1987). Diel feeding chronology, gastric evacuation and estimated daily ration of juvenile coho salmon, Oncorhynchus kisutch (Walbaum), in the coastal marine environment. *Journal of fish biology*, *31*(4), 465-477. http://onlinelibrary.wiley.com/doi/10.1111/j.1095-8649.1987.tb05252.x/abstract

Burke, J.L. 2004. Life Histories of Juvenile Chinook Salmon in the Columbia River Estuary, 1916 to the Present. Master's thesis. http://oregonstate.edu/dept/ODFW/freshwater/inventory/pdffiles/Burke_MSThesis_2004.pdf

Carter, J. A., G. A. McMichael, I. D. Welch, R. A. Harnish, and B. J. Bellgraph. 2009. *Seasonal Juvenile Salmonid Presence and Migratory Behavior in the Lower Columbia River.* PNNL-18246, Pacific Northwest National Laboratory, Richland, Washington.

Clarke, W. C., & Shelbourn, J. E. (1985). Growth and development of seawater adaptability by juvenile fall Chinook salmon (Oncorhynchus tshawytscha) in relation to temperature. *Aquaculture*, *45*(1), 21-31. http://www.sciencedirect.com/science/article/pii/0044848685902558

Connor, W. P., Sneva, J. G., Tiffan, K. F., Steinhorst, R. K., & Ross, D. (2005). Two alternative juvenile life history types for fall Chinook salmon in the Snake River basin. *Transactions of the American Fisheries Society*, *134*(2), 291-304. http://www.webpages.uidaho.edu/fish510/PDF/ConnorT03-131.pdf

Columbia River Estuary Study Taskforce. 2011. Collection & Analysis of Field and Lab Data, Summary Report, 2011. Report to the Bonneville Power Administration.

Diefenderfer H.L., G.E. Johnson, R.M. Thom, A.B. Borde, C.M. Woodley, L.A. Weitkamp, K.E. Buenau, and R.K. Kropp. 2012. *An Evidence-Based Assessment of the Cumulative Effects of Tidal Freshwater and Estuarine Ecosystem Restoration: Early Life-Stage Habitat Functions for Endangered Salmonids*. Draft Report Prepared by Pacific Northwest National Laboratory and NOAA Fisheries for the U.S. Army Corps of Engineers, Portland District, Portland, Oregon.

Fresh, K.L., E. Casillas, L.L. Johnson, and D.L. Bottom. 2005. *Role of the estuary in the recovery of Columbia River basin salmon and steelhead: an evaluation of the effects of selected factors on salmonid population viability*. U.S. Dept. Commer., NOAA Tech. Memo. NMFS-NWFSC-69, 105 p. http://www.nwfsc.noaa.gov/assets/25/6286_09262005_142538_EstuaryTM69WebFinal.pdf

Giannico, G. and J. Souder. 2005. Tide Gates in the Pacific Northwest: Operation, Types, and Environmental Effects. http://www.cooswatershed.org/Publications/tidegates_PACNW.pdf

Gray, A., C.A. Simenstad, D.L. Bottom and T.J. Cornwell. 2002. *Contrasting Functional Performance of Juvenile Salmon Habitat in Recovering Wetlands of the Salmon River Estuary, Oregon, U.S.A.* Restoration Ecology. 10: 514-526. http://tidalmarshmonitoring.org/pdf/Gray2002_FunctionalPerformanceOR.pdf

Greene, C., J. Hall, E. Beamer, R. Henderson and B. Brown. 2012. Biological and Physical Effects of 'Fish-Friendly' Tide Gates. Final Report for the Washington State Recreation and Conservation Office. 42pp.

Gregory, S. V., and P.A. Bisson. (1996). Degradation and loss of anadromous salmonid habitat in the Pacific Northwest. *Pacific Salmon and their Ecosystems: Status and Future Options. Springer-Verlag*, 277-314.

Haskell, C.A., and Tiffan, K.F., 2011, *Crims Island—Restoration and monitoring of juvenile salmon rearing habitat in the Columbia River Estuary, Oregon, 2004–10*: U.S. Geological Survey Scientific Investigations Report 2011–5022, 50 p. http://pubs.usgs.gov/sir/2011/5022/pdf/sir20115022.pdf

Hering, D.K. 2009. Growth, Residence, and Movement of Juvenile Chinook Salmon within Restored and Reference Estuarine Marsh Channels in Salmon River, Oregon [thesis]. [Corvallis, (OR)]: Oregon State University.

Hood, W.G. (2004). Indirect environmental effects of dikes on estuarine tidal channels: thinking outside of the dike for habitat restoration and monitoring. *Estuaries and Coasts*, *27*(2), 273-282.

Jacobson, K., B. Peterson, M. Trudel, J. Ferguson, C. Morgan, D. Welch, A. Baptista, B. Beckman, R. Brodeur, E. Casillas, R. Emmett, J. Miller, D. Teel, T. Wainwright, L. Weitkamp, J. Zamon and K. Fresh. 2012. The Marine Ecology of Juvenile Columbia River Basin Salmonids: A Synthesis of Research 1998-2011. Report of the U.S. National Marine Fisheries Service, National Oceanic and Atmospheric Administration Fisheries and Oceans Canada Kintama Research Services, Ltd. and Oregon State University to Northwest Power and Conservation Council.
http://www.nwcouncil.org/fw/budget/2010/rmeap/MarineEcology2012.pdf

Johnson, G., R. Thom, A. Whiting, G. Sutherland, T. Berquam, B. Ebberts, N. Ricci, J. Southard and J. Wilcox. 2003. An Ecosystem-Based Approach to Habitat Restoration Projects with Emphasis on Salmonids in the Columbia River Estuary. PNNL-14412.
http://www.pnl.gov/main/publications/external/technical_reports/PNNL-14412.pdf

Johnson, G.E., A.J. Storch, J.R. Skalski, A.J. Bryson, C. Mallette, A.B. Borde, E.S. Van Dyke, K.L. Sobocinski, N.K. Sather, D.J. Teel, E.M. Dawley, G.R. Ploskey, T.A. Jones, S.A. Zimmerman and D.R. Kuligowski. 2011. Ecology of Juvenile Salmon in Shallow Tidal Freshwater Habitats of the Lower Columbia River, 2007-2010. PNNL-20083. http://www.pnl.gov/main/publications/external/technical_reports/PNNL-20083.pdf

Johnson, G.E. and others. 2012. Evaluation of Cumulative Ecosystem Response to Restoration Projects in the Lower Columbia River and Estuary, 2010. PNNL-20296, prepared by Pacific Northwest National Laboratory, Richland, Washington for the U.S. Army Corps of Engineers, Portland District, Portland, Oregon.
https://www.salmonrecovery.gov/Files/2011%20APR%20files/New%20Folder%203/Johnson_et_al_2012_Cumulative_Ecosystem_Response_2010.pdf

Johnson G.E. and H.L. Diefenderfer (eds.). 2010. "Evaluating Cumulative Ecosystem Response to Restoration Projects in the Lower Columbia River and Estuary, 2009." PNNL-19440, prepared by Pacific

Northwest National Laboratory, Richland, Washington for the U.S. Army Corps of Engineers, Portland District, Portland, Oregon.

Johnson J. and T.A. Whitesel. 2011. Julia Butler Hansen National Wildlife Refuge: Post-Construction Assessment of Fishes, Habitats, and Tide Gates in Sloughs on the Mainland, 2011 Annual Report. U.S. Fish and Wildlife Service, Columbia River Fisheries Program Office.

Ke, Y., A.M. Coleman and H.L. Diefenderfer. 2013. Temporal land cover analysis for net ecosystem improvement. Ecohydrology & Hydrobiology 13:84-96. www.sciencedirect.com/science/pii/S1642359313000074

LCREP (Lower Columbia River Estuary Program). 1999. Lower Columbia River Estuary Plan, Comprehensive Conservation and Management Plan. Volume I, Portland, Oregon.

Levings, C. D., C. D. McAllister, and B. D. Chang. 1986. Differential use of the Campbell River estuary, British Columbia, by wild and hatchery-reared juvenile Chinook salmon (*Oncorhynchus tshawytscha*). Can. J. Fish. Aquat. Sci. 43(7):1386–1397.

Levings, C.D. and Bouillon D. 1997. Criteria for Estimating the Survival Value of Estuaries for Salmonids. In: Emmett RL and Schiewe MH, editors. 1997. Estuarine and Ocean Survival of Northeastern Pacific Salmon; Proceedings of the Workshop, March 20-22, 1996, Newport, Oregon. NOAA Technical Memorandum NMFS-NWFSC-29. National Marine Fisheries Service, Seattle, WA. http://www.nwfsc.noaa.gov/publications/techmemos/tm29/

Magnusson , A., and R. Hilborn. 2003. *Estuarine Influence on Survival Rates of Coho (Oncorrhynchus kisutch) and Chinook Salmon (Oncorhynchus tshawytscha) Released from Hatcheries on the U.S. Pacific Coast*. Estuaries. 26: 1094-1103. http://link.springer.com/article/10.1007%2FBF02803366#

Maier G.O. and C.A. Simenstad. 2009. "The Role of Marsh-Derived Macrodetritus to the Food Webs of Juvenile Chinook Salmon in a Large Altered Estuary. *Estuaries and Coasts* 32:984–998.

Mainstem Lower Columbia River and Columbia River Estuary Subbasin Plan. 2004. Prepared for the Northwest Power and Conservation Council. http://www.nwcouncil.org/fw/subbasinplanning/lowerColumbia/plan

Marcoe, K. 2013. Historical Habitat Change in the Lower Columbia River and Estuary. Presentation to the Landscape Planning Workshop.

McMichael, G. A., R. A. Harnish, J. R. Skalski, K. A. Deters, K. D. Ham, R. L. Townsend, P. S. Titzler, Hughes, M. S., J. Kim, and D. M. Trott. 2011. Migratory behavior and survival of juvenile salmonids in the lower Columbia River, estuary, and plume in 2010. PNNL-20443, Pacific Northwest National Laboratory, Richland, Washington.

Parker, R. R. (1971). Size selective predation among juvenile salmonid fishes in a British Columbia inlet. *Journal of the Fisheries Board of Canada*, *28*(10), 1503-1510. http://www.nrcresearchpress.com/doi/abs/10.1139/f71-231

Rechisky, E.L., D.W. Welch, A.D. Porter, M.C. Jacobs-Scott, and P.M. Winchell. 2013. Influence of multiple dam passage on survival of juvenile Chinook salmon in the Columbia River estuary and coastal ocean. Proceedings of the National Academy of Sciences. 110 (17): 6883-6888.

Reimers, P. E. 1973. The length of residence of juvenile fall Chinook salmon in Sixes River, Oregon. Ore. Fish Comm., Research report 4(2).

Rich, W.H. 1920. Early history and seaward migration of Chinook salmon in the Columbia and Sacramento rivers. Fish. Bull. 37:1–74.

Rich, W.H. 1939. Local populations and migration in relation to the conservation of Pacific salmon in the western states and Alaska. Am. Assoc. Adv. Sci. Publ. 8:45–50.

Roegner G.C., E.W. Dawley, M. Russell, A. Whiting and D.J. Teel. 2010. Juvenile Salmonid Use of Reconnected Tidal Freshwater Wetlands in Grays River, Lower Columbia River Basin. *Transactions of the American Fisheries Society*. 139:4, 1211-1232.

Roegner and others. 2013. The contribution of tidal fluvial habitats in the Columbia River Estuary to the recovery of diverse salmon ESUs. Draft report of research by Fish Ecology and Conservation Biology Divisions, Northwest Fisheries Science Center, National Marine Fisheries Service, for the U.S. Army Corps of Engineers, Northwestern Division.

Roni, P., and T. Beechie, 2013. *Stream and Watershed Restoration: A Guide to Restoring Riverine Processes and Habitats*. Chichester, West Sussex: Wiley-Blackwell.

Sagar, J.P., A. B. Borde, L.L. Johnson, C. A. Corbett, J. L. Morace, K. H. Macneale, W.B. Temple , J. Mason, R.M Kaufmann, V.I. Cullinan, S. A. Zimmerman, R. M. Thom, C.L. Wright, P.M. Chittaro, O. P. Olson, S. Y. Sol, D. J. Teel, G. M. Ylitalo and N.D. Jahns, 2013. "Juvenile Salmon Ecology in Tidal Freshwater Wetlands of the Lower Columbia River and Estuary: Synthesis of the Ecosystem Monitoring Program, 2005–2010," Prepared by the Lower Columbia Estuary Partnership for the Bonneville Power Administration, April, 2013, Available from the Lower Columbia Estuary Partnership, Portland, OR.

Sherwood, C. R., D. A. Jay, R. B. Harvey, P. Hamilton, and C. A. Simenstad. 1990. Historical changes in the Columbia River estuary. Prog. Oceanogr. 25:299–357.

Simenstad, C. A., C. D. McIntire, and L. F. Small. 1990a. Consumption processes and food-web structure in the Columbia River estuary. Prog. Oceanogr. 25:271–297.

Storch, A.J., and N.K. Sather. 2011. Feeding Ecology. In Ecology of Juvenile Salmon in Shallow Tidal Freshwater Habitats of the Lower Columbia River, 2007-2010, Johnson et al. 2011, pp. 4.1-4-20, PNNL-20083. Pacific Northwest National Laboratory, Richland, Washington.

Thom, R., C. Roegner, H Diefenderfer, A. Borde, G. Johnson, D. Woodruff. 2012. Ecology of Newly Restoring Floodplain and Tidal Wetlands in the Lower Columbia River and Estuary. Columbia River Estuary Conference. May 2012. http://cerc.labworks.org/2012/presentations/session2/Thom.pdf

Tomaro, L.M., D.J. Teel, W.T. Peterson and J.A. Miller, 2012. When is bigger better? Early marine residence of middle and upper Columbia River spring Chinook salmon. Marine Ecology Progress Series, Vol. 452: 237–252, 2012.

Volk. E.C., D.L. Bottom, K.K. Jones and C.A. Simenstad. 2010. Reconstructing Juvenile Chinook Salmon Life History in the Salmon River Estuary, Oregon, Using Otolith Microchemistry and Microstructure. *Transactions of the American Fisheries Society* 139: 535–549. http://oregonstate.edu/dept/ODFW/freshwater/inventory/pdffiles/Volk%20et%20al.pdf

Wagner, H. H., Conte, F. P., & Fessler, J. L. (1969). Development of osmotic and ionic regulation in two races of Chinook salmon *Oncorhynchus tshawytscha*. *Comparative Biochemistry and Physiology*, *29*(1), 325-341. http://www.sciencedirect.com/science/article/pii/0010406X69917538

Weitkamp, L.A., P.J. Bentley and M.N.C. Litz. 2012. Seasonal and interannual variation in juvenile salmonids and associated fish assemblage in open waters of the lower Columbia River estuary. Fish. Bull. 110: 426-450.