Factors influencing juvenile Chinook Salmon presence and density in the Skagit River estuary with application to restoration influencing the Swinomish Channel Corridor

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Aerial view of the McGlinn Island Jetty and Causeway at the junction between the North Fork and Swinomish Channel Corridor sub-delta areas within the Skagit River estuary. (Photo from https://apps.ecology.wa.gov/shorephotoviewer/Map/ShorelinePhotoViewer)

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Abstract

The 2005 Skagit Chinook Recovery Plan (SCRP) was written in response to the 1999 threatened listing of Puget Sound Chinook Salmon under the Endangered Species Act. The SCRP includes recovery strategies with candidate actions for geographic areas associated with specific Chinook Salmon life stages, including the Skagit estuary. Since the SCRP's inception, stakeholders began implementation of its candidate projects and other projects consistent with its goals and strategies. Within the SCRP are candidate projects aimed at (a) increasing estuary habitat area within the Swinomish Channel Corridor (SC) and (b) one project to improve fish migration pathways between the North Fork Skagit delta and the SC, which is predicted to improve access by juvenile Chinook Salmon to existing and potential (through restoration) estuarine rearing habitat within the SC and Padilla Bay. However, several modeling and feasibility studies completed to advance these projects have raised questions regarding the utility of doing restoration within the SC or reconnecting the SC with the North Fork Skagit delta on behalf of juvenile Chinook Salmon due the SC's high salinity water compared other areas in the Skagit estuary. In part, the questions are a result of two differing approaches used to infer juvenile Chinook Salmon estuary habitat value for restoration planning purposes. The SCRP used an empirical derived relationship of juvenile Chinook Salmon density as a function of landscape connectivity while the feasibility and modeling studies used numeric criteria for physical habitat attributes within hydrodynamic model frameworks to predict fish benefits. Landscape connectivity is associated with a fish passage ecological function while salinity is associated with the physiological transition from freshwater to seawater by fish. Both ecological functions are important to juvenile Chinook Salmon in estuaries, but applying the tools of both approaches did not lead to synchronous answers for candidate restoration sites.

At the time of SCRP development and its initial restoration implementation phases, inadequate local data were available to empirically evaluate the strengths and weaknesses between the landscape connectivity and salinity criteria approaches. However, this study - now eighteen years after the SCRP was published - uses twenty-one years of juvenile Chinook Salmon observations paired with salinity and landscape connectivity observations across the Skagit estuary to better inform restoration planning efforts and have resulted in the following keys findings and opinions.

- We did not find compelling support for salinity being a barrier or limitation to juvenile Chinook Salmon rearing in the Skagit estuary, including the polyhaline SC sub-delta area, through any of our statistical analyses.
- Between the two competing ideas related to the importance of landscape connectivity or salinity, the fixed effect 'salinity' was either not statistically significant or of minor significance compared to the random effect 'sub-delta area', suggesting landscape connectivity may be more important than salinity in structuring patterns of juvenile Chinook Salmon presence and density in the Skagit estuary.
- We found more statistical support for temperature variation being important to juvenile Chinook Salmon in the Skagit estuary than salinity variation, suggesting thermal regulation and bioenergetics are more important to site specific habitat selection of juvenile Chinook Salmon during their seasonal use of the estuary than salinity.
- A review of the natural history literature demonstrates juvenile Chinook Salmon rear in estuarine habitats with wide ranging salinities from complete freshwater to nearly full-strength seawater. We found numerous studies where juvenile Chinook Salmon have been documented rearing and/or successfully foraging in polyhaline salinities throughout the PNW, similar to salinities observed in the SC area of the Skagit estuary.

- We found ample literature that is suggestive that salinity tolerance of juvenile Chinook Salmon at outmigration can be population or even family specific, and based on observations from our study, the Skagit Chinook Salmon population may be among the more salinity tolerant groups.

We concluded that the criteria used in the initial Swinomish Channel modeling and restoration feasibility studies were based on an overly narrow view of suitable juvenile Chinook estuarine habitat. Reviewed literature and the empirical fish observations of this study suggest that high salinity is unlikely to limit juvenile Chinook Salmon use in the Skagit estuary and that other physical habitat factors are more important in structuring Skagit juvenile Chinook Salmon natal estuary rearing.

Introduction

Chinook Salmon are well known for utilizing natal river estuaries (Reimers 1973, Healey 1980). Several studies have linked population responses to availability of estuary habitat, either by examining return rates of groups of fish given access to different habitat zones (Levings et al. 1989) or by comparing survival rates of fish from populations with varying levels of estuary habitat degradation (Magnuson and Hilborn 2003). Simenstad et al (1982), in a review of the literature, argued that juvenile salmon rely on estuaries for rearing during seaward migration for three ecological functions: 1) productive foraging, 2) physiological transition, and 3) refuge from predators. A decade later Thorpe (1994) reviewed the literature and concluded "*the evidence for the foraging advantage strong, for the predator refuge equivocal, and for the physiological transition function applicable*" particularly for the Pacific salmon species that migrate at the fry stage, which are primarily pink, chum, and Chinook Salmon in the Skagit River. Included in both reviews was a seminal study from the Skagit River estuary (Congleton et al. 1981) where the authors estimated about one third of the Skagit River's 1.1 million Chinook Salmon fry reared in its salt marshes in 1979, with individual fish rearing for 3 to 6-days within a single 16 ha saltmarsh / blind tidal channel network. The authors noted the single 16 ha marsh/channel network is part of a 990-ha saltmarsh area which suggests whole system estuary residence could be much longer as fish could move from place to place within the larger estuary.

Collectively, these reviews and individual studies support the hypothesis that estuarine habitat is vital for juvenile Chinook Salmon. However, the reviews and studies did not address the question whether large-scale estuarine habitat restoration would benefit salmon population productivity and life history diversity, a question in need of answering to create recovery plans due to the 1999 threatened listing of Puget Sound Chinook Salmon under the Endangered Species Act. Rather than adopt hypotheses regarding the importance of estuarine habitat on Chinook Salmon populations from the broad reviews and studies conducted in other river systems, the Skagit co-managers developed and implemented a research plan to determine the role the Skagit estuary might play in recovering natural origin Skagit Chinook Salmon. Results from the Skagit estuarine studies were summarized in Beamer et al. (2005) and included elements relating to: (a) estuary habitat use by juvenile Chinook Salmon, (b) juvenile Chinook life history variation, (c) estuary habitat loss, and (d) Chinook Salmon marine survival by life history type. In summary, the Skagit specific research led to the management conclusion that natural origin Skagit Chinook Salmon populations should benefit from estuarine habitat restoration and improved migration pathways (i.e., connectivity) within and between Skagit estuary habitats. From these results predictive tools were developed to estimate benefits of candidate restoration sites thus linking potential estuary restoration with Skagit Chinook Salmon recovery goals. The research findings were incorporated into the 2005 Skagit Chinook Recovery Plan (SRSC and WDFW 2005, herein SCRP) that include recovery strategies with candidate actions for geographic areas associated with specific Chinook Salmon life stages. Included in the SCRP's estuary restoration strategy (Chapter 11 of the SCRP) are twelve large scale candidate estuary restoration projects within four sub-delta areas of the Skagit River estuary (Figure 1). The four sub-delta areas are: Fir Island Bayfront (BF), North Fork Delta (NF), South Fork Delta (SF), and Swinomish Channel Corridor (SC). Since the SCRP submittal to NOAA in 2005 and federal adoption in 2007 watershed co-managers and recovery plan stakeholders began implementation of SCRP candidate projects and other projects consistent with the goals and strategies of the SCRP. By 2019 nine Skagit estuary restoration projects had been completed restoring 164 hectares[1] of former estuary to tidal

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[1] Over the full habitat status and trends monitoring period of Beamer et al (2023) more than 255 hectares of estuary habitat have been restored to tidal inundation. However, the 91-hectare Deepwater Slough Phase 1 project completed in 2000 predates the SCRP implementation period so it is not included in the 164-ha estimate.

inundation (Beamer et al 2023) while several other large-scale restoration projects are well along in their planning and design processes working toward completion.

Within the SCRP for the SC sub-delta area are four candidate projects aimed at increasing estuary habitat area (SCRP projects: 11.3.3 Telegraph Slough-Phase 1, 11.3.8 Smokehouse Floodplain, 11.4.2 Telegraph-Phase 2, and 11.4.3 Smokehouse-Phase 2) and one project with the goal of improving fish migration pathways between the North Fork and Swinomish Channel Corridor (11.3.4 McGlinn Island Causeway) (Appendix 1-Figure 1). The McGlinn project seeks to improve hydraulic connection between the North Fork and Swinomish Channel either through a jetty located south of McGlinn Island and/or a causeway north of McGlinn Island (see cover page photo). The restoration is expected to improve access by juvenile Chinook Salmon to existing and potential (through restoration) estuarine rearing habitat along Swinomish Channel and Padilla Bay. SCRP implementation efforts to advance SC restoration projects have included completion of several physical water property modeling and feasibilities studies. These studies used limited literature to define "suitable" habitat for juvenile Chinook Salmon to evaluate their measured and modeled physical water properties results of estuarine habitat and have raised the issue whether the higher salinity water within the SC is a limiting factor for juvenile Chinook Salmon during their estuarine rearing life stage, which raises the general SC restoration feasibility question: *Is restoration within SC likely to benefit juvenile Chinook Salmon*? And more specifically to the concept behind the McGlinn Island Causeway project, *if restoration actions connecting the NF with the SC cannot significantly decrease salinity in the SC, is restoration within the SC likely to benefit juvenile Chinook Salmon*? Two modeling studies (Grossman et al 2007; Khangaonkar et al 2017) are good examples that have contributed to the questions regarding feasibility of SC restoration related to potential salinity constraints.

Grossman et al (2007) quantifies physical water properties and movement within the SC. To put the water property results into juvenile Chinook Salmon currency, Grossman et al (2007) defines the salinity criterion for suitable estuarine habitat for Chinook Salmon fry as <15-20 PSU water. Applying that criteria to modeled water properties, some key conclusions of the study are: (1) under the current circulation regime of the Swinomish Channel, suitable surface waters for Chinook salmon fry are largely restricted to Swinomish Channel's extreme southern end; (2) the high northward current velocities have the capacity to transport Chinook fry into high-salinity (> 20ppt) waters within hours, which is much less than the time considered adequate for juvenile Chinook to acclimate to high salinity. However, the strength of Grossman et al (2007) study is its directly measured and modeled physical properties of Swinomish Channel water (velocity, depth, current direction, temperature, salinity) not its salinity criterion for suitable estuarine habitat for Chinook Salmon fry. The reference for this criterion is attributed to Healey (1991) which is a chapter on Chinook Salmon within the Pacific Salmon Life Histories book by Groot and Margolis (1991). Healey (1991) is not definitive regarding what suitable salinities are for juvenile Chinook Salmon in estuaries or how rapid salinity acclimation occurs[2]. Healey (1991) cites studies where juvenile Chinook are rearing in estuaries with 'low' salinities, but also includes citations where juvenile Chinook are rearing in high salinities, commonly 15-20 PSU or higher. Healey (1991) cites several studies suggesting Chinook fry are unable to survive immediate transfer to salinities approaching full strength seawater (30 PSU) and other studies showing Chinook fry are able to survive transfer to 20 PSU, and that osmoregulatory capability develops quickly in fry exposed to intermediate salinities. Healey also offers from his personal experience observations of transferring

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[2] See Healey (1991) page 342. Note: salinity units are stated as 'ppm' which usually denotes 'parts per million.' However, based on knowledge of the cited studies and context of the text, 'ppm' is 'parts per thousand' (ppt), which is equivalent to 'practical salinity units' (PSU) over the range of water temperatures and salinities observed in Puget Sound estuaries. Within Groot and Margolis (1991) there is not an abbreviation key so we can only conclude the 'ppm' label is an error which should be 'ppt.'

Chinook fry from the Nanaimo River to full strength seawater (32 PSU) with no apparent short-term ill effects or retardation of growth compared with controls maintained in fresh water and brackish water (15 PSU), stating 'some Chinook fry appear to be able to tolerate immediate transfer to high salinity.'

Khangaonkar et al (2017) is a paper that uses a hydrodynamic model to predict sediment and salinity effects of candidate restoration alternatives for the McGlinn Causeway project on Swinomish Channel. To put the study's hydrodynamic model predictions into salmon habitat restoration currency, Khangaonkar et al (2017) used numeric criteria for water depth, salinity range, and peak velocity to characterize restoration-site hydrodynamic performance. The strength of the Khangaonkar et al (2017) paper is its predictions of physical water property and sediment flux change, not its numeric criteria for restoration-site hydrodynamic performance. Specifically, Khangaonkar et al (2017) states the numeric criteria for restoration-site hydrodynamic performance are categorized in 'broad rules' such as (a) desired minimum inundation depth and frequency (e.g., >0.3 m and >50% of time); (b) salinity range (e.g., 5–15 ppt); and (c) peak velocity (e.g., <0.5 m/s), citing the rules 'are species specific and vary from site to site' but it is clear from the paper's narrative, the Swinomish Channel habitat restoration focal species is juvenile Chinook Salmon. Khangaonkar et al (2017) does not document the source(s) of its broad rules but does cite Beamer et al (2005) and Danie[3] et al (1984) as support for the preferred salinity range of 5-15ppt. Danie et al (1984) is an Atlantic Salmon reference which likely has limited application value for juvenile Chinook Salmon salinity suitability. Beamer et al (2005) is silent on the topic of juvenile Chinook Salmon salinity criteria for suitable natal estuary rearing habitat. However, Beamer et al (2005) does articulate several assumptions about how Chinook fry can migrate from the natal river estuary to nearshore marine habitats of Skagit Bay. The assumption is: 'young Chinook Salmon fry prefer low salinity to high salinity water if available.' The assumption does not identify criteria for low salinity or the difference between high and low salinities. The assumption was made based on: (a) Yates (2001) observation of a northward decline in juvenile Chinook salmon abundance along Swinomish Channel where it was hypothesized to be associated with the sudden increase in salinity located at the southern end of Swinomish Channel at Hole-in-the-Wall, (b) observations by Beamer et al (2003) that fry sized Chinook Salmon transit the more marine water of Skagit Bay successfully to occupy pocket estuaries which were shown to include areas of lower salinity, and (c) drift buoy experiments reported in Beamer et al (2005) where tidal current trajectories were tracked from the mouths of Skagit estuary distributaries to shoreline areas of Skagit Bay illustrating how young Chinook fry can move into and across Skagit Bay from the Skagit estuary over one ebb tide period and maintain their position in relatively low salinity surface water.

In contrast to the use of criteria to define suitable juvenile Chinook habitat by Grossman et al (2007) and Khangaonkar et al (2017), the SCRP and Beamer et al. (2005) used an empirical derived relationship of juvenile Chinook Salmon density as a function of landscape connectivity as a predictor of candidate estuary restoration project fish benefits. The landscape connectivity index is a measure of the distance and complexity (as indicated by distributary channel branching) of pathways that juvenile salmon must travel to find habitat opportunities, which vary across the estuary. The inference is that if landscape connectivity improves (e.g., through restoration) to a habitat area within the estuary, then the juvenile Chinook benefits of that habitat area also improves. Conceptually, landscape connectivity is associated with a fish passage ecological function while salinity is associated with the physiological transition from freshwater to seawater by fish, which was postulated as an important function for juvenile salmon provided by estuaries (Simenstad et al 1982; Thorpe 1994). However,

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[3] Danie et al (1984) is erroneously cited as Daniel et al (1984) in Khangaonkar et al (2017)

landscape connectivity and salinity variation within the Skagit estuary correlate because of the delta's progressively bifurcating distributary channel network. The delta originates as a single mainstem river channel which is the area of highest landscape connectivity and lowest salinity. From the delta's freshwater origin, it progressively branches into many distributaries of varying widths to its fanlike terminus with Skagit Bay, which is the area of lowest landscape connectivity and highest salinity. Greene and Beamer (2005) explained how the landscape connectivity metric correlates with salinity in the Skagit estuary when describing the juvenile Chinook carrying capacity model which was used to quantify the fish benefits of SCRP candidate estuary restoration projects. The SCRP and Beamer et al (2005) also noted the low juvenile Chinook Salmon density potential in the less connected areas of the Skagit estuary (i.e., BF and SC) compared to its more connected areas (i.e., NF, SF). Because of the correlation between landscape connectivity and salinity, it is difficult to discern what variable is the cause of fish response, and there may be nesting or interaction of their effects because of their varying ecological associations (i.e., fish passage, osmoregulation).

To summarize, both approaches (suitable habitat criteria, landscape connectivity) to infer juvenile Chinook Salmon estuary habitat value for restoration planning have strengths and weaknesses. To date, the criteria approach used metrics that may not be correct because of (a) inadequate literature review and/or (b) inadequate literature understanding of the topic. The landscape connectivity approach is empirically based on local data, but it is unknown how much of the relationship is driven by fish passage or the physical water properties that fish also depend on for successful physiological transition from freshwater to sea.

At the time of SCRP development and its initial restoration implementation phases, inadequate data were available to empirically elucidate the difference between landscape connectivity and salinity preferences for juvenile Chinook Salmon estuary restoration planning application. Additionally, thorough literature-based criteria for 'suitable' estuarine habitat had not been developed either. Now eighteen years after the SCRP was published we have twenty-one years of juvenile Chinook Salmon observations to pair with salinity and landscape connectivity observations across the Skagit estuary to better inform restoration planning efforts. Specifically, in this study we

- analyze instantaneous juvenile Chinook Salmon data collected from sites throughout the Skagit estuary for patterns of presence and density due to environmental, seasonal, and landscape effects,
- compare monthly and annual average juvenile Chinook Salmon densities within sub-delta areas of the Skagit estuary to each other and other PNW estuary systems, and
- discuss the relevance of each analysis component of the study to over twenty-five literature references that postdate, or were not included, in the original juvenile salmon estuary reviews of Simenstad et al (1982) and Thorpe (1994)

to inform the discussion whether habitat within the Swinomish Channel Corridor is too saline for suitable juvenile Chinook Salmon estuarine rearing.

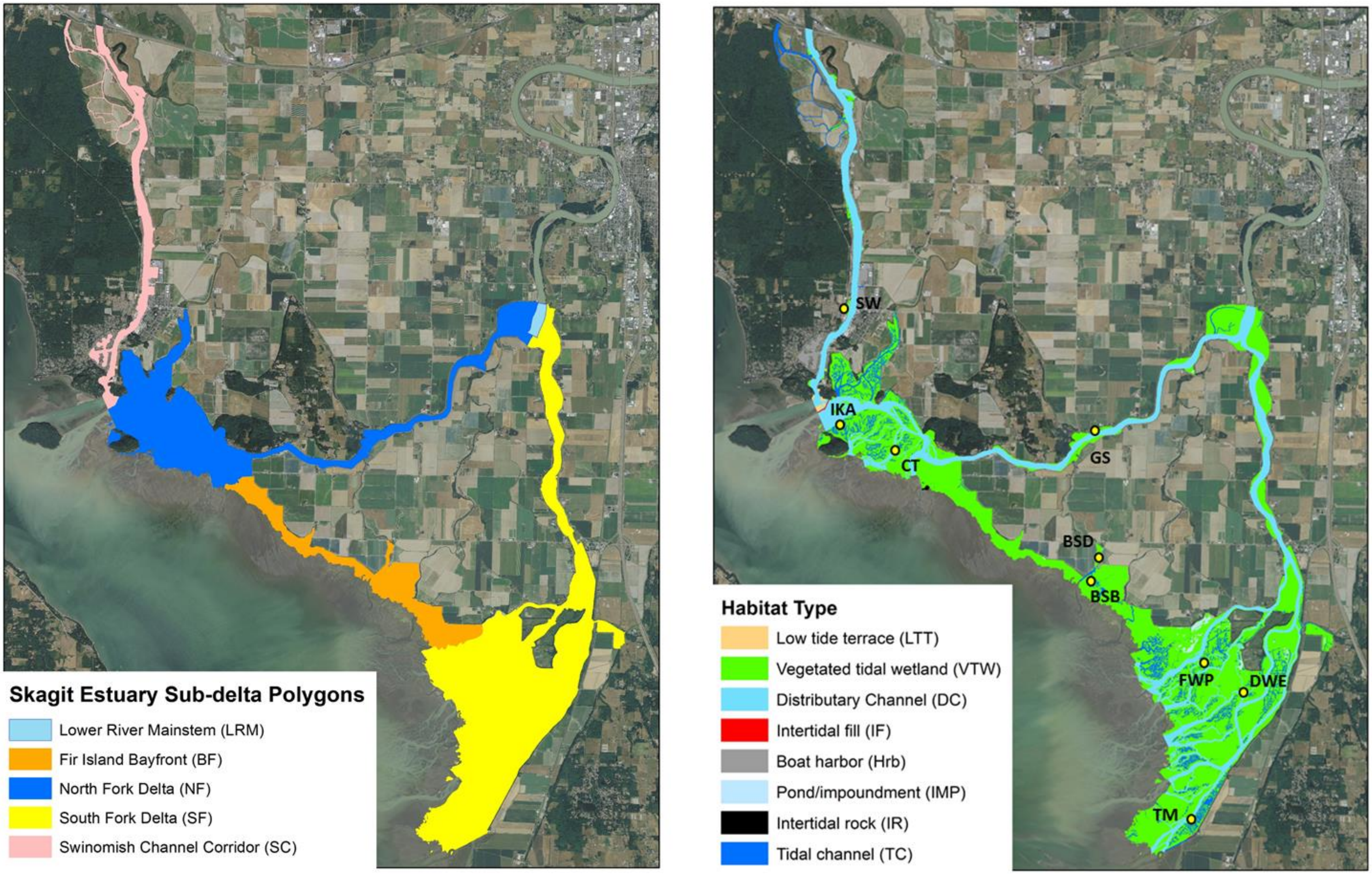

Figure 1. Map of Skagit Intensively Monitored Watershed (IMW) estuary sub-delta areas (left panel) and Skagit IMW juvenile Chinook Salmon sampling sites (right panel) Site name key: Browns Sl Barrow Ch (BSB), Browns Sl Diked Side (BSD), Cattail Saltmarsh (CT), DW Reference E Blind (DWE), FWP New Site (FWP), Grain of Sand (GS), Hall Sl Trib (HS), Ika Lower and Ika Upper (IKA), Swin Ch Old Bridge Blind (SW), and Tom Moore (TM).

Methods

Geographic setting

Data used in this study are from the long-term monitoring effort known as the Skagit Intensively Monitored Watershed (IMW) which is guided by Greene et al (2015), its most recent study plan. Greene et al. (2015) defined sub-delta areas within the larger Skagit estuary primarily to capitalize on their differences in past and planned restoration to implement its study design to determine juvenile Chinook Salmon population response to cumulative estuary restoration. Not only do the sub-delta areas vary in their restoration trajectories, but also vary by (a) landscape connectivity distribution (Beamer and Wolf, 2011), (b) exposure to natural processes that favor net gains or losses of estuarine habitat (Hood et al. 2016), and juvenile Chinook rearing habitat area magnitude (Beamer et al. 2023). For this study we used data from sites inclusive of the four Skagit estuary sub-delta areas: Fir Island Bayfront (BF), North Fork Delta (NF), South Fork Delta (SF), and Swinomish Channel Corridor (SC). (Figure 1).

Briefly, the SF area is the largest of the four sub-delta areas and consists of natural tidal habitat types (i.e., estuarine emergent/scrub shrub/forested tidal wetlands, distributary and tidal channels, and tidally influenced pond/impoundments). The SF area has had a net gain in tidal habitat area over the 30-year (1992-2021) habitat status and trends (HST) period through completion of five restoration projects, but the gains are partially offset by erosion of marshes and tidal channels on its seaward edge. The NF area is the second largest sub-delta area and consists almost entirely of natural tidal habitat types. No restoration has occurred within the NF area over the 30-year HST period. Yet, despite no restoration, the NF area has gained habitat in response to the formation of a new distributary that has changed sediment deposition patterns within the sub-delta area. The BF area is the third largest area and consists of natural tidal habitat types but lacks any distributary channel habitat because the area is separated from its historical distributaries. The BF area gained habitat through two large scale restoration projects but has shown an overall loss over the 30-year HST period primarily due to marsh and tidal channel erosion on its seaward edge. The SC area is smallest area and is dominated by a single dredged historical distributary channel and several large boat harbors and lacks the extensive vegetated tidal wetland / tidal channel mosaics common to the other Skagit sub-delta areas. The SC area has a net gain in tidal footprint over the 30-year HST period through completion of two restoration projects but much of the area's restoration gain was restored to muted tidal process via the use of self-regulated tide gates (SRTs) which have poor connectivity for fish and approximately one tenth the seasonal juvenile Chinook densities of adjacent reference habitats (Greene et al 2012). However, these areas are slated for dike setback restoration, so the future restored state will be full tidal connectivity and include large areas of adjacent vegetated tidal wetland habitat. There is no evidence of natural changes of habitat within the 30-year HST dataset for the SC area. Likely, this is because the area is sheltered from the seaward edge erosion processes experienced by the other sub-delta areas, and to date only small areas have been restored to full tidal process so there are limited opportunities where as-built habitat could transition over time as natural processes interact within their restored footprints.

Sites and sampling effort

Fish catch and environmental data (water temperature, salinity, and depth) are sampled twice a month over the period (February through August) during the spring tide series at index sites within blind tidal channel habitat. The effort started with four index sites in 1992 and expanded to six in 1995. Index fyke trap sites were selected to represent the three estuarine wetland zones (estuarine emergent, estuarine scrub-shrub, and riverine tidal) present within the Skagit delta and the two major delta rearing areas for subyearling Chinook associated with the Skagit River's two dominant distributaries, the North and South forks. The effort subsequently expanded to ten sites by 2001, including a site within the Swinomish Channel Corridor and sites along the Fir Island Bayfront, and to include environmental data collection for water temperature, salinity, and depth to temporally and spatial match the fish observations. For this study we used data from ten index sites within the four Skagit estuary sub-delta areas collected over the 2001-2021 period (Table 1).

Table 1. List of long-term fish monitoring sites by Skagit estuary sub-area (shown on Figure 1)

Site	**Years Sampled**	**Skagit Estuary Sub-delta area**
BSB	2001-2016	Fir Island Bayfront
BSD	2001-2021	Fir Island Bayfront
HS	2017-2021	Fir Island Bayfront
IKA	2001-2021	North Fork Delta
CT	2001-2021	North Fork Delta
GS	2001-2021	North Fork Delta
TM	2001-2021	South Fork Delta
FWP	2001-2021	South Fork Delta
DWE	2001-2021	South Fork Delta
SW	2001-2021	Swinomish Channel Corridor

Note: All but two sites were sampled 2001 through 2021. One site, Browns Sl Barrow Ch (BSB) was changed between the 2016 and 2017 sampling season due to the Fir Island Farms Restoration Project so the Hall Sl Trib (HS) replaced it and has been sampled 2017 through 2021.

Data collection

Juvenile Chinook catch: The Skagit IMW uses fyke trap methodology following Levy and Northcote (1982) to measure catch juvenile Chinook Salmon and other fish species in index blind tidal channel sites within the Skagit estuary. Fyke nets are constructed of 0.3 cm mesh knotless nylon with a 0.6 m by 2.7 m diameter cone sewn into the net to collect fish draining out of the blind channel site. Nets feature a lead line that sinks the bottom of the net to the benthos and a float line that maintains the top of the net at the water surface. Overall net dimensions (length and depth) vary depending on the blind channel's cross-sectional dimensions, but all nets are sized to completely block fish access at high tide. Fish are captured by setting the fyke trap across the mouth of the blind channel site at high tide and "fishing" through the ebbing tide. Fish are captured as they move out of the dewatering channel.

Environmental data: Salinity and temperature are measured just under the water surface at the start of trapping using a YSI meter. Water depth at the trap site is measured by water surface elevation data loggers and is the water surface elevation at the start (high tide) of a trapping event minus the channel's thalweg elevation.

Landscape connectivity: Landscape connectivity was calculated for all sites shown in Table 1. Landscape connectivity (LC) for each site is calculated:

$$LC = \frac{1}{\sum_{j=1}^{j_{end}} (O_j * D_j)}$$

where O_j = distributary channel order for channel segment j, D_j = distance along segment j of order O_j, j = count ($1...j_{end}$) of distributary channel segments, and j_{end} = total number of channel segments at destination or sample point. Methods are more completely described in Beamer and Wolf (2011). Because landscape connectivity can change over time due to changes in distributary channel patterns, we calculated a landscape connectivity result for each site/year combination using SRSC Habitat Status and Trends Program data for landscape connectivity for status periods: 2000, 2004, 2013, and 2019 (Hood et al 2019). We interpolated values between status periods and used trends from the data to forecast years after the 2019 status period. Landscape connectivity values are shown for each site/year combination in Appendix 2.

Juvenile Chinook Salmon Density

We only used catches of natural origin juvenile Chinook Salmon for analysis in this study. Juvenile Chinook Salmon catches are adjusted by fyke trap recovery efficiency (RE) estimates derived from multiple mark-recapture experiments at each site using a known number of marked fish released upstream of the trap at high tide. RE estimates are unique to each site and are often related to hydraulic characteristics of the site during trapping (e.g., change in water surface elevation during trapping or water surface elevation at the end of trapping). The mark and recapture experiments are typically conducted multiple times each year over most monitoring years yielding a large mark and recapture test dataset for each site. The mark and recapture test datasets at each site are used to either calculate an average RE at the site or develop a regression model to convert the "raw" juvenile Chinook catch to an estimated population within the habitat upstream of the fyke trap on any sampling day. Average RE for the index fyke trap sites ranges from 29-57%. The RE adjusted Chinook catch is divided by the top width channel area of the blind channel network upstream of trap to calculate a juvenile Chinook density for each fyke trap set. Top width channel area is measured in the field using RTK GPS.

Analytical Methods

We are interested whether salinity conditions within the SC sub-delta area preclude rearing of natural origin juvenile Chinook Salmon. We leveraged the Skagit IMW dataset (Greene et al. 2015) to evaluate the influence of salinity on juvenile Chinook Salmon presence and density across the Skagit estuary. We included other parameters in the models that are known or hypothesized to influence presence and density (Table 2). These parameters were analyzed within a generalized linear mixed effects model framework (GLMM). We recognize that nonlinear relationships are likely in the dataset, however given the primary question centers around salinity we believe that a linear analytical approach is sufficient to identify large effects if they exist.

Within the GLMMs, the response variables were juvenile Chinook Salmon presence that was evaluated in a negative binomial (logit) model and juvenile Chinook Salmon density when present in a Poisson (log) model. For each GLMM, we had fixed effects that included water depth, temperature and salinity. We employed random intercepts for year, month and sub-delta polygon. We used year to capture the between year variation that can include influences from annually varying Chinook smolt out-migrate abundances, river discharge, air temperature, and tides. We used month to account for the expected seasonal differences in juvenile Chinook Salmon outmigration. Inclusion of 'sub-delta polygon' was our solution to account for the varying location of sites within the Skagit estuary that can also influence juvenile Chinook presence and density patterns in natal estuaries (Beamer et al 2005; Greene et al 2021).

We used each model's parameter estimates to create predictor curves for salinity and temperature across the range of values encountered in the SC sub-delta area. We presented predictors across the season and for each sub-delta polygon. From these, we can infer how juvenile Chinook Salmon presence and density when present are influenced by the fixed effects, most notably salinity, across the Skagit estuary including the SC area.

Table 2. Potential effects on juvenile Chinook presence or density in Skagit estuary blind tidal channel habitat.

Effect	Hypothesis/mechanism
Water Depth	Presence and/or density of juvenile Chinook Salmon at sites within an estuary have a functional relationship with depth. The relationship may vary over the season as fish become larger with improved swimming speed capability.
Water Temperature	Presence and/or density of juvenile Chinook Salmon at sites within an estuary have a functional relationship with temperature. The relationship may link to species/stock specific physiological tolerances (McCullaugh 1999) and/or bioenergetic dynamics (Beauchamp and Duffy 2011) and vary over the season as fish size and temperatures increase.
Water Salinity	Presence and/or density of juvenile Chinook Salmon at sites within an estuary have a functional relationship with salinity. The relationship may link to species/stock specific physiological tolerances (Carl & Healey 1984; Taylor 1990; Keeger 1994, Johnson et al 1992, Wagner et al 1969) and vary over the season as fish become more osmoregulatory adapted.
Year	Annually varying abiotic (e.g., river discharge, air temperature, tidal fluctuations) and biotic (e.g., Chinook smolt out-migration abundances) factors influence juvenile Chinook Salmon presence and/or density at sites within estuaries. 'Year' captures annual variability in these extrinsic effects.
Month	Juvenile Chinook Salmon are only seasonally present and rearing in estuaries as they migrate from their natal river to the ocean. Month captures the known seasonal influence of juvenile Chinook Salmon presence or density in estuaries. Subyearling Chinook Salmon use of the Skagit River estuary can start as early as December of the previous year (SRSC Skagit IMW data) typically peaking in April and ending in August (Beamer et al 2022).
Sub-delta polygon	Presence and/or density of juvenile Chinook Salmon at sites within an estuary are a function of the distance and complexity of pathways that juvenile salmon must travel to find habitat opportunities, which vary across the estuary (Beamer et al 2005; Greene et al 2021). Inclusion of sub-delta polygon accounts for the varying position of sampling sites within the Skagit estuary.

Prior to selecting the final model parameters shown in Table 2, we evaluated the full dataset for cross correlation and potential biases of fixed effect model parameter estimates. We describe this evaluation in Appendix 3. We were especially concerned about the correlation between landscape connectivity and salinity, and whether to use Chinook smolt outmigration as a predictor in the models. For landscape connectivity, the metric has been developed and used in juvenile Chinook presence (Greene et al. 2021) and density evaluations (Beamer et al 2005; Greene et al. 2021) so it is an excellent candidate fixed effect variable for our purposes. However, our analysis in Appendix 3 found landscape connectivity is highly cross correlated with salinity, temperature, and depth. We thought we could better control for the effect of 'location within the estuary' by separating sites by sub-delta areas as defined by the Skagit IMW (Greene et al. 2015) and using sub-delta area as a random intercept in the models. This approach allows for accounting of the potential effect of location in the estuary system but limits strong cross correlations between landscape connectivity and other fixed effect model predictors. For Chinook smolt outmigration, it is well known that outmigration abundance influences juvenile Chinook density in estuaries (Beamer et al 2005; Greene et al 2021). As part of the Skagit IMW dataset, we have annual estimates for Skagit River juvenile Chinook outmigration from WDFW (Appendix 4) so we considered using either 'total sub yearlings' or 'fry only' outmigration abundances as a fixed effect predictor in our models. However, our models use instantaneous data for the response and fixed effect variables so using annualized Chinook smolt outmigration would be somewhat of a temporal mismatch compared to other data in the model. Given the Chinook outmigration data are annual estimates, and that our main study question is centered on learning about the effects of salinity on Chinook presence and density (not effects of outmigration *per se*), it seemed more appropriate to use 'year' as a random intercept which captures the effect of annual variation in Chinook smolt out-migration abundances as well as other annually varying environmental effects (e.g., river discharge, air temperature, and tides). By including the term ‘year’ we also minimize model parameters but retain maximum learning potential regarding the influence of the model’s fixed effects on juvenile Chinook presence and density.

Results

Landscape connectivity, salinity, and temperature patterns

Landscape connectivity, salinity, and temperature patterns across the Skagit River estuary varied by the sub-delta areas shown in Map Figure 1. The order of landscape connectivity by sub-delta area orders from highest to lowest: NF>SF>BF>SC (Figure 2, top panel). The NF and SF areas had the highest connectivity because they are closest to the source of juvenile salmon (i.e., the Skagit River mainstem) and directly fed by the delta’s two largest distributary channels, the North and South Fork channels. The BF and SC areas had lower connectivity because they are more distant from the source of juvenile salmon being located well downstream of the Skagit River mainstem. Additionally, fish must travel through the NF area to reach the SC area and travel through the SF or NF areas to reach the BF area.

Salinity patterns by sub-delta area were opposite of the connectivity pattern graphically illustrating the strong negative correlation between connectivity and salinity discussed in the methods and Appendix 3 (Figure 2, bottom left panel compared to top panel). Generally, the NF and SF sub-delta areas classified as oligohaline (salinities 0-5 psu) while the BF and SC areas classified as mesohaline (salinities 5-18 psu) and polyhaline (salinities 18-30 psu), respectively. However, salinities among the sub-delta areas varied seasonally (Appendix 5-Table 1). Specifically, salinity increased linearly by month within the SC and BF, but does not in the NF and SF. The NF and SF areas exhibited their lowest salinities during May and June corresponding to the Skagit River snowmelt runoff period.

Sub-delta area differences in temperature had a similar sub-delta pattern as salinity, only the differences between sub-delta areas were more muted (Figure 2, bottom right panel). The NF and SF areas had the coldest water while the BF area had the warmest water. Additionally, temperature varied seasonally (Appendix 5-Table 2). Temperature increased linearly in all sub-delta areas with the BF having the warmest water of all areas, especially from the month of April and beyond. Interestingly, temperatures in the most marine water influenced areas (SC and BF) leveled off by July and August while the more river-influenced areas (NF and SF) increased during July and August.

Juvenile Chinook Salmon

Overall data patterns

We observed that juvenile Chinook densities and presence seemed to be influenced by water temperature and not the other fixed effects parameters, salinity and depth (Figure 3). Over all sites and over the period of record, we observed juvenile Chinook Salmon presence across all observed salinities (0-34 psu), yet there seemed to be a slight downward trend in juvenile Chinook Salmon density with increasing salinity. No strong relationship can be visually observed between juvenile Chinook Salmon and depth among this dataset.

Related to effects associated with month and year, we observed the seasonal pattern of juvenile Chinook densities (Figure 4) and annual variation over the 21-year period of record (Figure 5). The distribution (5^{th} through 95^{th} percentiles) for juvenile Chinook Salmon density by month and sub-delta area are presented in Appendix 6-Tables

1. We refer to these results when discussing observed densities of juvenile Chinook Salmon in the Skagit estuary compared to densities reported in other PNW estuaries found in literature.

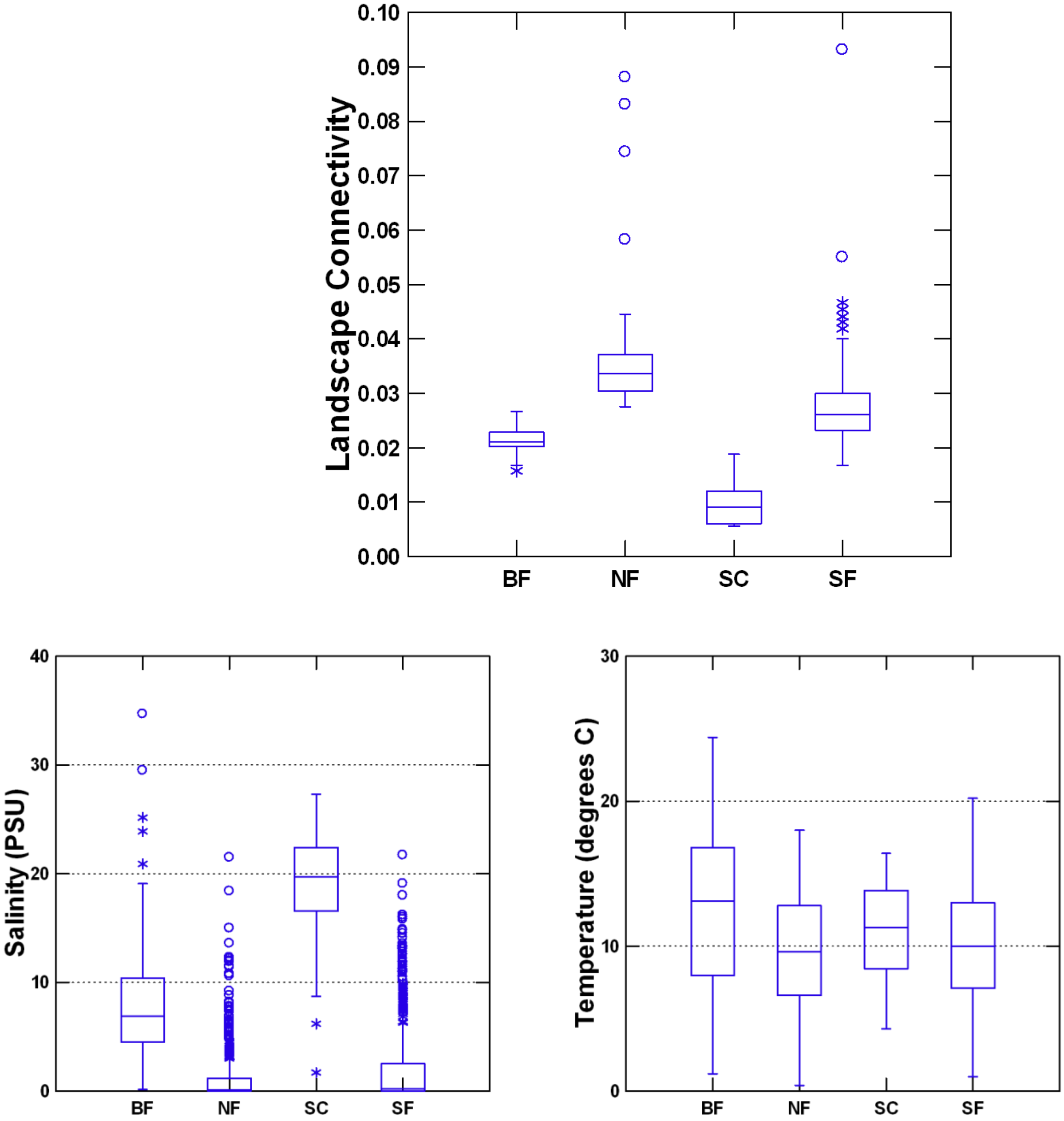

Figure 2. Range of landscape connectivity (top panel), salinity (left panel) and temperature (right panel) values for Skagit estuary blind channels by sub-delta polygons shown in Figure 1. The landscape connectivity values are from Beamer and Wolf (2011) and reflect connectivity conditions in 2000 for 593 blind channels (n=66 for BF, n=105 for NF, n=392 for SF, n=30 for SC). The salinity and temperature values are from fish sampling sites shown in Figure 1 for years 2001 to 2021 totaling 1,993 observations (n=479 for BF, n=682 for NF, n=604 for SF, n=228 for SC). Boxes show median, 25th and 75th percentiles. Whiskers show the 5th and 95th percentiles. Stars are observations that are still within the full distribution. Circles (if present) are outliers, i.e., observations outside the statistical distribution.

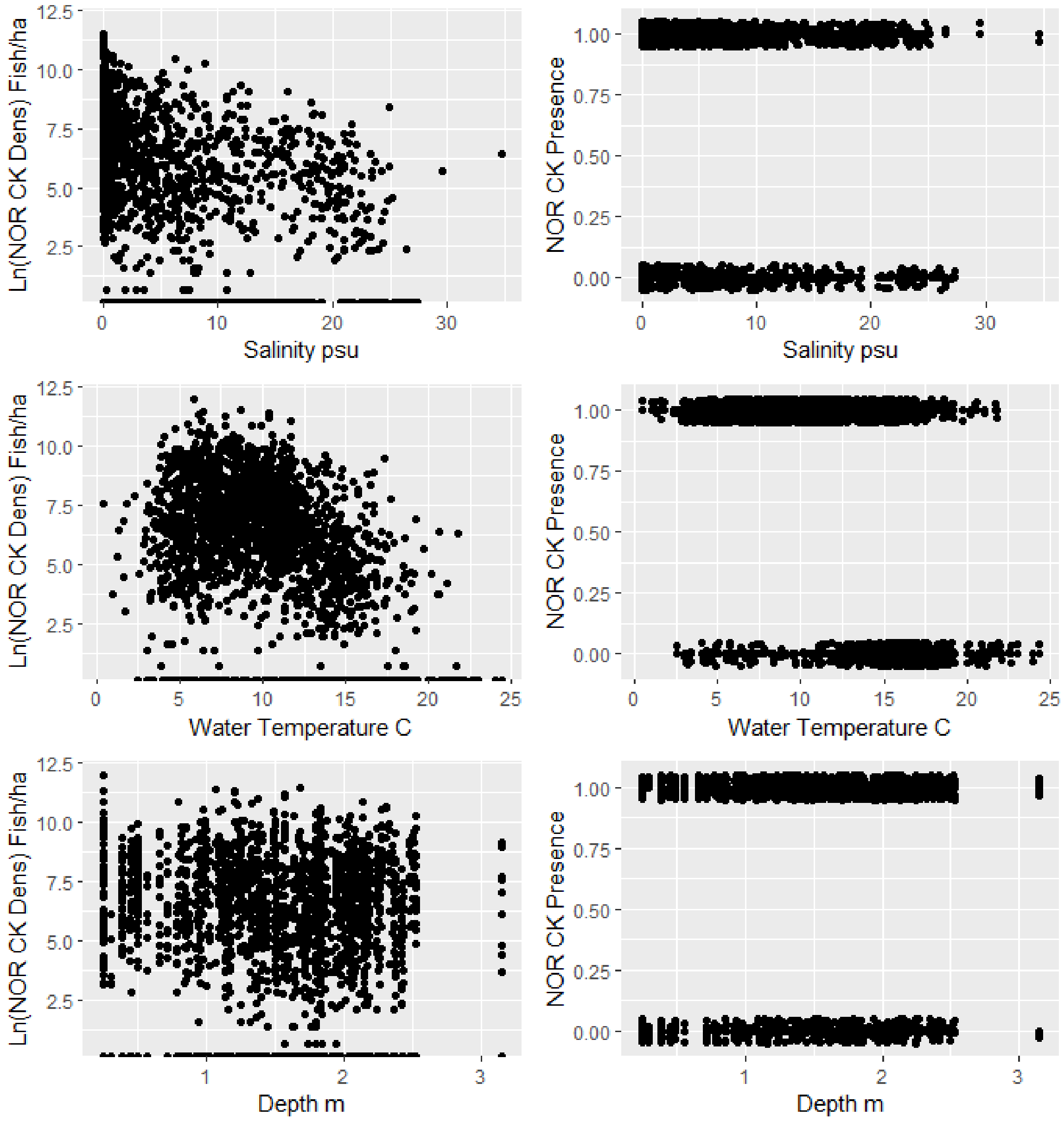

Figure 3. Plot of juvenile Chinook Salmon density (fish/ha) (left panels) and presence (right panels) with salinity (psu), water temperature (°C) and water depth (m). Chinook presence = 1; Chinook absence = 0.

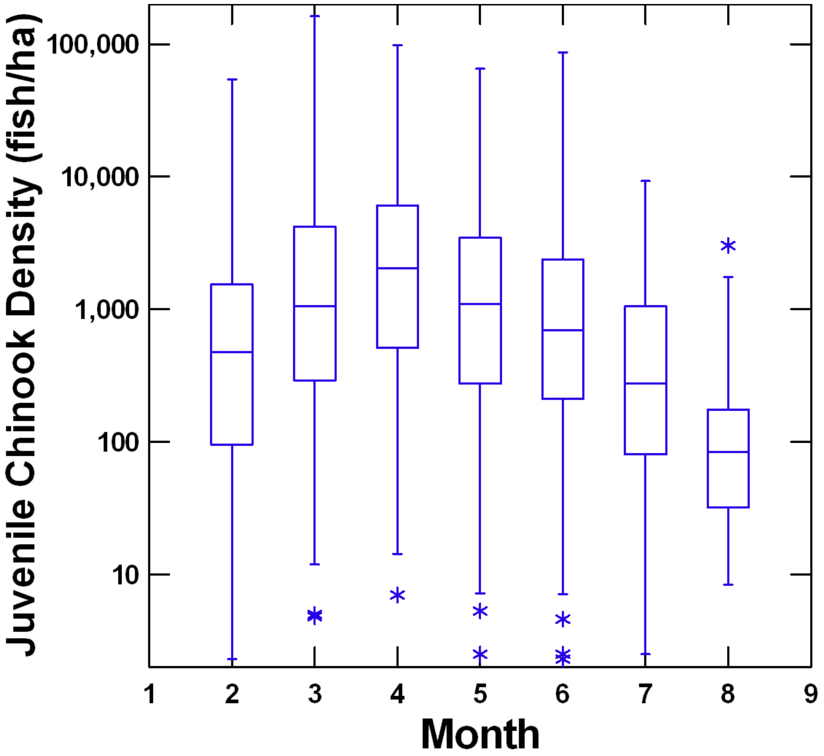

Figure 4. Range of seasonal juvenile Chinook Salmon density (fish/ha blind channel) observations in the Skagit estuary for years 2001-2021 (note log transformed y axis). Boxes show median, 25th and 75th percentiles. Whiskers show the 5th and 95th percentiles. Stars are observations that are still within the full distribution.

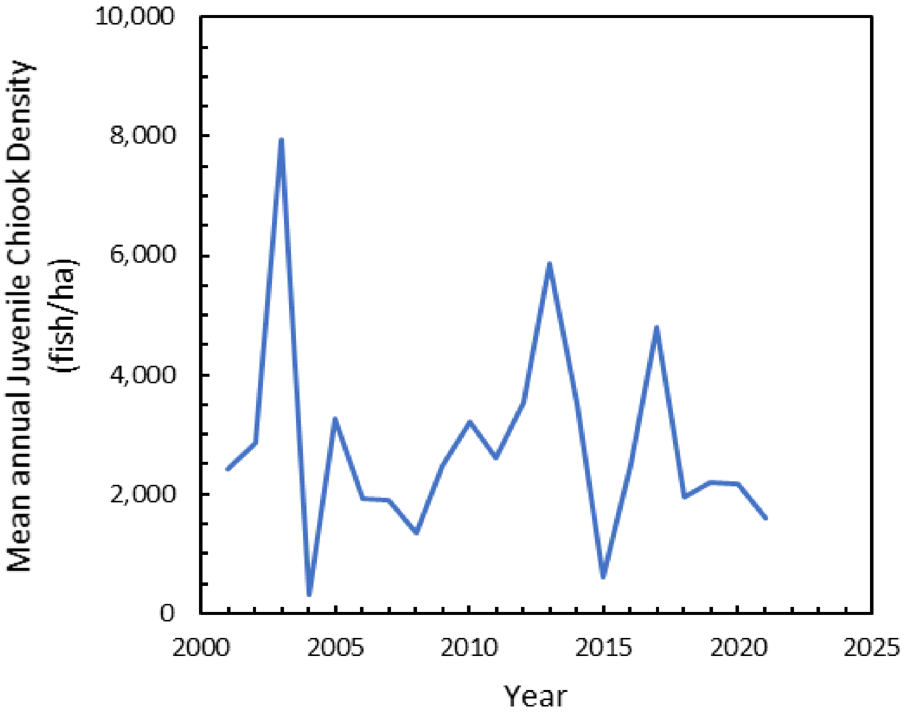

Figure 5. Trend of mean annual juvenile Chinook Salmon density (fish/ha blind channel) in the Skagit estuary by year.

Effects on presence

Chinook Salmon presence patterns within the Skagit estuary were explained by the random and fixed effects of interest (Table 3). Overall, the order of importance of statistically significant model parameters in predicting juvenile Chinook presence was: Month>Sub-delta area>Temperature>Depth.

For fixed effects juvenile Chinook Salmon presence did associate significantly with water temperature and depth but not salinity (Table 3). Water temperature and salinity had negative associations with juvenile Chinook presence while depth had a positive association. Of the three potential fixed effects, temperature had the largest effect on fish presence, approximately 3x and 8x stronger than the effects of depth and salinity, respectively. Significant random effects included month and sub-delta polygon but not year. Month had the strongest influence on fish presence (Figure 6) while sub-delta polygon only had a minor influence (Table 4).

We wanted to evaluate if the random intercept of month measured the known seasonal outmigration effect in the dataset. Figure 6 illustrates the strong seasonal effect on juvenile Chinook Salmon presence in the Skagit estuary. The pattern of random intercept values for month was congruent with observed presence for May, June, and July but are somewhat less well aligned for February-April and August, The difference between February to April and August may suggest important unspecified parameters not in the model (i.e., sub-delta area, temperature) also had an important influence on juvenile Chinook presence during the less aligned months.

Based on the model results, the probability of juvenile Chinook Salmon being present at a site in the Skagit estuary varied over space and time, as well as from the influence of fixed effects, mainly temperature. Since salinity was not a significant parameter in the presence model, we do not show a prediction of its influence on juvenile Chinook Salmon presence rate in the Skagit estuary.

Table 3. Negative binomial generalized linear model estimates for fixed effects regarding juvenile Chinook Salmon presence.

Parameter	**Estimate**	**Standard Error**	**P value**
Intercept (sum of random effects)	-0.40	0.13	0.002
Salinity	-0.03	0.03	0.373
Temperature	-0.25	0.06	<0.001
Depth	0.08	0.03	0.010

Table 4. Random intercept values for sub-delta polygons for juvenile Chinook Salmon presence.

Random Effect	**Intercept**
Bay Front	-0.01
North Fork	0.02
Swinomish Channel Corridor	0.01
South Fork	-0.02

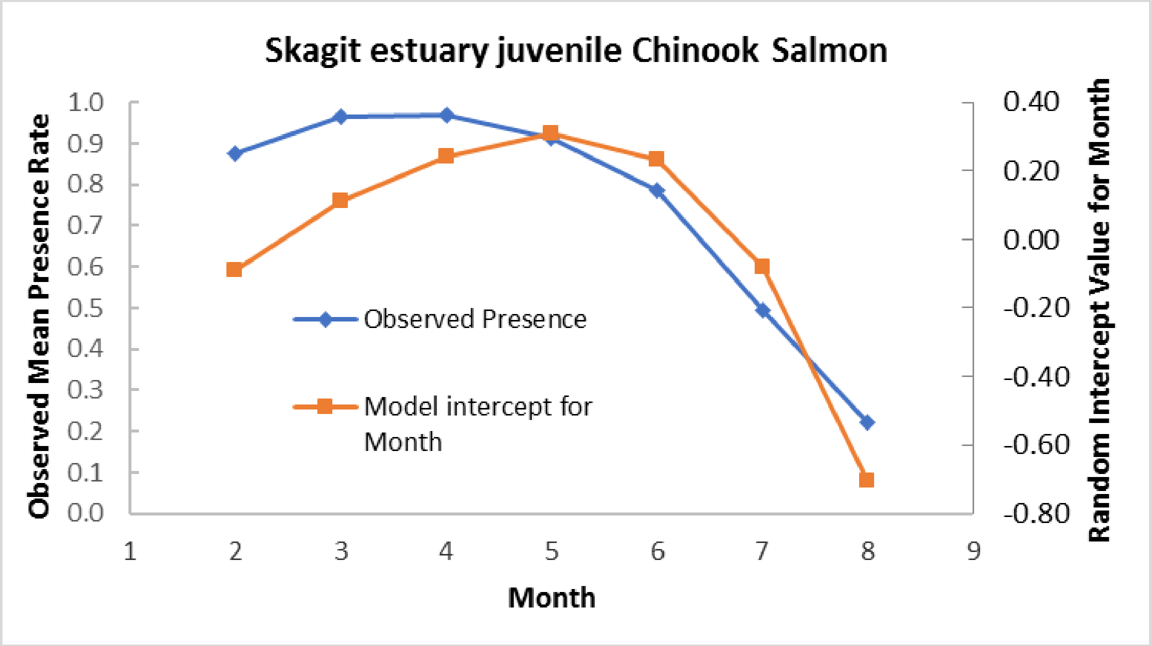

Figure 6. Observed monthly mean presence rate and random intercept values for month over the outmigration season for juvenile Chinook Salmon presence in the Skagit estuary, 2001-2021.

Effects on density when present

Random and fixed effects significantly shared in explaining patterns of juvenile Chinook Salmon density within the Skagit estuary. However, the sum of random effects had roughly an order of magnitude more influence than the fixed effects (Table 5). Overall, the order of importance in predicting juvenile Chinook density when present was: Year>Month>Sub-delta area>Temperature>Salinity>Depth.

For the fixed effects, juvenile Chinook Salmon densities when present associated significantly with all fixed effects predictors (Table 5). Water temperature and salinity had negative associations with juvenile Chinook Salmon densities while water depth had a positive association. Similar to the presence model results, water temperature had the largest effect on juvenile Chinook Salmon densities, approximately 3.4x and 1.3x stronger than the effects of depth and salinity, respectively (Table 5).

Significant random effects included year, month and sub-delta polygon suggesting juvenile Chinook Salmon density varied over years, the outmigration season (months), and by place within the Skagit estuary (Table 6, Figures 7 and 8). Year and month had the strongest influence on fish densities (Figures 7 and 8) while sub-delta polygon had about half the influence of these temporal effects (Table 6). Figure 7 illustrates the year effect on juvenile Chinook Salmon density in the Skagit estuary. Similar to the presence model, we wanted to evaluate if the random intercepts for year and month were measuring the known annual variation in outmigration abundances and the seasonal effect of outmigration in the dataset. The random intercept values for year generally tracked well with annual abundance estimates for Skagit River Chinook fry. In fact, the relationship between Skagit River Chinook fry outmigration and Model intercept values for year was significant ($p = 0.0005$; $R^2 = 0.49$), suggesting about half of the year effect is due to the number of Chinook fry recruiting to the estuary each year from the Skagit River. Figure 8 illustrates the strong seasonal effect on juvenile Chinook Salmon density in the Skagit estuary. The pattern of random intercept values for month match well with the observed density pattern, except for early (February) and late (July, August) in the season, suggesting other significant model parameters (i.e., sub-delta area, temperature) are had an important influence on juvenile Chinook density especially during the tails of the seasonal density curve.

Based on the model results, juvenile Chinook density when present at a site in the Skagit estuary varied over space and time, as well as from the influence of fixed effects: temperature, salinity, and depth. Figure 9 illustrates the model's prediction relative to the influence of salinity on juvenile Chinook Salmon, our main study topic. Using the model's parameters for prediction, we show juvenile Chinook Salmon densities decline with salinities observed in the SC sub-delta area and the neighboring North Fork sub-delta area (Figure 9). The model predicts juvenile Chinook densities decline in both areas as salinity increases but densities in the SC are always lower than in the NF. To highlight this difference the median juvenile Chinook density for the entire Skagit estuary over the entire period used for this analysis is 410 fish per ha. In the SC area, 410 fish per ha associated with a salinity of 8.8 psu while in the NF area the median fish per ha associated with salinities of 14.2 psu during the peak outmigration month of April. This difference is attributed to position in the estuary where the NF and similarly the SF areas tend to have higher densities than other areas of the Skagit estuary. This highlights the difficulty of parsing out cross correlated terms where both fish densities and salinities co-vary over space. However, looking at the raw observations we see that while the SC sub-delta area had high observed salinities compared to the other areas in the Skagit estuary, it also had comparable juvenile Chinook Salmon densities (Figure 10).

Table 5. Poisson generalized linear model estimates for fixed effects regarding juvenile Chinook Salmon densities (fish/ha).

Parameter	Estimate	Standard Error	P value
Intercept (sum of random effects)	6.67	0.52	<0.001
Salinity	-0.24	0.02	<0.001
Temperature	-0.31	0.02	<0.001
Depth	0.09	0.01	<0.001

Table 6. Random intercept values for sub-delta polygons for juvenile Chinook Salmon site densities (fish/ha).

Random Effect	Intercept
Bay Front	-0.58
North Fork	0.65
Swinomish Channel Corridor	-0.24
South Fork	0.17

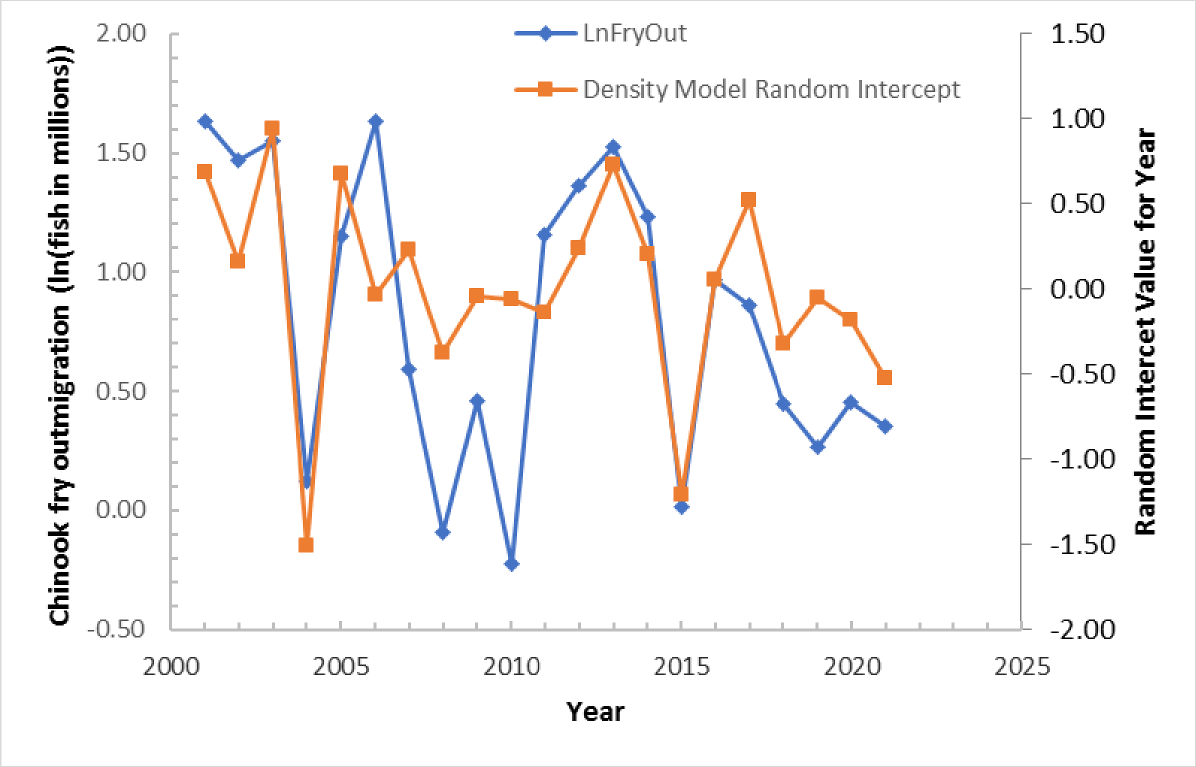

Figure 7. Trends in Skagit River Chinook fry outmigration abundance and the random intercept values for year from the density when present model.

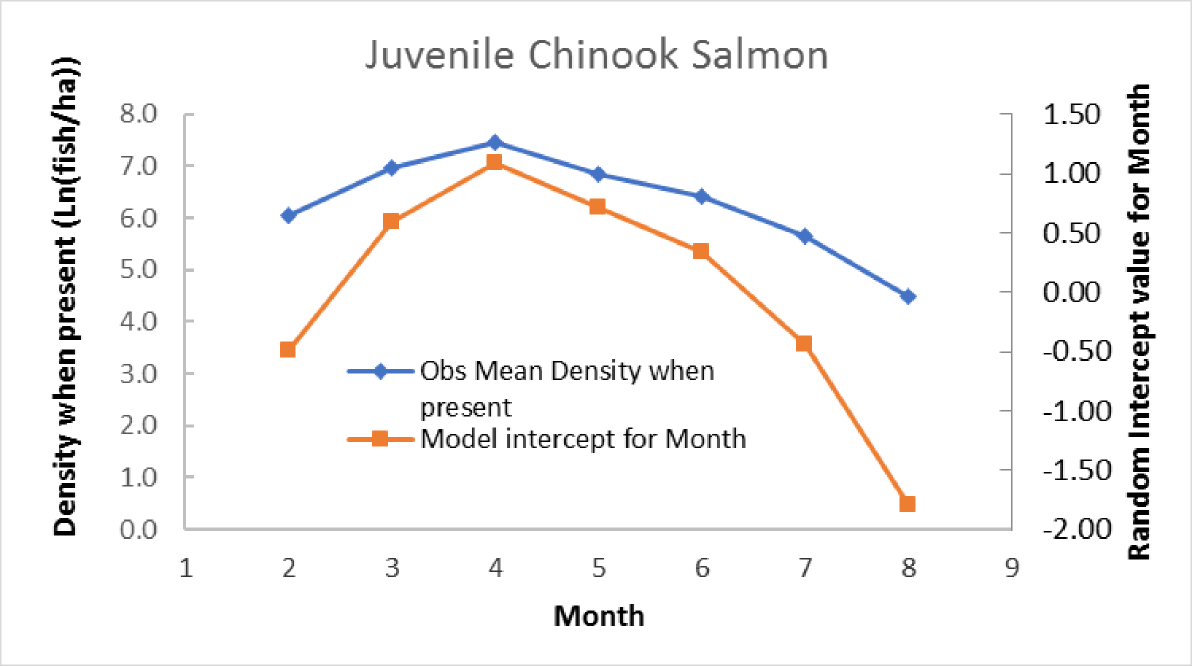

Figure 8. Observed monthly mean density when present and random intercept values for month over the outmigration season for juvenile Chinook Salmon in the Skagit estuary, 2001-2021.

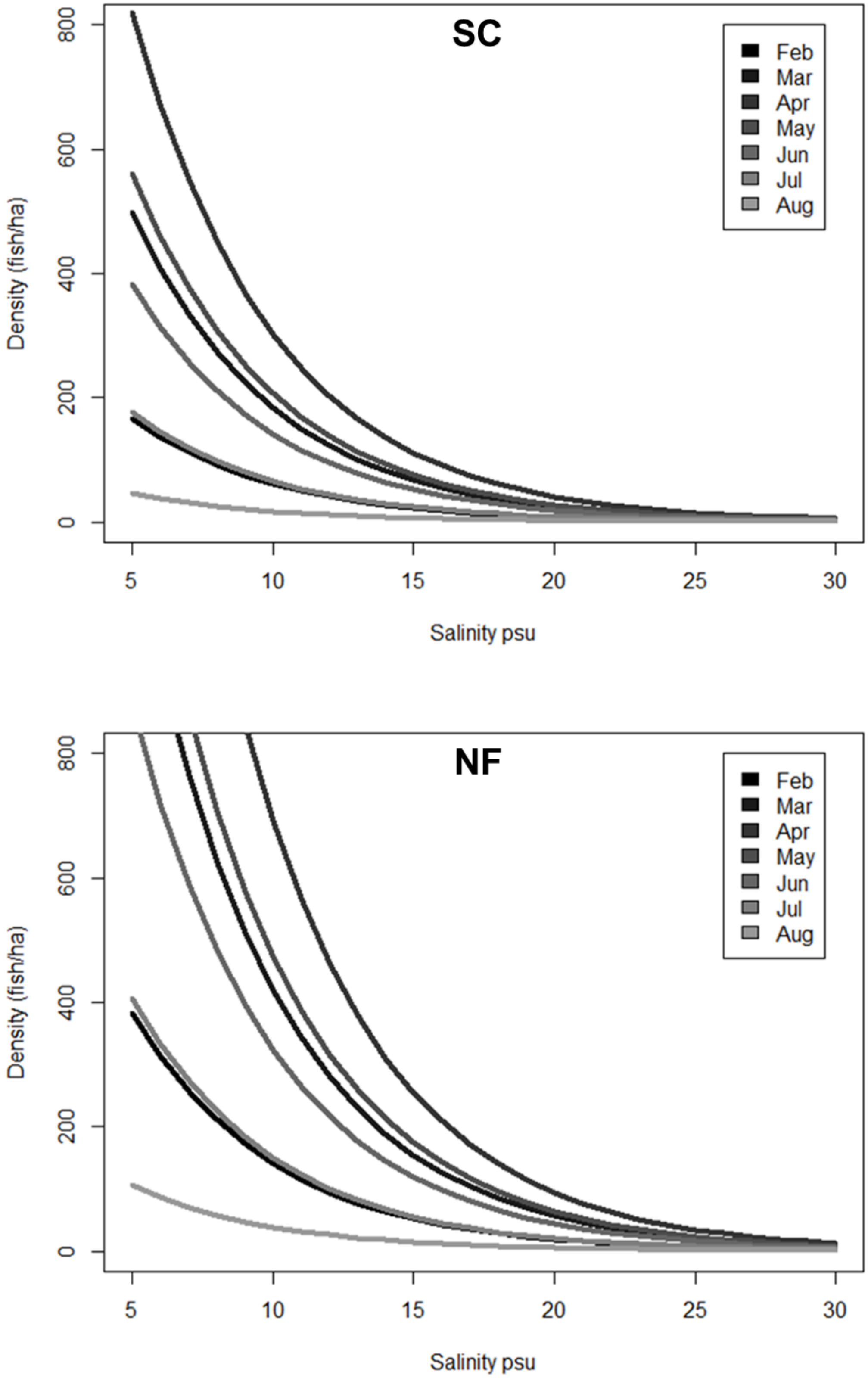

Figure 9. Predicted juvenile Chinook Salmon densities (fish/ha) for the SC sub-delta area (top panel) and NF sub-delta area (bottom panel) for each month of the outmigration season. Mean effect sizes for annual variation random effect and mean water temperature and depth were used to hold these predictors constant for comparisons.

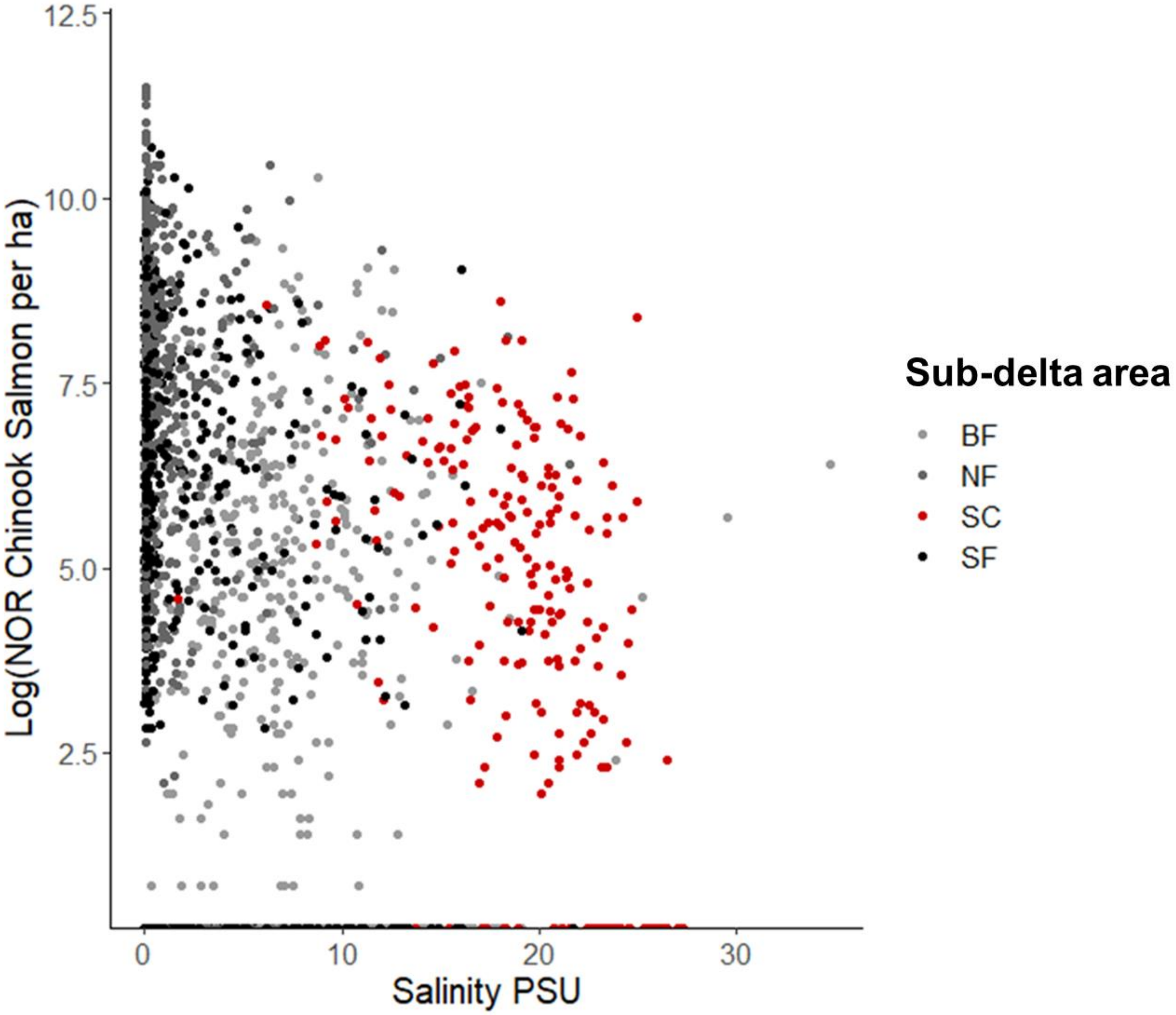

Figure 10. Comparison of log transformed Chinook Salmon densities (fish/ha) with observed salinities (psu) for the complete dataset with the SC sub-delta area observations highlighted in red.

Discussion

The focus of discussion for this study is related to the central issue whether the higher salinity water within the SC is a limiting factor for the juvenile Chinook Salmon estuarine rearing life stage, and links back to our introductory problem statement questions:

1. *Is restoration within SC likely to benefit juvenile Chinook Salmon*?
2. And more specifically to the concept behind the McGlinn Island Causeway project, *if restoration actions connecting the NF with the SC cannot significantly decrease salinity in the SC, is restoration within the SC likely to benefit juvenile Chinook Salmon*?

We address these questions by (a) discussing the strengths of our dataset and analytical approach, (b) discussing the results of our statistical analyses in light of a literature review on the effects of salinity on juvenile Chinook Salmon in estuaries, and (c) comparing juvenile Chinook Salmon densities in the Skagit estuary to other PNW estuaries and within sub-delta areas of the Skagit estuary.

Data and statistical considerations

Improved dataset

The dataset used in this study is superior to the dataset used by Beamer et al (2005) for application in the SCRP, and therefore has a better chance to improve our understanding of juvenile Chinook presence and density patterns across the Skagit estuary, and the factors that influence those patterns. Specifically, this study's dataset is spatially and temporally more extensive and has complete records for the fixed effect variables of interest (salinity, temperature, depth) (Table 7). By including sites from the BF and SC in this dataset we have observations of Chinook presence and density at considerably lower landscape connectivity and higher salinity values than the dataset of Beamer et al (2005) which used only sites from the NF and SF (Appendix 2, Appendix 5).

Table 7. Comparison of datasets used for this study and Beamer et al (2005).

Dataset attribute	This study	Beamer et al (2005)
Spatial coverage	NF (3 sites); SF (3 sites), BF (3 sites), SC (1 site)	NF (3 sites); SF (3 sites)
Temporal coverage	2001-2021 (21-years)	1992-2002 (11-years)
Observations	1,993 instantaneous observations	66 annualized observations

Statistical approach

Two different approaches used to predict juvenile Chinook benefits/value for estuarine habitats across the Skagit estuary are the impetus of this study because the application of the different approaches led to different answers about the value of the more saline habitats of the Skagit estuary for juvenile Chinook Salmon. One approach used values for estuarine water properties drawn from limited literature review to establish criteria for what is suitable habitat for juvenile Chinook Salmon in estuaries. In the case of this study, we are most interested in criteria for salinity. The other approach used an empirical derived relationship of juvenile Chinook Salmon density as a function of landscape connectivity to determine density potential of juvenile Chinook Salmon throughout the Skagit estuary. The two different approaches rely on different but related ecological functions for juvenile Chinook Salmon in estuaries. Landscape connectivity is associated with a fish passage function while salinity is associated with the physiological transition from freshwater to seawater by fish. However, landscape connectivity and salinity variation within the Skagit estuary strongly correlate because of the delta's progressively bifurcating distributary channel network. This correlation creates a significant complication to tease out their independent effects on juvenile Chinook Salmon presence or densities using data collected in a natural system without experimental manipulation (i.e., we did not conduct an experiment manipulating salinity while holding landscape connectivity constant, or vice versa). Thus, we chose a statistical approach to reduce or eliminate cross correlated effects of model terms in our analyses of Chinook presence and density when present by including salinity as a fixed effect and accounted for landscape connectivity differences of sites by including their sub-delta area as a random intercept variable. This approach allows for accounting of the potential effect of location in the estuary system but limits strong cross correlations between landscape connectivity and other fixed effect model predictors.

Juvenile Chinook Salmon

Statistical influences on presence and density

We found random and fixed effects were roughly equal in their importance in explaining patterns of juvenile Chinook presence across the Skagit estuary. Overall, the random intercept term for month had the strongest effect, suggesting the obligatory migratory nature of juvenile Chinook Salmon in estuaries is a dominant factor for their presence. Between the two competing ideas related to the importance of landscape connectivity (fish passage function) or salinity (physiological transition function), the fixed effect 'salinity' was not statistically significant while the random effect 'sub-delta area' was, suggesting landscape connectivity may be more important than salinity in structuring patterns of juvenile Chinook Salmon presence in estuaries at least over the range of salinity values in our dataset.

For the density when present model, we found the random effects were most important in explaining patterns of juvenile Chinook density when presence across the Skagit estuary. Overall, the random terms for year and month have roughly equal contributions to density patterns followed by sub-delta area. Much of the year influence associates with variation in Skagit River Chinook fry outmigration abundance (Figure 7). Regarding fixed effects, temperature, salinity, and depth were all significant with temperature being the strongest of the three effects. However, temperature alone and all three fixed effects together do not equate to the random effect of sub-delta area alone, suggesting location within the delta has more of an influence on Chinook densities over the range of temperatures, salinities, and depths observed at the Skagit estuary sampling sites.

Between the three fixed effects used in our study, we found temperature the strongest in both models suggesting thermal regulation and bioenergetics are more important to site specific habitat selection of juvenile Chinook Salmon during their February through August seasonal use of the Skagit estuary than salinity or depth. However, all three fixed effect variables are undoubtably ecologically important to juvenile Chinook Salmon in estuaries and there are possible interactions between the fixed effect variables which we did not include in our analyses. Thus, our conclusion regarding the importance of temperature compared to salinity and depth is based on the range of observations in our dataset which are: temperature (0.4 to 24.4 °C), salinity (0-34 psu), and depth (0.20 to 3.35 meters).

Taken together, our statistical analyses for juvenile Chinook presence and density when present do not find support for salinity being a barrier or limitation to juvenile Chinook rearing in the Skagit estuary, including the polyhaline SC sub-delta area as suggested by Yates (2001) and inferred by the salinity criteria adopted by Grossman et al (2008) and Khangaonkar et al (2017).

Literature review of salinity influence

As stated in the introduction, we believe the salinity criteria adopted by Grossman et al (2008) and Khangaonkar et al (2017) may be flawed due to (a) inadequate literature review and/or (b) inadequate literature understanding of the topic. In addition to discussing the findings from our statistical analyses, we looked to the literature for additional learning on the influences and associations between salinity and juvenile Chinook Salmon in estuaries.

Consistent with our study's findings, a recent multi-year field study in the nearby Fraser River estuary also did not find salinity significantly contributed to predictions of juvenile Chinook catches (Chalifour et al. 2019). Specifically, within Fraser estuary marsh habitats, Chinook catch was best explained by year, water temperature, pH, DO, and marsh elevation. Within Fraser estuary sandflat and eelgrass habitats, Chinook catch was best explained by year, DO, and habitat type. Our study and the recent Fraser estuary study may seem inconsistent with the reviews of Simenstad et al (1982) and Thorpe (1994) regarding the importance of osmoregulatory adaptation by juvenile Chinook Salmon in estuaries. However, we believe that is not the case. The reviews point out general principles with respect to ecological functions provided by estuarine habitat for juvenile salmon. There is much variation in how the different salmon species, and even stocks, may be influenced by estuary habitat conditions. Indeed, we found ample literature that is suggestive that salinity tolerance of juvenile Chinook at outmigration can be population or even family specific (Carl and Healey 1984; Taylor 1990; Keeger 1994, Johnson et al 1992, Wagner et al 1969) but is commonly considered not a limitation until >10 ppt (Taylor 1990; Keeger 1994) or higher (>20 ppt) (Clarke et al 1981) in part depending on population or race. Overall, Chinook Salmon populations dominated by subyearling outmigrants tend to tolerate higher salinities at smaller size and at earlier age. The Skagit Chinook Salmon population is dominated by subyearling outmigrants and the observations from this study of subyearlings in higher salinity habitats suggests Skagit Chinook may be among the salinity tolerant races.

There is also literature support for growth effects caused by salinity, and interactions between salinity and other environmental factors on juvenile Chinook Salmon. Specifically, juvenile Chinook Salmon growth decreased with increased salinity exposure (Morgan and Iwama 1991). However, the difference in growth with salinities were only significantly reduced at salinities > 28ppt (Morgan and Iwama 1991) which rarely occur in the SC, the saltiest of sub-delta area in the Skagit estuary (Figure 10, Appendix 5-Table 1). Clarke et al (1981) examined the effect of photoperiod, temperature, and salinity on the growth and smolting of fall Chinook Salmon fry. Of the three environmental factors investigated, temperature had the strongest influence on growth. Salinities up to 20 ppt had little effect on growth but did prevent loss of hypo-osmoregulatory ability at temperatures > 15 °C thus demonstrating there is an interaction influence of salinity with temperature when temperature levels become metabolically challenging.

Moreover, laboratory studies suggest the abiotic conditions experienced by juvenile Chinook Salmon interrelate and affect metabolic processes of their growth and osmoregulation capability, but foraging success and energy density of the foraged diet, will also influence their growth and osmoregulation, which seems to modify habitat occupation different from occupation solely due to abiotic conditions. Specifically, Hackmann (2005) conducted laboratory experiments to determine the physiological effects of juvenile Chinook Salmon associated with fluctuating salinities compared to fish in freshwater and seawater. The experiments found fish thrived in all treatments, suggesting juvenile Chinook Salmon have highly adaptable osmoregulatory abilities but the fish from the fluctuating salinity treatment group showed reduced growth rates compared with fish from the other treatments. Further laboratory experiments by Hackmann (2005) found a reduction in caloric intake significantly influenced osmoregulatory capability of juvenile Chinook Salmon during a 24-hour saltwater challenge test suggesting there is a minimum energetic requirement in order to maintain proper osmoregulation function. The Hackmann experiments suggest that although juvenile Chinook Salmon can quickly adapt to saltwater, the fluctuating salinities common in estuarine environments may influence a fish's ability to allocate energy to osmoregulation or growth, and that food availability within estuaries may have an influence on how well juvenile Chinook Salmon can successfully physiologically transition from freshwater to seawater during estuarine residence. Additionally, Webster and Dill (2006) used behavior titration experimental techniques to help understand the influence of salinity, temperature and physiological development on habitat choice by juvenile Chinook Salmon. Juvenile salmon showed a strong preference for saline water (27‰ or 15‰ vs 0‰) and for cold water (9 °C vs 14 °C). Webster et al (2007) demonstrated that juvenile Chinook Salmon prefer deep saline habitat to shallow freshwater habitats but will make brief forays into the freshwater habitat if food availability is sufficiently high. These studies demonstrate there are interactions between the local habitat conditions (salinity, temperature, depth) fish experience that influence their choice in habitat occupation. The Webster experiments suggest there is a positive effect of salinity on habitat occupation by juvenile Chinook Salmon. However, the fish used in the Webster experiments are on the large size of the juveniles utilizing the Skagit estuary (Appendix 7-Figure 1) and may better represent the fish that have migrated out of the Skagit estuary to the more marine waters of Skagit Bay.

To summarize, the natural history literature demonstrates juvenile Chinook Salmon rear in estuarine habitats with wide ranging salinities from complete freshwater to nearly full-strength seawater. The literature on laboratory experimentation does not seem suggestive that SC salinities are a juvenile Chinook Salmon limitation which would be an opposing constraint of life history expression above the benefit of anadromy for the species. At the same time, the literature provides some indication that mortality or stress has been associated with the physiological change that is osmoregulation under salinity gradients for some stocks of Chinook Salmon, however this evolved condition is what makes anadromy and likely attributes to increase productivity over a species life cycle (Sterns 2003). More simply stated, there is an overall population benefit to expression of anadromy for some species even though it may cause certain life stage specific constraints (e.g., juvenile survival depression during seaward migration).

Skagit densities compared to other PNW estuaries

Since the reviews of Simenstad et al (1982) and Thorpe (1994) many more juvenile Chinook estuarine ecology studies have been conducted throughout the PNW. Often, salinity regimes are not reported but can be inferred from study site descriptions of vegetation or are reported more broadly as oligohaline (0–5 psu), mesohaline (5–18 psu), or polyhaline (18–30 psu) habitats. While oligohaline and mesohaline marsh systems have often been the focus of studied areas, we found numerous studies where juvenile Chinook Salmon have been documented rearing and/or successfully foraging in polyhaline salinities throughout the PNW including Salish Sea estuaries [Campbell River – Levings et al. (1986), Nanaimo River – Healey (1980), Fraser River – Chalifour et al (2019), Nisqually River – David et al (2014, 2016), Duamish River – David et al (2016), SC sub-delta area of Skagit River estuary (this study)] and Coastal Oregon estuaries [Salmon River – Hering et al (2010), Nestucca and Coquille Rivers (David et al (2016)].

Additionally, our study demonstrates that juvenile Chinook Salmon in the more saline areas of the Skagit estuary (SC and BF) regularly exhibit a seasonal use curve with densities comparable to other PNW estuaries, including estuaries known for large scale restoration. Specifically, results in Figure 4 and Appendix 6-Table 1, provide a point of reference to compare Skagit River estuary natural origin juvenile Chinook Salmon densities to densities reported for PNW estuaries (Table 8). Bottom et al (2021) compared juvenile Chinook Salmon densities from five studies for four different estuaries and found spring peak densities in 2010 and 2011 of Columbia River estuary hatchery and natural origin juvenile Chinook Salmon combined averaged 0.53 fish/m^2 and over 1.0 fish/m^2 at some sites, similar to values reported for the Skagit River delta (0.32–1.20 fish/m^2; Beamer et al. 2005) but greater than the peak values for tidal marsh channels in the Salmon River, Oregon (0.04–0.09 fish/m^2; Bottom et al. 2005; Gray et al. 2002; Hering 2009); a marsh complex in the Fraser River estuary (0.35 fish/m^2; Levy and Northcote 1982); and selected Columbia River sites in the lower estuary (rkm 35–101; 0.05–0.20 fish/m^2; Bottom et al. 2011) and Sandy River delta (rkm 188–202; 0.12 fish/m^2; Sather et al. 2016).

The median value from twenty-two years of monitoring reported in Table 8 demonstrates the SC has comparable peak densities to the Salmon River estuary (Oregon) and some areas and years of the Columbia River estuary. Additionally, the 95th percentile density values are comparable or exceed the highest reported densities for these same estuaries as well as reported "high" densities for the Fraser and Nisqually River estuaries.

Table 8. Juvenile Chinook Salmon density results for PNW estuaries synthesized in Bottom et al (2021) compared to density distributions from this study for sub-delta areas of the Skagit estuary (gray shaded rows).

Juvenile Chinook Density				
fish/m^2	**fish/ha**	**Statistic**	**Reference**	**Estuary**
0.53-1.00	5,300-10,000	Average at peak of sites	Bottom et al 2021	Columbia R. (OR/WA)
0.02-0.11	200-1,100	Average at peak of sites	Bottom et al 2005	Salmon R. (OR)
0.35	3,500	Average at peak of sites	Levy/Northcote 1982	Fraser R. (BC)
0.05-0.20	500-2,000	Average at peak of sites	Bottom et al 2011	Columbia R. (OR/WA)
0.12	1,200	Average at peak of sites	Sather et al 2016	Columbia R. (OR/WA)
0.32-1.20	3,200-12,000	Average at peak of sites	Beamer et al 2005	Skagit R. (WA), NF&SF
0.66	6,634	Top 10% of Observations	Greene et al 2021	Nooksack R. (WA)
2.20	22,026	Top 10% of Observations	Greene et al 2021	Skagit R. (WA)
0.49	4,915	Top 10% of Observations	Greene et al 2021	Snohomish R. (WA)
0.18	1,808	Top 10% of Observations	Greene et al 2021	Nisqually R. (WA)
0.41-3.51	4,143-35,109	50th & 95th percentile of peak month	This Study, Appx 6-Table 1	Skagit R. (WA), NF
0.25-2.38	2,458-23,845	50th & 95th percentile of peak month	This Study, Appx 6-Table 1	Skagit R. (WA), SF
0.05-0.61	452-6,077	50th & 95th percentile of peak month	This Study, Appx 6-Table 1	Skagit R. (WA), BF
0.06-0.32	600-3,164	50th & 95th percentile of peak month	This Study, Appx 6-Table 1	Skagit R. (WA), SC

Lastly, we look at a restoration example in BF sub-delta area of the Skagit estuary. The BF has experienced large scale restoration which serves as an example of restoration within a lower connectivity and higher salinity area of the Skagit estuary. The Fir Island Farms (FIF) project, a dike setback project that restored 131 acres to tidal inundation, is located immediately adjacent to two of the Fir Island Bayfront sites shown in Figure 1 and was monitored using a BACI design for two years before and after restoration (Beamer et al 2018). Prior to restoration in 2015 and 2016, natural origin juvenile Chinook Salmon abundance for wetted areas within the FIF footprint was estimated at 118 and 566 fish per year. It was presumed the fish were within remnant channels within the project footprint due to leaking tide gates. Following dike setback restoration, total annual juvenile Chinook Salmon abundance for the restored tidal footprint was estimated at 50,522 and 11,124 fish in 2017 and 2018, respectively. The difference in Chinook Salmon abundance between the two years after restoration was attributed to different seeding levels by outmigrating Skagit River juvenile Chinook Salmon. The 2017 and 2018 outmigrations were 3.07 and 2.17 million natural origin subyearling Chinook Salmon, respectively. Based on the fish monitoring results and as-built habitat restored at FIF, juvenile Chinook Salmon estuarine rearing carrying capacity for FIF was estimated at 50,000 fish/year (Beamer et al 2018). These results show that the FIF restoration project is an example of an effective restoration project for Chinook Salmon recovery purposes consistent with the goals of the SCRP even though it has lower landscape connectivity and higher salinities compared to the NF and SF sub-delta area within the Skagit estuary. Therefore, it is reasonable to conclude that properly designed and built restoration projects along SC should be effective for Chinook Salmon too, especially since this study has shown juvenile Chinook Salmon densities are similar if not higher in the SC compared to the BF (Appendix 6-Table 1). This is a logical conclusion for the importance of habitats along the SC with or without the benefit of increased connectivity from an implemented McGlinn Island Jetty and/or Causeway project because all the SC juvenile Chinook density results used for comparison in this study have not yet benefited from increased connectivity from such a project.

Conclusions

The focus of our study's conclusions is related to the central issue whether the higher salinity water within the SC is a limiting factor for the juvenile Chinook Salmon estuarine rearing life stage, and links back to the two differing approaches (landscape connectivity, salinity criteria to define suitable habitat) used to infer juvenile Chinook Salmon estuary habitat value for restoration planning purposes. Landscape connectivity is associated with a fish passage function while salinity is associated with the physiological transition from freshwater to seawater by fish. In this study we found the following:

1. Landscape connectivity and salinity variation within the Skagit estuary strongly correlate because of the delta's progressively bifurcating distributary channel network, creating a significant complication to tease out their independent effects on juvenile Chinook Salmon. However, we chose a statistical approach that reduces or eliminates cross correlated effects of model terms to advance knowledge of the importance of landscape connectivity and salinity on juvenile Chinook Salmon in estuaries.
2. The dataset used in this study is superior spatially and temporally compared to the dataset used by Beamer et al (2005) for application in the SCRP. The new dataset also has complete records for the fixed effect variables of interest (salinity, temperature, depth), which Beamer et al (2005) did not, and therefore has a better chance to improve our understanding of juvenile Chinook Salmon patterns across the Skagit estuary.
3. Our statistical analyses for juvenile Chinook Salmon presence and density when present do not find support for salinity being a barrier or limitation to juvenile Chinook Salmon rearing in the Skagit estuary, including the polyhaline SC sub-delta area. Between the two competing ideas related to the importance of landscape connectivity (fish passage function) or salinity (physiological transition function), the fixed effect 'salinity' was either not statistically significant or of minor significance compared to the random effect 'sub-delta area', suggesting landscape connectivity may be more important than salinity in structuring patterns of juvenile Chinook Salmon presence and density in the Skagit estuary.
4. Temperature was the most important fixed effect in the models, suggesting thermal regulation and bioenergetics are more important to site specific habitat selection of juvenile Chinook Salmon during their seasonal use of the Skagit estuary than salinity or water depth.
5. The natural history literature demonstrates juvenile Chinook Salmon rear in estuarine habitats with wide ranging salinities from complete freshwater to nearly full-strength seawater. We found numerous studies

where juvenile Chinook Salmon have been documented rearing and/or successfully foraging in polyhaline salinities throughout the PNW including estuaries in the Salish Sea and coastal Oregon. Our study demonstrates that juvenile Chinook Salmon in the more saline areas of the Skagit estuary (SC and BF) regularly exhibit a seasonal use curve with densities comparable to other PNW estuaries, including estuaries known for large scale restoration.

6. We found ample literature that is suggestive that salinity tolerance of juvenile Chinook at outmigration can be population or even family specific. Based on observations from our study, the Skagit Chinook Salmon population may be among the salinity tolerant races. Moreover, the literature on laboratory experimentation does not seem suggestive that SC salinities are a juvenile Chinook Salmon limitation.
7. We conclude that the criteria used in the initial SC modeling and restoration feasibility studies were based on an overly narrow view of suitable juvenile Chinook estuarine habitat. Reviewed literature and the empirical fish observations of this study suggest that high salinity is unlikely to limit juvenile Chinook Salmon use in the Skagit estuary and that other physical habitat factors are more important in structuring Skagit juvenile Chinook Salmon natal estuary rearing.

Recommendations

Considering the conclusions, we make the following restoration planning recommendations:

1. The polyhaline habitats of the Skagit estuary are within the natural distribution of natal estuarine habitats of PNW Chinook Salmon. Additionally, the BF and SC habitats will always have lower landscape connectivity values than habitats within the NF and SF simply because of their proximity with each other and the Skagit River. In spite of these fixed geographic differences, restoration of connectivity between sub-areas will reduce some of the differences in landscape connectivity and salinity distributions, which should be beneficial to juvenile Chinook Salmon.
2. Restoration within any estuarine habitat zone, including the polyhaline zone, should be aligned to the natural processes that support ecological functions, such as prey production and foraging opportunity, and not just focus on singular abiotic habitat conditions such as a simplistic salinity criterion. That said, it is likely that lower salinities and more low salinity diversity within the SC would be better for Chinook Salmon rearing than the higher salinities of its current condition, which is heavily influenced by the jetty that blocks freshwater flow between the NF and SC. Thus, we recommend restoration objectives not focus on lowering salinity based on salinity magnitude criterion, but rather to focus on restoration of natural process and landscape conditions that reduce salinity magnitude and increase spatial patterns of lower salinity opportunity habitats. Specifically, natural estuarine systems have local scale (i.e., distributary channel width, blind channel network) that includes lateral and/or vertical variability in salinity thus providing fish with options for volitional salinity selection. For example, Grossman et al (2007) emphasizes the importance of SC edge habitats for salinity diversity. The edge habitats are described as shallow and are most likely to be the areas with localized freshwater inputs. Because the edge habitats are shallow and often along a curvy shoreline, their tidal currents are lower velocity than in the main channel so localized freshwater inputs are not easily mixed. Restoration within the SC should seek the conditions that allow for natural conditions of low salinity and salinity variability in its restoration planning in addition to restoration of landscape connectivity (i.e., bullet 1).

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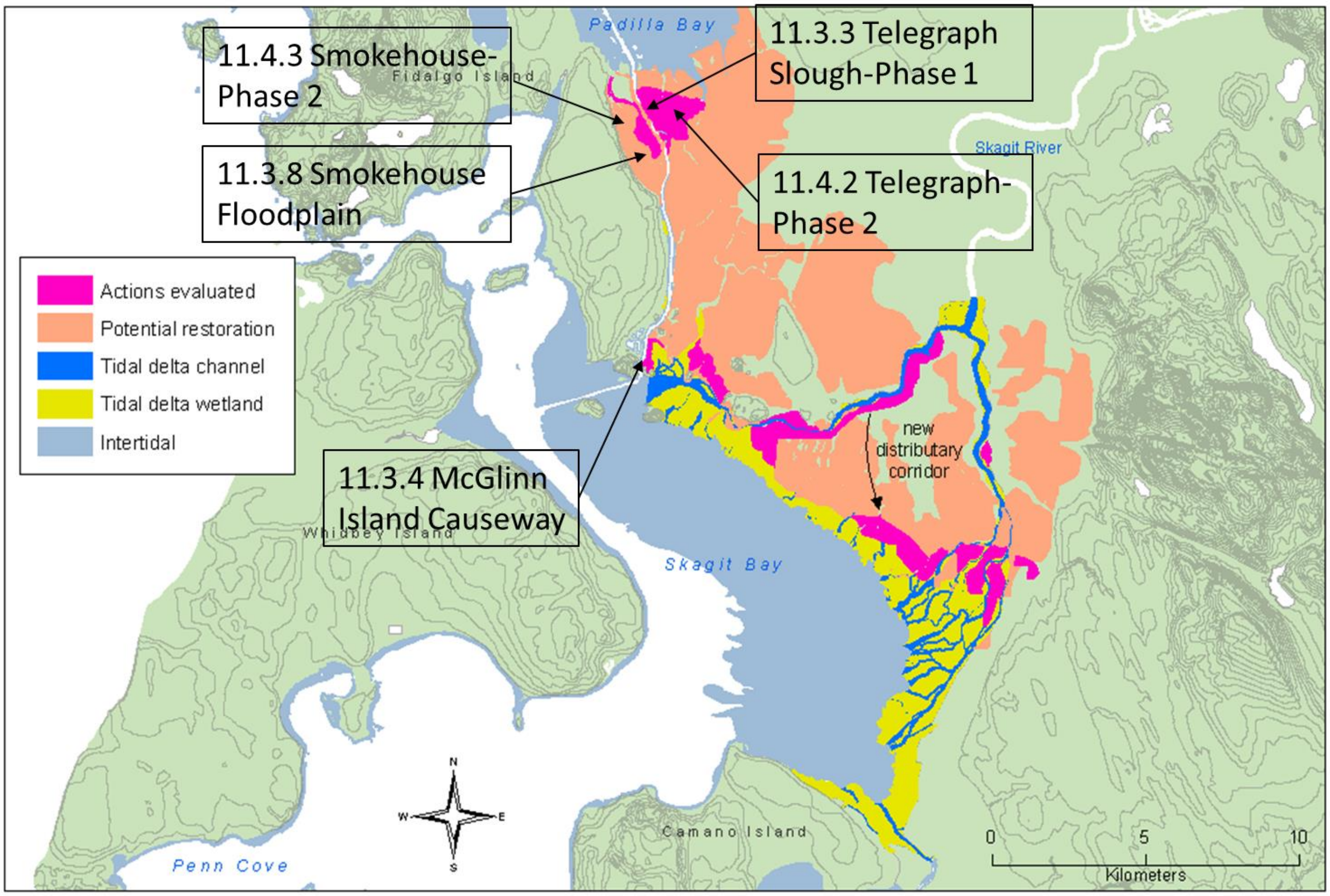
- Pacific Salmon Treaty Implementation funding administered through the Northwest Indian Fisheries Commission to Skagit River System Cooperative

Appendices

Appendix 1. Candidate estuary restoration projects from the 2005 Skagit Chinook Recovery Plan



Appendix 1-Figure 1. Existing delta habitats and potential restoration. Location of existing delta habitats that are easily accessible to delta rearing Chinook Salmon (yellow and blue polygons) and the location of SCRP candidate delta restoration (pink polygons). Polygons shown as “potential restoration” are areas where it is geomorphically possible to restore to tidal delta habitat (based on the historic limit of tidal delta habitat from Collins 2000). This figure is from Figure 11.2 in SCRP and Figure 7.1 in Beamer et al 2005. The five candidate restoration projects within the SCRP that would influence Swinomish Channel Corridor habitat are labeled.

Appendix 2. Landscape connectivity

Appendix 2-Table 1. Landscape connectivity values for Skagit estuary sites by year. Sites are shown on Figure 1. Site name key: Browns Sl Barrow Ch (BSB), Browns Sl Diked Side (BSD), Cattail Saltmarsh (CT), DW Reference E Blind (DWE), FWP New Site (FWP), Grain of Sand (GS), Hall Sl Trib (HS), Ika Lower and Ika Upper (IKA), Swin Ch Old Bridge Blind (SW), and Tom Moore (TM).

Year	BSB	BSD	CT	DWE	FWP	GS	HS	IKA	SW	TM
2001	0.0241	0.0241	0.0413	0.0312	0.0371	0.0894		0.0365	0.0174	0.0246
2002	0.0241	0.0241	0.0413	0.0312	0.0371	0.0894		0.0365	0.0174	0.0246
2003	0.0241	0.0241	0.0413	0.0312	0.0371	0.0894		0.0365	0.0174	0.0246
2004	0.0241	0.0241	0.0413	0.0312	0.0371	0.0894		0.0365	0.0174	0.0246
2005	0.0241	0.0241	0.0413	0.0313	0.0372	0.0894		0.0365	0.0174	0.0246
2006	0.0241	0.0241	0.0413	0.0314	0.0373	0.0894		0.0365	0.0174	0.0247
2007	0.0241	0.0241	0.0413	0.0316	0.0374	0.0894		0.0365	0.0174	0.0247
2008	0.0241	0.0241	0.0413	0.0317	0.0374	0.0894		0.0365	0.0174	0.0247
2009	0.0241	0.0241	0.0413	0.0318	0.0375	0.0894		0.0365	0.0174	0.0248
2010	0.0241	0.0241	0.0413	0.0319	0.0376	0.0894		0.0365	0.0174	0.0248
2011	0.0241	0.0241	0.0413	0.0321	0.0377	0.0894		0.0365	0.0174	0.0249
2012	0.0241	0.0241	0.0413	0.0322	0.0378	0.0894		0.0365	0.0174	0.0249
2013	0.0241	0.0241	0.0413	0.0323	0.0379	0.0894		0.0365	0.0174	0.0250
2014	0.0241	0.0241	0.0403	0.0325	0.0376	0.0894		0.0349	0.0166	0.0251
2015	0.0240	0.0240	0.0393	0.0326	0.0373	0.0894		0.0333	0.0158	0.0252
2016	0.0240	0.0240	0.0384	0.0327	0.0370	0.0894		0.0316	0.0150	0.0254
2017		0.0240	0.0374	0.0328	0.0367	0.0894	0.0197	0.0300	0.0141	0.0255
2018		0.0240	0.0364	0.0330	0.0364	0.0894	0.0197	0.0284	0.0133	0.0256
2019		0.0240	0.0355	0.0331	0.0362	0.0894	0.0197	0.0268	0.0125	0.0258
2020		0.0239	0.0345	0.0332	0.0359	0.0894	0.0197	0.0252	0.0117	0.0259
2021		0.0239	0.0336	0.0334	0.0356	0.0894	0.0197	0.0236	0.0109	0.0260

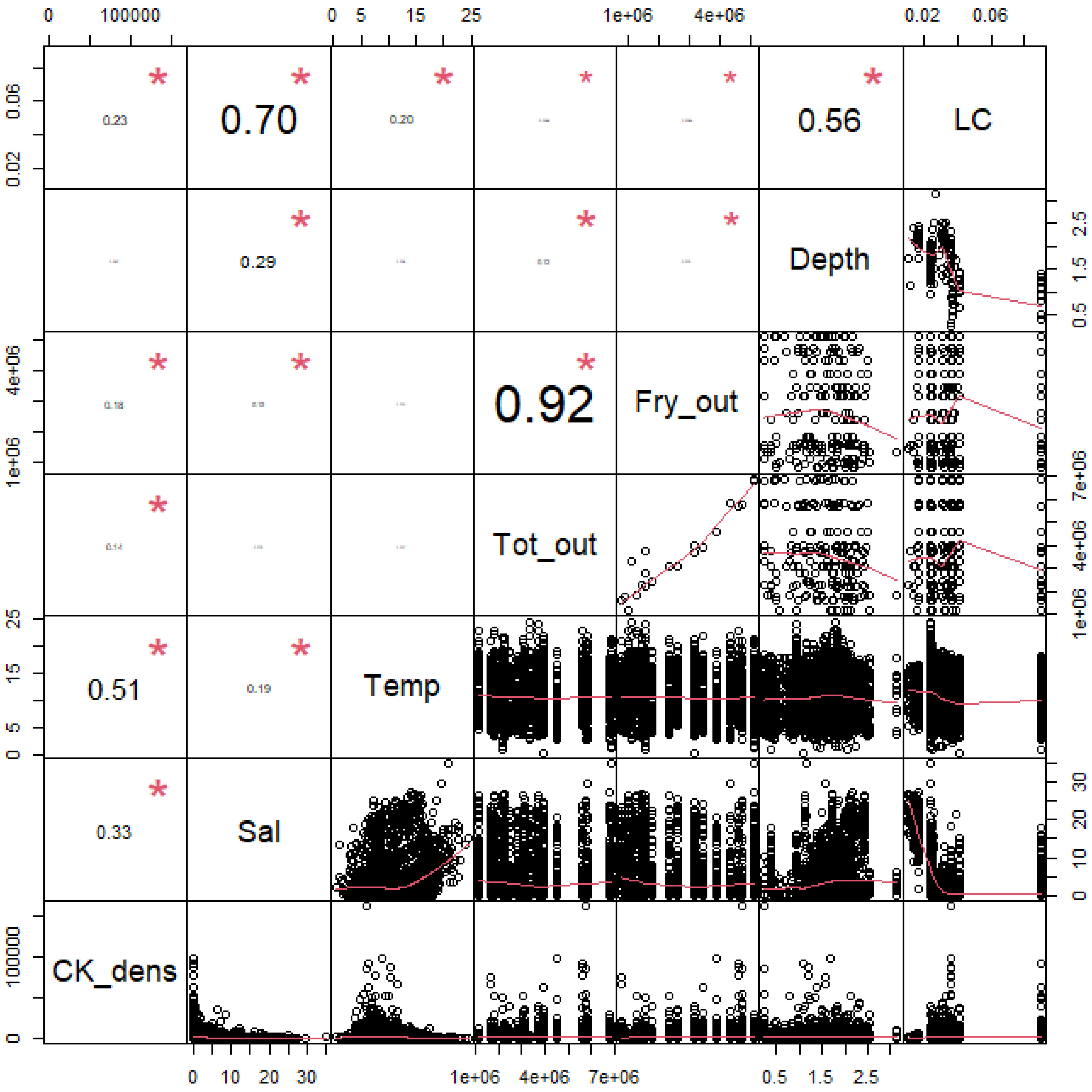
Appendix 3. Analysis of data cross correlation and bias

We evaluated cross correlation and potential biases of potential fixed effect parameters with simple pairs plot and variable influence index calculation in R. The dataset of interest is highly cross correlated with landscape connectivity being cross correlated with all parameters and the most strongly correlated with salinity, the specific parameter of interest (Appendix 3-Figure 1). The correlations between landscape connectivity and other parameters, especially salinity, raises concerns with increased uncertainty of statistical estimation for parameters.

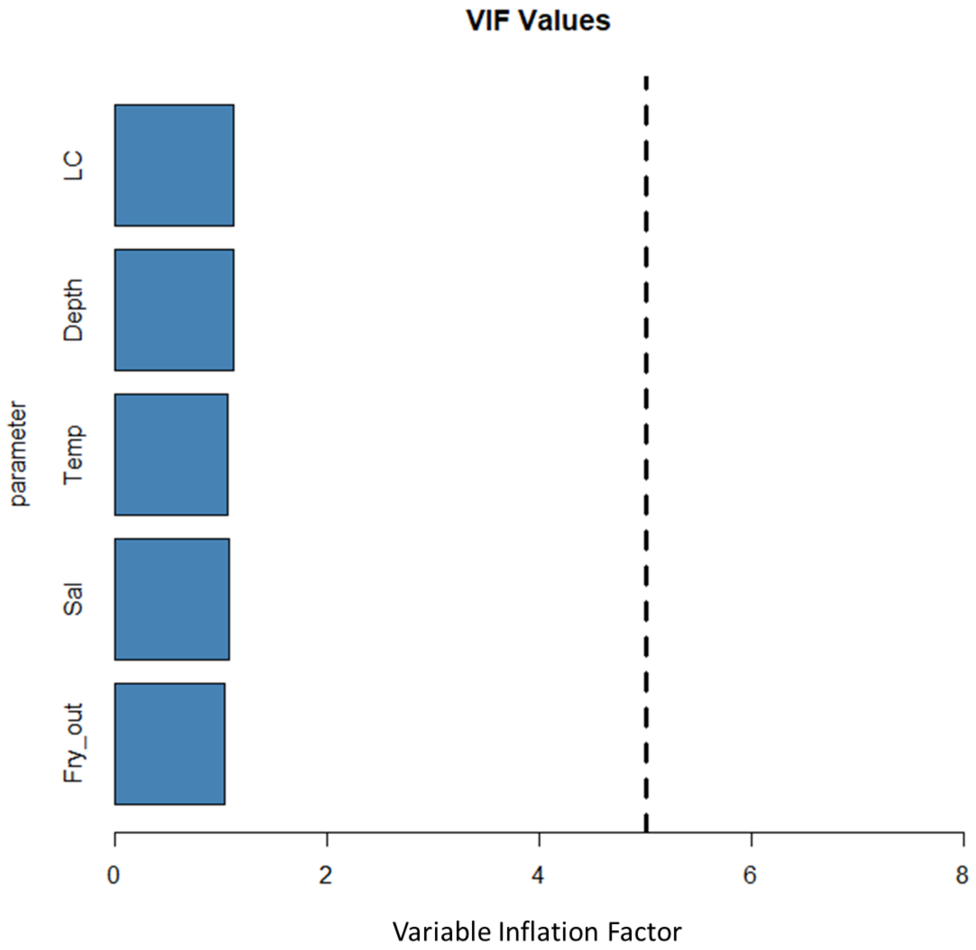
Given the correlations between independent predictors, we then tested for multicollinearity with variable inflation factor (VIF) estimation. Multicollinearity occurs when multiple predictors work together to inflate relationships with the response variable. To evaluate this potential effect, a simple linear model was applied to the log transformed juvenile Chinook Salmon density with the scaled (z-score) predictors. Generally, VIF scores greater than 2 are considered problematic and above 5 are considered to have multicollinearity. Multicollinearity was not present nor were there problematic parameters (Appendix 3-Figure 2). Overall, the dataset is highly cross correlated, but effect size of correlations on model parameter estimation is low.

However, VIF scores < 5 for parameters do not give us a free pass for their use in a model so caution of such parameter's use moving forward is warranted. Thus, landscape connectivity was still a concern for us because our main study question centers on how salinity influences juvenile Chinook Salmon presence and density, and salinity is the highest correlated variable with landscape connectivity. Thus, we thought we could better control for effect of 'location within the estuary' by separating sites by sub-delta areas as defined by the Skagit IMW (Greene et al. 2015) and using sub-delta area as a random intercept in the models. This approach allows for accounting of the potential effect of location in the estuary system but limits strong cross correlations between landscape connectivity and other fixed effect model predictors.

For Chinook Salmon smolt outmigration, it is well known that outmigration abundance influences juvenile Chinook density in estuaries (Beamer et al 2005; Greene et al 2021). As part of the Skagit IMW dataset, we have annual estimates for Skagit River juvenile Chinook Salmon outmigration from WDFW (Appendix 4) so we considered using either 'total sub yearlings' or 'fry only' outmigration abundances as a fixed effect predictor in our models. However, our models use instantaneous data for the response and fixed effect variables so using annualized Chinook Salmon smolt outmigration would be somewhat of a temporal mismatch compared to other data in the model. Given the Chinook Salmon outmigration data are annual estimates, and that our main study question is centered on learning about the effects of salinity on Chinook Salmon presence and density (not effects of outmigration per se), it seemed more appropriate to use 'year' as a random intercept which captures the effect of annual variation Chinook Salmon smolt out-migrate abundances as well as other annually varying environmental effects (e.g., river discharge, air temperature, and tides). By including the term 'year' we also minimize model parameters but retain maximum learning potential regarding the influence of the model's fixed effects on juvenile Chinook Salmon presence and density.



Appendix 3-Figure 1. Pairwise plot of candidate model variables in R with Spearman Rho correlation values plotted on the upper left with significant values denoted by **red** asterisk. The data are plotted to the lower right with a loess trend line applied. The figure uses untransformed data. Candidate model variables plotted are: natural origin juvenile Chinook Salmon density (CK_dens), water salinity (Sal), water temperature (Temp), annual natural origin subyearling Chinook Salmon outmigration (Tot-out), annual natural origin Chinook fry outmigration (Fry_out), water depth (Depth), landscape connectivity (LC).



Appendix 3-Figure 2. Variable inflation factor (VIF) scores for correlated variables considered for model inclusion. Candidate model variables plotted are: annual natural origin Chinook fry outmigration (Fry_out), water salinity (Sal), water temperature (Temp), water depth (Depth), and landscape connectivity (LC).

Appendix 4. Skagit River Chinook smolt outmigration

The number of juvenile Chinook Salmon migrating each year out the Skagit River will influence the number of juvenile Chinook Salmon utilizing the Skagit estuary. We used the population estimates made by WDFW of outmigrating natural origin Chinook fry to account for this source of variability on the catch of Chinook Salmon in the Skagit estuary.

WDFW operates a juvenile fish trap on the Skagit River at river km 39.1 in the city of Mount Vernon. Operation of this trap began in 1990 for the purpose of estimating coho smolt production. The focus of this trapping operation has expanded over time and now provides an estimate of the number of natural origin juvenile Chinook Salmon emigrating from the entire Skagit River Basin (Zimmerman et al. 2015). The juvenile trap is operated each year beginning in mid-January and continues through July. This time frame was selected based on results from three extended trapping seasons conducted in the mid-1990s. The freshwater juvenile monitoring provides both abundance and life history data and includes juvenile migrant abundance by migrant type (fry, parr, yearling), juvenile body size, and migration timing. The trap is actually two traps, an inclined-plane and a screw trap. The rectangular inclined plane trap (1.8 x 4.9 m) is fished by lowering the trap approximately 1 m into the water at an oblique angle, and the trap catches fish swimming in a 2 m^2 cross-sectional area near the surface of the water by forcing them onto the inclined plane and washing them into a collection box. The screw trap (2.5 m circular diameter) is fished by lowering it partially into the water. Fish swim downstream into the 2.35 m^2 cross-sectional entryway of the trap, and the rotation of plates within the trap forces fish into a collection box. The juvenile traps catch only a portion of the total juvenile Chinook emigrating from the Skagit River. Therefore, total abundance is estimated using a mark-recapture study design in order to expand the catch by a calibration factor. Missed catch is estimated during trap outages and is included in the final estimate. During the emigration period, a known number of marked fish (dye or fin-clip) are released upstream of the trap and a portion of these are recaptured in the trap. Releases of marked fish are conducted throughout the outmigration period in order to account for differences in trap efficiencies due to river conditions. The resulting trap efficiency data is applied to catch data in order to estimate total migrant abundance (details in Zimmerman et al. 2015).

Over the 2001-2021 period used in this report Skagit River natural origin Chinook fry outmigration population estimates have ranged from lows in 2008 and 2010 of 0.8-0.9 million fish and a high of 5.1 million fish in 2001 and 2006 (Table below). The overall average for the twenty-two-year period is 2.65 million fish.

Zimmerman, M. S., C. Kinsel, E. Beamer, E. Conner, and D. Pflug. 2015. Abundance, survival, and life history strategies of juvenile migrant Chinook in the Skagit River, Washington. Transactions of the American Fisheries Society. 144:3, 627-641, DOI: 10.1080/00028487.2015.1017658

Appendix 4-Table 1. Annual Skagit River subyearling Chinook Salmon outmigration population size by juvenile migration year (from WDFW).

Year	Subyearling Abundance	Fry Abundance	Parr Abundance
2001	6,793,436	5,111,937	1,681,499
2002	5,834,493	4,338,274	1,496,219
2003	5,764,557	4,702,344	1,062,213
2004	3,319,612	1,131,606	2,188,006
2005	3,965,424	3,160,558	804,867
2006	6,875,630	5,116,578	1,759,052
2007	2,427,626	1,808,798	618,828
2008	1,710,551	914,161	796,390
2009	2,796,241	1,580,141	1,216,100
2010	1,613,622	801,677	811,945
2011	3,677,939	3,177,656	500,283
2012	4,547,457	3,900,019	647,437
2013	5,644,466	4,603,262	1,041,204
2014	3,900,177	3,416,943	483,234
2015	1,132,766	1,016,166	116,601
2016	3,090,952	2,635,362	455,590
2017	3,069,457	2,359,067	710,389
2018	2,168,802	1,560,380	608,421
2019	1,801,632	1,304,069	497,563
2020	3,715,522	1,571,929	2,143,593
2021	2,241,135	1,425,109	816,026

Appendix 5. Salinity and temperature distributions by month and sub-delta area within the Skagit River estuary

Appendix 5-Table 1. Distribution of salinity by sub-delta area and month for period 2000-2021. Units are PSU.

Fir Island Bayfront	5th percentile	25th percentile	50th percentile	75th percentile	95th percentile
Feb	0.6	2.8	5.0	7.6	13.3
Mar	0.9	3.8	6.0	8.7	14.3
Apr	1.4	4.1	6.8	10.1	13.9
May	1.7	4.5	6.4	9.3	13.8
Jun	3.2	5.7	6.7	8.6	11.8
Jul	3.4	6.2	9.2	13.1	18.2
Aug	5.8	10.4	13.1	15.1	17.6

North Fork	5th percentile	25th percentile	50th percentile	75th percentile	95th percentile
Feb	0.0	0.1	0.9	1.8	6.5
Mar	0.0	0.0	0.5	1.6	7.4
Apr	0.0	0.0	0.1	1.2	6.3
May	0.0	0.0	0.0	0.4	2.7
Jun	0.0	0.0	0.0	0.3	2.8
Jul	0.0	0.0	0.1	0.5	3.5
Aug	0.0	0.0	0.1	1.9	6.8

Swinomish Channel Corridor	5th percentile	25th percentile	50th percentile	75th percentile	95th percentile
Feb	6.7	12.9	16.3	17.8	22.4
Mar	11.1	15.5	18.2	20.0	21.3
Apr	9.6	15.9	19.7	20.8	24.4
May	12.3	16.7	19.6	21.8	23.3
Jun	15.4	18.1	20.3	22.6	23.8
Jul	14.9	19.5	22.5	24.0	26.6
Aug	17.3	22.1	23.5	26.1	26.5

South Fork	5th percentile	25th percentile	50th percentile	75th percentile	95th percentile
Feb	0.0	0.1	1.7	4.1	9.1
Mar	0.0	0.1	1.0	4.2	12.5
Apr	0.0	0.0	0.3	2.7	10.6
May	0.0	0.0	0.1	0.4	5.1
Jun	0.0	0.0	0.0	0.2	5.6
Jul	0.0	0.0	0.1	1.3	11.4
Aug	0.0	0.1	1.9	6.1	14.9

Appendix 5-Table 2. Distribution of temperature by sub-delta area and month for period 2000-2021. Units are degrees C.

Fir Island Bayfront	5th percentile	25th percentile	50th percentile	75th percentile	95th percentile
Feb	2.8	4.1	5.7	7.0	8.3
Mar	4.9	6.6	7.5	8.9	10.6
Apr	5.7	8.4	10.4	12.4	15.5
May	10.7	12.0	14.2	15.8	17.9
Jun	12.1	14.9	16.4	18.5	21.4
Jul	14.2	16.4	18.2	19.5	22.5
Aug	15.0	16.0	17.3	18.9	22.1

North Fork	5th percentile	25th percentile	50th percentile	75th percentile	95th percentile
Feb	3.0	3.9	4.8	5.5	6.2
Mar	4.2	5.0	5.9	6.8	7.7
Apr	5.9	7.0	8.1	8.8	10.0
May	8.3	9.3	10.3	11.2	11.9
Jun	8.7	10.6	11.2	12.9	15.0
Jul	10.9	13.0	14.4	15.7	16.9
Aug	12.5	14.7	15.7	16.4	17.6

Swinomish Channel Corridor	5th percentile	25th percentile	50th percentile	75th percentile	95th percentile
Feb	4.9	6.4	6.9	7.7	8.4
Mar	6.4	7.3	7.8	8.6	10.1
Apr	7.8	8.7	10.5	11.1	12.1
May	9.9	10.8	11.6	12.8	13.4
Jun	10.7	12.3	13.5	14.1	15.5
Jul	13.4	14.2	14.8	15.6	16.1
Aug	13.4	14.1	15.1	15.6	15.8

South Fork	5th percentile	25th percentile	50th percentile	75th percentile	95th percentile
Feb	2.8	4.1	4.9	5.9	6.9
Mar	4.7	5.6	6.5	7.4	9.3
Apr	6.3	7.4	8.5	9.6	11.4
May	7.9	9.3	10.1	11.3	13.2
Jun	9.1	10.4	11.5	12.8	15.4
Jul	11.4	13.0	14.6	16.3	18.4
Aug	14.7	15.6	16.7	17.9	18.8

Appendix 6. Juvenile Chinook Salmon density distributions by month and sub-delta area within the Skagit River estuary

Appendix 6-Table 1. Distribution of natural origin juvenile Chinook Salmon density (fish/ha) by sub-delta area and month for period 2000-2021. Densities are fish/ha of bankfull blind channel area.

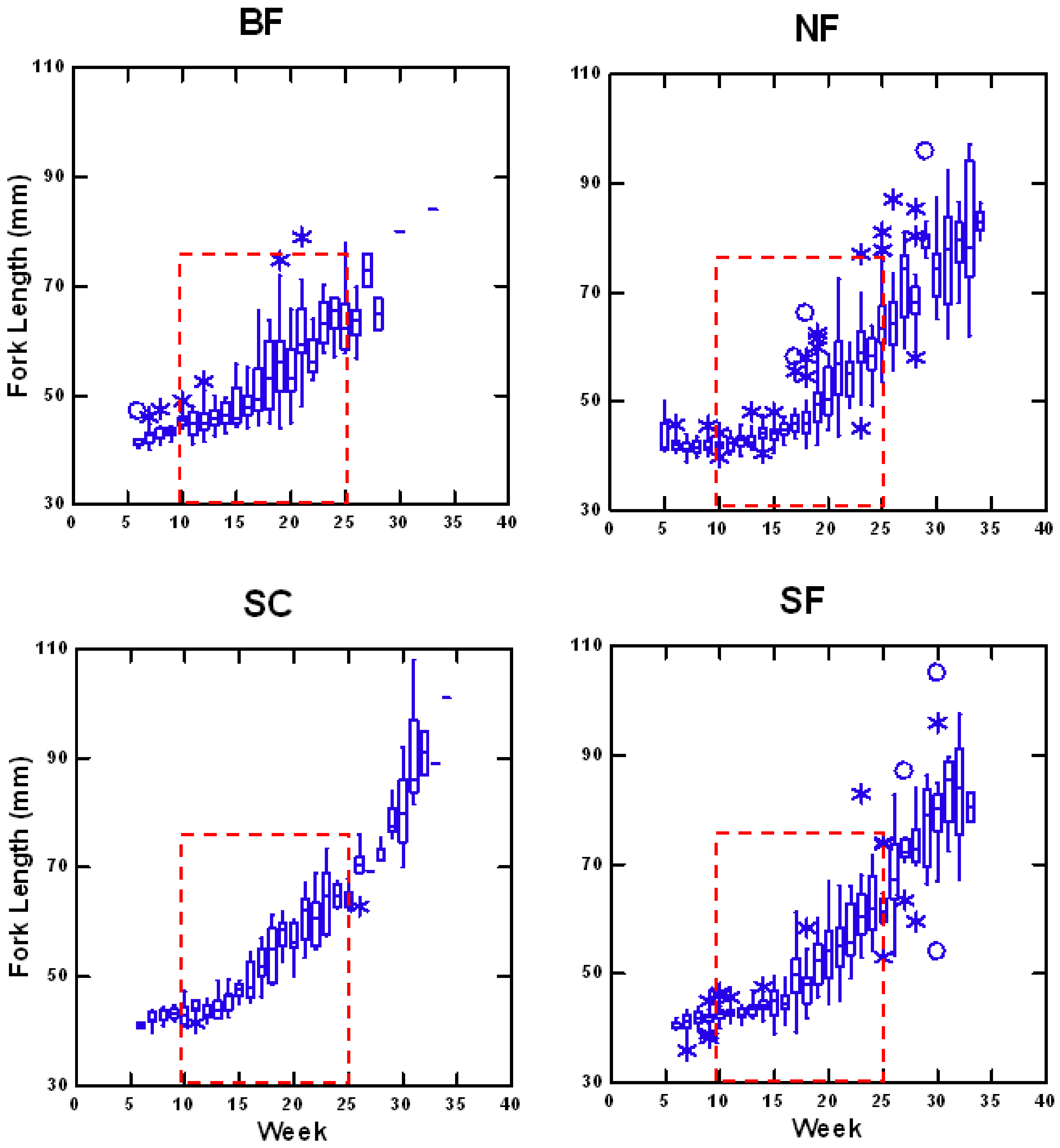
Fir Island Bayfront	5th percentile	25th percentile	50th percentile	75th percentile	95th percentile
Feb	0	5	31	164	1,137
Mar	5	110	333	954	4,822
Apr	8	139	452	2,038	6,077
May	0	10	73	237	1,851
Jun	0	0	4	65	595
Jul	0	0	0	0	80
Aug	0	0	0	0	0

North Fork	5th percentile	25th percentile	50th percentile	75th percentile	95th percentile
Feb	51	299	994	3,442	13,736
Mar	67	897	2,443	8,094	25,101
Apr	197	1,274	4,143	11,346	35,109
May	93	762	2,008	5,698	19,551
Jun	0	312	1,056	2,727	13,502
Jul	0	0	135	690	4,316
Aug	0	0	0	58	319

Swinomish Channel Corridor	5th percentile	25th percentile	50th percentile	75th percentile	95th percentile
Feb	0	50	177	313	2,122
Mar	12	130	600	1,356	3,164
Apr	22	181	423	965	2,510
May	11	129	345	797	1,488
Jun	0	9	73	262	1,258
Jul	0	0	5	25	86
Aug	0	0	0	0	24

South Fork	5th percentile	25th percentile	50th percentile	75th percentile	95th percentile
Feb	0	39	267	919	5,485
Mar	25	267	685	3,549	17,219
Apr	42	561	2,458	6,373	23,845
May	0	346	1,577	4,360	11,510
Jun	0	70	623	2,898	8,539
Jul	0	0	13	343	3,446
Aug	0	0	0	0	171

Appendix 7. Seasonal fork length distribution of juvenile Chinook Salmon in sub-delta areas of the Skagit estuary.



Appendix 7-Figure A10. Boxplot of weekly mean fork length of natural origin juvenile Chinook Salmon by Skagit estuary sub-delta polygon. The red dashed box indicates the weeks (weeks 10-25) that the majority of fish are present in the estuary and the size of the fish (~75 mm) used in the Webster and Dill (2006) and Webster et al (2007).