Juvenile Chinook Salmon Effectiveness Monitoring of Duwamish Shallow Water Restoration Sites, 2023

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Executive Summary

Estuaries are crucial transitional habitats for migrating juvenile salmonids, especially for species with longer estuarine residence times including Chinook (*Oncorhynchus tshawytscha*), chum (*O. keta*), and coho (*O. kisutch*). Off-channel estuarine habitats enable juvenile salmon to grow in low velocity, reduced predation environments, acclimate to saline water, and emigrate by choice rather than being transported out of the estuary, especially during high flow events.

We studied the efficacy of recent Duwamish transition zone restoration projects (Chinook Wind, Riverton Flapgate Removal, and Duwamish River People's Park [DRPP]) with a focus on juvenile Chinook salmon habitat, by monitoring fish assemblages and distributions at each site. Paired daytime sampling included shallow water, newly restored interior 'pocket' habitat, and the mainstem channel adjacent to the pocket habitat opening. All sampling occurred at high tide when pocket habitats were flooded with water. Surveying the mainstem channel provided a reference for habitat use around the entrance of restoration sites. The Riverton project also included sampling at the creek that connected the interior pocket habitat to the mainstem channel. To characterize most of the 2023 juvenile salmon outmigration period, we sampled once in February, twice in March and April, and once each in May and June.

To compensate for challenges associated with monitoring fish in turbid, estuarine environments with woody debris, we combined seine net and acoustic camera surveys. We used a 20 m river seine net in deep habitats and a 9.1 m pole seine net in shallow habitats. For net sampling, we measured the lengths of the first 20 fish of each species and counted all remaining fish. To identify Chinook and coho origins as hatchery or wild, each fish was checked for presence/absence of adipose fin, coded wire tag, and passive integrated transponder tags. For acoustic sampling, we mounted a dual-frequency identification sonar (i.e., acoustic camera) beneath a 4 m or 2 m kayak, depending on transect depth. The acoustic data was processed by viewing timestamped, recorded files to count and identify each fish to family, when possible, by relative size, shape, and swimming/shoaling behaviors.

We used Mann Whitney and Kruskal-Wallis tests on net sampling data to analyze wild Chinook salmon abundance between habitat types and among sites. There was no difference in Chinook salmon counts between habitat types or among sites, indicating that juvenile Chinook salmon were accessing and using new restored pocket habitats similarly to the channel. As vegetative and benthic invertebrate communities become more established at restored sites, we expect juvenile salmon usage to increase due to improved fish habitat. Our channel transects were adjacent to the restored sites, which may increase salmon use due to the proximity of restored habitat. Adjacent channel habitat is also often revegetated, as was the case for our sites.

Wild, juvenile Chinook were present in all months and in all restored pocket habitats and appeared to be more temporally consistent throughout pocket habitats than in the channel. Overall, we netted more wild (n = 103) than hatchery (n = 26) reared Chinook, with highest counts at Chinook Wind. More wild Chinook were present in the pocket habitats than the channel, and more hatchery Chinook were sampled in the channel than in pocket habitats.

Of the restored pocket habitats, Chinook Wind pocket had the greatest size range of wild Chinook, which included fry in February, and larger parr later in the season. The lowest counts of wild Chinook were in the DRPP pocket, which conversely had the highest chum counts.

We used generalized linear models to analyze combined juvenile salmon data, of which the majority (97%) were chum salmon. There were no statistical differences between pocket or mainstem channel juvenile salmon counts for either sampling method, indicating that juvenile salmon were using new restored pocket habitats similarly to the channel. Acoustic results showed that DRPP had twice as many juvenile salmon as Chinook Wind, and that Riverton had 1.5 times as many salmon as Chinook Wind. Seine net results showed that DRPP had 1.3 times as many salmon as Chinook Wind, and Chinook Wind and Riverton had similar salmon counts. Juvenile salmon predators were rarely seen in acoustic footage and only two potential predators (yearling Chinook and yearling coho) were netted. Finally, we did not find an association between salmon counts and large, woody debris.

Although DRPP was created as high marsh habitat in an effort to produce juvenile salmon prey, the site had the highest overall salmon counts, albeit mostly chum in deeper portions at the mouth of the pocket habitat adjacent to the mainstem. The remaining interior edges of DRPP emptied when the tide was below ~3 m (i.e. ~10 feet), which occurred through most of the tidal cycle. Low elevation sites that remain inundated at low tides will improve salmon access.

When considering future site restoration, we recommend reducing natural and artificial barriers to site access. The Riverton interior pocket was restricted at the connection of the creek to the mainstem, and the pocket mostly emptied during low tide. While Chinook and other salmonids were present at high tides, these fish may have been flushed out or moved during low tides, when water levels were low. The goose exclusion fence along the opening of the DRPP pocket habitat is likely a barrier to juvenile salmon and was removed on our field collection days. Physical barriers for geese should be constrained to aerial exclusions or along the periphery of the site, leaving the connection to the mainstem open for fish access. When restricting geese access around the periphery of the site, we recommend seasonal or above water line fencing, so juvenile salmon are not restricted from accessing the shallowest water at site edges.

For future studies, we recommend

- Identifying long-term benefits of restored habitats on juvenile salmon by quantifying how juvenile salmon usage, and vegetative and invertebrate assemblages (benthic and terrestrial) develop at restored sites, through time
- Juvenile salmon prey production studies and diet analyses within restored interior pocket habitats and revegetated channel habitats to identify and index potential value of locations as foraging locations for juvenile salmon (i.e., quantify potential versus realized diets)
- Studying water temperatures at access points to and within interior habitat locations to quantify potential thermal tolerance limits and identify temporal ranges that restrict juvenile salmon access and residency

- Identifying potential predation on juvenile salmon at pocket openings associated with tidal cycles due to access or flushing from sites (e.g., Riverton Creek or DRPP pocket)
- Quantifying potential impacts of goose exclusion methods on salmon site access and/or restriction from shallow water habitats around pocket perimeters
- Identifying potential impacts of relic debris and associated sediment deposits on salmon access to interior habitats
- Creating a trans-organizational database to house Duwamish salmon-associated research, including historic and anecdotal/qualitative reports to facilitate time series or meta-analyses, and future project coordination

Introduction

Estuaries provide crucial nursery functions for juvenile salmon, including refuge and growth opportunities, as they transition from fresh to saline waters (Healey 1982, Simenstad et al. 1982, Thorpe 1994). Growth during the first year of life is linked to marine survival and spawning (Reimers 1971, Magnusson & Hilborn 2003), with the highest proportional growth occurring during the juvenile life stage (Quinn 2018). Juvenile salmon estuarine residency varies by species and location, with habitat modifications altering prey availability, refuge, and habitat connectivity (Simenstad et al. 1982, Quinn 2018).

Historically, the Lower Duwamish estuary in Seattle, Washington, provided shallow, tidal wetland habitat for juvenile salmonids. Since the 1800s, dredging and filling of the area has resulted in industrialized estuarine habitat with high toxicant levels (King County 2022) and little secondary, shallow-water habitat (Water Resource Investory Area 9 [WRIA 9], 2021). Only 2% of the Duwamish tidal wetlands remain (WRIA 9, 2021). However, the estuary remains a transitional home to several salmonid species, including chum (*Oncorhynchus keta)*, pink (*O. gorbuscha*; even years), coho (*O. kisutch*), steelhead (*O. mykiss*), and Environmental Species Act-listed Puget Sound Chinook (*O. tshawytscha*). Chum and Chinook are the most estuary-dependent of the salmon species (Simenstad et al. 1982), with Chinook residency and use of secondary channel habitats longer, as they acclimate to marine water (Healey 1982). Off-channel estuarine habitats enable juvenile salmon to grow in low velocity, reduced predation environments, acclimate to saline water, and emigrate by choice rather than being transported out of the estuary, especially during high flow events (Simenstad et al. 1982, Simenstad & Cordell 2000).

Juvenile salmon entering the Lower Duwamish from the Lower Green River differ in their life histories, but predominantly enter as fry or parr, transitioning to the smolt phase before leaving. Few that enter the Duwamish as fry return to spawn (WRIA 9 2021), potentially indicating a need for shallow water habitat with foraging opportunities so they can remain in the estuary to grow and increase their chances of marine survival. Annual Chinook escapement from fisheries is currently heavily reliant on hatchery-origin salmon (WRIA 9 2021).

The purpose of our 2023 study was to measure restoration project performance in the Lower Duwamish, specifically addressing the extent that juvenile Chinook salmon use interior, shallow-water habitat at restoration sites. Our work builds on the work of Ruggerone et al. (2006), Cordell et al. (2011), Toft & Cordell (2017), and King County (2019), where they found consistent use of the Duwamish transition zone by juvenile salmon, including restored sites.

Methods

Sites

The three study sites at intertidal estuarine habitats were located at Duwamish River Miles 4.5 and 6.7, and included Chinook Wind, Riverton Creek Flapgate Removal, and Duwamish River People's Park (DRPP) (Figure 1). Construction at all sites was completed in 2021/2022 and all contained restored shallow-water pocket habitat connected to the channel at high tide.

1. **Chinook Wind** (RM 6.7; Figure 2) Completed in 2022, restoration included converting a former hotel site into 4 acres of estuarine wetland, aquatic, and riparian habitat (https://kingcounty.gov/en/legacy/services/environment/water-and-land/wetlands/mitigation-credit-program/mitigation-sites/project-chinook-wind). Buildings and asphalt were removed, and the soil was decontaminated. Chinook Wind has aquatic, intertidal mudflat, and marsh and riparian habitat. It does not fully empty at low tide.

2. **Riverton Creek Flapgate Removal** (RM 6.7; Figure 3) completed in 2021, had two culverts and flapgates removed, which restored connection of ¼ acre backwater habitat and 1400 linear feet of creek to the channel. Riparian vegetation was planted for water cooling and salmon foraging opportunities. https://www.govlink.org/watersheds/9/committees/archive/1905/9.1904_9581m_RivertonFlapgate_fact_final2.pdf

3. **Duwamish River People's Park** (RM 4.5; Figure 4) completed in 2022, had 14 acres of periodically inundated high marsh habitat restored. Designated a highly toxic "Early Action" superfund site, a cleanup to decontaminate the soil was completed, and marsh habitat that included thousands of vegetative plantings was constructed. https://www.portseattle.org/peoplespark

Sampling

Once or twice per month between February and June, at the highest daily tide, we sampled fish at the three restoration sites. Our sampling encompassed peak migration of wild and hatchery Chinook fry and parr smolts, and chum salmon. Netting can be difficult in estuarine habitats due to the occurrence and location of woody debris, vegetation, and water turbidity, so we complemented net sampling with active acoustics. To identify potential differences in salmon habitat use between the mainstem channel and restored pocket habitats, we sampled equitable length (acoustic) or volume (net) transects between the mainstem channel and pocket habitat at each site, with acoustic sampling always preceding net sampling.

Each sampling method has advantages and constraints. Net sampling enables species identification and length measurements, but it includes fish handling and is challenging to sample in fast moving water with objects in the water (e.g., logs, relic debris). Active acoustic sampling is a remote sensing, non-invasive method where large volumes of water can be sampled relative to netting or other visual methods (Martignac et al. 2015). Comparable to visual surveys, the high operating frequency and high data resolution of a multibeam sonar, in this case an acoustic camera, enables observers to identify species and to 'see' fish behaviors in real time (Helfman 1999). Acoustic cameras have been used to census small fish (Adams et al. 2015, Smith et al. 2021, Accola et al. 2022), but are limited in species identification and accuracy of length measurements for small fish (Foote 2009, Burwen et al. 2010).

Net Sampling

We used a boat-deployed 20 m river seine in the channel and in the Chinook Wind pocket habitat (Figure 5). For the remaining net sets, we used a land-deployed 9.1 m pole seine, as DRPP was too high in elevation for boat access, and Riverton Creek was inaccessible by boat due to the narrow width of the creek and location of logs. The day previous to sampling, Port of Seattle employees rolled back goose exclusion fencing separating the DRPP pocket from the mainstem channel so potential fish blockage would be minimized and sample site access was maximized. For volume sampled measurements of net sets, we incorporated the visually estimated percentage of net deployed in the water for river seine sets, and we accounted for transect width, length, and water depth or net height (depending on water level) for pole seine sets. Surface and bottom salinity and temperature were measured at each site.

We measured the length of the first twenty fish of each species and counted all fish, by species. We quantified juvenile Chinook presence, counts, lengths, and origin (natural or hatchery). Chinook and coho origin were determined by a combination of presence/absence of adipose fin and checking the fish for passive integrated transponder and coded wire tags (Figure 5).

Acoustic Sampling

We acoustically sampled using a dual-frequency identification sonar (DIDSON; Sound Metrics, Bellevue, WA, USA; www.soundmetrics.com). The DIDSON is a multibeam sonar that transmits sound pulses, with returning echoes digitized and converted into near-video-quality images (Figure 6). We mounted the DIDSON beneath a 4 m kayak in channel transects, the Chinook Wind restored pocket habitat, and in Riverton Creek. For the remaining transects that could not be paddled, we mounted the DIDSON beneath a 2 m kayak and propelled the kayak by swimming or walking behind. The DIDSON was angled 12° relative to the water surface to ensure that the middle and upper portion of the water column was ensonified and sampled with a horizontal acoustic beam swath of 2.5 m on either side of the kayak. The operating frequency was set at 1.8 MHz and transmitted at ~12 Hz, starting 1 m in front of the kayak for a range of 5 m. The DIDSON was connected to a laptop running data acquisition software (DIDSON V5-26) and a timestamped file was created for each transect. In the laboratory, each transect file was reviewed 2+ times to identify and count fish, verify identification and counting (for acoustic data processing see Accola et al. 2022), and to categorize association of fish with logs (i.e. if fish were present near logs).

Count Data Analysis

For wild Chinook analyses, we compared count differences between habitat types and among sites using Mann-Whitney U and Kruskal-Wallis non-parametric tests. We used generalized linear models (GLM), which account for non-linear data distributions, to characterize salmon counts at sites and between habitats. Previous research had converted salmon counts to densities (counts/surface area sampled), which we replicated to compare to previous restoration site analyses. In this study, we modeled count data as counts due to the ability of GLMs to account for overdispersion (high variance), a common occurrence in fish data, and potential zero inflation (more zeros than would be expected under varying count distributions). Net and acoustic data were analyzed separately because they are different sampling methods. Each model incorporated site and habitat type (mainstem channel, restored interior pocket), with net models also including volume of water sampled by pole and river seine sets. The water volume sampled was equal for acoustic sampling, since transect lengths were equal between habitat types at sites. We tested data dispersion and zero-inflation, and used corrected Akaike's information criterion to evaluate models (Hurvich & Tsai 1989). Finally, we calculated estimated marginal means (equally weighted marginal averages of model count predictions) for each habitat type and site.

All statistical analyses were performed using R Statistical Software (v4.2.2; R Core Team 2023). Data manipulation was performed using "dplyr" (v1.1.2; Wickham et al. 2022). We built GLMs using R package "glmmTMB" (v1.1.7; Brooks et al. 2017). We conducted Tukey-adjusted pairwise comparisons on the GLM estimated marginal means, using the package "emmeans" (v1.8.8; Lenth 2022). For data visualization, we used "ggplot2" (v3.4.4; Wickham 2016), "sjPlot" (v2.8.15; Lüdecke 2018), and "kableExtra" (v1.3.4; Zhu 2021).

Results

Environmental

Surface water temperatures ranged from 5.5^{o} C early in the season to 19.3^{o} C in June. Bottom temperatures ranged from 5.7^{o} C in March to 18^{o} C in June. The highest temperatures in June were all recorded at the three interior pocket habitat locations. Surface salinity ranged from 0 parts per thousand (ppt) to 10.3 ppt. Salinity at depth ranged from 0 ppt upstream to 23.8 ppt at the DRPP channel habitat.

Fish Counts

In total, 97% of fish netted were juvenile salmonids. The remaining 3% (*n* = 186) included sculpin *Cottus* spp *(n* = 8), shiner perch *Cymatogaster aggregata* (*n* = 6), starry flounder *Platichthys stellatus* (*n* = 9), three-spined stickleback *Gasterosteus aculeatus* (*n* = 146), and suckers *Catostomus* spp. (*n* = 17). Most non-salmonids were netted at the Chinook Wind restored pocket habitat.

Total salmon counts (6062 net, 5603 acoustics) differed among sites but were of the same order of magnitude (Table 1). Most sampled fish were salmon (net = 97%; acoustics = 93%), and most netted salmon were chum (*n* = 5930). The remaining netted salmon consisted of wild Chinook (*n* = 103), hatchery Chinook (*n* = 26), and coho (*n* = 3). Juvenile salmon were present at all sites and in both habitat types (Figure 7).

By site, net catches included 508 at Chinook Wind, 528 at Riverton, and 5026 caught at DRPP. Acoustic salmon identifications paralleled those caught in net samples: 244 at Chinook Wind, 649 at Riverton, and 4710 at DRPP. By habitat, net salmon catches were larger in interior pockets (3175), compared to channel sites (2887). In comparison, acoustic channel salmon identifications (3665) exceeded those at interior pocket habitats (1938). Net sampling counts were higher than acoustic counts at Chinook Wind and DRPP. After reviewing acoustic footage, we found no visual association of juvenile salmon with large, woody debris.

Chinook

Overall, we netted 103 wild and 26 hatchery Chinook. Wild Chinook were present in all months and in all restored pocket habitats (Figures 8 & 9). Mann Whitney and Kruskal-Wallis tests analyzing wild Chinook salmon count differences between habitat types and among sites found no statistical difference in Chinook counts between habitat types ($p = 0.72$) or among sites (chi-square = 3.7, $p = 0.16$) (Figure 10).

Wild Chinook appeared to be more temporally consistent throughout pocket habitats than the channel, and overall fork lengths increased throughout the season. We netted more wild Chinook in the pocket habitats, and more hatchery Chinook in the channel. Specifically, greater numbers of wild Chinook were netted in the restored pockets than in the channel at Chinook Wind and Riverton, while the lowest counts of wild Chinook were in the DRPP pocket.

The highest wild Chinook counts occurred at the Chinook Wind pocket, due to a fry school (n = 24) that conflated overall counts. However, Chinook Wind also appeared to have the greatest size range throughout the season. We sampled one yearling hatchery Chinook (fork length = 135 mm) in the Riverton pocket.

All Salmon

Final generalized linear models for all salmon incorporated site, habitat type, and water volume sampled by netting (Table 2). Net and acoustic count data followed negative binomial distributions with separate tests indicating zero-inflation for net sampling only. Site and habitat type did not have interactive effects.

Of the three sites, DRPP had the highest estimated marginal means for salmon counts for both sampling methods (net: EMM = 4.93 (counts), acoustics: EMM = 4.55) (Table 3). For netting, Chinook Wind and Riverton had equal salmon estimates (Chinook Wind EMM = 3.55, Riverton EMM = 3.36), and for acoustics, Chinook Wind (EMM = 2.28) had lower mean estimates than Riverton (EMM = 3.52). By habitat type, analysis of variance did not indicate a difference, but channel habitat had higher marginal mean estimates than pocket for netting (channel EMM = 4.13, pocket EMM = 3.76) and acoustics (channel EMM = 3.97, pocket EMM = 2.93). To correlate our work to past efforts (Toft & Cordell 2017, King County 2019), we re-ran net models to test density (counts/surface area) as a response variable. Density models also demonstrated no significant difference between habitat types and among sites.

Duwamish Gardens

Although not in the original study design, we acoustic-sampled the interior pocket and adjacent channel at Duwamish Gardens, restored in 2016, each time we sampled the Chinook Wind and Riverton sites. Duwamish Gardens was the only site that had more salmon in the interior pocket than in the adjacent channel (Figure 11) (pocket n = 506, channel n = 75). We attribute this observation to the fact that this site has established vegetation and is in close proximity to the mainstem channel. We net sampled at Duwamish Gardens once in March, April, and May, and captured three species of salmon (chum n = 3861, wild Chinook n = 12, coho n = 1) in the established pocket habitat.

Discussion

Our objective was to investigate juvenile Chinook salmon use of newly restored shallow habitats in the Duwamish transition zone to help advance WRIA 9 Chinook recovery efforts and inform restoration strategies. Specifically, we quantified occurrence of wild Chinook and other salmon between habitat types and among sites, if salmon used woody debris in restored interior habitats, and how net and acoustic technologies could be used to sample estuarine environments.

Salmon distributions

Habitat types

There was no statistical difference in juvenile salmon counts between channel and pocket habitats. Equal dispersion between habitat types may indicate juvenile salmon access restored interior habitats similar to the mainstem. Due to the sites' new construction, undeveloped vegetative and benthic invertebrate communities, and partial spatial and temporal fish access restrictions, we did not expect higher salmon counts in the interior pocket habitats than in the channel. We expect juvenile salmon usage to increase as sites become established. Restoring more and larger low-elevation off-channel sites will benefit juvenile salmon (Simenstad & Cordell 2000, Toft & Cordell 2017, King County 2019). Diet studies will broaden our understanding if and how juvenile salmon foraging behaviors within interior habitats is nutritionally advantageous.

Our channel transects were located adjacent to the restored sites, which may increase salmon use due to the proximity of restored habitat. Channel habitat adjacent to restored sites is also often partially or fully revegetated, as was the case for our locations. We recommend habitat use studies that include channel transects along restored and unrestored habitats. Restorative actions in the lower mainstem channel may be useful in addition to off-channel habitat restoration, as salmon migrate through the estuary more quickly than they do upstream (Ruggerone 2014).

Sites

Many more juvenile salmon were captured/observed in DRPP than in Chinook Wind or Riverton sites (Table 1), possibly due to its location further downstream or fish pooling at the edge of the pocket habitat. Most juvenile salmon at the shallower DRPP were chum, which use shallow habitats more extensively than Chinook (Fresh 2006).

We netted most wild Chinook at the Chinook Wind pocket, including a larger group of fry (n = 24) early in the season. Because we sampled few overall Chinook, we cannot state that Chinook Wind is preferred habitat. There is natural variation in fish sampling, so increasing the number of samples will increase the statistical power of the sample and potentially reduce variation associated with low sample sizes. Chinook Wind also had the most non-salmonid species

(Figure 12). We attribute increased fish diversity and higher Chinook counts to the site being deeper, larger, and more easily accessible to a wider range of fish species.

Despite the Riverton interior pocket nearly emptying at low tide, wild Chinook, one Chinook yearling, and two coho were netted at the habitat during high tide. Acoustic data showed consistent salmon shoals in the interior pocket, which may have included Chinook. Acoustic surveys also showed mid- and late-season salmon shoals outside the mouth of Riverton Creek in the channel. It is unknown if the salmon were exiting the creek due to low water levels, or if the narrow access to the creek was restricting access to the interior habitat.

Netting and Acoustic Comparison

Spatial

Netted salmon counts (*n* = 6062) were higher than verified acoustic identification (*n* = 5603) (Table 1), but the sampling methods yielded similar results. By percent, 97% net caught and 93% acoustically identified fish were salmon (Figure 13). If fish acoustically identified as 'unknown' were scaled to the same proportion of salmon (97%) in net samples (*n* = 293; 5%), given most fish sampled were salmon, then the counts from the two sampling technologies are even more comparable (modified acoustic count: *n* = 5896; 98% salmon).

Net counts were higher at Chinook Wind than acoustic counts, especially in the interior habitat (Table 1). We attribute the difference to sample timing. Acoustic sampling occurred before net sampling at the highest tide, due to a restricted time window to sample Riverton (too high of water levels restricted access under the Riverton bridge; too low drained the interior habitat), which was located across the channel from Chinook Wind. Therefore, Chinook Wind was fully inundated in shallow habitats blocked to acoustic sampling by goose exclusion fencing around much of the perimeter. By the time the Chinook Wind site was net sampled, the water level had dropped enough that most fish were forced into the main pocket habitat where net sampling occurred.

Acoustic counts were higher than net counts in Riverton Creek and in the DRPP channel. Riverton Creek is narrow and challenging to effectively net sample, yet not difficult to acoustic sample. It is also easy to kayak in the channel along the edge of the DRPP pocket just off the habitat ledge, where it is too deep to pole seine. We note again that most fish were either in the pocket opening at DRPP, or on the edge of the channel at the opening, so despite constraints among sampling gears, collective counts reflect fish that were in the same vicinity and there is no one sampling gear that is suitable for all locations and times.

Acoustic sampling is an asset to Duwamish juvenile salmon research. Most of the fish in the system are juvenile salmon, so identification to genus is straightforward and the sampling is non-invasive. The Duwamish River system is turbid and contains obstacles and debris (e.g., relic barbed wire fencing, woody debris) that can be challenging for visual counts and net sampling. We were unable to net sample on the mainstem channel adjacent to the mouth of Riverton Creek due to submerged logs, so a secondary location across the channel was sampled. Acoustic sampling also samples larger volumes of water than net or visual surveys, which increases the magnification factor of area/volume sampling to total domain (i.e., the area/volume represented by each sample). Acoustic sampling should always be conducted in conjunction with net sampling if species identification, length measurements, and knowledge of natal origin are objectives of the study.

Temporal

Temporal differences occurred between net and acoustic samples. We minimized time between acoustic and net sampling as much as possible, but we observed that salmon shoals sometimes moved after disturbance or tidal changes over short (less than one hour) time intervals. By month, net counts were higher than acoustic counts in March, April, and May (Table 1). The March/April differences occurred predominantly in the DRPP interior pocket. Both sampling methods detected more fish at DRPP during those months, but nets counts were higher. Net catches in May were primarily from DRPP, while acoustic salmon counts in that period had more spatial variation. Sampling mobile species (e.g., fish) is variable in time and space, so temporally indexed sampling can quantify variability and more extensive sampling can increase analytical power.

Interior Habitat Access

It is important to juvenile salmonids that interior restored habitats are accessible for extended periods through the tidal cycle if the restoration goal is increasing juvenile salmon use of shallow water habitat. The higher-elevated DRPP was created as high marsh habitat to produce salmon prey but is also categorized as high-priority salmon habitat. Incorporating United States Geological Survey gage height, where a monitoring instrument is located near DRPP, we calculated the proportion of time the site would have been inundated during February through June, key 2023 juvenile salmon migration months (Figure 14). Water levels at this site were rarely high enough to be well inundated for salmon habitat (+10 feet), and salmon congregated at the deepest part of the habitat (i.e., the opening). More low elevation sites along the Lower Green and Duwamish Rivers will enable juvenile salmon to reside for longer periods than a partial tidal cycle, and we predict that increased residence time will increase marine survival probabilities.

Juvenile salmon access to interior habitats is likely restricted by relic debris, installed fencing, and the size of the habitat opening. Relic barbwire fencing and its accumulated debris in Riverton pocket was likely restrictive to juvenile salmon entrance. Logs, trees, and relic fencing also prohibited net sampling in the channel adjacent to the opening of Riverton Creek. Installed goose exclusion fencing at DRPP potentially deterred juvenile salmon from accessing the pocket (Figure 4). If restored habitat access for juvenile salmon is a priority for DRPP, then we recommend a study that assesses juvenile salmon access to the DRPP pocket habitat while the fence remains in place. Goose exclusion around the perimeter of Chinook Wind may also have excluded juvenile salmon, so we recommend removing the fencing once vegetation is established. Goose exclusion can also be accomplished using aerial exclusions (e.g., posts with radial webbing) that will limit access.

Logs

We did not find an association between salmon counts and large, woody debris during our daytime surveys. There were several large, anchored logs at Chinook Wind whose vicinity we acoustically sampled but there were few fish directly associated with the logs. The logs placed in Riverton Creek and the pocket did not seem to impede salmon access, nor did they appear to attract salmon. We also did not identify salmon usage of logs at DRPP. In the future, we recommend overwater surveys, possibly by drones equipped with optical cameras, to identify potential associations of logs and juvenile salmon.

Summary

The most recent Duwamish restoration projects have demonstrated that juvenile Chinook and other fish are accessing restored pocket habitats. Wild Chinook were sampled in all interior pocket habitat sites and in all sampled months during the study. Juvenile salmon were also present in statistically equal quantities between the channel and the interior pockets. Juvenile salmon counts were highest at DRPP, and most of the salmon were chum. Most wild Chinook were sampled at Chinook Wind.

Additional low elevation restoration sites with ample access in the Lower Green River and the Lower Duwamish estuary will increase shallow-water habitat for juvenile salmon, potentially increasing growth, estuary survival (Carey et al. 2017, King County 2022), and first marine year survival (Magnusson & Hilborn 2003). When considering site restoration locations for juvenile salmon habitat, we recommend reducing natural and artificial barriers to site access, and choosing sites that maximize the time that a site will be inundated during key migration time periods. This approach will maximize site access.

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Figures

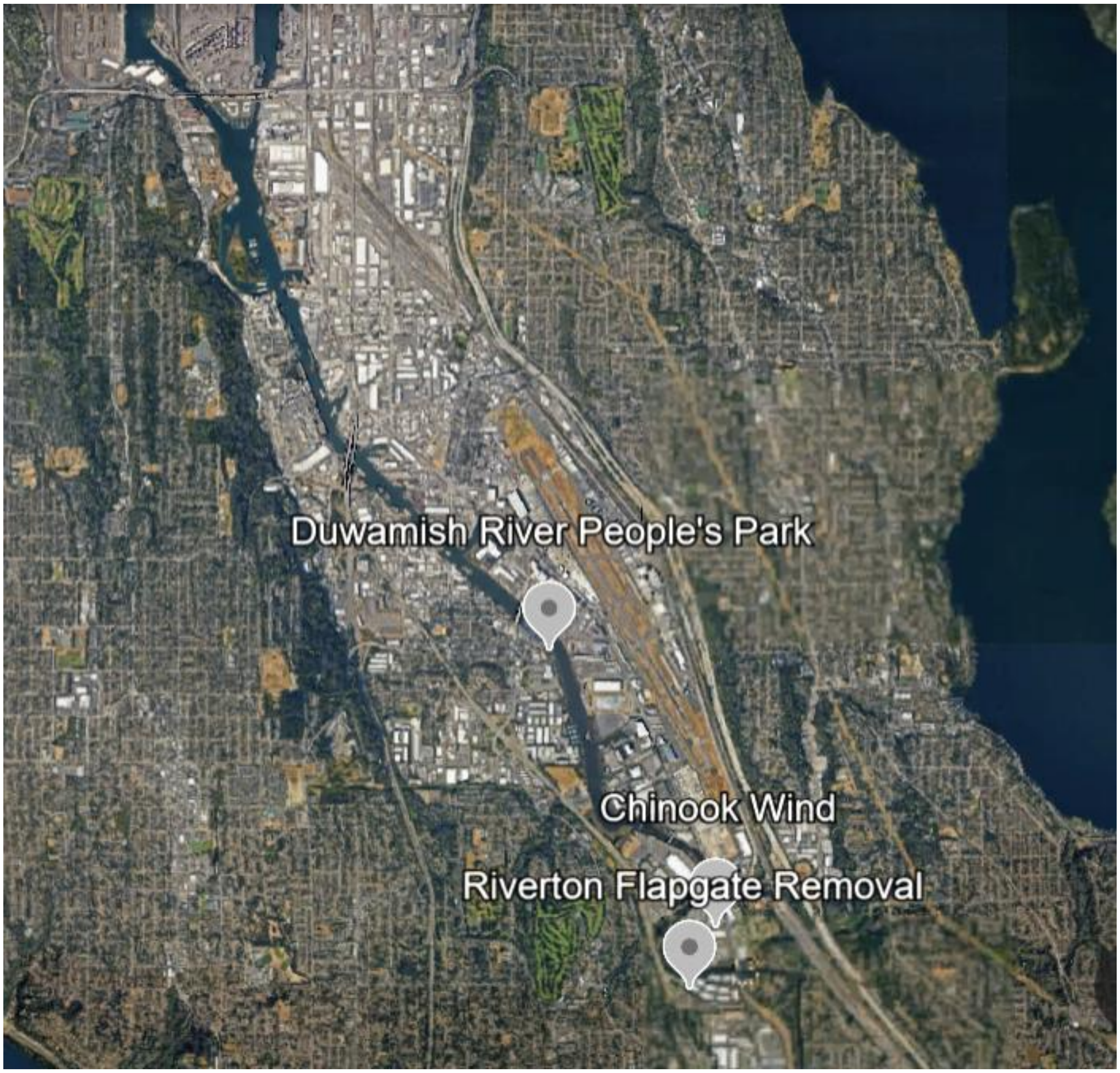

Figure 1: Map of the Lower Duwamish estuary, with the East and West Duwamish waterway at the northern edge of the map. The three restored habitat sites for this project are Duwamish River People's Park (RM 4.5), Riverton Flapgate Removal Project (RM 6.7), and Chinook Wind (RM 6.7). The sites are labelled in white. Google Earth, earth.google.com/web/

Figure 2: Chinook Wind restoration site, located at River Mile 6.7, pictured at low tide. The former site of a hotel, Chinook Wind restoration was completed in 2022. The buildings and asphalt were removed, the soil was decontaminated, and thousands of plantings were installed, resulting in 4 acres of aquatic, wetland, and riparian habitat. Photo credit: King County.

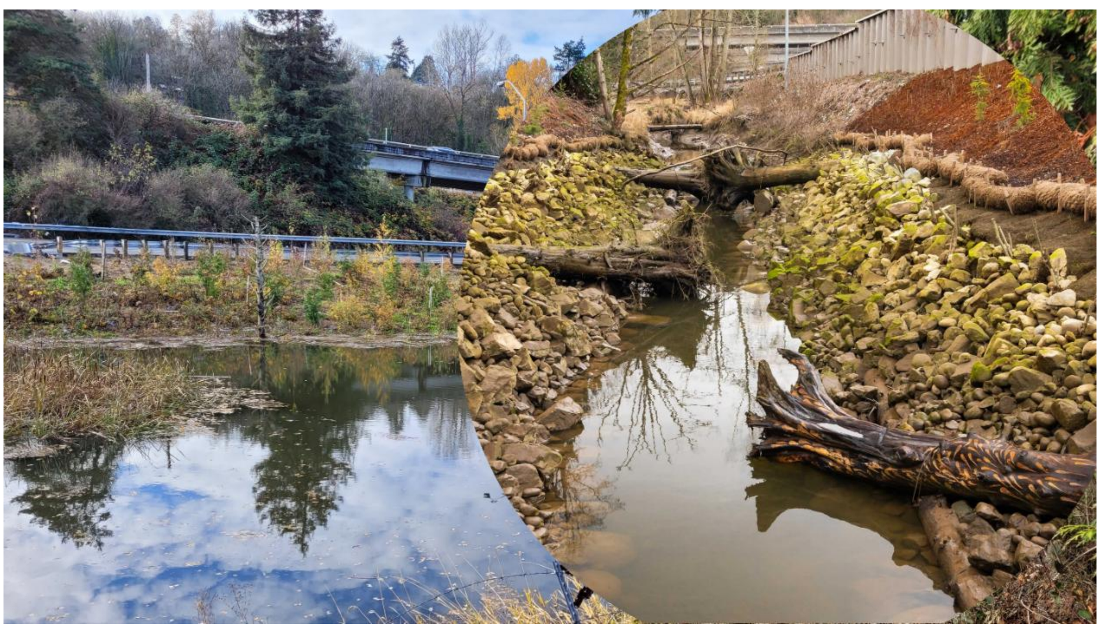

Figure 3: Riverton flapgate removal restoration site, located across the channel from Chinook Wind, at River Mile 6.7. Completed in 2022, including removal of culverts and flapgates, the connection between Riverton Creek and the Duwamish estuary was restored. Left: interior shallow-water habitat connecting to Riverton Creek. Right: Riverton Creek at low tide, connected to the lower Duwamish estuary. Photo credit: right – City of Tukwila.

Figure 4: Duwamish River People's Park at River Mile 4.5. Completed in 2022, 14 acres of marsh habitat were restored. The site was designated an "early action" superfund site by the Environmental Protection Agency. Soil was decontaminated and backfilled, hazardous materials were removed, and thousands of vegetative plantings installed. The site is inundated at higher high tides. Photo shows site at low tide, with the mainstem channel on the left, goose exclusion fencing, and the restored pocket habitat on the right.

Figure 5: Net sampling using river seine (left), pole seine (center), and (right) counting and measuring fish and identifying juvenile salmon origin via checks for adipose fin, passive integrated transponder tags, and coded wire tags.

Figure 6: Left: Schematic of a dual-frequency identification sonar (DIDSON) camera mounted to a kayak hull, ensonifying the water at a −12° angle and continuously sampling a 5 m range starting at 1 m in front of the kayak to a maximum distance of 6 m in front of the kayak. Right: acoustic still footage of a juvenile salmon shoal at Riverton pocket habitat.

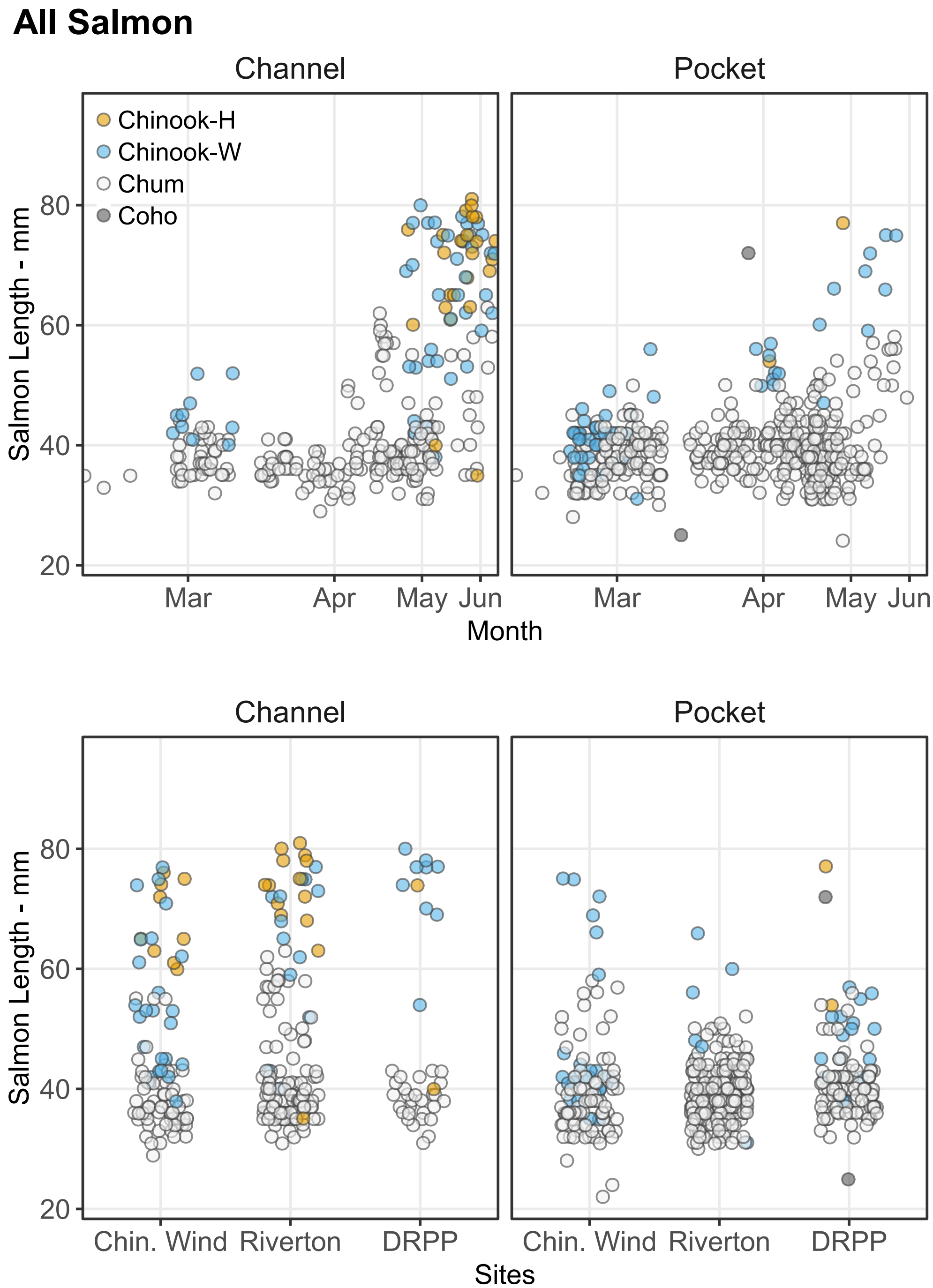

Figure 7: Net sampling dotplots depicting 2023 temporal (February – June; top), and spatial (among sites; bottom) juvenile salmon distributions, organized by fish fork length (y-axis). Dotplots include hatchery Chinook (Chinook-H), wild Chinook (Chinook-W), chum, and coho, and dots are color-sorted by species and natal origin (for Chinook). Each dot represents an individual salmon. Not plotted is a yearling hatchery Chinook (135 mm fork length) at Riverton pocket habitat.

Chinook

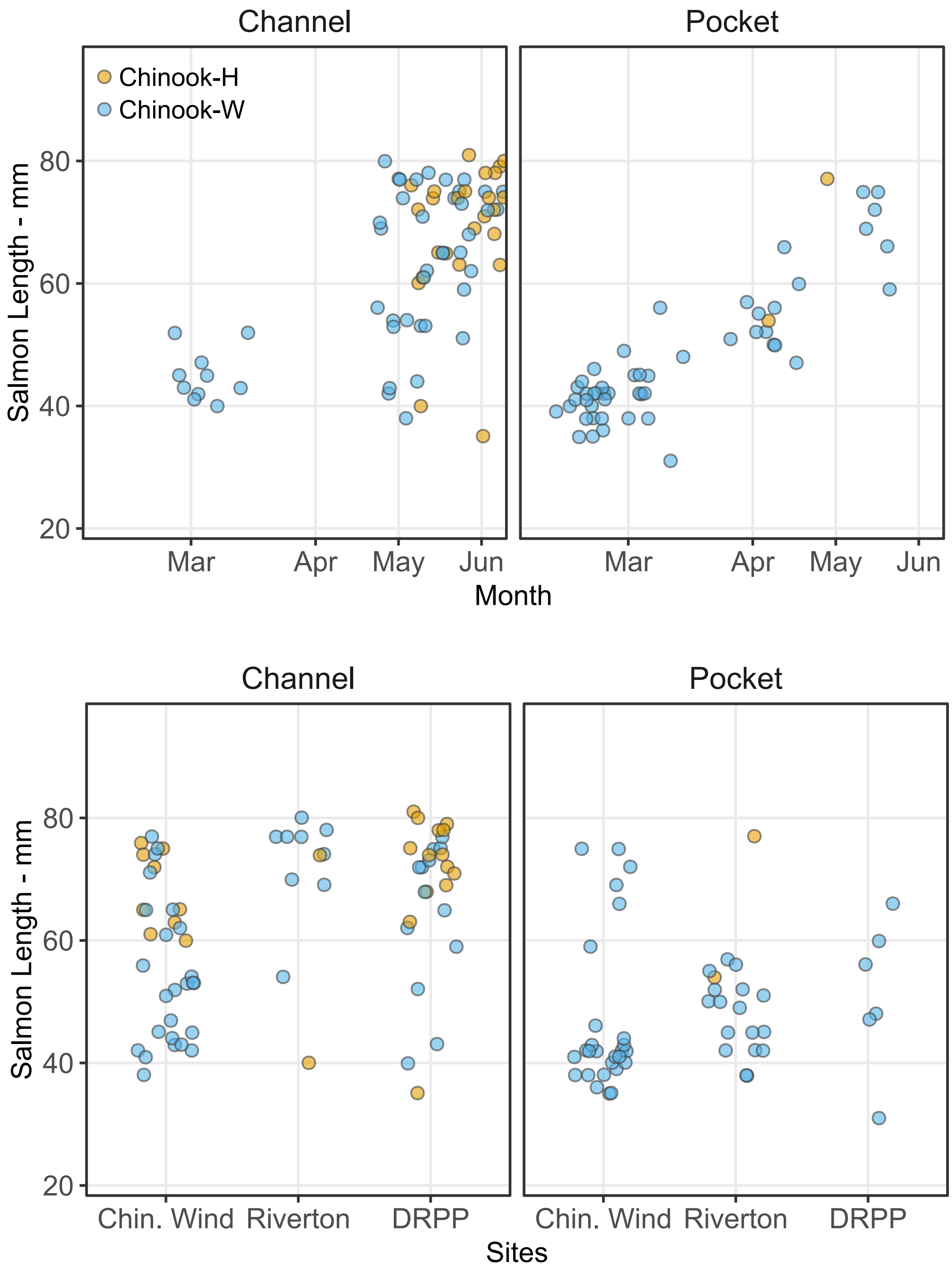

Figure 8: Net sampling dotplots depicting 2023 temporal (February – June; top) and spatial (among sites; bottom) Chinook distributions, organized by fish fork length (y-axis). Dotplots include hatchery Chinook (Chinook-H) and wild Chinook (Chinook-W), and dots are color-sorted by natal origin. Each dot represents an individual Chinook salmon. Not plotted is a yearling hatchery Chinook (135 mm fork length) at Riverton pocket habitat.

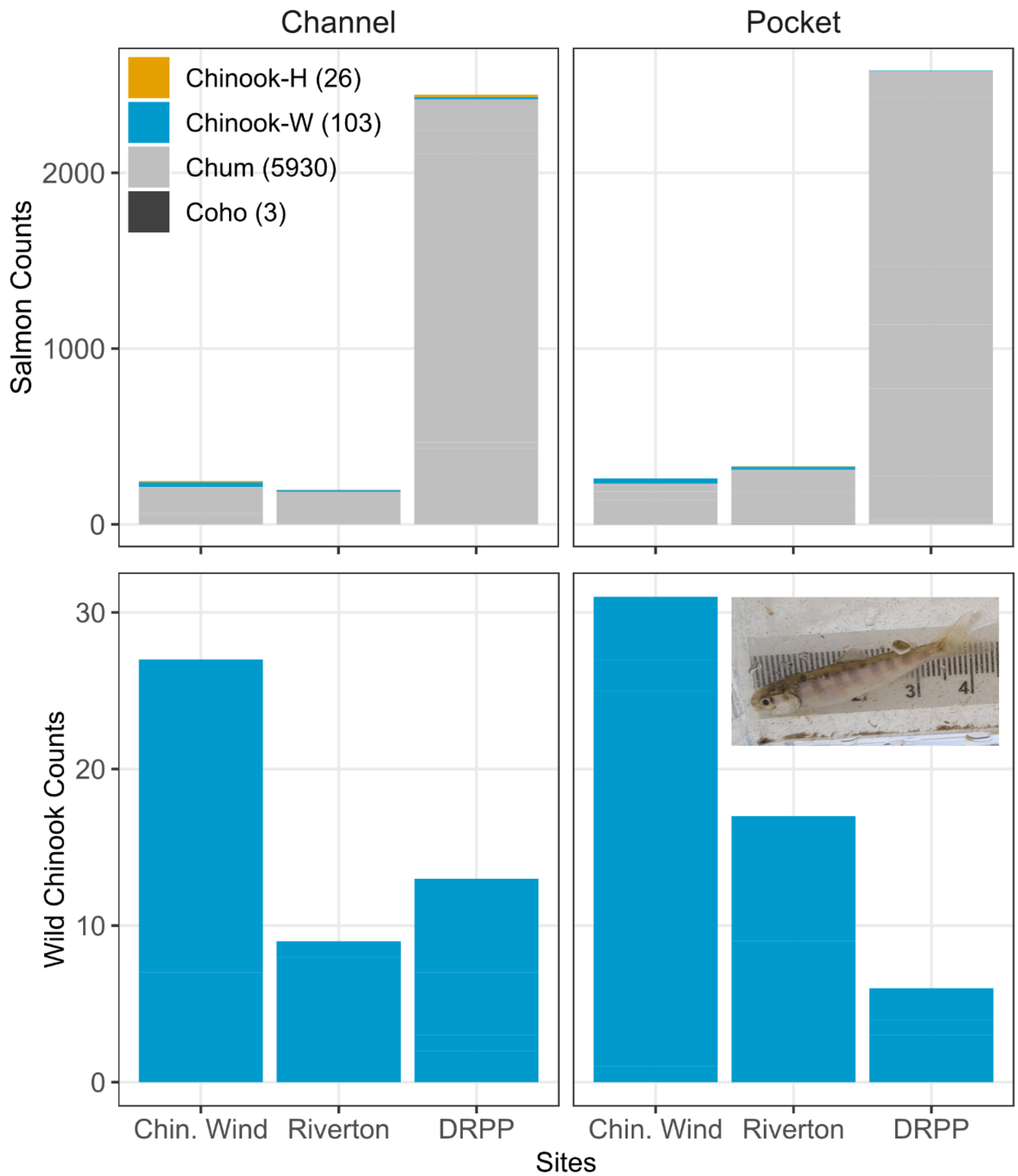

Figure 9: Barplots of 2023 juvenile salmon net counts for hatchery Chinook (Chinook-H), wild Chinook (Chinook-W), chum, and coho. Count plots are sorted by habitat types (channel, pocket) and among sites (Chinook Wind, Riverton, DRPP). Overall juvenile salmon counts (top) are color-sorted by species and natal origin (for Chinook). Bottom plot is wild Chinook-only.

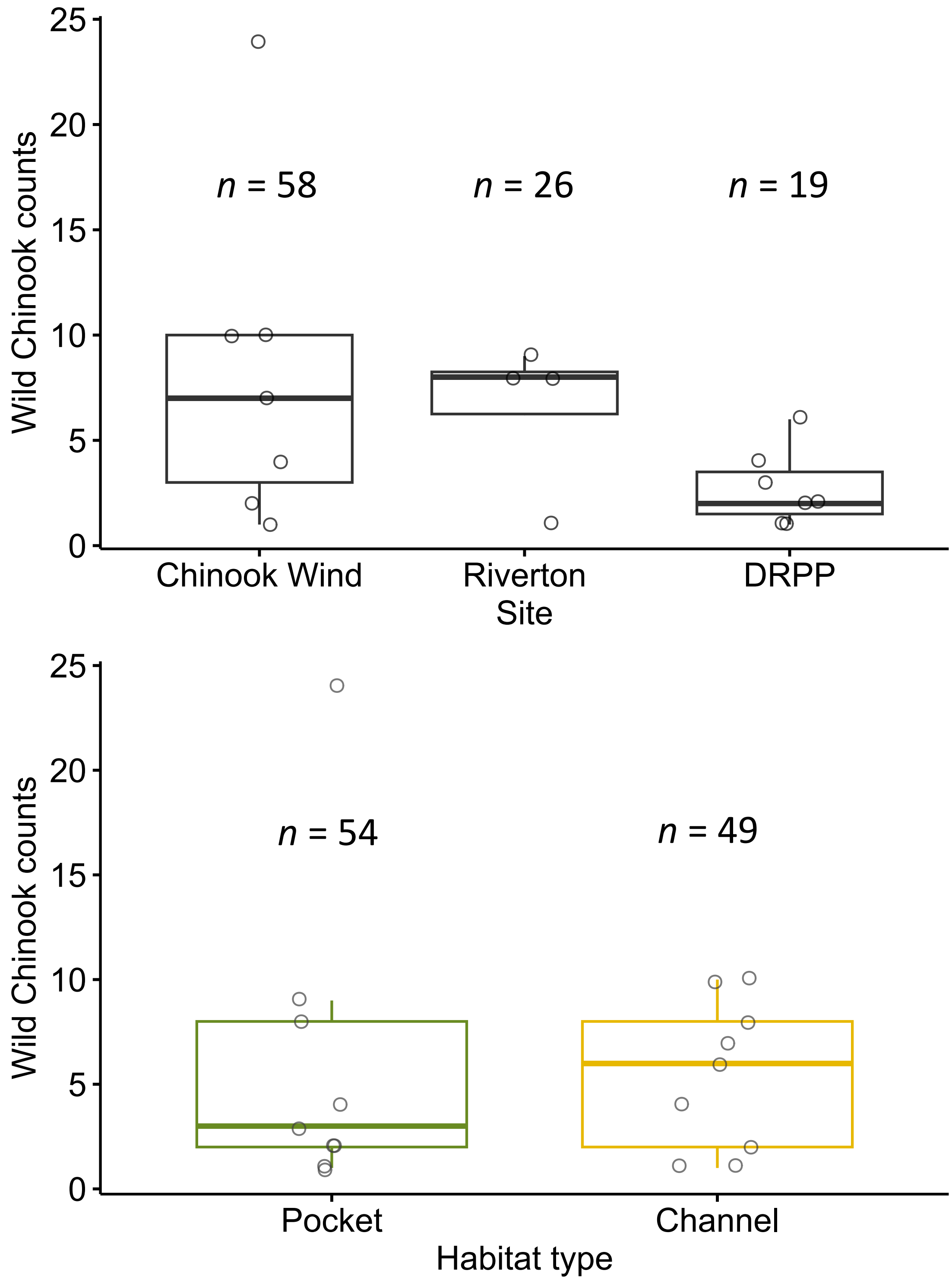

Figure 10: Boxplots of 2023 wild Chinook net sampling counts. Boxplots are sorted by site (top) and habitat type (bottom). Total wild Chinook counts are summed by site and habitat type.

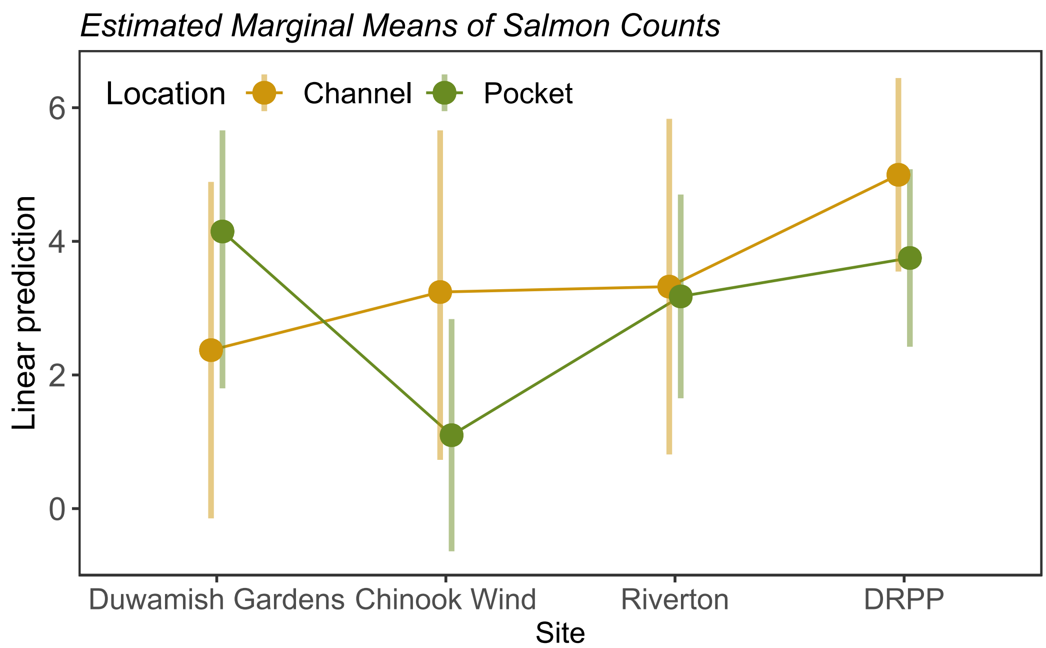

Figure 11: Interactive marginal means from a generalized linear mixed model, plotted by site, for both levels of habitat type. Plots are color-sorted by habitat type and present linear predictions of acoustic salmon abundances.

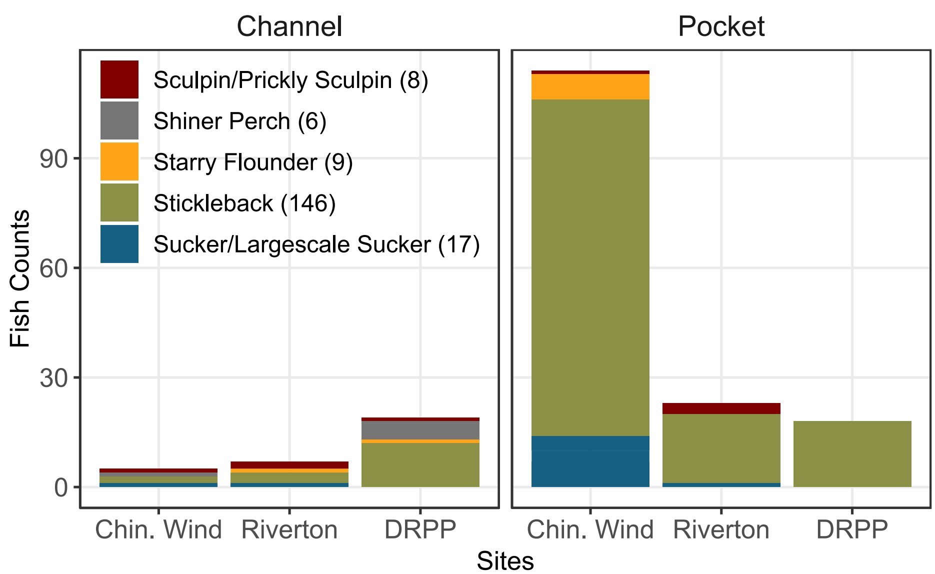

Figure 12: Barplots of 2023 non-salmonid net fish counts, including sculpin, shiner perch, starry flounder, three-spined stickleback, and suckers. Count plots are sorted by habitat type (channel, pocket) and among sites (Chinook Wind, Riverton, DRPP), and are color-sorted by genus or species.

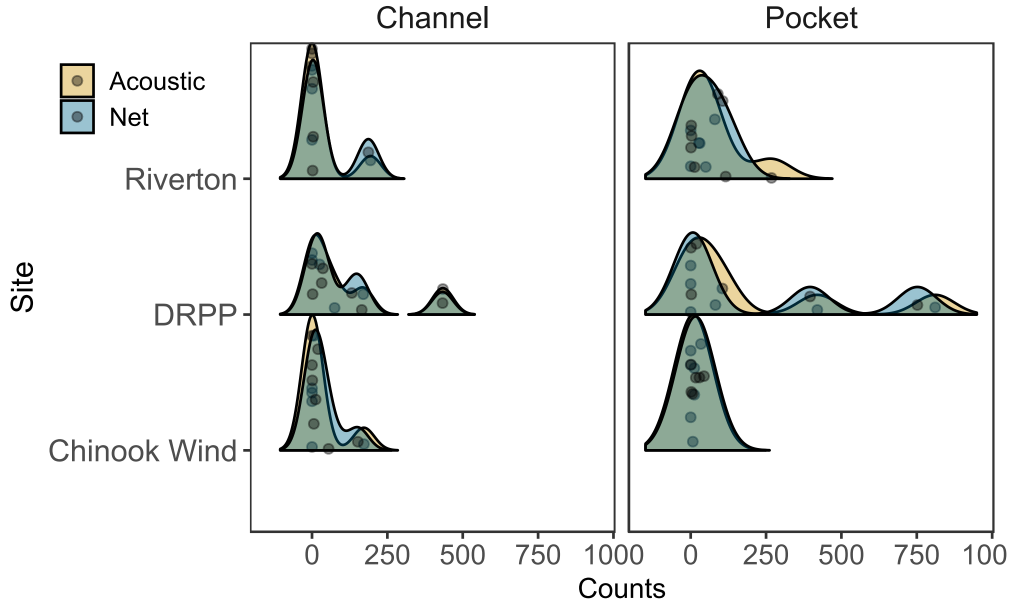

Figure 13: Density ridge plots that depict the overlapping distributions of salmon counts among the three sites, by habitat type. Plots are sorted by site and are color-sorted by sampling method (acoustics = yellow, net = blue, overlapping distributions = green). Each dot represents summed salmon counts for all samples at the habitat type and site for a single date. Two net and one acoustic count sums greater than n = 1000 are not plotted.

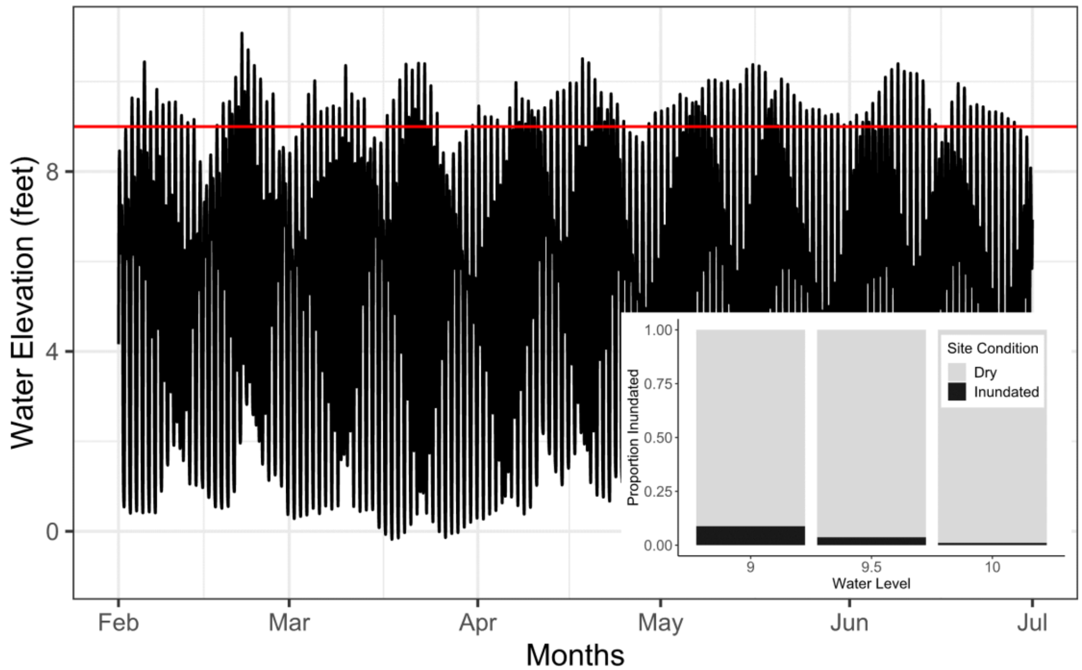

Figure 14: Main plot: Line plot showing gage height, i.e., the elevation of the water surface at the gaging station (located at RM 10.4) through mixed semidiurnal tidal cycles for February – June 2023. Above the red line, located at 9 feet, DRPP was partially inundated in the interior habitat. Inset plot: The proportion of the 2023 primary migration period (February – June) in which DRPP was above 9 feet, 9.5 feet, and 10 feet of water. +10 feet at the DRPP pocket is necessary for most of the DRPP pocket to be inundated with shallow water. Stacked bar plots are color-sorted by proportion of time the pocket was sufficiently inundated for salmon residence at each tidal height (black) or not sufficiently inundated (gray).

Tables

Table 1: Juvenile salmon counts by site and habitat type, and by month, for each sampling method (netting and acoustics). Counts include chum, Chinook, and coho salmon, but were predominantly (97%) chum.

	Chinook Wind		Riverton		DRPP	
Juvenile salmon counts	Pocket	Channel	Pocket	Channel	Pocket	Channel
Net	262	246	331	197	2582	2444
Acoustic	65	179	455	194	1418	3292
	February	March	April	May	June	SUM
Net	10	1573	2443	1958	78	6062
Acoustic	0	279	633	1231	3460	5603

Table 2: Generalized linear model summaries, including incidence rate ratios (logged quotient of the difference of expected counts), standard errors (SE), and p-values (highlighted in bold when p ≤ 0.05). Intercepts identify the reference categorical variable for Site and Habitat Type. Habitat and Site incidence rate ratios are compared only to reference variables and a ratio of 1 indicates group incidence rates are equal. Net sampling models account for water volume sampled that was dependent on net type, set efficiency, and water depth.

	Net Counts			**Acoustic Counts**		
Predictors	*Incidence Rate Ratios*	*SE*	*P*	*Incidence Rate Ratios*	*SE*	*p*
(Intercept) Location: Channel, Site: Chinook Wind	23.85	12.23	<0.001	16.50	14.30	0.001
Location: Pocket	0.69	0.32	0.430	0.35	0.28	0.196
Site: Riverton	0.82	0.48	0.741	3.45	3.72	0.252
Site: DRPP	3.96	2.31	**0.018**	9.61	8.94	**0.015**
Volume	0.63	0.13	0.027			

Table 3: Post-hoc tests estimating the marginal means (EMM) of salmon count predictions from generalized linear models for all factor combinations of Site and Habitat Type. Output includes chi-square EMM values, standard errors, and lower and upper confidence levels.

Estimated Marginal Means (EMM) for Juvenile Salmon Abundances								
		Net				**Acoustic**		
Site	*EMM*	*Standard Error*	*Conf Level-L*	*Conf Level-U*	*EMM*	*Standard Error*	*Conf Level-L*	*Conf Level-U*
Chinook Wind	3.55	0.59	2.39	4.72	2.28	0.77	0.78	3.79
Riverton	3.36	0.51	2.36	4.36	3.52	0.76	2.03	5.02
DRPP	4.93	0.35	4.24	5.62	4.55	0.53	3.51	5.58
Habitat type								
Pocket	3.76	0.36	3.05	4.48	2.93	0.48	1.98	3.88
Channel	4.13	0.50	3.14	5.12	3.97	0.64	2.71	5.23