Squamish Estuary Fisheries Monitoring Program Summary

2023-2024 Funding Year

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2. Introduction

The Squamish Estuary is a highly altered ecosystem at the landward terminus of Howe Sound, a narrow glacial fjord. Development and widespread logging have caused habitat loss, leaving the remaining estuarine floodplain fragmented and degraded (Figure 1). Prior to these developments, the Squamish Estuary was part of a productive salmon-bearing watershed, but as with many areas in British Columbia, salmon populations are currently depressed relative to historic levels (Wada and Sander 2005). For over 40 years the Squamish River Watershed Society (SRWS), Squamish Nation, Fisheries and Oceans Canada, and the Province of British Columbia have been restoring habitat in the Squamish River Watershed. The most recent iteration of these efforts is the Central Estuary Restoration Project (CERP), through which these project partners have been working to increase the exchange of water between the Squamish River and the rest of the estuarine floodplain, with a focus on improving water quality and estuary access for juvenile salmonids.

In the 1960s and 1970s, Squamish was identified as an important area for industrial development. Several large developments had been completed or were underway in the area such as the Squamish Terminals, and the FMC (fertilizer, machinery, chemicals) Chlorine-Alkali plant (Hoos and Vold 1975). At the time, the town was the southern terminus of the British Columbia Railway (BC Rail) and identified as a potential port for shipping of raw materials. In preparation to install a rail line, a 5 km berm was constructed by BC Rail in the early 1970s to constrain the Squamish River to its West bank and facilitate a proposed coal port (Figure 1,right panel; Hoos and Vold 1975; Levy and Levings 1978). However, during this period societal understanding of the importance of estuaries to the productivity of fisheries resources was rapidly expanding. In 1972, the then federal Department of the Environment, recognized a need for environmental impact studies prior to development of the port and suspended the ports authorization. Following the completion of environmental impact studies in 1972 and 1973, the federal government subsequently refused to authorize the coal port development due to the likelihood of serious environmental impacts to the Squamish River and estuary (Hoos and Vold 1975; Levy and Levings 1978). However, there was no requirement for BC Rail to remove the pre-constructed berm. The abandoned berm now serves to provide access to the estuary and Squamish River for multiple recreational interests. The most northern kilometer of the berm may also provide limited flood protection to the town of Squamish (Environmental Stewardship Division. Lower Mainland

Region 2007). This berm fragments estuarine habitat, preventing water and fish from passing between the Squamish River and its estuary.

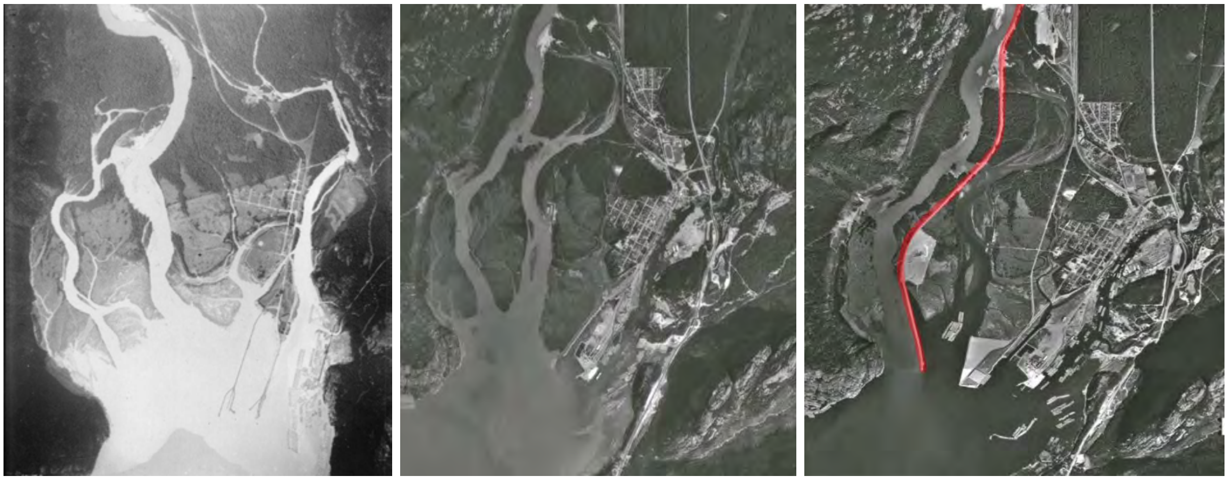


Figure 1 Aeiral images showing development in the Squamish Estuary since the 1950's. From left to right year 1930, 1969, and 1973. The berm, highlighted in red, keeps the Squamish River on the West side of the valley. Imagery obtained from ("Aerial Photographs - Squamish History Archives" 2015).

The berm in the Squamish Estuary was identified by the CERP partners as a limiting factor to the recovery of Squamish River Chinook Salmon populations. Estuaries are theorized to act as valuable stopover habitat for juvenile Chinook Salmon, providing a brackish environment that reduces the energy demands of osmoregulation (Webster and Dill 2006). Estuaries also provide shelter from predators (Bottom et al. 2005), and opportunities for growth (Moore et al. 2016). Juvenile Chinook Salmon express a continuum of migrant strategies that vary in emigration timing, and estuarine residence duration (Volk et al. 2010; Bourret et al. 2016). During their migration, yearling and sub-yearling Chinook Salmon have been found to stopover in estuary environments for a few days to over a month (Volk et al. 2010; Moore et al. 2016; Lingard et al. 2023). A recent study by Lingard et al. (2023) demonstrated that large sub-yearlings (> 70 mm) spend 1 to 43 days in the Squamish River Watershed's estuarine environment to the East of the berm when released at the northernmost reaches of the estuary. However, smaller sub-yearlings are thought to have longer stopover (ie. residence) durations and the greatest reliance on the estuary. During stopover they are able to reach the size needed to feed on fish in marine waters by consuming the abundant insects and invertebrates present in these productive floodplains (Weitkamp et al. 2014; Duffy and Beauchamp 2011; Chalifour et al. 2021).

Efforts have been made by the SRWS and their partners to restore aquatic habitat connectivity between the Squamish River and the Squamish Estuary since the 1990s using a variety of techniques. In the late 1990s and early 2000s, corrugated metal culverts (<= 1.2 m diameter) were installed at nine locations in the berm (Figure 2; Lingard et al. 2018). These structures passed water, but failed to provide adequate fish passage (Lingard et al. 2018). Monitoring revealed that they become clogged with debris, do not regularly have water flowing through them, and when they do, whirlpools are often created as water is sucked into the culverts at high velocities (Lingard et al. 2018). At two of these locations, metal culverts were replaced with three-meter concrete box culverts in 2019 and 2020 (Figure 2). The passage of juvenile Chinook Salmon through these box culverts was evaluated using acoustic telemetry between 2019 and 2021. Results revealed that an average of 76% of tagged fish did not pass to the other side of the berm and of those that did, most travelled around the berm entering via Howe Sound (Cook et al. 2019; Cook and Lingard 2020). To further increase estuary access, the top four meters of the berm (rock, sand, and gravel) was removed from the southernmost 850 m section extending into Howe Sound between 2022 and 2023. The partial opening, (hereafter 'the breach') will allow fish more opportunity to pass the berm and access the Squamish Estuary.

Since 2019, acoustic telemetry has been used to assess if juvenile Chinook Salmon are better able to access the Squamish Estuary through CERP-created water passages in the berm. This report details the results of the 2023 monitoring season and compares them to previous study years. Water quality metrics in the estuary including temperature, dissolved oxygen, and salinity are also reported.

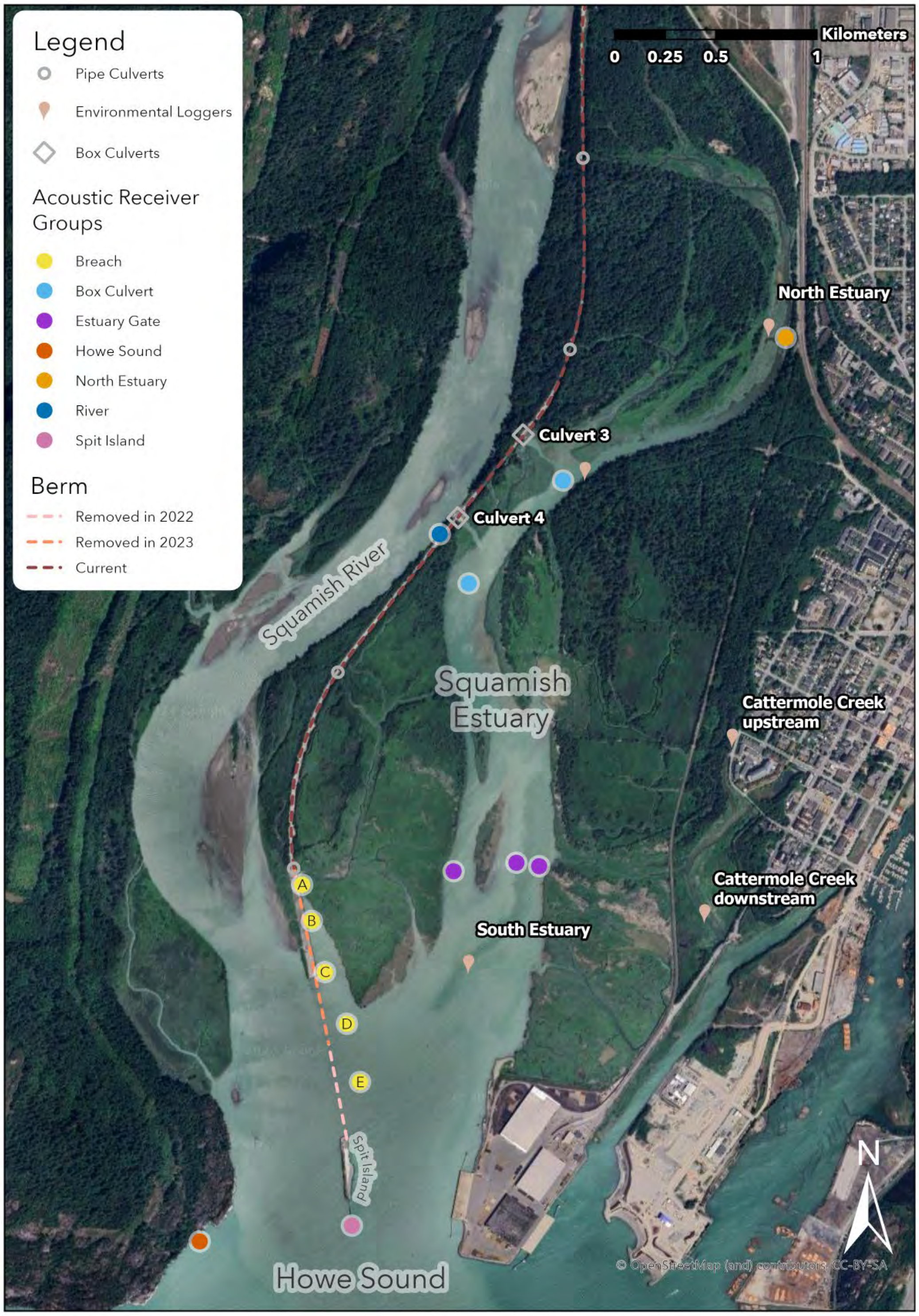


Figure 2 Map of the acoustic receivers and environmental loggers in the Squamish River Watershed. Environmental loggers include dissolved oxygen, salinity, temperature, and depth sensors. Portions of the berm were removed in 2022 and 2023. The tip of the berm was not removed, creating Spit Island. Pipe culverts installed in the late 1990s - early 2000s and box culverts installed in 2019 and 2020 are also shown.

3. Methods

3.1 Study Area

The Squamish River watershed covers an area of 3650 km^2 in the Coastal Mountain range of southern British Columbia and lies within the territory of the Squamish Nation (Wada and Sander 2005). The Squamish River is the largest tributary of Howe Sound with an average discharge of 300 m^3/s (Environment Canada 2023) and has four large tributary watersheds (Mamquam, Cheakamus, Ashlu and Elaho). Populations of nine species of salmon (Chinook, Coho, Chum, Sockeye, and Pink salmon) and trout (Dolly Varden, Cutthroat, Rainbow/Steelhead and Bull trout) exist in the watershed. The Squamish Estuary is oligohaline[1] when the Squamish River is in freshet and there is, in general, limited salt wedge intrusion due to the channelized and high energy nature of the river (Lingard et al. 2023, SRWS unpublished data). Salinities between 0 and 15 ppt dominate through much of the spring and summer, increasing to 15 to 25 ppt during the winter (Tryon and Togado 2020). Out-migrating salmon will not encounter brackish water until they have exited the Squamish River and entered the Squamish Estuary or Howe Sound. Howe Sound is highly influenced by the Squamish River. Surface waters are dominated by oligohaline and mesohaline (5 - 18 ppt) conditions through much of the year (Stockner et al. 1977). Water temperature in the Squamish River and its estuary are typically below 15ºC but some areas of the estuary can reach above 20ºC in summer (Tryon and Togado 2020). Our area of study encompasses the lower ~20 river kilometers of the mainstem Squamish River, the Squamish Estuary, and the entrance to Howe Sound.

3.2 Environmental Data

There are five water quality stations, each including a dissolved oxygen, temperature, depth, and salinity sensor (Innovasea DOT(D) and SAL aquaMeasure sensors; Figure 2). According to product specifications, dissolved oxygen is accurate ± 5 % between 0 – 120 %, temperature ± 0.2 °C between -5 – 35 °C, depth ± 1.5 m up to 100 m, and salinity ± 1 practical salinity unit (PSU; one PSU = one part per thousand) between 0 - 75 PSU. Loggers are deployed in stilling wells

[1] When referring to salinity classifications, we use the Venice Classification (freshwater < 0.5 PSU; oligohaline 0.5 - 5 PSU; mesohaline 5 - 18 PSU; polyhaline 18 - 30 PSU; euhaline > 30 PSU)

with ample openings for water and air exchange. Loggers are hung near the bottom of the water column, with all sensors within ~25 cm of the ground.

The South estuary, Culvert 3, and North estuary stations were installed in late February with the remaining stations installed in early May 2023. Data is summarized to monthly averages for each station through to October 2023. Measurements of each variable were taken every minute to ten minutes and matched with the closest 15 minute tide elevation prediction (Canadian Hydrographic Service 2023) to determine when sensors were underwater. The depth measurements produced by the Innovasea sensors proved to be too imprecise for the needs of this project, therefore, we have discarded this data and filtered out environmental data occurring at Squamish Inner tide elevations < 1.2 m (Canadian Hydrographic Service 2023). This elevation was selected based on observations in the field when downloading the stations. Readings occurring within 15 minutes of cleanings or downloads were removed, as well as when loggers were out for service.

3.3 Fish Capture and Tagging

Over the course of this study (since 2019), we have targeted juvenile Chinook Salmon with fork lengths between 75 and 95 mm because they are expected to be sub-yearlings based on length-based age data from morphometric scale analysis in the watershed (Lingard et al. 2023). While sub-yearlings less than 75 mm in fork length are thought to benefit from estuary access the most, they are not targeted because the tag burden for these small fish exceeds 8%, a threshold above which the risk of tagging associated mortality is increased (Collins et al. 2013). However, the project is ultimately limited to the fish available in the river each year and larger fish are included in the study as needed.

Juvenile Chinook Salmon were captured via beach seine (100' x 13' and 3/8" mesh) and raft in the Squamish River between May 8th and 31st, 2023. Fishing took place between river kilometer 16 and 20 (Figure 3) in the morning (6 am to 12 pm) or evening (6 pm to 11 pm), when juvenile fish are more active (Bradford and Higgins 2001) and easier to catch. Juvenile salmonids were retained, held in a cooler aerated with battery powered pumps, and promptly transferred to dark, covered, open containment pens (120 L) in a calm eddy until tagging. Juvenile salmonids were held for a minimum of 24 hours and a maximum of three days prior to tagging to reduce stress (Jepsen et al. 2001).

Acoustic transmitters (V3D predation transmitters; Innovasea Systems Inc; 4x15.5 mm and 0.33 g in air) were surgically implanted into captured juvenile Chinook Salmon (n = 75). Each tag transmits a unique even ID number upon activation. If a tagged individual is consumed by a predator, a trigger is activated by stomach acid and the tag begins to transmit the subsequent odd number. Prior to surgery, fish were anesthetized with clove oil (35 mg/ L) diluted 1:9 in ethanol, measured for fork length and mass. Implantation of the tags was modeled after Liss et al. 2021. A 3 mm incision was made in the abdomen of the fish just off the linea alba near the tip of the pectoral fin, a tag was inserted, and the incision was closed with a single suture of 5-0 Monocryl (Ethicon, Inc.). Fish were recovered in aerated buckets of river water before being placed back into holding pens for at least 24 hours. Untagged salmonids, including Chinook Salmon too small for tag implantation and other salmonids like Coho Salmon, were also anesthetized, measured, and recovered in the holding pens. All fish were released into the Squamish River close to the main fishing site (Figure 3) in groups comprised of untagged and tagged fish in order to reduce predation pressure on tagged individuals.

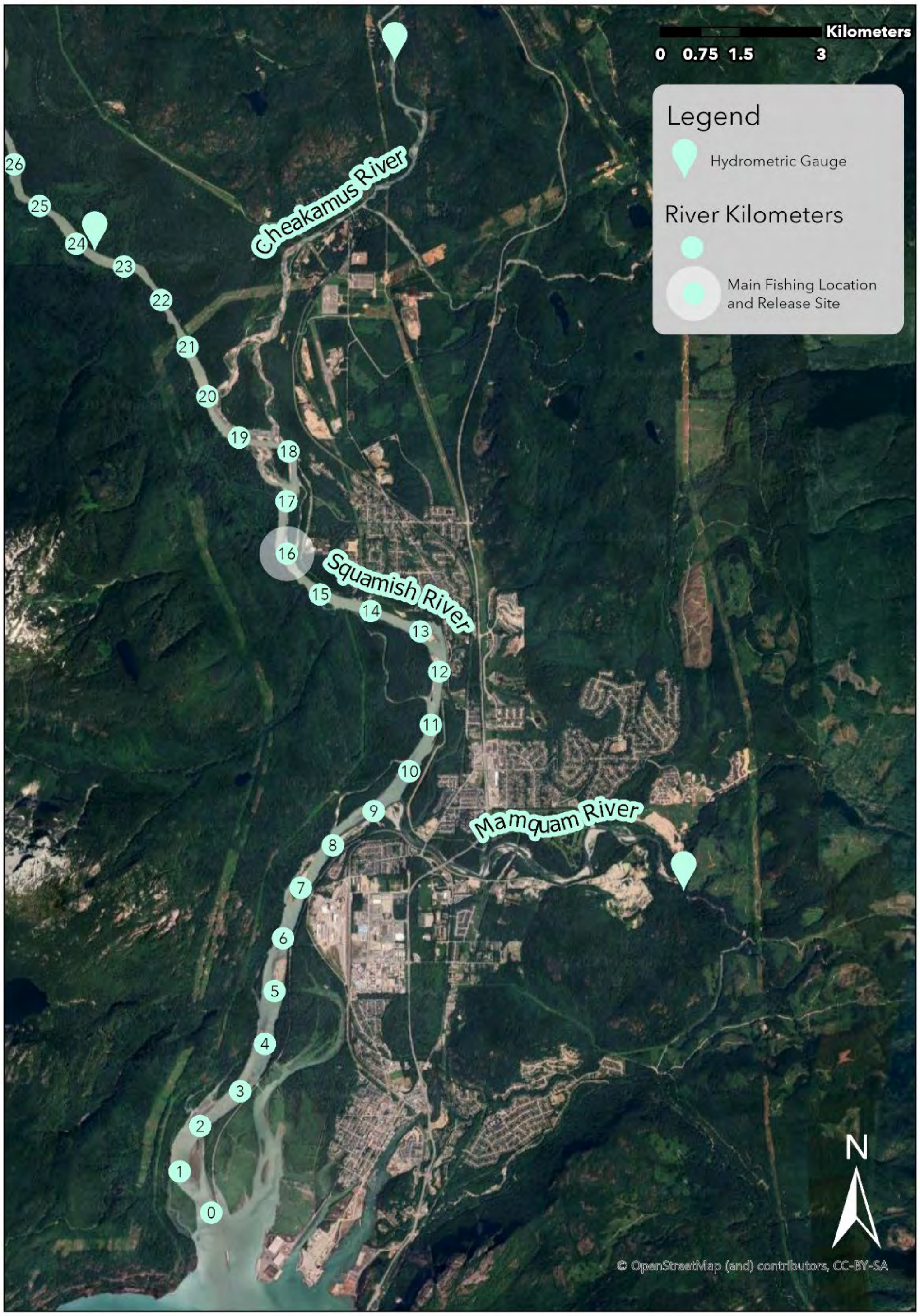


Figure 3 The Squamish River with river kilometers. The main fishing location is shown, but other locations between river kilometers 16 and 20 were also occasionally fished. The Cheakamus and Mamquam Rivers are major tributaries of the Squamish River. With the Squamish River's hydrometric gauge stationed above the Mamquam and Cheakamus River confluence, the hydrograph for all three rivers is summed to calculate the flow exiting the mouth of the Squamish River.

3.4 Acoustic Array Design

Fourteen HR3-307 Hz (Innovasea Systems, Inc.) receivers were strategically deployed between April 11th and May 9th, 2023 to determine emigration pathways taken by tagged individuals (Figure 2). Receivers were placed at the mouth of the box culverts (n = 2), in the Squamish River downstream of the box culverts (n = 1), across the breach (n = 5), in the North estuary (n = 1), at the gate of the estuary (n = 3), and at the mouth of the Squamish River (n = 2; Figure 2). Locations of receivers within the array have been modified annually since first using this technology in 2019 to adapt to the increasing number of CERP-created water passages in the berm. Each group of receivers were positioned to achieve a specific objective in terms of understanding how juvenile Chinook Salmon move from the Squamish River across the berm (including areas of the berm that have been removed) and into Howe Sound.

Deployment methods for receivers were unique to each location. Where receivers were deployed in shallow areas, they were buried in substrate with the hydrophone exposed to allow detection of fish across the range of tide levels experienced (n = 10). In the Squamish River, a receiver was lowered into the water column horizontally down a custom ramp bolted to riprap on river left, 50 m downstream of culvert 4. For a receiver in a deep channel along the estuary gate, a custom anchor held it flush to the substrate and oriented vertically. The Howe Sound receiver was installed vertically using a base anchor dropped to the bottom of the mudflat along the West sea wall approximately 1 km from the mouth of the Squamish River. Finally, a receiver just beyond the South end of Spit Island was encased and attached horizontally to a pilling, pointing into the sound (Figure 2).

The detection range of the receivers has been tested to varying degrees depending on location, with the most robust data available for the North estuary, box culverts, and estuary gate (Figure 2. The available testing data indicates detection range varies from 0 m at low tide (if dewatered or in little water) to 130 m at high tide (radius with receiver at center). Discharge also affects the range of each receiver through its influence on water available at low tide. In most cases, poor detection range at low water levels is unlikely to affect the results of this study because low water also, usually, means limited habitat availability (i.e., de-watered receivers mean the channel monitored by them has too little water to be inhabited by fish). Channel morphology also influences detection range as bends in channels, as well as debris and channel width, affect the ability of tag transmissions to reach the receivers. That is, the range of receivers will be restricted in narrower and more sinuous channels compared to wider straight channels.

Each receiver was placed to meet a certain objective in terms of understanding how juvenile Chinook Salmon use the study area. Based on the range testing data collected to date, we are confident that the North estuary, culvert, and estuary gate receivers are unlikely to miss fish traveling between them (Figure 2). These receivers distinguish if fish pass through the berm using culvert 3, culvert 4, or the northern most pipe culverts. Further testing of the breach receivers is needed to ensure that fish passing through the breach are detected. The Howe Sound and Spit Island receivers were added to the array in 2022 to act as checkpoints, helping to confirm that fish not passing through the berm have survived after release. These receivers are not guaranteed to detect every fish that passes by them because the distance between them exceeds the maximum range of the receivers. Thus, fish can pass by these receivers without being detected by either. Further, the Spit Island receiver was installed so that it would become dewatered and accessible to field crews at low tides. While dewatered, the Squamish River channel is still sufficiently deep to allow fish to exit the river undetected.

The inferences we are able to draw about the migration routes and survival of tagged individuals is limited by the challenge of operating and installing acoustic telemetry equipment in the Squamish River. We initially deployed receivers in our pilot year, 2019, in the Squamish River, but the environmental noise from the rushing water affected the ability of the equipment to detect tag transmissions. We also lost equipment from this region due to high water velocities and a lack of hard structures on which to mount equipment. Thus, we are limited to deploying the array in the Squamish Estuary or along the one hardened bank of the Squamish River. Unfortunately, the width of the river channel is three to five times the maximum detection range of the receivers, therefore we are unable to achieve adequate coverage across the whole width of the river by installing receivers on the hardened eastern bank.

3.5 Acoustic Detection Data Filtering

Raw detections from the receivers were filtered to remove suspected false positive detections and acoustic noise. False detections occur in three ways: (1) multiple tag IDs transmit at the same time interfering with each other and the receiver records a number that is a combination of these transmissions; (2) environmental noise interrupts the transmission of an ID and the receiver records an erroneous or incomplete ID (Simpfendorfer et al. 2015); (3) hard surfaces echo the ID transmission wave, causing duplicate detections on the receiver of the same ID (Kessel et al. 2015). The first two causes of false positives occur because the receiver hears part of a study tag's ID which results in false detections often being similar to tag IDs used in the study. To remove such false detections, we employed two filters. First, only detections matching the IDs of released tags were retained and any detections occurring prior to the release time of a fish were removed. Second, a filter removed any isolated detections (i.e., a single detection of a given tag on a receiver) with no other detections of that ID anywhere else in the study region within one hour. To remove echoes, successive detections of the same ID occurring within less than the minimum burst rate of the tag were removed.

3.6 Fish Movements

3.6.1 Passage Route

There are many water channels fish can use as passage routes from the West to the East side of the berm. The rules detailed in Table 1 are used to classify if fish pass the berm and if so, which route they take. Passage routes are compared across study years where possible.

Due to limitations of the acoustic array, the passage routes taken by some fish are undetermined (Table 1). Fish first detected on the Howe Sound and/or Spit Island receivers and then detected at the breach receivers, have undetermined passage routes. Similarly, we are not able to determine the route of passage taken by fish first detected by the estuary gate. It is possible that these fish passed through (1) the breach or (2) Howe Sound (by swimming around the South end of Spit Island) to get to the East side of the berm. Classifying the above detection sequence as "undetermined" is a methodological difference from 2022. In 2022 these fish would be assumed to have passed through Howe Sound to get to the East side of the berm.

Hatchery Chinook Salmon were tagged exclusively in 2019 and as a subset in 2022 (Table 2). The routes of passage taken by hatchery Chinook Salmon are reported separately given possible differences in life history and habitat use from wild fish.

Table 1 Rules applied to detection histories to determine the route fish used to pass from the Squamish River into the Squamish Estuary on the East side of the berm.

Classification	Passage Route	Detection Sequence
Did not pass berm	NA	Detected on River, Howe Sound, and or Spit Island receiver but never detected on the East side of the berm.
Passed Berm	North Pipe Culverts	First detected by North receiver, with no prior detections.
	Box Culvert 3	First detected by culvert 3 receiver, with no prior detections.
	Box Culvert 4	First detected by culvert 4 receiver, with no prior detections.
	Breach	First detected on the East side of the berm at the breach and not previously detected in Howe Sound.
	Undetermined (Breach or Howe Sound)	Detected on Howe Sound or Spit Island receiver prior to detection at a breach receiver, or detected at estuary gate first.
Mortality	NA	Not detected at all.

3.6.2 Hydrologic Conditions at Time of Passage

The hydrologic factors we believe are most important for passage from the Squamish River through CERP-created passage routes are water column depth and velocity. Sufficient water column depth (which is impacted by Squamish River discharge and tide height) is required to wet and move fish through passages in the berm. The lower the elevation of CERP-created passages, the more frequently they are wetted. Water velocity (which is impacted by Squamish River discharge and tide phase) influences the direction and speed at which fish travel. For these reasons it is important to consider both tidal and discharge conditions when considering passage opportunities.

Measuring water column depth and water velocity is outside the scope of this project. Therefore, we use discharge and tide elevation predictions as proxies to infer sufficient water depth at the time of fish passage across all study years. The total discharge of the Squamish River at CERP-created passage routes is calculated as the sum of Squamish River (08GA022), Cheakamus (08GA043), and Mamquam (08GA075) hydrometric gauges (Figure 3; Environment Canada

2022b, 2023). Tide elevation predictions were obtained from Canadian Hydrographic Service (2023). Fish with undetermined passage routes are not analyzed, nor are fish who we assumed to have passed via the North culverts as we are unable to determine time/route of passage and therefore hydrologic conditions at the time. To compare hydrologic conditions for fish passing through the box culverts prior to 2021 the historic analysis will need to be re-run to include Mamquam River discharge data, which is beyond the scope of this report. Data are only analyzed for wild origin fish at this time, in future reports we plan to include passage events for hatchery origin fish as well.

3.6.3 Stopover of Duration

After exiting the Squamish River, emigrants can stopover in the estuary or migrate directly into Howe Sound. Stopover duration in the Squamish Estuary can be estimated from detection histories. The calculation for stopover duration in the current report has been updated to suit the estuary's new hydrogeology and array design. In 2020 and 2021, stopover duration (previously known as estuary residence) was defined as time spent in the area on the East side of the berm. Stopover duration did not include detections from the Howe Sound and Spit Island receivers because these receivers were not installed. In 2022, the first year with the Howe Sound and Spit Island receivers, a more complex calculation of stopover duration was used. Fish were only determined to be in the estuary for the periods between detections on the receivers on the East side of the berm (ie. excluding River, Howe Sound and Spit Island). Any detections on the Howe Sound or Spit Island receivers qualified a fish as exiting the estuary and terminating its stopover. Total time in the estuary was summed over all "estuary" stopover periods (see Cook and Fortier 2023 for further details).

Habitat connectivity at the mouth of the Squamish River has been greatly improved by the 850 m breach. However, defining where fish are between detections on the Howe Sound, Spit Island, and breach receivers is virtually impossible with the current array design, complex habitat, and water currents in this area. For this reason, we have included detections on the Howe Sound and Spit Island receivers in this year's analysis of stopover duration. Stopover duration is estimated as the time difference between the first and last detections on the array, excluding the river receiver. We excluded the river receiver because fish are only detected at this location prior to entering the estuary. Due to these changes in the array (i.e., the addition of four receiver locations since 2021) and calculations, stopover duration is not directly compared over the years. In the future, we plan to revisit previous data summaries to standardize procedures across years, taking the ever-evolving telemetry array and hydrogeologic changes into account.

The number of detections of each individual fish on a given receiver can also serve as a proxy for habitat preference within the array area. A more robust means to assess fish behaviour would be to integrate a duration component to quantify a distinct period of presence within the range of the receiver. This task would include determining detection efficiency over the wide range of hydrologic conditions observed during this study, which is outside of the scope of this project and is likely impossible with the way the array has been configured; thus, we use the raw number of detections to elucidate behavior.

4. Results

4.1 Environmental Conditions

Squamish River discharge reached its freshet peak (max = 1181.6 m^3s) during the 2023 tag deployment period and receded during the final weeks of fishing (min = 137.0 m^3s; Figure 4). In previous study years, the peak was not reached until after the final fish release (Figure 5). The Squamish River's flow has been extremely variable over study years. In 2023 tagged Chinook Salmon were released over 20 days, the shortest duration since the study began (max = 40 days in 2021, mean ± SD = 32.2 ± 7.7 days).

Figure 6 summarizes monthly water temperature, salinity, and dissolved oxygen. All monthly averages were calculated with over 1240 data points, except for the North estuary salinity in August. Due to equipment failure, only 340 salinity observations were collected in the end of the month, which is evident by the large standard deviation seen in Figure 6. Dissolved oxygen values ranging from -0.5 to 158.6% were recorded across the estuary. On average, upper Cattermole Creek recorded lower dissolved oxygen values compared to the other environmental stations (Figure 6). Values exceeding the accuracy range (± 5 % between 0 – 120 %) of the dissolved oxygen sensor were recorded at all other stations, causing uncertainty in measurement accuracy for the higher values observed. Salinity values ranged from 0 to 28.8 PSU over the study period, with the lowest values coinciding with the peak of freshet (Figure 4 and Figure 6). Temperature values ranged from -0.77 – 26.38 °C with the warmest temperatures occurring in the summer months.

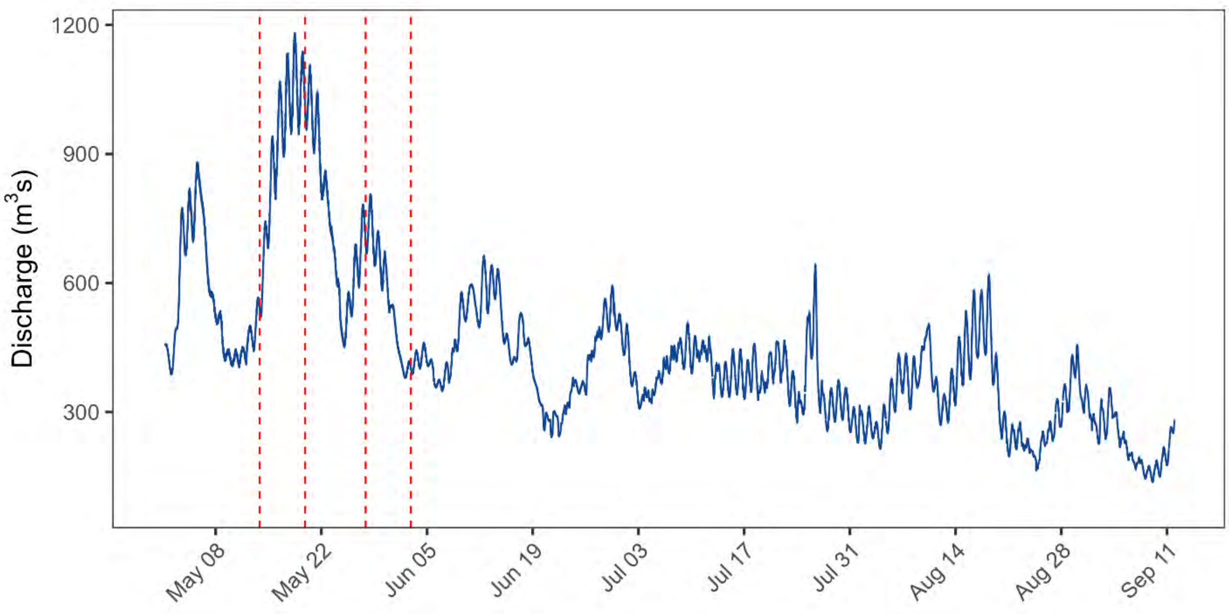


Figure 4 Total discharge **at the mouth of the** ***Squamish River (08GA022) including the Cheakamus (08GA043) and Mamquam (08GA075) tributaries during the 2023 monitoring season (Environment Canada 2023). The blue line shows discharge data in 5-minute intervals. The dashed red lines indicate release dates of tagged Chinook Salmon.***

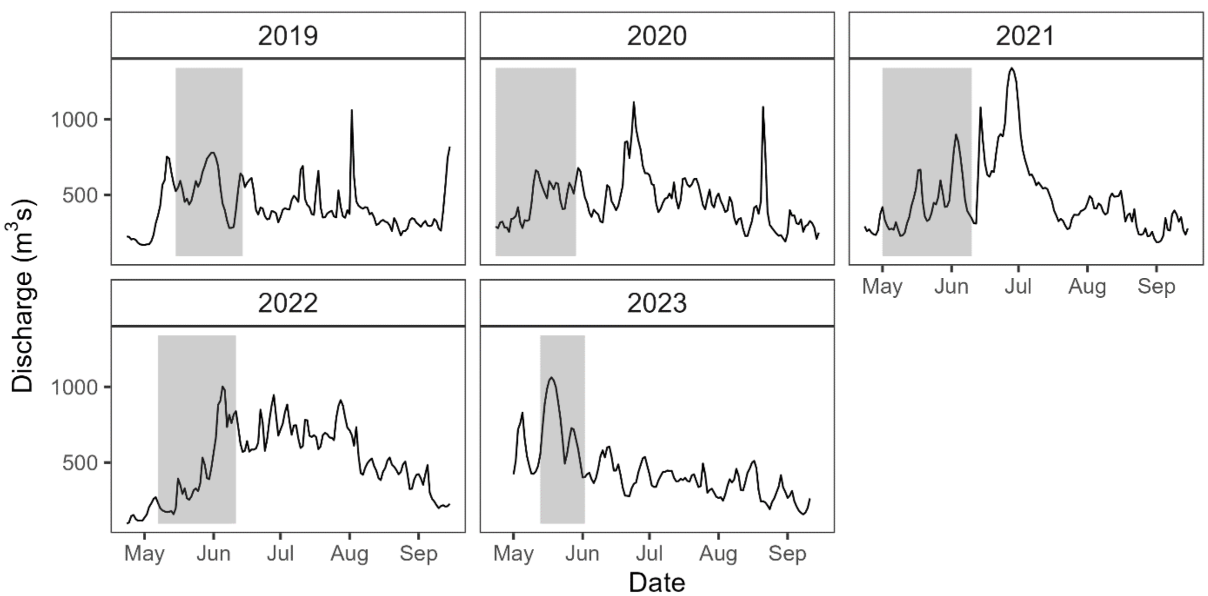


Figure 5 Daily average discharge of the Squamish River (08GA022) including the Cheakamus (08GA043) and Mamquam (08GA075 tributaries; Environment Canada 2022a, 2023) during the 2019 - 2023 monitoring seasons. The grey window indicates the release period for tagged wild juvenile Chinook Salmon each year.

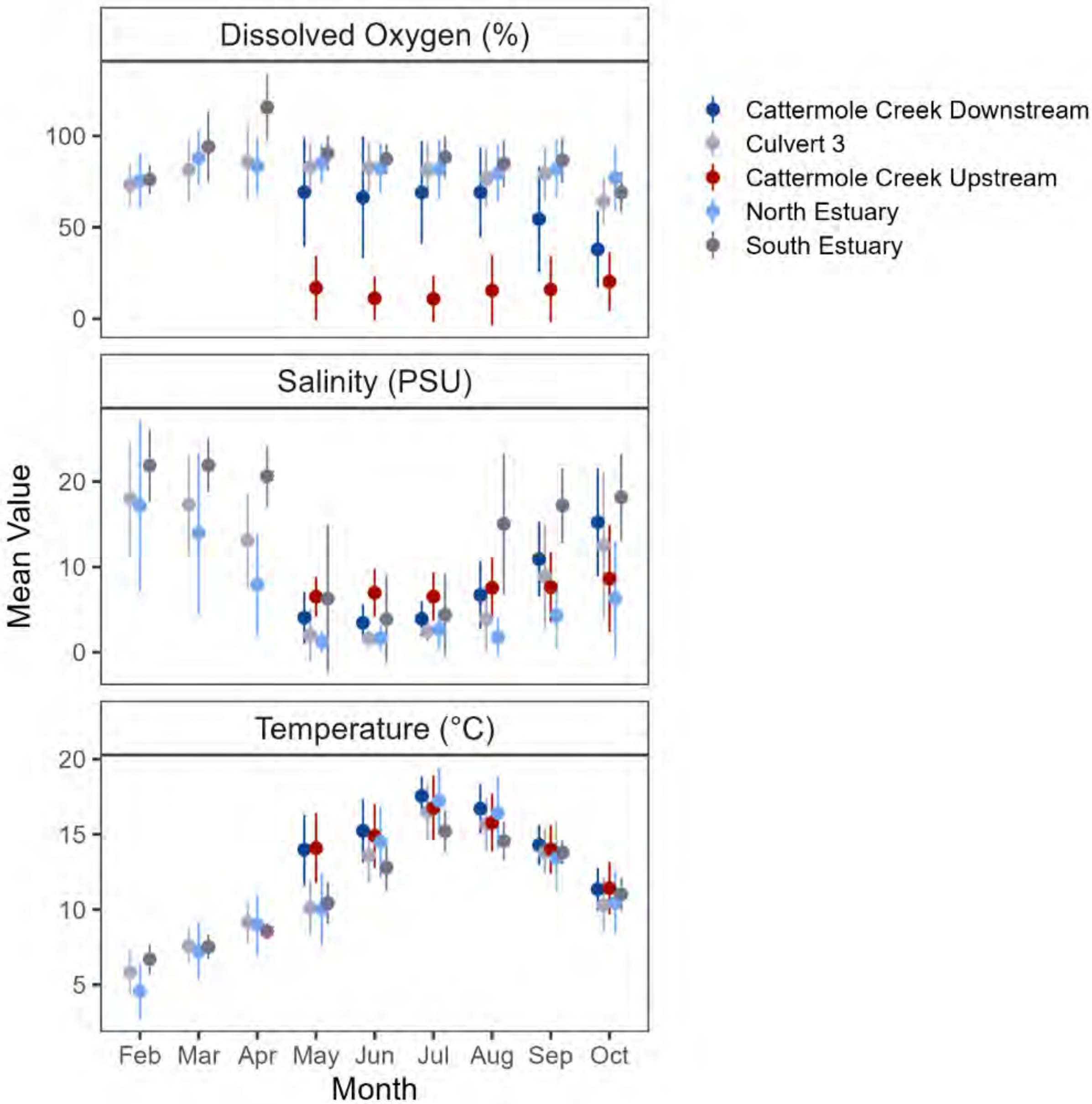


Figure 6 Monthly average dissolved oxygen, salinity, and temperature at environmental logger sites throughout the Squamish estuarine floodplain. Points represent the mean and bars show the standard deviation.

4.2 Fish Characteristics

Wild Chinook Salmon juveniles (n = 75) were released into the Squamish River with acoustic transmitters across four release groups between May 13 and June 2 (Figure 7). We aimed to maintain consistent fish size across release groups within the target size range, but we were ultimately limited to the fish that were caught. Overall size ranged from 71 to 123 mm fork length which likely includes both yearling and sub-yearling fish (mean ± SD = 91.3 ± 15.9 mm tagged;

Lingard et al. 2023). The bimodal distribution of fork lengths (Figure 8 – 2022 and 2023) further indicates that tagged fish are part of two distinct age groups. At the time of tagging, 19 fish in 2022 (n = 98) and 40 in 2023 (n = 75) were likely to be yearlings (being part of the right side of the distribution in Figure 8). Within the 2023 release groups, fork length (mean ± sd) ranged from 80.2 ± 12.2 mm (June 2 release) to 103 ± 1.41 mm (May 13 release; Figure 7). We maintained a mean tag burden of 4.9% with a maximum of 9.2%. Two fish were taken by predators with a tag burden of 3.3% and 8.5%. A total of 15 fish were not detected; these fish either emigrated past the array without being detected or were mortalities. Undetected fish had tag burdens ranging from 1.7 to 8% compared to detected fish that had tag burdens of 1.8 to 9.2%.

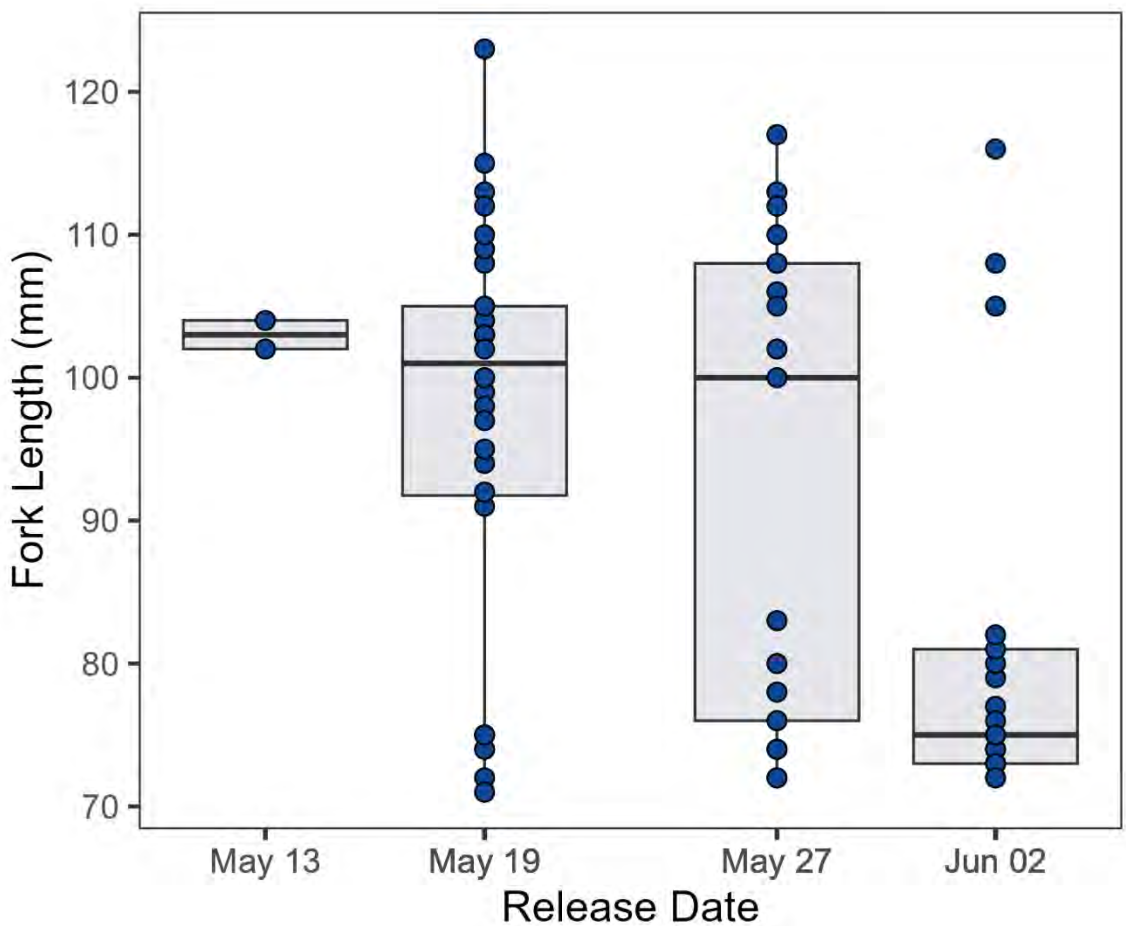


Figure 7 Fork lengths of Chinook Salmon tagged with acoustic transmitters in spring 2023 for each release group. All measurements from individual fish are shown (blue circles). Boxes represent the interquartile range (25th and 75th percentiles with median) and the box whiskers show minimum and maximums, calculated as 1.5x the interquartile range. Points outside of the whiskers are outliers.

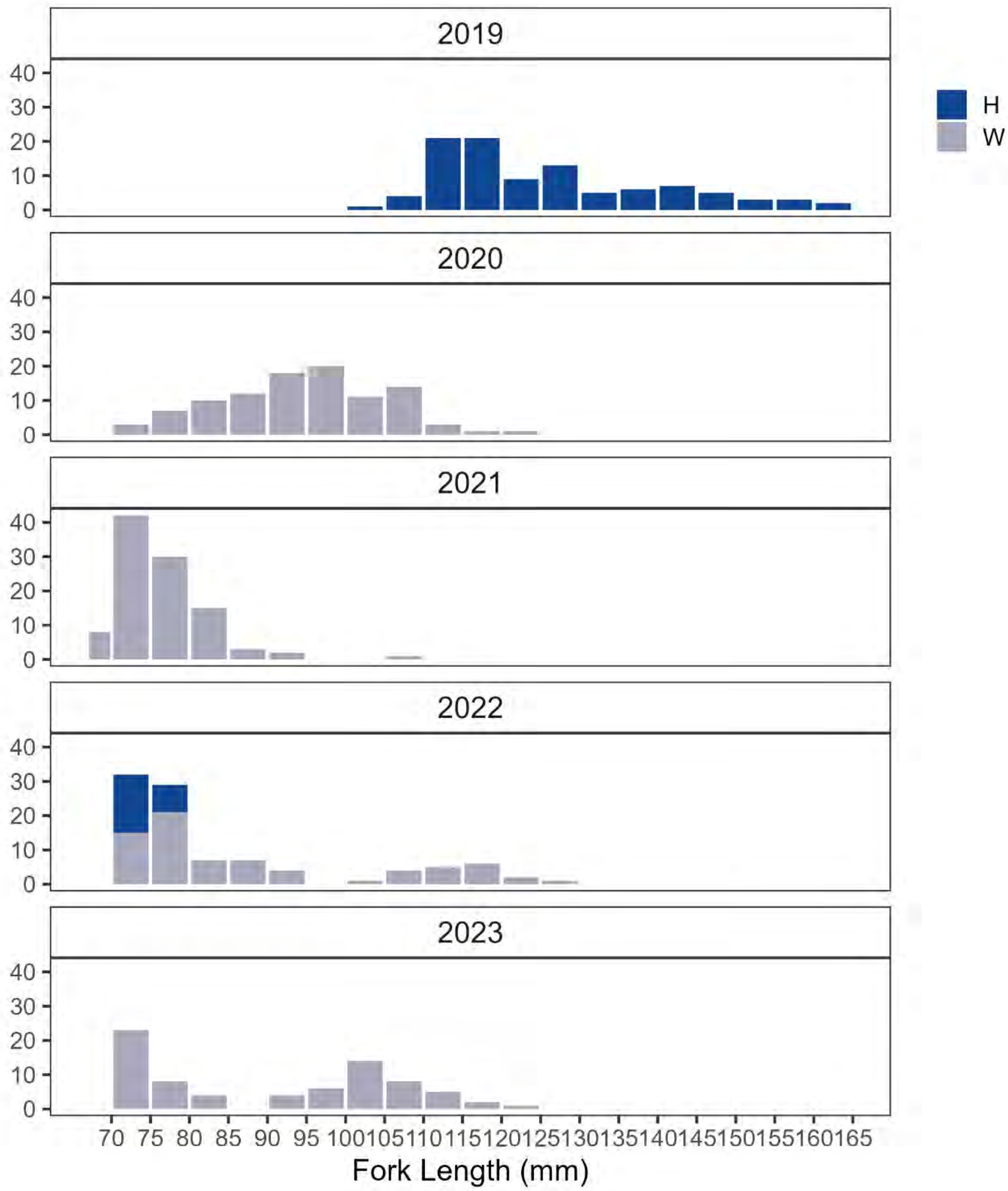


Figure 8 Fork lengths of Chinook Salmon tagged with acoustic transmitters from 2019 through 2023. Wild Chinook Salmon are represented by grey bars and hatchery fish are in blue.

4.3 Fish Movements

Data collected in 2023 add to an acoustic telemetry dataset that evaluates movements of juvenile Chinook Salmon between the Squamish River, Howe Sound, and the Squamish Estuary as connectivity is improved through CERP. Monitoring with acoustic telemetry began in 2019 when the first box culvert was under construction. Moving forward to 2023 we have expanded the acoustic array to focus on juvenile Chinook Salmon passage at the breach.

Below, the emigration of tagged wild Chinook Salmon juveniles is detailed including their route of exit from the Squamish River, the hydrologic conditions at their time of exit, and their stopover duration in the Squamish estuarine floodplain. Results are compared across study years since 2019 where possible.

4.3.1 Passage Route

Exit from the Squamish River is achieved one of four ways: through pipe culverts, box culverts, the breach, or Howe Sound. Exit routes are determined based on detection histories prescribed in Table 1. Chinook Salmon exited by each of these means in 2023. Of the 60 Chinook Salmon detected on the array, 33 passed into the estuarine floodplain on the East of the berm and 27 remained on the West side (Figure 9). Two fish were only detected on the river receiver. Fish passing the berm were further classified by route of entry: culvert 3 (n = 1), culvert 4 (n = 1), North pipe culverts (n = 1), breach (n = 22 - 30) or through Howe Sound (migrated around the berm; n = 0 - 8; Figure 9). Due to limitations of the acoustic array, the passage route used by eight fish is undetermined, with the most likely options being the breach or via Howe Sound (refer to Appendix A for the detection histories of these fish). We include these fish as an upper range value for each of these categories in Table 2 and text. After exiting the Squamish River through the breach or Howe Sound (Figure 9), nine Chinook Salmon doubled back, traveling North, at least as far as the estuary gate (into the central channel). Since three fish exited the Squamish River through culverts, a total of 12 tagged fish accessed the central estuary channel.

The percentage of tagged wild juvenile Chinook Salmon passing to the East side of the berm since 2020 has ranged from 24% (2022, n = 73) to 44% (2023, n = 75). In previous years, most tagged individuals accessed the East side of the berm by migrating through Howe Sound. This study year, 2023, is the first where most individuals did not use Howe Sound to pass the berm. Instead, 67 - 91% of tagged fish passing the berm (n = 33) used the newly created 850 m breach. Over the course of the study, culvert passage has not exceeded 10% of the tagged population.

Since the breach was first developed in 2022, breach passage has at least doubled culvert passage.

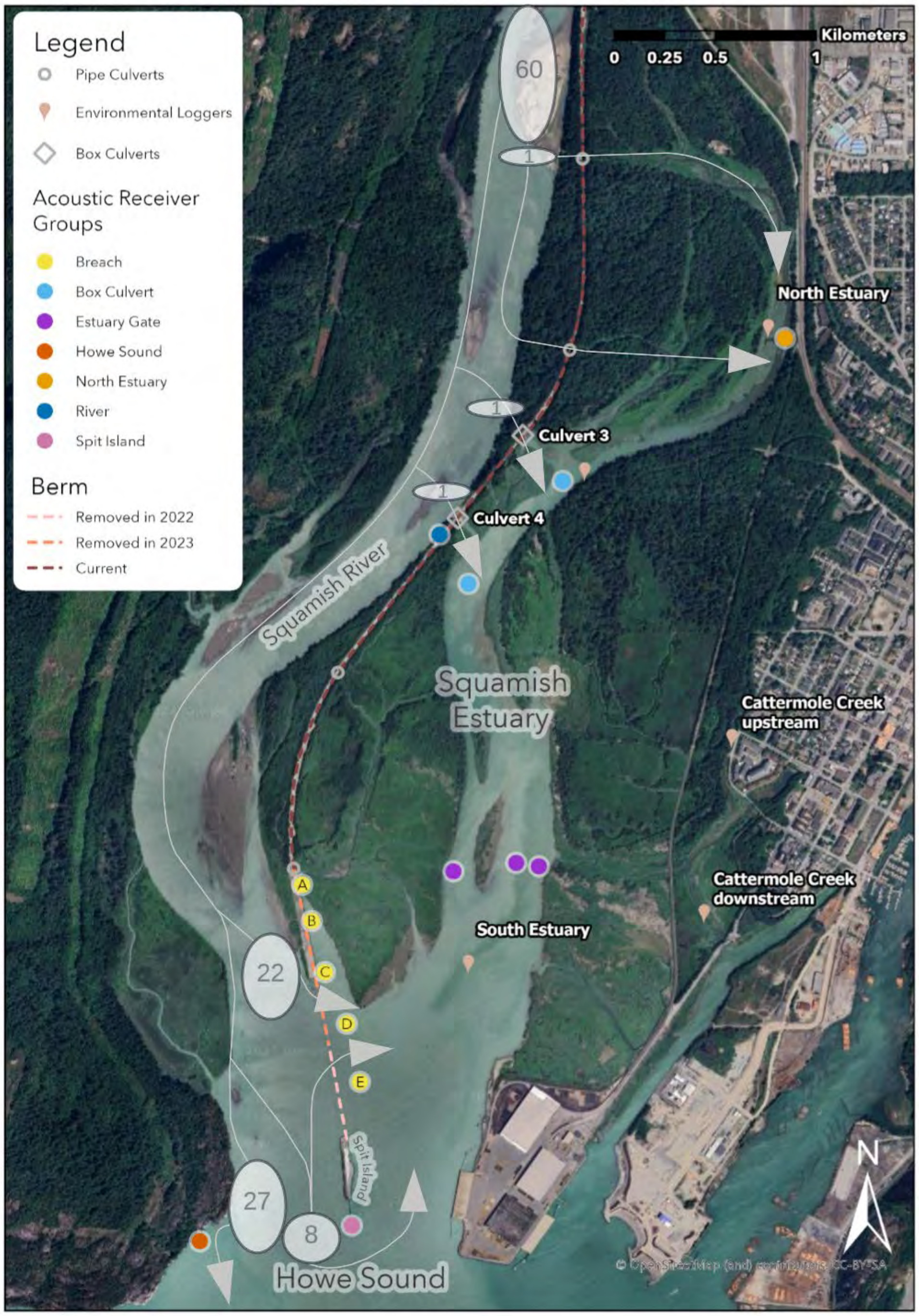


Figure 9 Summary of exit routes taken by tagged juvenile Chinook Salmon to leave the Squamish River in 2023. Sixty of the 75 tagged fish were detected on the array, 33 of which were confirmed to pass from the West to the East side of the berm (historic or current). One fish passed via a pipe culvert in the North estuary. One fish passed via box culvert 3 and another via box culvert 4. Twenty-two fish crossed via the breach. Eight fish have undetermined routes of exit, the most likely options being through the breach or around the South side of Spit Island (ie. Howe Sound). Twenty-seven fish were only ever detected on the West side of the berm. It is assumed that they went directly into Howe Sound, never passing to the East side of the berm. Fourteen fish were never detected and presumably did not survive to exit the Squamish River.

Table 2 Summary of passage routes taken by tagged juvenile Chinook Salmon to move from the Squamish River to the East side of the berm from 2019 to 2023. Routes determined using acoustic telemetry. CERP improvements refer to Central Estuary Restoration Project water passage construction projects. Sample size is the number of acoustically tagged juvenile Chinook Salmon. Percent of total passing the berm refers to the percent of the initial sample size that traveled from the West to the East side of the berm. With the sample size as the denominator, fish are categorized as passing via culverts in the berm, the breach in the berm, or going around the berm to get to the East side. We are uncertain if eight of the tagged fish in 2023 passed via Howe Sound or the breach so a range is given.

	2019	2020	2021	2022		2023
CERP improvements	Box culvert 3 complete late May 2019	Box culvert 4 complete Fall 2020 (after juvenile Chinook migration season)	Both box culverts operational	300 m breach in spit completed April 2022		850 m breach in spit completed mid-May 2023 with additional planning finished in October (after juvenile Chinook migration season)
Initial sample size	100	100	51	73	25	75
Number of fish detected	69	27	16	57	3	60
Percent of total passing the berm	14%	27%	31%	24%	4%	44%
Percent of total passing via culverts	1%	2%	10%	4%	4%	4%
Percent of total passing via the breach	NA	NA	NA	8%	0	29-40%
Percent of total passing via Howe Sound	13%	25%	22%	12%	0	0-11%
Origin of tagged fish	Hatchery	Wild	Wild	Wild	Hatchery*	Wild

*All fish released in mid-July, much later than other release groups

4.3.2 Hydrologic Conditions at Time of Passage

Plotting tide height and discharge during each passage event provides a visual of when passage into the estuary is available and conversely, when it is likely unavailable (Figure 10). These plots indicate Chinook Salmon are able to cross the breach at a wider range of hydrologic conditions than is possible for the box culverts (Figure 10 and 11). Since 2020, 11 tagged wild Chinook have passed the box culverts, and since 2022, 28 wild Chinook Salmon have passed the breach.

Considering tide elevation, passage through the breach and box culverts occurred over 52% of the predicted tide heights for the study period (Figure 11). In 2023, tagged fish crossed the breach at tides ranging from 2.05 to 4.52 m. In 2022, passage events occurred at tide elevations as low as 1.11 m. As well as tide height, tide phase affects passage opportunities by impacting water velocity and current direction, and therefore, fish movement over the breach. In 2023, passage through the breach was observed during all three tide phases (Appendix B), where in 2022 it was only observed during ebb/slack tides. Fish observed to pass during flood tides (n = 9) all crossed at the South end of the breach (being detected on the East side of the berm first by breach D or E receivers).

River discharge at times of passage through the breach or box culverts ranged from 408 to 1099 m^3s (Appendix B), which roughly aligns with the range of discharge values observed during the whole outmigration period (315 - 1182 m^3s; Figure 4). At 408 m^3s discharge (the lowest discharge at which passage was observed) a tide of 2.3 m was sufficient for fish passage of the breach, in 2023. The lowest discharge at which fish passed the box culverts in 2023 was 1023 m^3s, at a tide of 3.9 m. Between 2021 and 2023 the lowest river discharge at which box culvert passage was observed was 749.6 m^3s during a 4.1 m tide. With CERP improvements, passage has successively been available at a wider range of hydrologic conditions every year since 2021 (Figure 10).

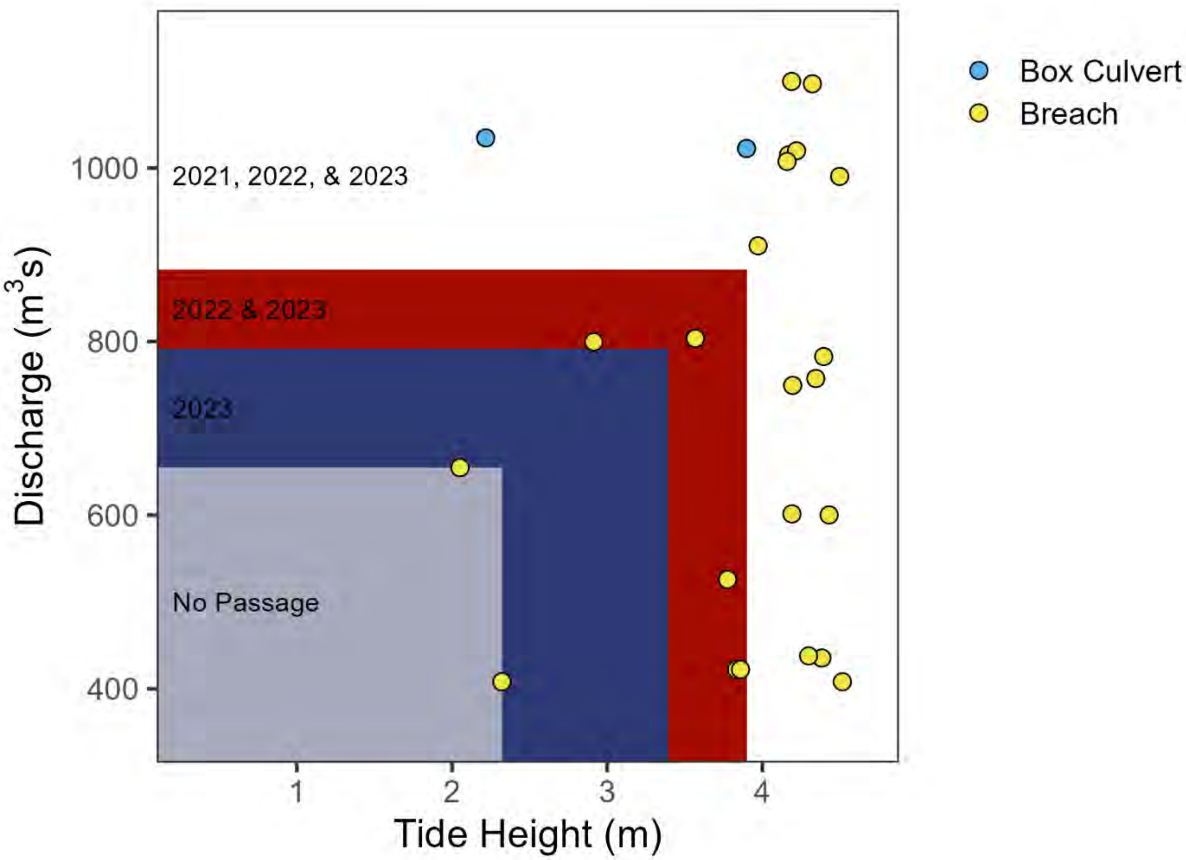


Figure 10 Each point represents 2023 passage of a tagged juvenile Chinook Salmon from the Squamish River, through the breach or box culverts to the East side of the berm. Fish with undetermined passage routes are not included. Points are plotted according to the hydrological conditions (Canadian Hydrographic Service 2023; Environment Canada 2022b; Environment Canada 2023) at the time of passage. Axes scales are set to represent the range of values observed during the 2023 outmigration period. The grey shaded box shows conditions where no passage was observed. The blue, red, and white area shows conditions where passage was observed in 2023. The red and white shaded areas show where passage was observed in 2022. The white shaded area shows the conditions where passage was observed in 2021.

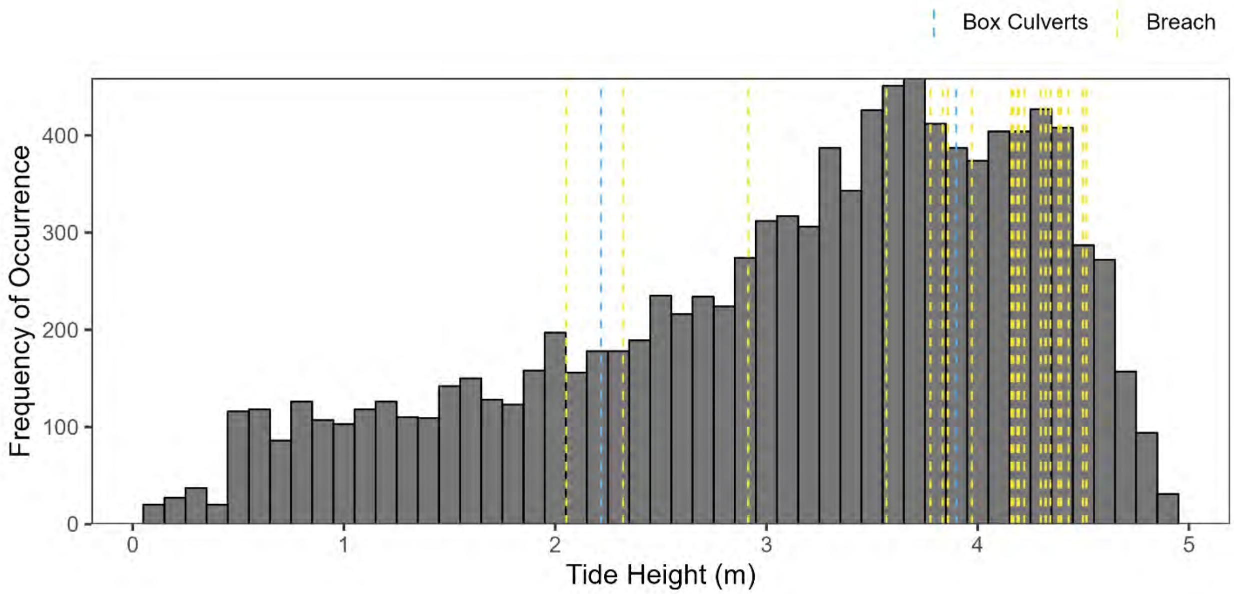


Figure 11 Bars show the frequency distribution of tide heights observed during the 2023 outmigration period for tagged juvenile Chinook Salmon (Canadian Hydrographic Service 2023). Dashed lines show the tide heights at which individual passage events from the Squamish River through the box culverts and breach occurred. Fish with undetermined passage routes are not included.

4.3.3 Stopover Duration

Chinook Salmon were detected exiting the Squamish River between 23 minutes and 17 days after release (n = 56; Figure 12). This implies that the fastest fish traveled ~ 16 river kilometers in 23 minutes or ~42 kilometers per hour. Four fish were omitted from this calculation as they were not detected at the time they exited the Squamish River or they never exited (additional details in Appendix A - ID 2746, 3210, 3228, and 3266). After being detected at an exit point, Chinook Salmon were continually detected on the array for 90 seconds to 112 days, with an average stopover duration of 8.3 ± 18.9 days (mean ± sd; does not include fish that were taken by predators).

The Howe Sound receiver detected the most fish (n = 37), followed by the Spit Island (n = 35), and breach (n = 31) receivers (Figure 13 - left panel). Mean number of detections per fish was highest at the Howe Sound receiver (mean ± sd = 6092 ± 8011). Certain individuals spent over a month around the Howe Sound receiver (see ID:2778 - Appendix A). The next highest value of detections was at the North estuary receiver (2667 detections of one fish) and the estuary gate (mean detections per fish ± sd = 2613 ± 3445; Figure 13 - right panel). The river receiver had the least detections per fish (mean ± sd = 12 ± 19), which is likely, in part, to do with the receiver's poor detection efficiency (57 fish are confirmed to have passed the river receiver but only 14 were detected; Figure 9 and Figure 13 - left panel). Similarly, the Spit Island receiver detected many fish but had a low number of detections per fish (35 fish detected with a mean ± sd = 60 ± 82). Individual nuances can be seen in detection history plots (Appendix A).

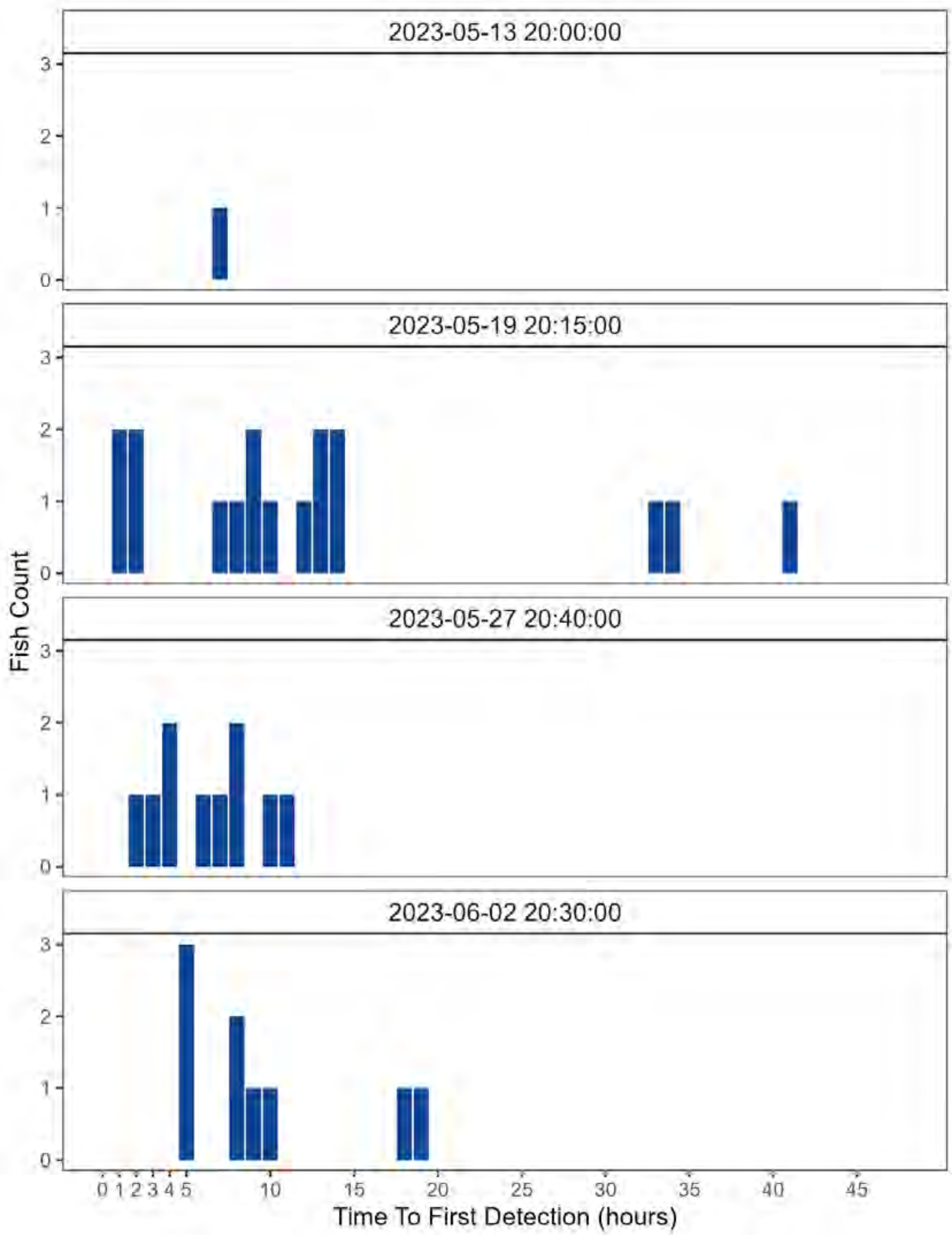


Figure 12 Time to first detection on the entire acoustic array after fish release. Plot faceted by release group. Plot only includes fish detected within the first two days after release.

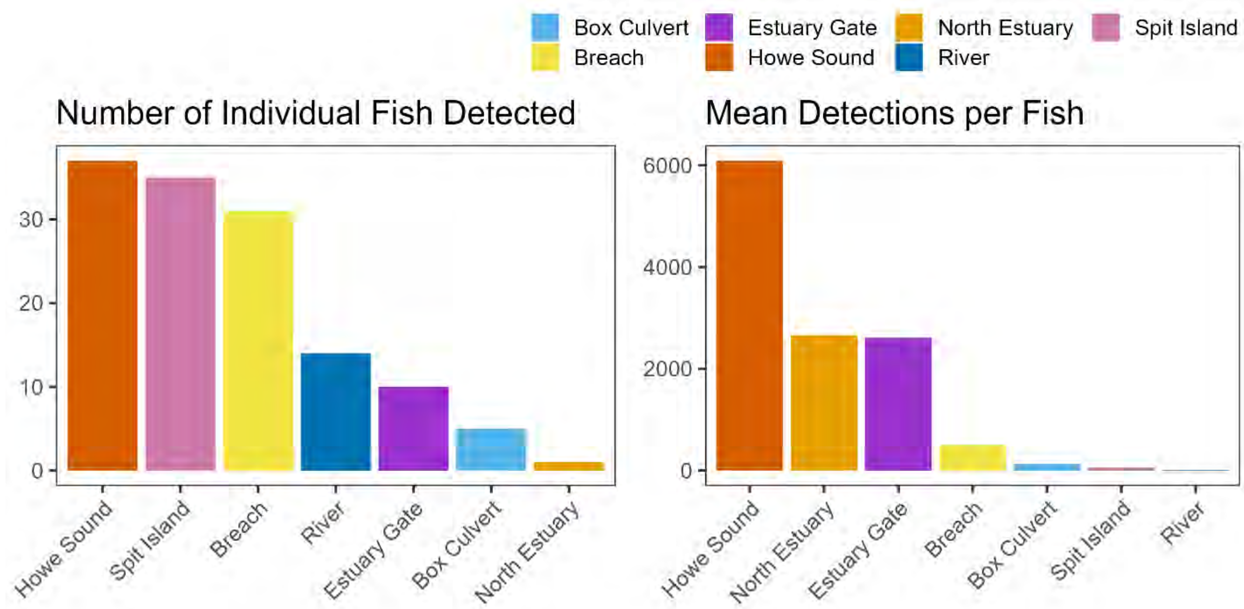


Figure 13 Number of individual fish detected and the mean number of detections among fish detected at each receiver grouping, coloured according to their location. These metrics serve as a proxy for habitat use. Standard deviations around the mean number of detections are large and thus not shown. This is indicative of the variability in fish behaviour observed.

Fish Taken by Predators

With only two tagged fish taken by predators, their raw detection histories are reported, as sample size is too small for analysis (refer to Appendix A for a graphic representation of detection histories). ID: 2744 was first detected on the array at the Howe Sound receiver on May 19th for 1 hour 57 minutes. The tag wasn't detected again for several months, finally being observed after predation at the estuary gate for 35 minutes on August 7th. ID: 3228 was first detected on the North estuary receiver on May 30th at 19:44 and last at the culvert 4 receiver on May 31st at 5:16 (duration of 9 hour 33 minutes). The predation code for the tag was detected shortly after at culvert 4, 7 hours 48 minutes later (May 31st 13:05). The predator moved between the North estuary, box culverts, estuary gate, and breach receiver regions fourteen times with its last detection at the North estuary receiver on June 3rd at 16:40 (duration of 75 hour 35 minutes).

5. Summary

Data collected in 2023 adds to an acoustic telemetry dataset that evaluates movements of juvenile Chinook Salmon through the Squamish Estuary as connectivity is improved through CERP.

Monitoring with acoustic telemetry began in 2019 when the first box culvert was under construction. Developments in 2023 include the expansion of the breach, the use of V3D predation tags, the addition of two HR3 receivers to the acoustic array, and the installation of five water quality stations.

Data from 2022 and 2023 indicate that fish are able to cross the breach at a wider range of hydrologic conditions. With the second phase of the breach opening completed, the Squamish River flow is more eastward into the South estuary (Asadollahi 2021) which may provide a more attractive migration route for fish over the smaller breach available in 2022. We also detected fish moving through the breach towards the estuary during flood tides in 2023 which did not occur in 2022. Fewer fish were observed passing the berm in 2022. However, it may not be that fish were unable to pass the breach on flood tides in 2022, but simply that we did not have a sufficient sample size or receiver coverage that events were observed at all passable conditions. It is also feasible that there are now more favorable water velocity conditions in the larger breach on flood tides for fish to pass. There are many possible reasons why the highest proportion (44%) of tagged individuals were observed passing to the East side of the berm since monitoring of wild Chinook Salmon began in 2020, however, without additional data to account for confounding factors we would be merely speculating. Additional acoustic receivers and range testing in the breach will provide confidence that all tagged fish using the passage route are detected. Ideally, we would like to be able to determine how fish moving into Howe Sound and back towards the breach (n = 8 in 2023) are using the area around Spit Island and the lower river. To do this, we would need to expand our array in this region. However, even excluding these eight fish with undetermined routes into the estuary, there was a high proportion of study fish (29%) that used the breach, which is much greater than the box culverts in any year. The results of this study indicate large natural breaches in infrastructure offer much greater habitat access for juvenile salmon over culverts.

Since the start of this study, sub-yearling Chinook Salmon have been targeted for tagging because they are thought to stopover in estuaries longer than yearlings, and therefore be good indicators of improved estuary access. Although we mainly report the percent of tagged fish using the CERP breach and box culverts to exit the Squamish River into the estuary (33 - 44% in 2023; n = 75) as our measure of success, the goal of the reconnection project is to increase the number of Chinook Salmon in the Squamish Estuary and in particular the central channel and other northern parts of the estuary. Due to the small size of the population and challenge of fishing the Squamish River to obtain individuals of the correct size for tagging, it is likely that both yearling and sub-yearling Chinook Salmon were tagged in 2022 and 2023. It is possible that larger tagged fish are less likely to enter the central estuary channel after exiting the Squamish River through the breach. Although, no analyses in individual study years have indicated that smaller tagged fish are more likely to enter the central estuary. In 2023, a total of 12 (16% of tagged individuals; three through culverts, nine from the breach and/or Howe Sound) fish moved into the central estuary. How the proportion of fish using the central estuary (detections on North estuary, culverts, estuary gate receivers) differs from past years is unknown because in the past the breach area was also considered part of the central estuary as it was on the East side of the intact berm. A re-analysis of past data is needed to determine if fish size has influenced the probability of fish entering the central estuary.

Due to the small size of the wild population, we tagged hatchery fish in 2019, and as a subset in 2022. While hatchery fish are known to have behavioral differences from wild fish (Beamish et al. 2012), other factors may have negatively impacted their odds of being detected passing the berm compared to other wild release groups. In 2019, hatchery Chinook, much larger than any other cohort in the study were tagged. Their large size may have negated their need to enter and feed in the estuary. Further, the breach and culvert 4 did not exist. The best CERP-passage option for the large hatchery fish was box culvert 3, which was not completed until part way through the 2019 outmigration season. In 2022, we tagged hatchery sub-yearlings of similar sizes to wild fish as we were unable to catch enough wild fish. In this year, hatchery fish passed the berm in a lower percentage (4%) compared to wild fish (24%; of their respective sample sizes). The 2022 hatchery fish were released in mid-July, much later than any other release groups in the study (other groups released between mid-April to early-June). The Squamish River's freshet peak had already passed, so the hatchery fish might not have had as much opportunity to use a CERP-passages as they would have been dry more frequently. Due to the late release, the period of monitoring for hatchery fish was also ~60 days shorter than for wild fish. It is possible that we would have seen more hatchery fish on the array if we had left the receivers out until October in 2022. Fall emigrations of Chinook Salmon sub-yearlings have been documented in other watersheds (Bottom et al. 2005).

Depredation is a key uncertainty in acoustic telemetry studies, especially with small fish. For the past three years we have observed complex movements of study tags moving both upstream and downstream within the study area over several months. We could not rule out that we were potentially monitoring the movements of predators that had consumed study fish. However, the use of the V3D predation tags this year allowed us to resolve some of this uncertainty with only two tagged fish taken by predators while they were in the estuary. After consuming tagged Chinook Salmon, we tracked each predator, following them through the estuary. Without the V3D predation tags we would not have been able to distinguish these movements as belonging to predators.

While the use of predation tags has been informative, there is uncertainty in the duration of time it takes the tags to trigger that they have been ingested. Slusher et al. 2021 demonstrates that tags implanted in rainbow trout juveniles begin pinging their predation code 1-27 hours after they are consumed by adult largemouth bass (*Micropterus salmoides*). Because ID: 2744 wasn't detected to be eaten until several months after first detections, we are relatively confident that it exited the Squamish River before being taken by a predator. After first being detected, tag: 3228 was detected as digested 17 hours 21 minutes later. As it may take up to 27 hours after consumption for the predation code to trigger, it is possible that the Chinook Salmon had been consumed before entering the North estuary. Variables identified to impact trigger time include the size of the prey, and temperature (Slusher et al. 2021). We could speculate that the tags predation trigger went off quickly relative to the rainbow trout in Slusher et al. 2021 due to the Chinook Salmon being relatively smaller (Slusher rainbow trout: mean ± SD = 27.9 ± 7.1 g; Chinook ID:3228 = 3.9 g). Further, we could expect the predation trigger to go off more quickly if the Chinook Salmon was consumed by a warm-bodied predator (ie. mammals and birds vs. the largemouth bass in Slusher et al. 2021), or more slowly because of the cold water conditions. The water temperature in the North estuary was 9 – 14°C around the time of predation where it was 18 – 24°C in Slusher et al. 2021. While we are confident that these fish were consumed by predators we cannot distinguish when they were with certainty. With continued use of the V3D predation tags we hope to collect sufficient data to compare the movements of juvenile Chinook Salmon to their predators. If prey and predators have distinct movements patterns, we may be able to identify predators (previously assumed to be live tagged Chinook Salmon) in previous study years where predation tags were not used.

There are many uncertainties in processing acoustic telemetry data including discerning false positive detections from real detections, and determining if the individuals being tracked are the study objects or predators. In 2023, we have partially resolved one of these issues with the use of the V3D predation tags. The filters we applied in 2023 to the acoustic telemetry detections were developed based on advice from the manufacturer and literature (Kessel et al. 2015; Simpfendorfer et al. 2015). However, filters applied across years have not been consistent. In 2021, we only removed detections before the release date of the tag, and echoes occurring within less than the minimum burst rate of the tags. In 2022, filtering was more conservative requiring two consecutive detections on the same receiver within a 6 second period as well as the same filters applied in 2021. In 2023, we have relaxed the consecutive requirement applied in 2022, based on advice from the manufacturer (Innovasea personal communication), and instead required two detections anywhere in the array with 1-hour to remove isolated detections that may be caused by environmental noise interrupting tag transmissions. A filter we have not applied is a minimum time to be detected on the array following release. Previous telemetry studies in larger rivers indicate average travel rates of one to two body lengths *per* second (Fraser River; Welch et al. 2007), 30 km *per* day (Columbia River; McMichael et al., 2013), or 4 km *per* 15 minutes (Columbia River; Harnish et al. 2012). Given that fish must travel 12 km to the most northerly receivers in our array, and 16 km to Howe Sound, from the release site, we expect it would take at least one hour at the fastest published rate, to two days at the slowest published rate. With our applied data filters, 3% of tagged fish (n = 75) reached the estuary in under 1 hour, and 44% between 1 hour and two days. Therefore, fish are either traveling more quickly than in previously published studies (Welch et al. 2011; Harnish et al. 2012; McMichael et al. 2013), or additional filtering is required to remove false positives on the array. This issue will be pervasive across years, as minimum time to reach the receivers is a consideration we have not made in the past.

The goal of CERP has been to increase the hydraulic connection between the Squamish River and Squamish Estuary which we have historically defined as the shallow marsh and mudflat floodplain area to the east of the abandoned berm (historic and current). However, Howe Sound itself is also an estuary and may be an important habitat for juvenile Chinook Salmon, especially the larger individuals targeted in this study. The high number of detections per fish at the Howe Sound receiver indicates that many fish are stopping over and or returning to this area along the West shore of Howe Sound. Each year, some fish are not detected for months, and then are detected at the Howe Sound receiver, indicating fish are potentially returning to or remaining in Northern Howe Sound for the entire summer. Although this finding does not necessarily inform the success of the CERP reconnection project, it is an important observation about the early marine ecology of Squamish River sub-yearling Chinook Salmon.

An equally important objective of the CERP project has been to improve water quality and flow between the Squamish River and Squamish Estuary. The data collected in 2023 indicates that there is poor water quality in the most eastern regions of the estuary floodplain (Cattermole Creek). This is an important finding towards the development of further restoration planning for this region. While there were successes in reinstating water quality monitoring in 2023, we did encounter some challenges. The depth sensors we purchased were found to be imprecise which limited us to filtering temperature, dissolved oxygen, and salinity data by tide elevation predictions which may impart a small amount of bias in estimates of average water quality presented in this report. We were also recently made aware of issues with the dissolved oxygen sensors and their robustness to being regularly dewatered in a tidal environment. We are working with the manufacturer of this equipment to resolve these issues and improve confidence in the environmental data being collected.

Despite the challenges of monitoring fish and environmental conditions in the dynamic environment of the Squamish Estuary, we feel 2023 has been another successful year. The data from 2022 and 2023 indicate the breach has dramatically improved juvenile Chinook Salmon access to the estuarine environment on the East side of the berm. We continue to build a novel and important dataset that can be used to evaluate the usefulness of various reconnection strategies in estuaries and other floodplain environments as well as important observations of the estuary ecology of juvenile Chinook Salmon. We look forward to preparing a cohesive analysis across study years in the future.

References

Aerial Photographs - Squamish History Archives. 2015. Available from https://squamishlibrary.digitalcollections.ca/aerial-photographs?page=6&onlyDirect=1&limit=10&sort=alphabetic&listLimit=10&sortDir=asc [accessed 23 January 2024].

Asadollahi, N. 2021. Squamish Training Berm Removal – Phase 2. Final Report, SNC Lavalin.

Beamish, R.J., Sweeting, R.M., Neville, C.M., Lange, K.L., Beacham, T.D., and Preikshot, D. 2012. Wild chinook salmon survive better than hatchery salmon in a period of poor production. Environ Biol Fish **94**(1): 135–148. doi:10.1007/s10641-011-9783-5.

Bottom, D., Simenstad, C., Burke, J., Baptista, A., Jay, D., Jone, K., Casillas, E., and Schiewe, M. 2005. Salmon at River's End: The Role of the Estuary in the Decline and Recovery of Columbia River salmon. Civil and Environmental Engineering Faculty Publications and Presentations. Available from https://pdxscholar.library.pdx.edu/cengin_fac/24.

Bourret, S.L., Caudill, C.C., and Keefer, M.L. 2016. Diversity of juvenile Chinook salmon life history pathways. Rev Fish Biol Fisheries **26**(3): 375–403. doi:10.1007/s11160-016-9432-3.

Bradford, M., and Higgins, P. 2001. Habitat-, season- and size-specific variation in diel activity patterns of juvenile Chinook salmon (Oncorhynchus tshawytscha) and steelhead trout (Oncorhynchus mykiss). Canadian Journal of Fisheries and Aquatic Sciences **58**. doi:10.1139/f00-253.

Canadian Hydrographic Service. 2023. Squamish Inner (07811). Available from https://www.tides.gc.ca/en/stations/7811 [accessed 31 December 2023].

Chalifour, L., Scott, D.C., MacDuffee, M., Stark, S., Dower, J.F., Beacham, T.D., Martin, T.G., and Baum, J.K. 2021. Chinook salmon exhibit long-term rearing and early marine growth in the Fraser River, British Columbia, a large urban estuary. Can. J. Fish. Aquat. Sci. **78**(5): 539–550. NRC Research Press. doi:10.1139/cjfas-2020-0247.

Collins, A.L., Clarke, T.D., Cooke, S.J., Hinch, S.G., and Welch, D.W. 2013. Intracoelomic Acoustic Tagging of Juvenile Sockeye Salmon: Swimming Performance, Survival, and Postsurgical Wound Healing in Freshwater and during a Transition to Seawater. Transactions of the American Fisheries Society **142**(2): 515–523. Taylor & Francis. doi:10.1080/00028487.2012.743928.

Cook, K., and Fortier, M. 2023. Central Estuary Fisheries Monitoring Program Summary. InStream Fisheries Research.

Cook, K., and Lingard, S. 2020. Squamish River Central Estuary Restoration Effectiveness Monitoring: Tagging and Monitoring of Juvenile Chinook Salmon, Year 2 (2020). Report prepared for Squamish River Watershed Society, Squamish, BC.

Cook, K., Lingard, S., and Martin, C. 2019. Squamish River Central Estuary Restoration Effectiveness Monitoring (Implementation Year 1: 2019). Report Prepared for the Squamish River Watershed Society, Squamish, BC.

Duffy, E.J., and Beauchamp, D.A. 2011. Rapid growth in the early marine period improves the marine survival of Chinook salmon (Oncorhynchus tshawytscha) in Puget Sound, Washington. Can. J. Fish. Aquat. Sci. **68**(2): 232–240. NRC Research Press. doi:10.1139/F10-144.

Environment Canada. 2022a, November 2. Station Information. Available from https://wateroffice.ec.gc.ca/report/real_time_e.html?stn=08MH056 [accessed 2 December 2022].

Environment Canada. 2022b, November 2. Historical Hydrometric Data Download. Available from https://wateroffice.ec.gc.ca/download/index_e.html?results_type=historical [accessed 2 December 2022].

Environment Canada. 2023. Water Level and Flow. Stations 08GA043, 08GA075, and 08GA022. Available from https://wateroffice.ec.gc.ca/index_e.html.

Environmental Stewardship Division. Lower Mainland Region. 2007. Skwelwil'em Squamish Estuary Wildlife Management Area. Management Plan, Ministry of Environment.

Harnish, R.A., Johnson, G.E., McMichael, G.A., Hughes, M.S., and Ebberts, B.D. 2012. Effect of Migration Pathway on Travel Time and Survival of Acoustic-Tagged Juvenile Salmonids in the Columbia River Estuary. Transactions of the American Fisheries Society **141**(2): 507–519. Wiley. doi:10.1080/00028487.2012.670576.

Hoos, L., and Vold, C. 1975. The Squamish River Estuary Status of Environmental Knowledge to 1974. Envrionement Canada.

Jepsen, N., Davis, L.E., Schreck, C.B., and Siddens, B. 2001. The Physiological Response of Chinook Salmon Smolts to Two Methods of Radio-Tagging. Transactions of the American Fisheries Society **130**(3): 495–500. Taylor & Francis. doi:10.1577/1548-8659(2001)130<0495:TPROCS>2.0.CO;2.

Kessel, S.T., Hussey, N.E., Webber, D.M., Gruber, S.H., Young, J.M., Smale, M.J., and Fisk, A.T. 2015. Close proximity detection interference with acoustic telemetry: the importance of considering tag power output in low ambient noise environments. Animal Biotelemetry **3**(1): 5. doi:10.1186/s40317-015-0023-1.

Levy, D.A., and Levings, C.D. 1978. A description of the fish community of the Squamish River estuary, British Columbia: relative abundance, seasonal changes, and feeding habits of salmonids. Fisheries and Marine Service: MS Rep. No. 1475: 63 p.

Lingard, S. 2021. Central Estuary Fisheries Monitoring Program Summary 2020-2021 Funding Year. Report Prepared for the Squamish River Watershed Society, Squamish, BC.

Lingard, S., Martin, C., Putt, A., and Swainson, D. 2018. Squamish River Estuary Juvenile Chinook Salmon Habitat Usage Survey: 2018 Report. Report Prepared for the Squamish River Watershed Society, Squamish, BC.

Lingard, S.A., Bass, A.L., Cook, K.V., Fortier, M., Price, G.G., and Hinch, S.G. 2023. Evaluating the influence of environmental and biological factors on migration behavior and residence duration of wild subyearling Chinook Salmon in a fjord estuary using miniature acoustic transmitters. Transactions of the American Fisheries Society **152**(5): 610–631. doi:10.1002/tafs.10429.

McMichael, G.A., Hanson, A.C., Harnish, R.A., and Trott, D.M. 2013. Juvenile salmonid migratory behavior at the mouth of the Columbia River and within the plume. Animal Biotelemetry **1**(1): 14. Springer Science and Business Media LLC. doi:10.1186/2050-3385-1-14.

Moore, J., Gordon, J., Carr-Harris, C., Gottesfeld, A., Wilson, S., and Russell, J. 2016. Assessing estuaries as stopover habitats for juvenile Pacific salmon. Marine Ecology Progress Series **559**. doi:10.3354/meps11933.

Simpfendorfer, C.A., Huveneers, C., Steckenreuter, A., Tattersall, K., Hoenner, X., Harcourt, R., and Heupel, M.R. 2015. Ghosts in the data: false detections in VEMCO pulse position modulation acoustic telemetry monitoring equipment. Animal Biotelemetry **3**(1): 55. doi:10.1186/s40317-015-0094-z.

Slusher, B., Thomas, M., Peterson, M., and Guignarn, J. 2021. V3D Predation Tag Testing. FISHBIO.

Stockner, J.G., Cliff, D.D., and Buchanan, D.B. 1977. Phytoplankton Production and Distribution in Howe Sound, British Columbia: A Coastal Marine Embayment–Fjord Under Stress. J. Fish. Res. Bd. Can. **34**(7): 907–917. NRC Research Press. doi:10.1139/f77-142.

Tryon, L., and Togado, A. 2020. Squamish Estuary Biophysical Monitoring Program Report. Prepared for the Squamish River Watershed Society, Squamish, BC.

Volk, E.C., Bottom, D.L., Jones, K.K., and Simenstad, C.A. 2010. Reconstructing Juvenile Chinook Salmon Life History in the Salmon River Estuary, Oregon, Using Otolith Microchemistry and Microstructure. Transactions of the American Fisheries Society **139**(2): 535–549. doi:10.1577/T08-163.1.

Wada, G., and Sander, B. 2005. Squamish River Watershed Salmon Recovery Plan. Golder Associated Ltd.

Webster, S.J., and Dill, L.M. 2006. The energetic equivalence of changing salinity and temperature to juvenile salmon. Functional Ecology **20**(4): 621–629. doi:10.1111/j.1365-2435.2006.01128.x.

Weitkamp, L.A., Goulette, G., Hawkes, J., O'Malley, M., and Lipsky, C. 2014. Juvenile salmon in estuaries: comparisons between North American Atlantic and Pacific salmon populations. Rev Fish Biol Fisheries **24**(3): 713–736. doi:10.1007/s11160-014-9345-y.

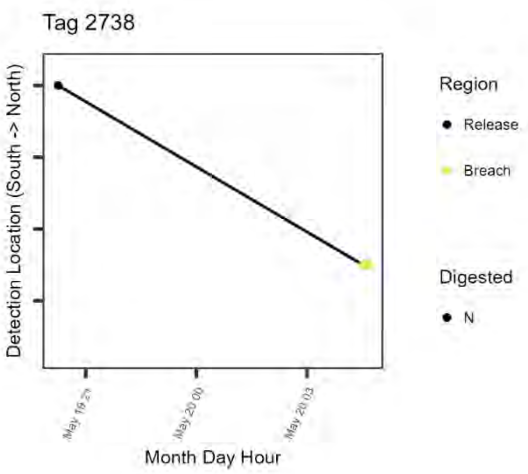
Welch, D.W., Melnychuk, M.C., Payne, J.C., Rechisky, E.L., Porter, A.D., Jackson, G.D., Ward, B.R., Vincent, S.P., Wood, C.C., and Semmens, J. 2011. In situ measurement of coastal ocean movements and survival of juvenile Pacific salmon. Proc Natl Acad Sci U S A **108**(21): 8708–8713. United States. doi:10.1073/pnas.1014044108.

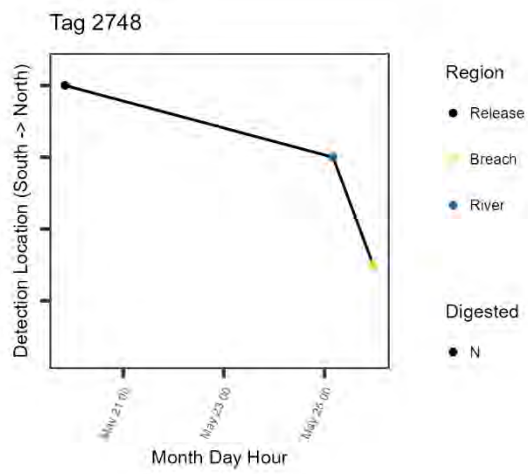
Appendix A: Detection Histories

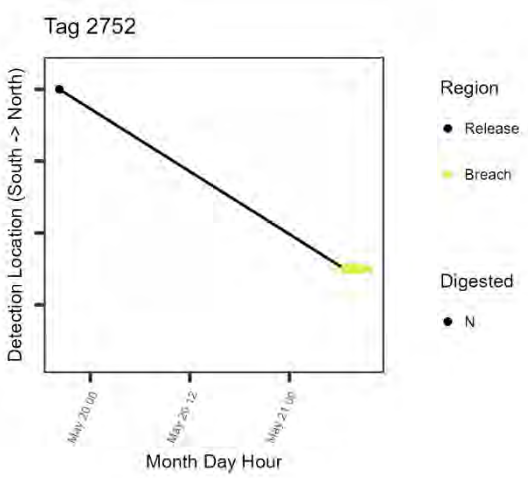
Detection histories are provided for the 60 tags detected according to how movement was classified.

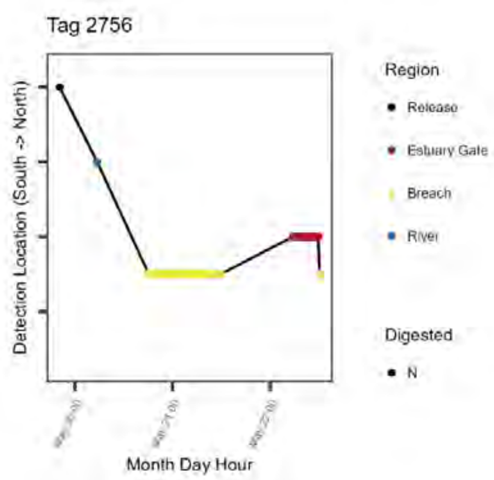
Fish ID is pasted above each plot. Detection points are positioned vertically on the plots according to the receiver location south (lower on y-axis) to north (higher on y-axis) and coloured according to detection region (as identified in the legend).

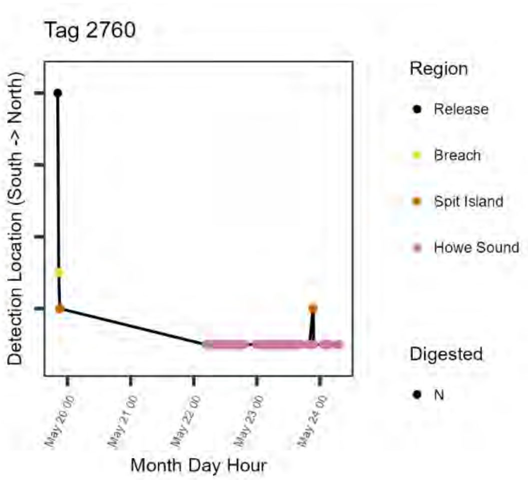
Passed Berm Via Breach (n = 22)

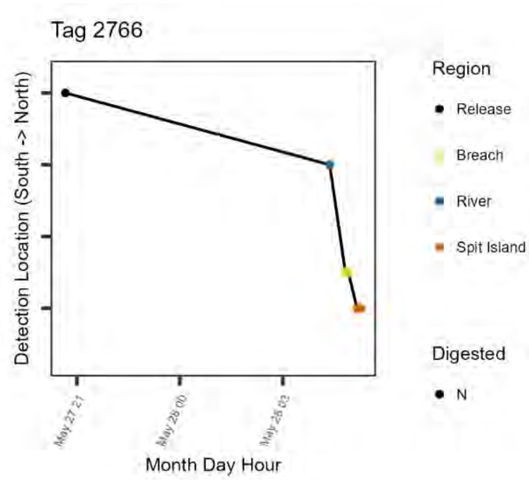

Tag 2738
Detection Location (South -> North)
Month Day Hour
Region
Release
Breach
Digested
N

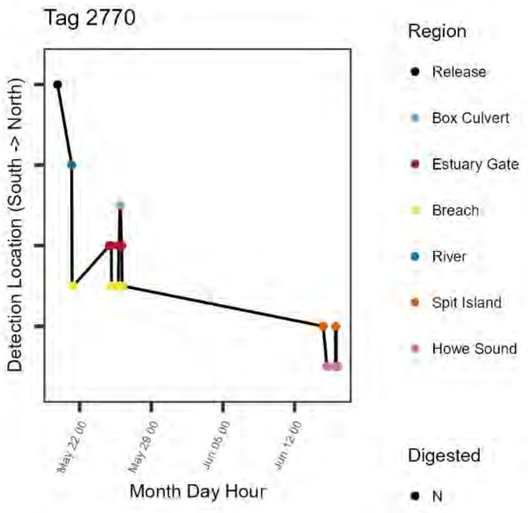

Tag 2748
Detection Location (South -> North)
Month Day Hour
Region
Release
Breach
River
Digested
N

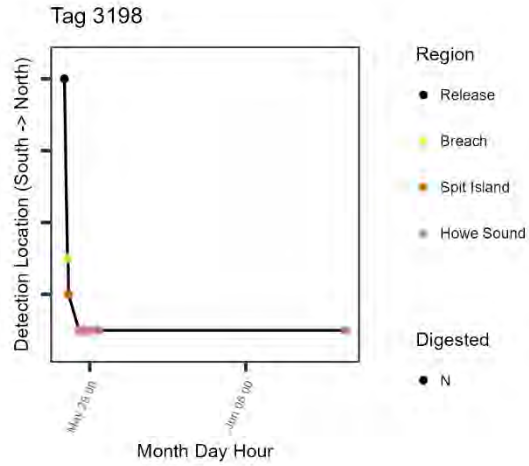

Tag 2752
Detection Location (South -> North)
Month Day Hour
Region
Release
Breach
Digested
N

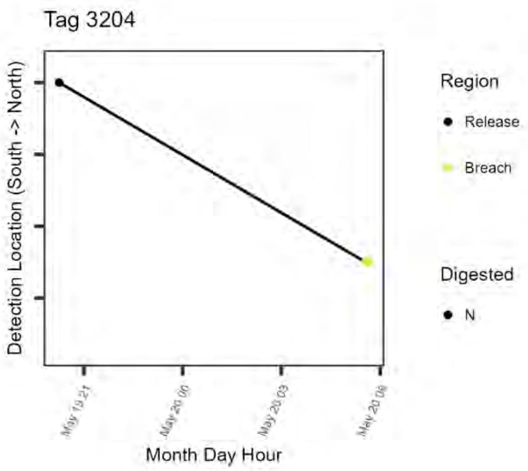

Tag 2756
Detection Location (South -> North)
Month Day Hour
Region
Release
Estuary Gate
Breach
River
Digested
N

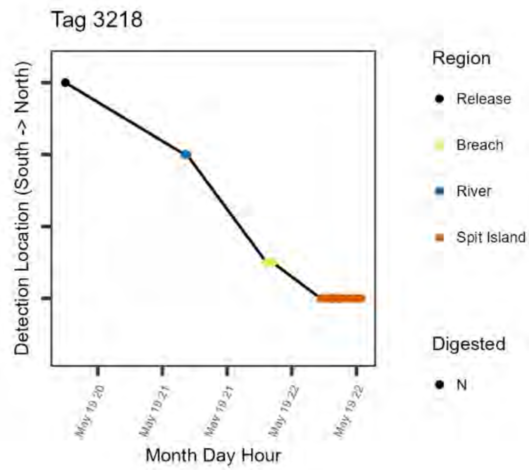

Tag 2760
Detection Location (South -> North)
Month Day Hour
Region
Release
Breach
Spit Island
Howe Sound
Digested
N

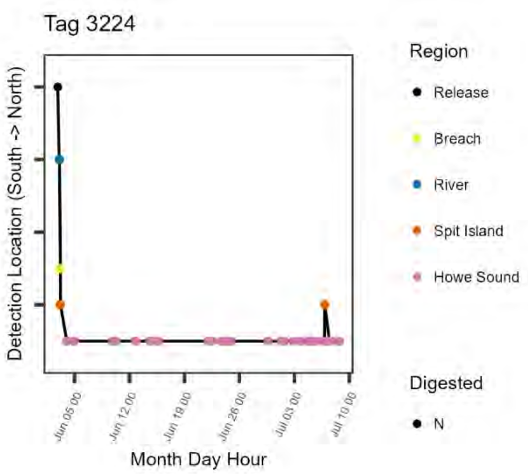

Tag 2766
Detection Location (South -> North)
Month Day Hour
Region
Release
Breach
River
Spit Island
Digested
N

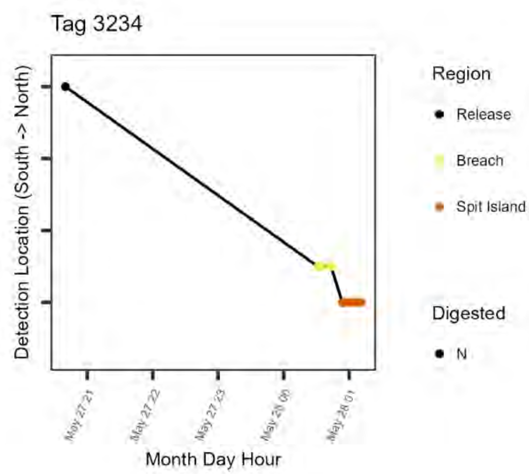

Tag 2770
Detection Location (South -> North)
May 22 00
May 29 00
Jun 05 00
Jun 12 00
Month Day Hour
Region
Release
Box Culvert
Estuary Gate
Breach
River
Spit Island
Howe Sound
Digested
N

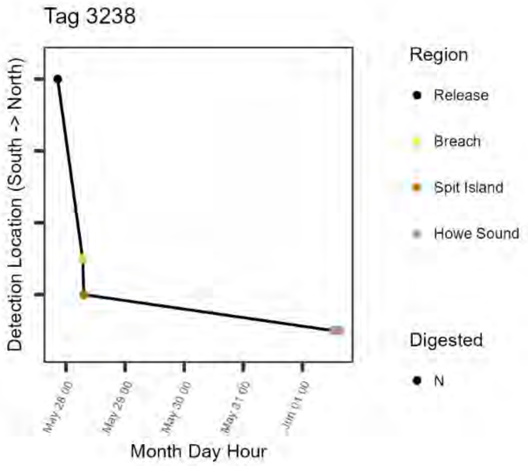

Tag 3198
Detection Location (South -> North)
May 26 00
Jun 05 00
Month Day Hour
Region
Release
Breach
Spit Island
Howe Sound
Digested
N

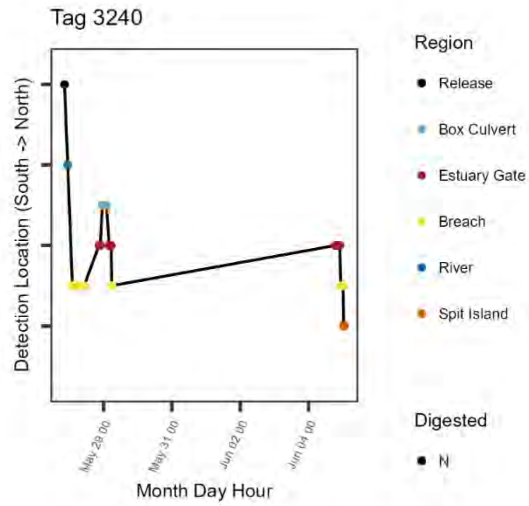

Tag 3204
Detection Location (South -> North)
May 19 21
May 20 00
May 20 03
May 20 06
Month Day Hour
Region
Release
Breach
Digested
N

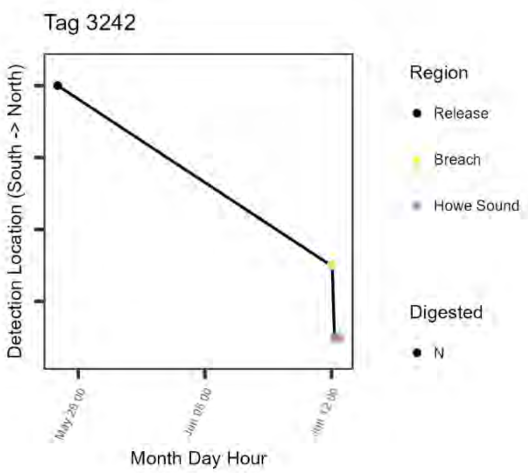

Tag 3218
Detection Location (South -> North)
May 19 20
May 19 21
May 19 21
May 19 22
May 19 22
Month Day Hour
Region
Release
Breach
River
Spit Island
Digested
N

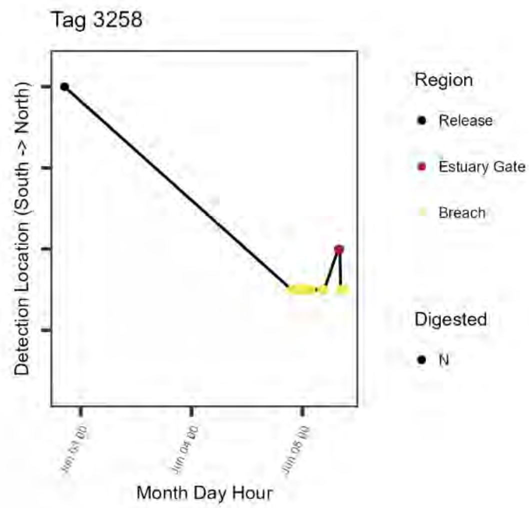

Tag 3224
Detection Location (South -> North)
Jun 06 00
Jun 12 00
Jun 18 00
Jun 26 00
Jul 03 00
Jul 10 00
Month Day Hour
Region
Release
Breach
River
Spit Island
Howe Sound
Digested
N

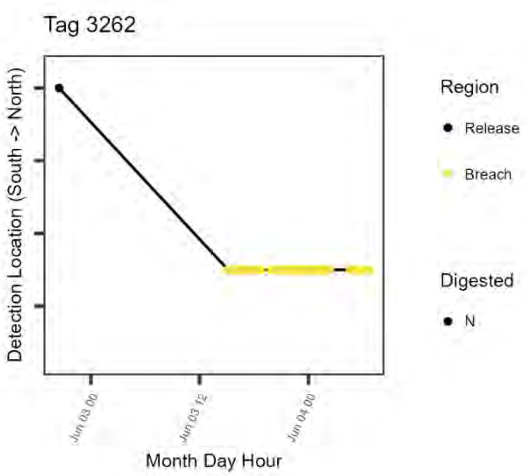

Tag 3234
Detection Location (South -> North)
May 27 21
May 27 22
May 27 23
May 28 00
May 28 01
Month Day Hour
Region
Release
Breach
Spit Island
Digested
N

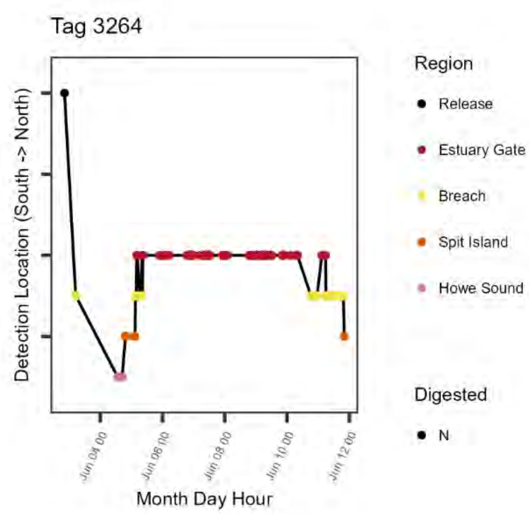

Tag 3238
Detection Location (South -> North)
Month Day Hour
Region
Release
Breach
Spit Island
Howe Sound
Digested
N

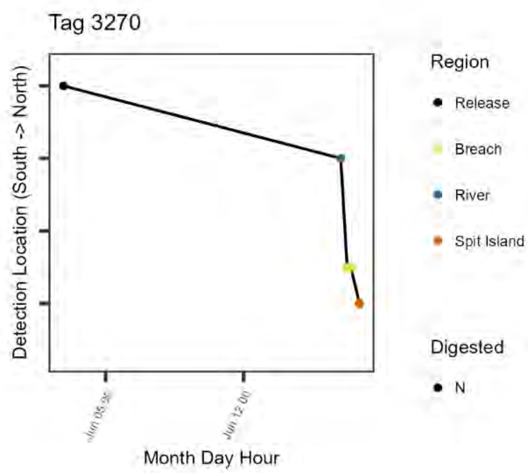

Tag 3240
Detection Location (South -> North)
Month Day Hour
Region
Release
Box Culvert
Estuary Gate
Breach
River
Spit Island
Digested
N

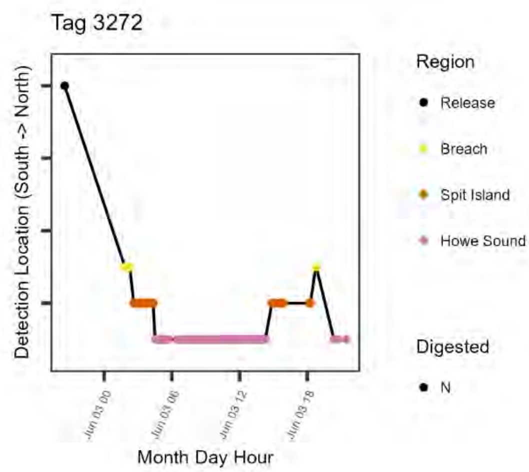

Tag 3242
Detection Location (South -> North)
Month Day Hour
Region
Release
Breach
Howe Sound
Digested
N

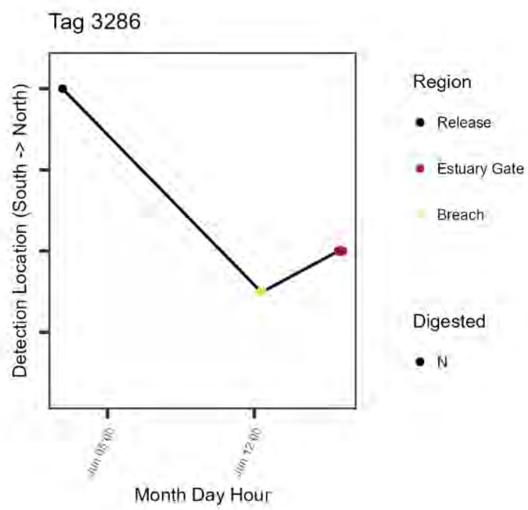

Tag 3258
Detection Location (South -> North)
Month Day Hour
Region
Release
Estuary Gate
Breach
Digested
N

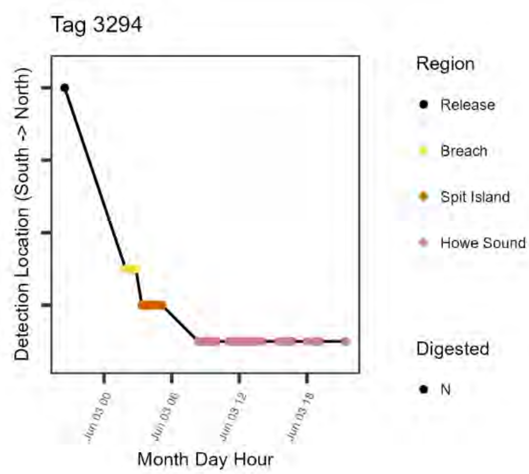

Tag 3262
Detection Location (South -> North)
Month Day Hour
Region
Release
Breach
Digested
N


Tag 3264
Detection Location (South -> North)
Month Day Hour
Region
Release
Estuary Gate
Breach
Spit Island
Howe Sound
Digested
N

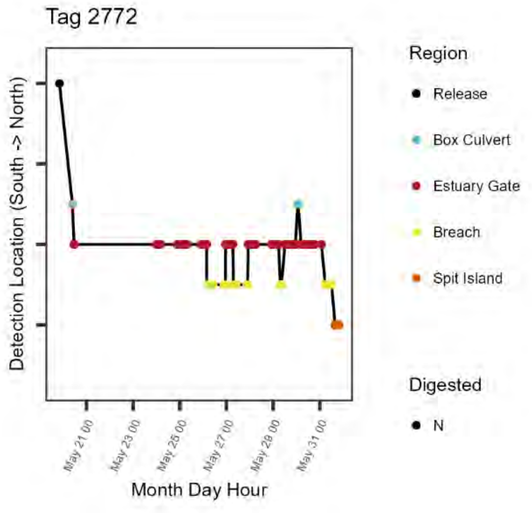

Tag 3270
Detection Location (South -> North)
Month Day Hour
Region
Release
Breach
River
Spit Island
Digested
N

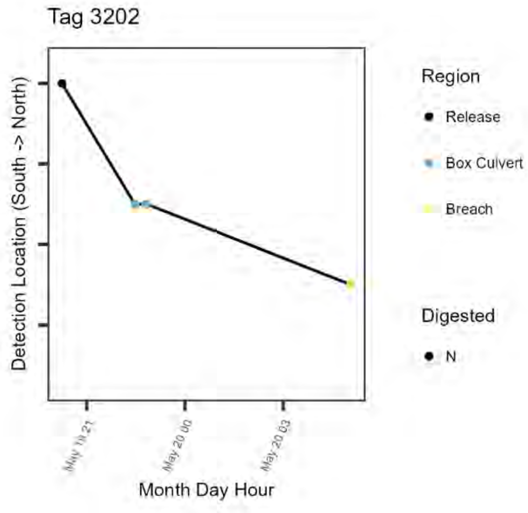

Tag 3272
Detection Location (South -> North)
Jun 03 00
Jun 03 06
Jun 03 12
Jun 03 18
Month Day Hour
Region
Release
Breach
Spit Island
Howe Sound
Digested
N

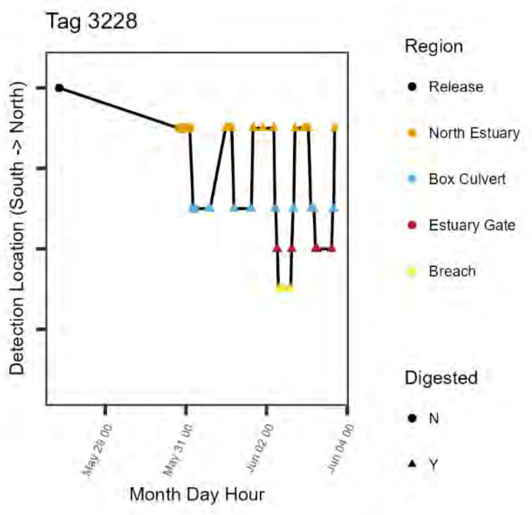

Tag 3286
Detection Location (South -> North)
Month Day Hour
Region
Release
Estuary Gate
Breach
Digested
N


Tag 3294
Detection Location (South -> North)
Jun 03 00
Jun 03 06
Jun 03 12
Jun 03 18
Month Day Hour
Region
Release
Breach
Spit Island
Howe Sound
Digested
N

Passed Berm Via Culverts (n = 3)

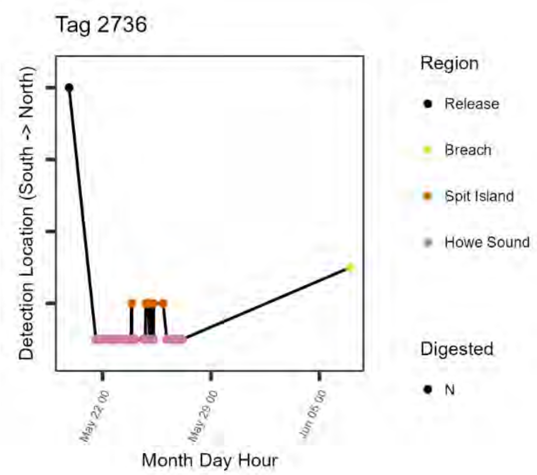


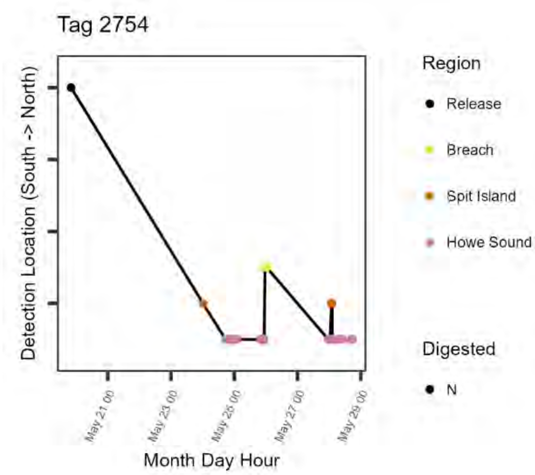


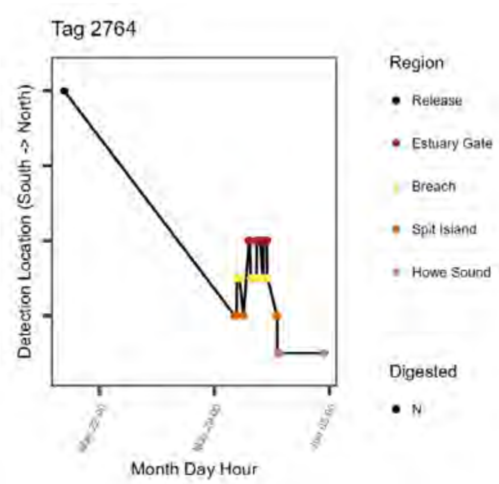


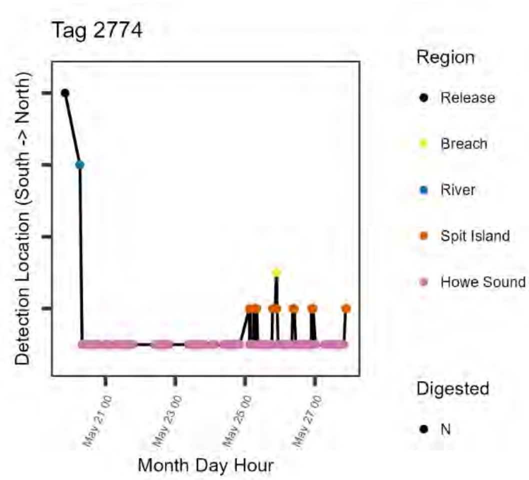
Due to first detection not being located directly at a Squamish River exit point and having a multi-day gap between release and first detection it cannot be explicitly determined when tag 3228 exited the Squamish River.

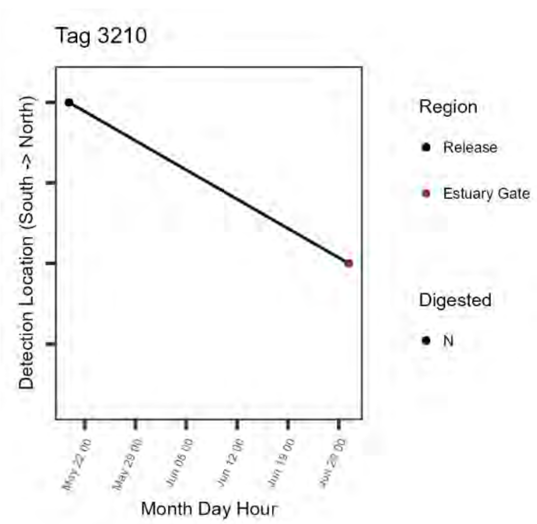
Passed Berm Via Undetermined Passage (n = 8)



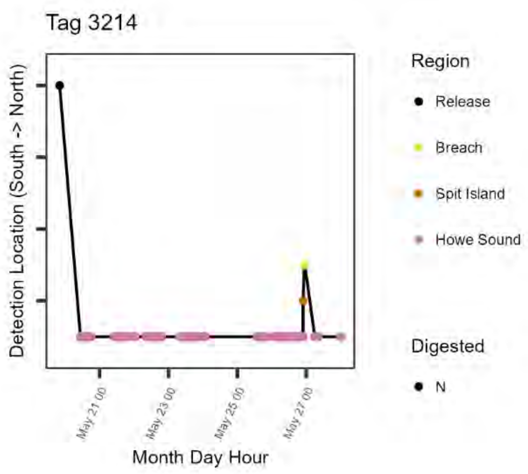


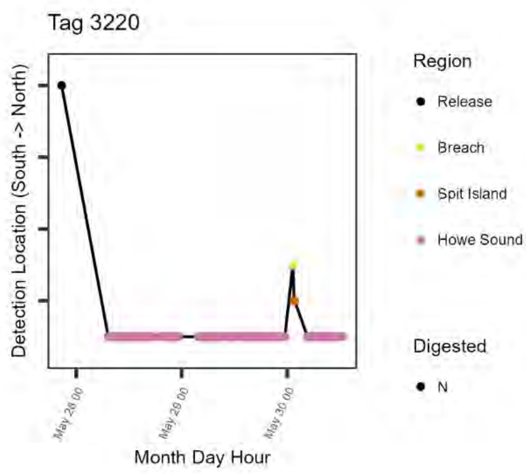


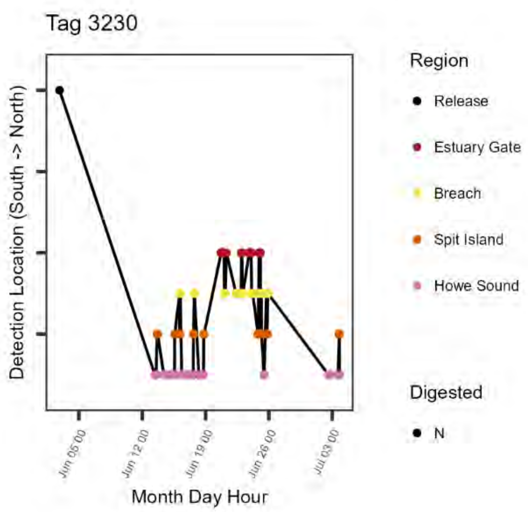




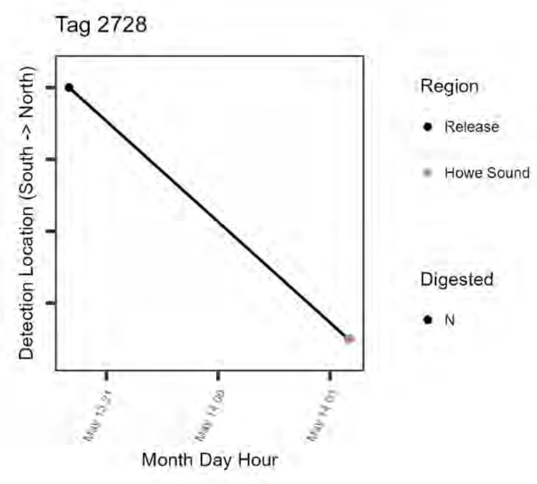
Due to first detection not being located directly at a Squamish River exit point and having a multi-week gap between release and first detection it cannot be explicitly determined when tag 3210 exited the Squamish River.

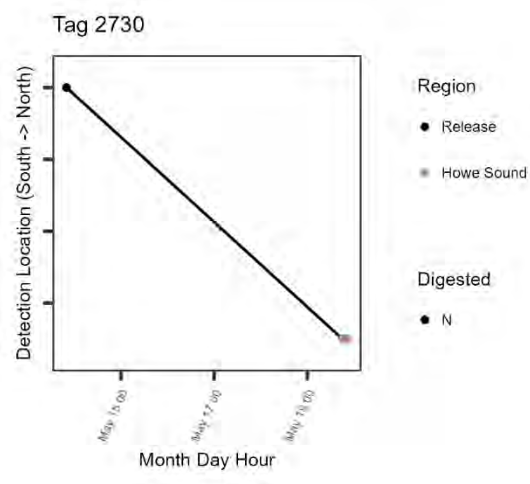

Tag 3214
Detection Location (South -> North)
May 21 00
May 23 00
May 25 00
May 27 00
Month Day Hour
Region
Release
Breach
Spit Island
Howe Sound
Digested
N

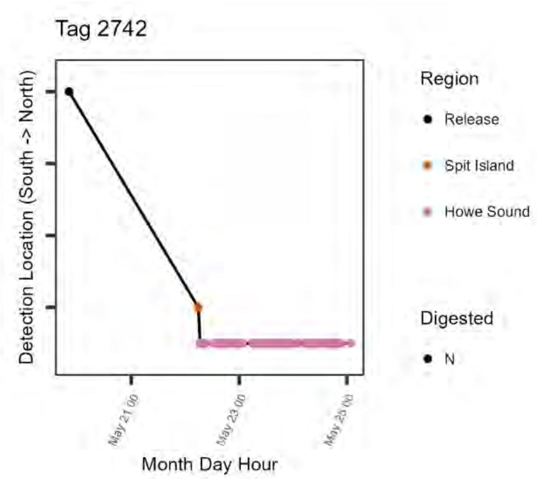

Tag 3220
Detection Location (South -> North)
May 26 00
May 28 00
May 30 00
Month Day Hour
Region
Release
Breach
Spit Island
Howe Sound
Digested
N

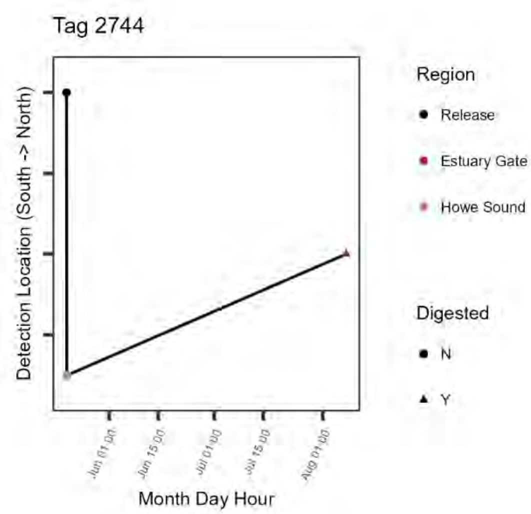

Tag 3230
Detection Location (South -> North)
Jun 05 00
Jun 12 00
Jun 19 00
Jun 26 00
Jul 03 00
Month Day Hour
Region
Release
Estuary Gate
Breach
Spit Island
Howe Sound
Digested
N

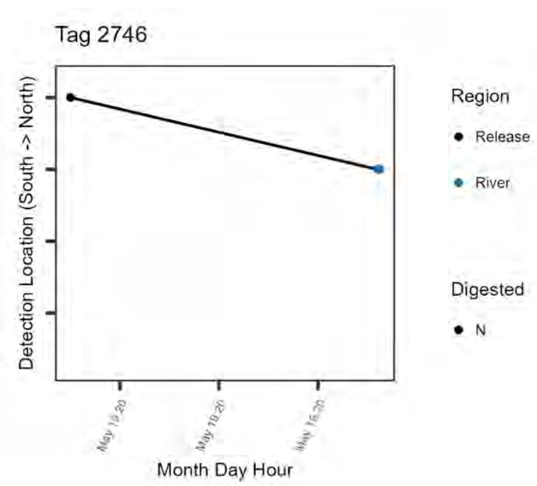
Did Not Pass Berm (n = 27)



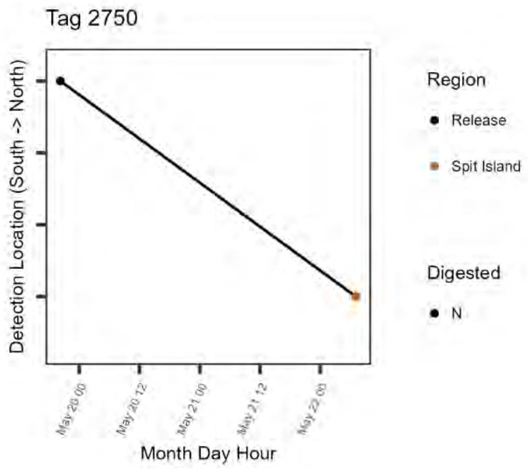


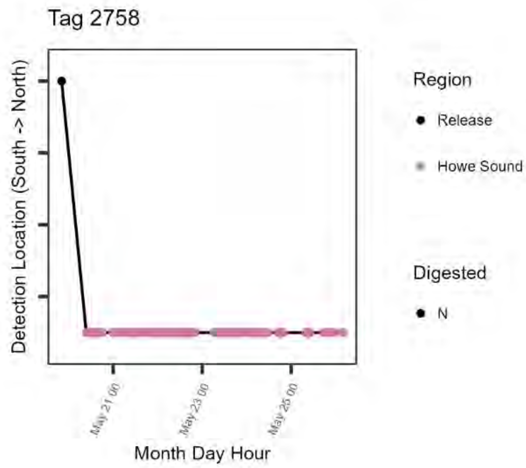


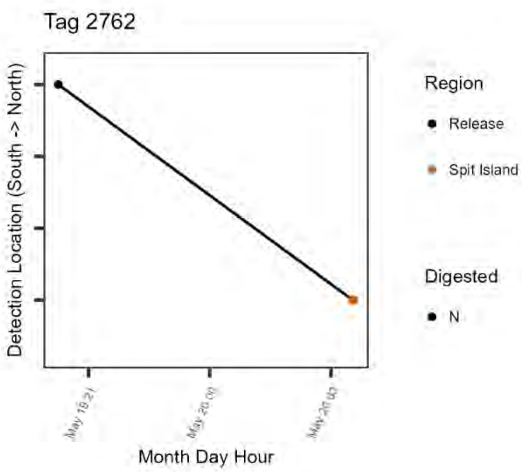


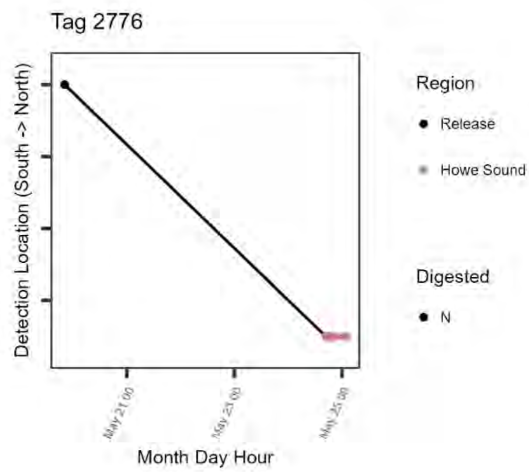


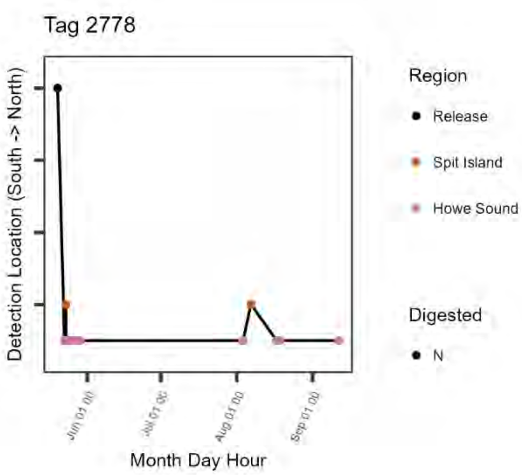
Estuary stopover duration is not calculated as ID 2746 was never detected in the estuary.

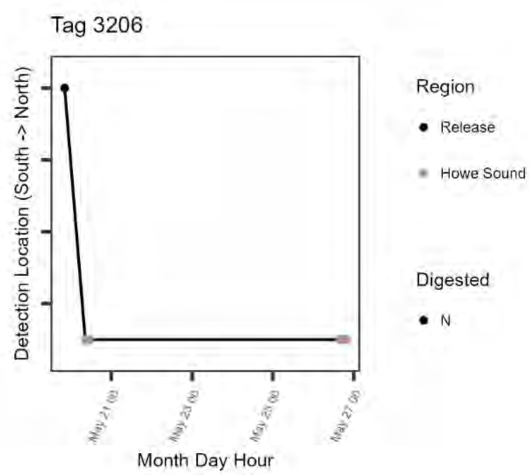

Tag 2750
Detection Location (South -> North)
Month Day Hour
May 20 00
May 20 12
May 21 00
May 21 12
May 22 00
Region
Release
Spit Island
Digested
N

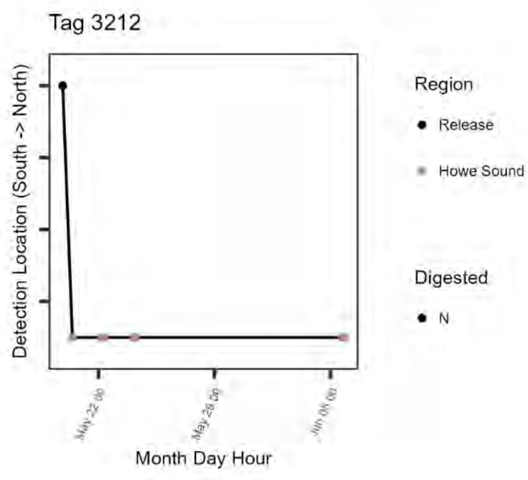

Tag 2758
Detection Location (South -> North)
Month Day Hour
May 21 00
May 23 00
May 25 00
Region
Release
Howe Sound
Digested
N

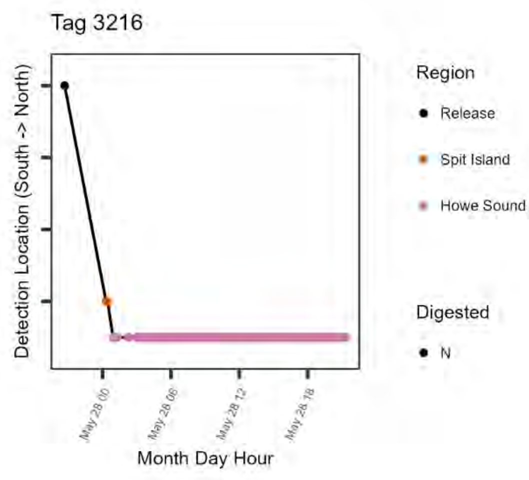

Tag 2762
Detection Location (South -> North)
Month Day Hour
Region
Release
Spit Island
Digested
N

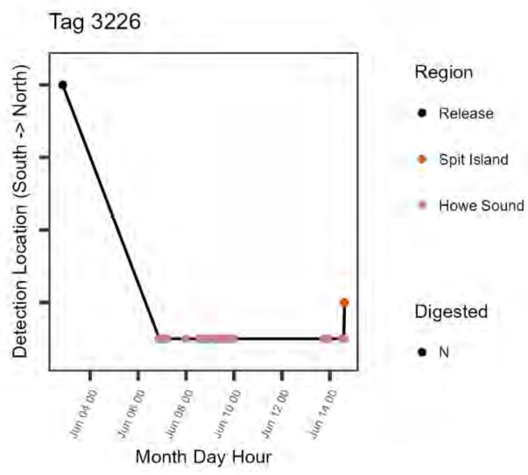

Tag 2776
Detection Location (South -> North)
Month Day Hour
May 21 00
May 23 00
May 25 00
Region
Release
Howe Sound
Digested
N

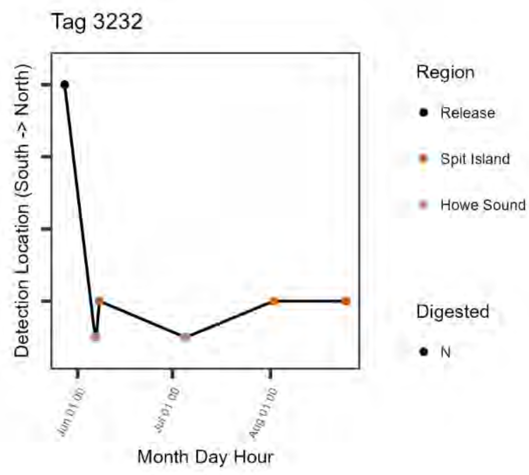

Tag 2778
Detection Location (South -> North)
Month Day Hour
Jun 01 00
Jul 01 00
Aug 01 00
Sep 01 00
Region
Release
Spit Island
Howe Sound
Digested
N

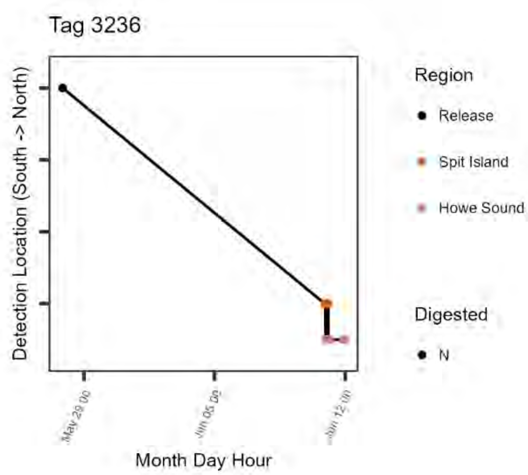

Tag 3206
Detection Location (South -> North)
Month Day Hour
May 21 00
May 23 00
May 25 00
May 27 00
Region
Release
Howe Sound
Digested
N

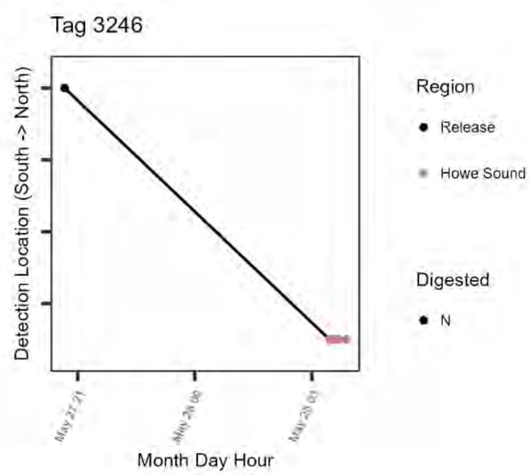

Tag 3212
Detection Location (South -> North)
Month Day Hour
Region
Release
Howe Sound
Digested
N

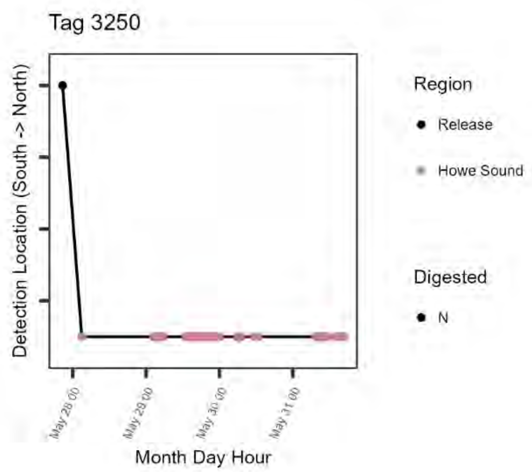

Tag 3216
Detection Location (South -> North)
Month Day Hour
Region
Release
Spit Island
Howe Sound
Digested
N

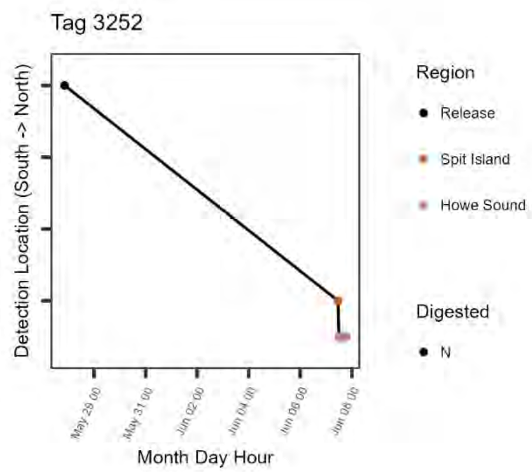

Tag 3226
Detection Location (South -> North)
Jun 04 00
Jun 06 00
Jun 08 00
Jun 10 00
Jun 12 00
Jun 14 00
Month Day Hour
Region
Release
Spit Island
Howe Sound
Digested
N

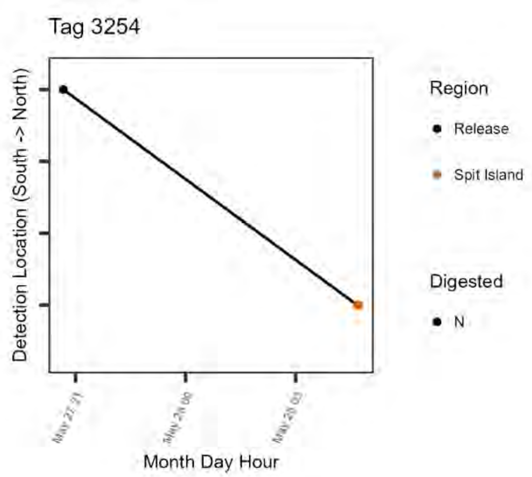

Tag 3232
Detection Location (South -> North)
Jun 01 00
Jul 01 00
Aug 01 00
Month Day Hour
Region
Release
Spit Island
Howe Sound
Digested
N

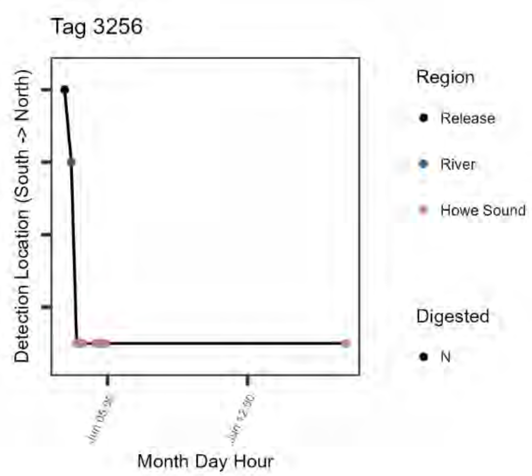

Tag 3236
Detection Location (South -> North)
Month Day Hour
Region
Release
Spit Island
Howe Sound
Digested
N

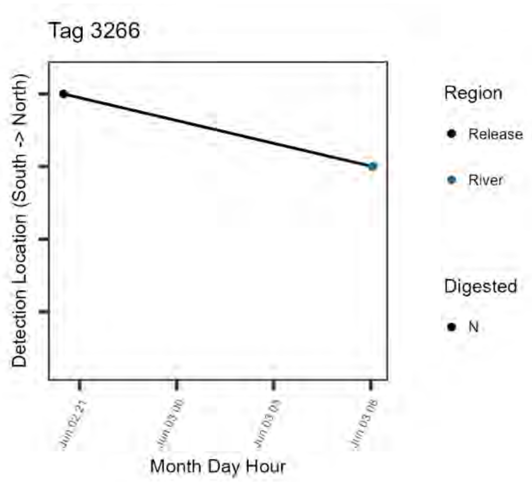

Tag 3246
Detection Location (South -> North)
Month Day Hour
Region
Release
Howe Sound
Digested
N





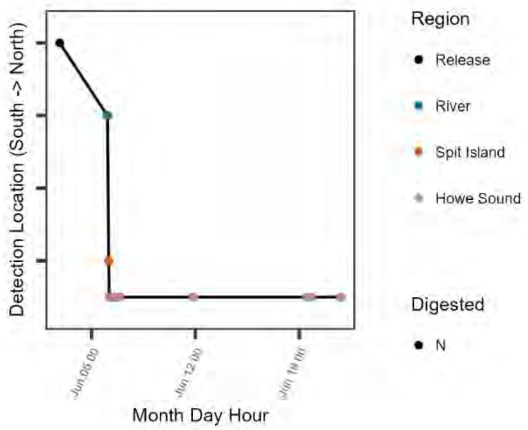






Estuary stopover duration is not calculated as ID 2746 was never detected in the estuary.

Tag 3268



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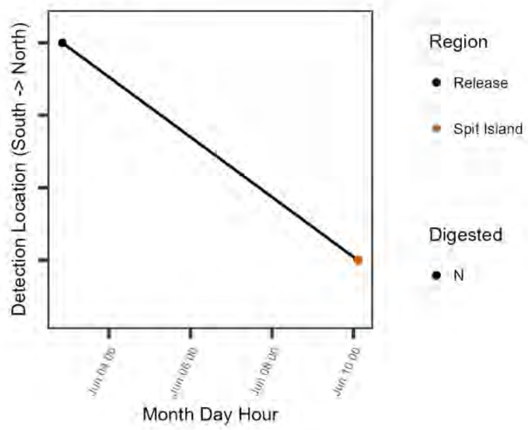

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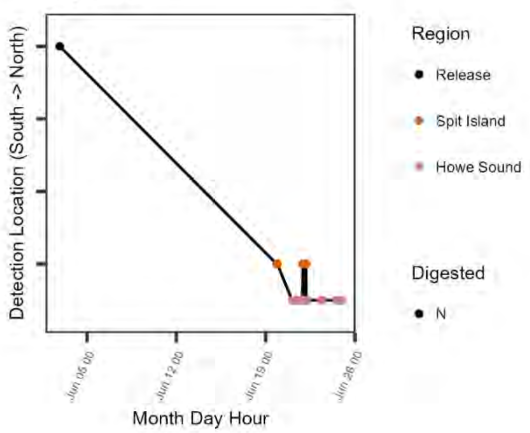

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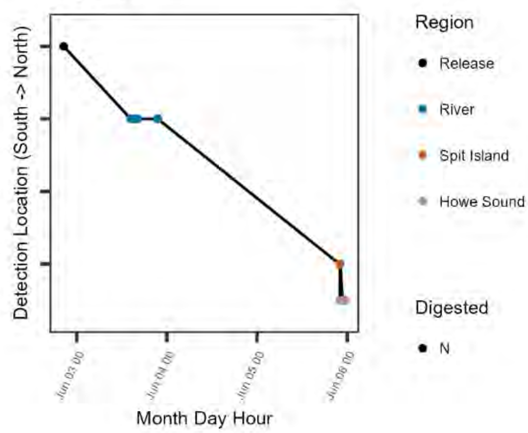

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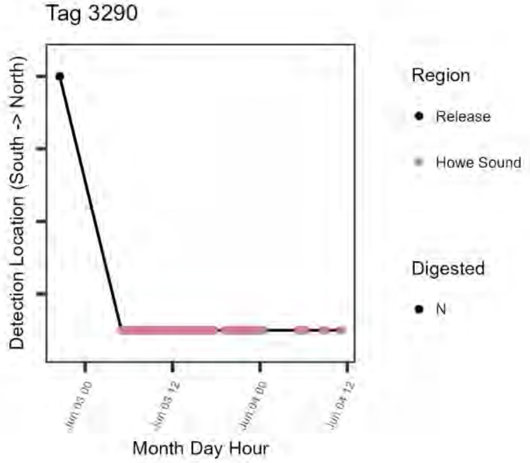

Appendix B: Hydrologic Conditions at Time of Passage

Discharge and tide conditions at the time of passage from the Squamish River through the box culverts and breach by tagged Chinook Salmon in 2023. Fish passing through undetermined passages or at undetermined times are not included. Discharge at mouth of Squamish River reported (08GA022) including the Cheakamus (08GA043) and Mamquam (08GA075) tributaries. Data obtained from the Water Survey of Canada (Environment Canada 2023). Predicted tide height obtained from station 07811 (Environment Canada 2022a).

ID	Release Time	Time of passage	Days to passage	Passage Route	Receiver	Discharge (m³s)	Tide height (m)	Tide Phase
2760	2023-05-19 20:15	2023-05-19 20:37	0	Breach	Breach D	990	4.50	ebb
3218	2023-05-19 20:15	2023-05-19 21:48	0.1	Breach	Breach D	1008	4.16	ebb
2738	2023-05-19 20:15	2023-05-20 4:30	0.3	Breach	Breach D	1100	4.19	flood
3204	2023-05-19 20:15	2023-05-20 5:33	0.4	Breach	Breach D	1097	4.32	slack
2756	2023-05-19 20:15	2023-05-20 18:10	0.9	Breach	Breach D	910	3.97	flood
2770	2023-05-19 20:15	2023-05-21 6:11	1.4	Breach	Breach C	1020	4.22	ebb/ slack
2752	2023-05-19 20:15	2023-05-21 6:39	1.4	Breach	Breach D	1015	4.17	ebb
2748	2023-05-19 20:15	2023-05-25 23:13	6.1	Breach	Breach D	600	4.43	flood
3198	2023-05-27 20:40	2023-05-27 23:55	0.1	Breach	Breach E	750	4.20	flood
3234	2023-05-27 20:40	2023-05-28 0:31	0.2	Breach	Breach E	758	4.34	flood
3240	2023-05-27 20:40	2023-05-28 2:10	0.2	Breach	Breach D	783	4.40	ebb
2766	2023-05-27 20:40	2023-05-28 4:49	0.3	Breach	Breach E	804	3.57	ebb
3238	2023-05-27 20:40	2023-05-28 6:47	0.4	Breach	Breach E	800	2.91	ebb
3272	2023-06-02 20:30	2023-06-03 1:50	0.2	Breach	Breach D	422	3.83	flood
3294	2023-06-02 20:30	2023-06-03 1:54	0.2	Breach	Breach D	422	3.86	flood
3224	2023-06-02 20:30	2023-06-03 4:26	0.3	Breach	Breach E	435	4.38	ebb/ slack
3264	2023-06-02 20:30	2023-06-03 5:07	0.4	Breach	Breach E	438	4.30	ebb
3262	2023-06-02 20:30	2023-06-03 15:07	0.8	Breach	Breach D	408	2.32	flood
3258	2023-06-02 20:30	2023-06-04 21:39	2	Breach	Breach D	408	4.52	ebb
3242	2023-05-27 20:40	2023-06-11 23:23	15.1	Breach	Breach D	602	4.19	flood
3286	2023-06-02 20:30	2023-06-12 7:24	9.5	Breach	Breach E	655	2.05	ebb
3270	2023-06-02 20:30	2023-06-17 6:12	14.4	Breach	Breach C	526	3.78	ebb

3202	2023-05-19 20:15	2023-05-19 22:28	0.1	Culvert 3	Culvert 3	1023	3.90	ebb
2772	2023-05-19 20:15	2023-05-20 9:33	0.6	Culvert 4	Culvert 4	1035	2.22	ebb