BOTTLENECKS TO SURVIVAL

OVERWINTER SURVIVAL OF HATCHERY COHO SALMON IN EARTHEN CHANNELS

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INTRODUCTION

Since its inception in 1977, the Salmon Enhancement Program (SEP) has played a pivotal role in enhancing the freshwater productivity of salmon populations across British Columbia (BC; MacKinlay et al. 2004). Enhancement of salmon in hatcheries is intended to support fisheries, conserve and rebuild populations, and engage communities in salmon stewardship. Hatchery-reared salmon generally exhibit lower ocean survival rates than their wild counterparts (Beamish et al. 2012; Irvine et al. 2013; Zimmerman et al. 2015), which may limit the effectiveness of hatchery production. However, a recent study by Irvine (2020) suggested that hatchery survival rates could be underestimated due to methodological biases in marine survival estimation. Specifically, prerelease mortality is often underestimated, biasing release numbers high and subsequent survival low. As a result of his work, Irvine called for additional analysis of survival biases to determine the extent of the bias in hatchery production.

To investigate prerelease mortality of hatchery-reared coho salmon (*Oncorynchus kisutch*) in BC, the Bottlenecks to Marine Survival Program, in collaboration with SEP, initiated the multi-year "*Coho Earthen Channel Overwinter Survival Study*". Specifically, the study focused on overwinter survival of coho in earthen ponds or channels – specialized, man-made, pond-like habitats excavated from the earth, designed for juvenile salmon rearing. After emergence in the winter, coho are often reared in circular tubs, concrete raceways or Burrow's ponds, marked (with coded wire tags [CWTs] and adipose fin clips) in the fall or winter, and transferred to earthen ponds where they rear for approximately one winter (August to May) until release the following spring. Given the extended period between tagging and release, it is expected that a proportion of those fish do not survive, affecting final release estimates. Some hatcheries apply a blanket mortality rate (i.e. often 1-5% mortality depending on the hatchery) to account for these losses, while others do not apply any correction for prerelease mortalities. Nevertheless, mortality rates are expected to be highly variable year to year and between facilities. Predators, disease and environmental stressors can cause significant mortality in earthen channels and it is believed that current mortality rates are underestimated.

While CWTs provide valuable information on overall survival of hatchery releases, they require lethal sampling for the tags to be recovered and manual processing in laboratories to extract and read the codes. Thus, passive observations of survival between tagging and return are not possible with this tagging method. Passive Integrated Transponder (PIT) tags allow for the fates of individual fish to be captured by reading the individual tag code when a fish passes over an antenna. They are not battery powered and are relatively affordable compared to other individual tagging methods. By PIT tagging hatchery coho prior to release and installing antennas within the earthen channel and downstream of the hatchery, survival rates in earthen channels can be evaluated using a passive mark recapture design.

Our primary objective was to estimate survival of juvenile coho salmon during earthen channel residency at four hatchery facilities on the east coast of Vancouver Island: Big Qualicum River, Nanaimo River, Quinsam River and Puntledge River Hatcheries. Juvenile coho from brood years 2019 and 2020 were PIT-tagged and overwintered in outdoor earthen channels at each hatchery for variable lengths of time. PIT receivers were installed at the outlet of each earthen channel to detect the outmigrating tagged coho upon release. The detection efficiency of each PIT receiver was calculated, ultimately allowing estimation of earthen channel survival for each cohort. A secondary objective was to estimate the survival to adult return for each cohort, which would provide further information on straying rates and age-2 return rates ('jacks') for each population. These hatchery- and year-specific survival rates can then be used to correct hatchery release numbers and improve the accuracy of hatchery survival estimates.

METHODS

Our study area is concentrated along the east coast of Vancouver Island, the northeastern portion of the Salish Sea, and includes three major operational SEP facilities (Quinsam, Puntledge, Big Qualicum) and one SEP community hatchery (Nanaimo; Figure 1; Table 1).

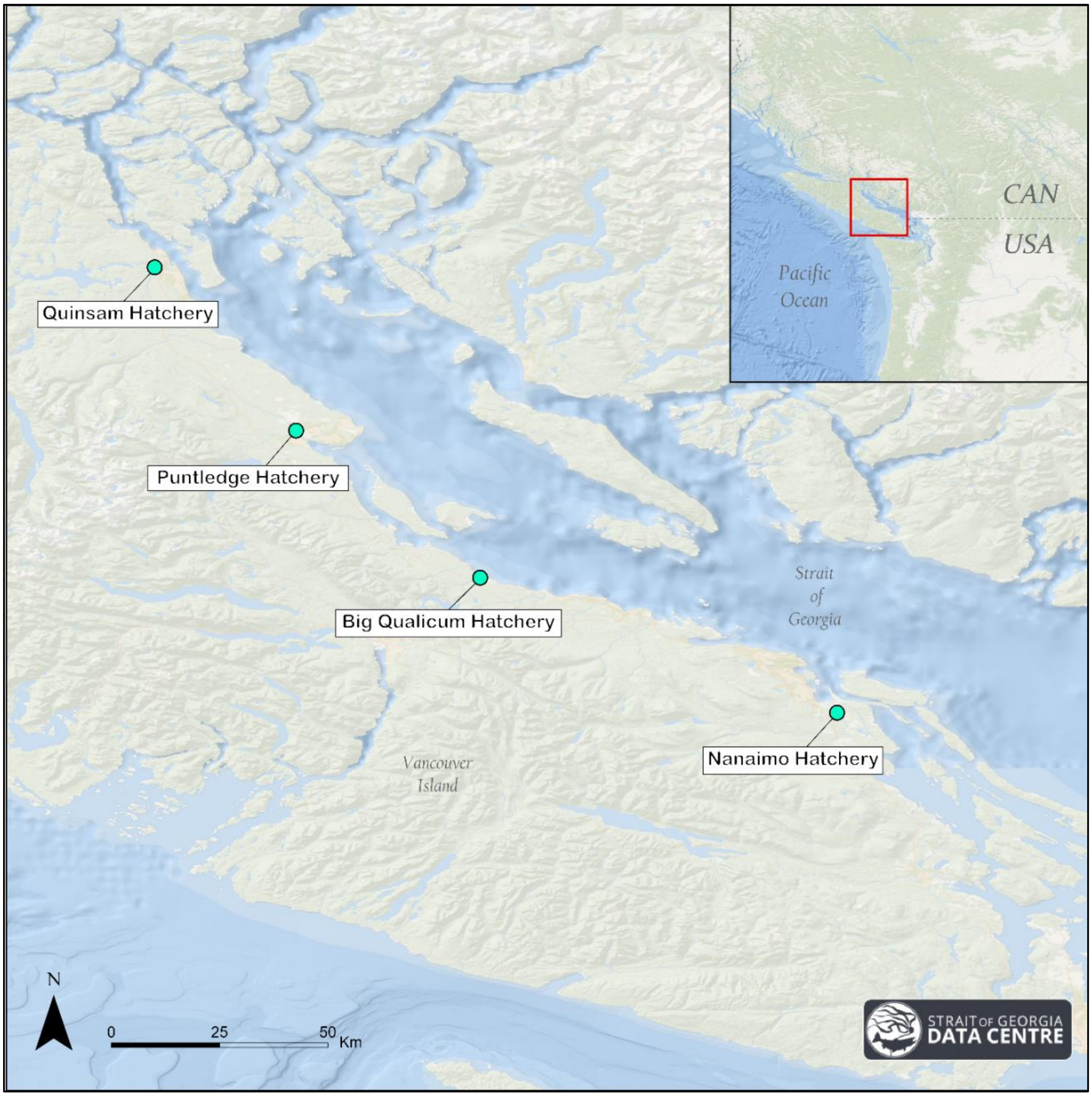

Figure 1. Map of the four hatcheries involved in the earthen channel survival analysis.

The installation of multiple PIT tag antennas is required to detect PIT tagged fish during their juvenile freshwater outmigration from the earthen channels and when they return to spawn. PIT antennas (single) and arrays (multiple antennas) come in a variety of sizes and were constructed and configured specifically to suit the requirements of each site (Figures 2-5). For a more detailed description of our PIT antenna installations, see the report "Bottlenecks to Survival Synthesis Report 2024".

The earthen channel PIT receivers were installed close to the release date, meaning these receivers were not in place or operational for the entire period of earthen channel residency.

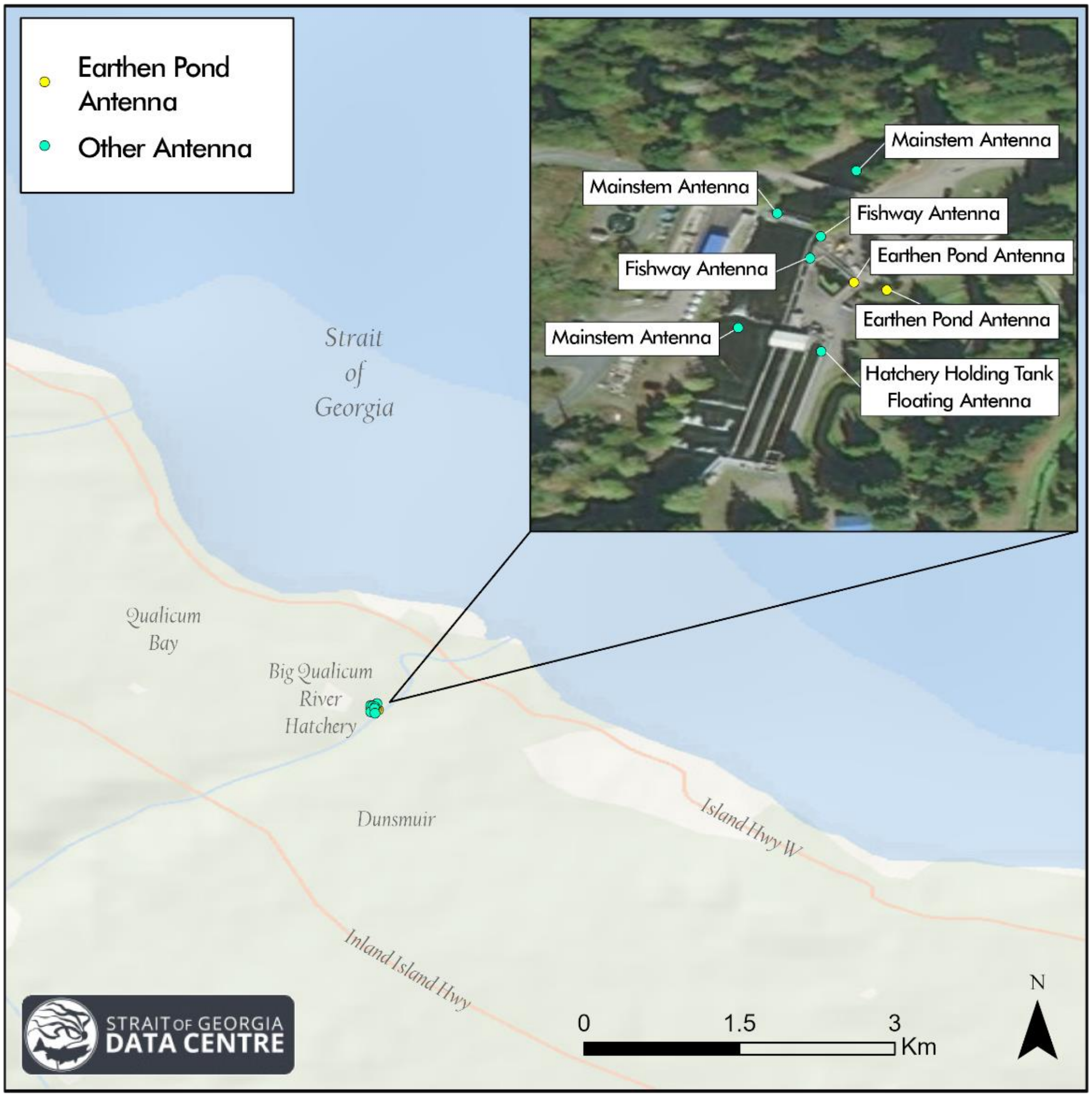

Figure 2. Location of earthen channel/pond antennas and other PIT antennas on the Big Qualicum River system.

Figure 3. Location of earthen channel/pond antennas and other PIT antennas on the Nanaimo River system.

Figure 4. Location of earthen channel/pond antennas and other PIT antennas on the Puntledge River system.

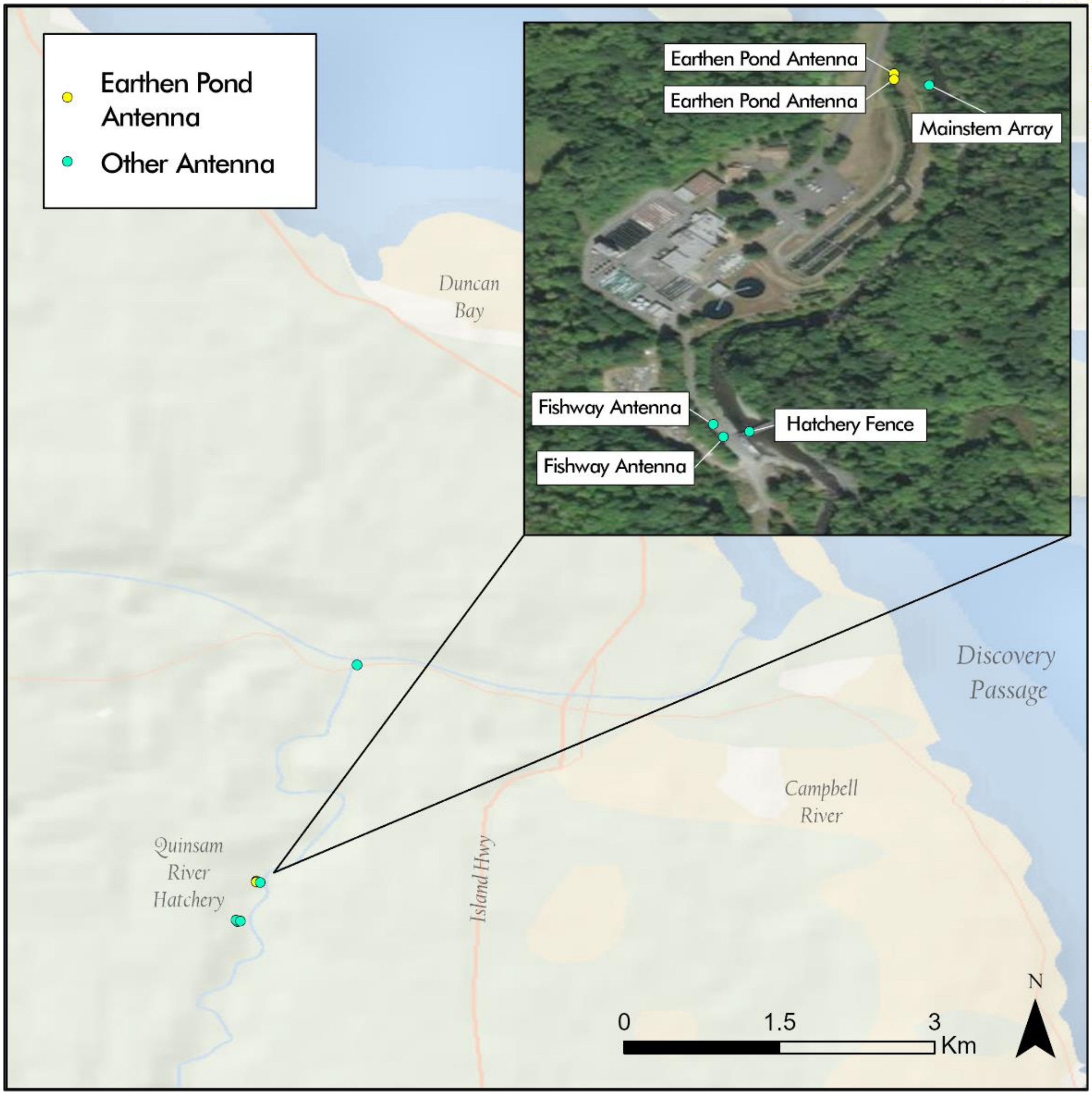

Figure 5. Location of earthen channel/pond antennas and other PIT antennas on the Quinsam River system.

Table 1. Summary of the total annual releases of coho from each hatchery, brood year, number of PIT tags applied each year and tagging dates, numbers of tagged fish ponded (i.e. transferred to earthen channels) and ponding dates, as well as release dates and residence length in the channels.

HATCHERY	TOTAL ANNUAL RELEASES	BROOD YEAR	PIT TAGGING DATE	TOTAL # PIT TAGGED	EARTHEN CHANNEL PONDING DATE	# PIT FISH PONDED	RELEASE DATE	CHANNEL RESIDENCE (DAYS)
Big Qualicum	400,000	2019	2021-04-14	5,000	2021-04-14	5,000	2021-05-04	20
		2020	2021-12-01		2021-12-20	4,886	2022-05-16	147
Nanaimo	84,000	2019	2021-03-17	5,000	2021-04-20	4,719	2021-05-04	14
		2020	2022-01-25		2022-02-16	4,978	2022-05-13	86
Puntledge	100,000	2019	2021-04-12	5,000	2021-05-15	4,963	2021-05-21	6
		2020	2021-12-02		2022-01-12	4,924	2022-05-19	127
Quinsam	400,000	2019	2020-09-17	5,000	2020-12-07	4,957	2021-05-10	154
		2020	2021-11-08		2021-11-30	4,949	2022-05-04	155

Fish handling and tagging

A total of 5,000 coho salmon juveniles were tagged for each cohort, which resulted in a total of 40,000 tagged fish across the two brood years and four facilities. Coho were removed from their primary populations and kept off food for 24 hours prior to tagging (Atkinson and Balfour 2024). On the day of tagging, coho were transferred from the holding tank into a static freshwater bath prepared with 50 mg/L of Tricaine methanesulfonate (TMS), with a sodium bicarbonate ($NaHCO_3$) buffer to reduce acidification. All anesthetization procedures followed the Canadian Council on Animal Care's standardized methodology (Ackerman et al. 2005; I. Keith, DFO SEP, pers. comm. 2021). All anesthetic baths included Vidalife (Syndel Canada, Nanaimo, BC), a water conditioner that preserve's the fish's natural mucous layer, preventing abrasions.

Once coho were adequately anesthetized (i.e., slowed breathing, subdued response to touch, movements slowed), they were handled carefully and quickly to reduce the exposer to both TMS and air. A 12 mm FDX-B PIT tags (Biomark, Boise, ID) was inserted into the peritoneal cavity at a 45-degree angle along the midline of the belly, just above the pelvic girdle (Figure 6). Only juveniles with >70 mm fork length were tagged to minimize the tag burden (Vollset et al. 2020).

Rearing and monitoring of the fish post-tagging was unique between each location due to site specific infrastructure. Generally, fish were moved directly into their holding circular tub (4.8 m radius x ~1 m deep) via aluminum flow-through tables immediately post-tagging. Tagged coho were monitored daily (except for on weekends) for tag rejections and tagging related mortalities (see Atkinson and Balfour 2024 report "Tagging Related Mortality and Rejections During a Large-Scale Chinook and Coho Marine Survival Project"). "Squibs", or tags that failed to inject and were subsequently found in the discarded needles post-tagging, were also recorded. After a minimum two-week monitoring period, the PIT tagged cohort were mixed back in with the larger untagged cohort.

There were a few notable exceptions to this process. In 2021, the Puntledge tagging event used static recovery bins to hold fish immediately post tagging before they were transferred into the long-term post-tag monitoring circular tub. Also in 2021, Big Qualicum coho were immediately released via flow through pipes into the earthen channel with no post-tagging holding period. In all years, the Quinsam hatchery required fish to be moved from flow-through recovery tanks at each tagging station into a larger metal tank (600 L) equipped with an air stone, to be transported directly into the long-term circular recovery tub.

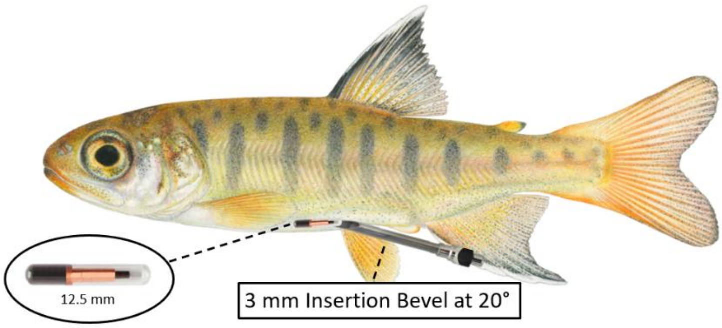

Figure 6. PIT tags are inserted into the body cavity of each fish anterior to the pelvic girdle using a sterile, one-time-use hypodermic needle (Illustration by Joseph R. Tomelleri, modified by J. Dingwall).

Releases and mobile scanning

Coho were released from the earthen channel in early to mid-May each year as per the hatchery release schedules (Table 1). Coho are typically released at the end of the workday, wherein the gate of the earthen channel is removed by hatchery staff and coho are free to outmigrate volitionally. However, the exodus occurs quite rapidly and the entirety of the population is typically moved out of the channels within 48 hrs.

To help inform earthen channel results, mobile PIT antennas (either custom built or Biomark's HPR Plus) were used to scan the floor of the earthen channel post-release to detect any overwintering tags in the substrate. Where possible, mobile scanning was conducted after the channels were dewatered and prior to cleaning. Crews swept the channel from opposite ends and crossed at the mid-point to ensure complete coverage.

Data analysis

All statistical analyses were performed using the R statistical software (version 4.2.2).

Data preparation

Tag rejections and tagging related mortalities that occurred during the post-tagging monitoring period were removed from the data set prior to analysis. Escapees from the earthen channel were identified if a fish was detected on any external PIT receiver during the period of earthen channel holding for each system. Known escapees that were detected were also removed from any further analyses.

Earthen channel PIT receiver detection efficiency

For each system, we first calculated the detection efficiency of the earthen channel PIT receiver. Any known earthen channel-related mortalities and escapees were removed from these analyses; therefore, only presumed earthen channel survivors were considered. Detection efficiency was calculated by first identifying future detections of any presumed earthen channel survivor on all other PIT receivers across the region, not including the earthen channel PIT receiver. Future detections included any detections on downstream PIT receivers during outmigration, adult returns to natal systems and adult returns to non-natal systems. If a tagged fish was detected at any PIT receiver following earthen channel release, that fish was a confirmed survivor of the earthen channel period and was therefore assumed to have passed over the earthen channel PIT receiver. Earthen channel PIT receiver *detection efficiency* was ultimately estimated by calculating the percentage of these confirmed earthen channel survivors detected on future PIT receivers (*number of future detections*) that were also detected on the earthen channel PIT receiver (*number of future detections also detected on the earthen channel PIT receiver*).

$$Detection\ efficiency = \frac{Number\ of\ future\ detections\ also\ detected\ on\ earthen\ channel\ PIT\ receiver}{Number\ of\ future\ detections}\ x\ 100 \qquad (1)$$

Confidence intervals for our detection efficiency estimates were calculated as the Wilson 95% confidence intervals for the Normal distribution (Agresti and Coull, 1998; Agresti and Caffo, 2000).

Earthen channel survival

To calculate earthen channel survival, we compared the number of unique tag numbers detected on the earthen channel PIT receivers to the known number of fish that were transferred to the earthen channel. However, the detection efficiency of the PIT receiver needed to be taken into consideration. The actual number of unique tag numbers detected on an earthen channel PIT receiver gives us the number of *confirmed survivors*. However, we know that the PIT receivers are not 100% efficient and some tags pass over without being detected. Using the *detection efficiency* of each PIT receiver, we were therefore able to calculate the number of *assumed survivors* that would have been detected by the PIT receiver, if the receiver was 100% efficient.

$$Assumed\ survivors = \frac{Confirmed\ survivors}{Detection\ efficiency}\ x\ 100 \qquad (2)$$

Earthen channel *survival* could then be estimated by calculating the percentage of *assumed survivors* compared with the *total number of tagged fish* that were transferred to the earthen channel. The *total number of tagged fish* includes all PIT tagged fish with tagging-related mortalities, squibs, rejects, and escapees removed.

$$Survival = \frac{Assumed\ survivors}{Total\ number\ of\ tagged\ fish}\ x\ 100 \quad (3)$$

Earthen channel PIT receiver detection efficiency with known error distributions were used to calculate earthen channel survival and confidence intervals were accordingly calculated using the propagation of error, assuming normal distribution and independent variables (Taylor, 1997).

For any systems where the number of assumed survivors was estimated to be greater than the total number of tagged fish, survival was additionally calculated by only considering the number of confirmed mortalities as a percentage of the total number of tagged fish.

In order to account for large differences in the residency time of fish in each earthen channel (see Table 1), we calculated the average daily mortalities for each earthen channel. Average daily mortalities were estimated by dividing the number of *assumed survivors* by the earthen channel *duration* (number of days in earthen channel).

$$Average\ daily\ mortalities = \frac{Assumed\ survivors}{Duration} \quad (4)$$

Survival to adult return

Finally, survival to adult return was calculated for all cohorts. Survival to adult return was measured in two ways: 1) from the date of entry into the earthen channel for each system and 2) from the date of release from the earthen channel. Adult returns were identified as any tagged earthen channel coho salmon detected returning on PIT receivers across all river systems. Adult returns included those returning as both age-2 ('jacks') and age-3 fish. These adult returns also included straying fish (fish that were detected returning on PIT receivers in non-natal rivers). The number of fish detected as strays was recorded for each cohort.

For each system, the total number of unique tags detected across all PIT receivers (within the time frame for adult spawning migrations, July to February) was calculated to give us the total number of *confirmed adult detections*. However, due to imperfect detection efficiency of PIT receivers, we also estimated the *adjusted adult detections* of the mainstem PIT receiver in each system. Detection efficiencies of the PIT receivers detecting adult returns in each river system were calculated as per Conolly (2010) for a two-array system and Connolly *et al.* (2008) for systems with more than two arrays. *Adjusted adult return detections* were then calculated using the *confirmed adult detections* at the mainstem PIT receiver and the calculated detection efficiency of that receiver:

$$Adjusted\ adult\ detections = \frac{Confirmed\ adult\ detections}{Detection\ efficiency}\ x\ 100 \quad (5)$$

Survival from ponding to adult return spans from the date of transfer into the earthen channel to spawning migration return for each cohort. Earthen channel mortality is therefore included in this survival to adult return estimate. This survival estimate was calculated as the *adjusted adult detections* as a percentage of the *total number of tagged fish* that were initially transferred into the earthen channel on the ponding date.

$$Survival\ from\ ponding\ to\ adult\ return = \frac{Adjusted\ adult\ detections}{Total\ number\ of\ tagged\ fish}\ x\ 100 \tag{6}$$

Because the *adjusted adult detections* of each study cohort have a given error distribution due to a level of uncertainty surrounding the detection efficiency of the adult return PIT receivers, 95% confidence intervals for 'survival from ponding to adult return' were calculated using the delta method (O'Hagan and Forster, 2009). The delta method utilizes a Taylor expansion, with the covariance matrix representing the variability and interdependencies among the random variables, to estimate the variance of the survival estimate. Confidence intervals can subsequently be calculated using this variance.

Survival from earthen channel release to adult return spans from the date of release from the earthen channel to spawning migration return for each system. Earthen channel mortality is therefore not included in this survival estimate. The number of earthen channel *assumed survivors* has previously been calculated for each system using the earthen channel PIT receivers (Equation 2). The survival from earthen channel release to adult return was calculate as the *adjusted adult returns* as a percentage of the earthen channel *assumed survivors*:

$$Survival\ from\ release\ to\ adult\ return = \frac{Adjusted\ adult\ detections}{Assumed\ survivors}\ x\ 100 \tag{7}$$

Confidence intervals for this 'survival from release to adult return' estimate were calculated in a similar method to that of 'survival from ponding to adult return' above. However here, the confidence interval estimate considers both the error distribution surrounding the adult return PIT receiver detection efficiencies and the error distribution surrounding the earthen channel PIT receiver detection efficiencies.

RESULTS

PIT-tagging

The number of tagging-related mortalities, squibs, and tagging rejections resulting from the tagging process for each study cohort is summarized in Table 2. The number of earthen channel mortalities detected by hatchery technicians is also provided. Tagging-related mortalities were low and averaged 1% across facilities and years. The highest tagging-related mortalities occurred at Nanaimo in 2021. Only 0.5% of applied tags were rejected on average. Subsequent earthen channel mortalities reported by hatchery technicians averaged 2.4% but ranged from 0.1-8.6%, with higher mortalities reported at Big Qualicum and Nanaimo in 2022.

We detected a total of six escapees from earthen channel across all systems and study years. Four escapees were detected from the Big Qualicum 2022 earthen channel release cohort; although, one of these escapees was detected on the Big Qualicum fishway PIT receivers on April 9th, 2022, which is before the earthen channel ponding date, suggesting these fish escaped from the hatchery facility as opposed to the earthen channel. One escapee was detected from the Nanaimo 2022 earthen channel and one escapee was detected from the Puntledge 2022 earthen channel release cohort (Table 2). No escapees were detected from any system in 2021.

Table 2. The number of tagging-related mortalities, tag rejections, squibs, and recovered tags where the fate of the fish was unknown summed together to provide the total non-viable tags. Earthen channel mortalities confirmed by hatchery technicians for each cohort and the number of confirmed escapees from each earthen channel is also shown.

SYSTEM	RELEASE YEAR	TAGGING-RELATED MORTS	REJECTS	SQUIBS	UNKNOWN	NON-VIABLE TAGS POST 30 DAY HOLDING	EARTHEN CHANNEL MORTS	ESCAPEES
Big Qualicum	2021	0	0	0	0	0	5	0
	2022	58	50	0	0	0	418	4
Nanaimo	2021	210	58	0	0	79	28	0
	2022	12	9	0	0	9	348	1
Puntledge	2021	26	2	0	2	10	50	0
	2022	47	20	0	0	37	55	1
Quinsam	2021	0	0	0	39	43	16	0
	2022	7	38	11	0	61	26	0

Earthen channel PIT receiver detection efficiencies

The detection efficiencies of the earthen channel PIT receivers were highly variable between systems and years (Figure 7; Table 3). The Quinsam earthen channel PIT receivers had the lowest detection efficiency of any system (43.12 ± 7.8 % in 2021 and 52.11 ± 9.75 % in 2022). The Big Qualicum earthen channel PIT receiver had the highest detection efficiency in 2022 (90.24 ± 5.39 %).

In 2021, Big Qualicum PIT receivers were only operating in the fishway; we estimated the detection efficiency of these receivers to be 71%. In 2022, PIT receivers were operational in both the fishway migration route and mainstem migration route; these two routes represented two separate migration routes in this year and so detection efficiencies and expanded detections was calculated separately. The detection efficiency of the mainstem PIT receiver was estimated to be 78% in 2022, while the detection efficiency of the fishway PIT receiver was estimated to be 100%.

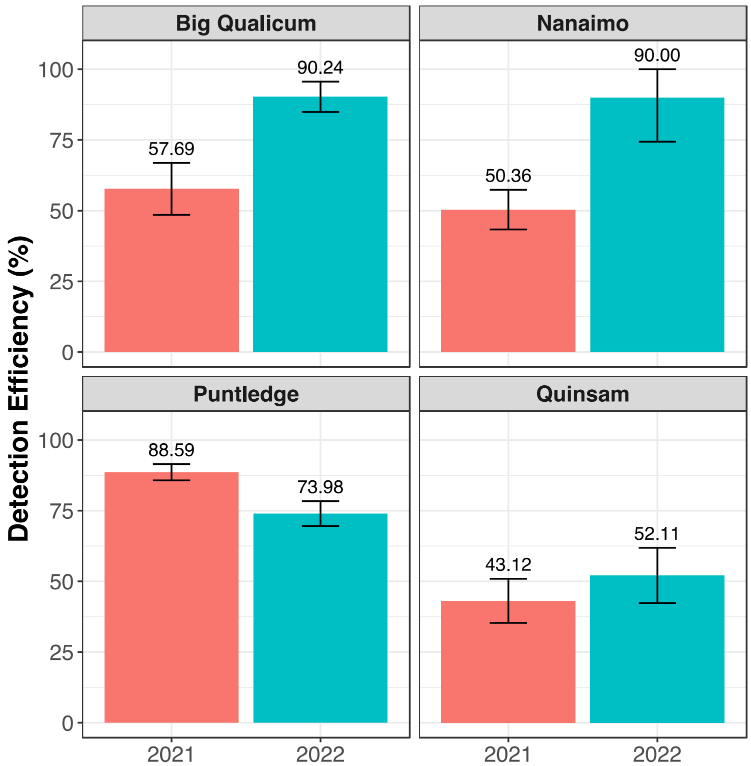

Figure 7. Detection efficiencies of earthen channel PIT receivers installed at the outlets of four earthen channels (Big Qualicum, Nanaimo, Puntledge, Quinsam). Detection efficiencies represent the percentage of PIT tagged coho salmon that passed over the PIT receiver that were successfully detected. Detection efficiencies for both release years, 2021 and 2022, are shown are shown in red and blue, respectively. Error bars represent the 95% confidence intervals.

In 2021, two separate migration routes existed during the Puntledge River spawning migration: the fishway route and the mainstem route. We therefore calculated detection efficiencies for PIT receivers in these two migration routes separately.

Table 3. Earthen channel PIT receiver detection efficiencies and earthen channel survival for each system in both 2021 and 2022.

SYSTEM	RELEASE YEAR	DETECTION EFFICIENCY (%)	95% CI	EARTHEN CHANNEL SURVIVAL (%)	95% CI	DAILY MORTALITIES	95% CI
Big Qualicum	2021	57.69	48.49 – 66.89	99.90	90.70 – 100.00	0.25	0.00 – 23.25
	2022	90.24	84.85 – 95.63	60.35	54.84 – 65.86	13.18	11.35 – 15.01
Nanaimo	2021	50.36	43.34 – 57.39	81.84	74.75 – 88.92	61.23	37.34 – 85.11
	2022	90.00	74.40 – 100.00	22.14	6.51 – 37.78	45.07	36.02 – 54.12
Puntledge	2021	88.59	85.72 – 91.45	98.99	96.12 – 100.00	8.33	0.00 – 32.11
	2022	73.98	69.58 – 78.38	90.92	56.47 – 95.37	3.52	1.79 – 5.25
Quinsam	2021	43.12	35.32 – 50.92	99.68	91.87 – 100.00	0.10	0.00 – 2.62
	2022	52.11	42.36 – 61.86	99.47	89.72 – 100.00	0.17	0.00 – 3.28

Earthen channel survival

Earthen channel survival rates were highly variable between years within each facility, as well as among facilities (Figure 8; Table 3). The exception to this was Quinsam, where survival rates were above 99% in both years. Survival rates were higher in the 2021 release cohort than the 2022 cohort across all hatcheries, with significantly lower survival in the 2022 release cohort at both Big Qualicum and Nanaimo. Quinsam had the highest survival rates (99.58%) and Nanaimo had the lowest survival rates (51.99%) when averaged over both years. Survival rates remained high (> 90%) in the Puntledge and Quinsam channels across both years.

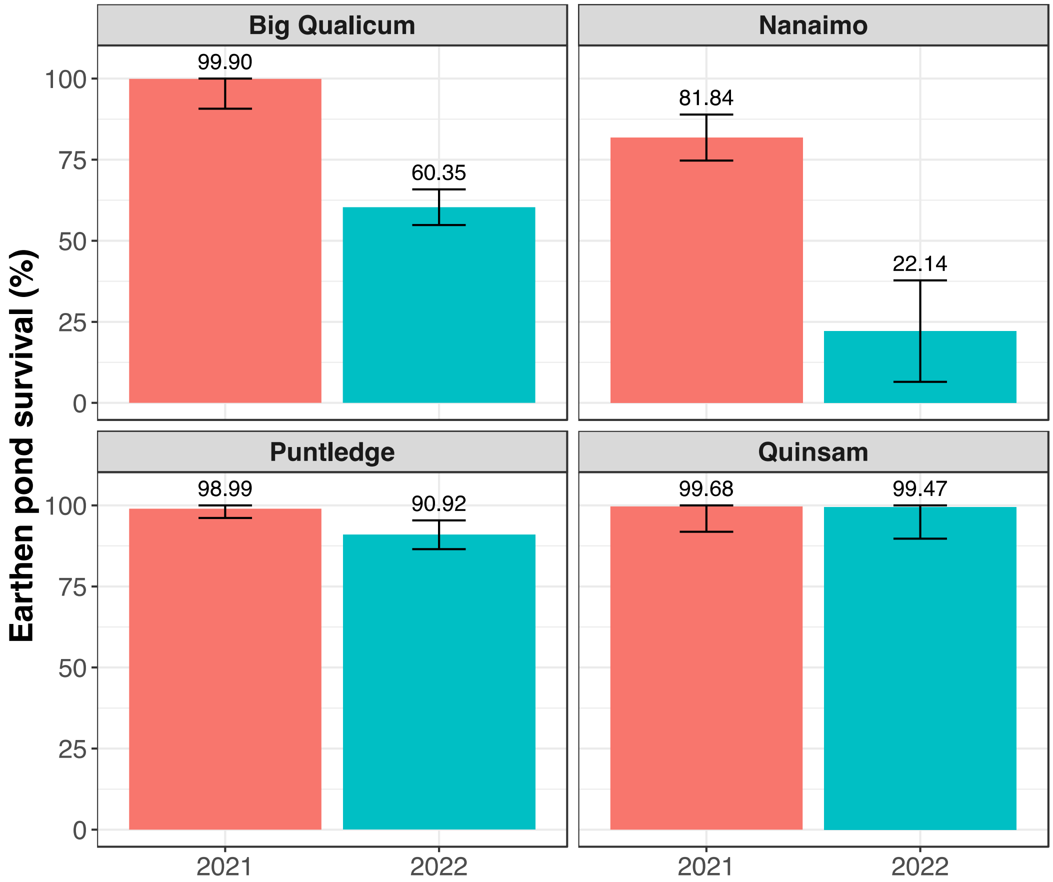

Figure 8. Survival of PIT tagged coho salmon held in earthen channels at four hatcheries (Big Qualicum, Nanaimo, Puntledge, Quinsam). Survival estimates represent the percentage of tagged fish that were transferred to the earthen channels estimated to survive to the date of earthen channel release. Survival estimates for both release years, 2021 and 2022, are shown in red and blue, respectively. Error bars represent the 95% confidence intervals.

Given the considerable variation in earthen channel residency (Table 1), daily mortalities can provide a more accurate comparison of pre-release mortality between years and hatcheries. Nanaimo's earthen channels were found to have the highest daily mortality rates compared with all other hatcheries, while Quinsam's earthen channels were found to have the lowest (Figure 9; Table 3).

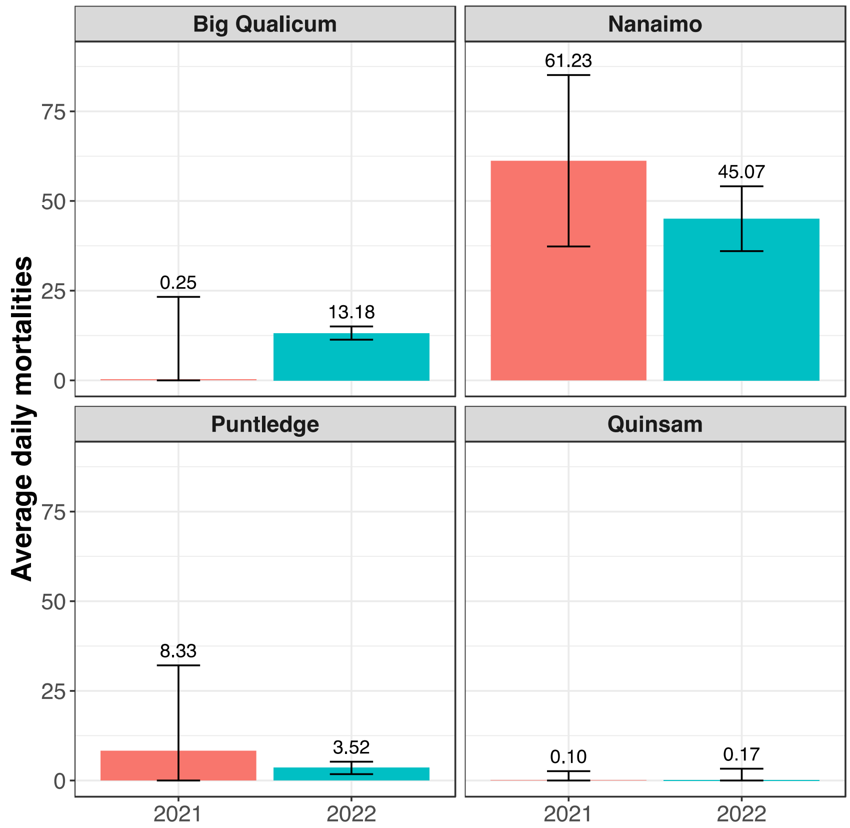

Figure 9. Estimated number of daily mortalities for each earthen channel system in both the 2021 and 2022 release cohorts. Average daily mortalities were calculated by dividing the total number of estimated mortalities for each earthen channel by the total residency time (in days) for each channel. Average daily mortalities for both 2021 and 2022 cohorts are shown in red and blue, respectively. Error bars represent the 95% confidence intervals.

Survival to adult return

Survival rates were highly variable across hatcheries and between years (Figure 10; Table 4). In both years, Puntledge coho had the highest survival rates for both ponding to adult return (2021: 9.25% ± 4.61%, 2022: 8.33% ± 2.29%) and release to adult return (2021: 9.34% ± 6.15%, 2022: 9.16% ± 6.21%). However, these estimates also have the most uncertainty given the low detection efficiency of the Mainstem PIT array (Table A1 in the Appendix). In 2021, survival rates were lowest for Big Qualicum coho (1.55 ± 0.23% and 1.56% ± 1.26% for ponding to return and release to return, respectively); in 2022, they were lowest for Nanaimo coho (0.15 ± 0.06% and 0.68% ± 1.37% for ponding to return and release to return, respectively). Detections of adult returns and expanded return values are presented in Table 5.

Calculating survival to adult return from the number of coho ponded resulted in lower or similar survival rates to those calculated from hatchery release to return (Figure 10; Table 4). The difference in survival estimates was particularly evident at Big Qualicum in 2022, and at

SYSTEM	RELEASE YEAR	TOTAL # PIT TAGS	ESTIMATED # PIT SMOLTS LEAVING EARTHEN CHANNEL	TOTAL # DETECTED ADULT RETURNS	EXPANDED # ADULT RETURNS	DATE RANGE OF ADULT (3 YO) RETURNS	% JACKS (2 YO)	DATE RANGE OF JACK (2 YO) RETURNS	% 4 YOS
Big Qualicum	2021	5,000	4,995	79	81	2022-10-02 - 2022-11-23	25.32	2021-10-05 - 2021-11-07	1.21
	2022	4,886	2,949	80	87	2023-09-23 - 2023-12-16	5.00	2022-10-13 - 2022-11-18	0.00
Nanaimo	2021	4,719	3,862	137	138	2022-09-26 - 2023-01-14	14.60	2021-10-01 - 2021-11-15	0.00
	2022	4,978	1,102	6	7	2023-10-13 - 2023-12-05	16.67	2022-11-05 - 2022-11-05	0.00
Puntledge	2021	4,963	4,913	333	469	2022-09-18 - 2022-12-27	33.64	2021-09-21 - 2021-12-03	2.15
	2022	4,924	4,477	269	410	2023-09-16 - 2023-12-30	18.59	2022-10-06 - 2022-11-30	0.00
Quinsam	2021	4,957	4,941	109	136	2022-09-19 - 2022-12-23	26.61	2021-09-28 - 2021-11-04	0.00
	2022	4,949	4,923	71	77	2023-09-17 - 2023-11-12	21.13	2022-09-24 - 2022-10-29	0.00

Nanaimo in both years.

Return Age

Jacks, or age-2 coho returns, made up almost a quarter of the returns on average across the four facilities (Table 4). The proportion of jacks returning was higher for the 2022 release cohorts from both Quinsam (27.27%) and Puntledge (40.93%) earthen channels relative to the 2021 release cohorts (21.32% and 23.58% at Quinsam and Puntledge, respectively).

Interestingly, we detected age-4 coho returns at both Big Qualicum and Puntledge. A single age-4 coho was detected returning to Big Qualicum in 2023. Meanwhile, 12 age-4 coho were detected returning to the Puntledge Hatchery between July 31st and September 23rd, 2023, which is notably earlier than the conventional return timing of age-2 and age-3 Puntledge coho (

Table 5).

Straying

Proportion of returns straying to other rivers was generally low (Table 5). The highest proportion of strays were observed at Big Qualicum in both years. In 2021, 7 fish strayed into the Little Qualicum River and 1 strayed into the Englishman River, and in 2022, 3 strayed into the Little Qualicum River and 1 strayed into an unknown system (unknown receiver ID). Nanaimo coho only strayed in 2021, with 2 returning to the Englishman River, 1 returning to the Big

Qualicum River, and 1 returning to the Little Qualicum River. For Puntledge coho, only 1 stray was detected returning to Big Qualicum in 2021 and 3 were detected returning to Big Qualicum in 2022. None of the Quinsam coho were detected straying into other systems.

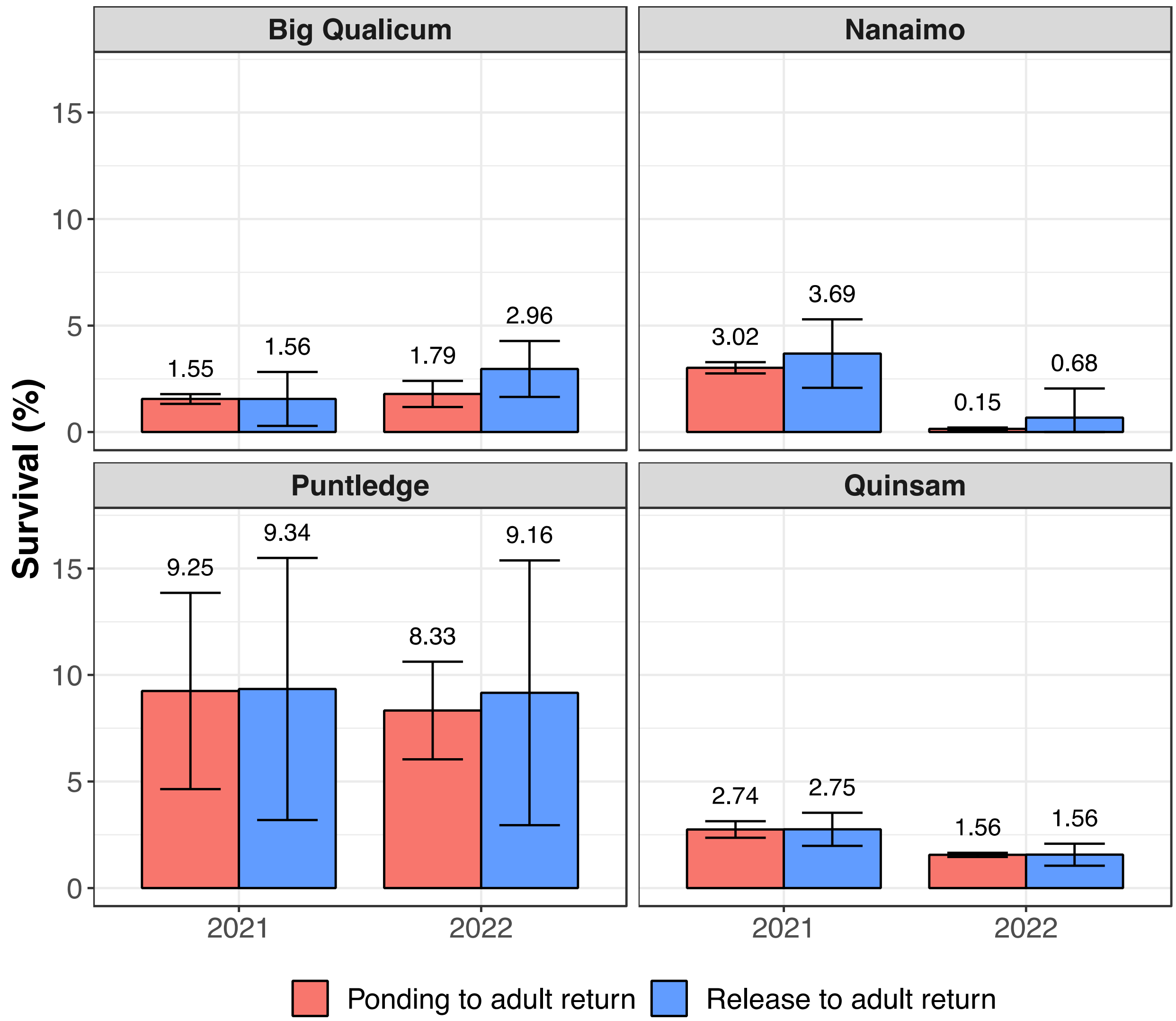

Figure 10. Estimates for survival from earthen channel entry/ponding to adult return (red) and earthen channel release to adult return (blue) for each cohort. The mean survival estimate value is shown directly above each bar. Error bars represent the 95% confidence intervals for each survival estimate.

Table 4. Summary of the survival from earthen channel entry/ponding to adult return and earthen channel release to adult return estimates. The 95% confidence intervals for each estimate are also presented.

SYSTEM	RELEASE YEAR	SURVIVAL: PONDING TO ADULT (%)	95% CI	SURVIVAL: RELEASE TO ADULT (%)	95% CI
Big Qualicum	2021	1.55	1.33 – 1.78	1.56	0.29 – 2.82
	2022	1.79	1.17 - 2.40	2.96	1.65 - 4.28
Nanaimo	2021	3.02	2.75 - 3.28	3.69	2.08 – 5.29
	2022	0.15	0.09 – 0.21	0.68	0.00 - 2.05
Puntledge	2021	9.25	4.64 – 13.86	9.34	3.19 - 15.49
	2022	8.33	6.04 – 10.62	9.16	2.95 - 15.38
Quinsam	2021	2.74	2.36 - 3.13	2.75	1.98 - 3.53
	2022	1.56	1.46 - 1.65	1.56	1.05 - 2.08

Table 5. The total number of coho tagged, leaving the earthen channel, returning as adults, as well as the return dates and proportion of jacks, 4-year olds (4 YOs), and strays for each system each year.

SYSTEM	RELEASE YEAR	TOTAL # PIT TAGS	ESTIMATED # PIT SMOLTS LEAVING EARTHEN CHANNEL	TOTAL # DETECTED ADULT RETURNS	EXPANDED # ADULT RETURNS	DATE RANGE OF ADULT (3 YO) RETURNS	% JACKS (2 YO)	DATE RANGE OF JACK (2 YO) RETURNS	% 4 YOS	DATE RANGE OF 4 YO RETURNS	% STRAYS
Big Qualicum	2021	5,000	4,995	79	81	2022-10-02 - 2022-11-23	25.32	2021-10-05 - 2021-11-07	1.21	2023-10-19	10.13
	2022	4,886	2,949	80	87	2023-09-23 - 2023-12-16	5.00	2022-10-13 - 2022-11-18	0.00		5.00
Nanaimo	2021	4,719	3,862	137	138	2022-09-26 - 2023-01-14	14.60	2021-10-01 - 2021-11-15	0.00		2.92
	2022	4,978	1,102	6	7	2023-10-13 - 2023-12-05	16.67	2022-11-05 - 2022-11-05	0.00		0.00
Puntledge	2021	4,963	4,913	333	469	2022-09-18 - 2022-12-27	33.64	2021-09-21 - 2021-12-03	2.15	2023-07-31 - 2023-09-23	0.31
	2022	4,924	4,477	269	410	2023-09-16 - 2023-12-30	18.59	2022-10-06 - 2022-11-30	0.00		1.12
Quinsam	2021	4,957	4,941	109	136	2022-09-19 - 2022-12-23	26.61	2021-09-28 - 2021-11-04	0.00		0.00
	2022	4,949	4,923	71	77	2023-09-17 - 2023-11-12	21.13	2022-09-24 - 2022-10-29	0.00		0.00

DISCUSSION

We used PIT technology to conduct a unique but simple mark-recapture study of juvenile coho reared in earthen channels at four hatcheries on the east coast of Vancouver Island. Tracking the fates of the PIT tagged coho allowed us to measure both survival in earthen channels and subsequent survival to adult return. Daily mortality rates were significant at some locations and directed efforts need to be taken to identify and mitigate the causes of mortality. This study revealed a high level of variability in prerelease mortality in earthen channels, suggesting that applying blanket mortality rates to earthen channel releases is likely to produce bias in overall hatchery survival estimates. From our earthen channel survival analyses, prerelease mortality ranged from 0.10-77.86%. Therefore, not accounting for prerelease mortalities or using a blanket percentage is not an effective method for estimating true release numbers and hatchery survival rates. We suggest that PIT tagging a proportion of earthen channel releases be continued to allow hatchery managers to improve their survival estimates.

Accounting for prerelease mortality

Big Qualicum River Hatchery does not apply a blanket prerelease mortality rate correction to their coho release from earthen channels, although estimates are made when significant losses are apparent. In 2022, earthen channel mortalities spiked in March-April, of which 7.5% were PIT tagged coho. While there were no known issues of predation or disease, the period of mortality coincided with an increase in feeding rations. There may be some interaction between tag placement in the body cavity and over-feeding; however, it is uncertain what caused this elevated mortality in the 2022 cohort, particularly in PIT tagged fish (Aaron Burgoyne, SEP, personal communication). Tagging-related mortality typically occurs within the first week post-tagging (Atkinson and Balfour 2024, in prep.); therefore, a delayed mortality effect from tagging is unlikely but could be further investigated. We measured 0.10% and 39.65% prerelease mortality in 2021 and 2022, respectively. However, it is worth noting that these values are based on the residency of PIT tagged coho in the earthen channels. Brood year 2019 coho were clipped, CWT'd and transferred into earthen channels from September 3-21, 2020 with 5,000 removed for PIT tagging on April 13, 2021 and immediately put back into the earthen pond, with no post-tagging monitoring. Big Qualicum coho were released on May 4, 2021. In this case, the PIT tags, and thus the survival estimates gained from them, were only in the channels for 20 days, however the coho themselves were in the channels for ~234 days. Similarly for the 2020 brood year, coho were clipped, CWT'd, and transferred to the channels between May 31 and July 14, 2021, with a subset removed for PIT tagging on December 2, 2021. Those PIT tagged coho were returned to the channels on December 20, 2021 and released with the rest of the coho on May 16, 2022. In 2022, the PIT tags resided in the channels for 147 days, while the coho resided in the channels for ~328 days.

A similar situation occurred with PIT tagging at Puntledge. The subset of fish to be PIT tagged were held back in tubs when the rest of the cohort were transferred into the earthen channels. Therefore, the 6-day rearing period in 2021 is representative of the time the PIT tagged individuals spent in the earthen channels, however the rest of the coho were in the channels for 72 days. Similarly, in 2022, PIT tagged coho spent 127 in the earthen channel, while the rest of the cohort spent 169 days. Puntledge River Hatchery is unique in that coho are not reared exclusively in the local earthen channel. Given warm water temperatures at this facility over the summer, coho are first transferred to earthen channels at other facilities before being returned to Jack Creek, the local earthen channel, in the fall or winter. During the two years of this study, Puntledge coho were held in the Big Qualicum earthen channels over the summer. Upon return to Puntledge, the coho were tagged with CWTs before being transferred to the earthen channel, providing a count of coho entering the channels. Puntledge has extensive predator control measures and therefore believe their earthen channel mortality rates are low and do not apply a prerelease mortality correction to their release numbers.

The values we have presented for Big Qualicum and Puntledge should be interpreted with caution. Our survival estimates represent survival of the PIT tagged individuals and their residence in the channels, rather than the entire cohort. Hypothetically, one could extrapolate the earthen channel survival for the full duration of channel residency from our daily mortality estimates. For instance, for the 2021 Puntledge release year, the average daily mortality rate was 8.33 fish/day. Therefore, if we imagine that our PIT tagged coho were residing in the channel for the full 72 days, we would get a survival rate of 88.65%, or a prerelease mortality of 11.34%. If we follow the same logic for the 2022 Puntledge release cohort, the estimated earthen channel survival would be 89.46% for the full rearing period, or 10.54% prerelease mortality. However, this method has its limitations. According to hatchery managers, earthen channel mortalities are known to increase in March and April prior to release as the temperatures increase and coho initiate smoltification. Therefore, using a daily mortality rate derived largely from this period would overestimate the prerelease mortality. Indeed, when the same calculations were applied to Big Qualicum, we estimated unrealistically low survival estimates for the 2022 release group.

Nanaimo and Quinsam coho were PIT tagged at the beginning of the earthen channel rearing period and, therefore, do not have the same limitations as described for Big Qualicum and Puntledge. Nanaimo does not have a standard method for accounting for prerelease mortalities. As a community hatchery, they do not have the resources available to tag their releases with CWTs like the larger SEP facilities. Consequently, it has been difficult to quantify prerelease mortality. Their earthen channel had some of the highest mortality rates in our study. In both years, otters in particular, as well as minks, were observed getting into the earthen channel despite electrical fencing and overhead netting. We measured 18.16% and 77.86% prerelease mortality in these two years, resulting in low release numbers and exceptionally low survival to adult return. Given the significant losses to predation experienced in recent years, Nanaimo is now building new tanks for rearing coho that will eliminate predation. These tanks will first be used for rearing coho in the fall of 2024.

After CWT tagging, Quinsam Hatchery applies a 5% mortality rate to their earthen channel Coho. However, in the two years of our study, we measured only 0.32% and 0.53% mortality in the earthen channel. Contrary to the under-estimated mortality found at the other facilities and reported by

Irvine (2021), this suggests that the release numbers were under-estimated, and therefore, survival to return will, in fact, be biased high.

PIT vs CWT survival

Survival rates of coho salmon estimated from PIT tagging may differ from those using CWTs due to differences in tagging and detection methods, the stages and locations where fish are detected, and sample sizes. PIT tags are detected at antennas in-river, while CWTs are captured in marine fisheries as well as in escapement surveys. Survival to adult return estimates based on traditional CWT methods were available for the three major SEP facilities: Big Qualicum, Puntledge, and Quinsam (Appendix Table A2; data from SEP). Of note, our survival estimates were lower or similar to the Big Qualicum CWT estimates, significantly higher for Puntledge, and comparable for Quinsam. One explanation could be the extensive release of adipose-clipped, non-CWT-tagged coho, which generates bias in the Fishery Regulation Assessment Model (FRAM) and contributes to high variability in stock-specific survival rates (Beacham et al. 2018). The drastic reduction in CWT recovery sample sizes, from 2014 to 2016 for Canadian-origin coho increases uncertainty in survival estimates (Beacham et al. 2018). Another possible explanation for the higher Puntledge coho survival reported in this study, particularly for the 2020 brood year, could be the increased frequency of high-water events in 2023. Higher water levels may have allowed more adult coho to bypass the fence, resulting in an under-estimate using CWTs.

Overall, the inherent differences in the two tagging approaches (PIT tagging and CWTs) are expected to produce varying survival estimates. Therefore, it is crucial to consider the context and limitations of each method when comparing and interpreting survival data. Since the estimation of fishery impacts with the FRAM depends on CWT recovery information, the greatly decreased number of CWT recoveries in recent years has increased the variance of the estimated stock-specific catch and exploitation rates in Chinook fisheries (Hinrichsen et al., 2016; Reisenbichler & Hartmann, 1980).

Novel findings

An unexpected finding of our analysis was the presence of age-4 coho returns at Big Qualicum and Puntledge River Hatcheries. Coho typically exhibit a 3-year life cycle, spending their first year in freshwater, and returning either the same year they outmigrate as age-2 returns or "jacks" or the subsequent year as age-3 adults. An age-4 return could indicate a unique life history that has not been recognized or managed to date. In particular, the 12 age-4 coho that returned to the Puntledge River arrived mostly in August (n=11). In contrast, the bulk of age-3 returns arrived between late September and December, suggesting a summer-run population with a unique life history. Further investigation and confirmation of the genetic identity of this population are recommended. The single age-4 return at Big Qualicum is also an interesting discovery. This individual appears to have been trapped in the earthen channel for an additional year and was detected outmigrating a year later than the rest of its cohort, thus returning as an age-4 fish with two years in freshwater.

Another noteworthy observation from this study was the consistent detections of PIT tagged cutthroat trout (*Oncorhynchus clarkii clarkii*) at the earthen channel antennas at Quinsam. Cutthroat trout were

PIT-tagged by Provincial Biologists as part of their cutthroat enhancement program at the Quinsam River Hatchery. We cannot confirm that trout were not present in other river systems. However, these observations suggest that cutthroat may be targeting juvenile coho released from earthen channels and could be a source of post-release mortality. Further study of cutthroat trout would be required to confirm this.

Limitations

One limiting factor of any PIT tag study is the detection efficiency of the PIT receivers. Our detection efficiencies were variable between systems and years, leading to higher levels of uncertainty around some of our earthen channel survival estimates. Large pulses of tags passing over an antenna at the same time can result in tag "collisions" where the antenna cannot read more than one unique ID at a given moment. To improve detection efficiency in the future, we recommend conducting a slow release from the earthen channels. Concurrent to the coho study, a similar earthen channel survival analysis was conducted at Little Qualicum River Hatchery with their fall Chinook in 2022. Unlike the coho releases, these Chinook (*Oncorhynchus tshawytscha)* were released gradually with controlled, small releases over the course of a week. This gradual release method allowed for better detections of individual fish passing over the antennas, resulting in a detection efficiency of 99.03%. As a result, our survival estimates (99.66% ± 0.32%) were far more precise than those reported for the coho earthen channels.

Recommendations

Thus, our recommendations for hatcheries utilizing earthen channels for rearing any of their salmon production are as follows:

- Apply 500 12 mm HDX-PIT tags to each earthen channel cohort each year to get an accurate estimate of pre-release mortality.
    - A low number of HDX tags will allow for higher detection efficiency at outmigration and can provide immediate overwinter survival information after the spring release.
    - HDX tags will not impact detection efficiencies of continued FDX-B tag-based programs (Bottlenecks).
- Apply PIT tags at the *beginning* of earthen channel residency for more accurate estimates of prerelease mortality.
- Install PIT antennas for the entire duration of earthen channel residency for better estimation of escapees.
- Release coho from earthen channels gradually to improve detection efficiencies and reduce uncertainty around survival and prerelease mortality estimates.
- Where predation is a recurring source of significant prerelease mortality, investigate and implement additional predator control measures.
- Monitor the prerelease mortality of Nanaimo coho in the new overwinter rearing containers and compare to previous years to measure effectiveness of this alternate rearing strategy.

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APPENDIX

Table A1. Overview of the PIT receivers installed in each river system to detect adult Coho salmon during their spawning migrations. The number of unique tags detected at each receiver (this will include age-2, age-3, and age-4 fish from separate study cohorts) and the estimated detection efficiency of receiver is given. Where detection efficiency was not possible to calculate, 'NA' is given. The PIT receiver and respective detection efficiency used to calculate the adjusted adult returns for each year is emboldened. We also report 95% confidence intervals for each PIT receiver detection efficiency estimate.

	UNIQUE TAGS DETECTED	DETECTION EFFICIENCY	95% CIS
Nanaimo River Coho Adult Return Detection Efficiency 2021			
Nanaimo River Mainstem 301	**18**	**0.86**	**0.70 - 1.01**
Nanaimo River Mainstem 302	14	0.67	0.50 - 0.84
Nanaimo 2021 system	*20*	*0.95*	*NA*
Nanaimo River Coho Adult Return Detection Efficiency 2022			
Nanaimo River Mainstem 301	50	0.42	0.34 - 0.50
Nanaimo River Mainstem 302	**109**	**0.92**	**0.88 - 0.96**
Nanaimo 2022 system	*113*	*0.95*	*NA*
Nanaimo River Coho Adult Return Detection Efficiency 2023			
Nanaimo River Mainstem 301	9	0.64	0.40 - 0.87
Nanaimo River Mainstem 302	**11**	**0.78**	**0.60 - 0.96**
Nanaimo 2023 system	*13*	*0.92*	*NA*
Quinsam River Coho Adult Return Detection Efficiency 2021			
Quinsam Fishway 9a	**29**	**1**	**1.00 - 1.00**
Quinsam Fishway 9b	29	1	1.00 - 1.00
Quinsam 2021 system (fishway route only)	*29*	*1*	*NA*
Quinsam River Coho Adult Return Detection Efficiency 2022			
Quinsam River Mainstem 91	**91**	**0.71**	**0.65 - 0.78**
Quinsam Fishway 9a	14	1	NA
Quinsam Fishway 9b	14	1	NA
Quinsam Fishway 9f	2	0.14	NA
Quinsam 2022 system (fishway route only)	*95*	*1*	*NA*
Quinsam River Coho Adult Return Detection Efficiency 2023			
Quinsam River Mainstem 91	103	0.4	0.35 - 0.45
Quinsam River Mainstem 921	**222**	**0.93**	**0.90 - 0.95**
Quinsam Fishway 9a	168	1	1.00 - 1.00
Quinsam Fishway 9b	94	0.56	0.50 - 0.62
Quinsam 2023 system	*237*	*0.96*	*NA*

Puntledge River Coho Adult Return Detection Efficiency 2021			
Puntledge River Camera-Box 71	**42**	**NA**	**NA**
Puntledge Fishway 7a	**98**	**1**	**NA**
Puntledge Fishway 7b	98	1	NA
Puntledge 2021 system	*108*	*(1)*	*NA*
Puntledge River Coho Adult Return Detection Efficiency 2022			
Puntledge River Mainstem 701	**31**	**0.06**	**0.04 - 0.08**
Puntledge River Camera-Box 71	42	NA	NA
Puntledge Fishway 7a	201	0.97	0.95 - 0.99
Puntledge Fishway 7b	208	1	1.00 - 1.00
Puntledge 2022 system	*262*	*(1)*	*NA*
Puntledge River Coho Adult Return Detection Efficiency 2023			
Puntledge River Mainstem 701	**225**	**0.64**	**0.60 - 0.68**
Puntledge River Camera-Box 71	88	NA	NA
Puntledge Fishway 7a	230	0.99	0.98 - 1.00
Puntledge Fishway 7b	209	0.9	0.87 - 0.93
Puntledge 2023 system	*320*	*(0.99)*	*NA*
Big Qualicum River Coho Adult Return Detection Efficiency 2021			
Big Qualicum Fishway 6a	**17**	**1**	**1.00 - 1.00**
Big Qualicum Fishway 6b	12	0.71	0.52 - 0.89
Big Qualicum 2021 system (fishway route only)	*17*	*1*	*NA*
Big Qualicum River Coho Adult Return Detection Efficiency 2022			
Big Qualicum River Mainstem 61	**12**	**0.78**	**0.55 - 1.01**
Big Qualicum River Mainstem 62	9	0.58	0.38 - 0.79
Big Qualicum Fishway 6a	**40**	**1**	**1.00 - 1.00**
Big Qualicum Fishway 6f	34	0.85	0.76 - 0.94
Big Qualicum 2022 mainstem system	*14*	*0.91*	*NA*
Big Qualicum 2022 fishway system	*40*	*1*	*NA*
Big Qualicum River Coho Adult Return Detection Efficiency 2023			
Big Qualicum River Mainstem 60	**42**	**0.51**	**0.42 - 0.61**
Big Qualicum River upstream 61	17	NA	NA
Big Qualicum fishway 6a	56	0.98	0.95 - 1.01
Big Qualicum fishway 6b	50	0.88	0.80 - 0.95
Big Qualicum 2023 system	*76*	*(0.99)*	*NA*

Table A2. Comparison of survival to return estimates from CWTs vs PIT tags applied to the coho from this study. CWT data were provided by the Salmonid Enhancement Program (DFO).

SYSTEM	BY	CWT SURVIVAL %	PIT SURVIVAL %	PIT 95% CI
Big Qualicum	2019	3.66	1.56	0.29 – 2.82
	2020	2.67	2.96	1.65 – 4.28
Puntledge	2019	6.00	9.34	3.19 – 15.49
	2020	2.69	9.16	2.95 – 15.38
Quinsam	2019	2.27	2.75	1.98 – 3.53
	2020	1.76	1.56	1.05 – 2.08

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