2023 Run Timing and Escapement of Wild Summer Coho Salmon in the Upper Sol Duc River Based on ARIS Multi-Beam SONAR

Photo: C. Kinsel

Washington Department of Fish and Wildlife

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Table of Contents

List of Tables iv
List of Figures v
Executive Summary 1
Introduction 2
Background 2
Study Location 2
Summer-Run Coho Escapement 3
Methods 4
Site Selection 4
Data Collection and Review 6
Species Composition and Size 7
Abundance Estimation 9
Run Timing and Environmental Variables 10
Results 10
Data Collection and review 10
Fish size and species composition 13
Abundance Estimation 15
Migration Timing and Environmental Variables 16
Discussion 20
Recommendations 23
References 24

List of Tables

Table 1. Binned adult summer Coho Salmon fork length (FL, cm) data from 1983-1984 Quileute tribal in-river fisheries. 7
Table 2. Summary of adult summer Coho Salmon fork lengths (cm) collected between November 1 and November 21, 2001, from the Sol Duc River between river miles (RMs) 61 and 65 (rkms 98.2 and 104.6). Sample also includes two fish collected from the North Fork Sol Duc River. Data from Olympic National Park (ONP). 8
Table 3. Hours by month that SONAR imagery was recorded, percent recorded, and total upstream and downstream counts of fish with fork lengths ≥45 cm. 11
Table 4. Total length (TL, cm) summary of adult and jack summer Coho Salmon collected in 2023. Data includes 190 TLs taken from hatchery fish at Sol Duc Hatchery and two wild adult TLs from the Salmon Cascades. 14
Table 5. Number of fish observed above and below Sol Duc Salmon Cascades during snorkel surveys in the SONAR index area during summer of 2023. 15
Table 6. Estimated summer coho escapement upstream of Sol Duc Salmon Cascades 2024. Total escapement, standard deviation, and 95% confidence interval (CI). 16

List of Figures

Figure 1. Location of Sol Duc Salmon Cascades (yellow hexagon), SONAR site (red triangle) and Sol Duc Falls (green hexagon). 5
Figure 2. Clockwise from top left: SONAR mounted on an aluminum ladder upstream of the Salmon Cascades on the Sol Duc River at river mile (RM) 56.8, jobsite storage box housing the batteries, inverter, and laptop, and solar panels used to power the ARIS Explorer 1800 SONAR unit. 6
Figure 3. Map of summer Coho Salmon snorkel survey area associated with the SONAR unit in the upper Sol Duc River. Numbers mark the coho holding pools from upstream to downstream. The SONAR location is marked by the grey arrow and the Salmon Cascades are marked with the white arrow. 9
Figure 4. Comparison of daily SONAR counts for a) upstream and b) downstream fish ≥45 cm total length between data reviewer A (CK) and B (JB) and length counts binned by 5 cm increments (35 to 80 cm) for c) upstream and d) downstream fish between data reviewer A and B. 12
Figure 5. Length frequency histograms for overlapping data review of two reviewers for all upstream and downstream fish with a fork length measuring ≥35 cm. 13
Figure 6. Length distribution of upstream and downstream fish ≥35 cm using ARIS fish software 14
Figure 7. Upstream and downstream summer coho counts with confidence intervals estimated during SONAR outages using the Bayesian spline model 16
Figure 8. Daily summer Coho Salmon (≥45 cm) upstream passage and cumulative proportion of run past the SONAR site, Sol Duc River, 2023. 17
Figure 9. Expanded daily upstream and downstream fish passage at the Sol Duc SONAR site in 2023. 18
Figure 10. Plots of a) upstream fish count (≥45 cm) at the Sol Duc SONAR station and daily average stream temperature (°C), b) fish count and daily mean stage height (ft) at Washington Department of Ecology Station 20A070, Sol Duc R. nr Quillayute, c) fish count as a function of stream temperature (°C), and d) fish count as a function of stage height (ft). 19
Figure 11. Daily mean stage height 2009-2023 from Washington Department of Ecology Station 20A070, Sol Duc River near Quillayute. 20
Figure 12. Escapement estimates for Quillayute summer Coho Salmon 1976-2023. Escapement estimates in 2022 and 2023 are yet to be finalized, pending co-manager agreement. 21
Figure 13. Redd-based escapement for Sol Duc summer coho in areas upstream and downstream of the salmon cascades compared with the SONAR-based escapement upstream of the Salmon Cascades in 2023. 22

Executive Summary

The Sol Duc River on the Olympic Peninsula of Washington State has a unique population of wild summer-run Coho Salmon (*Oncorhynchus kisutch*) that return to spawn during low summer flow conditions. Most of these fish spawn upstream of a partial natural barrier known as the Sol Duc Salmon Cascades. Above this barrier during the summer months, adult Coho Salmon are generally the only large-bodied salmonid present. Furthermore, essentially no hatchery summer coho have been documented upstream of this partial barrier. Traditionally, abundance estimation for these wild coho is accomplished by spawning ground surveys, using a redd-based methodology. However, recent discussions among co-managers determined that sound navigation and ranging, or SONAR, could provide an alternative method to enumerate Sol Duc summer coho above the Salmon Cascades. In 2023, a pilot study was initiated to compare SONAR counts with redd-based estimates at location above the Salmon Cascades. In addition to enabling abundance estimates, monitoring coho with SONAR also facilitated greater understanding of timing and environmental conditions associated with summer coho passage during their upstream spawning migration. We deployed an ARIS Explorer 1800 SONAR unit at an ideal location 415 m upstream of the Salmon Cascades throughout the entire spawning migration period and estimated an escapement of 161 fish, nearly 2.5 times higher than the redd-based estimate of 65 fish. Most coho passed the SONAR site upstream of the Salmon Cascades when water temperatures were between 8.5° to 11°C and when stage height at the Department of Ecology gauge was between 15.1 and 15.24 ft. The first adult coho observed using SONAR imagery occurred on July 29, 2023, and the last on November 10, 2023, with a median migration date of October 6, 2023. Stream flow during the late summer of 2023 was at or near record lows, likely delaying migration and passage of the Salmon Cascades, leaving many fish downstream of the partial natural barrier. Future years of SONAR operation will provide valuable insight into run-timing and environmental conditions for this unique population of Coho Salmon whose return timing makes them susceptible to changing environmental conditions. Continued operation will also provide managers with an alternative estimate to compare with redd-based abundance, and a way to potentially calibrate or correct estimates from other coarser methods. The skills and experience learned operating a SONAR unit at this location in 2023 will be transferable to other river systems and advancements in SONAR technology and data analysis will make SONAR a more viable tool for fisheries management and science.

Introduction

Background

The Sol Duc River is a tributary of the Quillayute River system that drains into the Pacific Ocean from Washington's Olympic National Park (ONP). The Sol Duc system supports wild runs of Chinook Salmon (*Oncorhynchus tshawytscha*), Coho Salmon (*O. kisutch*), Sockeye Salmon (*O. Nerka*), steelhead (*O. mykiss*), and Cutthroat Trout (*O. clarkii*). In particular, the Sol Duc supports a Coho Salmon population with unique run timing. Salmon run timing is classified by when adults begin upstream migration to spawn (e.g., spring-, summer-, fall-, or winter-run). Throughout most coastal Washington watersheds, Coho Salmon begin their spawning migration in fall and are classified as fall-run with normal (October-November) or late (December-January) run timing. However, in the Sol Duc, there's also a wild summer-run population that returns to freshwater and spawns approximately 7-weeks earlier than fall coho (K. Sutton, WDFW, pers comm.). These Sol Duc summer Coho Salmon typically enter the river in July, migrate 56.5 miles (90.9 km) upstream, and navigate Salmon Cascades on the Sol Duc River within ONP to spawn downstream of the physical barrier of Sol Duc Falls beginning in late September (peak in mid-October). Each year, thousands of visitors to the park observe the spectacle of summer coho ascending Salmon Cascades. It is estimated that >95% of coho that migrate past the cascades to spawn in the Sol Duc are summer-run, as opposed to the later fall-run. Also, there does not seem to be a significant interaction between wild and hatchery summer-runs on the spawning grounds based on decades of carcass recoveries and more recent snorkel surveys for population assessment (S. Brenkman, ONP, pers. comm.).

Study Location

The watersheds of the outer Olympic Peninsula located within the National Park are some of the most pristine in Washington State and favorable for Coho Salmon. These watersheds support diverse salmon and steelhead life histories and have some of the strongest populations. The Sol Duc River originates in headwaters of the ONP then flows west through the Olympic National Forest and Sol Duc Valley, where it joins the Bogachiel River at river mile (RM) 6 (rkm 10). From there, these systems combine to form the Quillayute River and flow out to the Pacific Ocean through the Quileute Tribe reservation and the town of La Push. The Sol Duc River is approximately 78 miles (126 km) long and the largest of the Quillayute's four major tributaries that also include the Bogachiel, Calawah, and Dickey rivers.

The Sol Duc watershed is owned and managed by a combination of the federal, state, local, and private timber companies. The Quileute Tribe also holds reservation lands along the Pacific Coast but maintains treaty rights to fishing that extend hundreds of miles beyond the reservation, in accordance with their usual and accustomed fishing areas. The headwaters have steep terrain in the Olympic Mountains; accumulated snow in the higher elevations plays an important role in seasonal flow to the system. A report by the North Pacific Coast Lead Entity for Salmon Restoration identified fish passage and habitat quality as limiting factors to guide salmon restoration in the Sol Duc watershed (NPCLE 2023). Restoration techniques such as carcass supplementation to support the Sol Duc freshwater ecosystem began as early as 1984 (Cederholm et al. 1989) and continue today with barrier removals, culvert corrections, riparian, and instream restoration projects. In addition, climate change has been impacting the Sol Duc River with more winter precipitation falling as rain as opposed to snow, reducing the snowpack and resulting in lower streamflow throughout the summer period (Ohlberger et al. 2019a).

Changing hydraulic regimes, especially low flows during summer, affects juvenile Coho Salmon production, distribution, migration, health, and overall survival of Sol Duc summer coho, therefore monitoring population abundance is essential for assessing the population's trajectory and vulnerability to environmental change.

Summer-Run Coho Escapement

There are sport and commercial fisheries in the ocean and terminal area (in-river) that target summer coho originating from the Sol Duc River from July to October of each year. Terminal area fisheries, on average, remove <40% of the terminal run and limited coded-wire tag data suggest ocean recovery rates for this population are low. To accurately manage these treaty and non-treaty fisheries, it is critical for co-managers to have accurate information on escapement of natural origin summer-run Coho Salmon. Washington Department of Fish and Wildlife (WDFW) has partnered with the National Park Service (NPS) and Quileute Tribe since 1973 to estimate wild salmon population abundance. Coho Salmon in the Quillayute is managed for wild spawning escapement, although there is also hatchery production for fall and summer coho in the Sol Duc. Currently there is no agreed upon escapement goal for wild summer coho with tribal co-managers; however, WDFW is using an escapement guideline of 900-1,200 wild summer coho based on population modeling (Ohlberger et al. 2019a). Spawning of natural origin summer Coho Salmon typically occurs in a stretch of the Sol Duc above the Salmon Cascades located at RM 56.5 and downstream of Sol Duc Falls RM 65 (rkm 91 to 104.6), with some spawning in Bear, Camp, and Beaver creeks in years of large run size (WDFW and WWTIT 1994). However, in recent years, concern has grown about summer coho, whose escapement numbers have been declining (Ohlberger et al. 2019b). Summer coho's early run timing make them vulnerable to fisheries and to environmental change. Indeed, low snowpack and subsequent low flows during the summertime reduce summer coho's ability to ascend the Salmon Cascades, leading to questions among co-managers about the efficacy of the current method for estimating escapement (Shirk et al. 2021).

Escapement surveys based on redd counts limit the ability of co-managers to assess stock strength during the entirety of the spawning migration because surveys are labor intensive and survey areas are remote and located in areas that are difficult to access. Snorkel surveys provide an alternative method to identify holding areas throughout the Sol Duc system, but only provide a snapshot of distribution during the migration. By contrast, sound navigation and ranging, or SONAR, provides an alternative method to enumerate run timing and spawner abundance. SONAR allows researchers to passively monitor fish movement past a fixed site and has the benefit of being able to be operated 24 hours a day in conditions with poor visibility (Wei et al. 2022). In addition, SONAR is non-invasive, meaning no fish handling is required that might interfere with fish behavior. In 2023, a SONAR unit was installed in the Sol Duc River to monitor summer coho run timing, provide weekly estimates of upstream passage, and generate an annual total of summer coho escapement past the Salmon Cascades to complement spawning ground and snorkel surveys conducted by WDFW, Quileute Tribe, and ONP. The objectives of this study were to: 1) provide an estimate of summer coho upstream of the Salmon Cascades in the Sol Duc River; 2) provide run timing information; 3) describe sources of error, including observer error and species composition error; and 4) make recommendations on how to improve the use of SONAR to enumerate Coho Salmon in the Sol Duc River in the future.

Methods

Site Selection

SONAR site selection was based on several criteria, including the likelihood that mostly summer coho would be passing by the SONAR unit without milling, that the SONAR beams would reach across the entirety of the river channel, and that there were no obstructions in the bathymetry of the river limiting SONAR imagery. A site that was secure and easily accessible was also a high priority. The selected site was 12.5 m wide and 1.2 m deep in the thalweg at summer low flows.

The location of the SONAR unit was chosen in an area just upstream of Sol Duc Salmon Cascades at RM 56.5 (rkm 90.9) within ONP. The Salmon Cascades are a set of falls that are a partial migration barrier to anadromous species. In fact, snorkel surveys conducted by ONP have confirmed that it is very rare for large-bodied salmonids other than coho to be present during the summer months upstream of the cascades (S. Brenkman, ONP, pers. comm). The Salmon Cascades also appear to be a natural barrier between summer-timed coho and fall coho, with nearly all the summer coho spawning occurring above the cascades each year and fall coho spawning occurring in the river and tributaries below the cascades. The Sol Duc salmon hatchery, located at RM 30.9 on the Sol Duc River, also releases hatchery summer coho into the river. These fish are adipose fin-clipped (ad-marked) for identification as hatchery fish. Snorkel surveys conducted by ONP have shown that the presence of ad-marked coho above the cascades is very low, with no ad-marked coho having been observed during their annual snorkel surveys. (S. Brenkman, ONP, pers. comm.). The location of the hatchery in the lower river and subsequent homing serves to segregate hatchery origin fish from wild naturally spawning summer fish.

Given the lack of other hatchery and other adult salmonids during the summer and fall months, we elected to place the SONAR upstream of the Salmon Cascades. This decision was made to simplify species composition work and to avoid fall coho, spring Chinook, and hatchery coho being detected by the SONAR unit. The location was chosen as close as possible to the cascades to account for all summer coho passing upstream. Site security was also an important consideration. We wanted a site that was generally out of view of the public to reduce potential theft and vandalism. Further, the site couldn't be too far off the road to facilitate ease of access and to minimize transport of batteries and solar panels required to power the SONAR unit. Ideally, the site also required an appropriate bathymetry to ensure that the SONAR transducer beams could completely ensonify the river profile and reach the far bank. After scouting the river above the cascades, a site was chosen that met the above qualifications. The site was located at RM 56.8 (91.3 km), about 415 m upstream of the Salmon Cascades (Figure 1)

The selected location had a shallow gravel bar that gently sloped away towards the far bank. This enabled high frequency detection of all fish swimming past the SONAR unit. This site was also favorable because it allowed us to re-position the SONAR up or down the slope of the gravel bar to maintain operation during variable flow conditions.

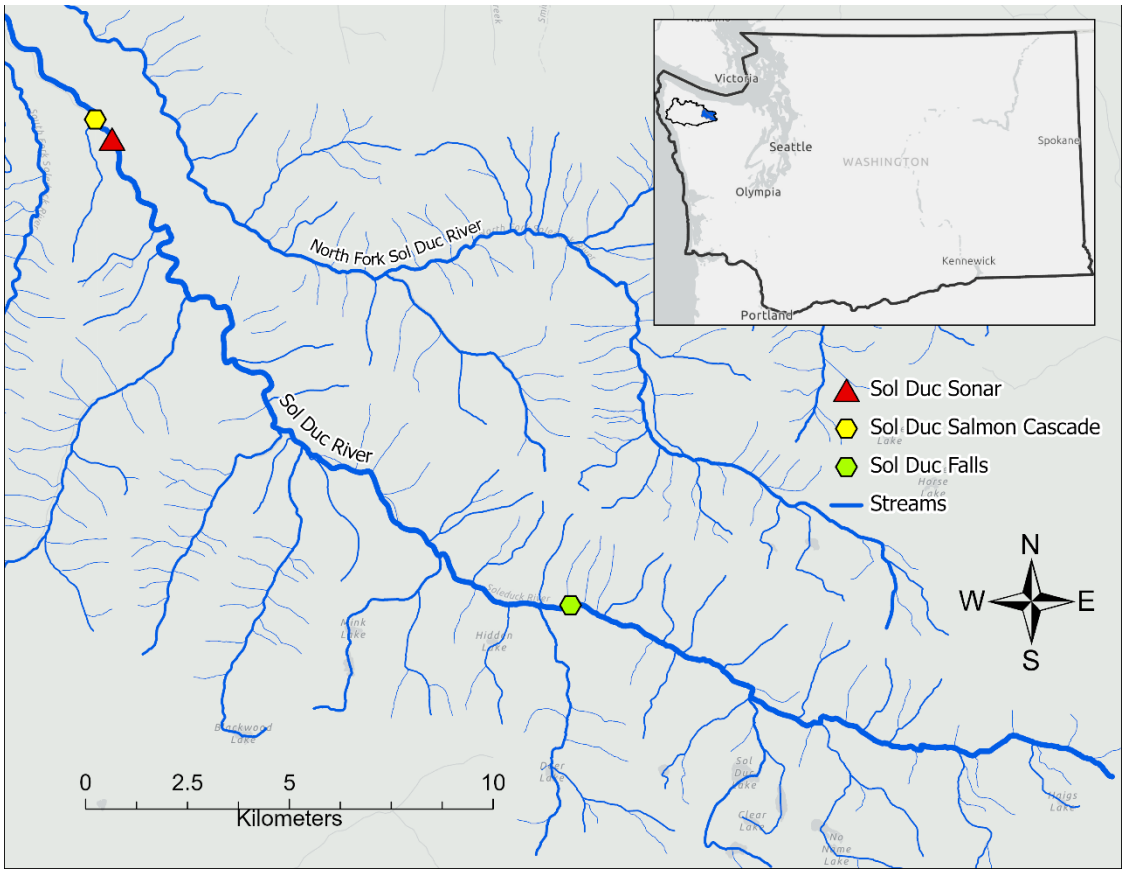

Figure 1. Location of Sol Duc Salmon Cascades (yellow hexagon), SONAR site (red triangle) and Sol Duc Falls (green hexagon).

To monitor Sol Duc summer coho, we used the ARIS Explorer 1800 SONAR unit developed by Sound Metrics. We attached the ARIS to a pole mount, fixed to a reinforced aluminum platform ladder in accordance with similar SONAR set-ups used in Washington State (Denton et al. 2023). The ladder was secured with custom mounting hardware and rebar stakes driven into the stream bed (Enzenhofer and Cronkite 2005). Other SONAR projects have utilized picket weirs to direct fish in front of the SONAR unit, but we deemed this unnecessary because the gravel bar behind the unit was too shallow for fish to pass upstream.

A power source was not available at the selected SONAR site within ONP. Given the remote location, we powered the SONAR unit and a laptop equipped with ARISFish software to record and analyze SONAR imagery using an array of solar panels that were continuously charging a bank of 12-volt 255-amp hour batteries. Data files were recorded and saved to a 2TB external hard drive (Figure 2).

Figure 2. Clockwise from top left: SONAR mounted on an aluminum ladder upstream of the Salmon Cascades on the Sol Duc River at river mile (RM) 56.8, jobsite storage box housing the batteries, inverter, and laptop, and solar panels used to power the ARIS Explorer 1800 SONAR unit.

Data Collection and Review

The SONAR unit was in operation 24 hours a day from July 17 to November 17, 2023. There were a few data gaps during this time due to weather or electrical issues. Overall, the SONAR was operational 81.5% of the time. For each hour of operation, two half-hour data files were recorded. Every half hour file was reviewed using ARISFish software and for all fish ≥35 cm, we recorded total length (cm), time, and noted whether movement was upstream or downstream, depending on direction traveled. We also applied a data review confidence level to each observation: Level 1 if the observer was confident that the observed target was a fish, Level 2 if somewhat confident, and Level 3 to note an object of interest or if the target needed further review.

To reduce potential observer error, two data reviewers began the season by reviewing data together to ensure targets were identified and measured consistently. As the season progressed, the two reviewers separately reviewed overlapping files from approximately one day per week to compare counts and fish measurements. Upstream and downstream counts of fish ≥45 cm were tallied for each reviewer and evaluated using R software and the FSA package (R Core Team 2022). An Evans and Hoenig test was used to compare paired counts for symmetry (Evans and Hoenig 1998). To assess length measurement bias between the two reviewers, length frequency histograms were generated and compared between reviewers. Paired size readings were also evaluated using the Evans and Hoenig test, and between

reviewers, absolute percent error was calculated for all upstream and downstream counts and fish lengths to check for potential observer bias.

Species Composition and Size

High-resolution SONAR images cannot discern between fish species. However, information collected on fish size, timing, and direction of travel (upstream or downstream) can be important metrics for determining species composition. To assign a target to a species using SONAR imagery, information about which species are present during SONAR operation and their size range are helpful. In the upper Sol Duc River, we used a combination of snorkeling and fish length data to inform our estimation of summer Coho Salmon migrating upstream of the Salmon Cascades.

For species composition, the decision was made not to capture, handle, and sample natural origin summer coho based on the low streamflow in the Sol Duc during the spring and summer of 2023. In fact, WDFW and ONP closed all sport fishing in the Sol Duc due to these conditions. For length determination of summer coho, we worked with the Sol Duc hatchery to collect fish length data on fish returning to the hatchery as a surrogate for wild summer coho. We assumed that the hatchery fish would provide a reasonable length surrogate for wild summer coho even though hatchery fish have a different rearing strategy than wild coho that spawn upstream of the Salmon Cascades. For instance, wild fish that spawn above the cascades rear in the Sol Duc River upstream of the cascades and migrate downstream to rear in the ocean. As adults, the natural origin fish must successfully leap the cascades, whereas the returning hatchery fish do not have to undergo this physical challenge, meaning that wild summer coho may be larger and more powerful leapers than their hatchery counterparts. However, returning adult hatchery and wild fish are genetically similar, experience the same ocean conditions, and therefore their size should be similar.

Other data sources were used to inform the expected size of summer coho. For example, data from Quileute tribal in-river fisheries from 1983-1984 suggested that most of the summer coho captured were 60-69 cm in fork length (FL) (Table 1, Quileute 1985). Another dataset obtained from ONP, collected from the Sol Duc in 2001, showed summer coho FL averaged 61.3 cm (Table 2).

We measured the total length (TL) of all fish observed on the SONAR imagery that were ≥35 cm. However, based on data from historical sampling, we chose to use ≥45 cm as a size threshold for identifying adult summer coho. Size data (TL) collected in season at the Sol Duc Hatchery in 2023 and size distribution data from the SONAR imagery were evaluated to confirm these size thresholds.

Table 1. Binned adult summer Coho Salmon fork length (FL, cm) data from 1983-1984 Quileute tribal in-river fisheries.

	30-39 cm	40-49 cm	50-59 cm	60-69 cm	70-79 cm	80-89 cm	# Sampled
# Fish	3	21	207	1,169	394	0	1,794
Proportion	0.2%	1.2%	11.5%	65.2%	22.0%	0.0%	100%

Table 2. Summary of adult summer Coho Salmon fork lengths (cm) collected between November 1 and November 21, 2001, from the Sol Duc River between river miles (RMs) 61 and 65 (rkms 98.2 and 104.6). Sample also includes two fish collected from the North Fork Sol Duc River. Data from Olympic National Park (ONP).

Sex	Number Sampled	Avg. Length	Min. Length	Max. Length
Male	23	58.2	51.2	64.4
Female	17	65.3	55.6	75.5
Not Determined	6	61.5	58.9	68.8
Total	46	61.3	51.2	75.5

After the SONAR unit was installed on July 17, 2023, weekly snorkel surveys of the stream around the SONAR unit were initiated upstream of the Salmon Cascades and in the pools below the cascades. The goal of these surveys was to identify which species were present and the approximate size of fish observed. These data were then used to verify observations from SONAR data. All fish ≥45 cm were assumed to be adult summer coho unless other fish species were observed of this size during weekly snorkel surveys. If other species in this size range were observed, catch was apportioned using snorkel observation data. During weekly snorkel surveys, we enumerated all fish from a large pool just upstream of the SONAR downstream to the Salmon Cascades. We also snorkeled the large plunge pool below the Salmon Cascades and the next two pools downstream. Each pool was numbered, and fish were counted in each pool (Figure 3). We counted all fish observed except for trout and coho fry. We identified coho as adult or jack and counted any ad-marked fish. We also counted trout parr (<20 cm) and adult trout (≥20 cm).

Figure 3. Map of summer Coho Salmon snorkel survey area associated with the SONAR unit in the upper Sol Duc River. Numbers mark the coho holding pools from upstream to downstream. The SONAR location is marked by the grey arrow and the Salmon Cascades are marked with the white arrow.

Staff from the ONP also lead an annual snorkeling event on the Sol Duc River. This survey covers the entire mainstem river from the Sol Duc Falls (barrier) to below the Salmon Cascades. In 2023, we asked surveyors to count all non-coho >45 cm in length to provide supplementary data on other fish species that may have been counted as summer coho in the SONAR imagery. Unfortunately, snorkel efforts were unexpectedly canceled during the 2023 season. However, we intend to collaborate with ONP staff on Sol Duc snorkel surveys in the future.

Abundance Estimation

To estimate abundance of adult wild summer coho that migrated upstream past the SONAR, we totaled upstream and downstream counts of fish that moved through the SONAR beams during each day (24-hour period). We chose to use only fish that were marked as confidence level 1 as only a few targets were identified as level 2. We reviewed 100% of the SONAR data that was collected and counted all fish that measured ≥35 cm. Using historical fish size information and size data collected from coho at the hatchery, we determined a minimum length of 45 cm to represent an adult coho salmon. All fish ≥45 cm were included in the counts. However, if snorkel surveys found other species of overlapping size present in the SONAR area, counts were apportioned based on those observations.

We tallied total fish upstream (U) and total fish downstream (D) for each day (24-hour) the SONAR operated. For each 24-hour period, we also recorded the precise start and end time to come up with a daily percentage the SONAR was operational (O). There were 54 days with partial SONAR coverage and 10 days with no SONAR coverage. For days with partial SONAR coverage, we calculated fish passage (P) by dividing the total fish upstream or downstream measured during that day by the daily percentage that the SONAR was in operation using the following equation:

Upstream (P_{up}):

$$P_{up} = U \div O$$

Downstream (P_{dn}):

$$P_{dn} = D \div O$$

When total upstream and downstream fish passage was not measured or calculated, fish passage on missed days was estimated using a Bayesian penalized spline (p-spline) that was developed by adapting code from the BTSPAS package (Bonner and Schwarz 2011, 2024). The model estimated fish passage upstream and downstream separately when the SONAR was not in operation for a full 24-hour period (10 days total). On days when the SONAR operated the entire 24-hour period, or for partial days, actual or expanded counts were used. To generate final estimates, splines were run with four Markov chain Monte Carlo (MCMC) chains and each chain had a total of 5,000 draws with the first 2,500 discarded as warm-up with no thinning for a total of 10,000 posterior draws. Model convergence was assessed by visually inspecting the trace plots and using the Brooks-Gelman-Rubin (BGR, Rhat) statistic. Models were considered to have converged if MCMC chains were fully mixed based on visual examination, the smallest number of effective draws was greater than 1,000, and Rhat was less than 1.1 for all parameters (Gelman et al. 2004). Daily net upstream fish passage (N) was estimated using the model output for upstream fish (U) and subtracted the model output for downstream fish (D) to arrive at net upstream fish for the day (Xie et al. 2005).

$$N = U - D$$

Run Timing and Environmental Variables

Coho that moved upstream past the SONAR leapt over the Sol Duc Salmon Cascades. This waterfall is a partial migration barrier that fish can only pass during certain flow conditions. To monitor environmental conditions, we installed a stream temperature logger at the SONAR site and collected data on rainfall, air temperature, and stream flow from nearby monitoring stations. We will continue to monitor these variables, along with migration timing past the SONAR unit, to learn more about how environmental covariates are associated with passage of summer coho over the Salmon Cascades.

Results

Data Collection and review

The SONAR was installed on July 17, 2023 at 17:13:49 and operated until removal on November 17, 2023, at 13:39:56. In total, the SONAR was operated and recorded data 81.5% of time during this period. Short SONAR outages occurred during August and September and were primarily due to technical

difficulties related to computer software and power supply. In late September through the remainder of the season we began to lose the ability to fully charge the battery bank using solar energy. At this point, we began transporting batteries off-site to charge, resulting in more frequent short SONAR outages. In November, there were two separate outage events due to storms, high flows, and debris. During these events, we operated the SONAR for as long as possible but were required to remove the unit in each case until flows dropped.

In total, we reviewed all recorded SONAR imagery and counted all upstream and downstream fish that measured ≥35 cm, but limited the analysis to fish measuring ≥45 cm. In total, we counted 702 fish (confidence level 1) and 38 fish (confidence level 2) moving upstream and downstream. However, for the analysis, we excluded all confidence level 2 fish, leaving 308 upstream and 176 downstream fish measuring ≥45 cm (Table 3).

Table 3. Hours by month that SONAR imagery was recorded, percent recorded, and total upstream and downstream counts of fish with fork lengths ≥45 cm.

Month	Hours Recorded	Hours Out	% Recorded	Upstream Count	Downstream Count
July (17-31)	342:20:40	17:39:20	95.1%	4	2
August	616:30:52	127:29:08	82.9%	46	29
September	648:18:38	71:41:22	90.0%	14	8
October	593:39:21	150:20:39	79.8%	238	136
November (1-17)	226:01:19	181:58:41	55.4%	6	1
Total	2426:50:50	549:09:10	81.5%	308	176

Data was reviewed by two different staff members. To test for potential observer error the reviewers overlapped on over 346 hours of SONAR data from 16 different days throughout the season. Upstream and downstream counts were highly correlated ($r > 0.98$) between reviewers with average percent error values of 20.1% (upstream) and 22.1% (downstream). There was no difference in counts based on the Evans and Hoenig test ($p>0.05$). However, length measurements varied slightly between reviewers. Average percent error was 15.3% for upstream measurements and 10.1% for downstream measurements, but these differences were also not significant ($p>0.05$, Figure 4). Length frequency histograms showed reviewer A(CK) measured upstream fish larger than reviewer B (JB) (Figure 5). The average upstream fish size (for fish ≥35 cm) for reviewer A was 51.5 cm and for reviewer B was 48.6 cm. Also, the length distribution for upstream fish for reviewer A was bimodal. For downstream fish the length distribution between reviewers was similar and bimodal with both reviewers recording fewer fish in the 50-55 cm bin. The average length for reviewers A and B was 49.8 cm and 49.9 cm, respectively for downstream fish, which was nearly identical. No substantial source of bias was identified between the reviewers on fish counts or lengths; therefore, no adjustments were applied to the estimates.

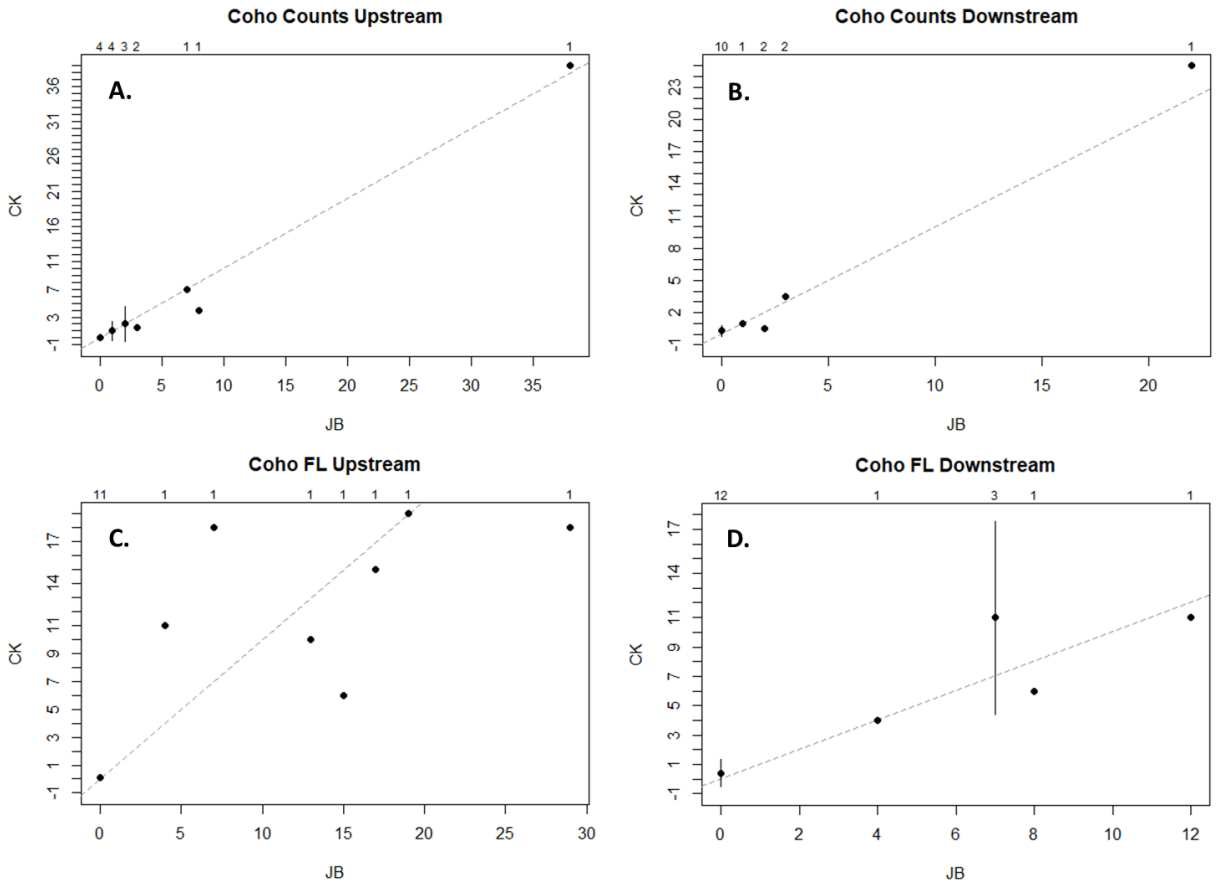

Figure 4. Comparison of daily SONAR counts for a) upstream and b) downstream fish ≥45 cm total length between data reviewer A (CK) and B (JB) and length counts binned by 5 cm increments (35 to 80 cm) for c) upstream and d) downstream fish between data reviewer A and B.

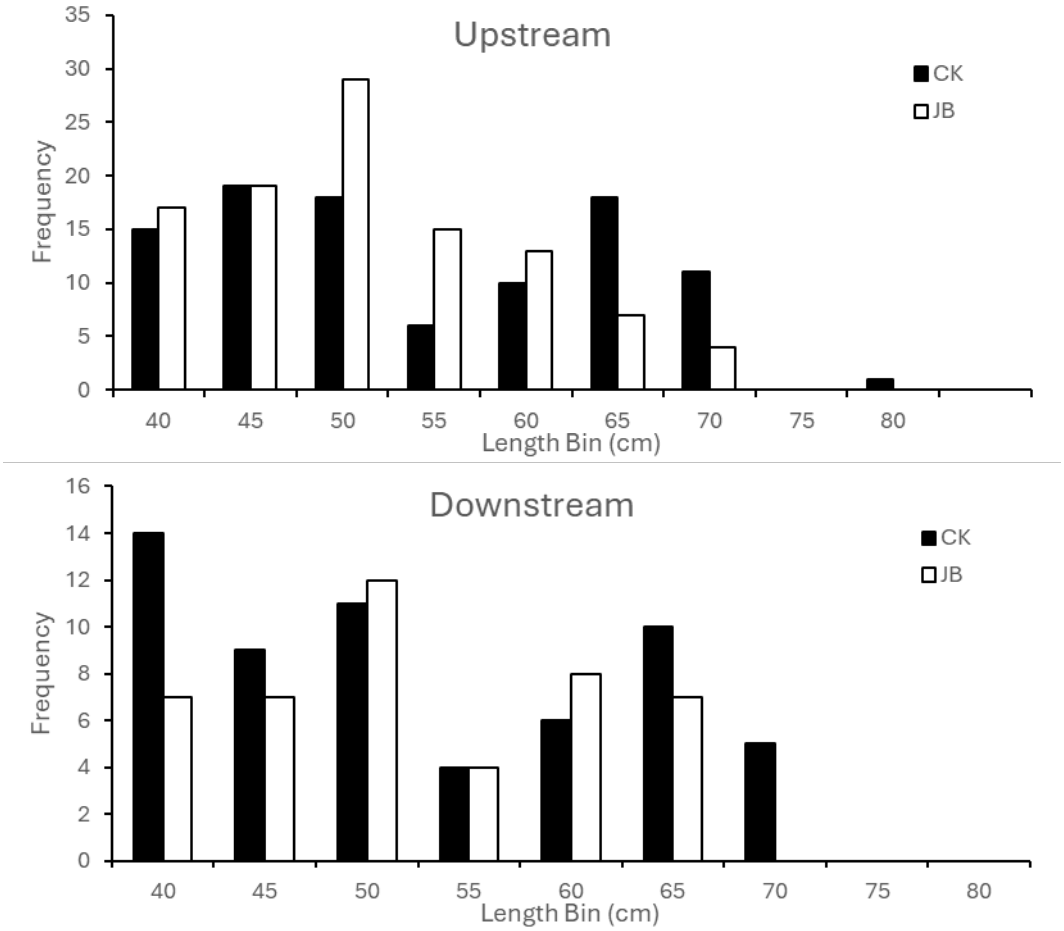

Figure 5. Length frequency histograms for overlapping data review of two reviewers for all upstream and downstream fish with a fork length measuring ≥35 cm.

Fish size and species composition

Total lengths (cm) were collected from 199 (190 adults and 9 jacks) hatchery summer coho at the Sol Duc hatchery on October 3, 2023. Lengths were collected from fish that were used for broodstock and for surplussing to avoid potential size bias associated with hatchery practices. Length data was also collected from two wild coho (one male: 58 cm and one female: 62 cm) that were found dead on the rocks at the Salmon Cascades that likely became stranded while attempting to ascend the cascades. In total, lengths were collected from 201 summer coho. The minimum length of an adult coho was 47 cm and total length averaged 63 cm (Table 4). This size was similar to those collected by ONP staff and from in-river fisheries in the 1980s and early 2000s. Based on these observations, we chose to use 45 cm as the minimum size threshold for adult coho in the SONAR imagery. The length distribution of all measured upstream and downstream fish from the SONAR imagery showed a somewhat bimodal distribution (Figure 6). However, we believe that there were small coho (45 to 47 cm) present as we observed a few adult coho in that size range during snorkel surveys.

Table 4. Total length (TL, cm) summary of adult and jack summer Coho Salmon collected in 2023. Data includes 190 TLs taken from hatchery fish at Sol Duc Hatchery and two wild adult TLs from the Salmon Cascades.

Sex	Number Sampled	Avg. Length	Min. Length	Max. Length
Male	93	61.0	47	70
Jack	9	35.1	31	38
Female	99	64.8	49	77
Adults	192	63.0	47	77

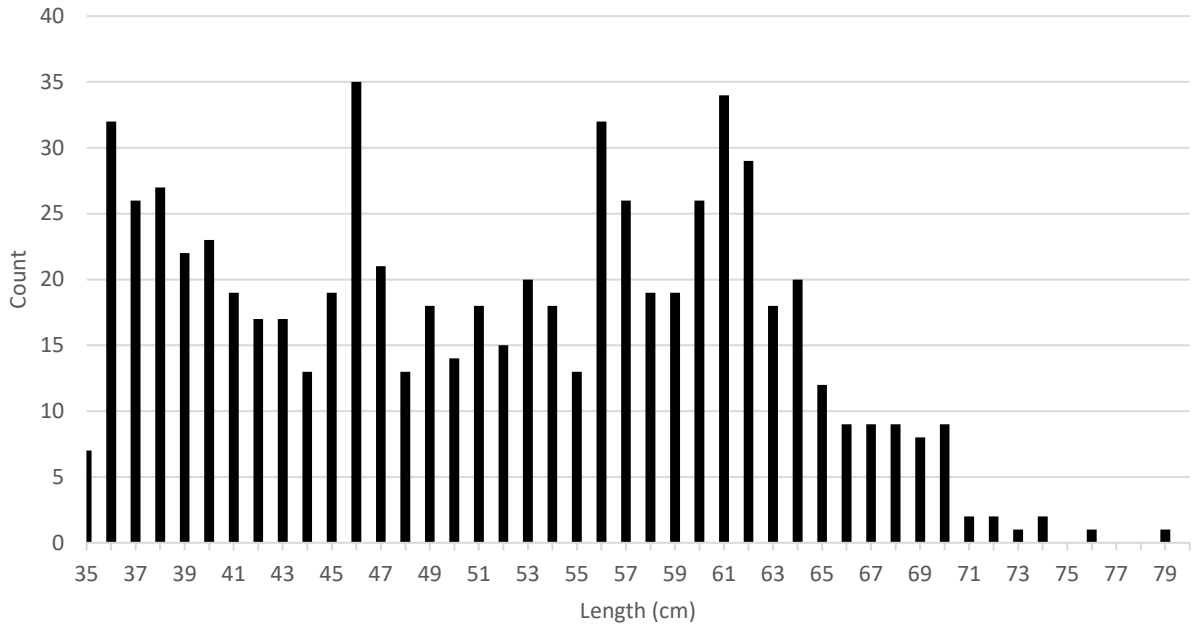

Figure 6. Length distribution of upstream and downstream fish ≥35 cm using ARIS fish software.

On July 18, 2023, one day after the SONAR was installed, we conducted our first snorkel survey of the SONAR index area. No Coho Salmon were observed during this first snorkel survey above or below the Salmon Cascades. The lack of fish recorded by the SONAR or observed during the first snorkel survey suggested that the SONAR was installed before summer coho began migrating upstream. The first adult summer coho were observed during snorkel surveys on August 8, 2023, in the plunge pool just below the Salmon Cascades and the first adult coho upstream of the salmon cascades was observed on August 17, 2023 (Table 5). The last snorkel survey of the season was conducted on September 7, 2023, due to a statewide moratorium on snorkel surveys. In total, we conducted 7 snorkel surveys upstream and downstream of the SONAR and observed no fish other than adult coho that were larger than 45 cm. Adult summer coho were observed in highest densities in the large plunge pool just below the Salmon Cascades (pool 5), and in another pool above the cascades just upstream of the SONAR site (pool 1).

Interestingly no adult coho were observed holding in pools 2-4 during any of the surveys, suggesting that fish moved quickly upstream past the SONAR soon after making the leap over the cascades. The largest adult trout that was observed was approximately 35 cm. Mountain Whitefish (*Prosopium williamsoni*) were observed; however, these fish were only observed below the Salmon Cascades during the surveys and all were smaller than 45 cm. Snorkel surveys conducted by ONP have never observed Mountain Whitefish above the Salmon Cascades, and they are not known to exist upstream of the Salmon Cascades (Sam Brenkman, ONP, pers. comm.). Similarly, no jack coho were observed upstream of the Salmon Cascades; however, ONP snorkel surveys in past years have seen low numbers of coho jacks above the cascades with zero jacks observed during 2021 and just three observed during 2022 surveys. Nonetheless, even if jacks made the leap over the Salmon Cascades, they were excluded from the SONAR counts as their size range (31 to 38 cm) was below the size threshold for inclusion.

Table 5. Number of fish observed above and below Sol Duc Salmon Cascades during snorkel surveys in the SONAR index area during summer of 2023.

	Adult Coho		Jack Coho		Adult Trout*		MT. Whitefish	
Date	Above	Below	Above	Below	Above	Below	Above	Below
7/18/2023	0	0	0	0	2	0	0	8
7/26/2023	0	0	0	1	5	2	0	10
8/8/2023	0	6	0	0	5	1	0	8
8/17/2023	1	3	0	0	2	0	0	10
8/23/2023	5	5	0	0	8	0	0	18
8/31/2023	9	7	0	0	4	0	0	10
9/7/2023	7	5	0	2	1	1	0	39

*Adult trout were a mix of Cutthroat and Rainbow. The largest observed was approximately 35 cm.

Hatchery summer coho are released from the Sol Duc Salmon hatchery, located 26.5 miles (42.6 km) downstream of the Salmon Cascades. Coho that returned to the hatchery during the summer of 2023 were from brood year 2020. Reported releases of summer coho smolts from this brood were 109,009 smolts, and it is estimated that >99% were visibly marked with an adipose fin clip (WDFW Plants database). Therefore, we would have detected and counted hatchery strays during snorkel surveys if they were present in the snorkel survey index. However, we observed no ad-marked hatchery coho in 2023. No ad-marked coho were observed during previous ONP snorkel surveys in an index area upstream of the Salmon Cascade from 2006-2010 (Brenkman et al. 2012). Similarly, unpublished data collected by ONP from snorkel surveys in 2021 and 2022 also reported no ad-marked adult coho in the index areas above and below the Salmon Cascades. Based on this information, all fish ≥45 cm from the SONAR imagery were regarded as wild summer coho.

Abundance Estimation

In total we counted 308 adult summer coho that passed upstream of the SONAR unit and 176 coho that passed downstream for net upstream passage of 132 adult summer coho during the time that the SONAR was operational. The SONAR operated for 2,426 hours, or 81.5% of the season, and all SONAR data collected was manually reviewed. We estimated missed fish passage for the 549 hours that the SONAR did not operate. Of the outage time, 309 hours occurred on days when the SONAR operated for

part of the 24-hour period. Many of these smaller outages were the result of battery swapping, data downloads, or adjustments to the power system. An estimated 36.7 upstream and 17.1 downstream coho were missed during these partial outage days based on coho count expansion. The Bayesian spline estimated a total of 358 upstream and 197 downstream fish for the season with a net upstream total of 161 summer coho that swam past the SONAR site (Table 6, Figure 7).

Table 6. Estimated summer coho escapement upstream of Sol Duc Salmon Cascades 2024. Total escapement, standard deviation, and 95% confidence interval (CI).

	Estimate	SD	Lower 95% CI	Upper 95% CI
Estimated Up	358	13.5	346	396
Estimated Down	197	11.6	192	230
Total Escapement	161			

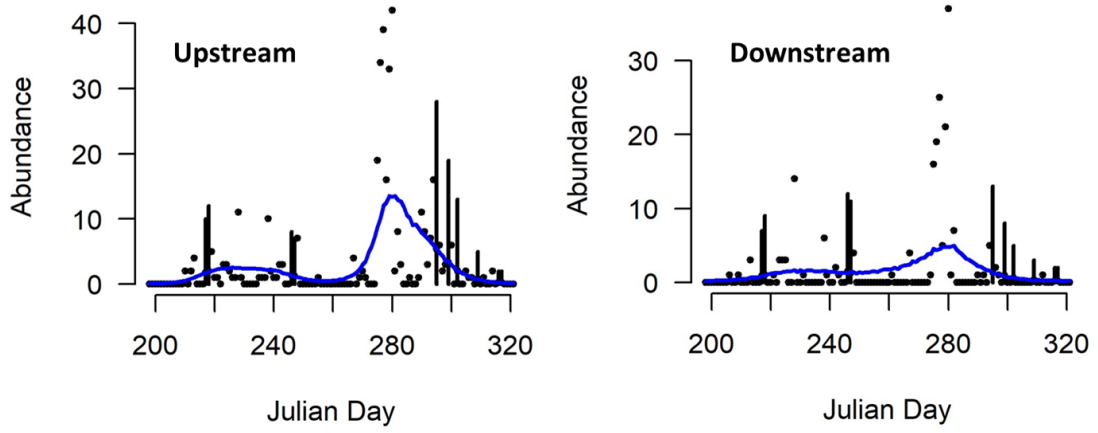

Figure 7. Upstream and downstream summer coho counts with confidence intervals estimated during SONAR outages using the Bayesian spline model.

Migration Timing and Environmental Variables

The first upstream coho at the SONAR site was recorded on July 29, 2023, and the median migration date for the run was October 6, 2023. The last coho observed in the SONAR imagery passed upstream of the ARIS on November 10, 2023 (Figure 8). We believe the entire duration of the summer coho return in 2023 occurred while the SONAR was operational based on the lack of fish during the first snorkel surveys of the season and absence of fish >45 cm detected using the SONAR during the first two weeks of deployment. Similarly, no coho were observed during the last week of SONAR operation and at the time, spawning activity was reported to be nearly complete by WDFW and ONP crews conducting spawning ground surveys.

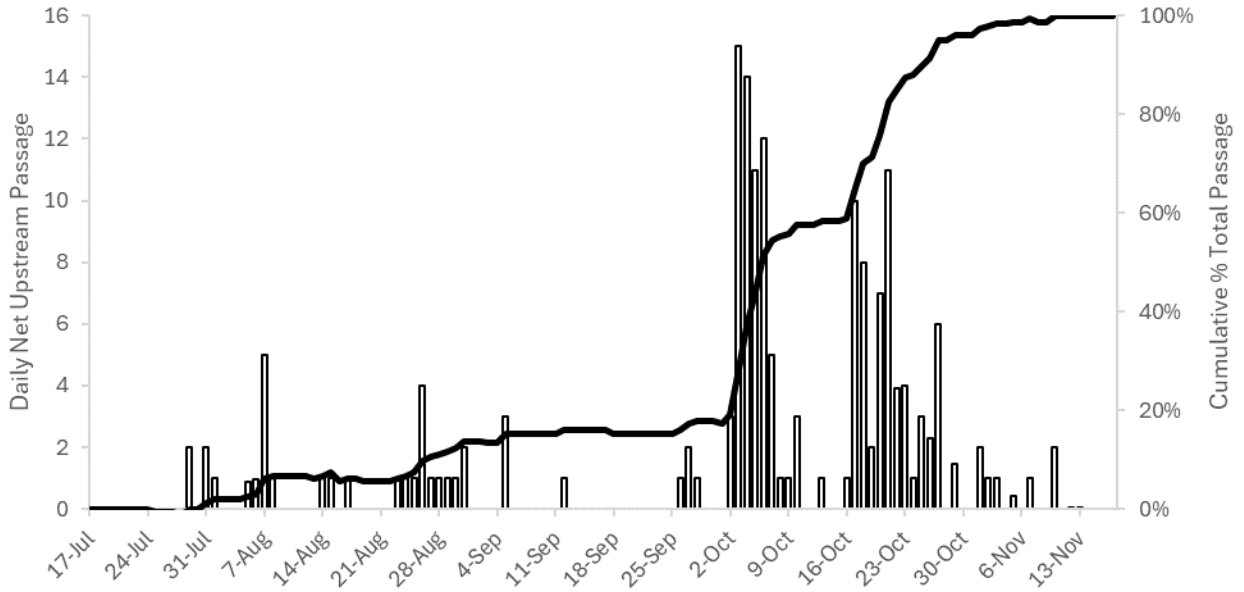

Figure 8. Daily summer Coho Salmon (≥45 cm) upstream passage and cumulative proportion of run past the SONAR site, Sol Duc River, 2023.

The SONAR unit was strategically placed on a gravel bar of a shallow, exposed pool that is not an ideal holding habitat for adult salmon to reduce the amount of milling. However, some milling activity was observed at the SONAR site as evident from the 176 downstream detections. When reviewing the imagery from the Sol Duc, it was clear that many adult coho swam upstream through the ensonified area and then passed back downstream shortly after, before ultimately moving back upstream again. In August and September, these fish were moving in low and clear water conditions and appeared to be cautious and explored the pool before moving upstream. The number of downstream movements relative to upstream movements decreased in the second half of October as precipitation and stream flow increased (Figure 9) and fish moved more directly passed the SONAR site.

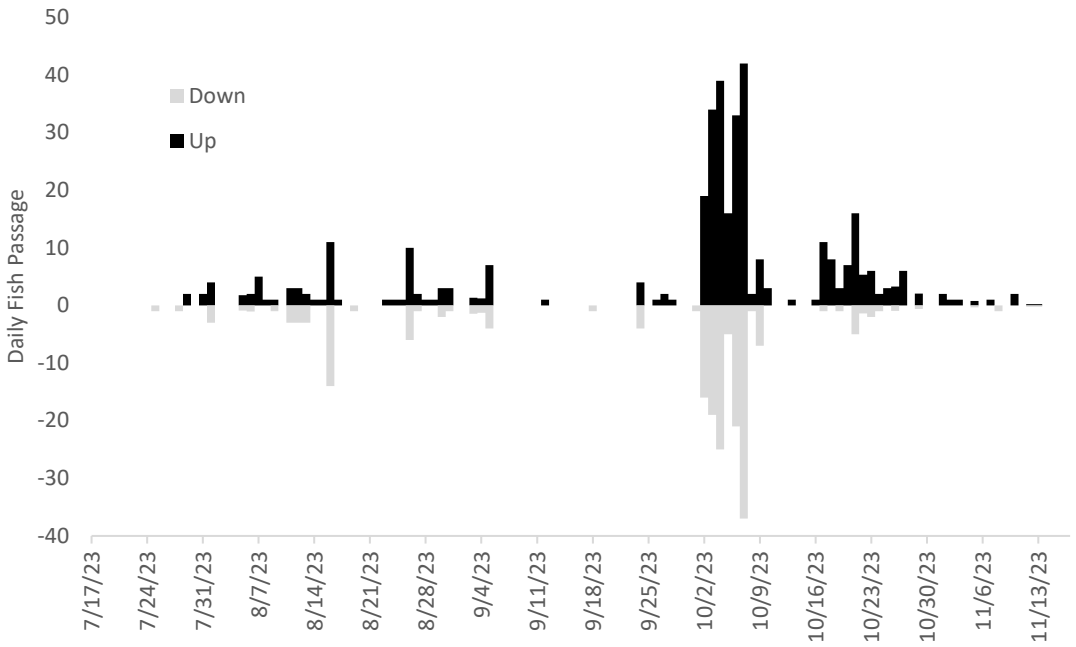

Figure 9. Expanded daily upstream and downstream fish passage at the Sol Duc SONAR site in 2023.

Water flow, temperature, and light likely influenced the ability of a salmon to ascend the Salmon Cascades. Given the lack of prime holding water as seen during snorkel surveys between the SONAR site and the Salmon Cascades, we suspect that upstream fish passage at the SONAR site is a strong surrogate for successful passage of the cascades. Most fish moved upstream past the SONAR station when daily average water temperatures were between 8.5°C and 11°C (Figure 10). However, a few fish did pass when temperatures were warmer in August. Fish movement declined rapidly after stream temperatures dropped below 9°C in late October. We did not have a direct measure of stream flow at SONAR site. The only flow station on the river is operated by Washington Department of Ecology at RM 13.8, roughly 42.7 miles downstream of the Salmon Cascades (Station 20A070, Sol Duc River. near Quillayute). Some fish were able to make passage during the low flows of August when the daily average stage height at the Sol Duc station measured 15 ft. A majority of the coho passed upstream of the Salmon Cascades after rain brought the stream flow up feet in early October and when flows were dropping and measured between 15.2 and 15.1 mean daily stage height at the Ecology station. Flows during the summer of 2023 were abnormally low across the region. By early September, daily mean stage height (Station 20A070, Sol Duc River near Quillayute) was the lowest observed between 2009-2023 (Figure 11). These low flow conditions and the lack of precipitation until late September likely explained the lack of fish movement through the month of September and appear to have slowed the migration of fish into the upper Sol Duc River.

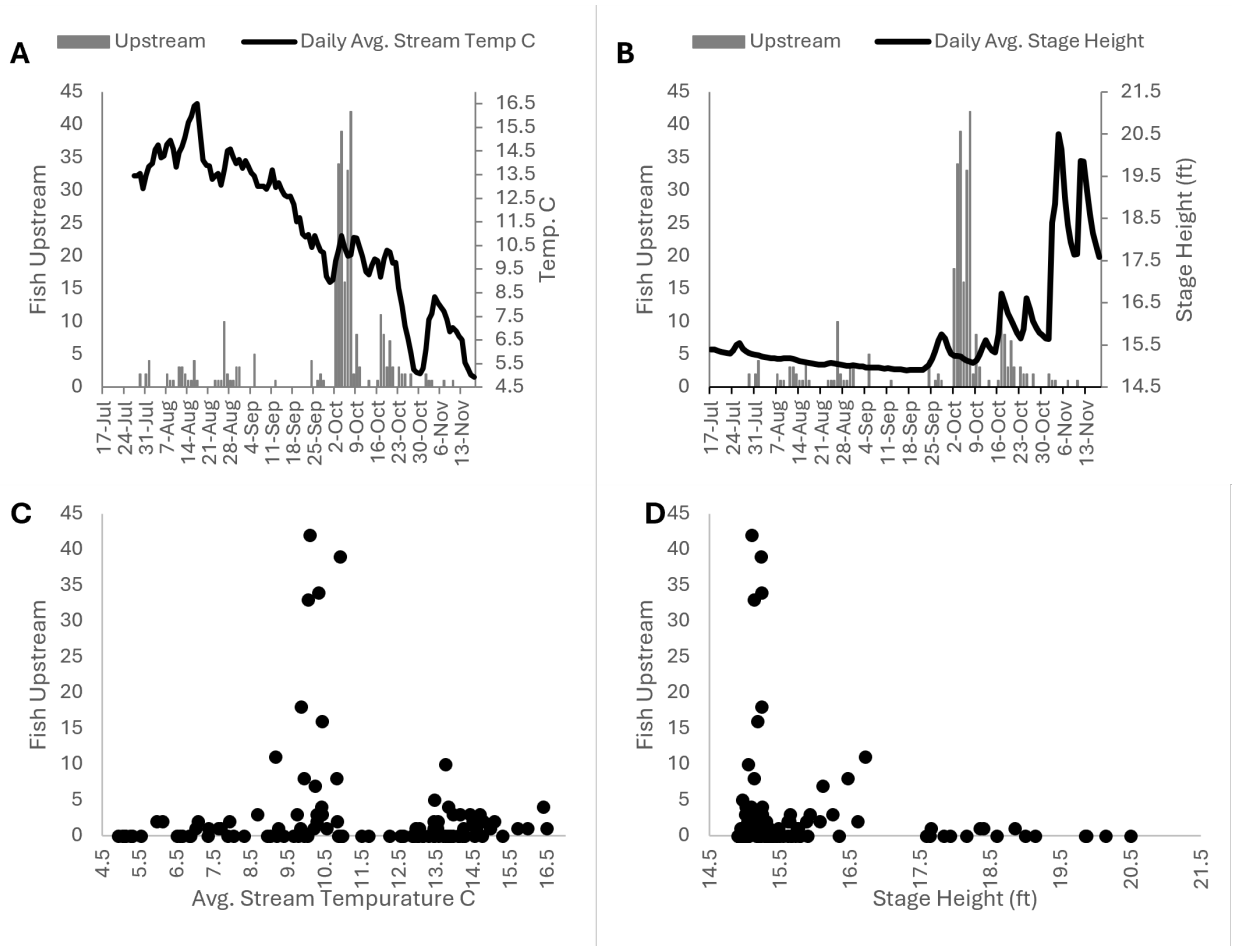

Figure 10. Plots of a) upstream fish count (≥45 cm) at the Sol Duc SONAR station and daily average stream temperature (°C), b) fish count and daily mean stage height (ft) at Washington Department of Ecology Station 20A070, Sol Duc R. nr Quillayute, c) fish count as a function of stream temperature (°C), and d) fish count as a function of stage height (ft).

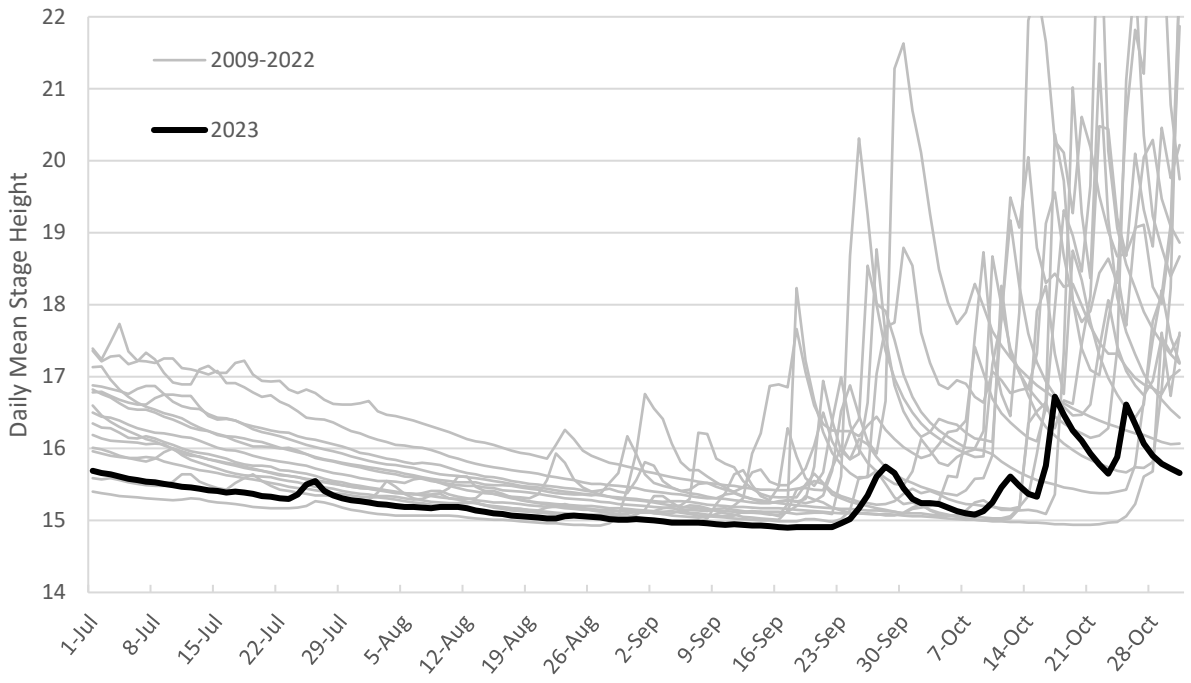

Figure 11. Daily mean stage height 2009-2023 from Washington Department of Ecology Station 20A070, Sol Duc River near Quillayute.

Discussion

This first season of SONAR operation on the Sol Duc River was a success as much was learned regarding maintenance, data review, and analysis. We refined our methods to keep the SONAR system maintained and operational throughout the summer coho migration. We estimated escapement of 161 adult summer coho above the Salmon Cascades and learned much about run timing and behavior of this unique population. However, it was an abnormal first year for the project as summer and fall flows were extremely low, seeming to limit passage over the cascades for many fish. Also, it was apparent that the return was low with the total summer coho return for the 2023 season estimated to be 324 for the Quillayute basin, the 4th lowest return estimated by co-managers and continuing a downward trend in abundance (Figure 12).

On October 3, 2023, approximately 300 fish were observed in the plunge pool below the Salmon Cascades. Over the next few weeks, these fish continually attempted to ascend the cascades, and it was clear that many of these fish were unable to do so. Most of these fish were dark and appeared in poor condition to make the leap once the flows increased and water temperatures dropped. With only 161 coho passing the SONAR unit, it appears many of these coho ultimately spawned downstream of the Salmon Cascades.

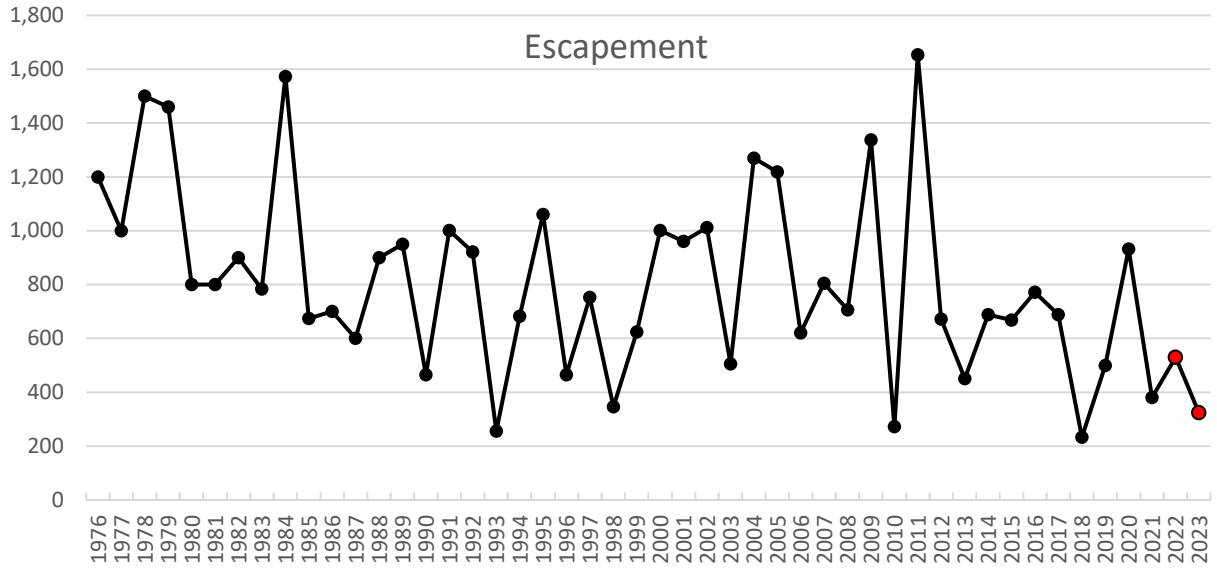

Figure 12. Escapement estimates for Quillayute summer Coho Salmon 1976-2023. Escapement estimates in 2022 and 2023 are yet to be finalized, pending co-manager agreement.

Crews from WDFW and ONP conduct spawning ground surveys annually for summer coho salmon, and these data are used to generate a total Quillayute basin escapement estimate. This redd-based escapement estimate includes summer coho that spawn above and below the Salmon Cascades and includes unmarked fish that occasionally stray that may have been observed spawning in other parts of the greater Quillayute watershed. In most years, the number of summer coho observed spawning outside the Sol Duc River in the Quillayute is usually zero or close to it. On average, 90% of the summer coho spawning is estimated to occur above the Salmon Cascades. However, in 2023, the redd-based escapement estimate for summer coho for the entire Quillayute was 324 fish, of which 320 were observed in the Sol Duc basin. In past years, redd-based escapement estimates were broken out into areas upstream and downstream of the Salmon Cascades. In 2023, the redd-based escapement method estimated 259 fish spawned below the Salmon Cascades and only 65 fish above. This is the highest number of summer coho spawning below the cascades observed, and for the first time, fewer summer coho spawned above the Salmon Cascades than below them. Moreover, the 65 fish above the cascades was the lowest number ever estimated upstream of the Salmon Cascades. These numbers suggest that many summer coho were unable to pass the Salmon Cascades during the 2023 season, presumably due to low flow.

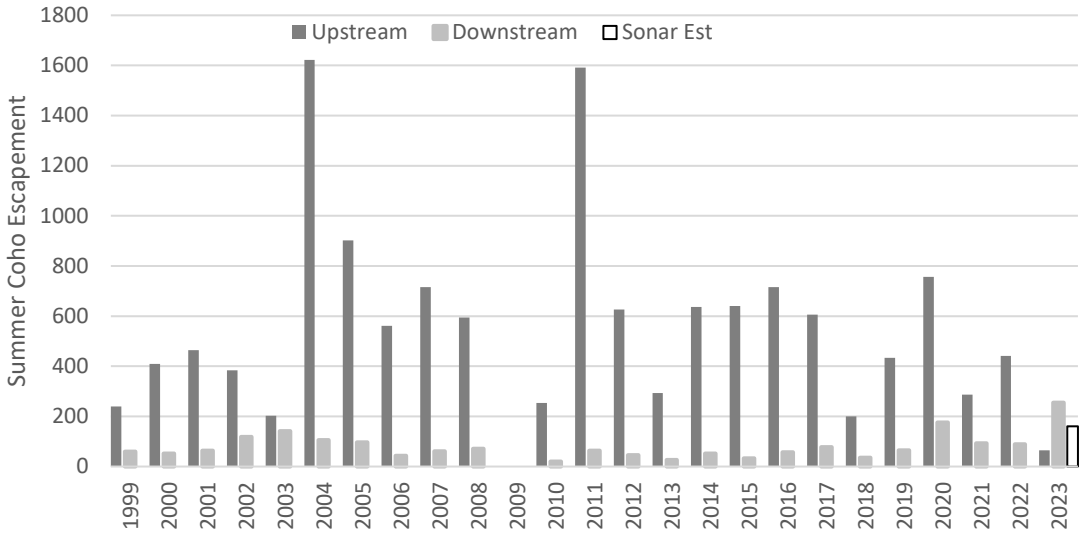

Figure 13. Redd-based escapement for Sol Duc summer coho in areas upstream and downstream of the salmon cascades compared with the SONAR-based escapement upstream of the Salmon Cascades in 2023.

In 2023, the SONAR estimate of 161 summer coho was 2.5 times higher than the redd-based estimate of 65 summer coho upstream of the Salmon Cascades. Similar results were found in other systems using SONAR, with SONAR escapement estimates exceeding redd-based estimates by twofold or more. On the Dungeness River, both SONAR-based and redd-based escapement estimates were determined for winter steelhead from 2019-2023. On average, the SONAR-based estimates were 2 times higher than the redd-based estimates (Craig et al. 2024). On the Elwha River, SONAR has been used to estimate escapement of steelhead, coho, and Chinook following dam removal in 2012. In this system, high turbidity from impounded sediment loads combined with the remoteness of the Elwha watershed make redd-based estimates of escapement unattainable. Spawning ground surveys in the Elwha system are generally used to collect information on spawning distribution and as an opportunity to collect biological samples; therefore, comparing SONAR and redd-based estimates of escapement is not feasible in the Elwha. However, Denton et al. (2023) determined that if the steelhead redd-data from the Elwha were expanded using 1.8 fish-per-redd expansion, in 2023, the redd-based escapement estimate would only be 29% of the SONAR-based estimate. The authors noted that this was not a perfect comparison of methods as survey coverage and consistency was not complete. However, both the Elwha and the Dungeness rivers have very remote reaches that are nearly impossible to survey given the rugged and inaccessible terrain. High flows or low visibility in some years also make surveys difficult or dangerous. For remote streams such as those that flow from the Olympic mountains, SONAR is a tool that could be used for escapement estimates, to learn more about run timing and kelting behavior in steelhead, or to compare and assess estimates from redd-based methodologies.

Recommendations

Sol Duc summer coho will be monitored again in 2024 using SONAR. For the 2024 season, we hope to again conduct snorkel surveys. If not, we may utilize camera surveys to verify the arrival and presence of summer coho in the SONAR area. We will also offer to participate in snorkel surveys conducted by ONP staff.

At the end of the 2023 season, we were not able to power the batteries consistently with solar power and began packing heavy batteries in and out of the site to charge them off station. To avoid this in the 2024 season, we plan to acquire lighter batteries and a small gas-powered generator to charge batteries on site.

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