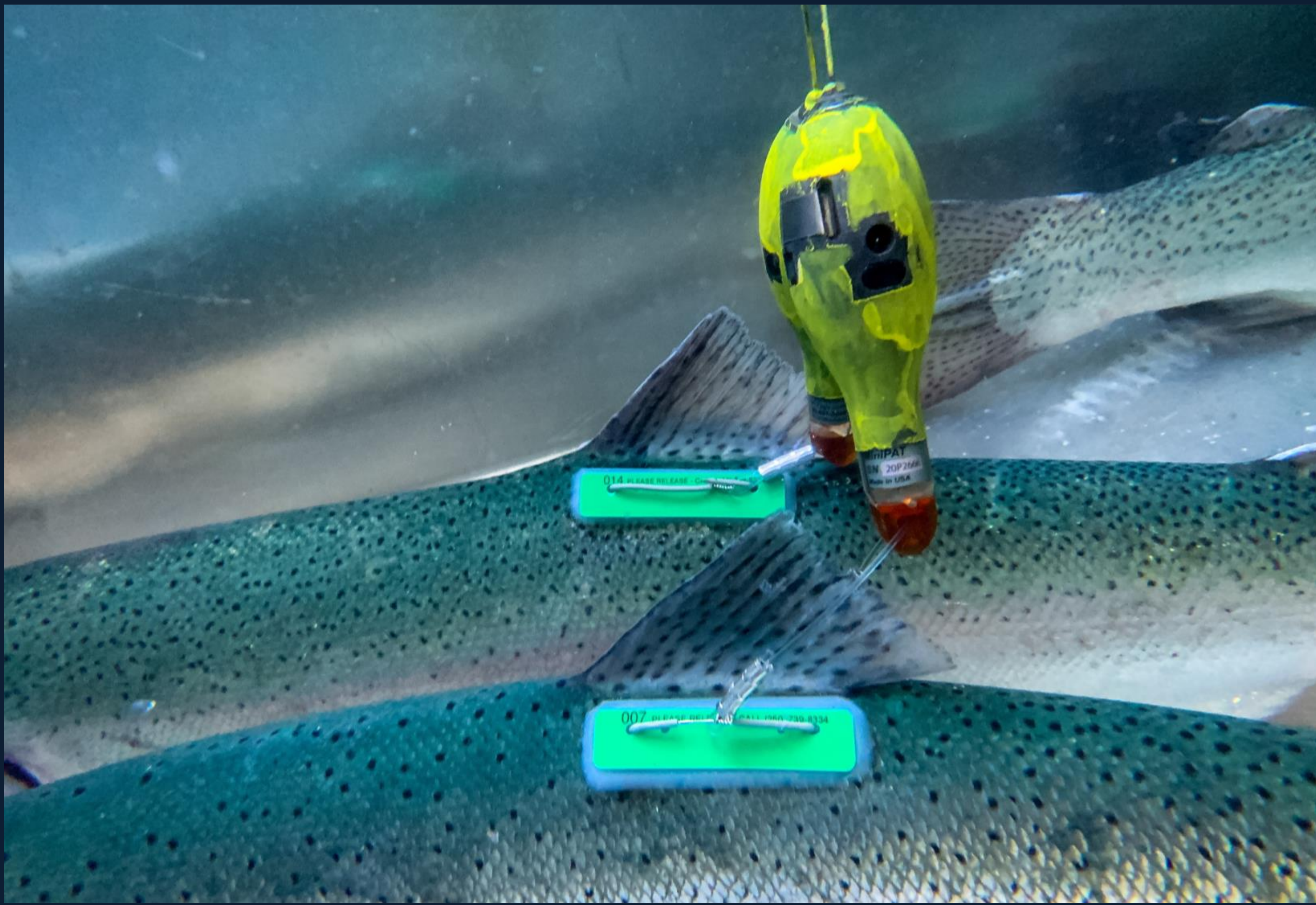

BOTTLENECKS TO SURVIVAL

MOVEMENT AND MORTALITY OF STEELHEAD TROUT (*ONCORHYNCHUS MYKISS*) IN THE NORTHEAST PACIFIC OCEAN, ELUCIDATED FROM POP-UP SATELLITE ARCHIVAL TAGS (PSATS)

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Photo credit: Danny Swainson

ABSTRACT

In April and May of 2021 through 2023, 47 (55 – 82 cm; mean: 68 cm) post-spawn winter-run steelhead (*Oncorhynchus mykiss*) trout were affixed with pop-up satellite archival tags (PSATs) from four rivers on Vancouver Island, Canada. The four rivers were the Keogh and Nahwitti, located at the northern tip of Vancouver Island, and the Cowichan and Englishman, located mid- to the South of Vancouver Island. Forty-two (89%) of the tags successfully transmitted data after deployment (1.1 – 89.1 days; mean: 19.7 days). Estimated location and travel pathways were approximations via a spatial state-space model (Wildlife Computers geolocation processing software (GP3) that used estimated times of sunrise and sunset with corresponding reference data on sea surface temperature. Travel distance was variable, with long travel distances associated with long deployment time (1.1 – 2993.8 km; mean: 401.8). The majority of kelts were short and proximal to shorelines, but extensive migrations indicated vectors towards the Aleutian Island chain in Alaska. Mortality was not identifiable in the majority of tag release events. However, 9 of the successfully recovered tags (23%) appeared to have been ingested by pelagic ectothermic fish, inferred from a change in diving behaviour and large reductions in light levels recorded by the tags before being expelled. The distance travelled by these ingested tags was inferred by the distance between the last light level-derived location and the first GPS-derived location after a tag had been successfully geolocated upon tag popup. Travel time and distance varied with tag ingestion time. Overall, the study demonstrated the utilization of satellite tags to collect information on a life stage that is relatively unknown for steelhead. The data suggests that among predators, pelagic fish may have a larger impact on adult steelhead survival than previously thought.

Citation:

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INTRODUCTION

Steelhead Trout (*Oncorhynchus mykiss)* stocks on Vancouver Island, British Columbia, have been severely depressed since the mid-1990s, with many populations in the (extreme conservation concern) status. Even in highly productive streams, steelhead abundances are only a fraction of other returning salmon species (Prov. B.C. 1990), making them extremely vulnerable to environmental and anthropogenic changes (Wilson et al. 2021, 2022). In the few systems currently being studied (Keogh, Englishman, and Gold rivers), total populations are routinely estimated to be less than 100 adult individuals, where historically hundreds or thousands had existed (FLNRO Archived data). Reasons for their dramatic decline are not well understood, but ocean productivity, climate change, quantity and quality of freshwater habitat, overfishing (typically bycatch in mixed stock fisheries), and increased predation events are some commonly referenced causes(Malick et al. 2022; Moore and Berejikian 2022; Wilson et al. 2022).

Pacific salmon populations returning to the Northeast Pacific have seen significant declines over recent decades, with steelhead trout (Steelhead; *Oncorhynchus mykiss*) being no exception (Kendell et al, 2017). Steelhead are an anadromous variant of rainbow trout whose range in North America extends from California to Alaska. Steelhead are one of the few members of the Oncorhynchus family native to the Northeast Pacific that are iteroparous thus having the ability to spawn more than once with the vast majority of these being females (Copeland et al. 2019; Keefer et al., 2008). After spending one to five years in freshwater post-hatch (but two to three are most common), steelhead undergo a smoltification process and migrate to the ocean to live out the pre-spawn adult portion of their life-history. After typically spending two or three years at large in the ocean, adults return to their natal streams to spawn. For most steelhead stocks, most male fish perish soon after spawning, although some post spawn females known as "kelts" will return to the ocean and spawn again one to two years later. During steelhead recovery, they regain their silvery appearance and migrate downstream back into the ocean; of these kelted fish, some (~15%; but is highly variable between river and stock) will return 1-2 years later to spawn again.

The details of the behaviour and fate of adult steelhead outside their freshwater environment are largely limited to fisheries interception data (see Myers et al. 2013), although some studies have used acoustic telemetry in near-shore studies. For example, acoustic telemetry tracked steelhead smolts from multiple systems on the East Coast of Vancouver Island during their early marine residence; however, these types of studies are limited by their receiver coverage, thus limiting inference for species with large migrations outside receiver coverage. As such, the fate and behaviour of fish outside of the coverage remain unknown.

Recent advancements in Pop-up Satellite Archival Tags (PSAT's) allow additional information to be collected without needing physical tag recovery. PSATs are designed to collect light-level data so tracks can be generated to understand large-scale movements and behaviour of fish and other animals which do not spend enough time at the surface to allow the use of real-time GPS location and data uplink to Argos satellite.

Purpose

Here, we exploit the iteroparous life-history of steelhead to understand migration patterns of adult steelhead in the Northeast Pacific and identify mortality mechanisms. We also tested the viability of kelt reconditioning as a potential method to increase return rates of steelhead kelts.

The primary goals of the study were to:

1. Determine the viability of, and refine techniques of tagging steelhead kelts with PSAT's
2. Identify the range and dispersal of steelhead kelts after leaving their spawning streams
3. Identify mechanisms of mortality of adult at-sea steelhead

This research will provide new insights into present and future management approaches of steelhead by identifying the mortality mechanisms that result in poor marine survival of adult steelhead while at large in the Northeast Pacific. The management applications of this research will provide a broad view of the possible outcomes of future management directions.

METHODS

From 2021 through 2023, a total of 47 adult steelhead kelts were captured from the Cowichan, Englishman, Nahwitti and Keogh rivers on Vancouver Island, Canada and were affixed with PSATs (Table 1). The study had a paired design with steelhead kelts being captured and released at locations near the mid to southern and northern regions of Vancouver Island (Figure 1). An effort was made to balance yearly releases between the two regions, but kelt capture rates made yearly equalization difficult. Ultimately, 24 and 23 kelts were released from the Northern and Mid-Island zones respectively (Table 1).

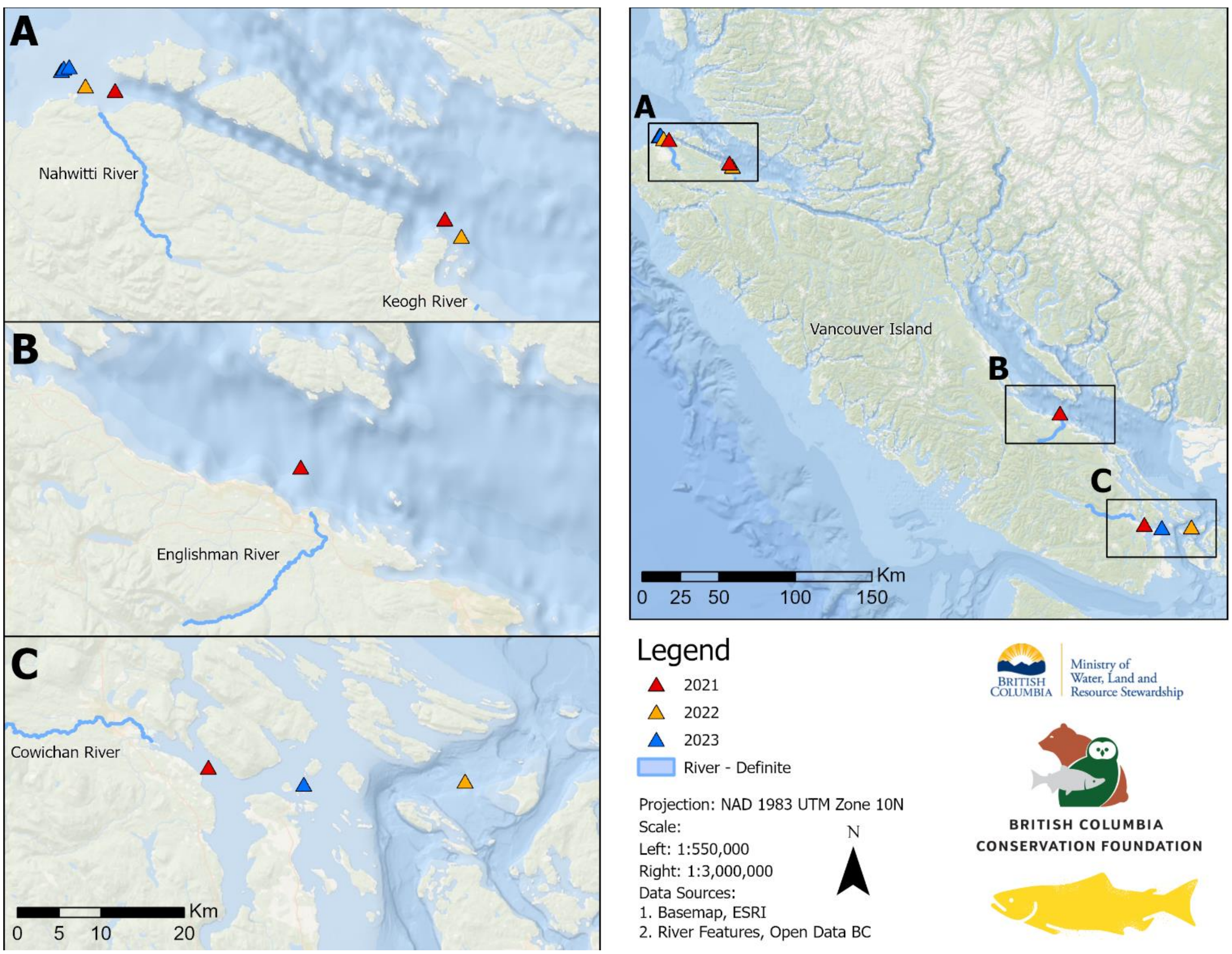

Figure 1. Map of steelhead kelt release locations on Vancouver Island for all study years (2021 – 2023).

Study Area

Vancouver Island is located in the northeastern Pacific Ocean, is 456 km in length and 100 km in width (at its widest point), and has a total area of 31,285 km^2. It is the largest island along the west coast of the Americas. Vancouver Island is surrounded by the Johnstone and Queen Charlotte straits on its north and northeast coasts and by the Salish Sea in the southern portion. Vancouver Island is home to hundreds of rivers of varying sizes and lengths, many of which are home to steelhead trout. This study targeted four steelhead populations, two of which were located in the northern region and two in the southern region (Figure 1).

Southern Region

The Salish Sea is an inland sea encompassing Puget Sound, the San Juan Islands, and the Strait of Georgia (Figure. 1). The area spans from Campbell River on Vancouver Island to the Olympic Peninsula. The Salish Sea is home to 37 species of mammals, 172 species of birds, 253 fish species and more than 3,000 species of invertebrates (Gaydos and Pearson 2011; Brown and Gaydos 2011) and multiple threatened or endangered species as listed under the Canadian Species at Risk Act and the US Endangered Species Act. These threatened species include the Southern Resident Killer Whales (*Orcinus orca*) and ecologically significant units or species of Pacific Salmon, such as the Nanaimo River Spring and Summer-run Chinook (*O. tschawystcha*).

Cowichan River

The Cowichan River originates at Cowichan Lake and flows east for approximately 47 km before reaching tidewater at Cowichan Bay. The Cowichan River watershed drains an area of approximately 940 km^2. The intertidal mudflats extend for an additional 2.5 km between the Tzouhalem Road bridges and deep water drop off within the bay. A bifurcation occurs 1.3 km upstream of the bridges (river km 1.3) which separates the river into the North and South Arms. The Trans-Canada Highway 1 crosses the Cowichan River at km 5.3 while Skutz Falls is located at river km 33.6. The Cowichan River is regulated by a weir operated under a provision rule curve. The mainstem Cowichan River sees input from multiple small creeks which drain the southern slopes of Mount Prevost, these include Inwood, Menzies, Bings, and Averill creeks. The latter three creeks including the Quamichan Creek drain into the Cowichan River via Somenos Creek.

Englishman River

From its headwaters at Mount Arrowsmith (1,817 m elevation), the Englishman River flows east draining 324 km^2 of the central east coast of Vancouver Island. The mainstem anadromous length is 15 km and end at the barrier in Englishman River Falls Provincial Park. The largest sub-basin, the South Englishman River, enters the mainstem 8.3 km upstream from the mouth. It drains 83 km^2 and has an anadromous length of 4.5 km. Other significant tributaries include Centre Creek (a sub-basin of the South Englishman), Morrison Creek and Shelley Creek with anadromous lengths of 5.2, 2.1 and 1.0 km, respectively (Lough and Morley 2002). The majority of the Englishman watershed is privately owned by Island Timberlands and TimberWest with holdings comprising 69 and 18% of the watershed area respectively. The majority of the mainstem's anadromous riparian corridor is contained within a mosaic of parks and protected areas managed by BC Parks, Regional District of Nanaimo, the Nature Trust and the City of Parksville.

Northern Region

Northern Vancouver Island is characterized by its rugged beauty and diverse ecosystems, encompassing areas like Johnstone Strait, Port Hardy, Cape Scott and Brooks Peninsula. The landscape features pristine estuaries, long sheltered fjords, old-growth forests, and dramatic mountain ranges. Brooks Peninsula, in particular, is unique as it escaped glaciation and thus hosts plant species found nowhere else on Vancouver Island. Marine ecosystems here are rich and vibrant, supporting a variety of species, including orcas, humpback whales, Pacific white-sided dolphins, and sea otters. Blackfish Sound and Queen Charlotte Strait are notable hotspots where visitors can observe large congregations of marine mammals feeding and exhibiting fascinating behaviors. The return of sea otters has transformed kelp forest ecosystems, enhancing biodiversity by controlling sea urchin populations. The town of Port McNeill (near the mouth of the Keogh River), is known for its proximity to the Broughton Archipelago, BC's largest marine park. This region is also culturally rich, with significant Indigenous heritage sites.

Keogh River

The Keogh watershed (130.2 km^2) is located on the northeast coast of Vancouver Island, approximately 11 km southwest of Port McNeill, BC. The Keogh River flows northeast for 33 km from Keogh Lake and drains into Queen Charlotte Strait. The majority of the Keogh watershed is on crown leased land managed by forestry companies. The river supports trout and several salmonid species (Ward and Slaney 1979) and is home to a provincial research station that has documented salmonid survivals in both freshwater and marine environments since the 1970s. In response to declining populations and reduced marine survival, extensive restoration work occurred on the river in the 1990s and early 2000s. However, summer base flows remain typically low (estimated <5% of mean annual discharge) and are thought to limit juvenile production.

Nahwitti River

The Nahwitti River, located approximately 26 km northwest of Port Hardy on the northern end of Vancouver Island, originates from Nahwitti Mountain and flows northwest into Goletas Channel near Hope Island. Spanning a watershed of 229 km^2, it supports a number of salmon, including sockeye, kokanee, coho, pink, and chum, as well as cutthroat, steelhead, and rainbow trout, and Dolly Varden char. The Nahwitti River has significant ecological value and is within the traditional territories of the Tlatlasikwala and Quatsino First Nations. The upper river is heavily logged, but the lower river flows through a largely undeveloped wilderness area within Cape Scott Provincial Park, known for its rich biodiversity and old-growth forests. However, timber harvesting activities are present within the watershed, with a large area of harvest occurring and additional areas to be harvested. Conservation efforts are important to maintain the river's ecological health and the habitats it supports.

Fish capture, transport, holding, and tagging

South Island

Between March 18 and April 13, 2021, and 2022, a total of 18 and 13 adult steelhead kelts were captured on the Cowichan River (Table 1). Angling (float, weight and lure) via drift fishing techniques was used to capture fish from a dory-style drift boat (BCCF Research Permits # NA20-605217, NA21-620245). To transport fish (Fed/Prov Live fish transport permits # 123491, 127512), the drift boat was outfitted with a 110 L cooler that was filled with fresh river water and a small portable air-pump and air stone (Marine Metal Aeratr Bubble Box 1.5v). Fish captured were gently netted, placed into the cooler, and transported to the nearest road access location. Partial water changes would occur every 15 – 30 minutes to ensure livewell temperatures remained consistent. From here, the fish were again netted and transferred into a truck equipped with a ~600 L aluminum fish transport tank, filled with fresh river water and equipped with an airstone and pure oxygen tanks.

Fish were transferred from the river to the Vancouver Island Trout Hatchery (VITH) site on Boys Road in Duncan, BC. Truck transport time was typically 20-25 minutes depending on the capture location. Once at the hatchery, a VITH staff member would receive the fish, anesthetize them using Eugenol (Clove oil mixed with 95% ethanol), at a concentration between 40 and 60 mg/l, and PIT-tag them with a 12 mm FDX–B (Biomark Ltd.) tag using a Mk 25 injector into the body cavity above the pelvic girdle. (see Appendix 2). Length (fork) and circumference (taken just anterior to the dorsal fin), sex, weight and a photo of each fish were taken before placing into a 4 m diameter x 1.5 m deep fibreglass circular tank for holding. Preference was given to post-spawn females and fish in visually found to be in good physical condition. Fish with open wounds, excess fungus, and most of the males were immediately released back into the stream at their capture location.

Water quality was monitored daily for temperature and dissolved oxygen. The fish were also fed a mixture of krill, as well as commercial trout food to try and improve condition factor and overall health of the fish prior to tagging. Mortalities were immediately removed, scanned for their PIT tag, and disposed of.

Reconditioning

Evaluation of the reconditioning process only occurred in 2021. In 2021, steelhead (n = 20) were captured throughout the spring. To determine whether holding and reconditioning would benefit the program, captured fish were held for up to 1 month before tagging. However, a total of 7 mortalities occurred during the 2021 study. Consequently, the reconditioning process was abandoned for years 2 and 3 of the study, and the amount of time steelhead spent in the hatchery environment was drastically reduced. For more details, please refer to "*Evaluating the Effectiveness of Cowichan River Steelhead (Oncorhynchus mykiss) Kelt Reconditioning*" Report.

Englishman River

In 2021, a single steelhead kelt was captured by angling in the Englishman River and transported to the VITH in Duncan, B.C. The Englishman River steelhead population took a drastic decline in 2020, post-project design. The number of adult steelhead declined from an estimated AUC average of 194 from 2010 to 2019 to 49 from 2020 – 2023. Due to the frailty of the Englishman River steelhead population, the authors removed the system from the study after the 2021 season.

North Island

Fishing success varied between years, which dictated release numbers from each river (Table 1). Fish were captured either by angling in the Nahwitti River or a combination of angling and seine net capture in the Keogh River at a fish enumeration facility located on the river (river kilometre 3). Fish were held in a vinyl brood tube in-situ for the duration of the angling day (typicallly 4-6 hours, before being transported to a light truck based based 600 l freshwater tank for the approximately one hour transport back to the North Vancouver Island Salmonid Enhancement Associations hatchery on the Keogh River in Port Hardy. Fish were held for variable lengths of time in each year until minimum sample and release sizes were attained. In the initial year of study fish were held for several weeks and reconditioning was attempted before tagging and release directly into the ocean. Steelhead did not appear to transition to food and individuals that were poorly conditioned or appeared to have patchy saprolegnia infections tended to decline in health with time spent in the facility based on visual inspection. No kelt reconditioning was attempted in subsequent years and efforts were made to release fish as soon as practical.

A total of 23 steelhead kelts were captured between the Nahwitti (9) and Keogh (14) rivers between all study years (Table 1).

Fish Tagging and Releases

South Island

On April 20, 2021, the 10 healthiest-looking female steelhead were selected for tagging with Mini-Pat PSAT tags, using a 'backpack' method as described in Courtenay et al. (2016) (Table 2). The fish were anesthetized, bio-sampled, and tagged at the VITH Boys Road facility. In addition to the 10 PSAT-tagged fish, 3 were tagged with acoustic tags using the same method but without PSATs. After tagging, the fish were transported in a 600 L fish transport tank on a sport fishing vessel and released into Satellite Passage, 7.5 km ESE of the Cowichan River mouth. The 3 acoustic-only tagged fish were released into the lower Cowichan River, 4 km upstream of tidewater.

On April 15, 2022, eight of the healthiest female steelhead were tagged with PSAT tags using identical methods to those in 2021. Post-tagging, the fish were transported and released into the ocean, but this time farther into the Southern Gulf Islands, East of Swartz Bay, approximately 32 km from the mouth of the Cowichan River. No acoustic-only tagged fish were deployed in 2022, and one fish was not tagged due to its small size and an eye injury.

Only five female steelheads were tagged on April 6, 2023, due to low capture rates. The tagging and release methods remained consistent with previous years. The tagged steelhead were again transported to the Southern Gulf Islands, East of Swartz Bay, 32 km from the Cowichan River mouth. No acoustic-only tagged fish were deployed in 2023.

North Island

In 2021, North Island kelts were tagged on three different dates between May 11th and May 26th. Three Nawitti steelhead were tagged and released on May 11th, and a total of three Keogh steelhead were released on May 12th (1) and May 26th (2) (Table 2). Only three Keogh River steelhead were tagged in 2022 between April 14th and May 19th (Table 3).

In 2023, all Keogh steelhead (8) were tagged at the North Vancouver Island Salmon Enhancement Facility and released on May 26, 2022 (Table 4). In 2023, most Nahwitti steelhead (6) were tagged and released on May 5, while one fish was released on May 12, 2023 (Table 4).

After tagging (Appendix 2), North Island steelhead were released in the marine environment closest to their natal stream mouth, either near the Nahwitti Bar, a few kilometres from the mouth of the Nahwitti River, or at Keogh Bank approximately 2 km North of the mouth of the Keogh River.

Pop-up Archival Satellite Tagging

Pop-up Satellite Archival Tags are a useful tool to estimate migration patterns of long-ranging marine fish and potentially identify locations and mortality mechanisms through cross-examination of the various data collected. We used MiniPAT-348K satellite tags (124 mm length, 38 mm diameter and weigh 60 g; www.wildlifecomputers.com). PSATs are equipped with onboard memory, which allows for data to be collected during deployment and stored until the tag is released from the host animal. Summary data is then uploaded to the Argos satellite network. Multiple data types are collected with these tags, such as temperature, depth, light level acceleration, and reason for tag release.

Sensor data are collected during deployment and archived in the tags onboard memory. Upon release from its host animal, by either a pre-selected release date (set before tagging), a predation event (where the tag is detached as a result of consumption) or if the premature release and mortality detection mechanism deems the animal has died, the PSAT surfaces, and transmits its data to the Argos satellite network (Table 5). If tags are collected after release, a full dataset can be downloaded directly from the tag. These tags have recently been reduced in size and can now be deployed on smaller animals, such as adult salmon-sized fish. Uploaded data can be of variable quality and quantity, depending on a tag's ability to successfully upload its data to the satellite network.

Steelhead migration pathway estimation

Steelhead tracks were estimated via the online processing portal on wildlifecomputers.com. The model is based on Pedersen et al. (2011) and uses a Hidden Markov model that incorporates light levels, sea surface temperature, maximum swimming depth, known release location and hypothesized swim speed to generate most likely travel pathways. Swim speed is supplied by the user within the data portal. We tested swim speeds of 1, 2 and 3 $m \cdot s^{-1}$ and selected the model with the highest score to use for fish pathway estimates.

Identification of predation mechanism

The mechanism of mortality was inferred from time series plots generated from recovered PSAT data. Here, we used a variety of metrics to attempt to identify predation events such as rapid changes in diving behaviour, a breakdown in the correlation between deeper depth readings and temperature, and a rapid reduction in light level readings, all of which suggest consumption by an ectothermic predator. A consistent rise in tag temperature to approximately 38°C and a reduction in light levels were classified to indicate ingestion by a marine mammal. No clear signal to identify predation mechanisms were classified as unknown.

RESULTS

Of the 47 tags deployed, 42 (89%) transmitted some data of varying quantity and quality (mean 65%), ranging from 100% of recovered tags to as low as 1% for transmitted tags (Appendix A: Tables 2,3,4). Sufficient light-level data was available to estimate travel pathways for 40 (85%) and 42 tags, which provided some data to allow for some time series analysis (Appendix A). Ten tags were physically recovered (four, one and five from years 2021, 2022, and 2023, respectively), which allowed for a full recovery of archived data. Rapid mortality (i.e. tag release) occurred to 14 (30%) steelhead (< 2 days) after release (not including the tag that did not transmit).

Pathway length was highly variable, with some very short tracks due to near-immediate mortality. The longest track of 2015.9 km (TagID 233529) was observed from a steelhead captured from the Nahwitti river and released in 2023 (Table 4; Figure 4).

Fish captured and released from the Mid-Island Region Island had a longer mean survival time (17.1 days) compared to the North Region (13.4 days; Table 5), however variability in survival time negated any significant difference (p=0.548). Track distance was similar with variability between the two locations resulting in no significant difference regardless of the difference in means (Table 5). Mean depth was also not significantly different (p=0.530).

At time of tag release, various codes are provided with the data to indicate the reason for the release of the PSAT from the tagged animal. Of the 42 tags successfully reported, the majority of the release codes (75%) were reported as "premature", meaning the tag was transmitted prior to the programmed time, and the steelhead likely died (Table 6). Other codes are "Too Deep" indicative that the tag fell below the pre-programmed. Unfortunately, the error codes give little insight into the mechanism of mortality and a closer examination of the time series data is needed.

Identification of predation mechanism

Predation mechanism was identified in 13 (28%) of the 47 tags deployed (Table 7). The majority of predation appeared to be caused by pelagic ectothermic fish (10; 21%), demersal ectothermic fish (2; 4%), and one from a marine mammal (2%). One fish survived until the tag self-released according to the recorded tag release code. One additional tag self-released, but it appeared to be within the stomach of a pelagic fish at the time. The remainder of the tags either did not report (n=5) or no predation mechanisms could be inferred from the track and time series data.

Tags appeared to remain ingested in pelagic fishes for long periods of time (see Appendix 3: Fish tracks and time series plots). Mean and maximum depth and mean temperatures were markedly different after fish/tag were ingested (Table 8).

DISCUSSION

The application of PSATs to understand travel pathways and mortality mechanisms of steelhead kelts provided novel insights into the ocean ecology of steelhead. Although there was little difference between release locations in terms of survival time, the long ocean migrations are consistent where steelhead have been captured in marine fisheries, notably south-eastern Alaska (Myers and Mantua, 2013).

The PSATs used in this study were large compared to the body size of the tagged steelhead, which may have introduced some behavioural biases in the results. Although the tags themselves were nearly neutrally buoyant and hydrodynamic, the drag on the harness and the tagging process may have affected survival and energetic costs to travel. Unfortunately, current studies quantifying the energetic costs associated with carrying PSATs in salmonids do not exist.

The lack of a clear predation signal in nearly 75% of the tags released suggests that the use of PSATs has limited ability to answer this question fully. The lack of clear signal could indicate seal predation as seals are known not to consume salmon (belly-biters) entirely and have a larger ability to handle prey than fishes. Further analysis of accelerometry data may provide information on predation events through changes in movement patterns that may assist in furthering our understanding of these unknown mortalities. Unfortunately, there is insufficient information to identify the cause of mortality for the majority of the fish tagged, at this time.

Predation signals for ectothermic pelagic fish of nearly a quarter of the released fish indicate that adult kelts, and possibly steelhead returning to spawn, are predated upon by species other than seals which generally gain the most attention, although primarily at the juvenile stage (Malick et al. 2022). This research suggests that a minimum of 25% of the steelhead were consumed by piscivorous fishes which suggests that calls for a seal cull may have a limited impact on the survival of returning adult steelhead.

Steelhead in British Columbia, particularly Vancouver Island, are currently in a low abundance regime. The information provided here gives some insights into a largely unknown life-stage. Repeat spawning is a life-history trait uncommon in long-ranging Pacific salmonids with several population-level advantages (such as fecundity and lifetime reproductive success). Better understanding of the marine centered life-stage provides insights into population dynamics and the potential efficacy of various management approaches to increasing population abundance.

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APPENDIX 1: REPORT TABLES

Table 1. Summarized release location and sample sizes for all steelhead kelts with available time series for fish released from 2021 through 2023. A total of 47 steelhead kelts were tagged and released but 41 tags transmitted data.

RELEASE YEAR	ISLAND REGION (N)	RIVER	RELEASED	DATA RECOVERED
2021	Mid-Island	Cowichan	10	9
		Englishman	1	1
	North-Island	Keogh	3	3
		Nahwitti	3	2
2022	Mid-Island	Cowichan	8	7
	North-Island	Keogh	3	2
2023	Mid-Island	Cowichan	5	5
	North-Island	Keogh	8	7
		Nahwitti	6	6
Total			47	42

Table 2. Summary of the 17 PSATs attached to Steelhead Trout released in 2021. Total tags released in 2021 were 11 from the southern region and six from the Northern region of Vancouver Island. Data recovery is the percentage of each time series associated with temperature and depth data for each archived time step. Data recovery values in parentheses is the proportion of uploaded data. Shaded area are North Region releases. Refer to tracks and time series in Appendix 3.

ID	RIVER	DEPLOY-MENT DATE	LENGTH (CM)	SEX	TRACK LENGTH (KM)	TRACK TIME (DAYS)	PREDA-TION TYPE	RELEASE TYPE	TAG RECOV-ERED	DATA RECOVERY
213742	Cowichan	4/20/2021	55.4	F	401.3	24.8	Unknown	Too Deep	No	94%
213743	Cowichan	4/20/2021	69.2	F	22.3	1.6	Unknown	Premature	Yes	100% (75%)
213744	Cowichan	4/20/2021	72.0	F	16.0	3.9	Unknown	Premature	Yes	100% (86%)
213745	Cowichan	4/20/2021	80.5	F	1462.4	68.6	Unknown	Too Deep	No	10%
213746	Cowichan	4/20/2021	68.7	F	347.2	7.8	Unknown	Premature	Yes	100% (92%)
213747[1]	Cowichan	4/20/2021	71.8	F	-	5*	-	Premature	No	0%
213748	Cowichan	4/20/2021	71.9	F	1180.2	54.8	Ecto-therm	Premature	No	90%
213749	Cowichan	4/20/2021	68.2	F	13.9	0.5	Unknown	Premature	Yes	100% (1%)
213750	Cowichan	4/20/2021	72.8	F	236.4	5.4	Unknown	Premature	No	13%
213751	Cowichan	4/20/2021	61.0	F	329.0	21.7	Unknown	Too Deep	No	92%
212904	English-man	5/10/2021	82.0	M	66.9	1.6	Unknown	Premature	No	81%
212895	Keogh	5/26/2021	81.0	F	269.5	10.0	Bottom fish	Exceeded Preset Depth	No	86%
212898	Keogh	5/12/2021	72.0	F	57.3	2.2	Unknown	Premature	No	77%
212899	Keogh	5/12/2021	63.1	F	637.8	22.0	Unknown	Premature	No	93%
212897	Nahwitti	5/11/2021	65.0	F	195.6	9.1	Unknown	Premature	No	83%
212905[2]	Nahwitti	5/11/2021	68.0	M	-	10*	-	Unknown	No	0%
212906	Nahwitti	5/11/2021	61.0	F	329.9	22.0	Ecto-therm	Premature	No	9%

[1]Tag transmitted with no usable data after 5 days. Track time estimated from difference between day of release and first data transmission day.

[2]Tag released and transmitted 10 days after release, but no data was uploaded successfully.

*Track time estimated from difference between day of release and first data transmission day.

Table 3. Summary of pop-up satellite archival tags attached to Steelhead Trout released in 2022. Total tags released in 2022 were 8 from the southern region and 3 from the Northern region of Vancouver Island. Data recovery is the percentage of each time series that has both temperature and depth data associated for each archived time step. Data recovery values in parentheses is the proportion of uploaded data. Shaded area are North Region releases. Refer to tracks and time series in Appendix 3.

ID	RIVER	DEPLOYMENT DATE	LENGTH (CM)	SEX	TRACK LENGTH (KM)	TRACK TIME (DAYS)	PREDATION TYPE	RELEASE TYPE	TAG RECOVERED	DATA RECOVERY
212896	Cowichan	04/14/2022	56.5	F	540.4	18.1	Unknown	Premature	No	88%
212900	Cowichan	04/14/2022	72.5	F	342.2	51.9	Ectotherm	Premature	No	69%
212901	Cowichan	04/14/2022	62.5	F	1.1	1.2	Unknown	Premature	No	40%
212902	Cowichan	04/14/2022	59.7	F	-	-	-	Did not transmit	No	0%
212903	Cowichan	04/14/2022	54.5	F	64.7	5.4	Unknown	Premature	No	78%
233472	Cowichan	04/14/2022	62.5	F	83.6	16.7	Unknown	Premature	Yes	100% (56%)
233525	Cowichan	04/14/2022	61.8	F	405.7	47.9	Ectotherm	Premature	No	86%
233526	Cowichan	04/14/2022	62.0	F	288.5	20.8	Ectotherm	Premature	No	12%
233530	Keogh	04/14/2022	67.1	M	4.8	1.9	Unknown	Premature	No	57%
233527	Keogh	5/29/2022	78.5	M	143.4	8.9	Ectotherm	Premature	No	87%
233522	Keogh	5/19/2022	67.5	M	-	-	-	Did not transmit	No	0%

Table 4. Summary of pop-up satellite archival tags attached to Steelhead Trout released in 2023. Total tags released were 5 from the southern region and 14 from the Northern region of Vancouver Island. Data recovery is the percentage of each time series that has both temperature and depth data associated for each archived time step. Data recovery values in parentheses is the proportion of uploaded data. Shaded area are North Region releases. Refer to tracks and time series in Appendix 3.

ID	RIVER	DEPLOY-MENT DATE	LENGTH (CM)	SEX	TRACK LENGTH (KM)	TRACK TIME (DAYS)	PREDATION TYPE	RELEASE TYPE	TAG RECOV-ERED	DATA RECOVERY
242721	Cowichan	04/06/2023	75.5	F	54.0	5.5	Unknown	Premature	Yes	100% (60%)
242722	Cowichan	04/06/2023	73.5	F	66.6	4.7	Unknown	Premature	Yes	100% (69%)
242723	Cowichan	04/06/2023	77.5	F	33.8	0.5	Marine mammal	Premature	Yes	100% (30%)
242724	Cowichan	04/06/2023	76.5	F	53.0	11.7	Unknown	Premature	Yes	100% (19%)
242725	Cowichan	04/06/2023	80.5	F	35.8	1.0	Unknown	Premature	Yes	100% (27%)
242729	Keogh	05/26/2023	60.5	F	3.8	1.1	Unknown	Premature	No	60%
233534	Keogh	05/26/2023	65.0	F	7.8	2.1	Ectotherm	Premature	No	90%
242730	Keogh	05/26/2023	61.5	F	35.6	6.1	Unknown	Too Deep	No	71%
233531	Keogh	05/26/2023	67.0	M	47.1	7.8	Possible ec-totherm	Premature	No	93%
233533	Keogh	05/26/2023	61.0	M	236.8	11.1	Ectotherm	Premature	No	88%
242731	Keogh	05/26/2023	61.0	F	32.5	1.1	Ectotherm	Premature	No	93%
233535[1]	Keogh	05/26/2023	73.5	M	-	<1	Unknown	Premature	No	48%
233523[2]	Keogh	05/26/2023	64.5	F	-	-	-	Did not transmit	No	0%
233528	Nahwitti	05/05/2023	65.5	M	69.3	2.6	Unknown	Floater	No	51%
242727	Nahwitti	05/05/2023	66.5	M	70.0	3.6	Unknown	Premature	No	74%
233524	Nahwitti	05/05/2023	69.0	F	103.6	4.6	Unknown	Premature	No	66%
242728	Nahwitti	05/05/2023	78.5	F	1644.8	53.7	Alive	Interval	No	1%
242726	Nahwitti	05/05/2023	60.5	F	125.7	11.7	Unknown	Premature	No	80%
233529	Nahwitti	05/12/2023	70.0	F	2015.9	72.6	Ectotherm	Interval	No	74%

[1]Fish died in <24 hours and no track could be produced

[2]Tag was miscoded and did not report back.

Table 5. Comparison of Mean track length (km) and mean depth during travel (meters) between the two Island Regions

	MEAN TRACK LENGTH (KM)	MEAN TRACK TIME (DAYS)	MEAN DEPTH (M)
North Island	317.4	13.4	3.5
Mid-Island	274.8	17.1	2.6

Table 6. Release Type code summary provided by transmitted tags.

RELEASE TYPE	COUNT
Premature	35
Too Deep	4
Exceeded Preset Depth	1
Did not transmit	4
Interval	2
Floater	1
Total	47

Table 7. Hypothesized cause of death in all fish with available time series for fish released from 2021 through 2023

PREDATION TYPE	MID-ISLAND	NORTH ISLAND	TOTAL
Alive	0	1 (4%)	1 (2%)
Bottom fish	0	1 (4%)	1 (2%)
Marine mammal	1 (4%)	0	1 (2%)
Pelagic Ectotherm	4 (17%)	6 (26%)	10 (21%)
Possible fish	0	1 (4%)	1 (2%)
Unknown[1]	19 (79%)	14 (61%)	33 (70%)
Total	24 (100%)	13 (100%)	47 (100%)

[1]Unknown predation assigned to tags that did not transmit.

Table 8. Comparison of mean travel depth, max depth, and temperature between steelhead and hypothesized predators. Refer to tracks and time series in Appendix 3.

ID	RIVER	YEAR	PREDATION TYPE	STEELHEAD			PREDATOR		
				MEAN DEPTH (M)	MAX DEPTH (M)	MEAN TEMP (°C)	MEAN DEPTH (M)	MAX DEPTH (M)	MEAN TEMP (°C)
213748	Cowichan	2021	Ectotherm	1.2	131.0	10.2	7.8	176.5	11.6
212895	Keogh	2021	Bottom Ectotherm	1.3	37.0	9.7	934.2	966.5	4.1
212906	Nahwitti	2021	Ectotherm	1.9	17.5	9.9	4.2	90.0	11.6
212900	Cowichan	2022	Ectotherm	1.3	142.0	9.6	4.0	80.5	11.4
233525	Cowichan	2022	Ectotherm	1.0	71.5	9.5	3.7	33.5	11.0
233526	Cowichan	2022	Ectotherm	3.6	22.5	9.1	154.1	172.0	7.2
233527	Keogh	2022	Ectotherm	1.1	51.5	9.6	14.5	150.0	11.1
242723	Cowichan	2023	Marine mammal	0.8	14.5	8.0	15.7	105.0	29.4
233531	Keogh	2023	Ectotherm	4.2	85.5	9.6	57.1	175.5	8.5
233533	Keogh	2023	Ectotherm	2.4	127.5	11.1	6.5	516.0	12.7
233534	Keogh	2023	Ectotherm	28.4	30.5	9.2	32.2	53.0	9.0
233529	Nahwitti	2023	Ectotherm	2.1	78.0	10.7	4.6	220.5	15.0

APPENDIX 2: TAGGING METHODOLOGY

Mini-Pat Satellite Tagging

The equipment used for the tagging of steelhead kelts was conducted using a method similar to that of Courtney et al. (2016). Mini-Pat tags were attached to two 50 mm long rigid backed plates using a nylon braid "tag backpack", which has been refined for salmonids of similar size (Courtney et al. 2016; Courtney et al. 2019; Strom et al. 2017) (Figure 2). Tag backpacks were secured through the dorsal musculature below the dorsal fin through the perygiophores using two biocompatible plastic-coated stainless wires (Figure 2). The braid attaching the PSAT to the harness was encapsulated in a plastic coating to lift the PSAT up from the back of the fish. A biocompatible silicon pad was glued on the inside of the plates to reduce abrasion on the skin and an acoustic tag (MODEL v9x2, Innovasea) was epoxied to one side of the backpack to track the fish if it happened to survive past the time the PSAT tag popped off (Figure 2).

Figure 2. Images depicting MiniPAT Satellite tag (top left), tag backpack with acoustic tag (Top right and bottom left), and hypodermic needles (bottom left) used for tagging.

Captured steelhead kelts were anesthetized using clove oil (Hilltech Canada, Canada) at a concentration of 40 mg/l. During the procedure, fish were provided with fresh water flowing over their gills (Figure 3). To attach the backpacks to the fish, two 100 mm hypodermic needles were used to thread 26 ga rubber-coated stainless steel tie wire through the dorsal musculature below the dorsal fin through the perygiophores (Figure 3). The wire, with ends stripped of the rubber coating, was secured with a 'haywire twist,' and held two small (10 mm x 50 mm, 1 plastic and 1 silicone) plates on either side of the fish's back. A short (~10cm) length of 80 lb. monofilament was crimped to each side of the backpack creating a loop that the PSAT tag was fastened to (Figure 3). After tagging fish were held in a live-well with oxygen for at least 1 hour before being transported by vessel and released near Saltspring Island, British Columbia.

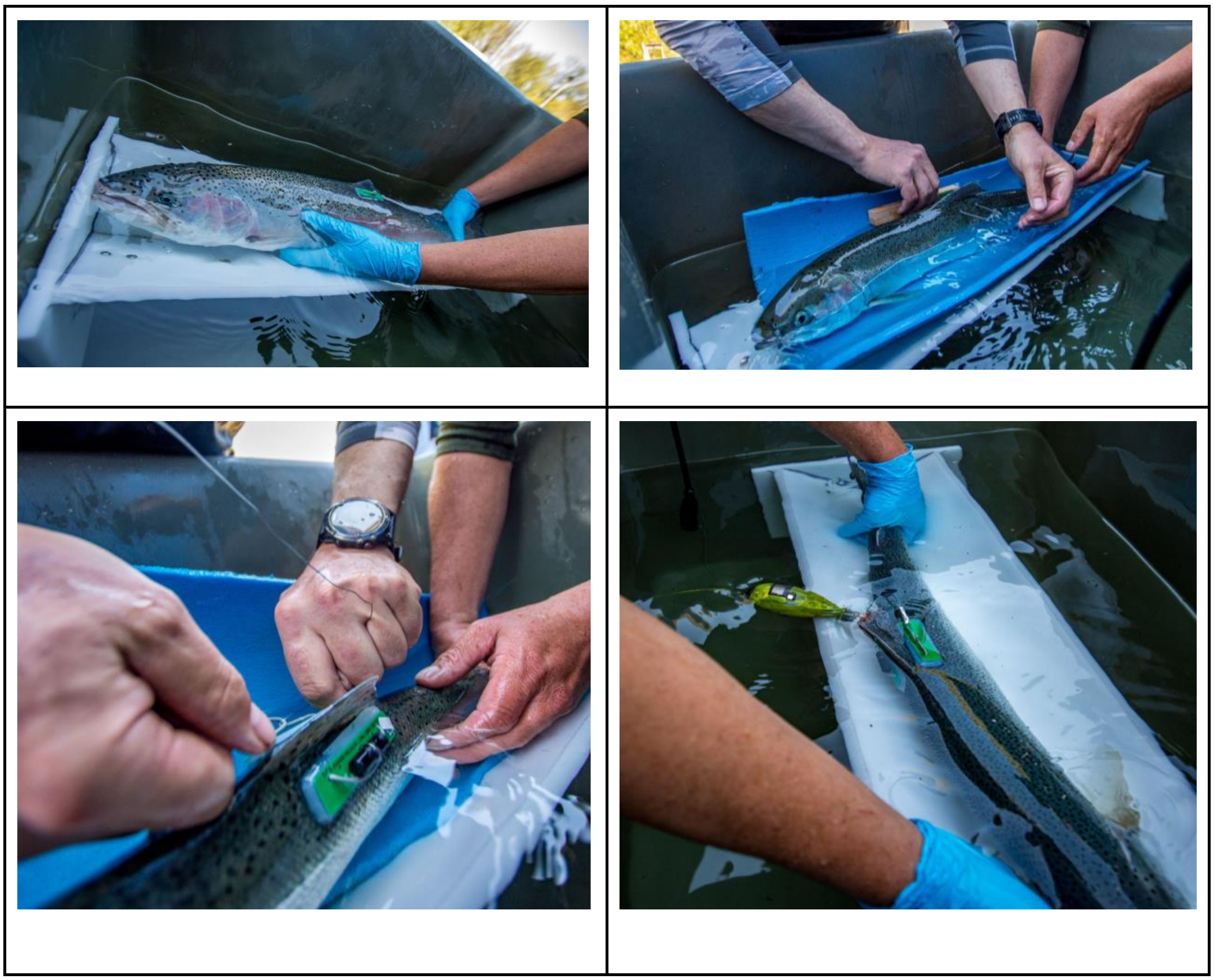

Figure 3. Images depicting MiniPAT Satelite tagging process. Showing the flow through tagging troughs (top left), and then the tagging process starting with the hyperdermic needles (top right), tying coated metal cables for the backpack (bottom left) and then attaching the MiniPat with wire crimps (bottom right).

APPENDIX 3: FISH TRACKS AND TIME SERIES PLOTS

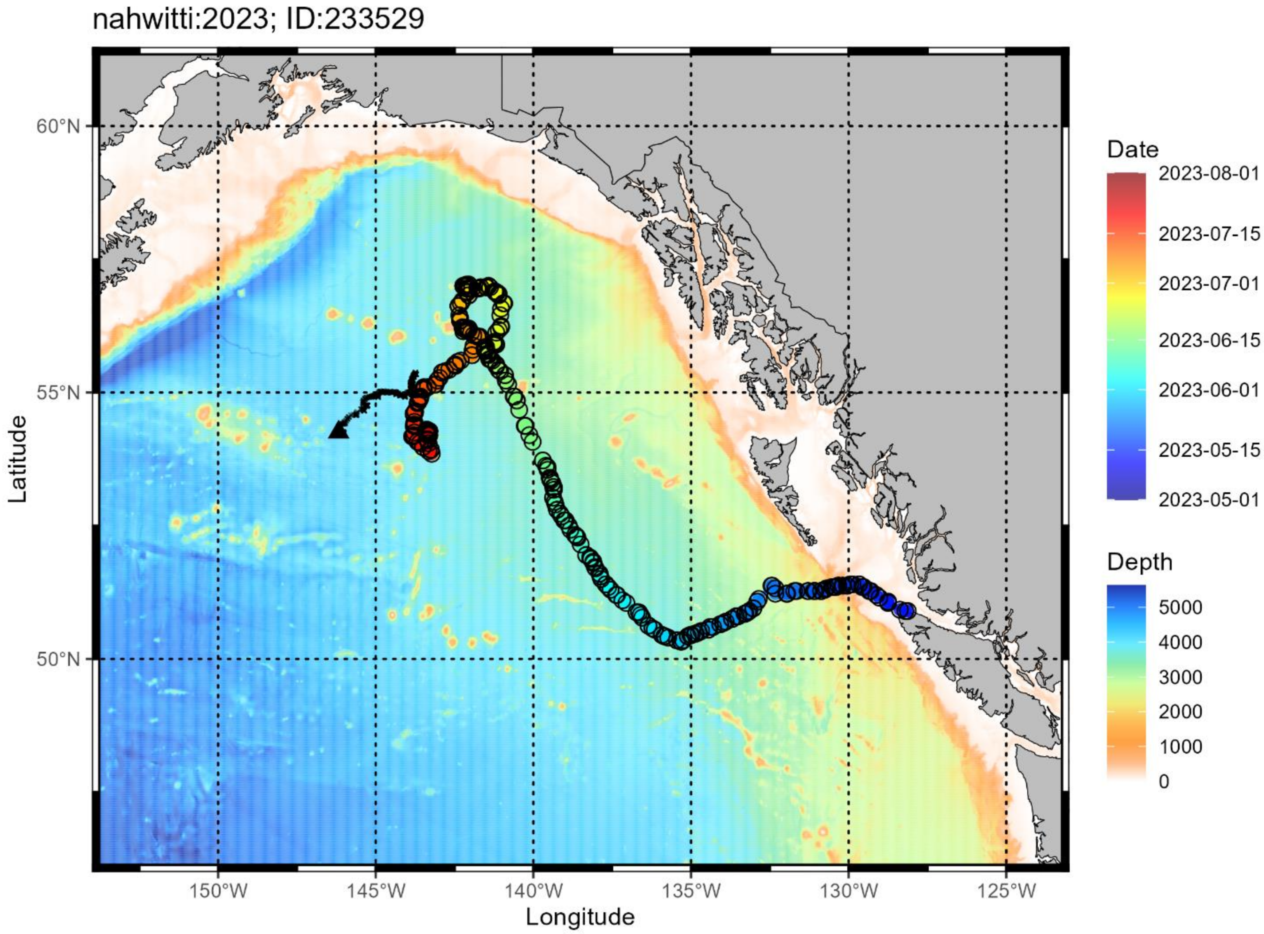

Figure 4. Migration track of a Nahwitti steelhead (ID 233529) tagged and released in 2023. Coloured circles show the dates of data transmissions from the miniPAT tag with blue being closer to the release date and red being closer to the final detection. The black triangle is where the satellite tag surfaced after a mortality event, with the black track showing the movement of that tag underwater before surfacing.

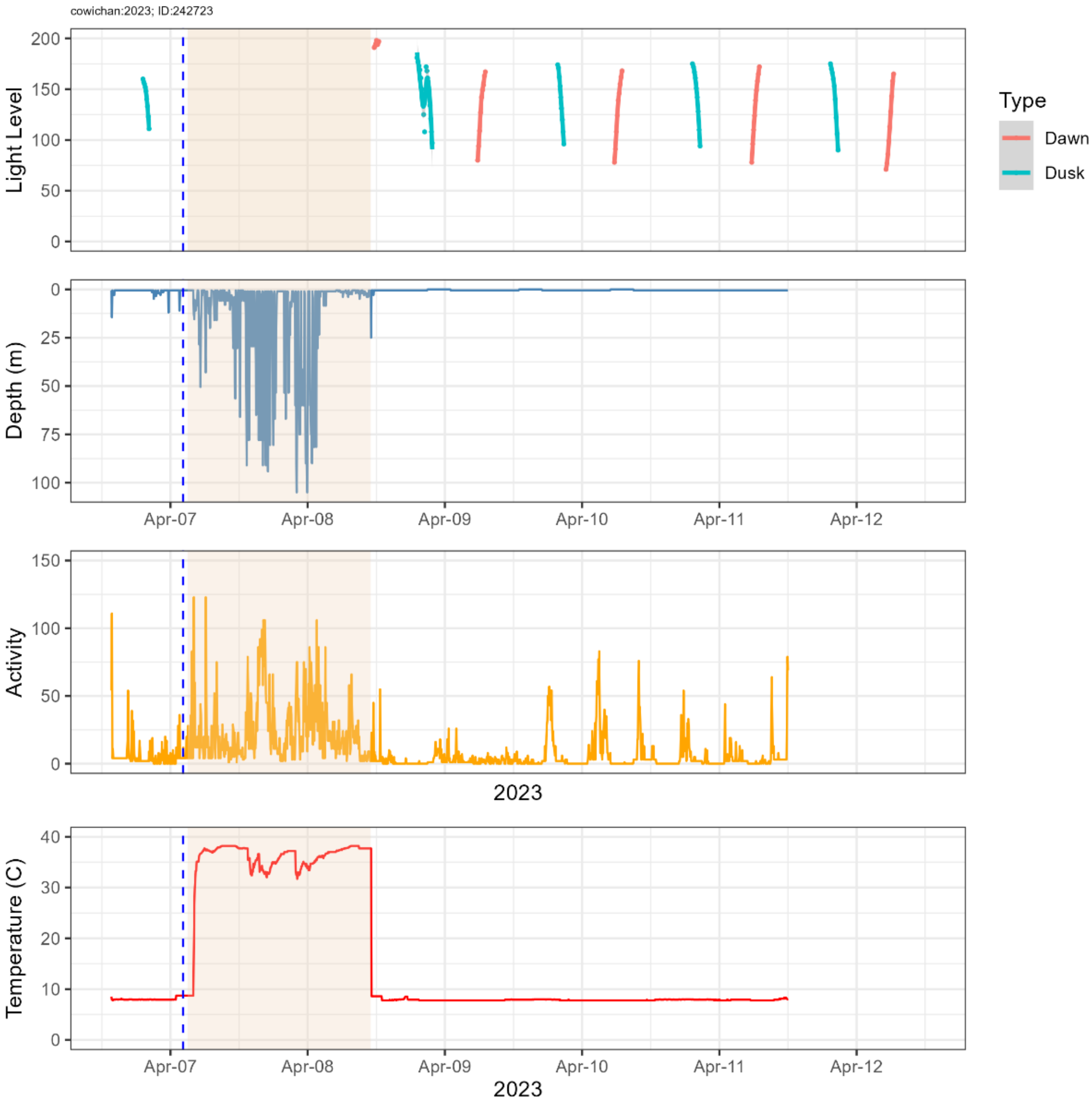

Figure 5. The light level, depth, activity (from accelerometer data) and temperature data retrieved from a Cowichan steelhead (ID: 242723) wherein rapid changes in sensor data suggest predation by a marine mammal.

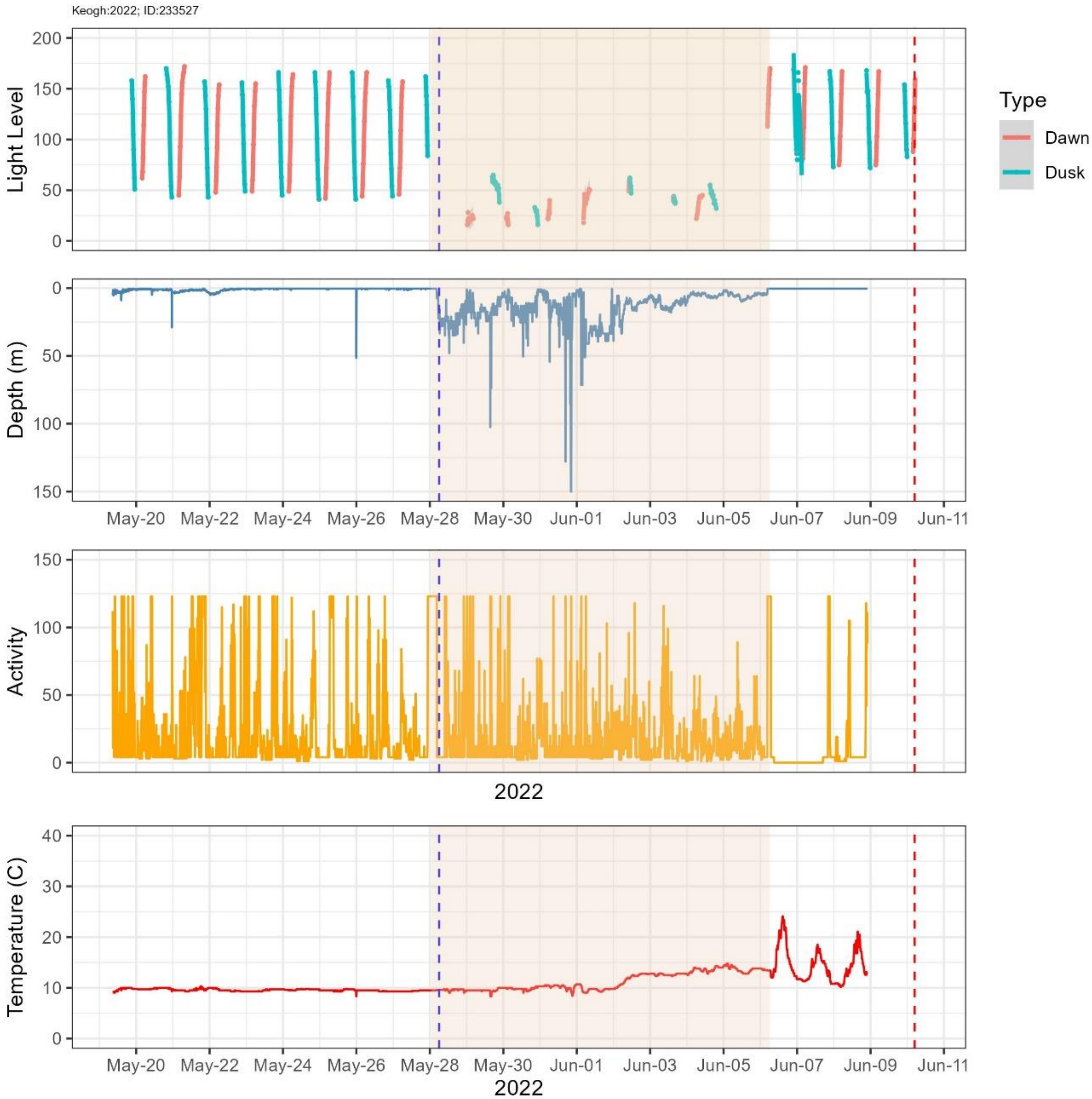

Figure 6. The light level, depth, activity (from accelerometer data) and temperature data retrieved from a Keogh steelhead (ID: 233527) wherein rapid changes in sensor data suggest predation by an ectotherm.

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