Assessing the fate of returning upper Yukon River Chinook salmon (2017-2020)

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Published May 18, 2021

Summary

Chinook salmon (*Oncorhynchus tshawytscha*) from the Upper Yukon River have faced severe declines relative to their estimated abundances several decades ago. To further our understanding of Chinook salmon spawning locations in this area, and potential factors limiting the recovery of this population, we completed a 4-year telemetry study from 2017-2020. Efforts were focused on understanding the effectiveness of the Whitehorse Rapids Fishladder at allowing salmon to pass upstream of the Whitehorse Hydro Plant. To answer these questions, a telemetry array was deployed throughout the upper Yukon River and supporting tributaries upstream of Lake Laberge, YT. Salmon of both wild and hatchery origin were gastrically implanted with acoustic/radio transmitters at the fish ladder viewing chamber or downstream following gill net capture to evaluate passage success and subsequent spawning locations. Over the course of four years, a total of 171 tagged salmon passed upstream of the Whitehorse Hydro Plant with 78% terminating in the Michie Creek - M'Clintock River system, with the remainder terminating in Wolf Creek, the Yukon River mainstem, the Takhini River, and the Southern Lakes. Salmon tagged below the hydro plant that approached the fish ladder often did not pass through the structure. Salmon ceased upstream migration at multiple points within the ladder, including the viewing chamber where a gate must be manually lifted by staff to allow salmon passage. Findings from this work may be used to inform future spawning ground surveys, restoration actions, and design and operational changes at the Whitehorse Rapids Fishladder.


Sonny Parker

The Upper Yukon River supports some of the world's most unique salmon populations. Entering the Yukon River at the Bering Sea, salmon travel north through Alaska before heading South into the Yukon to find their natal habitat to spawn. Salmon returning to Michie Creek travel nearly 3,000 km to make it home, one of the longest inland salmon migrations on Earth.

1. Introduction

1.1 History of the Upper Yukon River Chinook salmon

Upper Yukon River Chinook salmon (*Oncorhynchus tshawytscha*) populations (defined for the purpose of this study as fish that terminate in the mainstem Yukon River or its tributaries upstream of the Teslin River) have experienced similar declines to other Yukon River populations over the past 25 years. Greater declines probably occurred much earlier in the past century, possibly due to overfishing associated with human population increases in the region in the wake of the Klondike Gold Rush (Gilbert and O'Malley 1921; von Finster pers. comm.). Commercial fishing early in the 20^{th} century in the lower reaches of the Yukon River and near the river mouth are thought to have contributed greatly to declines (Gilbert and O'Malley 1921). Traditional ecological knowledge and historical accounts indicate that many Chinook salmon were harvested annually in the Michie Creek - M'Clintock River system (Cox 1997; Herkes 2015). It was alleged that Indigenous families would harvest 500 fish a season (Brown et al. 1976). Families would dry and smoke salmon along the banks of the M'Clintock River, and some caches of dried salmon were large enough to last through winter (Herkes 2015). In 1957, the Chief Biologist for the Pacific Area wrote to the Deputy Minister of Fisheries that "as many as 10,000 spring salmon were taken in the M'Clintock River some years ago" (Cox 1997). Similarly, a fishery officer recorded that as many as 25 families once harvested 300-400 fish each there, based on an interview with Johnny Joe (Cox 1997). However, by the mid-1950s, annual harvests appear to have declined to a few hundred fish or less per year (Cox 1997), and there was much debate about whether previous versions of the Lewes Dam (built in 1923) had contributed to this decline by acting as a barrier to migration (Cox 1997). Over the past 60 years, there has been an annual average return of 950 salmon to the Whitehorse Rapids Fishladder viewing chamber. Initial returns were ~1100 for the first four years, then declined until the late 1980's when returning hatchery-reared fish began to supplement wild returns (Yukon River Joint Technical Committee 2021). In 2019 and 2020, salmon returns to Whitehorse were of the lowest since 1959, and as a result, First Nations governments advised their citizens to stop harvesting salmon altogether to increase the number of salmon returning to spawning grounds. While the current spawning and rearing capacity of the primary spawning grounds upstream of Whitehorse, the Michie Creek – M'Clintock River system, is unknown, it is expected rearing capacity is not limited as juveniles can migrate downstream to access abundant rearing habitat in the Yukon River (von Finster pers. comm).

1.2 Previous research on salmon spawning locations

Contemporarily, the majority of Chinook salmon migrating upstream of the Whitehorse Hydro Plant (WHP) are believed to spawn in Michie Creek, particularly between Michie Lake and Byng Creek (de Graff 2015); although, the M'Clintock River upstream of Michie Creek has been identified as a historically important spawning location as well (Cox 1997; Herkes 2015). Previous radio telemetry studies (Cleugh and Russel 1980; Matthews 1999a) showed that 77% to 88% of these Chinook salmon traveled to the Michie Creek - M'Clintock River system, though sample sizes were small. It is also known that salmon spawn in Wolf Creek (Matthews 1999b), though the fate of a small proportion of Chinook salmon after they pass the ladder is uncertain. Salmon may spawn in other unknown locations between the Whitehorse Hydro Plant (WHP) and the Southern Lakes, or they may expire before reaching any spawning ground. Periodic captures of Chinook salmon in the Southern Lakes has raised speculation that perhaps some small, but unknown spawning populations exist in that area. Determining the terminal location of all Chinook salmon migrating upstream of the WHP will help identify management actions for restoring the habitat and vitality of this stock.

1.3 Chinook salmon and the Whitehorse Hydro Plant

The Whitehorse Hydro Plant is the leading source of energy production in the Yukon (40 MW), but has considerably changed the hydrology of the Yukon River since its construction in 1958. The power plant was originally 2 - 5MW turbines and was augmented by a third 10 MW turbine in 1969 and completed with a 20 MW turbine in 1984. The Lewes Dam is located further upstream and controls the water levels in Marsh Lake and the Southern Lakes. Dams are known to have numerous consequences to river ecosystems including the fragmentation of migratory pathways (Freeman 2003). A lack of run size enumeration prior to construction of the WHP, makes it difficult to assess how the population has been affected by its construction. Nonetheless, it seems possible that the WHP may restrict the movement of some salmon migrating upstream.

The Whitehorse Rapids Fishladder was built in 1959 to provide salmon a route upstream around the dam. The ladder was modified on several occasions including to accomodate the raise in the height of the dam in 1970. For a fish ladder to be effective, salmon must be able to find (attraction phase), enter (entrance phase), and pass through (passage phase) the structure, and maintain the ability to continue their migration and successfully spawn. More than five decades of passage and subsequent spawning in the Michie Creek - M'Clintock River system provide clear evidence of individual passage success at the Whitehorse Rapids Fishladder. However, it's unclear what proportion of salmon approaching the fish ladder actually pass, and whether there are sub-lethal and population-level consequences of passage. Insights from other river systems reveal that it is common for fish to approach and enter fish ladders but not pass through them (Bunt et al. 2012). Fish that do pass may experience delays, as well as acute energetic stress (Roscoe et al. 2010) resulting in suppression of reproductive hormones (Kubokawa et al. 2001). These studies show that most salmon recover relatively quickly from acute energetic stress associated with approaching and ascending fish ladders (Roscoe et al. 2010), yet post-passage mortality has still been observed (Burnett et al. 2017). No definitive studies on this specific site have been conducted although Cleugh and Russel (1980) found that of 12 fish captured or released downstream of the WHP, 7 passed after delays ranging from 10 hours to 10 days (average 3 days). Fishways for salmon in the Columbia River system have proven to be effective (Noonan et al. 2012), but differences in the study population, fishway design, and river conditions make it difficult to generalize these findings to the Yukon.

1.4 Project objectives

In 2017, we initiated a research program that would begin to evaluate the effectiveness of the Whitehorse Rapids Fishladder and identify terminal locations of spawning fish. Fish were tagged at the ladder viewing chamber to evaluate passage efficiency of the upper ladder and post-passage migration behaviour. We also began capturing fish by gill net downstream of the WHP to assess movement as fish approach the ladder.

This project has two primary goals. The first is to identify depleted stocks that are candidates for restoration, along with potential spawning restoration sites. Specific objectives associated with this goal are to assess:

1) What terminal locations exist above the WHP and what proportion of the population spawns in each location.
2) Where salmon spawn in the Michie Creek - M'Clintock River system;
3) Whether some fish that pass the WHP fail to reach spawning sites.

The second goal is to assess whether challenges associated with passage at the WHP are limiting production of upper Yukon River Chinook salmon stocks. Specific objectives associated with this goal are to assess:

4) What proportion of salmon of those approaching the WHP successfully pass through the fish ladder.
5) The behaviour of salmon approaching and within the ladder.
6) Whether there are certain sections of the fish ladder that are difficult for salmon to navigate.
7) What proportion of fish return downstream after passing the WHP.

Methods

2.1 Study Site and Receiver Locations

The 2020 study site consisted of the Yukon River and its tributaries upstream of Lake Laberge, near Whitehorse, YT. Between twenty (2017) and thirty nine (2020) Vemco VR2W receivers were deployed between the confluence of the Yukon and Takhini Rivers and Michie Lake as well as the Takhini River (Figure 1). Acoustic receivers were generally anchored with a cement block or sand bag and were tethered to a rope extending up to a sub-surface buoy. Receivers were tested prior to deployment and a subset of receivers were range tested. Range testing was completed in 2018 and 2020 at each site by placing a V16 or V13 range test transmitter at set distances from each receiver for a set time interval (generally 12 minutes or 100 potential detections). Range test results are presented in Appendix 1. Detection efficiency of acoustic receivers around the WHP was low in 2017 and 2018 (Appendix 2), so radio receivers were deployed instead of acoustic receivers given their higher performance in acoustically complex environments. Range testing was completed on these receivers to confirm their function, and gain was set such that the entrance receiver could only detect tagged salmon outside the ladder (87% efficiency at 2.5 m from the entrance). Additionally, Chinook salmon movement was monitored beyond Marsh Lake and into the Southern Lakes by the 20-receiver array maintained by Environment Yukon for a concurrent Lake Trout (Salvelinus namaycush) study (Figure 1).

2.2 Tagging methods

Chinook salmon were gastrically implanted with either a Vemco V16 acoustic transmitter (10.3 g; diameter = 16 mm x length = 68 mm; 90 s randomized ping) or a V13 transmitter (6 g; diameter = 13 mm x length = 36 mm; 30 s randomized ping) attached to a Sigma Eight TX-PSC-I-80 radio transmitter (4.2 g; diameter = 10 mm x length = 27 mm; 2.7 s randomized ping) with the latter used exclusively by 2020. These transmitters were affixed together with a marine-grade adhesive for ease of application in the salmon (combined weight = 10.2 g, diameter = 13 mm, length = 63 mm). The antenna of a transmitter was slid down a thin PVC pipe, and the pipe was used to guide the tag into the mouth of the fish for release into the stomach. A wooden dowel was then inserted into the pipe to release the transmitter, and the pipe and dowel were withdrawn from the stomach. The V16 transmitter did not have an antenna, so the entire tag was


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inserted into the PVC pipe. Subjects were then externally tagged behind the dorsal fin with a coloured Floy tag and marked with a hole punch through the caudal fin (genetic sample). External tags and markings allowed visual identification of treatment groups to avoid double tagging with acoustic transmitters. Only the hole punch was deemed necessary in 2020. Sex, origin (hatchery or wild), and fork length (cm) were recorded. Fish were kept in the water during sampling except during acoustic tagging.

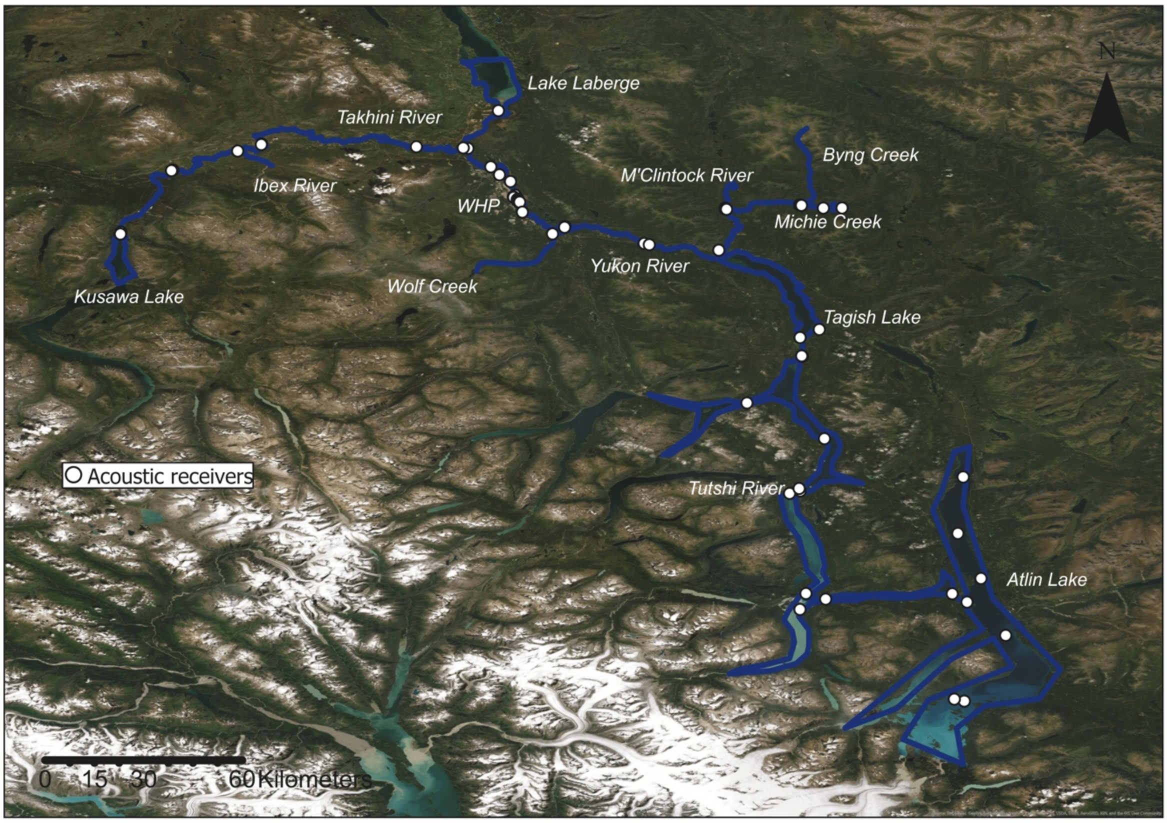

Figure 1. The acoustic and radio receiver array deployed throughout the Yukon and Takhini rivers upstream of Lake Laberge from 2017-2020. Note that receivers in Tagish and Atlin Lake were deployed by Environment Yukon and the BC. Ministry of Forests, Lands and Natural Resource Operations. Receiver locations changed over the course of the project such that not all locations shown above were monitored for all four years.

2.3 Tagging at the Fishladder viewing chamber

Chinook salmon were tagged at the Whitehorse Rapids Fishladder by ladder and hatchery staff with the same acoustic and radio transmitters as described previously. Fish were selected for tagging based on size, sex, origin, and arrival date at the viewing chamber, to mimic the characteristics of an average run (though proportionally less females were tagged; Table 1). Hatchery staff used their discretion to determine the number of transmitters applied daily in the viewing chamber, while also ensuring that a sufficient number of fish were kept as broodstock. Most tagged fish were of medium size, male, and wild. Fish that were selected for tagging were dip netted from the viewing chamber. Total handling time was ~2 min and air exposure was generally <20 s. Fish were released beyond the upstream gate of the viewing chamber. Proportionately less fish were tagged near the end of the run, to ensure that fish condition, which degrades throughout the migration, was suitable to support tagging.

2.4 Tagging downstream of the WHP

A gill net was used to capture fish downstream of the WHP approximately 9-12 km upstream of the confluence of the Yukon and Takhini rivers. The cable-laid gill net measured 30.5 m (100 ft) long, 3.05 m (10 ft) tall, and had a 3:1 hang ratio and 16.5 cm mesh size. The hang ratio encouraged entanglement over gilling to minimize harm and facilitate removal. Nets were set along eddy lines and were constantly watched over a 30-min soak period. Nets were checked immediately if the float line indicated a fish capture, and were otherwise checked at the end of the soak period. Fish were lifted on board and were quickly unrolled. Scissors were used to cut the net (typically 1-2 panels per fish) to decrease the amount of time spent entangled. One fish was captured while drifting the net, rather than the set net approach described above. Fish were immediately placed into a tote filled with river water and an oxygen pump set at 25 mg/L. Fish were sampled as described above (with the combined acoustic/radio transmitters) while a boat driver moved approximately 500 m upstream to a release site. Fish were released upstream to reduce the likelihood of recapture in the gill net. A small proportion of captured fish (5%) was released without a transmitter, and one fish died during capture. These capture events only occurred in 2017 when nettings methods were being developed.

Similar tagging was completed in the Takhini River in 2018 and 2019. The Takhini River is unimpounded (no physical barriers to migration), so an inability of Chinook salmon to complete their migration could be attributed to a combination of natural pre-spawn mortality and instantaneous or latent mortality from gill netting and handling. Conversely, if fish complete their migration in the Takhini River after gill net capture, tagging, and handling, then we would expect salmon in the Yukon River to have similar success completing their migration if there are no effects of the hydro plant on migration. Using similar methods in the lower Yukon River, Eiler et al. (2014) observed a 98% post-tagging recovery rate.

2.5 Active radio-tracking

Fish were tracked using a Lotek SRX800 radio receiver attached by coaxial cable to a three or four prong Yagi antenna. Tracking was conducted approximately every three days during the last week of August and first two weeks of September. Tracking was completed by jet boat and covered the area between McIntyre Flats and the WHP tail race. The stretch of river between the confluence of the Yukon and Takhini rivers and the Lewes Dam was tracked once each year in 2019 and 2020 after salmon had ceased upstream migration. Active tracking was also completed in 2019 and 2020 over the M'Clintock River, Michie Creek, the Yukon River mainstem, and Wolf Creek using a Cessna 206.

2.6 Carcass surveys

Carcasses were collected downstream of the hydroplant (n=146) and on the nearby free-flowing Teslin River (n=105) from 2018-2020 (as outlined in Twardek et al. 2021). Carcasses downstream of the hydro plant comprise those spawning their natally, and those failing passage at the fishway. Carcass survey data in combination with telemetry data was used to provide a secondary estimate of passage success at the fishway (see full details of this analysis in Appendix 5). Briefly, we estimated what proportion of the carcasses downstream of the WHP would have to have failed to pass the fishway and reach upstream natal spawning areas to observe the lower levels of complete spawning (ie. <100 eggs retained; Quinn et al. 2007) in female carcasses downstream of the hydro plant compared to those on the Teslin River. We operated under the assumption that salmon with spawning sites upstream of the fishway could spawn partially but not completely after failing to pass the fishway, and that the proportion of females completely spawning downstream of the hydroplant is equivalent to the proportion of male salmon completely spawning downstream of the hydro plant. Telemetry data were used to identify the proportion of fish that terminated upstream and downstream of the fishway, with no assumption of passage motivations for fish that terminated downstream. Telemetry data (which identified successful passage) was combined with carcass data (which estimated the proportion of salmon failing passage in the downstream carcass population) to calculate fishway passage success.

2.7 Data analysis

Terminal reaches reflected areas between adjacent receivers and were based on the receiver that fish were detected at by September 5th. However, if fish spent five or more days in an upstream reach, followed by downstream movement late in the season, the upstream reach was designated as the terminal reach. For some fish terminating in Michie Creek near Byng Creek it was difficult to assign one reach as the terminal location as salmon repeatedly moved up and down from the confluence (and likely spawning occurred in both reaches). Single downstream movements were observed for a few fish after September 5th, but these movements likely represented downstream carcass or post-spawning drift and were not included in analyses. Survival of fish that moved back through the WHP was based off detection patterns. Fish that moved upstream were designated as alive, as were fish that were detected consistently over multiple discrete periods at a receiver over the span of several hours (indicating active movement in and out of a receiver's detection range). Detection probability was calculated as the number of fish successfully detected by a receiver divided by the number of fish detected upstream of this receiver (Appendix 2).

Fishway efficiency calculations only included fish that were detected entering the tail race and approaching the hydroplant (i.e. detected at receivers ~400 m from the ladder entrance).

Table 1. Origin, sex, and length of fish implanted with acoustic transmitters from 2017 - 2020 for three treatments. Small Chinook salmon were defined as having a fork length <70 cm, medium as between 70 and 100 cm, and large as >100 cm.

Fish type (historic %)	Viewing chamber	Gill net - Yukon	Gill net - Takhini
Large wild male (<1%)	1 (<1%)	1 (2%)	1 (7%)
Medium wild male (40%)	81 (51%)	23 (41%)	8 (53%)
Medium wild female (21%)	28 (18%)	26 (47%)	6 (40%)
Small wild male (7%)	16 (10%)	-	-
Medium hatchery male (21%)	20 (13%)	3 (5%)	-
Medium hatchery female (7%)	7 (4%)	3 (5%)	-
Small hatchery male (3%)	7 (4%)	-	-
Mean fork length (cm±SD)	**78±9 cm (n=160)**	**83±7 cm (n=56)**	**88±6 cm (n=15)**

Table 2. The proportions of tagged Chinook salmon that terminated at various locations in the upper Yukon River each year that telemetry projects have been completed in Whitehorse, YT.

Location	1979 (N=15)	1998 (N=33)	2017 (N=50)	2018 (N=55)	2019 (N=40)	2020 (N=26)
Michie/M'Clintock system	87%	82%	88%	80%	75%	65%
Wolf Creek	0%	3%	6%	9%	0%	0%
Fell back downstream of the WHP	0%	12%	4%	9%	15%	27%
Mainstem Yukon River	0%	3%	0%	0%	3%	8%
Southern Lakes	13%	0%	2%	2%	7%	0%

Efficiency calculations followed those used previously (Dodd et al. 2017). Attraction efficiency was calculated as the proportion of fish that approached the ladder entrance (<10 m) of those that approached the facility (<500 m). Entrance efficiency reflected the proportion of fish entering the ladder of those attracted, whereas passage efficiency described the proportion that passed the ladder of those that entered. The number of approach, attraction, and entrance events was quantified as the number of unique movements to either the tailrace entry (approach), ladder entrance (attraction), or first step (entrance) following detection downstream. Overall passage success of the ladder was defined as the proportion of fish passing the facility of those that approached the facility. The elapsed times to attraction, entrance, and overall passage were calculated using the first detections at each receiver (similar to Silva et al. 2018). Duration of time spent at the viewing chamber was calculated as the elapsed time between first and last detections at the chamber. Upper ladder migration rate was calculated for Chinook salmon tagged at the ladder viewing chamber based on the elapsed time from the last detection in the viewing chamber (to allow for salmon to recover from tagging), and the first detection at the ladder exit. The duration between first and last passage attempts (defined as the time elapsed between first and final detections in the tail race; Rotary foot bridge) was calculated for those fish that failed to pass the ladder. The timing of ladder attraction phase detections, entrance phase detections, and viewing chamber detections was categorized as day or night using the *suncalc* package in R. Migration rate was calculated for the mainstem Yukon River (from Schwatka Lake to the Lewes Dam), the M'Clintock River (from the M'Clintock River Bridge to Michie Creek), and Michie Creek (between the M'Clintock River and Byng Creek) using the elapsed times between first detections at each receiver. Statistical tests were undertaken to determine whether there were significant relationships between explored variables. Statistical tests included t-tests, analysis of variance, and chi-square tests. All statistical tests were conducted in 'R' Statistical Software (R Core Team 2021).

Results

3.1 Overview

Chinook salmon were tagged at the ladder viewing chamber (n=160) and by gill net in the Yukon River (n=56) (Table 1).

3.2 Terminal locations of Chinook salmon

A total of 171 tagged Chinook salmon migrated beyond the WHP via the ladder from 2017-2020.

3.2.1 Michie Creek

Michie Creek is the primary spawning tributary for Chinook salmon upstream of Whitehorse, YT with 74% of all tagged salmon passing the WHP terminating in that system (Figure 2). Most of the tagged salmon entering the Michie Creek-M'Clintock River system terminated in Michie Creek upstream of Byng Creek (55%) while 38% terminated in Michie Creek between Byng Creek and the M'Clintock River, though many of these salmon first reached the confluence of Byng Creek and Michie Creek, and terminated just downstream of this confluence. Nonetheless, it was common for both male and female tagged salmon to terminate throughout the entirety of the creek. Finer scale terminal locations of fish in Michie Creek were determined by manual radio tracking on foot and in a Cessna 206 (Figure 3; Appendix 3, 4).

3.2.3 Byng Creek

No tagged salmon terminated in Byng Creek over 4 years of study. Occasionally (n=4), male salmon would enter the creek for brief periods of time, but this was highly infrequent, and was likely not for a sufficient time to complete spawning.

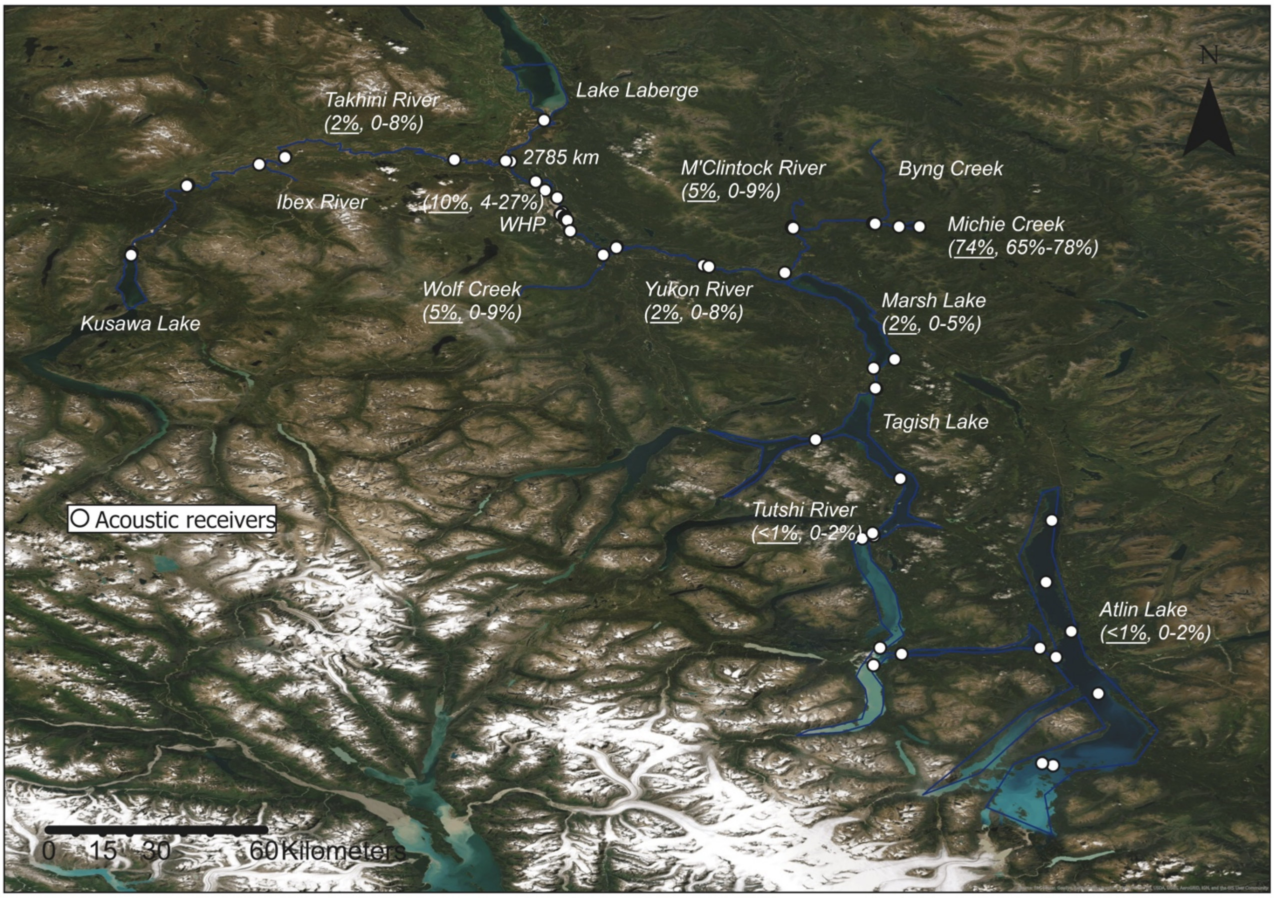

Figure 2. The terminal reaches of tagged Chinook Salmon (assigned as the reach between adjacent receivers) that passed the Whitehorse Rapids Fishladder from 2017-2020. Data are presented as (4 year mean, range of annual means).

3.2.2 M'Clintock River

Overall, 5% of all tagged salmon passing the hydro plant and 7% of tagged salmon entering the Michie Creek-M'Clintock River system terminated in the M'Clintock River. All but one of these salmon terminated in the upper reaches of this river upstream of the confluence with Michie Creek, while the other terminated immediately downstream of the confluence. The proportion of Michie-M'Clintock salmon terminating in the M'Clintock River was considerably higher in 2017 (8%) and 2018 (9%), than in 2019 (3%), and 2020 (0%).

3.2.4 Fox Creek

Fox Creek (upstream of Michie Lake) does not appear to be a terminal location for Chinook salmon, however, one tagged wild male salmon in 2020 was frequently detected in Fox Creek over 20 hours before returning back downstream to the upper reaches of Michie Creek.

3.2.5 Michie Lake

At least two salmon appear to have spent considerable amounts of time in Michie Lake (one in 2019 and one in 2020, though Michie Lake data does not exist for 2017 and 2018). In 2020, an acoustic receiver was positioned at the Michie

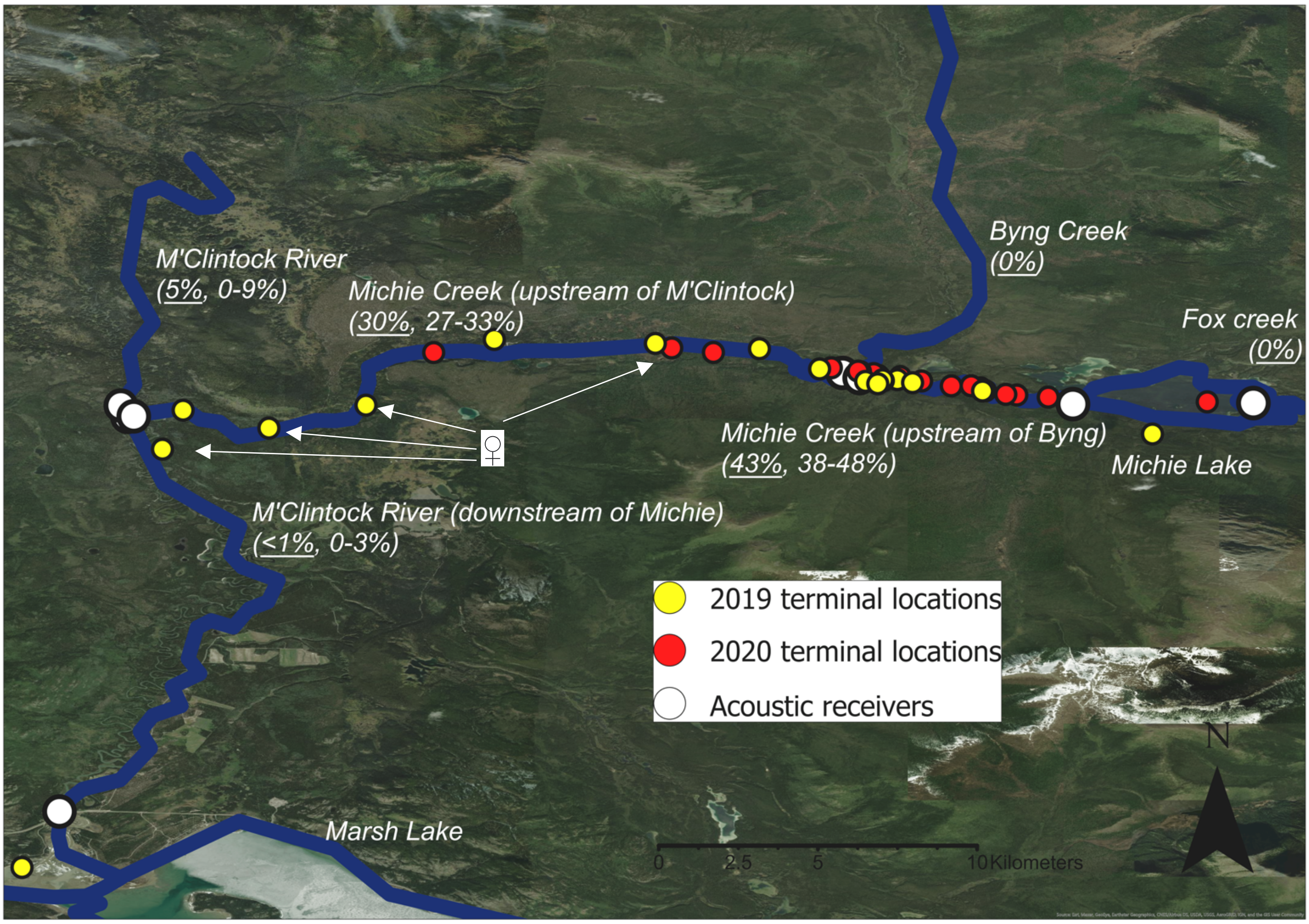

Figure 3. The terminal reaches of tagged Chinook Salmon in Michie Creek in 2019 and 2020. Data are presented as the proportion of all tagged salmon passing the WHP that terminate in each reach (4 year mean, range of annual means).

Lake outlet into Michie Creek. It was common for salmon to move back and forth in Michie Creek between Michie Lake and Byng Creek, and potentially spend time in Michie Lake. It is unclear whether salmon spawn in Michie Lake based on our study, though it appears salmon access this habitat during the spawning period. The two fish detected by radio telemetry in Michie Lake were assigned the terminal reach of 'Michie Creek upstream of Byng Creek' given that they spent time in the creek and the lake.

3.2.6 Wolf Creek

Several salmon of both wild and hatchery origin were last detected entering Wolf Creek (5% of those passing the hydropower plant) over the course of the study, though this only occurred in 2017 (6%), and 2018 (9%). In 2018, one tagged salmon was detected upstream of the Wolf Creek Fish Ladder at the Alaska Highway, though it is possible more tagged salmon passed this receiver as its detection probability was low. Some salmon entered Wolf Creek for short periods of time on their way to other terminal locations (e.g. Michie Creek). Wolf Creek has relatively cold water and may serve as an important thermal refuge for migrating salmon. Interestingly, one male hatchery salmon spent 10 days in Michie Creek (near Byng Creek) but returned back to Wolf Creek on September 9th, 2017.

3.2.7 Yukon River mainstem spawning

Over the course of 4 years, three salmon (2%) terminated in the mainstem Yukon River upstream of the Whitehorse Hydro Plant. One of these tagged salmon (a female) was recovered in 2020 as a completely spawned carcass downstream of Wolf Creek, providing strong evidence for successful spawning in this area (Figure 4).

A large proportion of the salmon tagged by gill net downstream of the hydro plant terminated downstream of the hydro plant (82%), many of which never attempted passage at all (33%). Female salmon terminating below the dam were often detected on the spawning grounds by Robert Service Way (63%) but only 42% were detected there for more than a few hours which would likely be the minimum amount of time needed to deposit eggs. Recovery of one tagged female carcass

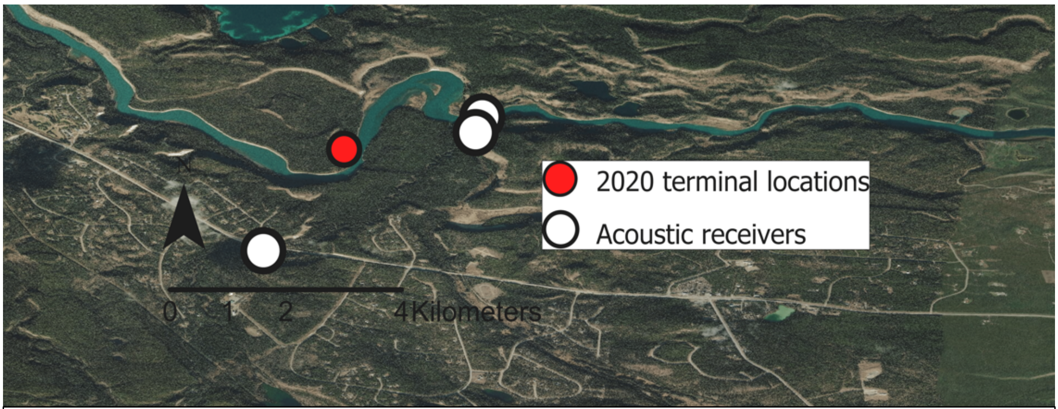

Figure 4. Terminal location of a wild Chinook Salmon female that was recovered as a completely spawned carcass in the Yukon River downstream of Wolf Creek in 2020.

in 2020 indicated it had mostly spawned, yet it was never detected by Robert Service Way, suggesting other spawning locations exist between the hydro plant and McIntyre Flats. Given that nearly all female salmon downstream of the hydro plant deposit some eggs (95%), and only 63% of salmon move into the known spawning habitat by Robert Service Way, it can be estimated that the other 32% of female salmon spawn elsewhere in this stretch of river. The locations of these potential additional spawning sites are unknown, though multiple salmon were detected, observed, and collected as carcasses in a ~100 m stretch in 2020 (60.738886, -135.065302).

It was also common for salmon passing the Whitehorse Hydro Plant to return downstream, presumably via the spillway (12%). This was uncommon in 2017 (4%) but was considerably higher in 2020 (27%). Salmon falling back through the WHP generally terminated on Robert Service Way (4% of all tagged salmon passing the dam), or between McIntyre Flats and Robert Service Way (5% of all tagged salmon passing the dam).

3.2.8 Southern Lakes

Over the course of four years, five tagged salmon of wild origin terminated in the Southern Lakes (3%). Two of these salmon (males) terminated in Marsh Lake in the area between the Yukon River and the M'Clintock River in 2019. One other female salmon was last detected at the north end of the Tagish River in 2017, though it did not get detected at the south end of the river. Further tracking in Marsh Lake did not identify the terminal location of this salmon.

In 2018, a tagged wild male salmon migrated directly to Atlin Lake, and made multiple movements between the north and south ends of the lake. It is unclear whether this salmon entered any tributaries to the lake, or if it was able to successfully spawn. The final salmon entering the Southern Lakes did so in 2019. This wild male disappeared between two receivers located either side of the Tutshi River (most likely into the Tutshi River). Ten days later, this salmon was again detected just downstream of the Tutshi River, potentially indicative of post-spawn movement or carcass drift. In each of 2019 and 2020, a single hatchery male ventured as far as Tagish Lake near the Tutshi River (2019) and the Six Mile River (2020) before returning back downstream to alternative sites.

3.2.9 McIntyre Creek

Over the course of 4 years, none of the 56 salmon tagged downstream of the WHP terminated in McIntyre Creek. One salmon that passed the WHP in 2020, returned back downstream and entered McIntyre Creek three separate times (~1 hr each) before migrating upstream in the Yukon River a few kilometres.

3.2.10 Takhini River

A small proportion of tagged salmon passing the Whitehorse Hydro Plant returned back downstream and terminated in the Takhini River (2%). This behaviour occurred in tagged salmon in both 2017 (2%; a single hatchery male) and 2020 (8%; a wild male and female). In 2020, these salmon migrated past receivers at Stoney Creek with one moving as far upstream as Kusawa Lake. It is unclear whether these salmon were of Takhini or Yukon origin.

3.3 Passage of Chinook salmon at the Whitehorse Hydro Plant

3.3.1 Passage overview

56 fish were captured and tagged on the Yukon River in August of 2017-2020, 36 of which approached the hydropower plant (834 ± 74 mm; 40% female). Over the same period, 15 control fish were captured and tagged on the Takhini River (879 ± 63 mm; 40% female). Entanglement periods in the gill net averaged 109 ± 61 s (Yukon River only) while air exposure averaged 54 s ± 29 s. The total tagging period from entry in the gill net to release upstream was just under 9 min. Most fish resumed upstream migration (96%;

n=71) though three fish (one from the Takhini River and two from the Yukon River) were never detected upstream after tagging. These fish were not included in further analysis or any summary statistics. According to ladder staff, one tagged female fish appeared to be struggling in the upper ladder and was taken for the hatchery program. This fish was included in measures of within ladder performance up to the viewing chamber but not in measures of behaviour in the viewing chamber or overall passage success. Mean August daily water temperatures in the fish ladder remained similar between 2017 (15.3[13.1-18.2] °C), 2018 (15.7[13.8-18.2] °C), 2019 (15.1 [12.4-17.6] °C), and 2020 (14.3 [12.9-16.1] °C).

3.3.2 Overall passage success

Salmon were significantly more likely to migrate 15 km upstream of tagging sites on the free-flowing Takhini River (100%; n=14) than on the Yukon River where salmon had to pass the hydro plant to migrate 15 km upstream (31%; n=35; χ^2=16.17, p<0.01). Salmon were also significantly more likely to arrive at upstream spawning sites on the Takhini River (100%; n=14) than on the Yukon River (29%; n=35; $\chi2$=22.90, p<0.01). Passage success at the fishway varied considerably across years with the lowest passage rates observed in 2017 (0%; n=6) and 2020 (0%; n=5), which also had the smallest sample sizes. Across all years, attraction (86%; n=21), entrance (77%; n=18), passage (36%; n=11), and overall passage success (31%; n=35) were recorded for Chinook salmon at the Whitehorse Rapids Fishladder. Upon entering the fishway, most salmon reached the turning basin (79%; n=14), and most moved beyond to the viewing chamber (73%; n=11). Upon reaching the viewing chamber, 69% of salmon passed the upstream gate and subsequently passed the fishway exit (n=16). Based on the proportion of completely spawned carcasses found downstream of the hydroplant, it was assumed none of the salmon approaching the hydroplant were natal to the habitat downstream (ie. had simply over shot downstream spawning grounds). Correspondingly, the combination of telemetry data and carcass survey data resulted in a fishway passage success estimate of 31.3%. Similarly, this combined approach yielded a female passage success estimate of 17.5%.

From release, it took Chinook salmon much longer to migrate 15 km and pass the hydro plant on the Yukon River (142.8 ± 180.8 h; median = 74.3 h; n=8) than to migrate a similar distance on the free-flowing Takhini River (27.2 ± 18.8 h; median = 23.4 h; n=14). Fish spent an average of 118 [27-564] h (median = 50.3 h) passing the fishway upon entering the tail race (n=8), which included attraction, entrance, and passage times. In comparison, 60.5 ± 40.8 h (median = 50. 3 h; n=100) was the time it took salmon to travel 78 km upstream to Michie Creek (the primary spawning tributary) after passing the hydro plant. Migration rates varied considerably throughout different components of the passage event (See Table 3) with the slowest passage rates observed for salmon entering the fishway, in the lower fishway, and around the viewing chamber.

Salmon often completed various passage sections more than once. For example, some salmon reapproached the hydroplant (14% of salmon; 1.3±0.8 approaches; n=36), reapproached the fishway entrance (31% of salmon; 1.5±1.9 times; n=16), and reentered the fishway (58% of salmon; 1.5±1.7 times; n=12). In one instance, a salmon moved 23 km downstream before returning to and passing the fishway 3 weeks later. This salmon had approached and entered the fishway several times prior to its 3 week departure. Salmon that failed to pass spent an average of 44.5±56.6 h (median = 31.3 h; n=18) between their first and last passage attempts. After failing to pass the fishway, most salmon were detected on the nearest known spawning ground located 1.5 km downstream (66%; n=18), though 16% were there for only a couple of hours.

Table 3. The timing of various components of passage for upper Yukon River Chinook salmon at the Whitehorse Rapids Fishladder, Yukon from 2017-2020. Passage time metrics include all salmon that attempted passage regardless of whether they ultimately passed the fishway.

Passage time metric	Average±SD (h)	Median	Distance (m)	Median migration rate (km/h)	n
Overall passage	118±183	50.3	834	0.017	8
• Attraction	1.6±1.7	1.0	410	0.41	13
• Entrance	49.1 ± 149.1	1.3	10	0.008	12
• Passage	34.8±8.3	37.0	414	0.011	3
Lower fishway	*13.8±14.3*	*10.1*	*56*	*0.006*	*9*
Turning basin	*0.1±0.1*	*0.1*	*3*	*0.3*	*9*
Mid-fishway	*4.4±5.9*	*0.7*	*47*	*0.067*	*7*
Viewing chamber area	*28.8±38.9*	*13.7*	*132*	*0.01*	*16*
Upper ladder	*0.8±0.2*	*0.8*	*176*	*0.22*	*6*
Spawning tributary mouth after passage	60.5 ± 40.8	50.3	78000	1.3	100

3.3.3 Diel Patterns of Fishway Passage

Salmon spent time at various sections of the fishway both during the day and at night, with the majority of detections occurring during day light (Figure 5). Of greater relevance to this fishway is whether salmon first arrived at the viewing chamber during hours of operation (9:00-20:00) or during close (when passage through the fishway is impossible). Indeed, more than half of all salmon arrived at the viewing chamber for the first time when the facility was closed (53%; n=17), and 34% of overall detections in the viewing chamber occurred during closed hours (Figure 5). Salmon that failed to pass the viewing chamber, spent more time attempting passage at the viewing chamber (50.6 [4-121] h; median = 30.9 h; n=5) than salmon that passed the viewing chamber (18.8 [0.1-105] h; median = 1.7 h; n=11; t=-1.59, P=0.14). Salmon that failed to pass typically also entered the chamber during daylight hours when passage should be permitted, though the upstream chamber gate can often remain closed during the day to permit counting, and adult collection for the hatchery.

3.3.4 Post passage migration success

160 Chinook salmon were tagged at the viewing chamber from 2017-2020 (778 ± 88 mm; 22% female; 79% wild origin) to quantify post-passage migration rates and arrival at spawning sites. Upon leaving the viewing chamber area, tagged salmon exited the fishway to the upstream reservoir in 2.2 ± 1.5 h (n=130). Migration success (>50km travel upstream to spawning tributaries; 87.8%; n=171) was high for fish that successfully passed the hydro plant, indicating that fish passage generally did not inhibit a fish's ability to migrate to spawning sites. Many fish did fall back however (12.2%), after passing the fishway. Detection data indicated these salmon did not move downstream through the fishway, and it seems likely they returned downstream through the spillway vs. the turbines given they appeared to survive and that turbine intakes are blocked with racks. Only one of these fallback events occurred shortly after passage (<1 hr), while most fallback events occurred after multiple days (5.7 ± 6.9 days; n=20) and after movement many kilometres upstream (i.e. overshoot). Upon returning downstream of the dam, 73.7% of these salmon (n=19) were detected on a known mainstem spawning area, though only 36.8% were repeatedly detected in this area (suggestive of spawning activity).

3.4 Movement ecology of Chinook salmon in the Upper Yukon River

Salmon migration rates in the mainstem Yukon River upstream of the WHP (1.6 ± 0.7 km/hr) and in the M'Clintock River (1.6 ± 0.5 km/hr) were much greater than that in Michie Creek (0.4 ± 0.2 km/hr). Migration rates tended to vary across years, particularly in Michie Creek where migration rates were low in 2018 and 2019. There was little difference in migration rates between wild and hatchery origin salmon or males and females. Migration rate was closely correlated with passage date at the WHP, with salmon passing later in the season moving significantly faster to Byng Creek (n=82; t-value = -6.9, P<0.01).

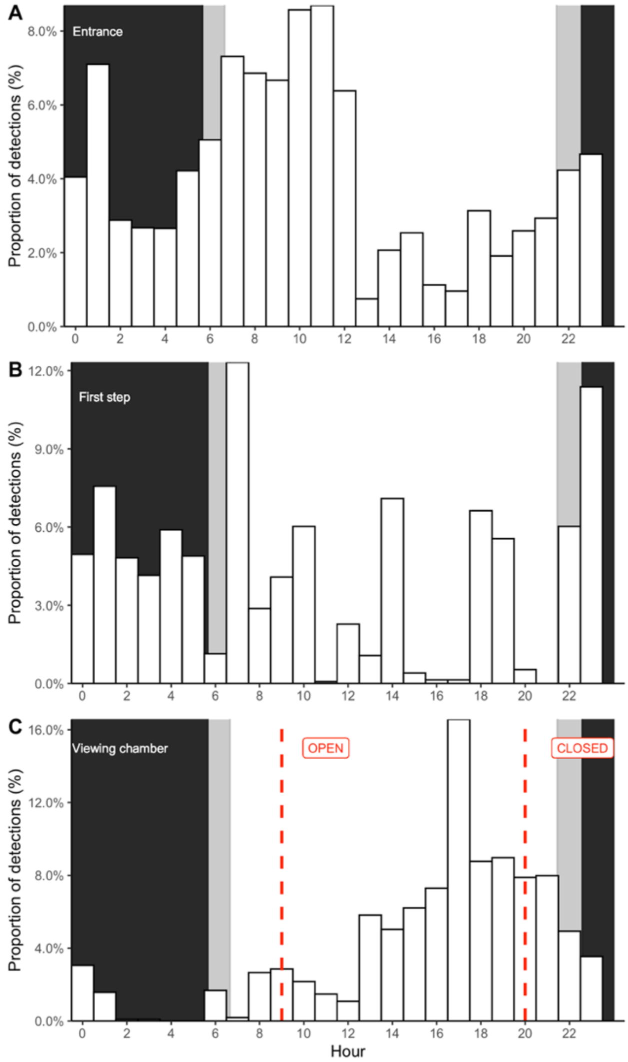

Figure 5. Diel ladder use of Yukon River Chinook Salmon measured as the proportion of all detections at A) the ladder entrance (n=10846) B) the first step of the ladder (n=1494) and C) the ladder viewing chamber (n=1014) over a diel period. Constant nighttime hours are shown in black while grey areas reflect the shifting sunrise and sunset times over the course of the migration. Red lines indicate the opening and closing hours for the ladder viewing chamber. Data were combined for all years (2017-2020).

Discussion

4.1 Project overview (2017-2020)

From 2017-2020 an ambitious project was undertaken to understand the factors limiting recovery of upper Yukon River Chinook salmon upstream of Lake Laberge. Specifically, this project sought to gain insight on the terminal locations of Chinook salmon upstream of Whitehorse and whether the fish ladder at the hydropower plant was effectively allowing salmon to pass upstream. Over the course of 4 years, 231 salmon were tagged as part of this study, providing important insights on salmon migrations in this stretch of river. Findings from this study revealed the proportions of salmon terminating in various locations upstream of Whitehorse, emphasizing the importance of known spawning grounds, and potentially identifying areas for restoration actions. As is evident by 60 years of passage, the fish ladder clearly allows salmon to pass upstream of the hydropower plant, but our study has revealed that some salmon that attempt to pass are unable to do so. We are hopeful that findings from this study can be used to inform changes in the design and operation of the Whitehorse Rapids Fishladder.

4.2 Terminal locations of Chinook salmon upstream of Lake Laberge

4.2.1 Michie Creek

The distribution of terminal locations from 2017-2020 confirms traditional knowledge and other biological studies stating that the majority of Chinook salmon that pass upstream of Whitehorse spawn throughout the Michie Creek - M'Clintock River system (Cox 1997; Table 2). Cleugh and Russel (1980) found that 87% of the run terminates in Michie Creek, whereas in 1993 and 1994, 56% and 44% of the run counted at the ladder were counted entering Michie Creek (Matthews 1999b). Our results from 2017-2020 suggest that 73% of fish that pass the WHP terminate in Michie Creek. Within Michie Creek, Cleugh and Russell (1980) found that all radio tagged salmon terminate in Michie Creek upstream of Byng Creek. In 1998, 0% of 35 radio tagged Chinook salmon reached Byng Creek (Matthews 1999a) but it was deemed that this was likely due to a beaver dam ~7 km downstream of Byng Creek (Matthews 1999b). Annual spawning ground surveys from KDFN have shown the continued importance of this habitat (de Graff 2019). From 2017-2020 we found that approximately half of all salmon in Michie Creek terminated upstream of Byng Creek. In 2020, an additional receiver was positioned at the outlet of Michie Lake, which revealed a large proportion of salmon passing Byng Creek move all the way to Michie Lake. It is unclear whether salmon spawn in the lake though it seems unlikely given there are no reports of Chinook salmon spawning in lakes elsewhere (Arostegui and Quinn 2019). One tagged salmon was detected in Michie Lake during an over head flight, and this salmon was also detected by an acoustic receiver in Fox Creek. This was the only observation of a tagged salmon in Fox Creek over the course of 4 years, suggesting this tributary is likely of low importance for spawning salmon. Similarly, over the course of four years no salmon terminated in Byng Creek, though a small proportion entered the creek for short durations. This creek is relatively cold and while it may not be currently suitable for spawning, it may become valuable in the future as temperatures rise with climate change. It is also worth considering the large proportion of fish in Michie Creek that terminate downstream of Byng Creek. While many of these salmon first reached the confluence of Byng Creek and then moved back downstream, it is clear that some salmon are completing their migration in the lower reaches of Michie Creek. Manual radio tracking by plane in 2019 and 2020 highlighted several locations that Chinook salmon may be spawning in this stretch of river or alternatively succumbing to en route mortality (Figure 3). Future surveys in this area to document spawning behaviour may be warranted.

4.2.2 M'Clintock River

Across all years of study, 5% of tagged salmon passing the WHP terminated in the M'Clintock River though this varied from 11% in 2017 to 0% in 2020. In 1998, a tagging study found 20% of salmon terminated in the M'Clintock River upstream of Michie Creek (Matthews 1999a). All tagged salmon terminating in the M'Clintock River did so upstream of Michie Creek, though one salmon in 2019 terminated just downstream of the confluence with Michie Creek. A large waterfall exists in the M'Clintock River a few kilometres upstream of the confluence with Michie Creek and its believed most spawning occurs in close proximity to the falls (de Graff 2019). This waterfall may pose a barrier to migrating salmon, limiting the available habitat in the river.

4.2.3 Southern Lakes

Historically, there is evidence to suggest salmon were common in the Southern Lakes. Brown et al. 1976 reports salmon being angled in the Tagish River, and Paul Brisley – Resident of Tagish and member of the Carcross Tagish RRC reported his father in law Walter (Wally) Ward, who came up to the Yukon with the army during the 1940's, angled and caught Chinook salmon in the Tagish River regularly during the 1940's and 1950's and as late as the 1960's. A 1975 tagging program attempting to find where Chinook spawn upstream of the dam indicated that a few Chinook salmon migrated upstream of Tagish River, suggesting possible spawning areas of the Tutshi and Atlin rivers (Discussed in Brown et al. 1976). Contemporarily, observations of salmon in the Southern Lakes has raised interest in the possibility that salmon may return to spawn in this area. In 2015, two male salmon were captured in Deep Bay of Tagish Lake, one was captured in the narrows of Nares Lake in 2018, and one was seen in Tagish River in 2019 (pers. comm. Karlie Knight). Our study revealed that a small proportion of salmon terminate in the Southern Lakes (<2%). Salmon terminating in the

Southern Lakes could be returning to natal spawning habitat or simply be straying into these areas. In the Columbia River, a study of ~1,000 Chinook salmon found a 2.5% stray rate from known natal spawning areas (Keefer et al. 2008). While it is unclear whether salmon are spawning successfully in the Southern Lakes, we have detected salmon in areas where spawning has previously been deemed most likely (Tutshi River and Atlin Lake). T.K. Elliott, the Area Director of Fisheries for DFO in 1959, stated that "I have been informed that there is a possibility that the spring salmon that passed through the Whitehorse Rapids Dam Fishway this year and could not be located could have gone to the Tutshi River to spawn. This man says that he has seen them spawning in this river on several occasions but was not there last year. Elliot also stated that "I have been told that salmon have been known to enter this lake [Atlin Lake] but have not had a definite indication as to where they might spawn. From a flight over it I noticed that there are several streams which might be suitable." Jackie Williams (a Taku River Tlinqit elder from Atlin who fished on Atlin Lake and River all his life), in response to a question regarding observations of Chinook salmon in the Atlin Lake area, mentioned catching a few large red fish every year in Atlin Lake around the 1940's which he believes were Chinook salmon. Jackie also mentioned another Elder, John Bone, observed salmon carcasses in Pine Creek near Atlin. A radio telemetry study in 1979 indicated that one salmon likely terminated in Pine Creek off Atlin Lake (Cleugh and Russell 1980). It seems unlikely that the wild male salmon tagged in our study terminated in Pine Creek, though we cannot rule out the possibility that it entered Pine Creek, or any other tributary for a short period of time before returning to the lake. It should also be noted that 6% of all tagged hatchery salmon passing the WHP (two male fish) migrated into the Southern Lakes before returning back downstream. Both Pine Creek and the Tutshi River may warrant further spawning surveys and potentially restoration effort (e.g. stock enhancement) in the future.

4.2.4 Wolf Creek

Over the course of 4 years of study, about 5% of all salmon passing the hydropower plant terminated in Wolf Creek. Wolf Creek has been the site of fry stocking by the Whitehorse Rapids Fish Hatchery every year since its founding in 1986 (Joint Technical Committee 2021). Previous studies based on stream counts estimated that 1.9%, 3%, and 11.5% of fish passing the WHP terminated in Wolf Creek (Matthews 1999b). Brown et al. 1976 stated that salmon use Wolf Creek for spawning in very limited numbers. In 2017 and 2018, 4% and 9% of tagged fish passing the WHP terminated in Wolf Creek. The return of wild fish in 2017 (2% of all tagged fish that passed the WHP) and 2018 (7% of all tagged fish that passed the WHP) suggests there is natural recruitment within this system. In 2018, one fish entering Wolf Creek was detected upstream of the ladder installed in Wolf Creek at the Alaska Highway, approximately 2.5 km upstream of the mouth of the creek.

4.2.5 Yukon River mainstem spawning

Historically, the Yukon River mainstem upstream of the WHP appeared to have productive spawning habitat. In 1887, George Dawson stated that, "Large numbers of salmon were found dead or dying along the banks for a few miles above the canyon (Miles Canyon), and the grass along the shores was trodden down by bears attracted here by this circumstance." The construction of the reservoir upstream of the Whitehorse Hydro Plant would have changed the habitat in this area, though suitable spawning habitat has since been identified in this reach (Access Consulting Group 2015). From 2004-2017 approximately 24,500 juveniles were outplanted into this area each year though none of snorkel, aerial, or carcass surveys revealed any indication of spawning (Access Consulting Group 2015). Our study suggests spawning is uncommon in this area, though recovery of a spawned wild female carcass suggests it does occur.

Many salmon also returned downstream of the WHP and terminated in the Yukon River mainstem. It was common for salmon to settle on the Robert Service Way spawning grounds, an area previously identified as supporting spawning habitat (Access Consulting Group & Yukon Engineering Services 2002). Many other salmon terminated downstream of this reach from Robert Service Way to the downstream end of McIntyre Flats. It is difficult to assign terminal locations in this reach given the high level of carcass drift. However, many salmon were detected and observed in the river downstream of the Walmart flats and were observed on McIntyre Flats (pers. Comm. Brandy Mayes, 2020).

4.2.6 McIntyre Creek

Despite no evidence from our tagging study of spawning in McIntyre Creek, juvenile Chinook salmon were identified in McIntyre Creek near Yukon College during an electrofishing course in 2020 (pers. Comm Degraff, 2020). It is unclear whether these juveniles were born in McIntyre Creek or if they moved into the creek from upstream spawning areas for rearing or feeding purposes. In 1998, a counting weir observ ed 8 adult salmon entering Wolf Creek of both sexes and origins (Waugh and Young 1998).

4.3 Passage at the Whitehorse Rapids Fish Ladder

4.3.1 Passage success

Fish passage assessments were conducted from 2017-2020 at the Whitehorse Hydro Plant generating a passage success estimate for the fish ladder. There are numerous points of uncertainty associated with this estimate that should be considered when interpreting our study findings. Annual sample sizes remained low, and the overall sample size remained moderate across all four years. Low annual sample size makes annual passage rates particularly uncertain and prone to sampling bias. For instance, in 2017 and 2020 we calculated 0% passage success, though counts by ladder staff clearly indicate passage was occurring through the ladder. As such, the actual passage rate likely varies from our calculated 31% passage success estimate.

Salmon tagged as part of our study may also have been impacted by the tagging procedure, compromising their ability to migrate through the fish ladder compared to untagged fish. Tagging can have sublethal impacts on salmon (Corbett et al. 2012) and we observed a few incidents of this in our study including injury to the stomach where tags were deposited. It is unclear how common these injuries were or if they had any impacts on fish behaviour given that salmon stop feeding during migrations and degenerate their gastrointestional tract (McBride et al. 1965). However, observation of one tagged salmon struggling to leave the upper ladder (pers. comm Lawrence Vano), suggests that for this individual, capture and tagging affected passage ability. To separate the influence of capture and tagging stress on migration success from passage failure, we tagged a control group of fish on the Takhini River. Our control group on the Takhini River had high migration success, with 93% of salmon migrating at least 50 km upstream after tagging. Further, fish tagged at the fish ladder viewing chamber had very high success migrating to spawning grounds, indicating tagging did not impair their migration ability. Given high migration success of tagged salmon upstream of the hydro plant and on the Takhini River, it is believed impacts of capture and tagging were low and infrequent and were not driving passage outcomes at the fish ladder.

Mechanisms behind relatively low passage success at the Whitehorse Rapids Fishladder are unclear given it has a similar design (pool-and-weir) and slope of highly successful fishways (~86% passage; Appendix 6). Though our study was not designed to assess the effectiveness of various design features or operational schemes on passage, we were able to identify sections of the ladder salmon failed to navigate. An inability for salmon to find the ladder (ie. attraction) appeared to be one source of failed passage. Salmon can have difficulty locating ladder entrances as they become attracted to the many other sources of discharge in the dam tailrace (Bjornn et al. 1995). Auxiliary flows diverted to the fishway entrance have increased salmon attraction even at very large hydropower schemes (Katopodis 2005). Increased velocity through weir orifices has also reduced the number of Chinook salmon leaving the lower sections of fishways back to the tailrace (Naughton et al. 2007). Salmon also ceased their upstream migration partway through the fish ladder. The use of multiple slots per weir in Columbia River fishways (vs. a single slot in Whitehorse) creates different hydraulic conditions within each pool, which may influence passage efficiency.

Some salmon failed to pass a viewing chamber located partway up the ladder (ie. a fish trap with a slotted gate that can be lifted to allow passage). This gate remains closed throughout the day, and is opened once salmon are observed in the chamber. Staff are present to operate the gate during the day (9:00-20:00) but outside of these hours the gate remains closed, preventing salmon from moving upstream. Our study found that salmon would often enter and use the ladder outside opening hours, including at night, a finding in contrast to Chinook salmon movement in several Columbia River fishways that found passage at night to be just a fraction of that during the day (though these fishways are at a much lower latitude with less light at night; Caudill et al. 2007; Keefer et al. 2004). Transient barriers such as fish traps are common in fishways, and have been associated with delays for migratory salmonids (Clabough et al. 2014; Murauskas et al. 2014; Morrisett et al. 2019). These delays can have post-passage consequences such as a compromised ability for salmon to arrive at spawning habitat (Morrisett et al. 2019). Delays at the viewing chamber were substantial for Yukon River Chinook salmon and some salmon ceased their upstream migration after delays averaging two days at the chamber. Interestingly, even when the gate was lifted during the day, some Yukon River Chinook salmon appeared hesitant to pass through the relatively small opening in the upstream gate and often needed chasing by means of a pole to move upstream. The presence of humans above the viewing chamber could invoke a predation threat response in salmon, causing delays, and even downstream movement. Similarly, chase and capture by hatchery staff in the viewing chamber for broodstock collection could potentially result in the release of human cues into the ladder. Chinook salmon appear to avoid fishways when mammalian (including human) cues are introduced (Brett and MacKinnon 1954; Ferguson et al. 2002). Failure to pass the Whitehorse Rapids Fishladder viewing chamber could be due to fish encountering a closed gate, human activity, or both.

Unique characteristics of the upper Yukon River Chinook salmon run may also have contributed to low passage success. Recent evidence has found that successful fish passage may be driven by collective migration (whereby social interactions improve animals' ability to find their way; Okasaki et al. 2020). The sensing of conspecific pheremones is likely an important aspect of collective navigation, particularly in the absence of strong natal cues which may be difficult to follow in dam tail races where flows are complex (Bett and Hinch 2015; Quinn et al. 1989). Given the low population size returning to Whitehorse, density remains low at the ladder compared to other systems where higher Chinook salmon passage has been observed (Appendix 6), potentially impacting the opportunity for collective migration. As salmon move downstream after failed passage attempts at the Whitehorse Rapids Fishladder, they may then be attracted to conspecific cues from the spawning population downstream of the WHP and/or effluent from the Whitehorse Rapids Fish Hatchery, located 1 km downstream of the WHP. Attraction to these sites could reduce the likelihood of salmon re-attempting passage at the fish ladder.

Further, exhaustion related to the extraordinary length of the migration prior to the WHP may affect passage ability at the ladder. However, exhaustion did not prevent tagged Takhini

River Salmon or Yukon River salmon that had passed the fish ladder from completing their migration. For exhaustion to explain our findings its impact would have to be such that it did not restrict routine migration, but compromised fish performance during passage (perhaps impacting fish of the lowest body condition). Female Chinook salmon are often impacted more by migratory challenges than males (Hinch et al. 2021). Female salmon invest more energy into gonads, perhaps limiting remaining energy available to respond to migratory challenges (Brett 1995). In the Seton River, it was found that female Sockeye salmon relied more on anaerobic swimming in the tail race than males, potentially explaining reduced passage success (Burnett et al. 2014). Females also attempted passage for longer periods than males before ceasing upstream migration, perhaps reflecting greater motivation to reach intended spawning sites (consistent with Burnett et al. 2014). Females that terminated below the WHP have high egg retention rates compared to females from a nearby free-flowing tributary where egg retention was markedly lower (Twardek and Lapointe 2021).

Passage success varied greatly across years perhaps due to environmental differences across years (e.g. temperature, flow). Challenging conditions during 2019 and 2020 may have reduced ladder passage success and our overall passage estimate relative to other years. Both years involved the lowest returns on record since hatchery operation began in the late 1980s. Salmon were delayed in reaching spawning locations, perhaps due to warm temperatures in the Yukon River in 2019, and high water levels in 2020, both of which have been implicated with delayed migrations in other Chinook salmon populations (Keefer et al. 2004; Salinger and Anderson 2011). Water temperatures and flow are expected to increase in the Yukon, as is the frequency of extreme climate conditions (Goulding 2011), which will undoubtedly affect Chinook salmon migrations in the terminal reaches of the upper Yukon River.

A portion of fish that approached and entered the fish ladder could also have ‘over shot’ intended natal spawning areas near Robert Service Way, eventually returning downstream (Keefer et al. 2008). Under this hypothesis, we also would expect hatchery salmon (all of which are stocked upstream) to have much higher passage success than wild fish in our study. This was not the case, but we were only able to tag five hatchery salmon that approached the fish ladder over four years of study. Of the five tagged hatchery fish that approached the ladder, two successfully passed (40%) compared to 30% of tagged wild salmon. Further, abnormally high levels of egg retention in females downstream of the hydro plant further corroborates our passage efficiency estimate (See details in Appendix 5).

Natural barriers can also impede salmon migration and passage success may not have been 100% through the Whitehorse Rapids prior to the damming of the river in 1958. While little information exists on migratory conditions at these rapids, the rapids were described coarsely in 1897; “*The rapids are about half a mile long, and the immense volume of water, with swirling and high-breaking waves, sweeps down the incline at a speed of 15 miles an hour. The river, which is 300 feet wide at the head of the rapids, contracts to 40 at the foot, where the confined waters rush through the narrow gateway with foam-crowned turbulence and then sweep on with a seven-mile current for a few hundred yards, finally resuming their placid course."* – Dunham 1898. While it is unclear whether this prevented some salmon from accessing upstream spawning grounds, it is known that salmon can have difficulty passing major natural migration obstacles (e.g., rapids, canyons, waterfalls; Hasler et al. 2011; Hinch and Bratty 2000) though this will depend on their unique hydraulic conditions. The most robust approach to evaluating the impacts of the Whitehorse Hydro Plant on salmon passage would have been a before-after control-impact design where passage was assessed before and after the dam was constructed.

4.3.2 Post-passage consequences

Across all years of study, 12% of fish that passed the WHP returned back downstream of the facility via the spillway, and did not return upstream via the ladder. This trend was also observed in 1998, when 12% of fish fell back downstream of the WHP, all of which terminated on the Robert Service Way spawning grounds (Matthews 1999a). Migrating fish are rheotactic (face oncoming current) and can be attracted to the water passing through a spillway upon entering reservoirs (discussed in Boggs et al. 2004); however, most fallback events that we observed occurred after fish had moved upstream away from the spillway, indicating that fallback did not result from confusion or exhaustion upon exiting the ladder. Fallback may also occur for fish that ‘over shoot’ downstream spawning grounds (Ricker 1972). In 2020, two salmon returned back downstream through the spillway, moved to the Takhini River, and terminated near Kusawa Lake. More commonly, salmon that fell back terminated in the nearby vicinity of the hydropower plant. In the Columbia River basin, overshoot averaged 15% for Chinook salmon populations, and typically lasted less than 5 days (Keefer et al. 2008). After falling back, Yukon River Chinook salmon often visited the nearest spawning habitat located 1.5 km downstream of the hydropower plant. Regardless of the mechanism, fallback through spillways can decrease survival to spawning grounds in Chinook salmon and lead to injuries such as bruising (Wagner and Hilsen 1992; Bjornn et al. 1998). All tagged salmon that moved back, presumably through the spillway, appeared to survive the event based on their detection patterns downstream of the WHP. It is unclear whether these fish suffered injuries, or whether they spawned successfully downstream of the dam.

Salmon passing the Whitehorse Hydro Plant were typically delayed by multiple days compared to salmon migrating through the free-flowing Takhini River. Fish ladders can be energetically costly because fish undertake burst swimming to navigate areas of high water velocity (Burnett et al. 2014).

Depleted energy reserves following dam passage may lead to en route or pre-spawn mortality and reduced spawning success in Chinook salmon (Gilhousen 1990; Geist et al. 2000; Cooke et al. 2006). A previous study documented 1.2-12.3% en route mortality following fish passage at 8 fishways in the Columbia River Basin and attributed this mortality to delayed fish passage (Caudill et al. 2007). Over the three years of our study there has been little indication that salmon have failed to reach spawning areas after passage, though we cannot rule out that there may have been impacts on spawning success. However, recovery of carcasses from Michie Creek in 2006 suggested that salmon passing the WHP almost always spawn completely if they arrive at spawning sites (pers. comm de Graff).

4.4 Behaviour of Chinook salmon in the Upper Yukon River

This study revealed interesting insights into Chinook salmon behaviour in the terminal reaches of the Upper Yukon River. For instance, salmon migration rates in the Yukon River were similar for wild and hatchery salmon, suggesting similar swimming performance of fish from different origins. Migration rates were also similar between male and female salmon. Migration rates were fastest in the Yukon River mainstem and were slowest in Michie Creek. It was also common for salmon to move downstream during migrations. Many salmon moved from upstream of the Lewes dam back to Schwatka Lake a few times before either returning below the dam or continuing their migration upstream. Salmon also appear to actively move around in spawning areas. Salmon arriving at spawning habitat upstream of the confluence of Byng and Michie Creek often made repeated movements back and forth between this confluence and Michie Lake, located approximately 5 km upstream.

4.6 Future directions

Findings from our study may be used to inform future monitoring projects, management decisions, and research questions.

Monitoring

- Given that many salmon (including females) terminate in lower Michie Creek, spawning ground surveys may be be warranted in this stretch of river, in addition to the Byng-Michie Lake reach where survey work has traditionally focused.

- Habitat evaluations could be undertaken on the Tutshi River to assess whether it has suitable habitat to support Chinook salmon spawning and rearing.

Research

- Are their environmental factors (e.g. flow) driving migration rates in Michie Creek, and can habitat management (e.g. beaver dam removal) help facilitate migration to spawning grounds?

- Why is overshoot/fallback at the Whitehorse Hydro Plant so frequent? Why are many male salmon not progressing to known spawning sites upstream?

Management

- High rates of fallback after passing the Whitehorse Hydro Plant suggest that estimates of spawning escapement through Whitehorse should be reduced by 12% (4-year average). Adjustments should reflect differences in fallback rates between male (14.9%) and female (2.7%) salmon

- Based on the finding that salmon were delayed in the viewing chamber during 'closed' hours over night as well as during the day (and in some cases ceased migration), alternate management approaches at the viewing chamber could lead to improved passage rates.

- Some salmon did not enter the fish ladder despite arriving outside of the entrance, or left the ladder shortly after entering. Improvements to attraction and entrance efficiency should be explored through alteration of attraction flows or through structural changes.

Acknowledgements

This project was completed with the assistance of several different organizations and individuals, who provided considerable amounts of time and financial support to contribute to the collective goals of this study. We would like to thank the Yukon River Panel, Yukon Energy Corporation, the Pacific Salmon Foundation, the Northern Scientific Training Program, and the Canadian Wildlife Federation for their direct financial support of this project and support from The W. Garfield Weston Foundation Fellowship Program, a program of the Wildlife Conservation Society Canada funded by The W. Garfield Weston Foundation. We extend our gratitude to Carcross/Tagish First Nation for extensive in-kind field support including both staff time and vehicles, particularly the efforts of Karlie Knight, Tami Grantham, Dan Cresswell, Coralee Johns, and Sonny Parker. This work could not have been completed without generous equipment loans provided by DFO and we thank DFO staff for their expertise (particulary Trix Tanner, Oliver Barker, and Vesta Mather). We are grateful to Yukon Government for sharing acoustic telemetry data from their Southern Lakes acoustic array. We thank the Yukon Energy Corporation and the Whitehorse Rapids Fishladder and hatchery staff for their advice and field assistance, including implanting transmitters into Chinook salmon, particularly Travis Ritchie, Lawrence Vano, Warren Kapaniuk, and Shae Thomas. We would also like to thank Ta'an Kwäch'än Council (particularly Kristina Beckmann and Jenna Duncan), Kwanlin Dün First Nation (particularly

Brandy Mayes and Cheyenne Bradley), Champagne and Aishihik First Nations, the Yukon Fish and Game Association, the Canadian Conservation Corps (Ciaran Shemmans and Kay Madere), Environmental Dynamics Inc. (Ben Schonewille), Carleton University (James Sebes, Connor Reid and Steven Cooke), Dennis Zimmerman and numerous volunteers for their in-kind support and assistance in the field. We thank Nick de Graff for his advice and field support and Al von Finster for his expertise and review of this report.

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Appendix 1. Detection rate of a range test tag placed near each receiver for a fixed period of time (100 potential detections) in 2018 (V16 tag) and 2020 (V13 tag).

Receiver location	Test tag location	Dist. (m)	Detection rate
2018			
Confluence of the Yukon and Takhini rivers	Directly across from receiver on opposite bank	150	24%
Takhini River km 11	Directly across from receiver on opposite bank	87	74%
Industrial boat launch	Upstream of receiver on opposite bank	280	0%
Rotary Park	Directly across from receiver on opposite bank	150	0
~500m downstream of ladder	Directly across from receiver on opposite bank	71	7%
Viewing chamber	At lower end of the chamber	5	70%
Viewing chamber	First step below	7	44%
Viewing chamber	Second step below	10	0%
Spillway	Near receiver	3	0%
Spillway	Lower end of eddy	30	0%
Upper Wolf Creek	Near receiver	1	~25 %
Upper Wolf Creek	Near receiver	1.5	~25 %
Upper Wolf Creek	Near receiver	2	~25 %
Upper Wolf Creek	Downstream run	10	0%
Upper Wolf Creek	Downstream run	12	0%
Lewes Dam	Upstream of receiver, just downstream of the Lewes Dam	450	48%
Mouth of the M'Clintock River	Directly across from receiver on opposite bank	55	75%
Michie Creek, upstream of Michie Lake	Same bank	5	42%
2020			
Ladder entrance	Lower ladder (first step)	4	0%
Ladder entrance	Lower ladder (bend below first step)	3	0%
Ladder entrance	Ladder entrance (in outflow)	2	93%
Ladder entrance	Ladder entrance (8 m away)	8	77%
Lower ladder (first step)	Ladder entrance (in outflow)	4	0%
Lower ladder (first step)	Lower ladder (bend below first step)	3	48%
Lower ladder (first step)	Lower ladder (first step)	1	92%
Lower ladder (first step)	Lower ladder (second step)	3	0%
Ladder turning basin	One step below turning basin	3	6%
Ladder turning basin	Lower turning basin	1	87%
Ladder turning basin	Upper turning basin	1	78%
Ladder turning basin	One step above turning basin	3	25%
Viewing chamber	One step below viewing chamber	5	0%
Viewing chamber	Viewing chamber	2	70%
Viewing chamber	Immediately before bend upstream	100	11%
Viewing chamber	Immediately after bend upstream	105	0%

Appendix 2. The detection efficiency of fish passing each receiver based on subsequent detection at upstream receiver sites in 2020. Fish were counted as having been detected at a receiver if one or more transmissions were detected there, followed by one or more detections at any receivers upstream of that site. Only the first pass by a receiver was considered in calculations.

Receiver	Detection efficiency (%)
Industrial Boat Launch	100% (n=5)
Rotary Park	100% (n=5)
Rotary Centennial Bridge	100% (n=4)
Ladder entrance	100% (n=2)
Ladder first step	100% (n=1)
Ladder turning basin	100% (n=1)
Viewing chamber	92% (n=26)
Schwatka Lake	88% (n=26)
Below Lewes Dam	100% (n=24)
Above Lewes Dam	100% (n=18)
Yukon @ Wolf Creek	100% (n=24)
Mouth of M’Clintock River	Not retrieved in 2020
Michie Creek at the M’Clintock River	100% (n=18)
Michie Creek at Byng Creek	100% (n=13)

Appendix 3. The terminal locations of each Chinook salmon tagged with an acoustic transmitter in 2019. Fish were captured and tagged at the Whitehorse Rapids Fishladder viewing chamber (n=36), by gill net downstream of the WHP in the Yukon River (n=29), or by gill net in the Takhini River (n=5). For each fish, the acoustic ID#, date, sex, length (FL; cm), and origin are listed. For each fish with an additional radio tag, specific terminal locations are provided with error estimates (UTM). 'Exact location' refers to GPS points taken after the tag was physically retrieved (3 m error), 'minimal error' refers to GPS points taken while walking or boating in the immediate vicinity of a tagged fish (3-100 m error), 'low error' was assigned to fish that had several GPS points taken while flying overhead, with final location based off the detection with the highest recorded signal strength (<1 km error). Where provided, ±location errors were assigned based on the approximate distance between the two furthest detections for a single transmitter.

Tagging Location	ID #	Date tagged	Sex	FL; cm	Origin	Terminal Location
Ladder	17837	05/08/2019	M	74	wild	Michie Creek upstream of Byng Creek 8 V 540431 6727793 (minimal error)
Ladder	30458	06/08/2019	F	81	wild	Michie Creek upstream of Byng Creek
Ladder	17840	10/08/2019	M	62	wild	Michie Creek downstream of Byng Creek 8 V 540158 6727772 (±1 km)
Ladder	17880	11/08/2019	M	79	wild	Michie Creek upstream of Byng Creek 8 V 540348 6727699 (minimal error)
Ladder	24473	11/08/2019	M	72	wild	Michie Creek upstream of Byng Creek
Ladder	17839	12/08/2019	M	93	wild	Michie Creek upstream of Byng Creek 8 V 540646 6727831 (minimal error)
Ladder	24393	12/08/2019	M	76	hatch	Michie Creek upstream of Byng Creek
Ladder	17846	13/08/2019	M	85	wild	Michie Creek upstream of Byng Creek 8 V 540348 6727699 (exact location)
Ladder	17858	14/08/2019	F	86	hatch	Yukon River mainstem upstream of dam 8 V 502849 6720727 (exact location)
Ladder	17859	15/08/2019	F	85	wild	Michie-M'Clintock Confluence 8 V 529335.90, 6725533.78 (low error)
Ladder	24401	15/08/2019	M	71	wild	*Last detected upstream of Lewes Dam*
Ladder	24448	15/08/2019	F	83	wild	Michie Creek upstream of Byng Creek
Ladder	17852	16/08/2019	F	92	wild	Michie Creek upstream of Byng Creek 8 V 540350 6727714 (exact location)
Ladder	17857	16/08/2019	M	87	wild	Michie Creek upstream of M'Clintock River 8 V 529644.14, 6726762.65 (low error)

Ladder	24464	16/08/2019	M	68	wild	Michie Creek upstream of Byng Creek
Ladder	17861	17/08/2019	F	85	wild	Michie Creek upstream of M'Clintock River 8 V 532462.83, 6726944.08 (low error)
Ladder	24444	17/08/2019	M	71	wild	Michie Creek upstream of Byng Creek 8 V 540882 6727735 (exact location)
Ladder	17853	18/08/2019	M	89	wild	Yukon River between Rotary Park and McIntyre Creek
Ladder	17854	18/08/2019	M	85	wild	Michie Creek upstream of Byng Creek 8 V 540417 6727823 (minimal error)
Ladder	17862	18/08/2019	M	85	wild	Michie Creek upstream of Byng Creek 8 V 544599 6726169 (high error)
Ladder	17867	20/08/2019	F	81	hatch	Michie Creek upstream of M'Clintock River 8 V 539442.99, 6728154.37 (low error)
Ladder	24399	20/08/2019	M	63	hatch	Michie Creek upstream of Byng Creek
Ladder	17868	21/08/2019	M	54	hatch	Tagging mortality
Ladder	24405	21/08/2019	M	87	wild	Michie Creek upstream of Byng Creek
Ladder	24418	21/08/2019	M	85	wild	Robert Service Way spawning grounds
Ladder	24474	21/08/2019	M	66	wild	Michie Creek upstream of Byng Creek (confluence)
Ladder	24422	22/08/2019	M	78	wild	Michie Creek upstream of M'Clintock River
Ladder	24454	22/08/2019	M	88	wild	Michie Creek upstream of Byng Creek
Ladder	17841	23/08/2019	M	80	wild	Michie Creek upstream of Byng Creek 8 V 541963 6727488 (±4 km)*
Ladder	17875	24/08/2019	M	76	wild	Marsh Lake near the M'Clintock River 8 V 527267.86, 6712369.15 (high error)
Ladder	17813	25/08/2019	M	84	wild	Yukon River between Rotary Park and McIntyre Creek 8 V 495800 6736912 (minimal error)
Ladder	17812	26/08/2019	M	78	wild	Michie Creek upstream of M'Clintock River 8 V 534420.60, 6729029.42 (low error)
Ladder	17818	26/08/2019	M	79	wild	Michie Creek upstream of M'Clintock River 8 V 538510.38, 6728780.60 (low error)
Ladder	17819	26/08/2019	M	82	wild	Marsh Lake near the Yukon River 8 V 526205, 6711780 (exact location)
Ladder	17868	26/08/2019	M	73	wild	Robert Service Way spawning grounds
Ladder	24409	30/08/2019	M	73	wild	Robert Service Way spawning grounds

Downstream gill net	17844	1-08-2019	M	85	wild	Michie Creek upstream of M'Clintock River 8V 536903.02, 6728928.56 (low error)
Downstream gill net	17878	11-08-2019	F	78	hatch	Yukon River between Rotary Park and McIntyre Creek
Downstream gill net	17842	11-08-2019	F	83	wild	Michie Creek upstream of M'Clintock River 8 V 530971 6726212 (±1 km)
Downstream gill net	17849	11-08-2019	M	92	wild	Yukon River between Rotary Park and McIntyre Creek 8 V 495685 6736190 (minimal error)
Downstream gill net	17845	17-08-2019	F	77	wild	Downstream of tagging site on Yukon River
Downstream gill net	17855	17-08-2019	F	92	wild	Robert Service Way spawning grounds 8 V 495545 6737291 (minimal error)
Downstream gill net	17847	18-08-2019	M	82	wild	Robert Service Way spawning grounds 8 V 495715 6736182 (minimal error)
Downstream gill net	17836	18-08-2019	M	81	wild	Michie Creek upstream of Byng Creek 8 V 540417 6727823 (exact location)
Downstream gill net	17850	18-08-2019	M	87	wild	Robert Service Way spawning grounds/YR mainstem downstream of dam 8 V 495756 6735942 (exact location)
Downstream gill net	17851	18-08-2019	F	80	wild	Robert Service Way spawning grounds 8 V 497080 6730445 (minimal error)
Downstream gill net	17843	18-08-2019	F	79	wild	Yukon River between Rotary Park and McIntyre Creek 8 V 497293 6731951 (exact location)
Downstream gill net	17876	18-08-2019	F	81	wild	Robert Service Way spawning grounds/YR mainstem downstream of dam 8 V 495911 6736695 (minimal error)
Downstream gill net	17863	18-08-2019	F	87	wild	Downstream of tagging site on Yukon River 8 V 495801 6756068 (minimal error)
Downstream gill net	17864	18-08-2019	F	84	wild	Downstream of tagging site on Yukon River 8 V 495720 6736156 (minimal error)
Downstream gill net	17865	18-08-2019	M	73	wild	Robert Service Way spawning grounds/YR mainstem downstream of dam 8 V 495585 6736531 (exact location)
Downstream gill net	24425	18-08-2019	F	81	wild	Robert Service Way spawning grounds/YR mainstem downstream of dam

Downstream gill net	17869	20-08-2019	M	79	wild	Yukon River between Rotary Park and McIntyre Creek
Downstream gill net	17870	21-08-2019	F	88	wild	Robert Service Way spawning grounds/YR mainstem downstream of dam 8 V 495146 6736928 (exact location)
Downstream gill net	17871	21-08-2019	M*	74	wild	Robert Service Way spawning grounds 8 V 496601 6733814 (exact location)
Downstream gill net	17866	21-08-2019	M	75	wild	Yukon River between Rotary Park and McIntyre Creek
Downstream gill net	17860	22-08-2019	M	82	wild	Robert Service Way spawning grounds 8 V 495641 6755226 (minimal error)
Downstream gill net	17874	22-08-2019	M	89	wild	Yukon River between Rotary Park and McIntyre Creek
Downstream gill net	17877	22-08-2019	M	95	wild	Yukon River between Rotary Park and McIntyre Creek
Downstream gill net	17816	22-08-2019	F	84	wild	Yukon River between Rotary Park and McIntyre Creek
Downstream gill net	17820	22-08-2019	F	80	wild	Viewing chamber
Downstream gill net	17814	22-08-2019	F	90	wild	Robert Service Way spawning grounds 8 V 497080 6730445 (minimal error)
Downstream gill net	17821	22-08-2019	F	78	wild	Yukon River between Rotary Park and McIntyre Creek 8 V 495907 6736801 (minimal error)
Downstream gill net	17815	22-08-2019	F	92	hatch	Yukon River between Rotary Park and McIntyre Creek 8 V 497251 6730288 (minimal error)
Downstream gill net	24462	22-08-2019	M	74	wild	Michie Creek upstream of M'Clintock River
Takhini gill net	24402	14-08-2019	F	85	wild	Upstream of Takhini River km 87
Takhini gill net	24439	14-08-2019	M	87	wild	Upstream of Takhini River km 87
Takhini gill net	24442	14-08-2019	M	91	wild	Upstream of Takhini River km 87
Takhini gill net	24400	16-08-2019	F	77	wild	Upstream of Takhini River km 87
Takhini gill net	24406	16-08-2019	F	81	wild	NO DATA (likely between Takhini River km 0 and km 12)

*Fish 17841 was detected at the mouth of Michie Lake on August 19, 2019 but later appeared to move downstream to spawn.
+UTM coordinates provided for fish that terminated in the Yukon River mainstem downstream of the dam indicate locations that carcasses drifted to, which are likely multiple kilometres downstream of where fish died/spawned. Fish were detected at many locations temporarily, but generally settled on McIntyre Flats. In several cases, transmitters were retrieved from the riverbank after the tagged fish was preyed/scavenged upon.

Appendix 4. The terminal locations of each Chinook salmon implanted with an acoustic transmitter in 2020. Fish were captured and tagged at the Whitehorse Rapids Fishladder viewing chamber (n=29) or by gill net downstream of the WHP in the Yukon River (n=7). For each fish, the acoustic ID#, date, sex, length (FL; cm), and origin are listed. For each fish with an additional radio tag, specific terminal locations are provided with error estimates (UTM). 'Exact location' refers to GPS points taken after the tag was physically retrieved (3 m error), 'minimal error' refers to GPS points taken while walking or boating in the immediate vicinity of a tagged fish (3-100 m error), 'low error' was assigned to fish that had several GPS points taken while flying overhead, with final location based off the average detection location weighted by signal strength (<500 m error).

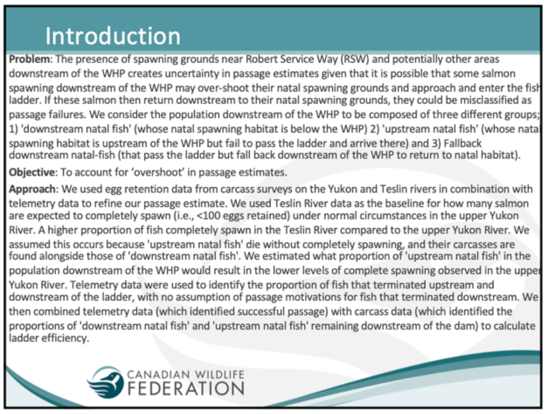
Tagging Location	ID #	Date tagged	Sex	FL; cm	Origin	Terminal Location
Ladder	54539	06/08/2020	m	76	w	Yukon River between Rotary Park and McIntyre Creek
Ladder	54540	07/08/2020	f	83	w	Takhini River upstream of Stoney Creek
Ladder	54536	10/08/2020	f	93	w	Yukon River upstream of Whitehorse 60.6219786, -134.9346036 (exact location)
Ladder	54534	10/08/2020	m	69	w	Michie Creek upstream of M'Clintock River 60.6863349375, -134.266256675 (low error)
Ladder	54533	12/08/2020	m	81	h	Michie Creek upstream of M'Clintock River 60.683543, -134.238094 (low error)
Ladder	54542	12/08/2020	m	60	w	Michie Creek upstream of M'Clintock River 60.68528035, -134.2612303625 (low error)
Ladder	17815	13/08/2020	m	74	w	Michie Creek upstream of Byng Creek 60.68370738, -134.24902846 (low error)
Ladder	17835	14/08/2020	m	72	w	Yukon River between Rotary Park and McIntyre Creek 60.773427, -135.084853
Ladder	17848	14/08/2020	m	77	w	Takhini River upstream of Stoney Creek
Ladder	17828	15/08/2020	m	87	w	Michie Creek upstream of M'Clintock River 60.6858104666667, -134.262539811111 (low error)
Ladder	17826	18/08/2020	m	63	w	Michie Creek upstream of Byng Creek 60.6874497375, -134.2744885375 (low error)

Ladder	17872	18/08/2020	m	73	w	Yukon River between Rotary Park and McIntyre Creek 60.754321, -135.068583 (minimal error)
Ladder	17838	19/08/2020	f	87	w	Michie Creek upstream of Byng Creek 60.67992445, -134.22526395 (low error)
Ladder	17879	20/08/2020	m	75	w	Michie Creek upstream of Byng Creek 60.6917236166667, -134.38669195 (low error)
Ladder	17832	21/08/2020	m	72	h	Michie Creek upstream of Byng Creek 60.680940375, -134.2310161875 (low error)
Ladder	17836	21/08/2020	m	73	w	Michie Creek upstream of Byng Creek 60.682354525, -134.2350320375 (low error)
Ladder	17817	21/08/2020	m	82	w	Michie Creek upstream of Byng Creek 60.6817821555556, -134.232399211111 (low error)
Ladder	17852	23/08/2020	m	80	w	Michie Creek upstream of M'Clintock River 60.6917816125, -134.307766225 (low error)
Ladder	17820*	23/08/2020	m	93	w	Yukon River upstream of Whitehorse 60.6791661333333, -134.213285833333 (minimal error)
Ladder	17843	24/08/2020	m	80	w	Robert Service Way spawning grounds 60.709895, -135.05275 (minimal error)
Ladder	17819	24/08/2020	m	93	w	Michie Creek upstream of Byng Creek 60.6791661333333, -134.213285833333 (low error)
Ladder	17871	25/08/2020	m	91	w	Michie Creek upstream of Byng Creek 60.6848225111111, -134.2608059 (low error)
Ladder	17850	26/08/2020	f	82	w	Michie Creek upstream of M'Clintock River 60.6930573714286, -134.3195114 (low error)
Ladder	17865	27/08/2020	m	84	w	Michie Creek upstream of Byng Creek 60.68231765, -134.240620975 (low error)
Ladder	17846	29/08/2020	m	71	w	Michie Creek upstream of M'Clintock River 60.6849286875, -134.25504735 (low error)
Ladder	17858	30/08/2020	m	78	h	Yukon River between Rotary Park and McIntyre Creek
Downstream gill net	54551	21/08/2020	F	86	w	Yukon River between Rotary Park and McIntyre Creek 60.760329, -135.082781 (exact location)
Downstream gill net	54549	21/08/2020	F	90	w	Yukon River between Rotary Park and McIntyre Creek 60.762271, -135.078125 (minimal error)

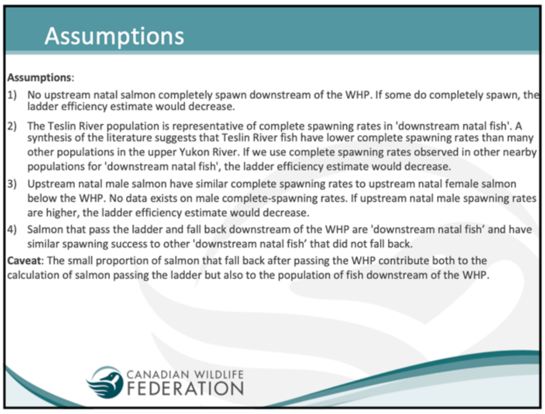
Downstream gill net	54554	22/08/2020	F	82	w	Yukon River between Rotary Park and McIntyre Creek 60.743577, -135.062251 (minimal error)
Downstream gill net	54552	23/08/2020	M	91	w	Yukon River between Rotary Park and McIntyre Creek 60.743577, -135.062251 (minimal error)
Downstream gill net	54548	24/08/2020	M	92	w	Yukon River between Rotary Park and McIntyre Creek 60.769482, -135.075334 (exact location)
Downstream gill net	54538	19/08/2020	M	98	h	Yukon River between Rotary Park and McIntyre Creek 60.77847, -135.074419 (exact location)
Downstream gill net	54544	25/08/2020	F	87	w	Yukon River between Rotary Park and McIntyre Creek 60.713848, -135.044785 (minimal error)

*Fish 17820 terminated downstream of the WHP but first spent several days in the Yukon River mainstem above the WHP
+UTM coordinates provided for fish that terminated in the Yukon River mainstem downstream of the dam indicate locations that carcasses drifted to, which are likely multiple kilometres downstream of where fish died/spawned. Fish were detected at many locations temporarily, but generally settled on McIntyre Flats. In some instances, transmitters were retrieved from the riverbank after the tagged fish was preyed/scavenged upon.

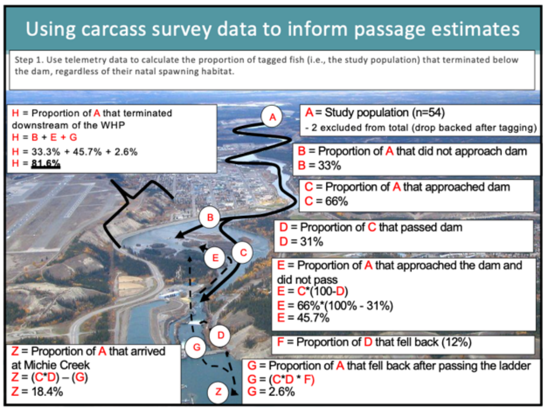
Appendix 5. Additional calculation of passage success using a combination of both telemetry and carcass survey egg retention data from 2017-2020.



1



2



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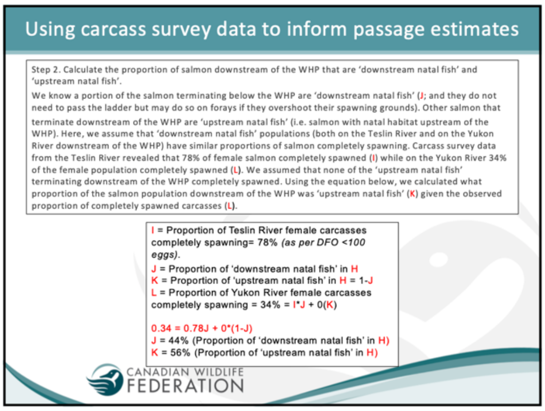

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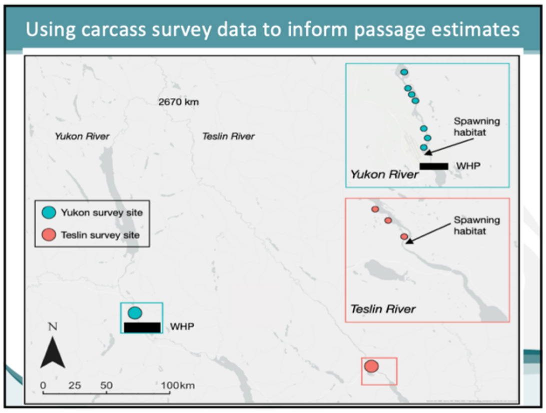
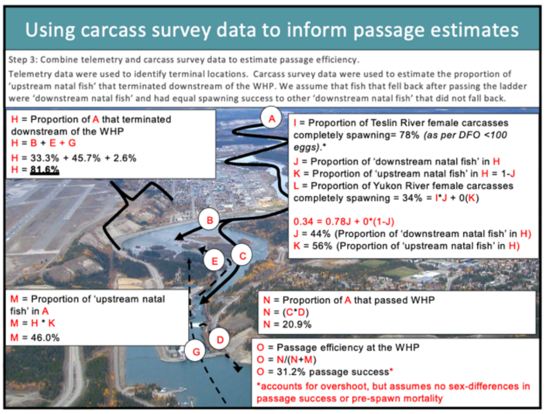


5



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Appendix 6. Previous published reports of Chinook salmon attraction, entrance, passage, and overall efficiencies at fishways located at other hydropower plants throughout North America. Studies incorporated into Noonan et al. 2012 are included (1960-2011) and a brief search from 2011 onwards.

Location	Year	Run	Str. Type	Ht.	Attn (%)	Ent (%)	Pass (%)	Overall (%)	n	Ref
Bonneville Dam			Pool-and-weir	18.3	-	-	98%	82%	85	Brown et al. 2006
Bonneville Dam	1996-2003	Fall	Pool-and-weir	18.3	-	-	-	77%	2398	Caudill et al. 2007
The Dalles Dam	1996-2003	Fall		61				84%	1535	Caudill et al. 2007
John Day Dam	1996-2003	Fall	Pool-and-weir	32				87%	1491	Caudill et al. 2007
McNary Dam	1996-2003	Fall	Pool-and-weir	22.7				93%	1222	Caudill et al. 2007
Ice Harbour Dam	1996-2003	Fall	Pool-and-weir	30				89%	231	Caudill et al. 2007
Lower Monumental Dam	1996-2003	Fall		30				88%	146	Caudill et al. 2007
Little Goose Dam	1996-2003	Fall	Pool-and-weir	30				88%	104	Caudill et al. 2007
Lower Granite Dam	1996-2003	Fall	Pool-and-weir	11.9				86%	63	Caudill et al. 2007
Lower Granite Dam	2001	Fall/Spring/Summer	Pool-and-weir	11.9	100 %	100 %	100 %	100%	472	Naughton et al. 2005
Lower Granite Dam	2002	Fall/Spring/Summer	Pool-and-weir	11.9	100 %	100 %	100 %	100%	291	Naughton et al. 2005