Survival, behaviour and physiology of migrating adult late-run Fraser River sockeye: identifying the cues and causes of abnormally high mortality prior to spawning

Final Report for 2004 Research Activity

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Overview of Final Reporting Information

Deliverables:

Were the stated objectives of the project met ?

Yes, details are provided in the document.

Project Schedule:

Did the project run according to schedule ?

Yes, the project ran exactly as anticipated with the one small exception that blood samples to assess some aspects of fish physiology are pending. This does not affect the overall interpretation of the main results. These analyses will be complete within the next month and summaries provided to PSC/DFO staff. Details are provided in the document.

Quality Assurance / Quality Control:

How was progress towards completion measured ?

We followed field methodologies and field schedules exactly as we had pre-determined. All transmitters were applied and fish sampled/tracked as pre-determined. Each research methodology and analytical milestone that was laid out in the original proposal was met in the expected time-frame. Data have been screened and checked multiple times to ensure validity of results.

Monitoring and evaluation:

Is this being done?

Post-project monitoring is not required as all adult fish died last fall. Our data and interpretations are under continual consideration and re-consideration in preparation for imminent peer-review submission and presentation at conferences.

Benefits:

What tangible benefits have resulted from the project ?

We now have a clear understanding of the role that specific temperatures can play during the migration of late-run sockeye, and the role that lake thermal refuges can play in reducing enroute migration mortality. This information can now be used by fisheries managers to aid in preseason or inseason predictions of migration mortality. These benefits are elaborated on in the text.

Budget:

Was the project completed on budget ?

Yes. A detailed breakdown of budgetary expenses will be forthcoming in separate correspondance from the Financial Services Department, UBC.

Executive Summary

In recent years, large numbers of Late-run Fraser River sockeye salmon have died in freshwater before reaching the spawning grounds. The purpose of this investigation was to examine the extent and causes of mortality in Late run Fraser River sockeye salmon. The investigations described here focused on the pre-spawning behaviour and survival of Late-run sockeye returning to Weaver Creek and the lower Harrison River. The study includes two components, 1) a field-based assessment of fish behaviour, mortality, and thermal biology, and 2) an experimental assessment of these same issues using laboratory interventions and field releases. We were particularly interested in the relationship between water temperature and mortality. Earlier controlled experiments in our lab have shown that moderate increases in migratory temperatures elicit high levels of mortality, even when temperatures at spawning were cooled to reflect normal conditions. Mechanisms of mortality have not yet been elucidated, but leading candidates include increases in parasitic infection and higher rates of energy use. Recent lab work has identified a 350-450 degree day threshold for high rates of parasitic infection and mortality.

The first component of the project involved tagging ~100 sockeye salmon captured in the Harrison River downstream from the natal Weaver Creek with acoustic depth tags (n=39) and radio tags (N=58). Tagging was conducted in cooperation with the Chehalis Band at the “Park” between 25 August and 29 September 2004 when river temperatures varied between 15 and 18.5 ºC. DNA analyses at capture and terminal spawning ground recoveries revealed that 46 of 58 radio tagged fish were assigned to

Weaver Creek, 9 to Harrison River and, 3 to Big Silver stock. Data from four fixed radio-telemetry stations and numerous mobile tracking surveys were used to track the movements of sockeye into, within, and out of Harrison Lake. These data were also used to determine when the fish entered known spawning areas and assess overall survival. The median travel times between the release sites in the lower Harrison River and a fixed-station located near the outlet from Harrison Lake was 0.2 d. Of the 46 tagged Weaver sockeye, 28 fish were detected in the upper Harrison River, of which 19 entered Harrison Lake. Four of those 19 later emerged from the lake and were subsequently tracked to Weaver Creek. Survival to spawning for Weaver Creek sockeye (N=8) was 0% for fish tagged in late August, 24% for those tagged in the first half of September (N=25), and 85% for those tagged late September (N=13). The respective river water temperatures in Harrison River were near 18.5ºC in late August, but were between 15 and 16ºC for most of September. We noted a strong relationship between water temperature in the lower Fraser River at time of river entry and mortality. Fish that migrated in late August and early September experienced water temperatures in the Lower Fraser in excess of >20ºC and had high levels of mortality (over 90%). Later migrants (late September) experienced low water temperatures (14ºC) during migration and exhibited low mortality (<10%).

Because radio telemetry is ineffective in large lakes, we also implanted an additional 39 fish with acoustic transmitters containing pressure sensors which allowed us to determine both the depth and position of fish in Harrison Lake. Coupled with temperature-depth profiles generated by temperature loggers placed throughout the watershed, we were able to reconstruct the thermal history of individual fish. A total of

11 fixed station acoustic receivers were used to assess fish behaviour, residency and fate. DNA analysis revealed that all 39 fish were of Weaver stock grouping. Of these fish, only 25.6% (N = 10) reached spawning grounds. When examined temporally, fish released between August 30 and September 3 had low survival to spawning grounds (5.3%, 1 of 19) whereas survival improved to 45% (9 of 20) after that period (i.e., September 20 to September 29). The only fish from the early tagging group that survived resided primarily in Harrison Lake and spent much of the time below the thermocline and accrued less than 450 degree days. The majority of the fish that died accumulated degree days in excess of 600 and/or experienced water temperature during their Fraser River migration that exceeded 19ºC. Conversely, fish that migrated in later September experienced lower water temperatures and spawned soon after arriving in the Harrison system. In addition to elucidating thermal biology and behaviour, the depth transmitter provided novel information on the location of mortalities. Our depth tags indicated that in Harrison Lake and Harrison River, all dead salmon tended to sink. In the lake, mortalities (as indicated by static depth reporting from the tag) were often observed at depths exceeding 100 m. While conducting our research on the Harrison system, we never observed any floating sockeye salmon in Harrison Lake or Harrison River.

The second experiment involved a series of field interventions. For this component, we experimentally tested the hypothesis that migratory salmon accruing >400 riverine degree days would exhibit inefficient behaviours (swim speeds) and signs of energetic and physiologic stress relative to fish that had accrued <350. To test this, we intercepted salmon en route to a natal spawning stream and biopsied them nonlethally for plasma biochemistry and somatic energy status. Fish were then held in large experimental tanks at one of two different temperature regimes (8 and 18º C), reflecting a range of natural temperatures, until they had accumulated 320 or 510 riverine degree days. Salmon were biopsied a second time and fitted with gastric acoustic transmitters (N=61) prior to release back to the river, and migratory behaviours were monitored using a fixed telemetry array leading to spawning grounds. Salmon with >400 degree days suffered higher mortality, both during the experimental holding period (70% warm vs. 15% cold) and when migrating to spawning areas (60% warm vs. 28% cold). Salmon >400 degree days also had delayed migration rates and fewer individuals were detected on spawning grounds. Somatic energy values upon release did not correlate with degree days or ultimate fate, but additional physiological plasma assays are pending. These results suggest that 'normal' timed migrants, if chronically exposed to warm river temperatures, can have their migratory performance and survival negatively affected.

Collectively, the findings from these studies emphasize the pivotal role of water temperature on the behaviour and survival of sockeye salmon. Thermal experience during early phases of migration (an acute stressor) can be important as we observed a strong relationship between high water temperature at Fraser River entry and subsequent mortality. Similarly, prolonged exposure to warm temperatures (a chronic stressor) can also be detrimental as degree days accumulate and accelerate disease development, energy use, and senescence. Future work should focus on exploring these relationships in other stocks and in other seasons. In addition, experimental manipulations should be encouraged to validate patterns observed in the field.

Introduction

This project represented a partnership between academia, government, First Nations and the private sector, examining the early migration/high mortality phenomenon in late run Fraser River sockeye salmon (See Cooke et al. 2004). The work described here was supported by the Southern Endowment Fund of the Pacific Salmon Commission and builds on the on-going work of the Natural Sciences and Engineering Research Council team (NSERC) led by Dr. Hinch. In 2003, the NSERC Research Team used telemetry and physiological assessments of late-run Adams sockeye near spawning grounds. They discovered unusual blood clotting and ionic balance problems in early migrants (which suffered high migration mortality). However, because sample sizes were low and the observational study opportunistic, the results from 2003 were compelling but equivocal.

Experiments mounted in 2004 were designed to further explore the cues and causes of abnormal migration timing and mortality in Late run Fraser River sockeye salmon. In 2004, efforts were focused on the commercially valuable Weaver late run stock, which has experienced high levels of en route and prespawning mortality since 1995, with four specific objectives.

Objective # 1. Document locations of mortality in Weaver-Harrison system relative to timing of arrival and spawning, and couple this with physiological assessments to understand why fish are dying. A better understanding of mortality locations/timings could be used to recommend harvest opportunities.

Objective # 2. Test specific hypotheses on the role of arrival timing, temperature, and Parvicapsula infection (See St-Hillaire et al. 2002) on migration mortality in the lower Fraser and Weaver-Harrison system. This advanced understanding will elucidate mortality mechanisms that will underpin future predictive models.

Objective # 3. Disseminate findings (presentations and reports) to partners including the fisheries managers responsible for the Fraser River Late-run sockeye salmon.

Objective # 4. Utilize findings to further focus research and management efforts in coming years when Late-run sockeye salmon will be more abundant.

To address the objectives, we focused our research efforts on two complimentary projects. A brief overview of the purpose and approach for each of these projects is outlined below.

Project 1. Fish were collected by beach seine in the Fraser River near the Weaver-Harrison system from the end of August to mid September reflecting a gradient of ‘early’ to ‘normal’ arrival timed migrants. Fish were non-invasively sampled for physiological and energetic status and implanted with either an acoustic or radio transmitter. Receivers were deployed throughout the Weaver-Harrison system to identify holding areas and confirm movements into spawning areas. These data were used to provide an independent (relative to the Mission hydroacoustic facility) assessment of timing based mortality patterns, and link mortality with water temperature, parasite infection (analyses being conducted by DFO), energetics, and physiology. There was evidence that segments of the Weaver run spend time in Harrison Lake before spawning. Survival to spawn may thus rely on migrant's ability to occupy deep, cold water regions in the lake for a set period. Cooler temperatures could retard accumulation of degree-days, which would retard both energy expenditure and the development of Parvicapsula infection. This project enabled us to document the patterns and locations of sockeye salmon mortality in the Harrison watershed.

Project 2. In project 2 we conducted an experiment to test hypotheses involving migration timing, encountered temperature, and enroute mortality. We captured fish on 13-14 September, the beginning of historic 'normal' migration timing period, and held them for 2-3 weeks in freshwater tanks at Cultus Lake Laboratory at either cool or warm temperatures. The cool temperature regime was similar to that experienced by sockeye holding in deep water of Harrison Lake, and the warm temperature regime was similar to that experienced by sockeye holding in the lower Harrison River. Moreover, these two thermal regimes simulate general differences in migration conditions between early and normal-timed late-run migrants. We released surviving fish and monitored their upstream migrations using an acoustic telemetry array. .

Below we provide a detailed summary of the methods and findings for each of the two project components. At the conclusion of the report we provide a synthesis and comment on how we achieved the four specific objectives.

Study Area

The Harrison River drains Harrison Lake and enters the Fraser River near the town of Agassiz, BC (Figure 1). There are several sockeye salmon stocks that spawn or migrate in this system. Harrison River adult sockeye salmon (a Late run stock) spawn in Harrison River and juveniles rear in Harrison Lake. Weaver Creek adult sockeye salmon (a Late run stock) spawn in the Weaver Creek Spawning Channel which drains into Harrison River. Juvenile Weaver sockeye rear in Harrison Lake. Other stocks include Big Silver Creek, which drains into Harrison Lake, and the Birkenhead River, upstream of Lillooet Lake. The main study area for Project 1 extended from the confluence of the Fraser and Harrison rivers, to Harrison Lake (Figure 1). Project 2 included the same study area, but also included downstream reaches of the Fraser River.

Project 1.

Background

Our understanding of the behaviour and fate of individual sockeye salmon is limited. This information is essential to understand the role of migratory timing and environmental conditions (especially water temperature) on fish survival. In recent years, early migrating fish have suffered high enroute and pre-spawning mortality. Temperature plays an important role in sockeye migration, and may be particularly important for fish that enter the river early and expose fish to thermal conditions that are atypical for these stocks. Furthermore, early migration has also apparently altered the host-parasite interactions between a myxozoan parasite (i.e., *Parvicapsula*) and sockeye salmon. Because the prevalence and severity of parasite infection is correlated with accumulation of thermal units, it is possible that the combined effects of water temperature and parasite infection may be the proximal cause of the mortality observed in early migrants. At present, however, there is little information on the thermal ecology of late run sockeye salmon including early and normal timed migrants. It is believed that some sockeye that migrate early may hold in freshwater lakes and seek cooler hypolimnetic waters to minimize their exposure to warm water temperatures. Here, we use several telemetry techniques to quantitatively and qualitatively assess the role of migration timing and environmental conditions on the survival and behaviour of migratory sockeye salmon.

Methods

Sockeye were collected by beach seine in the lower Harrison River from the end of August to mid September reflecting a gradient of early to normal arrival timed migrants. Some fish were to be destructively sampled for relevant physiological, energetic, and disease measures (work ongoing by David Patterson of Fisheries and Oceans Canada) while others were non-invasively sampled for physiological and energetic status and implanted with either acoustic or radio transmitters. Both transmitter types were used as they have different capabilities. Specifically, radio transmitters function well in shallow riverine environments but provide little information when fish are in deep lakes. Conversely, acoustic telemetry is well suited for deep environments but does not perform well in noisy shallow environments such as spawning streams. In addition, we were interested in the thermal biology of free-swimming sockeye salmon so we used depth reporting acoustic transmitters coupled with several arrays of thermal loggers to reconstruct the thermal history of acoustically tagged fish.

The radio transmitters used during this study were model MCFT-3A micro-coded fish transmitters manufactured by Lotek Wireless, Inc. of Newmarket, Ontario. They were 16 mm in diameter, 46 mm long, with a 460 mm antenna. The transmitters had an expected life of 761 d, but were programmed to stop transmitting after 154 d to minimize interference with other studies. Transmitters were on six different frequencies in the 150 MHz band. Within each frequency, three different pulse intervals (4.5, 5.0, and 5.5 s) were used to reduce the incidence of signal collisions when several transmitters were present at the same location at the same time. Acoustic transmitters used in this study were model V-16P coded transmitters with pressure sensors. They were 16 mm in diameter and 70 mm long. The transmitters had an expected life of 80 days. All transmitters operated on 69kHz. Transmitters sent out a signal on average once every 60 sec but randomly varied the timing (range of 30 to 90 sec) to minimize signal collisions.

Sockeye salmon were intercepted in the Harrison River between mid-August and late September 2004, a period that spans the majority of the migration period for Late-run Weaver sockeye salmon through the Harrison River. Fish were caught by beach seine in cooperation with the Chehalis Band First Nations fishery program. The fishing location was limited to a 150 m section of the river traditionally used by First Nations fisheries and termed “the Park”. A beach seine was loaded on the back of a jet boat and set around an area that typically holds upriver migrating sockeye. Once the net was pulled in, fish were individually netted out using dip nets and placed into a holding pen (1.5 m X 1.5 m X 3 m) located in the river. Fish were held in the pen for no more than 1 hour as they were processed. In an effort to collect “fresh” fish as they first passed “the Park” area, only fish that had loose scales, silver coloration, and poorly developed secondary sexual characteristics were selected.

Sampling methods were refined from earlier detailed descriptions provided by Cooke et al. (Accepted). No anaesthesia was used on fish to limit handling effects. Single fish were transferred from the holding pen by dip net and placed ventral side up in a foam-lined v-shaped trough, which was supplied with flowing river-water that entered the trough and was directed towards the mouth of the fish. The trough was angled slightly so that the water was deep enough to cover the entire head of the fish while leaving the caudal peduncle only partially submerged. The fish was held by one or two people, while a third person collected a blood sample via caudal puncture (Houston 1990) using a syringe (1.5”, 21 gauge) and vacutainer (3 ml), which was immediately stored in an ice-water slurry. If blood was not drawn within 1 min, the fish was excluded from the study and immediately sacrificed by concussion. Once the needle was removed, pressure was applied to the puncture site to facilitate blood clotting. A portion of the adipose fin was collected and stored in ethanol for DNA analysis. Each fish was measured for length (nose-fork) and two scales were removed from the lateral surface of the fish using standard methods developed by the Pacific Salmon Commission for stock identification of sockeye salmon. A small pair of linesmans pliers were used to remove 0.3 g of gill filament tips for osmoregulatory assays. A micro-wave energy meter (Distell Fish Fatmeter model 692; Distell Inc., West

Lothian, Scotland, UK) was used to assess somatic energy levels following the methods in Crossin and Hinch (2005). While in the trough, the left side of the fish was partially lifted out of water to permit the energy meter to be placed on two locations of the body wall near the dorsal fin. Gender was assessed using external secondary sexual characteristics. Blood samples were centrifuged within 10 min of storage on ice and two 0.5 ml plasma aliquots were immediately removed, stored on dry ice in the field and transferred to -80ºC upon return to the lab. Blood plasma assays are pending. We expect that these will be complete in June of 2005 in time to assist with planning management and research activities for the summer of 2005. These data will be shared with DFO and PSC staff as soon as they are complete.

A total of 59 fish were gastrically implanted with radio transmitters through the mouth and into the stomach using a plastic tag applicator (English et al. 2004; Ramstad and Woody 2003) and successfully released into the river. The implant was performed immediately after the biopsy had been completed. The antenna was folded such that it trailed along the side of the fish. Acoustic depth tags were implanted in 38 individuals using the same techniques outlined above. External cinch tags were also applied anterior to the dorsal fin to identify individuals. The tagging and sampling procedure were terminated if the procedure took longer than 2.5 min or if the fish escaped from the trough. Immediately after tagging, fish were transferred to a 3 m 3 transfer tank and transported to the Chehalis Hatchery. The transfer tanks held a maximum of 18 fish. At the hatchery fish were placed in concrete raceways (depth = 0.5 m) for 8 to 36 h and held at 14ºC. During this time, scales were returned to the Pacific Salmon Commission for analysis in an effort to focus tagging efforts on sockeye of Weaver stock origin.

When stock identification was determined, appropriate fish were released and fish of wrong or uncertain stock identification had transmitters removed. In some cases fish were released alive, whereas others were biopsied to obtain *Parvicapsula* samples and the carcasses then delivered to the Chehalis Band for their Elders or for cultural and educational programs. Fish that were released were netted individually from the raceways and placed in the transfer tank for return to the Harrison River. Fish were released at the site of capture after verifying that all transmitters were functional. DNA analyses were used to ascribe stock identity to fish that were not tracked to terminal spawning grounds.

The techniques used in this study have been independently verified in previous assessments (Cooke et al. Accepted), therefore no pre-season assessments were conducted. During the raceway holding period, none of the transmitter-implanted fish regurgitated their transmitters. Although one fish died during this period, this was more likely attributed to previously undetected seal wounds rather than to the tagging procedure. All fish were in good condition upon release and swam rapidly away from the release site. Therefore, the evidence from in-season tagging suggests that post-implantation transmitter regurgitation and short-term tagging-induced mortality were not issues.

Both fixed stations and mobile tracking were used to monitor radio-tagged tagged sockeye salmon. Radio tags were tracked using SRX 400 radio receivers manufactured by Lotek Wireless, Inc., and 3-4-element Yagi antennas. Fixed-stations similar to those used in 2002 and 2003 (English et al. 2004) were deployed at four sites along the lower

Harrison River and Weaver Creek (Figure 2). The first, most downstream station, was located at the Harrison and Fraser confluence and served to monitor any fish leaving the Harrison Watershed. Two fixed stations were installed at Weaver Creek, (one at the mouth and one 5 km upstream from the mouth at Morris Lake), and the a fourth station was situated at the Harrison Lake outlet. Several antennas were used at each site to determine the direction of movement of tagged fish based on their sequential detection pattern. Multiple antennas used at tributary junctions were positioned to detect fish downstream of the station, up a tributary (if present), and upstream of the station. For each site, signal collisions and environmental noise that would affect the detection of tagged fish were monitored periodically, and adjustments were made when required, thereby minimizing interferences and monitoring gaps during the survey period. Mobile radio tracking was conducted to confirm arrival at terminal spawning locations and to provide additional data on fish locations throughout the study period. Fish were tracked by foot as well as by boat. During both foot and boat surveys, a hand-held 3-element Yagi antenna was used to position radio tagged fish. Fish positions were recorded on scale maps and marked using a GPS receiver.

Acoustic tags were also monitored using both fixed and mobile tracking. Radio tags were tracked using Vemco VR-60 receivers for mobile tracking and Vemco VR-2 receivers for fixed stations. Fixed-stations were deployed at 11 sites along the Harrison River, Weaver Creek, lower Harrison Lake, and Big Silver (Figure 3). The first and most downstream station, was located at the Harrison and Fraser confluence and served to monitor any fish leaving the Harrison Watershed. Fixed stations were also deployed at the Agassiz Bridge, the Park, the confluence of Weaver Creek and Harrison River, Morris Lake, the outlet of Harrison Lake, and the southern shallow basin of Harrison Lake. Four additional VR2's were deployed in Harrison Lake. VR2's were either secured to appropriate structures (pilings) or suspended using an anchor and float system. Mobile radio tracking was conducted to confirm arrival at terminal spawning locations and to provide additional data on fish locations throughout the study period. Fish were tracked by foot as well as by boat. Fish positions were recorded on scale maps and marked using a GPS receiver.

Data from fixed radio stations were downloaded at regular intervals, depending on the number of fish passing the stations and their accessibility (about every 7 d for remote stations, and 2-3 d for closer stations monitoring large movements). After downloading, and prior to erasing the internal memory in the receiver, a diagnostic program was run on the download file to ensure that all data had been transferred, the file was readable, and the receiver and antennas had been operating properly. Data from the acoustic VR'2s were downloaded at the conclusion of the study.

Radio telemetry tagging records were processed and analyzed using LGL Inc. custom database software that facilitates data organization, noise filtering, record validation, and analysis. Original data sets were archived so that data selection criteria could be modified to achieve estimates with specified spatio-temporal resolutions. Before analyzing the telemetry data, false records in the receiver files caused by electronic noise were removed. Records were only considered valid if they had power levels >50 (1-232 scale) and two detections within 20 min in a zone located in the middle of two detection sites. After the removal of false records, a compressed database was created to hold the sequential detections for each radio-tagged fish. Each record identified an individual fish by a unique combination of tag number, a zone number (antenna or general location), the first and last time and date for the sequential detections in a specific zone, and the maximum power for all detections in that interval. Similar approaches were used for the acoustic data set although data were sorted manually using a database program. Survivors were considered those fish tracked to predefined spawning areas such as Weaver Creek, Harrison River and Big Silver River during the spawning periods.

Results/Discussion

Thermal profiles of Harrison River and Harrison Lake are provided to add context the discussion below (Figure 4). These data were collected by D. Patterson (DFO).

Radio Telemetry

In total there were 58 radio-tagged fish released in the Harrison River during 2004, all of which were physiologically sampled. Seventeen radio-tagged sockeye were assumed to be part of the Weaver Creek stock because they were detected in that creek. DNA micro-satellite analyses provided estimates of stock origins for the other 41 fish. Weaver Creek sockeye represented 79% of the tagged fish. The remainder of the fish sampled were Harrison River (16%) or Big Silver (5%).

Out of a total of 46 radio-tagged Weaver Stock sockeye releases, 38 (83%) sockeye immediately migrated upstream and were detected either at the mouth of

Weaver Creek station or at the upper Harrison River station. Of the remaining eight fish, seven were detected downstream from the release, at Harrison/Fraser junction and one was never detected and was assumed to have done likewise. Three of the seven downstream fish subsequently traveled upstream past the Weaver Creek station, and the other four were never detected again.

A total of 26 (56% of a possible 46 Weaver fish tagged) fish appeared at the mouth of Weaver Creek and they consisted of mostly of fish tagged in September (25 fish, 96%; Figure 2). Thirteen of the fish (50%) traveled to or above the upper Harrison station. The timing of entry into Weaver Creek measured for 17 fish started on the 7th September and ended on the 20th October. The median residence time in the Harrison System (calculated from the point of release to the point the fish entered Weaver Creek) was considerably larger for the second release group (26.5 d) compared to the third release group (2.7 d). Out of 17 fish that successfully entered Weaver Creek, a total of four fish entered and resided in Morris Lake for an extended period (median 22.1 d).

As the release site in Harrison River was located only 3 km downstream from the Weaver Stock fish destination area (i.e., Weaver Creek), the travel rates within the Harrison River likely represented delays associated with recovery from post-release stress and a milling behaviour likely related to reorientation to the river system. The upstream movement rates for all Weaver stock fish within Harrison River were 33 km/d for fish tagged in early September and 6 km/d for those tagged in mid September. These river migration rates were faster than the migration rate within Weaver Creek, 0.25 km/d. A slow movement within Weaver Creek is most likely attributed to fish holding in Morris Lake.

The entrance of sockeye salmon into Weaver Creek coincided with water temperatures that ranged from 16 to 13 ^{0}C (Figure 4). The median residence time in the Harrison Watershed for fish that entered the lake and then survived to Weaver Creek was 39 d, compared with the value of 15 d for those that did not enter the lake and survived. The values for those fish that were tracked in to Weaver Creek (18 d) were substantially different from those that did not enter Weaver Creek (31d).

The overall stock-specific survival estimates for Weaver, Big Silver and Harrison stocks were 39.1%, 33.3% and 11.1%, respectively. Survival to spawning for Weaver Creek stock sockeye was 0% for sockeye tagged in late August, 24% for those tagged in the first half of September and 85% for those tagged in late September.

We noted a strong relationship between water temperature in the lower Fraser River at time of river entry and mortality (Figure 5). Fish that migrated in late August and early September experienced water temperatures in the Lower Fraser in excess of >20ºC and had high levels of mortality (over 90%). Later migrants (late September) experienced low water temperatures (14ºC) during migration and exhibited low mortality (<10%).

Acoustic Depth Telemetry

DNA analyses on the 39 fish tagged with acoustic depth transmitters revealed that they were all of Weaver stock origin. Of these fish, only 25.6% (n = 10) reached spawning grounds. Half of the fish (N=19, 49%) were confirmed mortalities, 7.7% fell back downstream (presumed mortalities, N=3), and the fate of 7 individuals is unknown

(17.9%) but they were also believe to have died. When examined temporally, fish released between August 30 and September 3 had low survival to spawning grounds (5.3%, 1 of 19) whereas survival improved to 45% (9 of 20) after that period (e.g., September 20 to September 29). No fall backs were observed in the second timing group, but three fish fell back in the early timing group.

There were two distinct residency patterns evident among 26 of the tagged fish. Nine fish (34.6%) resided in Harrison River whereas 17 fish (65.4%) resided in Harrison Lake. Coupled with temperature-depth profiles generated by temperature loggers placed throughout the watershed, we were able to use the data from the depth tags to reconstruct the thermal history of individual fish. The only fish from the early tagging group that survived resided primarily in Harrison Lake and spent much of the time below the thermocline and accrued less than 450 degree days (Figure 6). The majority of the fish that died accumulated degree days in excess of 600 (Figure 7) and/or experienced water temperature during migration that exceeded 19ºC. These fish also tended to occupy shallow habitats rather than deep hypolimnetic waters (Figure 7). Conversely, fish that migrated in later September experienced lower water temperatures and spawned soon after arriving in the Harrison system, accruing fewer degree days (Figure 8,9).

In addition to elucidating thermal biology and behaviour, the depth transmitter provided novel information on the location of mortalities. Although the prevailing thought is that dead salmon float, our depth tags suggest that in Harrison Lake and Harrison River, dead salmon tend to sink (e.g., Figure 10). In the lake, mortalities (as indicated by static depth reporting from the tag) were often observed at depths exceeding 100 m (Figure 10). Mortalities tended to be randomly distributed throughout the south end of Harrison Lake (Figure 11). While conducting our research on the Harrison system, we never observed a floating sockeye salmon in Harrison Lake or Harrison River.

Project 2.

Background

The effects of temperature on fish metabolism, energy use, and disease are well known from observational field studies. This experiment was conducted to expose sockeye to current and historic thermal regimes experienced as they make there way through the Fraser River to spawning grounds. In recent years, early migrating fish are those that suffer high pre-spawning mortality. We tested the hypothesis that an accumulated exposure to critical temperatures affects the survival of adult salmon homing through freshwater to natal areas. We predict that sockeye accruing >400 degree days (i.e., accumulated thermal units [ATUs]) during the freshwater component of their upriver migration will show energetic and behavioural inefficiency (i.e., reduced swim speeds, increased travel times and transport costs, and erratic migration patterns). We also predict that sockeye accruing >400 ATUs will show increased measures of stress (i.e., plasma lactate, cortisol, glucose).

Methods

Sockeye from the Weaver population were captured en route to spawning grounds (Figure 12) by beach seine on 13-14 September, 2004 when water temperature in the Harrison River was 16ºC. These dates fall within the 60-year average of normal run-timing for this population. Details of capture methods and study site are as in Project 1 above. Fish were biopsied as above (including application of an external tag for individual identification) and then transported to experimental tanks at the Cultus Lake Laboratory where they were exposed to one of two experimental temperature regimes: 10 or 18 ºC. Fish were held for a day at Chehalis Hatchery at 11ºC. Temperatures were then adjusted to treatment levels incrementally over a period of two days. Fifty fish were assigned to each treatment. Sex could not be determined definitively at time of capture but was qualitatively assessed by secondary sexual characteristics. Sex will be confirmed by pending reproductive hormone analyses.

Fish were held until each treatment until they had accumulated 325 and 510 degree days, respectively. These levels approximate historic (pre 1995) and current levels (abnormal-timed migrant segments, post 1995) that this population of sockeye typically encounters when migrating through the Fraser and Harrison River watersheds en route to spawning grounds. Mortality was monitored over the course of the experimental holding period and the experiment ended on 9 October. Surviving cold treatment (N=31) and warm treatment (N=17) fish were sampled a second time for the energy and blood variables listed above, were fitted with a gastric acoustic transmitter, and returned to the Fraser River 85 km downstream from the initial collection site (Figure 12). The transmitters used for this experiment were model V16H (Vemco Inc.). They were 16 mm in diameter and 58 mm long. The transmitters had an expected life of 80 days. All transmitters operated on 69kHz. Transmitters sent out a signal on average once every 60 sec but randomly varied the timing (range of 30 to 90 sec) to minimize signal collisions.

Homing behaviour and fate were monitored through an acoustic receiving array placed at intervals leading to the Weaver spawning grounds (Figure 12). The array operation and receiver locations are described above in Project 1 (i.e., Figure 3). In addition, we also made use of 3 pairs of VR-2 receivers deployed on the Fraser River (See Figure 12). The first returning experimental fish arrived at the Weaver Creek Spawning Channels on 13 October. On 12 October, 13 additional sockeye were captured upon arrival at Weaver Creek and sampled for somatic energy and blood variables. These fish were marked with spaghetti tags and fitted with gastric acoustic transmitters and transported 85km downriver to the site where the experimental fish were released. These fish thus represent a pseudo-control in which fish were transported and released without experimental treatment.

Results/Discussion

Previous migratory simulation experiments (S. Larsson, unpub data) in our lab have shown that chronic exposure (e.g. more than 1 week) to extremely warm temperatures (e.g. >19 C) can cause high levels of immediate mortality in adult sockeye being held under lab conditions - latent mortality was also high even when temperatures were cooled (e.g. < 12 C) during subsequent weeks of holding. We have also found that initial chronic exposure to temperatures of ~ 15 C, causes relatively lower initial mortality rates but that fish begin to succumb within 1-2 weeks as temperatures are increased (S. Larsson, unpub data). Mechanisms of mortality have not yet been elucidated, but leading candidates include increases in parasitic infection and higher rates of energy use. Subsequent lab work has also identified a 350-400 accumulated thermal unit (ATU) threshold for high rates of *Parvicapsula* infection.

Results based upon our current simulated migration indicate that salmon from the warm treatment (accruing >400 ATUs and simulating early migration) suffered significantly higher mortality than those fish exposed to a simulated normal timed migration and associated lower water temperature (70% mortality warm vs. 15% cold, $P>0.01$; Figure 13). These data and are previous lab studeis represent the first laboratory assessments of migration mortality in response to water temperature that exist for Fraser Sockeye. Earlier lab assessments from the 1970's of adult sockeye exposed to different temperature levels used antibiotics and exposure times far short of typical migration times which would have led to conservative mortality estimates which also do not reflect typical migratory conditions.

To supplement the laboratory based mortality experiments, we released surviving fish from each of the two treatments into the Fraser River to assess *in situ* migration mortality and behaviour. Interestingly, 60% warm of the warm treated fish died prior to reaching spawning grounds whereas only 28% of the cold-treated fish perished ($P>0.01$; Figure 14). There were also sub lethal behavioural impairments associated with exposure to warm water temperatures. The warm treated fish exhibited delayed migration rates relative to cold-treated fish (Figure 15). Thus, for longer distance migrants, the reduced migration speed would lead to even further accumulation of degree days en route to spawning grounds.

We also biopsied fish in an effort to understand the physiological and energetic impacts of exposure to different thermal regimes. Somatic energy values upon release did not correlate with ATUs or ultimate fate, but the microwave methodology may not be appropriate for determining energy use at this late stage of migration. Blood plasma assays are pending. We expect that these will be complete in June of 2005 in time to assist with planning management and research activities for the summer of 2005. These data will be shared with DFO and PSC staff as soon as they are complete. Results thus far suggest that moderate increases in river temperature can negatively affect the migratory performance and fate of individual migrating salmon.

Summary of Key Findings

- Accumulation of degree days can serve as a predictor of mortality in fish that are chronically exposed to warm water temperatures (<18ºC) for extended periods (as observed in the field and experimentally). However, acute exposure to extremely warm temperatures (>19ºC) can also lead to high levels of mortality. The field thermal manipulation experiment revealed that fish exposed to accumulated thermal units reflecting 'normal' timed late-run migrants exhibited mortality rates comparable to those found in the wild under normal late-run timing conditions (~28%). Fish exposed to thermal units reflecting 'early' timed late-run migrants exhibited twice the mortality rates (~60%), comparable to those found in recent years for abnormally early migrants. Prolonged exposure to water temperatures around 18ºC also resulted in slowed migrations.

- Behavioural selection of cooler water in Harrison Lake appears to have prevented mortality of some individuals. The only depth tagged fish from the early release group to reach spawning grounds resided below the thermocline and thus retarded its accumulation of thermal units. Fish which entered the lake and eventually returned to spawning grounds generally utlilized predominantly areas below the thermocline. However, for most early fish, residing below the thermocline did not guarantee survival providing more evidence that acute exposure to high water temperatures earlier in the migration can be detrimental.

- Dead fish do not float. Under the conditions experienced in Harrison River and Harrison Lake during the study period in 2004, we observed no evidence to support the contention that dead sockeye salmon float. Conversely, we accumulated substantial evidence that fish which died tended to sink to vast depths in Harrison Lake (in some cases <100 m) and accumulate on the bottom in Harrison River (Personal Observation).

Revisiting the Objectives

Here we briefly restate the objectives of the study and comment on how they were achieved.

Objective # 1. Document locations of mortality in Weaver-Harrison system relative to timing of arrival and spawning, and couple this with physiological assessments to understand why fish are dying. A better understanding of mortality locations/timings could be used to recommend harvest opportunities.

Based on our findings it appears that the key factor in fish mortality prior to spawning is water temperature. Early migrants experience high water temperatures and then spend several weeks holding in freshwater prior to spawning. Some of these fish will die immediately from exposure to high water temperatures in the lower Fraser River. Other fish will develop severe parasitic infections and deplete energy resources over time as they accrue degree days. A small number of early migrants can survive to spawn. For example, one early migrant we observed in our study moved into Harrison Lake and spent the majority of time below the thermocline thus retarding disease development and energetic exhaustion. Normal timed migrants typically encounter cooler water temperatures in the Fraser main stem and in home tributaries. Some of these fish can still accrue lethal levels of degree days (>450) if they do not select cool water refuges in lakes and thus not all survive. However, the majority of the normal timed migrants are able to successfully reach spawning grounds. Our physiological analyses which will provide even more information on the mechanisms of mortality are still pending as those assays require much care and time. Those data will be shared with PSC staff as soon as they are available.

As outlined above, we were able to identify specific locations of mortality. Early migrants were more likely to fall back downstream after release and leave the Harrison system never to return again. These fish are likely mortalities and probably accumulate downstream of the Harrison-Fraser confluence. The majority of the early migrants that died moved into Harrison Lake or the upper reaches of the Harrison River. It is unclear whether these locales would provide viable locations to harvest fish that are likely to die in years with early migration and high temperatures. Our data also provided some scientific data in support of the "missing salmon debate". In particular, we revealed that dead salmon tended to accumulate in the bottom of Harrison Lake and Harrison River and did not float.

Objective # 2. Test specific hypotheses on the role of arrival timing, temperature, and *Parvicapsula* infection on enroute migration mortality in the lower Fraser and Weaver-Harrison system. This advanced understanding will elucidate mortality mechanisms that will underpin future predictive models.

Through field observations and experiments, we were able to illustrate that exposure to high water temperatures for short periods, or extended exposure to warm water temperatures, can kill fish. In particular, we found a strong relationship between mortality and water temperature in the Fraser River at time of river entry. Forthcoming data on disease development (histology of *Parvicapsula* infections - D. Patterson and S.Jones, Fisheries and Oceans Canada) will provide additional support on the relationship between degree day accumulation and both mortality and performance. Our data provide a novel perspective on the importance of temperature on fish survival and point towards the need to understand both acute and chronic stressors. Fisheries and Oceans Canada is now investigating the use of degree day accumulating in estimating mortality as part of their Environmental Watch Program and EMA modelling.

Objective # 3. Disseminate findings (presentations and reports) to partners including the fisheries managers responsible for the Fraser River Late-run sockeye salmon.

We have made several informal presentations to PSC and DFO staff members over the past few months (Steve Macdonald, David Patterson, Mike Lapointe). In addition, our team delivered two presentations to the Fraser River Panel in January. Our recent data also formed the basis of two key presentations for the "missing sockeye salmon" issue in 2004: in December our team presented findings to a Parliamentary Committee, and in February we provided testimony at the William's inquiry. In January we presented the findings at the Canadian Conference for Fisheries Research in Windsor, Canada. The findings will also be presented at the European Fish Telemetry Conference in Portugal in June and at the American Fisheries Society Annual Meeting in Alaska in September. We will continue to share and disseminate information locally (PSC meetings, DFO meetings) and more broadly to the scientific community through peer reviewed literature. We also just held our annual NSERC planning meeting where we gave recent updates to DFO/PSC staff (M. Lapointe, S. Macdonald, K. Millar).

Objective # 4. Utilize findings to further focus research and management efforts in coming years when Late-run sockeye salmon will be more abundant

Our data pointed to specific hypotheses that can be explored in future years. For example, there is a need to understand the relationship between both degree day accumulation and lower Fraser River temperature and mortality for additional stocks. More importantly, our data provide some direction to fisheries managers. Specifically, we have clearly elucidated (both observationally and experimentally) the role of water temperature on fish mortality. We have also highlighted the importance of using degree day accumulation to estimate mortality. Our model of river entry temperature and mortality is also suggestive that this could be used as a predictive tool in future years. Finally, the data on location of fish mortalities provides a starting point for searching for carcasses in the coming years. The largest remaining uncertainty in terms of the late run issue is the early arrival problem that again repeated itself in 2004. Once fish are more abundant (e.g., 2006), we can use our telemetry partners and techniques that we have refined to conduct studies examining coastal migrations of late run fish. We plan on using the POST array to examine behaviours of physiologically-sampled (i.e., biopsy of telemetered individuals) fish, and, conduct intervention experiments by exposing fish to saline gradients to test hypotheses about triggers of early migration.

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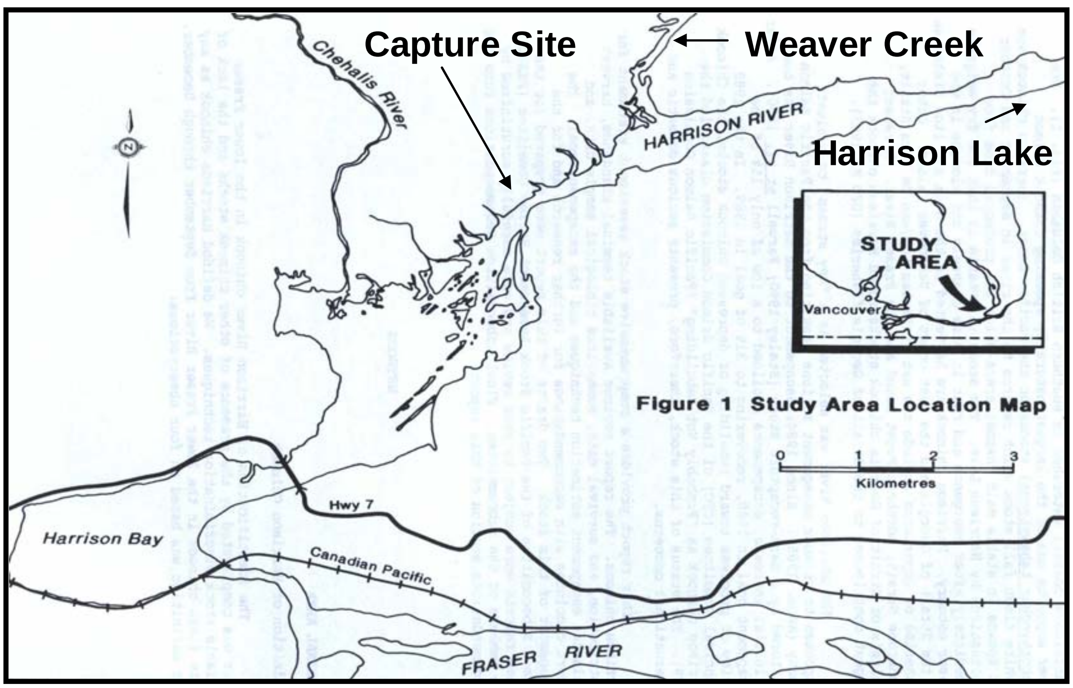
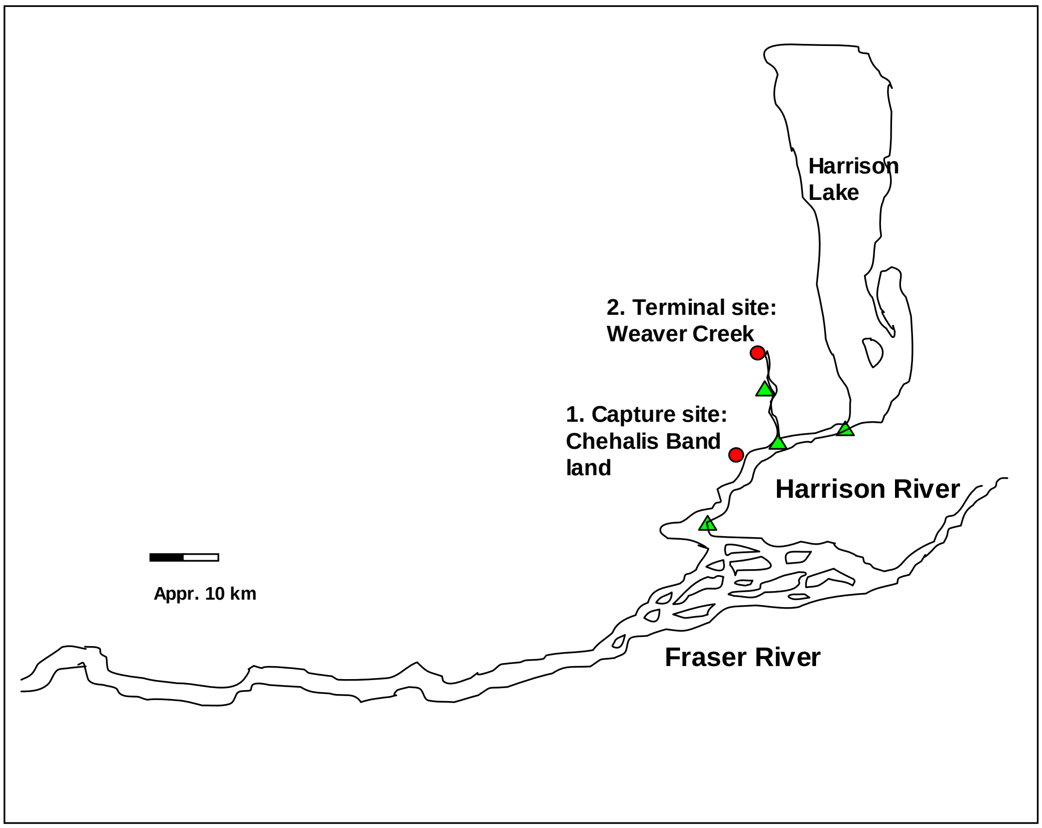
Figure 1.



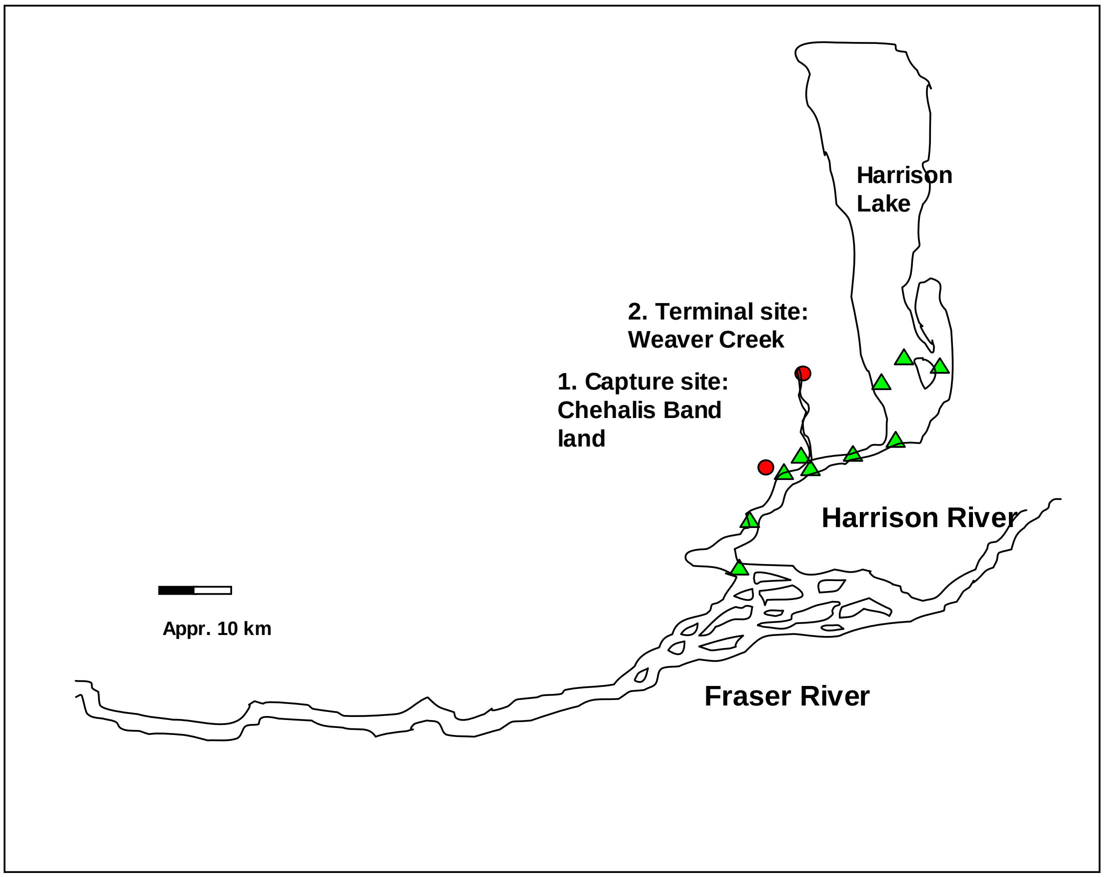
Caption: Overall Map of the Harrison Watershed study area utilized in 2004. Capture site for fish (i.e., the "Park" on Chehalis Band land) and the terminal spawning grounds for the Weaver Creek stock are illustrated on the map.

Figure 2.



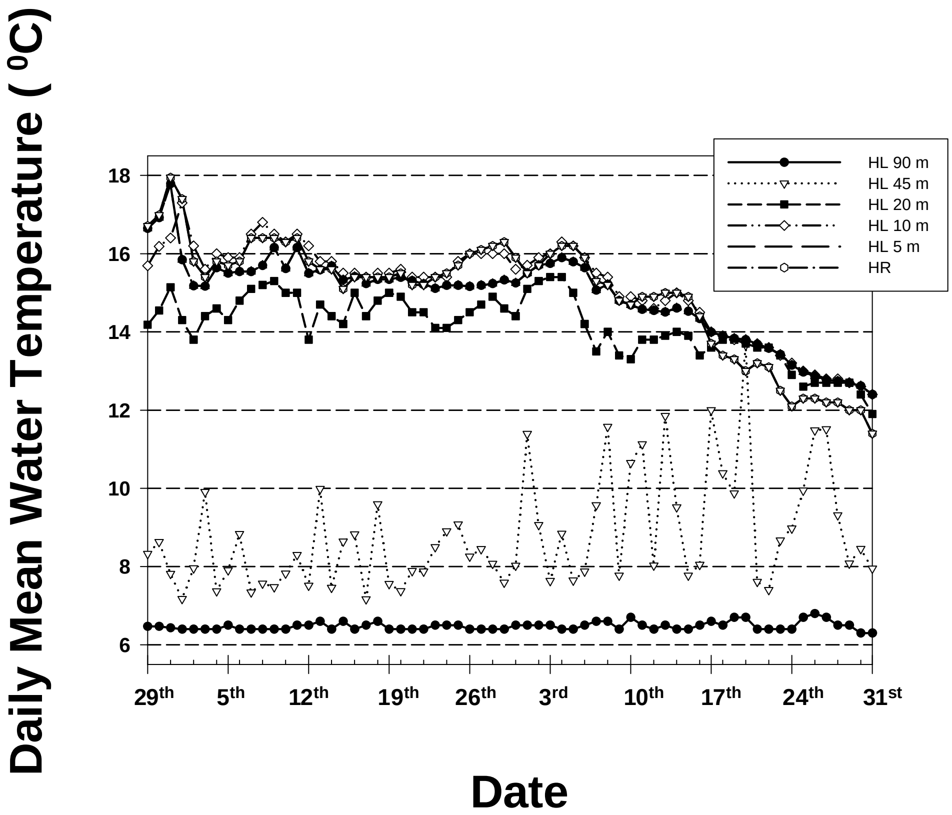
Caption: Map of the lower Fraser and Harrison Rivers showing the locations of fixed radio telemetry receiving stations (triangles).

Figure 3.



Caption: Map of the lower Fraser and Harrison Rivers showing the locations of fixed acoustic telemetry receiving stations (triangles).

Figure 4.



Caption: Daily mean water temperatures for five depths within Harrison Lake, and for a temperature logger mid- Harrison River (29th Aug – 31th Oct 2004). Source: David Patterson (DFO). Depths listed in the legend are in meters.

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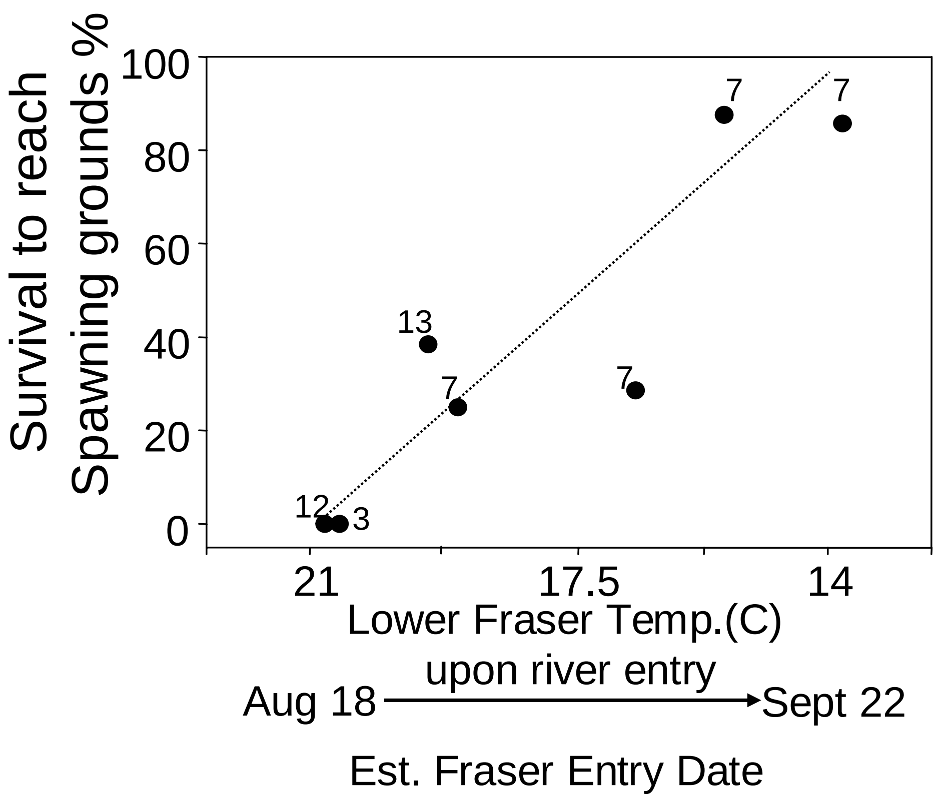
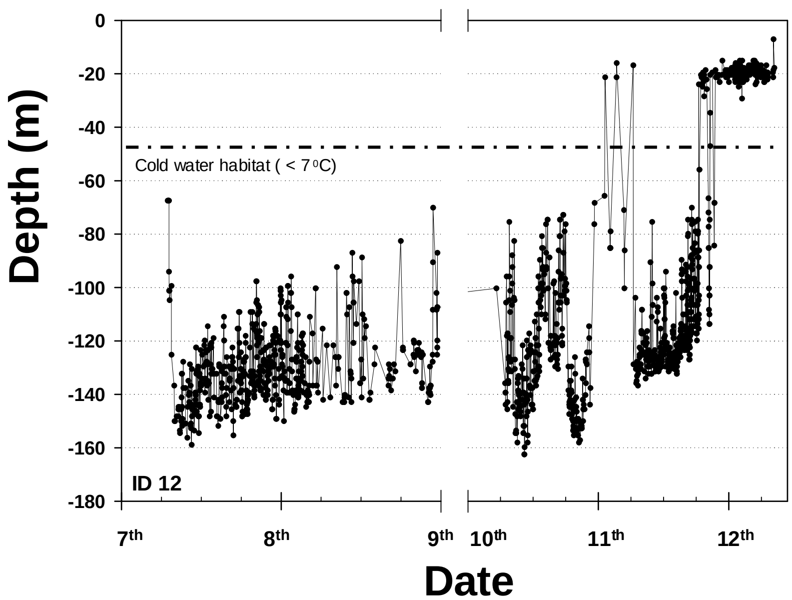
Figure 5.



Caption: Relationship between water temperature (in the lower Fraser River) at time of entry into the Fraser River relative to survival rate. Fish arrived at Harrison River capture location ~ 1 week after entering the Fraser River. Note that early timed migrants that experienced high water temperatures at time of river entry all perished prior to spawning. As water temperature fell, survival improved over the season. Numbers indicate sample sizes. Data are derived from the radio telemetry data for all tagged sockeye salmon.

Figure 6.



Preliminary DD Estimate - *Early-timed Weaver Sockeye that was detected on the spawning ground (ID 12).*

Fraser R.	River Detection		Lake Detection		River Detection		
	Park	Morris Slough	W. Echo Is.	NE Echo Is.	Upper Harrison R.	Morris Lake	Weaver Spawning Chanel
< 1 Sep	1 Sep	2 Sep	16-18 Sep 7-12 Oct	2, 16 Sep 7-12 Oct	12-Oct	13-14 Oct	17-Oct
5 days @ 20°C	1 day @16°C		40 days (34.2 days @ 6.5°C and 5.8 days @14°C) *spent 85.5% of the time deep		2 days @ 15°C		44 days (from release)
100 ATUs	+ 16 ATUs		+ 303.5 ATUs		+ 30 ATUs		= 449 ATUs

Caption: Depth recordings over time for an acoustic/depth tagged sockeye salmon. This early-timed sockeye salmon occupied cold, deep water habitats in Harrison Lake, BC from (7th - 12th Oct, 2004). The majority of the time spent in Harrison Lake were in the cold water habitats. Notice the Sockeye rises to the epilimnion 16 hours prior to re-entry into Harrison River. This is the only early timed fish that we tracked with acoustic telemetry that successfully reached spawning grounds.

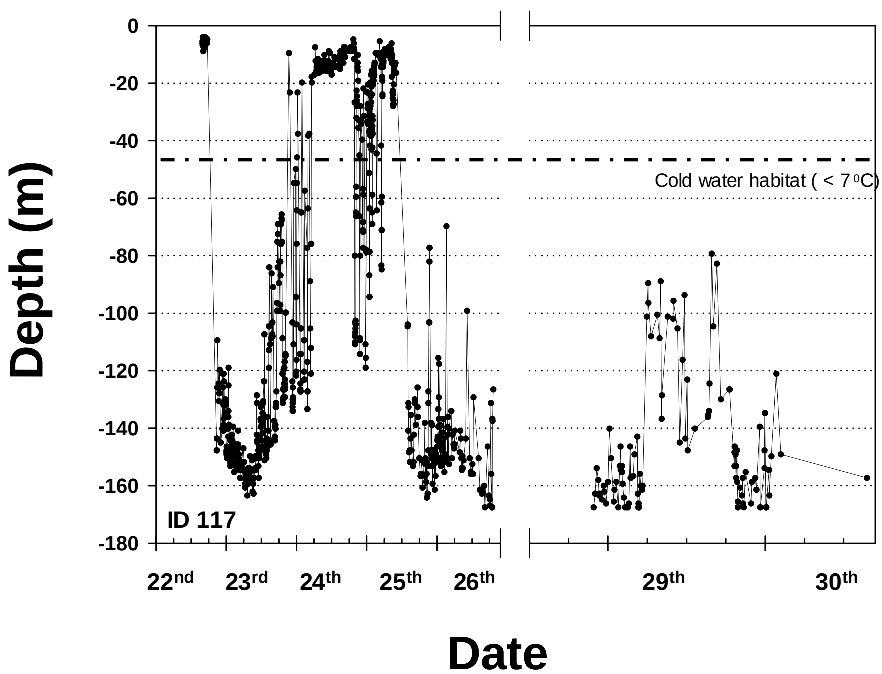
Figure 7.

Preliminary DD Estimate - *Early-timed Weaver Sockeye that died in Harrison L. (ID 5)*

Fraser R.	River Detection			Lake Detection			
	Park	Morris Slough	Upper Harrison R.	W. Echo Is.	Big Silver	NE Echo Is.	
< 1 Sep	1 Sep	1 Sep	1 Sep	1-2 Sept 9-11 Oct	6-7 Oct	2 Sep	11 Oct
5 days @ 20^{o}C	.5 day @16^{o}C			40 days (37.3 days @ 14^{o}C and 2.7 days @ 6.5^{o}C) *spent 93.3% of the time shallow			Mortality
100 ATUs	+ 8 ATUs			+ 539.8 ATUs			= 647.8 ATUs

Caption: Thermal history of an early timed sockeye salmon that died in Harrison Lake, BC. Based on the VR2 receiver records, this sockeye was at depth below 45m for 93.3 % of the time while it was in Harrison Lake. Thus, we reconstructed the thermal history using information on depth and water temperature profiles. In this case, the fish failed to reach spawning grounds and accumulated ~650 degree days.

Figure 8.

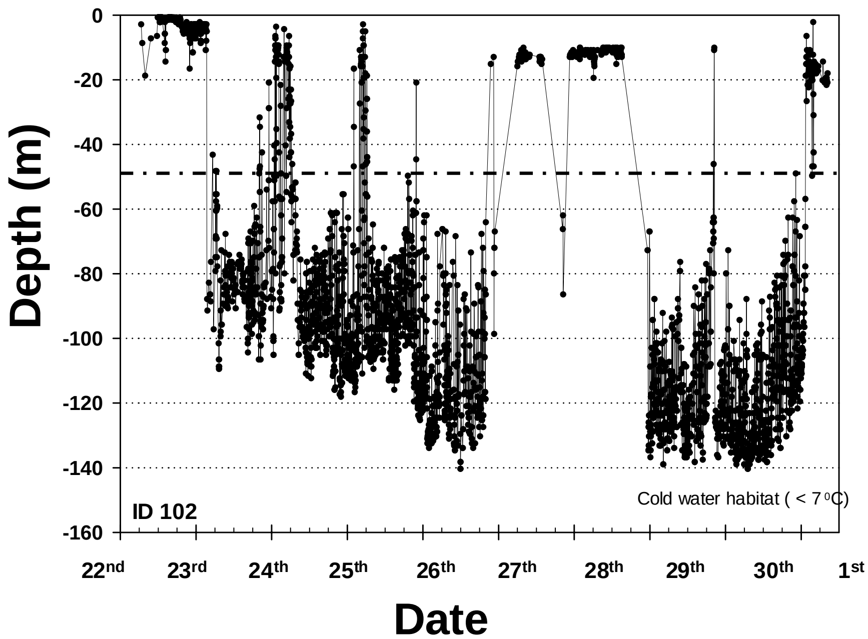


Preliminary DD Estimate - *Normal-timed Weaver Sockeye that was detected on the spawning ground (ID 117).*

Fraser R.	River Detection		Lake Detection		River Detection		
	Park	Morris Slough	W. Echo Is.	NE Echo Is.	Upper Harrison R.	Morris Lake	Weaver Spawning Chanel
< 21 Sep	21-Sep	21-Sep	22-26, 28-30 Sep 13 Oct	22-26, 28, 29 Sep 13 Oct	13-Oct	16-Oct	17-Oct
5 days @ 17.5°C	1 days@16°C		21 days (13 days @ 6.5°C and 8 days @14°C) *spent 61.7% of the time deep		3 days @ 15°C		25 days (from time of release)
87.5 ATUs	+ 16 ATUs		+ 196.5 ATUs		+ 45 ATUs		= 345 ATUs

Caption: Depth distribution of a normal-timed sockeye salmon in Harrison Lake, BC (22nd Sept – 30th Sept, 2004). Based on the VR2 receiver records, this sockeye was at depth below 45m for 67.1 % of the time while it was in Harrison Lake. Thus, we reconstructed the thermal history using information on depth and water temperature profiles. In this case, the fish survived to reach spawning grounds and accumulated ~350 degree days. Note that DD accumulation could be lower if the sockeye depth patterns were consistent for the missing days (27th –28 Sept).

Figure 9.

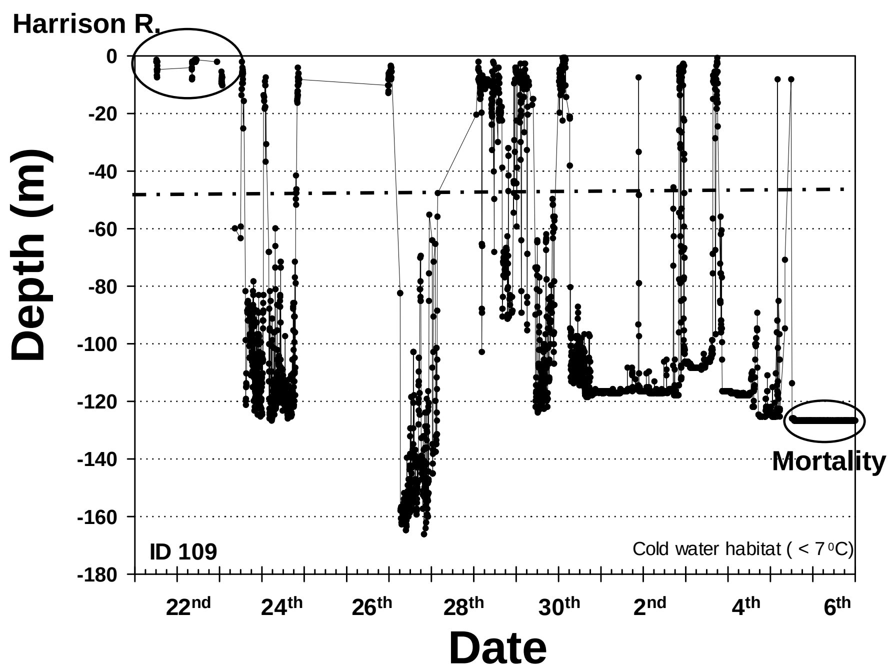


Preliminary DD Estimate - *Normal-timed Weaver Sockeye that was detected on the spawning ground (ID 102)*

Fraser R.	River Detection			Lake Detection		River Detection		
	Park	Morris Slough	Upper Harrison R.	W. Echo Is.	NE Echo Is.	Upper Harrison R.	Morris Lake	Spawning Grounds
< 21 Sep	21-Sep	21-Sep	21-Sep	22 Sep - 1 Oct 22 Oct	23, 25 Sep - 1 Oct 22 Oct	23-Oct	26-Oct	26-Oct
5 days @ 17.5°C	1.5 days@16°C			30.5 days (23.5 days @ 6.5°C and 7 days @14°C) *spent 77.2% of the time deep		3 days @ 15°C		24 days (from release)
87.5 ATUs	+ 24 ATUs			+ 250.8 ATUs		+ 45 ATUs		= 407.3 ATUs

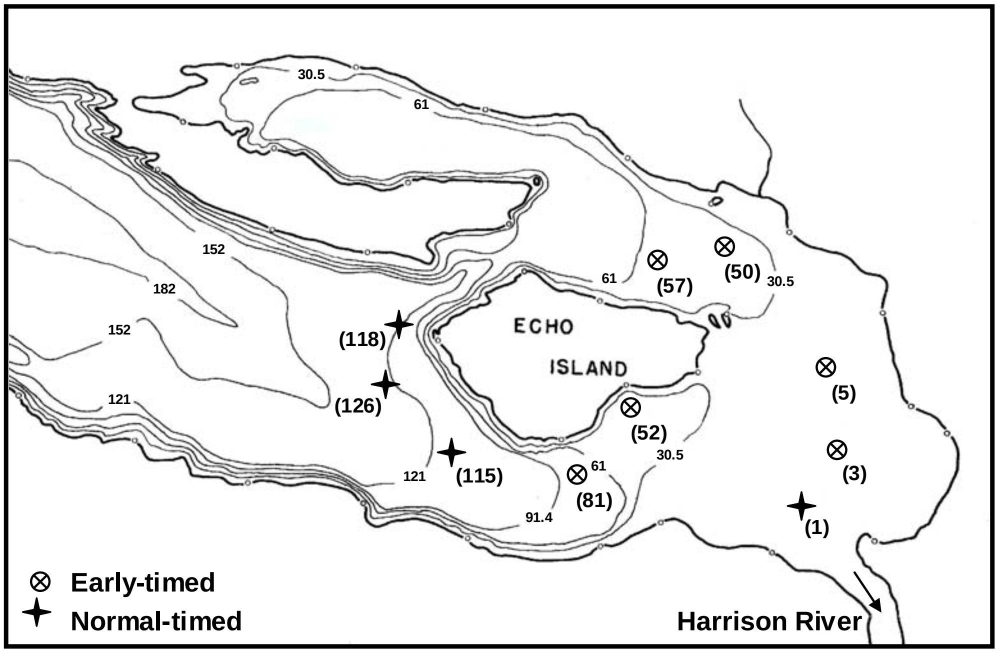
Caption: Depth distribution of a normal-timed sockeye salmon in Harrison Lake, BC (22nd Sep – 1st Oct, 2004). Based on the VR2 receiver records, this sockeye was at depth below 45m for 77.2 % of the time while it was in Harrison Lake. Thus, we reconstructed the thermal history using information on depth and water temperature profiles. In this case, the fish survived to reach spawning grounds and accumulated ~400 degree days.

Figure 10.



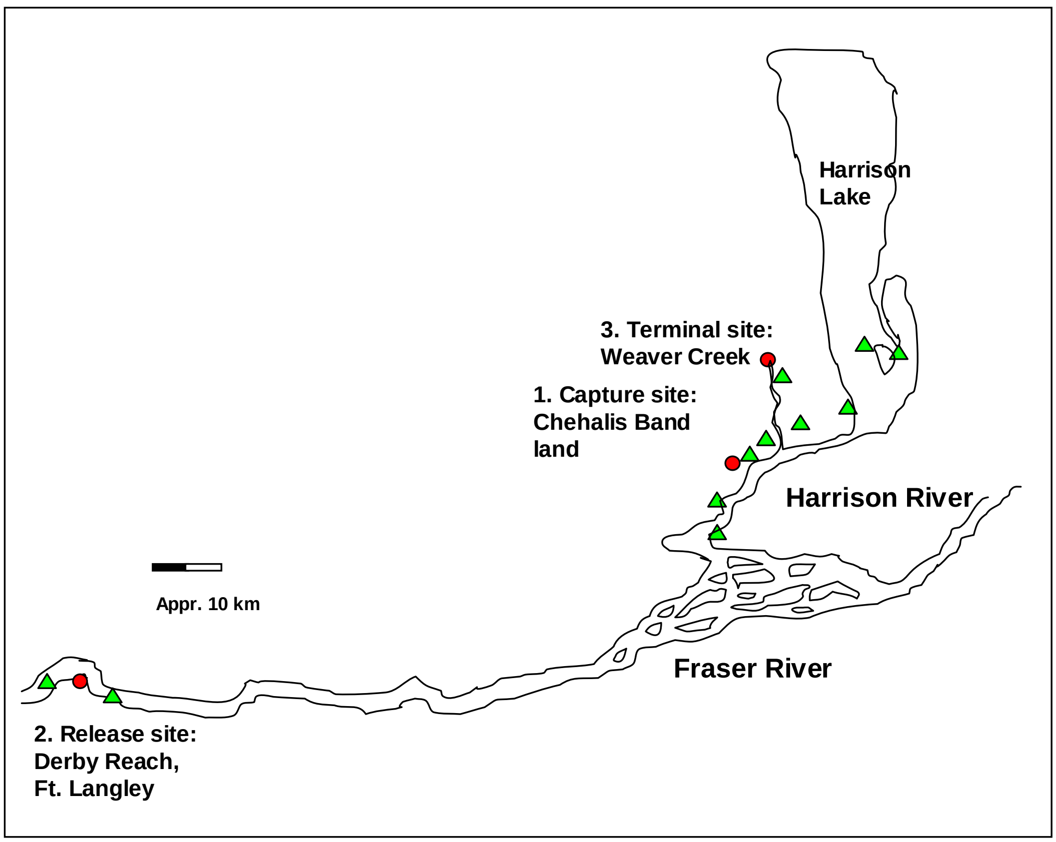
Caption: Depth distribution of a normal-timed sockeye salmon from release in Harrison River to death in Harrison Lake (22nd Sep to 8th Oct, 2004). Once entering Harrison Lake, the fish spends close to 90% of the time in cold, deep water habitats. Mortality occurs on the 6th of Oct and is evidenced by stable depth records.

Figure 11.



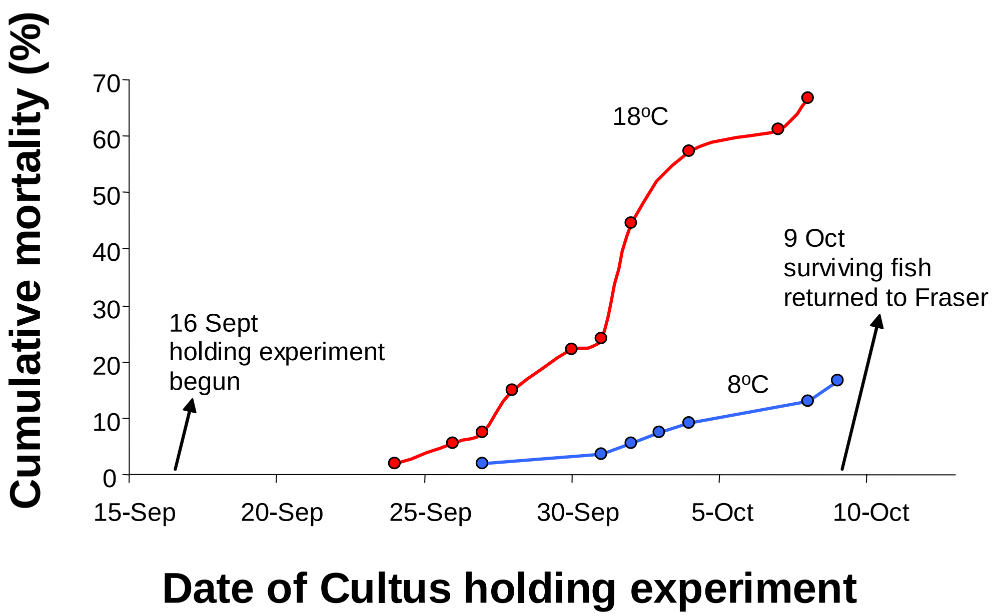
Caption: Examples of some sockeye salmon mortalities in lower end of Harrison Lake (Fall 2004) as revealed by acoustic depth telemetry. Fish locations are approximations and depths are in meters. The map shows that both early and normal-timed sockeye died and sank to the bottom of Harrison Lake. Dead fish were randomly distributed and were found in depths of 1 to 126 meters.

Figure 12.



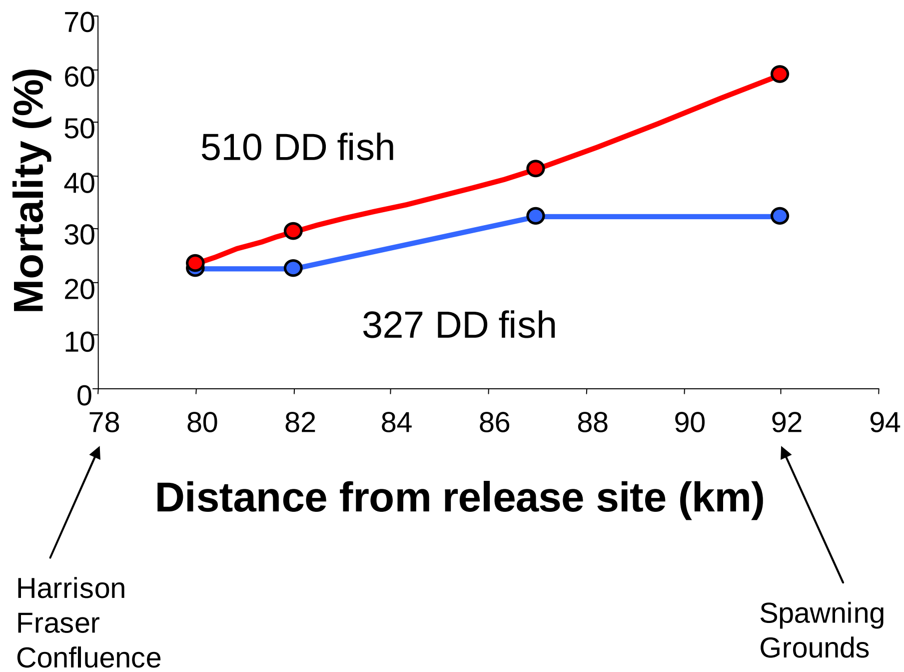
Caption: Map of the lower Fraser and Harrison Rivers showing the capture and release sites (circles) and locations of acoustic receiving stations (triangles) for Project 2.

Figure 13.



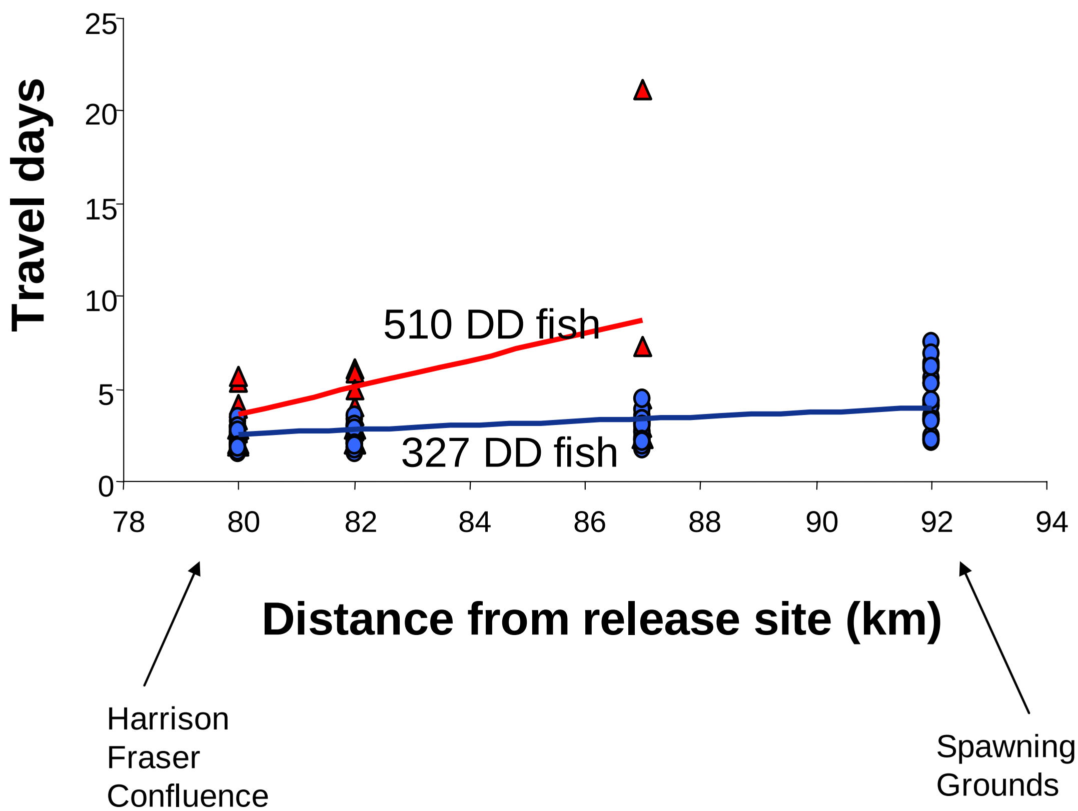
Caption: Temperature related mortality in sockeye salmon over the course of a holding experiment in which thermal regime was increased (18ºC) or decreased (8ºC) from ambient temperatures. The temperatures were chosen to simulate the thermal experience of early and normal timed migrants.

Figure 14.



Caption: Mortality rates for sockeye salmon en route to the Weaver Creek spawning grounds. Fish were exposed to either 8 or 18ºC to alter degree day (DD) accumulation. Fish were released at Albion, BC. Fish movements were assessed using acoustic telemetry.

Figure 15.



Caption: Migratory travel time in days from the Ft Langley release site (approximately 80km downstream from the Fraser-Harrison confluence) to three upriver acoustic receiving stations for sockeye salmon. Triangles represent fish exposed to high water temperatures (i.e., 18ºC; and thus high degree day [DD] accumulation) and diamonds represent fish exposed to low water temperatures (i.e., 8ºC; and thus low DD accumulation).