Passage Efficiency and Migration Behaviour of Salmonid Fishes at the Seton Dam Fishway

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Executive Summary

Fishways have the potential to provide connectivity between habitats located upstream and downstream of barriers provided that fish are able to locate and successfully ascend the fishway. Unfortunately, many of the existing fishways built pre-1990 have not been formally assessed to determine if they actually can effectively pass fish. Our research efforts focused on evaluating the Seton Dam Fishway (SDF) in Lillooet, British Columbia. The SDF was constructed in 1956 as part of the Bridge River Hydroelectric Complex. The fishway is a vertical slot pool configuration enabling fish to swim through the vertical slots and rest in the pools between. To successfully pass through the SDF, fish must swim at least 106.7 m in length and ascend an elevation of 8.22 m (overall grade of 7.5%) by passing through 32 vertical slots (thus encountering an elevation change of ~ 0.23 m per pool). A series of upstream stop logs are used to control flow and a supplementary flow is used to enhance attraction to the entrance. An electronic resistivity counter is used to enumerate rates of upstream passage and to date, has served as the only source of information of fishway performance. Here, we describe the findings of a study conducted in 2005 to evaluate the SDF and associated infrastructure and operations on the migration biology of upstream migrating Pacific salmonids.

We addressed five specific objectives in this study; 1) quantify the attraction efficiency of the fishway for adult migrating sockeye salmon; 2) quantify the passage efficiency and areas of difficulty for migratory salmonids; 3) evaluate if fishway passage has consequences on adult sockeye salmon that affect their ability to reach terminal spawning locations but are not detectable until after they have left the fishway; 4) assess the potential role of the fish resistivity counters on fish passage, particularly as it related to large fish; 5) assess the potential impacts of Cayoosh flow dilution and the Carpenter Lake inflow from power generation on adult sockeye

salmon behaviour and thermal experience in Seton Lake. Each objective is briefly described below.

1. To assess the attraction efficiency of the SDF we employed a combination of radio telemetry with physiological sampling of migrating pink and sockeye salmon. Of thirty sockeye salmon captured in the fishway, and released downstream of the fishway with radio transmitters, 23 successfully re-located and passed the fishway. The remaining fish were presumed to have fallen back downstream. There was no difference in the amount of time that sockeye spent in the tailrace from release for either those individuals that passed or fell back. Nine pink salmon were captured in the fishway, implanted with radio transmitters, and released downstream of the fishway - only two of those fish successfully re-located the fishway. Occasionally sockeye and pink salmon would become entrained in the radial-gate spillway on the north side of the dam. For sockeye, we also conducted physiological analyses and revealed that measures of physiological stress (i.e. lactate, glucose, Na+, osmolality, hematocrit) did not statistically differ between sockeye that were able to successfully locate and pass the fishway, and those that did not. However, sockeye that fell back downstream were generally larger than those that were able to locate and pass the fishway suggesting possible size-specific migratory challenges.

2. We used a combination of electromyogram telemetry (EMG), radio telemetry, and physiological sampling to determine if there were areas of passage difficulty within the fishway by capturing fish at the top of the fishway and then releasing them in pool number three. Seven of fifteen EMG tagged sockeye successfully re-ascended the fishway on their first attempt following release, and all exited the fishway at the top. Of the eight that moved out of the fishway, two re-entered and successfully ascended and exited the fishway on later dates. The remaining six that failed to re-enter the fishway, fell back down Seton Creek. All six of the pink salmon carrying EMG transmitters fell out of the fishway following release and generally held

position just downstream of the fishway in Seton Creek. After several days of holding, these fish all moved downstream, dropping back from Seton Creek to the Fraser River. Average time required to ascend the fishway was 63.5 ± 7.7 min (mean ± S.E.) for sockeye. Mean swim speeds, estimated from EMG pulse intervals, exhibited by individuals during ascent varied substantially from as low as 2.6 $cm \cdot sec^{-1}$ to as high as 86.0 $cm \cdot sec^{-1}$. From the EMG data recorded for the fish that successfully passed on the first attempt, two separate ascent strategies were apparent and were reflected in the mean swim speeds exhibited by fish. One group of fish demonstrated a more conservative swim speed strategy, only employing fast swim speeds (>100 $cm \cdot sec^{-1}$) during upstream pool-to-pool movements with few other exceptions. Another group of fish appeared to be less discriminate in utilizing higher swim speeds, and frequently exceeded 100 $cm \cdot sec^{-1}$ throughout their passage. Physiological analyses revealed that fish that failed to re-ascend on their first attempt had lower levels of Na+ in their plasma - an indication of physiological stress.

3. Using an acoustic telemetry array in Seton and Anderson Lakes, we evaluated if fishway passage has consequences on sockeye salmon that affect their ability to reach terminal spawning locations but are not detectable until after they have left the fishway. In total, 50 sockeye salmon were tagged with acoustic transmitters, of which 30 were Gates stock and 20 were Portage stock. The Gates sockeye salmon experienced high mortality during their migration from the SDF to spawning grounds. Of thirty Gates fish tagged at SDF, only 14 fish reached terminal spawning grounds. Of the fish that failed to reach spawning grounds, upon release two passed downstream through the fishway, sluice, siphons, or the power generation canal. Ten fish were classified as in-lake mortalities as evidenced by manual tracking or automated telemetry station positions and the remaining 4 fish may have been harvested. Conversely, mortality rates of Portage sockeye were relatively low with only 2 or 20 fish not reaching terminal spawning

grounds. Combined physiological analyses revealed that fish that were successful in reaching spawning grounds had relatively similar physiological and energetic characteristics to those that failed to reach spawning grounds, aside from plasma lactate concentration, an indication of physiological stress, which was higher in failed migrants.

4. We assessed the potential role of the fish resistivity counters on fish passage, particularly as it related to large fish using videography and visual assessments. Although we were unable to study Chinook salmon because of low run sizes, we were able to evaluate general impacts of the counters on the broader fish community. Interestingly, estimates of fish passage out of the fishway from the video playback were inconsistent with the values recorded by the counter. Early in the season, the counter over-estimated fish abundance, and later in the season, the counter drastically underestimated passage. Visual observations suggested that the vast majority of fish approached the counters from the lower depths of pool 32. Over the course of approximately 30 hrs of video playback, no observations of large fish failing to pass a counter occurred. During August 2005, debris accumulation varied between each of the six counter tunnels. The larger tunnels appeared to accumulate more debris more frequently than the smaller tunnels. Debris typically consisted of loose vegetation and small woody debris, however, in mid to late September we observed accumulations of pink salmon carcasses on the fishway counters. At times, upstream passage of fish was blocked by debris.

5. We assessed the potential impacts of Cayoosh flow dilution and the Carpenter Lake inflow from power generation on adult sockeye salmon behaviour and thermal experience in Seton Lake using thermal loggers deployed in Seton Lake, thermal loggers deployed on fish, and behavioural observations from the acoustic telemetry array. Almost all of the fish released at Seton Dam were subsequently detected on the receiver in the vicinity of the Cayoose outflow. The mean time that fish spent in this area was approximately 4 hours, but was significantly less

than the time that fish spent at an upstream receiver outside of the influence of the Cayoose outflow. Fish spent substantially more time in the vicinity of Receiver 5 than in the vicinity of Receiver 4. Thermal records recovered from two fish that had thermal loggers and which reached spawning grounds provided no evidence that fish were residing in the region of the Cayoose inflow, despite the fact that water temperatures were cooler and more variable there (at a depth of 1 m) than at the water surface near the fishway. However, there was some evidence that fish spent time in the vicinity of the Carpenter lake inflow. The mean duration that fish were in the vicinity of Receiver 8 while they were alive and prior to spawning was 31.8 ± 16.1 hrs (mean ± S.E.). At a depth of 20 m, the Carpenter Lake inflow was the coolest region of Seton Lake relative to the area near the Portage Creek inflow or the eastern end of the Seton Lake.

Based on our findings, we developed several recommendations; 1) Increase visitation to the fishway during key migratory periods in order to ensure that it is functioning and free of debris; 2) Reconsider the use of the resistivity counters at the fishway exit pool; 3) Daily SDF fish counts should be annotated with details on blockage and debris accumulation; 4) Improve trash racks upstream of counter and/or fishway exit to reduce blockage; 5) Consider modifying the wall that separates the radial gate spillway from the main spillway to minimize entrainment of fish in radial gate spillway; 6) Address the issue of fishway entrance attraction through further study and possibly operation/structural changes such as testing attraction under higher and lower spill rates, than occurred during our study, and modifying the arrangement of the baffle blocks to alter downstream flows; 7) Conduct detailed thermal modeling on the plume dynamics of the Cayoose inflow and the Carpenter Lake inflow to assess their potential influence on fish migration.

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General Introduction

Fishways are important enhancement and mitigation techniques to restore or improve passage of fish across barriers such as dams constructed to generate electricity (Odeh 1999). Fishways have the potential to provide connectivity between habitats located upstream and downstream of barriers. During the construction of the Bridge River Hydroelectric Complex, the Seton Dam was developed on the lower reaches of the Seton River, effectively blocking passage of fish. A fishway was constructed in 1956 that was intended to enable fish to move freely upstream and downstream of the dam. The fishway is a vertical slot pool configuration enabling fish to swim through the vertical slots and rest in the pools between. A series of upstream stop logs are used to control flow and a supplementary flow is used to enhance attraction to the entrance. An electronic resistivity counter is used to enumerate rates of upstream passage and to date, has served as the only source of information of fishway performance. In addition to the ecological benefits of enabling fish passage through the dam, small but important food fisheries occur annually upstream of the dam near terminal salmon spawning grounds at D'Arcy (Gates Creek) and Seton Portage (Portage Creek).

Recently, there have been considerable efforts to evaluate the passage efficiency of fishway facilities across North America in an effort to maximize fishway passage (Odeh 1999). It has often been found that large numbers or certain sizes or species of fish are unable to ascend fishways but scientific information is generally lacking for most fishways. There have been few rigorous attempts to do this on large rivers in British Columbia. One of the few was by researchers from the University of British Columbia who assessed salmon passage at the Hell's Gate vertical slot fishways on the Fraser River for one stock of salmon in 1994 (Hinch and Bratty 2000). They found that over 30% of sockeye during early July were unable to pass and that the fishway entrance was clearly the primary obstacle.

To successfully pass through the 107 m long Seton Dam Fishway (SDF), fish ascend an elevation of 7.4 m (overall grade of 6.9%) by swimming through 32 vertical slots (thus encountering an elevation change of ~ 0.23 m per pool). Flows can range between 0.85 m^3 and ~1.3 m^3 within and among years. Current assessments at SDF focus on the number of fish recorded exiting (i.e. ascending) the fishway using an electronic counter. These data provide no information on numbers of fish unsuccessful at passage, a phenomenon which occurs because: 1) fish may be unable to locate the fishway entrance and thus are unable to attempt passage; or 2) fish locate the entrance but are unable to successfully ascend the fishway. Knowledge of both attraction (proportion of fish that locate the fishway entrance relative to those that are attempting to move upstream) and passage efficiency (proportion of fish that enter and successfully ascend relative to those that enter the fishway, but are unsuccessful at reaching the end) are both critical to understanding the effectiveness of fishways (Bunt et al. 1999). This information can be used to identify often-simple design alterations (such as entrance modifications) that enhance both attraction and passage efficiency, hence lessening the footprint of the barrier (e.g., Bunt 2001). Anecdotal information suggests that sockeye salmon may be attracted to discharges at SDF from the radial gate distracting them from the fishway entrance (Andrew and Geen 1958).

Our overall project goal was to evaluate the performance of SDF for migrating adult salmonids in order to identify locales where attraction or passage efficiency was hampered so that we could recommend ways to improve both. To attain our goal, we had three specific objectives: 1) quantify the attraction efficiency of the fishway for adult sockeye salmon; 2) quantify the passage efficiency and areas of difficulty for all migratory salmonids; and 3) evaluate if fishway passage has consequences on sockeye salmon that affect their ability to reach terminal spawning locations but are not detectable until after they have left the fishway. During the review of this proposal by the BCRP technical committee, two additional issues were identified that we were able to incorporate without the need to alter the original budget. Specifically, the technical review committee requested that we also: 4) assess the potential role of the fish resistivity counters on fish passage, particularly as it related to large fish and 5) assess the potential impacts of Cayoosh flow dilution (at downstream end of Seton Lake) and the Carpenter Lake inflow from power generation (at the upstream end of Seton Lake) on adult behaviour and thermal experience in Seton Lake.

Study Objective Overview

1) quantify the attraction efficiency of the fishway for adult migrating sockeye salmon

2) quantify the passage efficiency and areas of difficulty for migratory salmonids

3) evaluate if fishway passage has consequences on adult sockeye salmon that affect their ability to reach terminal spawning locations but are not detectable until after they have left the fishway

4) assess the potential role of the fish resistivity counters on fish passage, particularly as it related to large fish

5) assess the potential impacts of Cayoosh flow dilution and the Carpenter Lake inflow from power generation on adult sockeye salmon behaviour and thermal experience in Seton Lake

Study Site Description

Our study site focuses primarily on the Seton Dam and its fishway which is located approximately 5 km southwest of Lillooet, B.C. (Figure 1), however we also assess areas upstream of SDF in terms of salmon migratory passage through Seton and Anderson Lakes, and assess spawning ground arrival by migrants at the Gates Creek spawning channel, and at the Portage River, located in D’Arcy, and Seton-Portage, respectively, B.C (Figure 2). The Seton Dam is a diversion dam located 760 m downstream of Seton Lake, and spans Seton Creek, a tributary of the Fraser River (Figure 3). The Seton Dam is approximately 7.6 m in height and consists of a radial gate spillway, five siphon spillways, a fish water sluice, and a vertical-slot fishway (Figure 4). A canal extends from the diversion dam 3.8 km to a powerhouse located on the Fraser River, downstream of the confluence of the Fraser River and Seton Creek (Figure 4). The downstream end of the canal feeds into a 5.5 m diameter penstock that runs an additional 113 m to a single 58,500 horsepower turbine located within the powerhouse. Operation flow is provided in part from water diverted from neighboring Cayoosh Creek, which is routed through a 490 m tunnel from a dam on Cayoosh Creek to Seton Lake. Additional water is diverted from the Bridge River watershed, located adjacent to the Seton basin. Additional details on the Seton Dam can be found in Andrew and Geen (1958).

During salmon spawning migrations, a minimum flow of 11.3 $m^{3}\cdot s^{-1}$ is released from Seton Dam into the channel of Seton Creek. During other times of year, this minimum is reduced to 5.7 $m^{3}\cdot s^{-1}$. Historic anadromous fish populations of sockeye (*Oncorhynchus nerka*), Chinook (*O. tsawyt*scha), pink (O. *gorbuscha*), and coho (*O. kisutch*) salmon, along with steelhead (*O. mykiss*) had spawning grounds upstream of the Seton Dam (see SRWP). At present, sockeye are the most numerically dominant species that spawns upstream of the dam, although there is growing interest in restoring endemic runs of Chinook salmon. Pink salmon also regularly ascend the fishway, but spawning locations are limited. Rainbow trout (*O. mykiss*) and bull trout (*Salvelinus confluentus*) are other migratory salmonids also present downstream and upstream of SDF.

Study Animals

Choice of study animals was determined by biological and logistic constraints. Specifically, we focused our research efforts on sockeye salmon as a model species due to their known spawning ground destination and their importance to the economy, the environment, and First Nations culture. There are two populations or stocks of sockeye which spawn upstream of SDF. The Portage stock spawns in the Portage River, which connects Seton Lake to Anderson Lake, and the Gates Creek stock spawns in Gates Creek and in an artificial spawning channel located next to the creek, both of which are situated at the western end of Anderson Lake (Figure 2). Despite spawning predominantly downstream of SDF, some adult pink salmon can spawn upstream of SDF. During our study, pink salmon were extremely abundant in Seton Creek and many were ascending the fishway, thus we incorporated this species into our research activities. Our initial proposal also included an interest in examining a larger bodied species (e.g., adult Chinook salmon) as they may encounter difficulty navigating in the fishway and may be less able than smaller fish to reach the top (see Seton River Watershed Plan (SRWP)). In addition, there was some suggestion (discussed in the SRWP) that adult Chinook salmon could become “stuck” in the fishway resistivity counters. However, despite being at SDF almost daily during August and September, we never observed a single Chinook salmon either visually or using underwater videography in the fishway. We also were interested in studying other endemic salmonids such as bull trout and rainbow trout. However, as with Chinook, we were unable to capture these animals in the fishway. We were able to collect some opportunistic observations on the presence of rainbow and bull trout (as well as catostomids) using underwater videography.

Fishway Description

The SDF is a vertical slot type, consisting of a baffled concrete channel extending a total distance of 107 m. It consists of 32 pools and makes two 180^o turns (Figure 5). At each pool, the fishway ascends 0.23 m in elevation, for a total elevation gain of 7.4 m at SDF. This equates to an overall grade of 6.9 %. Typical pools found between vertical baffles within the fishway channel measure

2.4m in width by 3 m in length. Vertical slot fishways are designed to create complex flow patterns that improve the dissipation of energy within each pool (Clay 1961). These complex flows include low velocities, creating areas of refuge for fish to use during fishway ascent. Water passes among pools via vertical slots measuring 41 cm in width, with maximum flow velocities of roughly 1.3 $m^{3}\cdot s^{-1}$. Water depth within the fishway is approximately 1.5 m, and because the vertical slot extends to the bottom of the fishway channel, fish may pass between pools at any chosen depth. The two pools found at points where the fishway makes a 180^{o} turn are roughly twice the length of the regular pools and are characterized by a greater availability of low-velocity refuge areas.

Fish are attracted to the entrance of the fishway by flows released through the fish-water sluice and the five siphon valves (Figure 4). The siphon valve located closest to the fishway is positioned slightly lower than the other siphons in order to create flows that attract fish as close as possible to the fishway entrance. The fish-water sluice provides further attraction flow via water discharged through a gated opening submerged adjacent to the fishway entrance. Fish that have successfully ascended the fishway must pass through an automated fish counter at the top of the fishway before moving into the fore bay of Seton Dam. The fish counter consists of six separate slots for fish to move through; four smaller units measuring approximately 10 X 18 cm and two larger units measuring approximately 20 X 24 cm. Within each slot, a series of copper electrodes, when triggered in order, record a passage event. Data recorded by the fish counter provide an estimate of the spawning run size and timing.

Objective 1. Quantify the attraction efficiency of the fishway for migratory salmonids.

Rationale

For a fishway to be useful, fish must first be able to locate the entrance. To minimize migration delay, fishways and associated infrastructure are designed to efficiently attract fish to the fishway entrance and minimize false attraction. This is often accomplished by releasing water adjacent to the fishway entrance (Clay 1961; Odeh 1999). However, the nature of flows released specifically for attracting fish is poorly understood (Northcote 1998), and migration delays may result from non-optimal attraction flow arrangements. While delay can make fish more susceptible to predation as they amass downstream of a fishway (Gowans et al. 2003), there are other issues associated with delay that may affect migration success. For example, long periods of delay on fish with low energy reserves or with high levels of physiological stress may prevent them from successfully reaching spawning grounds. To assess the attraction efficiency of the SDF we have employed a combination of radio telemetry with physiological sampling of migrating Pacific salmon.

Methods

Fish capture and handling

Attraction efficiency was primarily assessed through the use of positional radio telemetry. Sockeye and pink salmon were both used in this component of our research. Sockeye salmon from the Gates Creek stock were captured and tagged during from August 9 to September 22, 2005. Pink salmon were captured and tagged from September 5 to 13, 2005. Despite employing various netting techniques, we were unable to safely capture adult sockeye immediately downstream from the Seton Dam in the Seton River, therefore, all fish used in our study were captured in the fishway. Fish were caught by large dip nets in the upper pools of the SDF, and most from the resting pool prior to the fishway exit. Upon capture, fish were immediately transferred to a V-shaped padded trough filled with water. The trough was lined with foam, contained an integrated measuring tape, and was supplied with flowing fresh 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 capture and tagging team consisted of at least three individuals. Members of our research team at the University of British Columbia pioneered a novel technique for linking individual physiological status with behaviour and fate. We have used this approach extensively for assessing the migration biology of sockeye salmon (Cooke et al. 2006; Young et al. 2006) and have shown that these handling and sampling approaches have no negative effects on salmon migration behaviour, survival or spawning (Cooke et al. 2005). We briefly summarize these approaches below.

Biopsy and Tagging Procedure

The first step involved restraining the fish in the trough. During preliminary evaluations we determined that using two sets of wet hands was the best method to restrain the fish without excessive removal of slime or scales. One individual always held the head of the fish, gently covering the eyes and keeping the head down. A second individual held the caudal peduncle region and placed their other hand on the mid-section of the fish. The two individuals restraining the fish were positioned on either side of the trough. When the fish was restrained, the third individual stood at the caudal end of the trough and gripped the caudal peduncle region with one hand. At this point, the other individual restraining the caudal region moved their hand slightly anterior to provide room for the hand of the blood sampler, but while still assisting with restraining the tail. Using their other hand, the vacutainer syringe (1.5”, 21 gauge) was aligned with the caudal hemal arch and when the fish was still, it was plunged into the caudal vessel. Detailed descriptions and diagrams of caudal sampling blood from fish can be found in Houston (1990). The vacutainer (3 ml) was then activated, usually resulting in the immediate collection of blood. On some occasions, the fish would move, bending the needle or terminate the vacuum, or blood did not immediately begin to enter the vacutainer. If subtle adjustments to the position of the syringe did not remedy the problem, the blood sampler then used a new, pre-rigged vacutainer and syringe. If the blood was not drawn within 1 minute, the fish was excluded, no transmitter was implanted, and the fish was released. If successful, the blood sampler left the caudal region to place the vacutainer in an ice water slurry and to dispose of the sharp. The individual restraining the tail applied light pressure to the puncture site to facilitate clotting. Next, a tissue sample was removed from the adipose fin using a hole punch and placed in ethanol (for DNA analysis). The length of the fish was also recorded (Total length in mm). Finally, we used a micro-wave meter to assess somatic lipid concentrations (Distell Fish Fatmeter model 692, Distell Inc, West Lothian, Scotland, UK; See Hendry & Beall, 2004; Crossin & Hinch, 2005). This hand-held device houses a microwave oscillator that emits a low powered wave (frequency, 2 GHz, 2000 MHz; power, 2 mW) that interacts with water in the somatic tissues. Drawing from the strong, inverse relationship between the water and lipid content in fish tissues, microwave sensors convert water concentration to estimates of lipid concentration. The fat probe requires that the fish be held slightly out of water, straight and generally relaxed. The probe was placed on the left side of the fish in two locations to obtain measurements of the energetic status. Data collected from sockeye by the fat probe were converted to estimates of gross somatic energy (GSE) density following relationships described in Crossin and Hinch (2005). For pink salmon, relative measures of energy density were taken using the fat probe, however, no relationships have been established with actual GSE; therefore no data conversions were made for these fish.

The final step of the biosampling and tagging process involved the insertion of telemetry transmitters in the stomach using a plastic tag applicator (Eiler, 1990; Ramstad & Woody, 2003). We used two sizes of positional tags, both manufactured by Lotek Wireless, Newmarket, Ontario. Larger transmitters were 49 mm in length by 15 mm in diameter, weighed 12.5 g in air and were inserted into larger fish. The smaller transmitters were 43 mm in length by 11 mm in diameter, weighed 7.9 g in air, and were inserted into smaller fish. Following tag application, fish were transferred from the sampling trough to a 100 l cooler full of fresh water drawn from the fore bay of the dam. Fish were then transported to a location < 3 m downstream of the fishway and approximately 15 m downstream of the fishway entrance (see Figure 5), where they were released into low velocity flow. Upon release, all fish immediately began actively swimming.

Tracking

Following release, fish were manually tracked using radio telemetry receivers (Lotek Wireless, model SRX_400) and three-element Yagi antennas. Time-stamped notes were taken with regards to fish location. Fish were manually tracked throughout the day, while an array of two receivers- one positioned at the top of the fishway, and one at the bottom were deployed overnight. These were positioned at the end of each day with antennas arranged so as to detect and record tagged fish movements specifically through the top and bottom pools of the fishway. This allowed us to determine with certainty whether a fish had moved through the fishway overnight. Radio-tagged fish that disappeared from the tailrace of the Seton Dam, and did not show up on overnight recordings were presumed to have moved downstream and would be referred to as ‘fall backs’.

Tracking of individual fish continued until they either passed upstream of the dam or fell back downstream greater than 1 km.

Physiological Analyses

Plasma ion (Cl-, Na+), lactate, glucose and osmolality measurements followed the procedures described by Farrell et al. (2001). After centrifugation in the field, plasma samples were immediately placed on dry ice for temporary storage. After transfer from dry ice, samples were subsequently stored at –80°C prior to analysis in the laboratory. Plasma lactate and glucose concentrations were measured using a YSI 2300 STAT Plus glucose and lactate analyzer (YSI Inc., Yellow Springs, Ohio). Plasma chloride concentrations were measured in duplicate using a model 4425000 digital chloridometer (Haake Buchler Instruments, Saddle Brook, N.J.). Concentrations of plasma sodium and potassium ions were measured using a model 510 Turner flame photometer (Palo Alto, Calif.). Plasma osmolality was measured using a model 5500 vapour pressure meter (Vapro, Wescor, Logan, Utah). Detailed description of all assays presented here including the inter-assay variability and quality control criteria are provided in Farrell et al. (2001).

Data analysis

Data from field notes were transcribed and imported into a data-base. Detailed telemetry records providing information on fish behaviour were reconstructed using information for manual and fixed tracking. We assessed whether any relationships existed among the amount of time fish spent in the tailrace vicinity following release and their physiological condition using Pearson correlation analyses.

Results

Sockeye salmon

Thirty sockeye salmon were released with radio transmitters. Of these, 23 successfully located the fishway, ascended it, and exited the most upstream resting pool, five fish failed to enter the fishway and were presumed to have fallen back downstream, and two fish were still in the fishway tailrace by the time that the study concluded. Frequent searches for tagged fish that fell back downstream in Seton Creek rarely resulted in any detections, suggesting that fish that fell back likely re-entered the Fraser River. Following release, sockeye salmon typically took-up position in the main spillway of the dam, just beyond the extent of the whitewater caused by water spilled from the dam (Figure 5). Frequent forays into the whitewater were common amongst most sockeye, generally followed by downstream movements into calmer water. Occasionally sockeye would become entrained in the radial-gate spillway on the north side of the dam. Here, fish could spend several hours before moving back into the main spillway area.

For 27 of the radio tagged sockeye we were able to obtain accurate estimates of the total amount of time that fish spent downstream of the Seton Dam from release until passage or fall back. No difference was observed in the amount of time that sockeye spent in the tailrace from release to either passage (n = 22) or fall back (n = 5) (18.02 ± 4.72 hrs vs. 21.65 ± 10.33 hrs respectively, mean ± SE; Wilcoxon test; $Z = 0.094$, $P = 0.925$). Regardless of fate, individual sockeye were actively tracked on average for 10.23 ± 1.56 hrs (mean ± SE; Table 1). In addition, there was no difference in the proportion of time spent in the radial gate spillway for fish that were able to locate the fishway and those that fell back (Pass versus Fall back [mean ± S.E.] 0.728 ± 0.309 % vs. 1.450 ± 0.757 %, Z = 1.465, df = 26, P = 0.143).

Between August 10 and 23 of 2005, 15.8 $m^3.s^{-1}$ were spilled from the Seton Dam as attraction water. From August 23 to September 6, 2005, this was decreased to 12.7 $m^3.s^{-1}$. In order to assess whether this change in discharge had any influence on sockeye attraction, we compared the times spent in the tailrace by radio tagged fish that had been released and tracked during each of the two aforementioned periods. No difference was detected between the two groups of sockeye that corresponded with the higher discharge (n = 14) and those corresponding with the lower discharge rate (n = 6; Wilcoxon test; $Z = 0.866$, $P = 0.387$).

Pink salmon

Nine pink salmon were implanted with radio transmitters. Of these, two successfully located the fishway, and seven fell back downstream; none of the fall-backs were further detected. Accurate estimates of the total time spent downstream of the Seton Dam in the tailrace vicinity were obtained for all radio-tracked pink salmon. Of the two pink salmon that were able to locate and pass through the fishway one spent 4.8 hrs in the dam tailrace, while the other spent 46.9 hrs. Of the seven that fell back downstream, each spent, on average, 104.3 ± 28.9 hrs (mean ± S.E.) in the tailrace. In general, following release, pink salmon would move slightly downstream (<100 m) and hold position in slower moving water (Figure 4). Occasional forays towards the dam were not uncommon during the days immediately following release, however, such behaviour would typically cease thereafter. Pink salmon that approached the dam would often become entrained in the radial-gate spillway located on the North side of the Seton Dam (see Figure 5) where they would remain for several hours before moving back downstream. Individual pink salmon were actively tracked on average for 16.22 ± 3.72 hrs (mean ± SE; Table 1).

Physiology

Overall, measures of physiological stress (i.e. lactate, glucose, Na+, osmolality, hematocrit) did not statistically differ between sockeye that were able to successfully locate and pass the fishway (n = 23), and those that did not (n = 5; Table 2). Gross somatic energy density did not differ among these fish, however, fish that fell back downstream were generally larger than those that were able to locate and pass the fishway (t_{25} = -2.514, P = 0.019). For sockeye salmon, no significant correlations existed between time spent in tailrace and any of the physiological variables we measured (Table 3). Because only two radio-tagged pink salmon were able to locate and ascend the fishway, we could not statistically compare successful with failed pink salmon, however, a summary of the physiological data are provided in Table 4.

Discussion

Sockeye and pink salmon displayed different behaviours in the tailrace of the Seton Dam. Specifically, individual sockeye salmon were able to locate the fishway entrance more frequently than pink salmon. This may be partially due to the fact that these sockeye have historic spawning grounds found upstream of the SDF whereas spawning channels downstream of SDF are available to and commonly used by pink salmon. Moreover, previous studies comparing migratory behaviour and energetics have observed fundamental differences between these two species of Pacific salmon (Hinch et al. 2002; Standen et al. 2002; Crossin et al. 2003, 2004; Hinch et al. 2005; MacNutt et al. 2006). Pink salmon exhibit high inter-individual variability in their swimming performance. Some individual Pink salmon have swimming capabilities that are as good as that of sockeye and in fact have maximum aerobic performance and metabolic scopes that surpass most salmonids, however, others are extremely poor swimmers (MacNutt et al. 2006). It is uncertain why such variability exists within pink salmon populations, however, this could explain why so many of pink salmon did not re-ascend the fishway. Previous physiological telemetry studies have found that pink salmon do not rapidly ascend areas of difficult passage and when they do ascend, it is done with relatively slow and steady swim speeds compared to sockeye salmon (Hinch et al. 2002). It has been proposed that pink salmon may be a more exploratory migratory species than sockeye (Crossin et al. 2003, 2004), preferring and actively seeking migration routes with lower encountered water velocities (Xie et al. 1997).

There are some caveats that must be discussed in terms of the rates of fishway attraction observed in our study. These values could be over-estimated by the fact that our study animals had already successfully located the entrance and ascended the fishway, therefore, we may not be studying a segment of the population which for some reason was not able to initially locate and ascend the fishway. Similar challenges have been reported by Bunt et al. (2001), but those authors still felt that their findings were representative of fishway attraction efficiencies because there is always a proportion of a population that does not have the motivation to migrate further (e.g., pink salmon in our study). On the other hand, our estimates could be under-estimated by the fact that initial fishway passage could in some way have reduced their ability to re-located and re-ascend the fishway. However, there is little evidence for physiological disturbance from previous fishway ascent driving the fallback of sockeye or pink salmon as there was no difference in the physiological stress measures of failed versus successful migrants.

Interestingly, we did find that fish which failed to relocate the fishway tended to be larger. This may suggest that larger fish had more difficulty in locating the fishway entrance. Although we did not track Chinook salmon, this finding may provide support for the idea that Chinook salmon have difficulty with not only passing through the resistivity counter, but also with fishway ascent. This requires additional research, but will unfortunately be challenging due to the low overall abundance of Chinook salmon in the Seton system.

Typically, flows adjacent to a fishway entrance are designed to maximize fish attraction (Clay 1961, Odeh 1999), however, the actual relationship between attraction flow and fish attraction is poorly understood (Northcote 1998, Laine 2002). In the present study, water discharged from the dam was decreased following pre-set operational protocol. This decrease did not appear to affect the amount of time that fish were delayed downstream of the dam. Previous studies have documented increases in attraction efficiency with increases in the rate of water discharged from the dam (Laine et al. 2002). We did not see a decrease in attraction efficiency with lower flows. This may be due to the change in flow (-20%) being too small to have an effect. Visually, the currents in the immediate vicinity of the fishway entrance were not substantially altered after the change in flow. Also, the layout of the Seton Dam is relatively simple, with only the radial-gate spillway (with no flow during the study period) separated from the main spillway area.

The SDF was constructed prior to fishway design emerging as a science. Little was known about fish behaviour or the factors that contributed to successful attraction or passage. The entrance to SDF is comprised of a narrow vertical slot with a width less than 1% of the river width. When fish were within the region immediately downstream of the entrance (within 3 m), they almost always entered the fishway. However, fish spent some time trying to move to or locate these areas. The area where fish seemed to be most disoriented was the region immediately downstream from the radial arm gate. Fish were able to move into this region and would become behaviourally entrained. Visual observations revealed sockeye (and pink) salmon swimming in circles, often times upstream of the downstream extent of the radial arm gate wall. Thus, fish would have needed to move downstream, cross the channel, and then approach the fishway. Previous fishway attraction efficiency studies have documented problems with fish unable to find the fishway entrance. Bunt et al. (1999) used knowledge on attraction difficulty to modify the fishway entrance and enhance attraction efficiency. In that study, a section of the fishway wall was removed which made the entrance of the fishway extend downstream from the dam face. The fishway entrance at Seton Dam is flush with the dam face on the south side of the river. However, the radial arm gate wall prevents fish from freely moving along the dam face if they are upstream of the wall on the north side of the river. During future dam maintenance activities, it may be worthwhile to explore the partial or full removal of the radial arm gate wall to provide more unimpeded movement of fish along the dam face, which would reduce behavioural entrainment and delay, and would likely enhance attraction efficiency.

While we presumed that all fish that failed to pass the fishway had fallen back downstream, it is possible that they may have been taken by natural predators or other means (i.e. fisheries). As fish congregate downstream of a bottleneck they may be more susceptible to predation threats. Direct and indirect observations of black bears (Ursus americanus) in the vicinity of the Seton Dam tailrace suggested that this was a fairly well-used hunting ground. Though no radio tags were ever detected in carcasses drawn up on the shore, it is possible that carcasses were either moved further inland or drifted down Seton Creek to the Fraser River. Mortality associated with delay downstream of dams has been previously reported (Gowans et al. 2003).

Objective 2. Evaluate passage efficiency of migrating adult salmonids through the SDF and identify specific areas of passage difficulty within the fishway

Rationale

Fishways are constructed to mitigate the negative effects of passage barriers to adult fish migration, and have the potential to connect habitats upstream and downstream of passage obstructions (Clay 1961; Odeh 1999). While the primary function of such facilities is to enable passage, it is also of particular importance, especially for adult salmonids during spawning migrations, that this is allowed to happen in as short of a time period as possible, and without fish having to expend large amounts of energy or experience high levels of physiological stress during passage, either of which could negatively affect migration success or impair reproductive development (Hinch et al. 2005). Within the SDF (or most vertical slot fishways for that matter), complex flow patterns and resulting areas of refuge offer ascending salmon the opportunity to reduce energy consumption and stress by taking advantage of areas with lower water velocities. Using electromyogram (EMG) radio telemetry in conjunction with non-invasive physiological sampling we have attempted to elucidate insights into how a fish's physiological condition affects its ability to pass and its behaviour within the SDF. EMG telemetry is a proven technique for studying migration energetics and activity of sockeye salmon (Hinch et al. 1996; Hinch and Bratty 2000) and is useful for documenting areas of difficulty within fishways (reviewed in Cooke et al. 2004a). Unlike conventional telemetry, EMG telemetry provides detailed information on the fine-scale behaviour and swimming patterns of fish. In the context of fishways, EMG can be used to identify areas of passage difficulty and to ascribe activity levels associated with passage. When combined with non-lethal physiological sampling, it is possible to evaluate detailed links between behaviour and physiology that can reveal areas of passage difficulty. We focused our efforts on sockeye and pink salmon as they were the only salmonid species that were found to commonly ascend the fishway.

Methods

Capture and biosampling

Despite employing various netting techniques, we were unable to safely capture adult sockeye immediately downstream from the Seton Dam in the Seton River, therefore, all fish used in our study were captured in the fishway. Sockeye and pink salmon were captured by dip net at the top of the fishway following the same protocol as described above for assessment of Objective 1. All fish for this part of the study were captured, sampled, and tagged individually. Following capture, fish were immediately transferred to a V-shaped holding trough that was supplied with fresh water where blood was drawn and fork length was recorded (see details described in Objective 1 for methods, assays, and analysis techniques). Individual fish were placed in an anesthetic bath (in an 80 liter cooler) of MS-222 (tricaine methanesulfonate) (65 $mg \cdot l^{-1}$), buffered with $CaCO_3$ (65 $mg \cdot l^{-1}$). As fish were anesthetized, physiological biopsy was carried out (described in detail above for assessment of Objective 1). Following complete anesthetization, fish were gently moved to a neoprene-lined v-shaped surgery trough that held the fish inverted and partially submerged. A cycling maintenance bath of buffered anesthetic (30 mg MS-222 l^{-1}) was continuously pumped across the gills of the fish during the course of EMG transmitter implantation.

EMG telemetry transmitters

EMG transmitters are a well established tool now commonly used in fisheries science (Cooke et al. 2004a). Transmitters were cylindrical in shape, measuring 53 mm in length by 16 mm in diameter with mass in air of 18.5 g. EMG tags are similar in dimensions to standard positional tags (as were used for Objective 1), with the exception of two additional 20 cm external electrode wires which are used to detect bioelectrical voltage changes in the main swimming musculature. Fourteen karat gold tips were attached to the electrode wires forming a ‘T’ shape that would hook into the musculature when inserted. Voltage changes detected between the electrodes are stored in a capacitor until a preset threshold is reached, at which point the transmitter sends a signal to a radio receiver (details provided below). Muscle activity is proportional to the frequency with which signals (termed ‘pulse intervals) are transmitted (e.g. fast swimming fish transmit more frequent signals). EMG pulse intervals are recorded approximately every 2-3 seconds. Using previously developed calibrations for migrating adult salmon (Hinch et al. 1996; Standen et al. 2002), we were able to convert field-collected EMG values to ‘instantaneous’ estimates of swimming speeds. EMG transmitters and receivers used in this study were manufactured by Lotek Engineering, Newmarket, Ontario.

Surgical procedures

A 2.5-3 cm incision was made on the ventral side of the fish, anterior to the pelvic girdle. EMG transmitter electrodes were inserted through the incision, and into the axial musculature just under the skin of the fish along the lateral line. This was done using specialized hollow plungers (2 mm inside diameter) designed to force the electrode tip up through the muscle and then to deposit them in the desired location (Hinch et al. 1996). The two electrodes were spaced approximately 1cm apart and were located inline approximately 2 cm posterior of the origin of the dorsal fin. After the electrodes were placed, the plungers were removed and a hole was punctured posterior of the incision using a 2 mm inside-diameter hollow needle. The transmitter antenna was inserted into the hollow needle, pulled through the hole, and left exterior of the fish. The transmitter body was then carefully inserted through the incision and placed into the body cavity. The incision was then closed with five to six sutures (2-0 Ethicon braided silk) and the fish was transferred to a cooler equipped with a constant flow of fresh water to recover. The entire surgical procedure generally took approximately eight minutes to complete (including induction of anesthesia).

Following surgery, fish were transferred to a 100 l cooler with a continuous supply of fresh water pumped through, to facilitate recovery (Farrell et al. 2001). Typically, fish had regained their equilibrium and were moving around within 10 minutes of revival. We held fish for 60 to 90 minutes to ensure recovery prior to their release. Fish were released in the 3rd pool from the bottom of the fishway (see Figure 5). This pool represented one of the two points where the fishway makes an 180° turn. As such, it offered greater areas of low velocities where the fish could orient themselves without potentially being immediately flushed out of the fishway. Fish were released into the fishway in order to maximize our opportunities to manually track upstream movements in the fishway. Generally, two fish were tagged per day every two to five days in order to ensure adequate time to track individuals. Females were exclusively targeted in order to maximize sample sizes and to eliminate possible sex-specific effects (as per the recommendations of Cooke et al. 2006).

Tracking

Upon release, fish were manually tracked using data-logging telemetry receivers (Lotek model SRX_400) and three-element Yagi antennas. EMG pulses were recorded by the receiver, along with a time stamp that was matched to detailed notes and time recordings by the tracker. Fish that successfully moved up the fishway were tracked until they had passed through and into the dam fore bay. As fish ascended, each movement into the next pool was recorded along with any other relevant details such as location within a given pool. Fish that fell out of the fishway and into the tailrace of the dam subsequent to release were also tracked until they either passed or permanently fell back in Seton Creek.

Manual tracking of fish carrying EMG transmitters occurred during the day, while an array of two fixed receivers - one positioned at the top of the fishway, and one at the bottom were deployed overnight. These fixed receivers and antennas were positioned so as to detect fish movements through the top and bottom pools of the fishway. We were unable to record EMG signals at night from fish moving through other parts of the fishway. However, we were able to confirm with certainty whether fish had exited the fishway.

Data Analysis

Data from EMG recordings were converted to instantaneous swim speeds interval using formulas described in Hinch and Rand (1998). Physiology, energy, and length data were $\log_{10}$ transformed to meet normality assumptions for the majority of variables, however, fork length (FL) and osmolality required non-parametric tests. Bartlett's test was used to assess variance equality. Univariate tests were used to make all comparisons of physiological, energetic and length variables among groups of fish. Two-way t-tests were performed on parametric data, while Wilcoxon tests were used on non-parametric data. All statistical tests were assessed for significance using a Sequential-Bonferroni corrected alpha of 0.05.

Results

Fifteen Gates Creek sockeye and six pink salmon were implanted with EMG transmitters and physiologically sampled. Gates Creek sockeye were captured and tagged during the period of August 11 to September 20, 2005, and pink salmon during the period of September 6 to September 13, 2005. Seven sockeye successfully re-ascended the fishway on their first attempt following release, and all exited the fishway at the top. Of the eight that moved out of the fishway, two re-entered and successfully ascended and exited the fishway on later dates. The remaining six that failed to re-enter the fishway, fell back down Seton Creek, presumably to the Fraser River (fish were never again located within 1 km downstream of Seton Dam). One of the sockeye that fall back was subsequently located in the tailrace of the Seton hydroelectric facility on the Fraser River (situated just downstream from the confluence of the Seton and the Fraser

Rivers; Figure 3), where it remained for several hours before disappearing with no further detections. All six of the pink salmon carrying EMG transmitters fell out of the fishway following release and generally held position just downstream of the fishway in Seton Creek. After several days of holding, these fish all moved downstream, dropping back from Seton Creek to the Fraser River, as no detections were made in the vicinity of the Seton Creek spawning channels. None of these fish were again detected within 1 km of the SDF.

Within fishway behaviour

EMG signals recorded from tagged fish provided a unique record of activity exhibited by each individual during fishway ascent. Of the seven sockeye that passed on their first attempt, strong signals were recorded for six individuals. One EMG tag was found to be defective and provided no useful data on fish movements. However, this fish was still included in terms of physiological analyses and ascent time, as the defective nature of the tag would not have had any unusual effect on these variables. Average time required to ascend the fishway was 63.5 ± 7.7 min (mean ± S.E.). Using the swim speed values derived from EMG signals, we averaged all signals recorded during the course of fishway ascent in order to calculate an overall mean swim speed for each fish. Total number of EMG signals captured for each fish ranged from 1062 to 2745 and are summarized in Table 5. Mean swim speeds, estimated from EMG pulse intervals, exhibited by individuals during ascent varied substantially from as low as 2.6 $cm^{\cdot}sec^{-1}$ to as high as 86.0 $cm^{\cdot}sec^{-1}$ (see Table 5). During ascent, fish would spend, on average 21.7 ± 5.3 min in the pool midway through the fishway that turned 180^{o} (pool 17). In this pool, average swim speeds of fish ranged from 1.6 $cm^{\cdot}sec^{-1}$ to 70.1 $cm^{\cdot}sec^{-1}$, and were significantly lower than those exhibited during total fishway ascent (paired t-test, $t_5 = -2.239$, $P = 0.038$) (see Table 5).

From the EMG data recorded for the fish that successfully passed on the first attempt, two separate ascent strategies were apparent and were reflected in the mean swim speeds exhibited by fish. One group of fish (n = 3) demonstrated a more conservative swim speed strategy, only employing fast swim speeds (>100 $cm^{\cdot}sec^{-1}$) during upstream pool-to-pool movements with few other exceptions (see Figure 6). This type of ascent strategy is reflected in a distribution of instantaneous swim speeds that is highly skewed towards lower values (see Figure 7). Another group of fish (n = 3) appeared to be less discriminate in utilizing higher swim speeds, and frequently exceeded 100 $cm^{\cdot}sec^{-1}$ throughout passage time (see Figure 6). In contrast to the first group, the distribution of swim speeds for these fish was bimodal, split between slow and fast swim speeds (see Figure 7).

Physiology

Physiological and morphological analyses contrasted sockeye which were able to pass through the fishway on the first attempt with those that fell back following release. No differences were found between groups in terms of gross somatic energy or body length. Stress indicators including hematocrit, and plasma concentrations of lactate, glucose, and osmolality did not vary among these two groups of fish (see Table 6). However, fish that re-ascended on their first attempt had higher levels of Na+ (t-test, $t_{13} = -2.981$, $P = 0.011$). Of the sockeye that were able to re-ascend the fishway on the first attempt, non-parametric tests revealed no differences in any of the physiological indicators among the two observed ascent strategies (Table 7).

As all of the EMG-tagged pink salmon fell out of the fishway, and subsequently back down through Seton Creek to the Fraser River, no comparisons could be made in terms of their physiology. Summary statistics for physiological variables for these pink salmon are provided in Table 8.

Discussion

Although we observed a fallback rate of 40% for sockeye salmon, this is not necessarily indicative of overall passage success for our study population. It was not possible to capture, tag and release fish in the approach sections below the fishway entrance - an approach needed to more accurately assess population level fallback. Our approach however enabled us to assess how fish with demonstrated capabilities for fishway ascent, behaviourally use the fishway, and whether certain sections of the fishway appear to provide migration challenges. One of our goals was to identify specific areas of passage difficulty within the fishway. Collectively, our data revealed that once a sockeye salmon committed to ascend the fishway (i.e., moved upstream from pool 3 where they were released), all fish were able to successfully reach the top of the fishway. We did not document any regions within the fishway where fish encountered any significant difficulties. From time of release, successful fish only required about 1 hour to reach the top of the fishway. Interestingly, much of this time was spent in the release pool (pool 3) where fish probed the upstream “exit”. Thus, although total passage times from release were roughly an hour, the actual ascents typically only took about 30 min. Most of the ascent time was spent in resting pool 17 where fish delayed for about 20 min. As the intention of a “resting pool” is to provide fish the opportunity to recover from strenuous exercise, such a delay is likely beneficial and does not indicate that this is an area of difficulty. As the fishway makes a 180° turn at pool 3, there may be some behavioural challenges for fish. Specifically, some species of fish, such as walleye, have been observed to have difficulty in locating the upstream exit when the fishway makes a turn (Peake 1997; Bunt et al. 2000). However, this phenomenon has not be identified in salmonids so it is likely that the time spent in pool 17 represents resting rather than difficulty in orienting to upstream reaches.

It is quite interesting that such a large fraction (~ 40%) of our telemetered sockeye were unable to re-ascend the fishway. While fall back out of fishways is phenomenon that is being recognized more commonly for migratory salmonids (Bernard et al. 1999; Bjornn et al. 2000; Young et al. 2006), the explanation for this phenomenon is not clear. In our study, there were few differences (e.g. in handling, size, energy density, and most physiological stress measures) between successful and unsuccessful migrants in terms of re-ascension. In fact, the suite of indicators for physiological stress that we used generally revealed that upon capture, our telemetered sockeye were not excessively stressed. For instance, relatively high plasma lactate or glucose levels would indicate that migrants had encountered difficult passage conditions or other related stressful events within the past 72 hours (Frisch and Anderson 2005). Mean lactate concentrations from in our study fish were lower than those measured from fish after routine exercise in the laboratory (Hinch et al. 2005). Our values for lactate and glucose were similar to averages obtained for other Fraser sockeye populations (e.g. Weaver Creek, Adams River) that were sampled during their spawning migrations and for which we know were eventually successful at reaching spawning grounds (Young et al. 2006; Cooke et al. 2006). The only difference we could identify in terms of re-ascension success was that unsuccessful fish had lower concentrations of plasma Na+. Relatively low levels of plasma ions can be indicative of physiological stress (Ackerman et al. 2000). Unsuccessful fish had mean Na+ concentrations that were much lower than typical levels expressed by successful migrants from other Fraser sockeye populations or from fish that were exercised in the lab (Hinch et al. 2005; Young et al. 2006). In summary, there is some indication that unsuccessful migrants were modestly physiologically stressed, though the response was not broadly reflected among stress indicators. There was no indication that successful migrants were stressed in any way.

If we assume that once fish enter the fishway their passage progress is relatively quick (i.e. we found ascent taking approximately 1 hour from pool 3 so it may take 1.5-2 hours to pass from the entrance to exit), then our results suggest that passage through the SDF did not cause physiological stress. In general, the stress indicators we examined usually respond within 30 minutes or less to significant stressful events (e.g. encountering high flows, high temperatures, or struggling from capture - Frisch and Anderson 2005, Black et al. 1960). The fact that unsuccessful migrants had depressed Na+ levels suggests that these fish may have encountered some type of stressor prior to entering the fishway. Indeed, in locating the fishway entry, we found that sockeye salmon would spend, on average, 18 hrs in the tailrace of the Seton Dam (see above section for Objective 1). During this period of time, radio tracking revealed that fish would commonly move into areas of high flow velocity in search of upstream passage. Previous telemetry studies of migrating fish encountering fishways have revealed hard swimming efforts associated with negotiating the fishway approach (e.g. Hinch and Bratty 2000). Repeated attempts to locate the fishway entrance over the course of 18 hours may have been responsible for the depressed Na+ levels that we observed in some fish in the present study.

Why did fish with depressed Na+ levels not re-ascend? Plasma ion imbalance (and other stress responses not exhibited by our fish such as elevated plasma lactate and glucose) can prevent or interfere with strenuous activity (Wood et al. 1983) potentially preventing re-ascent. Moreover, with extreme levels of stress, metabolic acidosis can occur whereby fish succumb and die due to plasma pH levels that become too acidic (Hinch and Bratty 2000 and references within). The behavioural physiology of fish migrations is an emerging science (Hinch et al. 2005) and it is difficult to say with any confidence exactly how specific stressors affect migration success, or in the case of the present study, why some fish were unable to re-ascend.

Two different ascent strategies were observed among sockeye salmon that successfully ascended the fishway. One group adopted a conservative strategy and only used high swim speeds when making pool to pool movements. Another group exhibited more heightened and variable swimming speeds, often in excess of 1 ms^{-1}. Interestingly, there were no clear physiological correlates with these different ascent strategies. In a previous study of sockeye fishway use, Hinch and Bratty (2000) revealed that sockeye that failed in fishway ascent were those that had more varied swimming speeds. Conversely, they found that successful migrants adopted a “slow but steady” approach to fishway ascent. In this case of the SDF, migrants adopting either strategy were successful in ascending the fishway. Perhaps this reflects differences in fish condition among studies or differences in the difficulty of the fishways. Hinch and Bratty (2000) investigated the Hell’s Gate Fishway Complex which was clearly identified as having areas of difficult passage, and is impassable at certain discharge levels. Conversely, once in the SDF and committed to moving beyond pool 3, our data suggest that sockeye salmon do not experience regions of difficulty that would impede migration.

Unlike sockeye salmon, none of the pink salmon we implanted with EMG transmitters were able to successfully re-ascend the SDF. However, these data must be interpreted cautiously for several reasons. Pink salmon spawning areas are limited upstream of Seton Dam, and they have excellent spawning habitat in the area immediately downstream of the dam (including adjacent spawning channels). Thus, there is no specific need *per se* for pink salmon to ascend the fishway. We therefore interpret this extent of fallback among pink salmon as being reflective of their lack of motivation for ascending the fishway rather than any specific difficulty in doing so. Indeed, one must recall that all of these pink salmon were successful in ascending the fishway as we captured and tagged fish from the fishway exit pool.

Objective 3. Evaluate if fishway passage has consequences on sockeye salmon that affect their ability to reach terminal spawning locations but are not detectable until after they have left the fishway

Rationale

Although fishways provide fish with opportunities to pass barriers, fishways themselves can impart stress that has the potential to affect fish behaviour and physiology after ascent. Fishways require fish to swim at high speeds, often utilizing burst swimming and producing anaerobic byproducts such as lactate. Previous research has revealed that high levels of lactate can lead to mortality and altered swimming activity (e.g., Black 1957; Farrell et al. 2001). The Seton Fishway proximity to specific and known spawning grounds provides the opportunity to use physiological (noninvasive biopsies) and behavioural (acoustic telemetry) tools to assess if fishway passage has consequences on sockeye salmon that affect their ability to reach terminal spawning locations but are not detectable until after they have left the fishway.

Methods

Fish capture and handling

Sockeye salmon for this assessment were captured in the upper reaches of the Seton Fishway in the most upstream resting pool prior to fish exiting the fishway. Large dip nets as described above were used to quickly sample fish that had recently ascended the fishway. Upon capture, fish were immediately transferred to a V-shaped padded trough filled with water and biosampled as above. The final step of the biosampling and tagging process involved the gastric insertion of an acoustic telemetry transmitter (Ramstad and Woody 2003). We used a combination of positional and depth sensing acoustic transmitters. Positional transmitters weighed 18 g in air and 10 g in water and measured 16 mm in diameter and 48 mm in length. Depth sensing transmitters weighed 24 g in air and 14 g in water and measured 16 mm in diameter and 60 mm in length. Several transmitters were also equipped with temperature loggers as discussed under Objective 5.

Telemetry Technology

Although the initial BCRP proposal indicated that we would utilize radio telemetry for this study, after several field visits, testing of equipment, as well as the addition of study objectives by the BCRP Technical Review Committee that required information on in-lake behaviour, it was determined that radio telemetry would be inappropriate for this phase of the study. Radio telemetry does not perform well in deep water and could only have been used for monitoring fish passage through shallow riverine environments such as the Portage Creek or Gates Creek. Therefore, we used an automated acoustic telemetry system. Acoustic telemetry performs well in large deepwater systems such as Seton and Anderson Lake. In addition, acoustic telemetry receivers can be fully deployed underwater and log signals automatically for 6 months, reducing need for regular site visits and providing enhanced security. Automated acoustic telemetry systems require use of coded telemetry transmitters which utilize up to 256 codes on a single frequency to maximize detection and identification of individual telemetered fish. Automated telemetry arrays have become incredibly popular in recent years, providing detailed information on fish behaviour and fate in marine and freshwater systems.

Telemetry Array

Acoustically tagged fish were monitored by an array of receivers that had been placed throughout Seton and Anderson Lakes (Figure 8). The receivers were VR2's from Vemco Inc (Shad Bay, NS) and were able to record and log signals from telemetry transmitters for 6+ months. The devices were fully submersible allowing underwater deployments. In total, 15 receivers were deployed in Seton and Anderson Lakes during June of 2005 (Table 9). Five of the receivers were fixed to structures (e.g., docks, dead-heads) and the remaining ten receivers were suspended in the water column using a combination of sandbags, rope, and subsurface buoys. GPS locations were recorded for all of in-lake deployments. The general arrangement of the VR2s was intended to provide coverage for the entire system such that we were able to detect and log fish as they moved past various checkpoints. Receiver locations were chosen based on spacing to provide adequate coverage, but also at constrictions (to enable detection of the entire width of the lake) and other strategic sites (e.g., near the Cayoose inflow and the Carpenter Lake penstocks). Indeed, ten of the VR2s had detection efficiencies of 100% (i.e., every fish that was picked up on subsequent receivers was detected on a given receiver). This level of detection efficiency is considered quite high and suggests that the receiver array provided excellent coverage. Three of the receivers had detection efficiencies between 93.8 to 97.2%. Only one receiver had low detection efficiency (62.9%, receiver 11). Receiver 11 was located at the outlet of Anderson Lake and was placed in 4 m of water on a large submerged log. The noisy environment (near rapids), shallow placement, and presence of debris may have led to the reduced detection efficiency relative to other receivers.

Physiological Analysis

The analysis focused on fish from the Gates and Portage sockeye salmon stocks. Stock identity was confirmed using either information on arrival at terminal spawning grounds or alternatively DNA analysis when fish behaviour did not provide conclusive evidence as to stock origin. Stock origin was ascribed to other fish by DNA analyses (Beacham et al. 1995; 2004). Stock assignment through DNA analysis is a standard technique in fisheries management and research for Fraser River sockeye salmon and has 96% accuracy in stock assignment (Terry Beacham, Pacific Biological Station, Personal Communication). In our study, we only focused on differentiating fish into two stock groupings (i.e., Gates and Portage). Thus, for our purposes DNA accuracy may have been higher than 96% as the genotypes for these populations are quite different.

Plasma ion, lactate, and glucose measurements followed the procedures described by Farrell et al. (2001). After centrifugation in the field, plasma samples were immediately placed on dry ice for temporary storage. After transfer from dry ice, samples were subsequently stored at –80°C prior to analysis in the laboratory. Plasma lactate and glucose concentrations were measured using a YSI 2300 STAT Plus glucose and lactate analyzer (YSI Inc., Yellow Springs, Ohio). Plasma chloride concentrations were measured in duplicate using a model 4425000 digital chloridometer (Haake Buchler Instruments, Saddle Brook, N.J.). Detailed description of all assays presented here including the inter-assay variability and quality control criteria are provided in Farrell et al. (2001).

Data Analysis

VR2 acoustic receivers were downloaded and data was imported into a database for analysis. Individual fish behaviour and fate was reconstructed using time stamped data. Fish were determined to be failed migrants when the transmitter (and presumably fish) were static for extended periods of time and failed to reach spawning grounds. Depth sensors provided additional confirmation as they would report a static depth. Fishery removals were determined based on visual observations of fishing activities near the Portage Creek inflow in Seton Lake. In fact, we had several transmitters directly returned by the public suggesting that fish were indeed harvested.

Results

A summary of all tagging and fate information is provided in Tables 10 and 11. Acoustic tagging began on August 9, 2005 although netting attempts began more than two weeks earlier. Run size had to reach a certain threshold before it was possible to capture fish in the fishway. The last fish was tagged on October 1, 2005, although we attempted to capture fish up to October 14. In total, 50 sockeye salmon were tagged with acoustic transmitters, 9 of which had depth sensors. Arrival at terminal spawning grounds and/or DNA analysis revealed that we tagged 30 Gates stock and 20 Portage stock sockeye. Gates stock fish appeared in the fishway first and were last seen on September 21. Portage sockeye were first tagged on September 20. In total, 896,761 valid positions were detected and logged for the 50 sockeye salmon tagged and released with acoustic telemetry devices upstream of the Seton Fishway. The range in detections for an individual fish was 139,521 for a maximum and 0 for a minimum (average was 17,935 per fish). The fish that were detected more than 10,000 times on a single receiver tended to be those that died in the vicinity of a receiver reception cell.

Fates of the Gates Sockeye

The Gates sockeye salmon experienced high mortality during their migration from the SDF to spawning grounds. Of thirty tagged fish, only 14 of 30 fish tagged at the fishway successfully reached terminal spawning grounds. Of the fish that failed to reach spawning grounds, upon release two passed downstream through the fishway, siphon, or the power generation canal. One of these fell back within 2 minutes of release (August 9, 6:52). The second initially swam upstream after release (August 26, 8:37) and was detected on receiver 1 and then 2 but reversed direction towards receiver 1 where it was last observed at 10:04.

Ten fish were classified as in-lake mortalities as evidenced by manual tracking or automated telemetry station positions (Tables 10 and 11). For example, Fish 105 was released on August 16 at 10:28 and proceeded to move through Seton Lake and into Anderson Lake. It never moved beyond the midpoint of Anderson Lake and was last observed on an automated receiver on September 5 at 15:12. Subsequent mobile tracking located the fish near the automated telemetry receiver number 13 (in the mid section of Anderson Lake). Similar patterns were observed for fish 399, 396B, and 407 with mortality occurring mid-lake in Anderson Lake. Fish 412 died in Seton Lake within the reception zone of receiver 4 (leading to more than 48,000 signals on that receiver) without ever moving to Anderson Lake.

Four of the 16 suspected mortalities may be related to fishing activities. We received anecdotal reports of fisheries captures where black cylindrical devices were reported in the body cavities of fish. Although we received a number of radio tag returns from fisheries, we did not have any depth tags returned. Mobile tracking in an around the outflow of Portage Creek revealed static tags implying that the fish died or transmitters were removed and thrown in the lake. We classified these fish as potential fishery removals.

The 14 Gates sockeye that successfully reached spawning grounds were characterized by rapid travel rates to spawning grounds. Fish tended to move quickly through Seton Lake and spent little time holding in Anderson Lake prior to entering Gates Creek. At least six acoustic transmitter fish successfully spawned in the Gates spawning channel and their tags were recovered and returned to our research team.

Fates of Portage Sockeye

Mortality rates of Portage sockeye were relatively low (Tables 10 and 11). Only two fish that we tracked did not reach terminal spawning grounds on Portage River (i.e., 10% mortality rate). Specifically, Fish 439 reached receiver 8 (Figure 8) before moving back down lake towards the Seton River and then died in the reception area of receiver 5 (with more than 21,000 hits from this single fish on that receiver). Fish 440 exhibited a similar behaviour, although it only reached receiver 7 and died between receiver 7 and 8 (as verified with manual tracking). Successful Portage fish moved quickly towards spawning grounds and spent little time holding in Seton Lake. One interesting observation was that eight of the successful fish also briefly entered Anderson Lake. Many of these fish stayed near receiver 11 or 12, but one fish (Fish 973) swam to the end of Anderson Lake (receiver 15) before returning to the Portage River. Several fish spent hour to days in the Portage River and then returned to Seton Lake where they died (presumably after spawning). Fish that successfully spawned in the Portage River seemed to accumulate near Seton River suggesting that either the fish move in that direction prior to death or that carcasses move in that direction, likely on the surface. As we observed no floating carcasses, we presume that fish actively moved downstream (to the eastern end of Seton Lake) prior to death

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Physiological and behavioural consequences of fishway passage

Exploratory multivariate analysis using MANOVA with physiological/energetic data (i.e., hematocrit, plasma lactate, glucose, Cl-, energy density, total length) revealed that there were not significant (i.e., P>0.05) stock-specific differences in physiology. As such, we combined fish from Gates and Portage and focused our analyses on contrasting the physiology of successful and failed migrants. Fish that were suspected fisheries harvests (N=4) were excluded from any physiological analyses. In addition, data from other fish were unable to be used for final physiological analyses due to small amounts of plasma.

Overall, fish that were successful in reaching spawning grounds had relatively similar physiological and energetic characteristics to those that failed to reach spawning grounds (Table 12), although there was one exception (plasma lactate concentration). Longer-term indicators of energetic and physiological status such as proximate body composition (energy density) and body size (total length) did not differ between failed and successful migrants (energy density, t=0.551, df=44, P=0.584; total length, t=-1.645, df=44, P=0.107). Some shorter term indicators of stress (e.g., glucose and Cl- ions) did not differ among successful and failed migrants (glucose, t=1.576, df=42, P=0.122; Cl-, t=-1.472, df=41, P=0.149; hematocrit, t=0.435, df=42, P=0.660), although the plasma metabolite lactate was an exception (i.e., plasma lactate was higher for failed migrants; t=2.836, df=42, P=0.007). From a behavioural perspective, the relative time spent by failed and successful migrants in the vicinity of the release site (measured as the sum of all fish positions on receivers 1,2, and 3 for each fish) did not differ (t=-0.833, df=44, P=0.382). In addition, there was no difference in the time required for fish to travel from release site to receiver 3 or receiver 5 for successful or failed migrants (time to receiver 3, t=-0.651, df=42, P=0.518; time to receiver 5, t=-1.147, df=42, P=0.258).

We also assessed whether there was a relationship between the physiological and energetic status of individual fish and their dwell time in the vicinity of release (measured as the sum of all fish positions on receivers 1,2, and 3 for each fish). However, none of the variables that we measured were related to dwelling time (total length, r^2=0.0001, P=0.932; hematocrit, r^2=0.034, P=0.207; energy density, r^2=0.031, P=0.224; plasma lactate, r^2=0.0001, P=0.942; plasma glucose, r^2=0.054, P=0.114; Cl-, r^2=0.0045, P=0.655). We also more directly assessed the effects of physiological status on the behaviour of fish by assessing the relationship between physiological status and the time between release and first signal detection for each fish at Receiver 3 and Receiver 5. Similar to our assessment of dwell time, there were no significant relationships between fish condition and behaviour for time to travel to receiver 3 (total length, r^2=0.005, P=0.635; hematocrit, r^2=0.032, P=0.232; energy density, r^2=0.003, P=0.716; plasma lactate, r^2=0.002, P=0.771; plasma glucose, r^2=0.046, P=0.152; Cl-, r^2=0.027, P=0.248) or receiver 5 (total length, r^2=0.017, P=0.369; hematocrit, r^2=0.039, P=0.130; energy density, r^2=0.047, P=0.140; plasma lactate, r^2=0.0007, P=0.848; plasma glucose, r^2=0.059, P=0.105; Cl-, r^2=0.003, P=0.712).

Discussion

This is the first study to evaluate if fishway passage has consequences on sockeye salmon that affect their ability to reach terminal spawning locations but are not detectable until after they have left the fishway. Fishway passage can undoubtedly be stressful on fish and may have consequences even after successful ascent. In this study, we observed very limited evidence supporting the idea that the passage of the SDF created sufficient stress to induce significant alterations in fish behaviour or survival after fish had successfully ascended the dam. In fact, the only clear evidence that we observed that was notable was the fact that fish which died after ascending the fishway had higher lactate levels than fish that survived to terminal spawning grounds. Lactate has been linked to mortality in salmonids (e.g., Black 1957; Farrell et al. 2001), however, the lactate values that we observed here were not remarkably high (Hinch et al. 2005; Young et al. 2006). Had elevated lactate affected swimming behaviour, we would have expected to see relationships between the magnitude of physiological disturbance and the dwell time or swimming speeds upon release. In actuality, we observed no relationships between any physiological or energetic variables and fish travel times. Nonetheless, there may be opportunities to enhance the ability of fish to locate or use the fishway to ensure that plasma lactate levels remain low. In years when fish are in poor condition (e.g., low energy reserves) or water temperatures in the Seton Fishway or Seton and/or Anderson Lakes are exceptionally high, moderate levels of lactate may be more detrimental than we observed in 2005 during a reasonably benign temperature period in 2005.

In this study we did observe significant mortality among the summer run Gates sockeye salmon. However, mortality rates were quite low for the late run Portage stock. Of the 30 summer run Gates sockeye released, less than 50% reached terminal spawning grounds. Conversely, only 2 of 20 (or 10%) of the late run Portage sockeye died between the release site and the spawning grounds. Why did so many summer run fish die? And is this mortality linked to fishway passage? These two questions are difficult to answer with any certainty. In a given year, a proportion of any sockeye salmon population will die en route to spawning grounds. Past research in the Fraser River has revealed that mortality rates can very extensively (0 - 95%; Cooke et al. 2004b). A telemetry study in 2002 and 2003 in the Fraser River revealed that summer run stocks of sockeye salmon such as the Gates fish experienced low levels of mortality in the Fraser River (<20%; English et al. 2005; Cooke et al. 2006). However, neither of these studies explicitly focused on the Gates population or on any population after they left the main stem Fraser River. Knowledge of sockeye salmon behaviour in the final phases of migration or in lake type environments is poor, with only one study on this topic (Cooke and Hinch 2005). The level of mortality observed in this study may in fact be quite typical and represent natural phenomena. Interestingly, in recent years late run stocks (such as Portage) have been experiencing exceptionally high en route mortality associated with anomalous migration timing (Cooke et al. 2004b). Perhaps the en route mortality occurred in the main stem Fraser prior to reaching spawning grounds, but it did not occur in the lake environment, even after exposing fish to fishway ascent.

One of the primary determinants of salmon mortality during freshwater migration is water temperature. High water temperatures (i.e. ~18C) can lead to heightened energy expenditure, slowed migration, accelerated disease development, and stress, all of which can result in enroute mortality of Fraser sockeye adults (Cooke and Hinch 2005). Temperatures above 19-20C can cause 50% mortality in as little as 9 days (Hinch, unpub. data). In 2005, Fraser River water temperatures experienced by Gates summer run sockeye were high (summer water temperatures in the Fraser River typically are near 18°C) during their migration in the Fraser River relative to the waters that the fish encountered once they arrived in the cooler Seton and Anderson Lakes (i.e., opportunity to move to cooler deeper waters; Dave Patterson, Fisheries and Oceans Canada, Unpublished Data; see Objective 5 below for more details on thermal ecology of Seton Lake). It is possible that we observed latent mortality arising from this earlier thermal experience. However, temperature as a stressor rarely acts alone. For example, it is possible that the cost of fishway ascent coupled with earlier thermal experience was sufficient to cause mortality in some fish. However, we observed no behavioural observations in fish with high lactate or that died before spawning so this seems unlikely. Further, we found in work for Objective 2 that fishway passage did not seem to generate significant levels of physiological stress. Another possible cause is from injuries and stress experienced from earlier fisheries where fish were either caught and released (by one of the three fishing sectors) or struggled out of fishing gear (such as gill nets). We noted high levels of external wounds induced by gill nets in the early phases of our study. In fact, 6 of 30 sockeye tagged had obvious gill net scars and in some cases, had fungus. Only one of these 6 fish successfully reached terminal spawning grounds.

Two tagged fish fell back after tagging. Unfortunately, we were unable to position receivers downstream of the Seton Dam to determine the route of fall back because acoustic telemetry does not work well in fluvial systems. In addition, we were unable to use the single receiver at site 1 (on the dam face) to precisely determine downstream passage route because the single receiver had a reception cell that covered the entire dam face. In our estimation, fish that moved downstream had three options: i) go back in the fishway entrance, ii) go through the fishway siphon, or iii) go through the power canal. Based on our observations of fish at time of release, all sockeye swam to deeper water and were lost from view. Fish were released in the upstream of the radial arm gate. Although this release site is approx. 20 m away from the fishway entrance and 30 m away from the power canal, we felt that this was a representative place to release the fish immediately after handling. Even though fish were kept in water for all procedures, some recovery time would be required prior to fish being able to rheotactically orient to the Seton River flow. Entrances to the power canal or fishway are shallow so it is unlikely that the sockeye, which fell back selected those routes. Instead, we believe that the most likely route of fallback was through the fishway sluice or the siphons located near the base of the dam in deeper water.

For Fish 406, we logged a number of signals in the vicinity of Receiver 1 and 2 prior to the fish suddenly disappearing. No other signals were logged for this fish on any other receivers during our study. Interestingly, Fish 406 had the lowest Cl- ion concentration out of all the fish that we assayed. When stressed in freshwater, fish tend to lose ions (Barton et al. 2002). As such, this fish may have been stressed, although lactate and glucose were not remarkably high. Instead, this fish seemed to differ from the other fish that died en route to spawning grounds as only the plasma Cl- ion concentration was anomalous. In fact, the value observed for this fish is approaching the level where survival would be unlikely (i.e., >10% change; Barton et al. 2002).

It is difficult to determine whether the loss of ions was related to fishway passage, however, because lactate and glucose were high, this may represent a longer term indication of problems with ionic/osmotic balance. For Fish 937, no signals were ever logged on our receiving system. We are confident that the telemetry transmitter was functional as all tags were tested immediately prior to release. The physiology and condition of this fish was unremarkable (similar to "normal" values; Hinch et al. 2005). Instead, we believe that the fish fell back immediately upon release (and prior to receiving the first signal which would have occurred between 30 and 90 sec after release. Fallback is beginning to be recognized as a common phenomena in migratory salmonids. In a study of sockeye salmon in the Thompson River, sockeye that fell back tended to have high levels of plasma lactate (Young et al. 2006).

Overall, this component of our study revealed that successful ascent of the SDF had no clear implications for fish survival aside from the fact that lactate was elevated in fish that died before reaching spawning grounds. Although this is not necessarily causal, it may be a consequence of other factors, and appears to have little effect on migration behaviour in the lake.

Objective 4. Assess the potential role of the fish resistivity counters on fish passage

Rationale

The BCRP Technical Review Committee requested that we incorporate an assessment of the resistivity counter tubes in terms of their ability to accurately estimate fish passage abundance and whether they created obstacles to migration. The resistivity counter tubes are located within the fishway and are used to estimate abundance of fish that pass the fishway and derive estimates of run timing. Different sizes of these devices are deployed in an effort to accurately count both small and large fish. However, when small fish pass through the large counter, they tend not to be recorded as a passage event. An automatic enumeration system is built into the counter and is designed to record both upstream and downstream movements of fish. A series of copper sensors when triggered in a linear sequence records a passage event. However, this system is not ideal, as it requires the passing fish to touch all sensors. In addition to concerns over inaccurate passage estimates, there are other issues associated with large fish being unable to fit through the small counter, and the accumulation of debris on the upstream opening of the counters, which could potentially hinder or prevent passage. To assess the performance of the fishway counter, we used video recordings to verify automated enumeration and fish behaviour adjacent to the counter, as well as daily assessments of debris accumulation within the counter tunnels.

Methods

In order to assess the resistivity counter for potential effects on passage of fish we placed a high definition, underwater camera in the uppermost pool of the fishway (pool 32). The camera was angled perpendicular to the flow of water such that the entrances for each of the six tubes of the resistivity counter were within view. The camera was connected to a videocassette recorder. Several hours of footage were recorded on each day that the camera was utilized. Video playback was used to 1) develop a separate database of fish movements through the counters that could be compared with the numbers recorded by the automated counter system, and 2) make visual observations regarding fish movements within the vicinity of the counter entrances.

Video recordings were time-stamped so that fish passing through the counter tunnels, when viewed during playback, could be related back to real time events. We obtained summary information on the numbers of fish moving through the counter tunnels were from BC Hydro. We transcribed fish passage through all counter tunnels per hour (i.e. there are four small tunnel counters and two large tunnel counters) and summarized them into two groups (small and large tunnels). For purposes of analysis, we combined data among all tunnels. Linear regression was used to assess relationships between the hourly counts of fish passing provided by the counter tunnels and that from video recordings. In addition to estimating fish passage abundance, visual observations of fish movements near the counter were made from the video recordings; particular attention was paid to movements of larger fish.

To assess the extent to which debris accumulated on the counter, daily monitoring, consisting of visual inspection, was performed throughout the month of August, 2005. Each opening in the counter was assigned a number based on a five-point scale to describe the extent to which debris had accumulated (see Table 13). In addition, the debris racks surrounding the counter, and the fishway were also inspected for blockage.

Results

Estimates of fish passage out of the fishway from the video playback along with the numbers recorded by the counter are summarized in Table 14. In terms of data from the counter, inconsistent tallies characterized the early days of the salmon migration while dramatic underestimation characterized latter dates in the migration when migrant numbers could exceed 100 fish per hour. We found a weak though significant correlation between total hourly passages recorded by the counters and those recorded by video (n = 25 hours of observation, $r^2 = 0.381$, $P = 0.001$. Because the significant relationship appeared to be driven by gross differences in passage abundance, we broke the dataset into two portions, examining the relationship during a period of low abundance (< 16 fish per hour - before August 8, 2005) and a period of high abundance (> 20 fish per hour - after August 18, 2005). No relationship was observed between total hourly passages recorded by the counters and those recorded by video during low abundance (n = 17, $r^2 = 0.053$, $P = 0.374$) or high abundance (n = 8, $r^2 = 0.003$, $P = 0.897$) situations (Figure 9).

Visual observations suggested that the vast majority of fish approached the counters from the lower depths of pool 32. Occasionally, fish would approach tunnels but subsequently turn back without entering. Over the course of approximately 30 hrs of video playback, no observations of large fish failing to pass a counter occurred. In fact, only sockeye and pink salmon along with several resident species (e.g. suckers *Catostomus* spp.) were observed within the fishway.

During August 2005, debris accumulation varied between each of the six tunnels (Table 15). The larger tunnels (5 and 6) appeared to accumulate more debris, more frequently than the smaller tunnels. Debris typically consisted of loose vegetation and small woody debris, however, in mid to late September we observed accumulations of pink salmon carcasses accumulating on and blocking the fishway counters.

Discussion

Based on our video observations, the resistivity counter is clearly inaccurate. During early stages of salmon migrations, anomalous tallies were frequent. This may be due to resident fish moving upstream and/or downstream within the counters. Suckers were visually observed feeding within pool 32 of the fishway. As migrant numbers increased, it became evident that the counter was severely underestimating the total number of fish that passed. Even when an excess of 100 fish passed within an hour, fewer than 10% may have actually been recorded. Accurate enumeration depends on fish detection by a series of copper sensors. However, clearly the sensors are unable to detect all of the fish suggesting that their sensitivity is not optimized. Over the course of the entire migration (e.g. with the whole dataset), we found a relatively weak, though significant, correlation between the video recordings of the total number of fish passing through the counter and those recorded by the counter. However, only 38% of the variation in actual fish passage abundance (from video) was reflected by the counter. Within periods of low or high migration abundance, the fish passage abundance from the counter did not reflect the observations of the video recordings.

As we made no observations of large fish (i.e. Chinook salmon) being unable to move through the counter, we are unable to comment on this issue here. However, sockeye salmon appeared to be delayed downstream of the counter for an average period of time of 17.5 minutes, with a maximum period of delay of 45 minutes. In comparison, fish were observed to be delayed downstream of the fishway in the Seton Dam tailrace for 18 hours on average, and as long as 107 hours prior to passage. This suggests that in relative terms, delay induced specifically by the counter is minimal. Furthermore, pool 32, the location where fish stage prior to exiting through the counter is characterized by low flow velocities and extensive cover as it passes directly through the dam. This may provide fish with an optimal location to recover from fishway ascent as it is protected and appears to require little effort for fish to hold position.

Frequent observations of fish approaching the counter from lower depths in pool 32 of the fishway suggest that the position of the counter within the water column may not be optimal. The exit from the last pool of the fishway into open water measures 2.4 m in width, and is approximately 2 m in submerged depth. However, fish can only exit the fishway through the counter as closely spaced debris racks block all other areas of passage. These debris racks are intended to accumulate debris that may otherwise become lodged further down the fishway. Debris is manually cleared from the rack approximately once a week, however, our assessment of the debris accumulation would suggest that accumulated debris remains in place until it is manually removed. This can be problematic as large accumulations can infiltrate the fishway counters and effectively block all fish from upstream passage of the Seton Dam. The larger two counter tunnels appeared to be more susceptible to debris accumulation than the four smaller tunnels. From visual observations this appeared to be due to sticks becoming lodged at angles within the large tunnels. Smaller vegetation, which would not normally accumulate in the tunnels, would then in turn become lodged against the sticks. In this way debris accumulation would propagate until passage through a given tunnel was completely obstructed.

Objective 5. Assess the potential impacts of Cayoosh flow dilution and the Carpenter Lake inflow from power generation on adult sockeye salmon behaviour and thermal experience in Seton Lake

Rationale

The BCRP Technical Review Committee requested that we incorporate greater consideration of the impacts associated with water inflow in Seton Lake from adjacent watersheds (i.e., the Cayoose Creek flow dilution and the Carpenter Lake penstock inputs). Although this objective deviated from the core focus of the fishway assessment, it does take advantage of the fact that we were able to release telemetered fish into Seton Lake to assess behaviour. To achieve this objective, we strategically deployed receiving stations to ensure that we provided coverage of the two potential distracting flow sites: both Cayoose Creek and Carpenter Lake provide potential distraction due to differential odor bouquet and thermal variation.

Methods

Fish Handling and Thermal Monitoring

Basic tagging and fish handling techniques were the same as in Objective 3 as this study utilized the same individual fish. The only difference was that the current analysis also included using archival thermal loggers that were placed in nine fish destined for Gates Creek. We only released thermal sensors on Gates fish as potential recovery rates were estimated to be much higher than for Portage. Although the fish carried positional telemetry transmitters, the temperature loggers (which were attached to the telemetry transmitter) required downloading to obtain the data. The temperature loggers used were called “I-Buttons” and were set to record water temperature (± 0.1ºC) every 30 minutes. Loggers were randomly affixed to acoustic transmitters using hot glue. This increased the size of transmitters by 4 mm in length. The diameter of the I-Buttons was the same as the diameter of the transmitters.

Telemetry Array

We used the same automated acoustic telemetry system (15 Vemco VR2 receivers) outlined under Objective 3. When planning the receiver deployments, two receivers were strategically positioned near the Cayoose Creek inflow (Receiver 4) and the Carpenter Lake penstocks at the Bridge-Seton Generating station (Receiver 8).

Fixed Thermal Logger Deployments in Seton Lake

Thermal loggers were deployed throughout Seton Lake in an effort to understand the thermal ecology of migratory salmonids and the potential influence of Cayoose Creek and Carpenter Lake inflow on fish behaviour. All thermal sensors were manufactured by Vemco and recorded temperature at 1 hour intervals. Three of the thermal loggers were deployed at a depth of 20 m on VR2 acoustic receiver deployment ropes in key locales in Seton Lake including the regions near the Portage Creek inflow (at Receiver 10), the Carpenter Lake inflow (at Receiver 8), and the downstream end of Seton Lake (approx 2 km from Seton Dam; at Receiver 5). One thermal logger was deployed on the Seton Dam face at a depth of 1 m from the surface, mid channel, immediately in front of the Seton Dam fishway exit. The final thermal logger was deployed in the Cayoose Creek inflow at a depth of 1 m, 15 m from the culvert exit.

Analyses

These analyses of telemetry data exclude two fish that fell back prior to entering Seton Lake and thus are limited to a sample size of 48. Whenever fish died and transmitters were positioned in a reception cell indefinitely, these fish were also excluded from analyses as the number of hits or time in station did not actually reflect fish behaviour or thermal experience. Analyses focus on descriptive and summary statistics for this section as this was not the primary objective of the fishway assessment and thus only represents preliminary data. Where appropriate, we drew comparisons between fish residency times or the number of telemetry detections on strategically placed receivers at the Cayoose and Carpenter inflows with paired receivers that were nearby, yet unlikely to be influenced by the inflows. Only with extensive real time mapping of plume dynamics would it be possible to assess fish thermal ecology an potential impacts of these inflows with any certainty.

Results

Summary Statistics

Almost all of the fish released at Seton Dam were subsequently detected on Receiver 4 (see Figure 8) (97.3%). One fish was able to move past Receiver 4 either indicating that the fish was not detected or alternatively that it did not pass through the reception zone. The mean time that fish spent in the reception zone of Receiver 4 was approx. 4 hours (n=48, mean ± SE, 249 ± 62 minutes) with a low of 23 min and a high of 40 hours (or 2407 min). To assess whether fish were delayed in this region, we compared the residency time in the vicinity of Receiver 4 with Receiver 5 (see Figure 8). Receiver 5 was located immediately upstream of Receiver 4 where there was no overlap of reception cells. In addition, Receiver 5 had 100% detection efficiency and covered the entire cross section of Seton Lake. In addition, Receiver 5 was out of the zone of thermal or odor influence from the Cayoose inflow and served as an appropriate comparison. Fish spent substantially more time in the vicinity of Receiver 5 than in the vicinity of Receiver 4. Time spent in receiver 5 during upstream movement ranged from a low of 27 minutes to a high of more than 10 days (n=48, mean ± SE, 36 ± 6 hours).

Although not all fish survived to reach Receiver 8, all fish that were detected upstream of this receiver were also detected on Receiver 8 (i.e., detection efficiency was 100%). Dwell time on Receiver 8 was more difficult to assess because fish often would mill in the vicinity of Portage Creek before either proceeding to Gates Creek (for Gates sockeye) or to Portage spawning grounds. In addition, many fish died in the vicinity of the Portage Creek outlet (some naturally after spawning and others as pre-spawn mortalities) making it necessary to filter the detections from those fish that died within a reception cell and then continued to be recorded indefinitely. After correcting for those transmitters, the sum of all detections on Receiver 8 was 32,325, nearly twice that on Receiver 9 (total detection = 64,089) which was adjacent to and just slightly upstream from Receiver 8. The mean duration that fish were in the vicinity of Receiver 8 while they were alive and prior to spawning was 31.8 ± 16.1 hrs (mean ± SE) with a maximum of 406 hrs and a minimum of <1 hr.

Thermal Conditions in Seton Lake

Water temperatures at the Seton Dam Fishway exit pool were variable throughout August (both within and among days), but tended to stabilize in September and October. On average between the 8th of August and the 19th of October 2005, water temperatures in the Cayoose outflow were 3.56 ± 0.037ºC lower than at the exit pool of the Seton Dam Fishway (paired t= -96.56, df=1736, P<0.0001; Figure 10). The magnitude of difference between the two sites was less for the first few weeks, but much greater in September and October. The variability of water temperature was much greater at the Cayoose inflow than at the Seton Dam Fishway (Levene's test, F=256.729, df=3472, P<0.0001).

Water temperatures in other regions of Seton Lake were also variable. For example, we evaluated the thermal conditions at a depth of 20 m near the Portage outflow, the Carpenter Lake penstocks, and in the eastern part of Seton Lake. Matched pair analysis revealed that on an hourly basis, water temperatures were significantly different among sites between August 8th and October 19th (Matched Pair Analysis, all P's <0.0001). Water temperature was coldest near the Carpenter Lake penstocks and the warmest at the eastern end of Seton Lake (Figure 11). Water temperatures were intermediate near the Portage inflow (Figure 11).

Reconstruction of Thermal and Movement Histories

Although we released 9 fish carrying both thermal loggers and acoustic transmitters, only two of these fish were recovered on terminal spawning grounds. Using movement detection histories from the receivers and the thermal records from the loggers, it was possible to reconstruct the behaviour and thermal ecology of two Gates stock sockeye. These reconstructions provide a powerful means to assess fish behaviour in the vicinity of the Cayoose Creek and Carpenter Lake inflows.

FISH 970A

The 60 cm female Gates fish was released on August 9th at 7:28am. The fish moved quickly from the release site, reaching Receiver 5 in 169 minutes (Figure 11). In total, only 79 minutes were spent in the vicinity of Receiver 4 and 48 minutes in the vicinity of Receiver 5. The waters in the vicinity of Receiver 4 are some of the shallowest in the lake and the Cayoose inflow is typically much colder than the ambient Seton Lake water temperature. There was no evidence in the thermal history of fish 970 that the fish was delayed in a thermal or odor distraction from the Cayoose inflow. In fact, it is only when the fish moves beyond Receiver 5 that the fish is found in cool water temperatures (below 15°C). Between time of release and arrival at the end of Seton Lake and detection on Receiver 10 (a distance of 21.9 km), only 13 hrs and 10 minutes transpired. This would yield an in-lake swimming speed of approx 1.6 km/hr or 0.44 m/sec. The fish stayed downstream of Portage River in Seton Lake for about 9 days and occupied water temperatures of about 14ºC. The majority of the receiver “hits” were logged on Receivers 9 and 10 and in total, less than 6% of the time in the lake prior to entering the Portage River was spent in the vicinity of Receiver 8 where the Carpenter Lake water flows into Seton Lake through the penstocks. Fish 970 entered Portage River on Aug 20 at 15:30. Upon entry into Portage River, water temperatures rose dramatically to more than 18ºC. The fish swam slowly through the Seton River, requiring 12.5 hours to travel a distance of 2.75 km (0.22 km/hr). The fish entered Anderson Lake on Aug 21 at approx. 02:00 and then moved directly to Gates spawning grounds where it left the lake on Aug 23 at 21:08 and was subsequently recovered on spawning grounds on August 27th. The cumulative migration time was 326 hours. The fish accumulated 202 degree days during migration upstream of Seton Dam.

FISH 396A

The 56 cm female Gates fish was released on August 16th at 10:01am (Figure 12). The first 12 hours after release were spent in the immediate vicinity of the release site (mostly at Receiver 1). During this time the fish experienced water temperatures of >18° C. When the fish began to move towards the spawning grounds, it moved quickly. It took only 61 minutes to move from Receiver 3 to Receiver 5, indicating that the Cayoose inflow was not a significant distraction. The fish arrived at Receiver 10 (the end of Seton Lake) at 03:45 on August 18th. However, the fish did mill in the vicinity of the Carpenter Lake penstocks (Receiver 8) for up to 22 hours and 28 minutes beginning on August 17th. The fish appeared to move between Receivers 8, 9, and 10 during the milling period and was not continuously recorded on a single receiver (thus the 22hr, 28 min period is an overestimate). Indeed, more signals were recorded for Receivers 9 (N=235) and 10 (N=236) than for Receiver 8 (N=229). Some of the coldest water temperatures experienced by Fish 396 while in Seton Lake were during this milling period perhaps indicating that the fish was occupying waters that were thermally impacted by Carpenter Lake. However, similarly cool water temperatures were experienced the previous day during active migration near receivers 5 to 7 – areas where presumably there was no clear thermal influence from Carpenter Lake. By noon on August 18th, the fish had presumably moved into shallower water near the outflow of Portage Creek. Water temperatures rose until the fish actually entered the creek at 20:12 on the 18th. Water temperatures experienced by the fish during passage through Portage Creek exceeded 21° C. Transit through Portage Creek required about 16 hours. Upon entering

Anderson Lake, the fish occupied water temperatures of about 10° C. Just after 6 am on August 21st, the fish left Anderson Lake and was recaptured in the Gates Spawning Channel on August 25th. The total duration of the active migration was 137 hours. During this period, the fish accumulated 98 degree days.

Discussion

Using an acoustic telemetry array and thermal loggers on fish, we were able to assess the potential impacts of Cayoosh Creek flow dilution and the Carpenter Lake inflow from power generation on adult sockeye salmon behaviour and thermal experience in Seton Lake. Migratory adult sockeye salmon were found within the vicinity of both the Cayoose Creek inflow and the Carpenter Lake inflow in Seton Lake. In fact, almost every sockeye we tagged were logged on the receivers placed at these locales. However, it is important to note that the receivers have reasonably circular reception cells that can have a radius of more than 1 km. Therefore, presence of a fish on either Receiver 4 or 8 does not necessarily mean that an individual fish is actually responding to the presence of any cues (thermal, odor, etc) from Cayoose or Carpenter Lake. Although we did record detections on both receivers 4 and 8, the number of signals logged and/or time spent on these receivers was still lower than on adjacent receivers (receiver 5 and 9 respectively).

Recovery of two fish equipped with thermal loggers and telemetry devices did not reveal any extended delays in the vicinity of the Cayoose or Carpenter inflows in Seton Lake. When the thermal histories were reconstructed, there were no clear anomalous thermal conditions that suggested that fish were utilizing thermal refugia that may have been provided by these inflows. Fish 396A did experience some of the lowest water temperatures during its Seton Lake residency when milling near Receivers 8 and 9 near the Portage inflow. Based on temperatures experienced by fish in Portage River (all quite high, >18C for fish 970A and >21C for fish 396A), the cool water temperatures were not a result of the inflow from Portage (and thus Anderson Lake). In lake systems, sockeye salmon typically swim at depth, spending much of their time at or below the thermocline. Temperature records for both Seton and Anderson Lake reconstructed from the two recovered loggers suggested that fish occupied regions of lower temperature in Anderson Lake than Seton Lake, perhaps reflecting availability or preferences. Thus, it is possible that the cool temperatures observed for Fish 396A simply reflect the fish swimming at depth rather than attraction to the Carpenter inflows. However, our limited thermal monitoring did reveal that the water temperatures near the Carpenter Lake penstocks (at a depth of 20 m) were lower than in other regions of Seton Lake (at 20 m).

Our data did not reveal any clear evidence of delays attributable to the Cayoose or Carpenter inflows. The only substantive observation was the fact that surface waters at the SDF were variable in August. The specific cause for the thermal variability is unclear and may simply reflect natural variation in lake thermal conditions (driven by wind and solar radiation). If this is the case, the system would experience some of the most dramatic natural thermal variation that our research team has observed. It is thus possible that the Cayoose inflow (of varying quantity) coupled with flow dynamics (driven by wind, water temperature, etc) results in high thermal variability. Indeed, the thermal conditions of the Cayoose inflow were substantially higher than those at SDF. Although there is little known about the effects of fluctuating water temperatures on fish, it may be energetically costly and could evoke a stress response. Future research efforts could include detailed modeling/mapping of the Cayoose inflow and its effects on the Seton River water temperature. At present, we do not believe that sockeye salmon behaviour relative to the Cayoose or Carpenter Lake inflows into Seton Lake requires additional research activity.

Although this study was not a rigorous assessment of the issue, our data failed to illustrate any clear negative consequences of these inputs on sockeye migration.

As this objective was not one of the primary purposes of the fishway study, the methods used reflect synergies with other objectives. Future studies directed at assessing fish behaviour relative to either the Cayoose or Carpenter Lake inflows should utilize telemetry arrays with smaller reception cells or ideally a 2 or 3 dimensional positioning system. In addition, telemetry transmitters that report both depth and temperature would provide more detailed information on fish behaviour in these regions. Finally, any future telemetry studies should be coupled with detailed dynamic mapping of the thermal plumes from these two inflows as well as the inflow from Gates Creek (into Anderson Lake) and Portage Creek (into Seton Lake).

Recommendations

Typical BCRP projects are on-the-ground restoration projects. The focus of this project was somewhat different in that it was focused on evaluating existing mitigative infrastructure (i.e., the Seton Dam Fishway) to determine if it enabled fish to successfully pass Seton Dam. The recommendations below should be viewed as opportunities to further enhance the ability of fish to find and ascend the fishway. Essentially, the objective of any fishway project should be to make a barrier (or dam) invisible to the fish such that there is no appreciable delay or negative consequences of passage. Thus, our recommendations are focused on achieving that objective. Many of the recommendations are simple and reflect basic operational changes. Other recommendations involve potential alterations to dam infrastructure and should be considered during dam upgrades/maintenance in future years.

Recommendation 1. Increase visitation to the fishway during key migratory periods in order to ensure that it is functioning and free of debris. It was clear from our appearance at Seton Dam that the fishway was not visited frequently by personnel with the purpose of ensuring that the fishway was free of debris. Debris (mostly wood) can become lodged in pools and vertical slots creating blockages. In addition, the screen on the upstream fishway pool is intended to keep debris out of the fishway and funnel fish out of the resistivity counters. As revealed by our data, the counters were frequently blocked. We suggest that the fishway should be tended at least daily during key migratory period by an individual (or team) with the sole purpose of assessing fishway performance and clearing debris. Quite simply, a blocked fishway is not a functional fishway. A small amount of debris can permanently block all fish passage until the next staff visit, effectively halting the entire upstream migration of fish bound for the Seton watershed.

Recommendation 2. Reconsider the use of the resistivity counters at the fishway exit pool. Our observations suggest that the fishway counters act as a potential bottleneck for migration of salmonids, and, they do not produce accurate estimates of fish passage abundance. The most immediate priority should be to determine if and how the counter data are used. If the data are useful for management, then perhaps it would be better to locate the counter lower in the water column as fish tend to approach it from below. Our video observations revealed fish staging in the water column below the exits. Alternatively, it may be worthwhile to explore other tools for estimating fish passage rates and abundance. If the data are not used, then the fishway counters should be removed.

Recommendation 3. Daily Seton Dam Fishway counts should be annotated with details on blockage and debris accumulation. The proposed increased visitation of the fishway should be coupled with more complete reporting of blockages to help focus debris removal activities. A simple spreadsheet can be used to document the amount of debris removed during each cleaning and the extent to which fish passage was impeded or blocked.

Recommendation 4. Improve trash racks upstream of counter and/or fishway exit to reduce blockage. As debris accumulation at the fishway exit pool is a clear impedance to fish passage, any efforts to reduce debris accumulation should enhance passage. To that end, we suggest developing improved trash racks to collect debris while maintaining fish passage opportunities.

Recommendation 5. Consider modifying the wall that separates the radial gate spillway from the main spillway to minimize entrainment of fish in radial gate spillway. From a biological perspective, the wall that separates the two spillways could be “shortened” such that it does not extend downstream beyond the siphon exits on the dam face to enable free movement of fish along the dam face and into the fishway entrance. We are unsure of the original purpose or function of this wall (which may be structurally important), but a previous study has shown that altering fishway infrastructure can greatly enhance attraction efficiency.

Recommendation 6. Address the issue of fishway entrance attraction through further study and possibly operation/structural changes such as testing attraction under higher and lower spill rates and modifying the arrangement of the baffle blocks to alter downstream flows. There was some evidence that fish had some difficulty in approaching the entrance, resulting in migration delays in dam spillways. We suggest further telemetry-based studies to assess this aspect of the hydro-complex design. Future telemetry studies should attempt to capture fish at a location downstream of the fishway in order to better understand the extent to which migrants passed or fell back. Efforts should also be made to capture fish as they arrive rather than fish that may have been previously delayed. Though we found no differences in attraction rates under the two spill rates that we observed, potential improvements in attraction efficiency may be realized under flow regimes not studied in this report. By altering operational flows to produce either higher or lower spill rates than those assessed here, a telemetry study may be able to elicit potential benefits in terms of reducing migration delay. In terms of structural changes, the rearrangement of the baffle blocks may better maintain attraction flows while simultaneously providing fish with easier paths to the fishway entrance. We are unable to propose specific configurations, but feel that the fishway attraction flow may have provided a challenging downstream flow environment for some fish. Additionally, efforts to provide fish with temporary refugia in high flow regions may be beneficial.

Recommendation 7. Conduct detailed thermal modeling on the plume dynamics of the Cayoose inflow and the Carpenter Lake inflow to assess their potential influence on fish migration. Our study provided some of the first thermal ecology information on the Seton watershed. Although we deployed thermal loggers in several locales, we contend that there is a need for a detailed study on the thermal plumes of these two sites.

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Table 1. Hours of tracking for radio tagged sockeye (S) and pink (P) salmon studied in Objective 1. (-) indicates that this fish did not pass through the SDF.

Species	Fish #	Hours tracked	Pass time (day/night)
S	3006	10	night
S	3007	16.5	night
S	3013	1	night
S	3017	11.5	day
S	3018	10.75	day
S	3019	2.5	day
S	3022	4	day
S	3023	7.5	-
S	3026	6	-
S	3029	11.5	day
S	3030	11	night
S	3033	44.25	night
S	3039	30.75	-
S	3041	11	night
S	3045	3.5	night
S	3063	10.5	night
S	3064	10.5	night
S	3076	7.5	night
S	3077	16.5	night
S	3080	8.5	night
S	3081	4.5	day
S	3108	4.5	day
S	3109	6.5	night
S	3110	6.5	night
S	3122	8	day
S	3123	4	day
S	3139	13.5	-
S	3142	7.5	-
S	3144	12	-
S	3166	4.5	-
P	3088	33	-
P	3089	36	-
P	3090	12	day
P	3091	14	-
P	3101	17	-
P	3102	6	-
P	3104	5	day
P	3105	15	-
P	3106	8	-

Table 2. Mean and standard error (SE) of physiological and size measures for radio tagged sockeye salmon that successfully located and passed the fishway, and those that fell back down Seton Creek. P-values and degrees of freedom (df) associated with the statistical contrast are presented. Significant results using sequential-Bonferroni $\alpha = 0.05$ are bolded.

	Pass (n = 23)		Fall back (n = 5)			
	mean	SE	mean	SE	P	df
Lactate (mmol/L)	2.455	0.255	2.404	0.445	0.901	26
Glucose (mmol/L)	5.565	0.851	4.394	0.258	0.596	26
Na+ (mmol/L)	145.000	1.585	147.300	1.281	0.530	26
Osmolality (mmol/L)	303.609	2.320	302.100	2.861	0.617	26
Hematocrit (%)	38.522	0.622	39.800	1.655	0.570	26
Gross somatic energy (MJ/kg)	5.552	0.229	6.403	0.437	0.118	26
Fork length (cm)	56.930	0.510	60.300	1.546	**0.013**	26

Table 3. Pearson correlations (r) [and the associated probability level (P)] between time spent by radio-tagged sockeye (n = 28) in the Seton Dam tailrace and physiological and size variables.

	r	*P*
Lactate (mmol/L)	-0.257	0.195
Glucose (mmol/L)	-0.148	0.462
Na+ (mmol/L)	0.178	0.375
Osmolality (mmol/L)	0.230	0.249
Hematocrit (%)	0.297	0.132
Gross somatic energy (MJ/kg)	0.155	0.439
Fork length (cm)	0.257	0.195

Table 4. Mean and standard error of physiological and size measures for radio tagged pink salmon that successfully located and passed the fishway, and those that fell back down Seton Creek. We were unable to assess absolute energy levels on pink salmon - relative energy density is a unit-less measure directly obtained from the fat probe.

	Pass (n = 2)		Fall back (n = 7)	
	mean	S.E.	mean	S.E.
Lactate (mmol/L)	6.635	2.495	5.974	1.046
Glucose (mmol/L)	5.705	1.125	5.091	0.203
Na+ (mmol/L)	145.250	0.250	139.643	3.338
Osmolality (mmol/L)	307.750	3.750	306.000	4.033
Hematocrit (%)	36.500	3.500	39.857	1.738
Relative energy density	1.025	0.025	1.186	0.198
Fork length (cm)	55.500	0.500	51.714	1.169

Table 5. Time to pass through the SDF, mean and maximum ascent speeds, mean swim speeds in pool 17, and total number of EMG pulse interval signals recorded for each individual EMG-tagged sockeye that successfully re-ascended the fishway.

Fish #	Fishway passage time (min)	Mean ascent swim speed (cm/sec)	Max swim speed (cm/sec)	Time in pool 17 (min)	Mean swim speed in pool 17 (cm/sec)	Number of EMG signals recorded
3020	67	28.5	139	5.23	17.6	2220
3024	52	2.6	92.4	16.68	1.6	1062
3025	89	11.7	223.9	18.02	7	2338
3040	74	44.9	218.1	35.82	46.2	2745
3042	80	7.4	194.7	38.80	3.4	2068
3079	55	86.0	382.2	15.77	70.1	2319
3027	28	n/a	n/a	n/a	n/a	n/a

Table 6. Mean and standard error (SE) for the physiological and size measures for EMG tagged sockeye salmon that successfully re-ascended the fishway on the first attempt, and those that fell out into the spillway. P-values associated with the statistical test are included. Significant P-values using sequential-Bonferroni $\alpha = 0.05$ are bolded.

	Pass on first try (n = 7)		Fall out of fishway (n = 8)		
	mean	SE.	mean	SE	*P*
Lactate (mmol/L)	1.833	0.318	2.870	0.612	0.202
Glucose (mmol/L)	4.666	0.303	4.593	0.468	0.764
Na+ (mmol/L)	149.642	1.741	143.813	1.172	**0.010**
Osmolality (mmol/L)	306.214	1.924	301.688	3.452	0.451
Hematocrit (%)	40.571	1.131	40.250	0.726	0.836
Gross somatic energy (MJ/kg)	6.489	0.273	6.587	0.463	0.863
Fork length (cm)	58.143	1.004	58.000	0.845	0.520

Table 7. Mean and standard error (SE) for physiological and size measures for the two ascent strategies observed among EMG tagged sockeye salmon that successfully re-ascended the fishway on the first attempt. Ascent strategy 1 refers to fish that minimally used high swim speeds (>100 $cm^{\cdot}sec^{-1}$), while ascent strategy 2 refers to those that frequently used high swim speeds (>100 $cm^{\cdot}sec^{-1}$). P-values associated with the statistical tests provided.

	Ascent strategy 1 (n = 3)		Ascent strategy 2 (n = 3)		
	mean	SE	mean	SE	*P*
Lactate (mmol/L)	2.130	0.615	1.814	0.414	1.000
Glucose (mmol/L)	5.020	0.486	4.477	0.535	0.663
Na+ (mmol/L)	151.000	2.566	147.000	2.784	0.383
Osmolality (mmol/L)	306.833	3.941	306.667	2.892	0.825
Hematocrit (%)	40.667	0.667	42.000	2.000	1.000
Gross somatic energy (MJ/kg)	6.183	0.217	6.789	0.618	0.663
Fork length (cm)	58.333	1.202	57.333	2.167	1.000

Table 8. Mean and standard error (SE) of the physiological and size data collected for EMG-tagged pink salmon (n = 6). As no EMG-tagged pink salmon re-ascended the fishway, no statistical comparisons could be made between re-ascent and non re-ascent. We were unable to assess absolute energy levels on pink salmon - relative energy density is a unit-less measure directly obtained from the fat probe.

	mean	SE
Lactate (mmol/L)	6.088	0.793
Glucose (mmol/L)	4.240	0.344
Na+ (mmol/L)	139.750	2.610
Osmolality (mmol/L)	304.917	2.275
Hematocrit (%)	36.667	0.422
Relative energy density	1.117	0.214
Fork length (cm)	51.833	0.307

Table 9. Acoustic receiver station identification numbers, geo-location information, receiver detection efficiency and deployment mode for acoustic telemetry study. See Figure 8 for corresponding map locations.

Receiver ID Number	Receiver ID Code	Latitude	Longitude	Distance Between Receiver Sites (km)	Receiver Detection Efficiency (%)	Deployment Type
1	2058C				93.8	Structural
2	2055C				100	Structural
3	2059C				100	Structural
4	2063C	50 39.888'N	121 59.583'W		97.9	Structural
5	5109C	50 40.550'N	122 01.782'W	2.8626	100	Subsurface
6	5105C	50 41.210'N	122 05.535'W	4.5787	100	Subsurface
7	5107C	50 42.665'N	122 10.453'W	6.3786	100	Subsurface
8	5108C	50 43.630'N	122 14.025'W	4.5618	100	Subsurface
9	5114C	50 42.878'N	122 14.554'W	1.5273	100	Subsurface
10	5113C	50 42.399'N	122 15.854'W	1.767	100	Subsurface
11	2056C	50 42.157'N	122 18.167'W	2.7546	62.9	Structural
12	5106C	50 39.758'N	122 22.154'W	6.4635	95.2	Subsurface
13	5110C	50 37.931'N	122 24.537'W	4.3987	100	Subsurface
14	5111C	50 33.711'N	122 27.852'W	8.7487	100	Subsurface
15	5112C	50 33.132'N	122 28.336'W	1.2163		Subsurface

Table 10. Summary information on the sockeye salmon tagged with acoustic transmitters. Data recorded includes fork length (FL, mm), sex, the transmitter code, the presence of a temperature sensor, the date of tagging, and the fate of the fish. Transmitter codes a and b represent fish that were tagged with the same transmitter after the device was recovered from spawning grounds. Fate categories were survive to terminal spawning grounds (S), mortality (M), and fishery harvest (F). Stock refers to Gates or Portage (Port).

Fish #	Stock	FL (mm)	Sex	Transmitter Code	Temperature Sensor	Tagging Date	Fate
1	Gates	61	F	937	N	8/9	M
2	Gates	57	F	948	N	8/9	M
3	Gates	60	F	970a	N	8/9	S
4	Gates	63	F	933a	N	8/9	S
5	Gates	59	M	930	N	8/9	F
6	Gates	56	F	114a	N	8/9	S
7	Gates	57	F	926	N	8/10	M
8	Gates	57	F	954	N	8/10	F
9	Gates	58	M	972	N	8/10	F
10	Gates	52.5	F	949	N	8/11	M
11	Gates	61	M	102	N	8/11	F
12	Gates	55	F	940	N	8/11	M
13	Gates	57	F	943a	N	8/16	S
14	Gates	56	F	396a	Y	8/16	S
15	Gates	55.5	F	395a	N	8/16	S
16	Gates	58	M	394a	N	8/16	S
17	Gates	58	F	105	N	8/16	M
18	Gates	61	M	399	N	8/25	M
19	Gates	58	M	406	N	8/26	M
20	Gates	55.5	F	412	N	8/26	M
21	Gates	52	F	396b	Y	8/30	M
22	Gates	54	F	970b	Y	8/30	S
23	Gates	54.5	F	114b	N	8/30	S
24	Gates	56	F	395b	Y	9/5	S
25	Gates	57	M	933b	N	9/5	S
26	Gates	63	M	943b	Y	9/5	S
27	Gates	54	F	394b	Y	9/10	M
28	Gates	55	F	407	N	9/10	M
29	Gates	56	M	409	N	9/10	S
30	Port	60	M	400	Y	9/20	S
31	Port	53	M	403	Y	9/20	S
32	Port	55	F	74	N	9/20	S
33	Port	56.5	F?	408	N	9/21	S
34	Port	59	M	973	N	9/21	S
35	Gates	59	M	77	N	9/21	S
36	Port	61	F?	440	N	9/22	M
37	Port	58	F?	405	N	9/22	S
38	Port	60.5	F?	68	N	9/22	S

39	Port	57	F	402	N	9/22	S
40	Port	58	M	438	N	9/22	S
41	Port	56	F	441	N	10/4	S
42	Port	58	F	432	N	10/4	S
43	Port	59	m	426	N	10/4	S
44	Port	53	f	439	N	10/4	M
45	Port	57	f	80	N	10/4	S
46	Port	58	m	424	N	10/4	S
47	Port	62	m	75	N	10/4	S
48	Port	59	f	433	N	10/4	S
49	Port	60	f	431	N	10/4	S
50	Port	59.5	m	404	N	10/4	S

Table 11. Fates of acoustically tagged sockeye salmon in Seton and Anderson Lake. Fishery removals are difficult to quantify with certainty and these fish may represent additional natural mortality.

Fate		Gates Stock	Portage Stock
Survivor	N	14	18
Survivor	%	46.9%	90%
In Lake Mortality	N	10	2
In Lake Mortality	%	33.3%	10%
Fallback Mortality	N	2	0
Fallback Mortality	%	6.6%	0%
Fishery Removal	N	4	0
Fishery Removal	%	13.2%	0%
Total Fish	N	30	20

Table 12. Summary information on the sockeye salmon tagged with acoustic transmitters and their physiological status. Data recorded includes fork length (FL, mm), the transmitter code, the fate, hematocrit (HCT), and plasma lactate, glucose, and chloride. Fate categories were survive to terminal spawning grounds (S), mortality (M), and fishery harvest (F) as above. Stock refers to Gates or Portage (Port).

Fish #	Stock	FL (mm)	Transmitter Code	Fate	HCT (%)	Lactate (mmol l^{-1})	Glucose (mmol l^{-1})	Cl- (mmol l^{-1})
1	Gates	61	937	M	42	2.040	3.930	138.2
2	Gates	57	948	M	41	1.940	3.670	136.1
3	Gates	60	970a	S	NA	1.640	3.730	137.75
4	Gates	63	933a	S	36	NA	NA	NA
5	Gates	59	930	F	40	1.670	4.870	140.3
6	Gates	56	114a	S	39	0.652	4.320	138.45
7	Gates	57	926	M	42	2.900	5.550	142.85
8	Gates	57	954	F	44	1.730	4.360	135.25
9	Gates	58	972	F	45	5.840	4.340	116
10	Gates	52.5	949	M	45	9.290	6.320	130.75
11	Gates	61	102	F	39	4.320	5.260	141.6
12	Gates	55	940	M	44	4.640	5.090	143.65
13	Gates	57	943a	S	38	2.250	4.590	136.2
14	Gates	56	396a	S	47	4.380	7.280	150.75
15	Gates	55.5	395a	S	43	1.320	4.270	137.5
16	Gates	58	394a	S	38	1.590	5.640	140.9
17	Gates	58	105	M	39	1.310	7.180	139
18	Gates	61	399	M	NA	NA	NA	NA
19	Gates	58	406	M	38	5.200	2.870	123.85
20	Gates	55.5	412	M	41	17.700	5.680	104.05
21	Gates	52	396b	M	38	2.730	3.790	134.75
22	Gates	54	970b	S	39	2.080	3.810	137
23	Gates	54.5	114b	S	37	2.030	5.310	138
24	Gates	56	395b	S	38	3.260	3.500	135.85
25	Gates	57	933b	S	41	3.120	4.150	136.95
26	Gates	63	943b	S	42	2.150	3.900	134.35
27	Gates	54	394b	M	36	5.280	6.100	141.95
28	Gates	55	407	M	37	2.130	5.130	141.25
29	Gates	56	409	S	35	1.360	4.500	136.05
30	Port	60	400	S	39	3.440	3.700	138.7
31	Port	53	403	S	37	0.917	2.98	NA
32	Port	55	74	S	35	3.000	4.840	141.4
33	Port	56.5	408	S	36	3.000	3.560	135.4
34	Port	59	973	S	49	3.000	6.470	140.45
35	Gates	59	77	S	39	3.220	5.270	142.15
36	Port	61	440	M	38	1.780	4.810	136.55
37	Port	58	405	S	43	2.510	4.920	136.6

38	Port	60.5	68	S	37	1.480	3.780	136.95
39	Port	57	402	S	36	3.76	3.890	140.6
40	Port	58	438	S	40	1.720	4.680	139.5
41	Port	56	441	S	36	2.430	3.440	139.3
42	Port	58	432	S	39	4.040	4.360	141.65
43	Port	59	426	S	38	1.120	4.310	137.1
44	Port	53	439	M	37	5.870	3.900	146.6
45	Port	57	80	S	43	4.000	3.760	144.85
46	Port	58	424	S	40	2.080	3.810	137
47	Port	62	75	S	41	2.210	5.630	139.45
48	Port	59	433	S	43	3.260	3.500	135.85
49	Port	60	431	S	37	3.120	4.150	136.95
50	Port	59.5	404	S	40	2.150	3.900	134.35

Table 13. Descriptions of each classification of counter tunnel blockage. Classes were assigned to each tunnel on a daily basis throughout the month of August, 2005.

Class	Description
1	Clear- no blockage
2	Minimal debris- unlikely to impede movement
3	Moderate debris likely to impede movement, but fish can generally pass
4	Extensive debris- large fish cannot pass, small fish are likely impeded
5	Completely blocked- no fish can pass

Table 14. Summary of enumeration data collected from video playback and from the automated counter system. Tallies indicate the number of fish that moved upstream through each set of tunnels and in total. Small tunnels include tunnels 1-4 and large tunnels 5 and 6. Each line represents fish passage for the hour starting as indicated. Data specific to each set of tunnels was not discernable for the video captured on September 5, 2005.

		Video			Counter		
Date	Hour Start	Small tunnels	Large tunnels	Total	Small tunnels	Large tunnels	Total
Aug-02	15:00	0	0	0	5	1	6
Aug-02	16:00	0	1	1	1	3	4
Aug-05	17:00	1	0	1	2	0	2
Aug-05	10:00	0	1	1	0	0	0
Aug-05	11:00	1	0	1	0	0	0
Aug-05	12:00	0	0	0	0	0	0
Aug-05	13:00	0	0	0	0	0	0
Aug-05	14:00	0	0	0	0	0	0
Aug-05	15:00	3	1	4	0	0	0
Aug-05	16:00	1	1	2	0	0	0
Aug-07	12:00	0	0	0	0	0	0
Aug-07	13:00	0	0	0	0	1	1
Aug-07	14:00	9	5	14	0	0	0
Aug-07	15:00	7	8	15	1	3	4
Aug-07	16:00	5	4	9	1	3	4
Aug-07	17:00	2	2	4	0	4	4
Aug-07	18:00	0	2	2	0	2	2
Aug-19	15:00	13	5	18	0	1	1
Aug-19	16:00	23	22	45	0	4	4
Aug-19	17:00	16	33	49	4	13	17
Sep-05	11:07	n/a	n/a	137	0	4	4
Sep-05	12:07	n/a	n/a	72	4	9	13
Sep-05	13:07	n/a	n/a	103	4	2	6
Sep-05	14:07	n/a	n/a	86	8	3	11
Sep-05	15:07	n/a	n/a	104	5	6	11

Table 15. Summary of the debris accumulation for each of the six tunnels comprising the resistivity counter throughout the month of August, 2005. Values are expressed in terms of the percent of the month that each tunnel was associated with each debris classification. Debris classes range from clear (1) through completely blocked (5); details are provided in Table 13.

Debris class	Small Tunnels			Large tunnels		
	Tunnel 1	Tunnel 2	Tunnel 3	Tunnel 4	Tunnel 5	Tunnel 6
1	94%	85%	85%	88%	64%	46%
2	3%	12%	12%	3%	18%	24%
3	-	-	-	6%	3%	15%
4	-	-	-	3%	3%	6%
5	3%	3%	3%	-	12%	9%

Figure Captions

Figure 1. Map showing location of study site in British Columbia, Canada. The study site is contained within the subsection as indicated within the figure. The cities of Vancouver, B.C. and Lillooet, B.C. are shown for reference. Figure plate was adapted from Andrew and Geen (1958).

Figure 2. Map showing the geographic extent of the present study. All fish used in this study were captured at the Seton Dam. The location of Gates Creek Spawning Channel and Portage Creek, terminal spawning destinations for the Gates Creek and Portage Creek sockeye stocks respectively, are indicated on the map. Figure plate was adapted from BCRP Strategic Plan (SRWP).

Figure 3. Map of Seton Creek, with detail shown from the confluence with the Fraser River to Seton Lake. Seton Dam and fishway are noted as is the diversion canal leading to the hydro-power generating station located adjacent to the Fraser River. Salmon spawning channels along Seton Creek, primarily used by pink salmon are indicated. Figure plate was adapted from BCRP Strategic Plan (SRWP).

Figure 4. Detailed schematic of the Seton Dam. The diversion canal leads to the Seton power house, while Seton Creek continues to the confluence with the Fraser River. The location of the fishway is indicated along the South bank of Seton Creek, adjacent to the Seton Dam. Upstream of the fore bay is Seton Lake. Figure plate was adapted from Andrew and Geen (1958).

Figure 5. Detail of the Seton Dam and fishway showing the locations where radio-tagged salmon were released for the attraction section of the study (1), and the location where EMG-tagged salmon were released (pool 3) for the passage section of the study (2). The extent of the whitewater (i.e. higher flow velocities spilled from the dam) is roughly indicated by (3). Figure plate was adapted from Andrew and Geen (1958).

Figure 6. Examples of the two different ascent strategies observed among fish that successfully re-ascended on the first attempt. A) A swimming trace specific to fish #3042 as it ascends from pool 3 to pool 17 of the fishway over the course of approximately 7 minutes. B) A swimming trace specific to fish #3040 as it ascends from pool 3 to pool 16 of the fishway over the course of approximately 7.5 minutes. Each swim trace represents approximately one half of the fishway in terms of distance traveled, and was shown in this way to increase clarity of swimming behaviour of each fish. (*) represents an upstream passage event into the next pool. Swim speeds (y-axis) are shown in $\text{cm}\cdot\text{sec}^{-1}$, and actual ascent time along the x-axis.

Figure 7. Swim speed distributions for each of the two fish in Figure 6, over the course of their ascent. A) The distribution of swim speeds for fish #3042 during fishway ascent from pool 3 to pool 17. B) The distribution of swim speeds for fish #3040 during fishway ascent from pool 3 to pool 16. Swim speeds range from <12 $\text{cm}\cdot\text{sec}^{-1}$ (slow) to ~144 $\text{cm}\cdot\text{sec}^{-1}$ (fast).

Figure 8. General locations of VR2 acoustic receivers in Seton and Anderson Lakes. Each number represents the location of a VR2 receiver in sequential order starting from the most downstream location (1) at the Seton Dam. Gates Creek and Portage Creek sockeye spawning

locations are noted for reference. See Table 9 for more details. Figure plate was adapted from BCRP Strategic Plan (SRWP).

Figure 9. Relationship between the number of fish recorded moving upstream through the resistivity counter by the automated counter device and those observed on video playback. Each point represents the number of fish passing through all tunnels combined for a given hour as assessed independently by both the counter and the video recordings. A) The overall relationship based on data collected from August 2 - September 5, 2005. B) The relationship only with data collected prior to August 8, 2005, during the early stages of sockeye migration. C) The relationship only with data collected after August 18, 2005, during the mid to late stages of sockeye migration. Further details are provided in Table 14.

Figure 10. Trace of thermal recordings at the Seton Dam (black diamonds) and Cayoose inflow (grey diamonds) in 2005 at a depth of 1 m. Thermal loggers were fixed to stationary objects at each location.

Figure 11. Trace of thermal recordings at the Portage Creek inflow (grey triangles), the Carpenter Lake penstocks (open squares), and the eastern end of Seton Lake (black diamonds) in 2005 at a depth of 20 m. Exact deployments were on the acoustic receivers located at Receiver 10, 8, and 5, respectively.

Figure 12. Thermal history of a Gates stock sockeye salmon (Fish 970a) in Seton and Anderson Lakes relative to position of acoustic telemetry receivers. The fish was recovered on the Gates Creek Spawning Channel. Details of the tracking and thermal history are available in the text.

Figure 13. Thermal history of a Gates stock sockeye salmon (Fish 396a) in Seton and Anderson Lakes relative to position of acoustic telemetry receivers. The fish was recovered on the Gates Creek Spawning Channel. Details of the tracking and thermal history are available in the text.

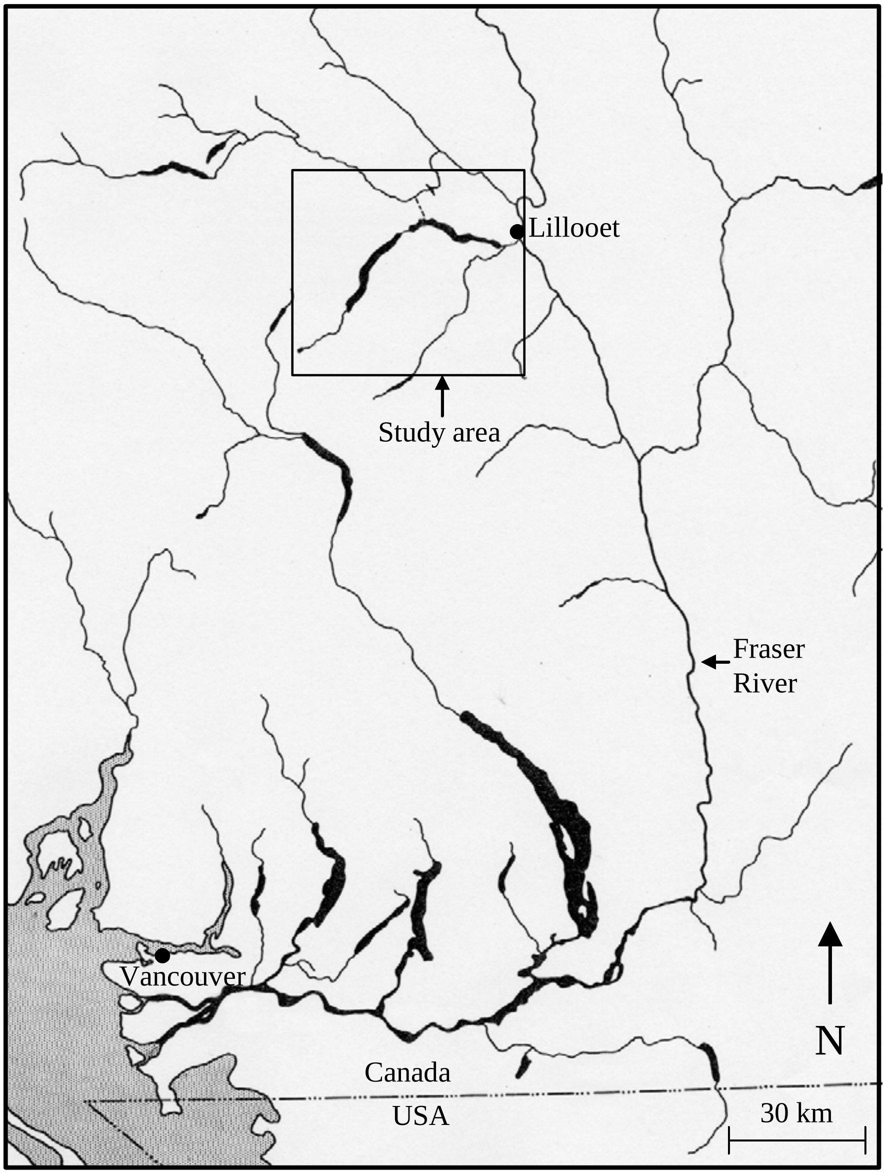


Figure 1 – Pon et al. BCRP project S06-01

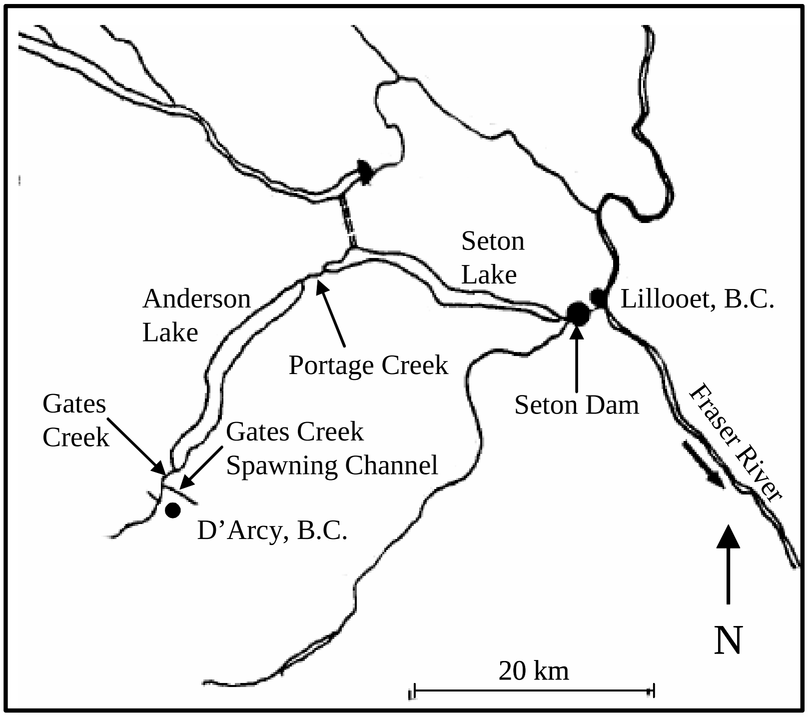


Figure 2 – Pon et al. BCRP project S06-01

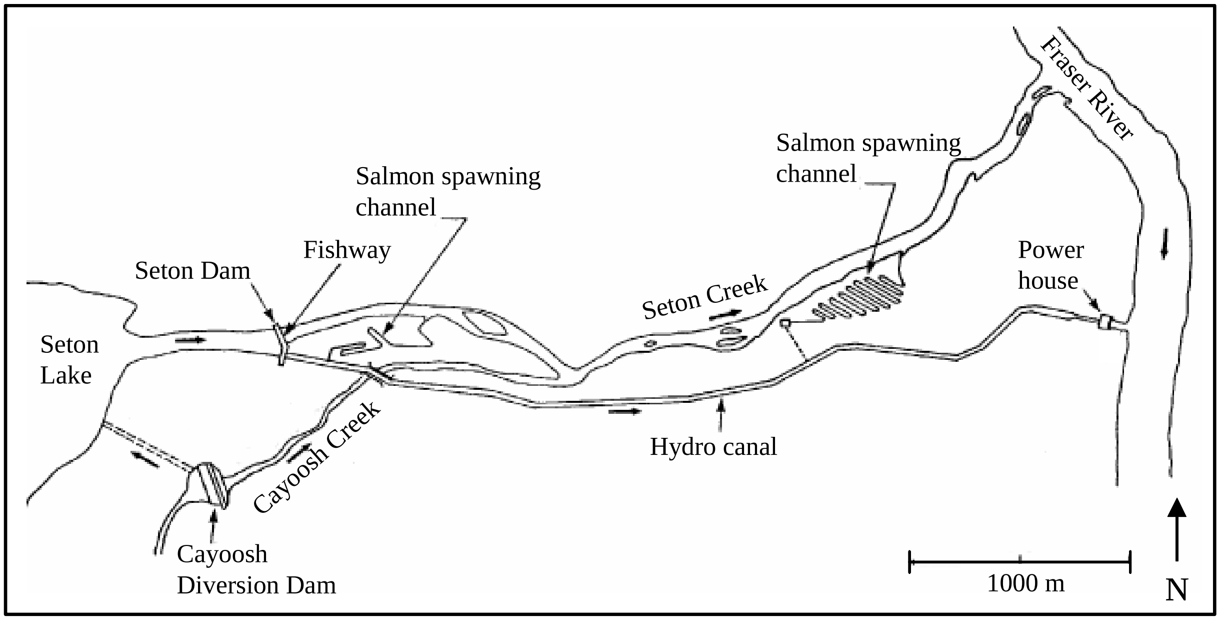
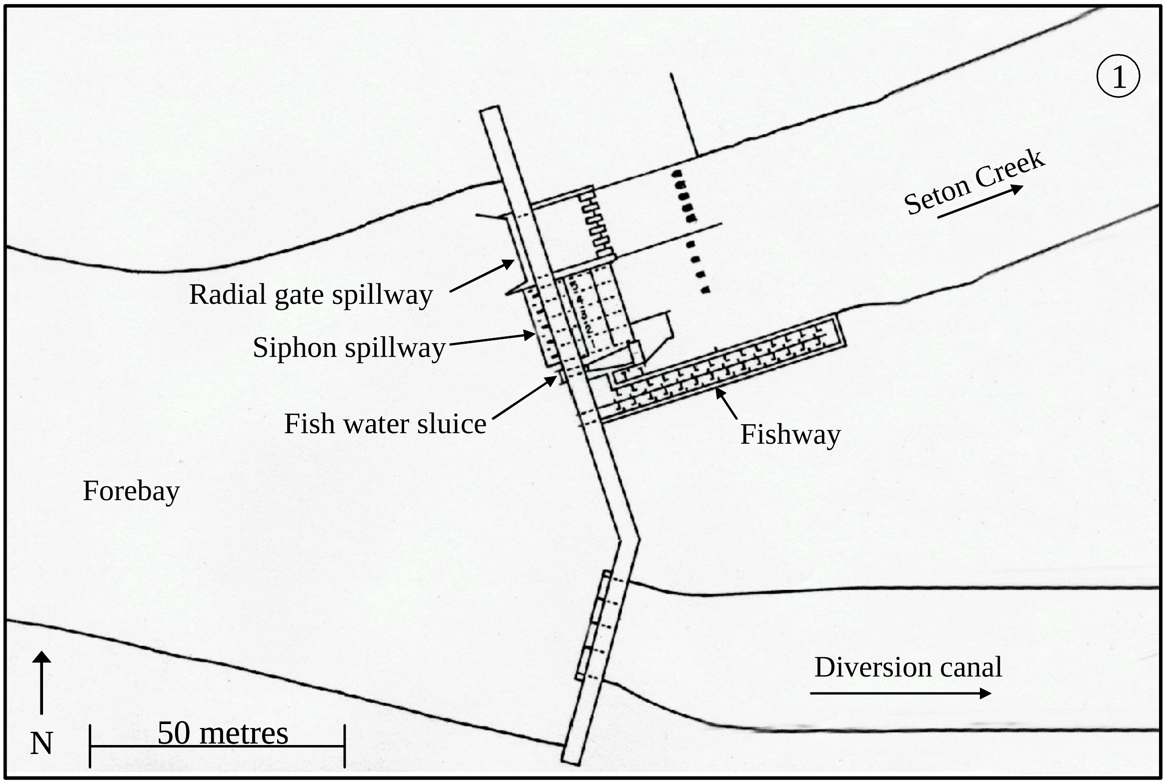


Figure 3 – Pon et al. BCRP project S06-01



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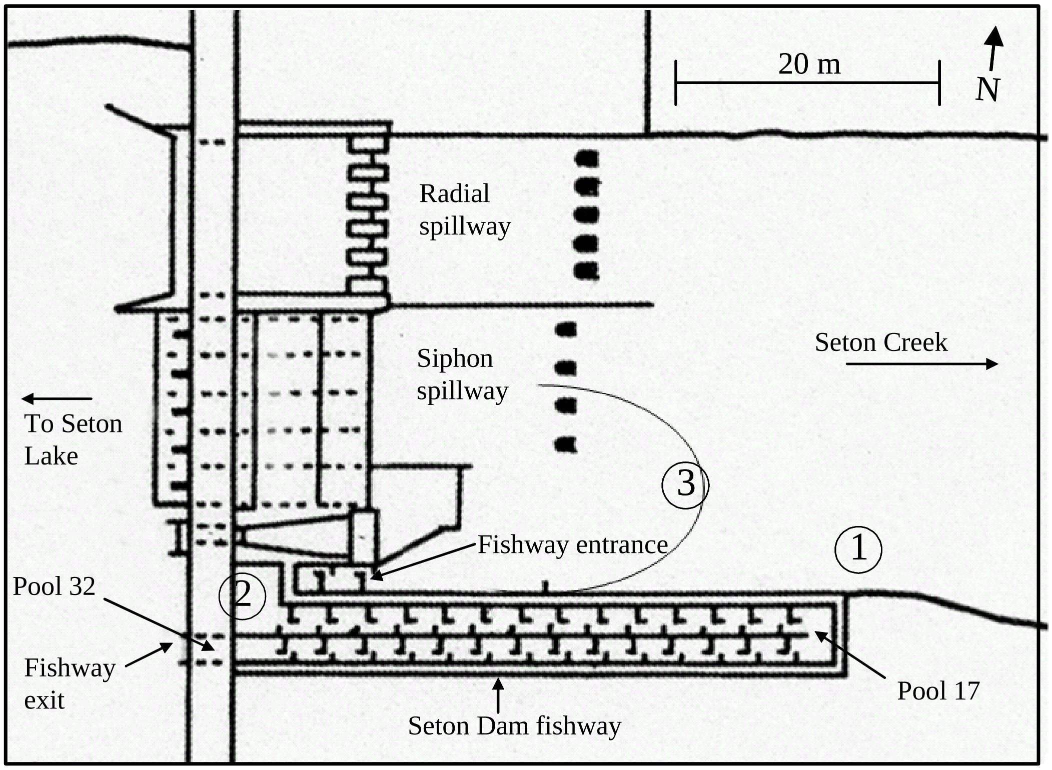

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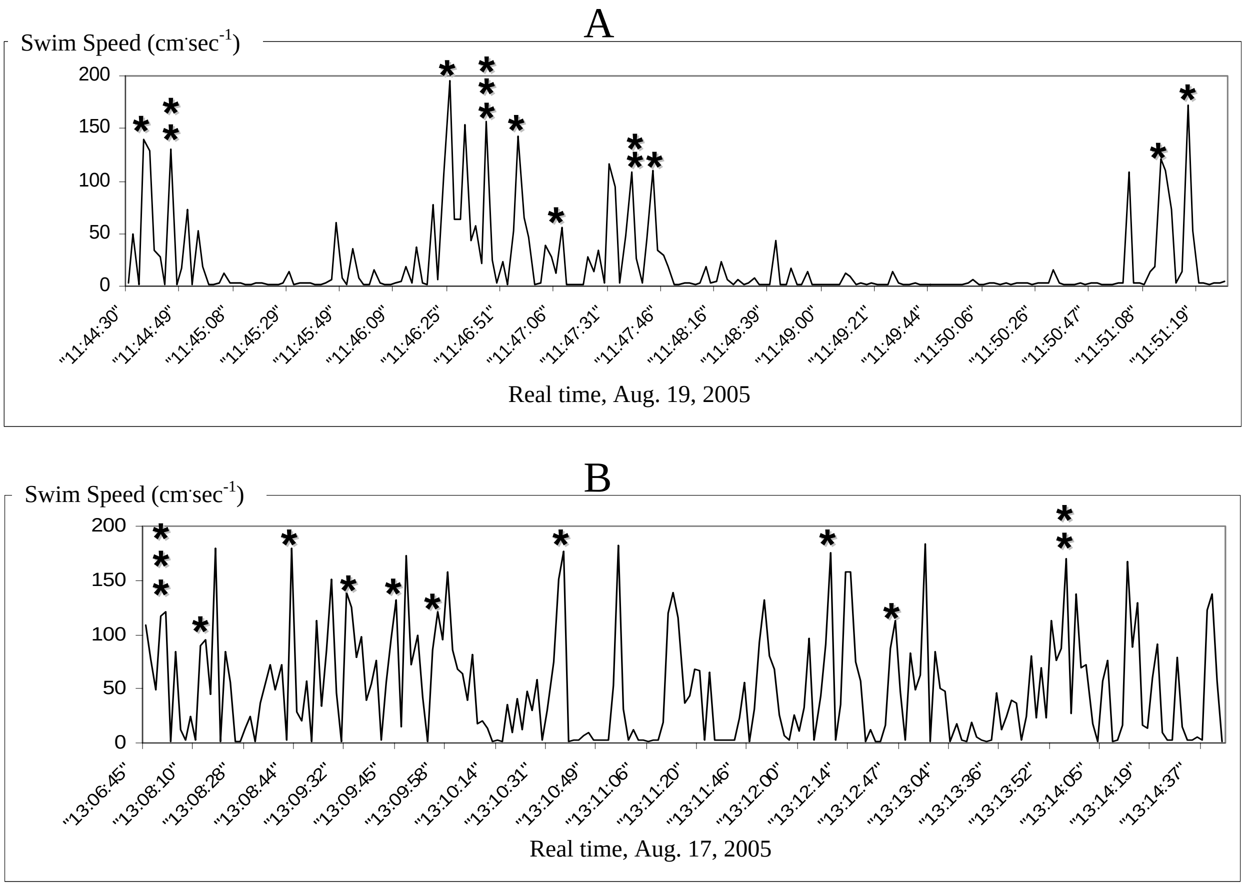

Figure 6 – Pon et al. BCRP project S06-01

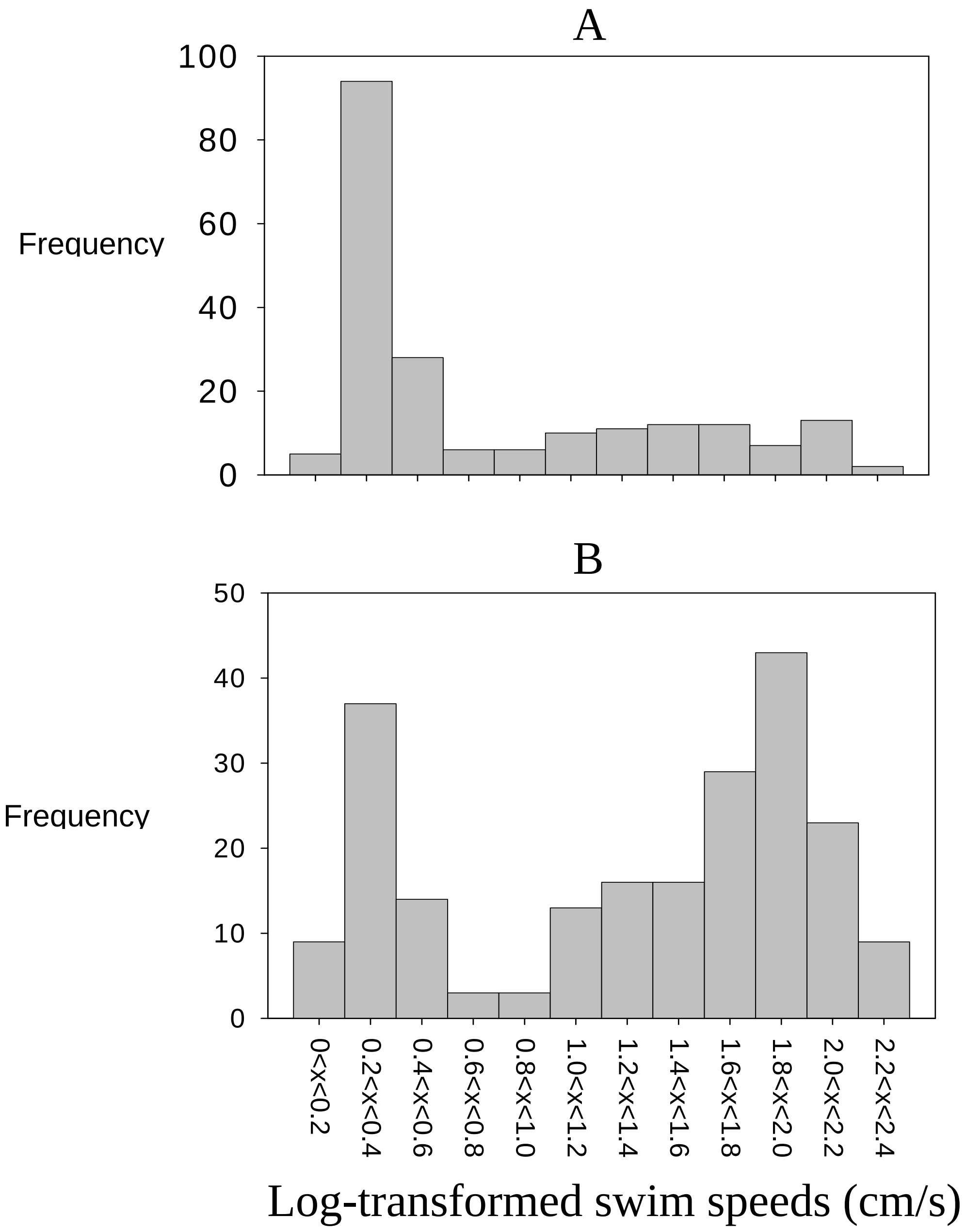

Figure 7 – Pon et al. BCRP project S06-01

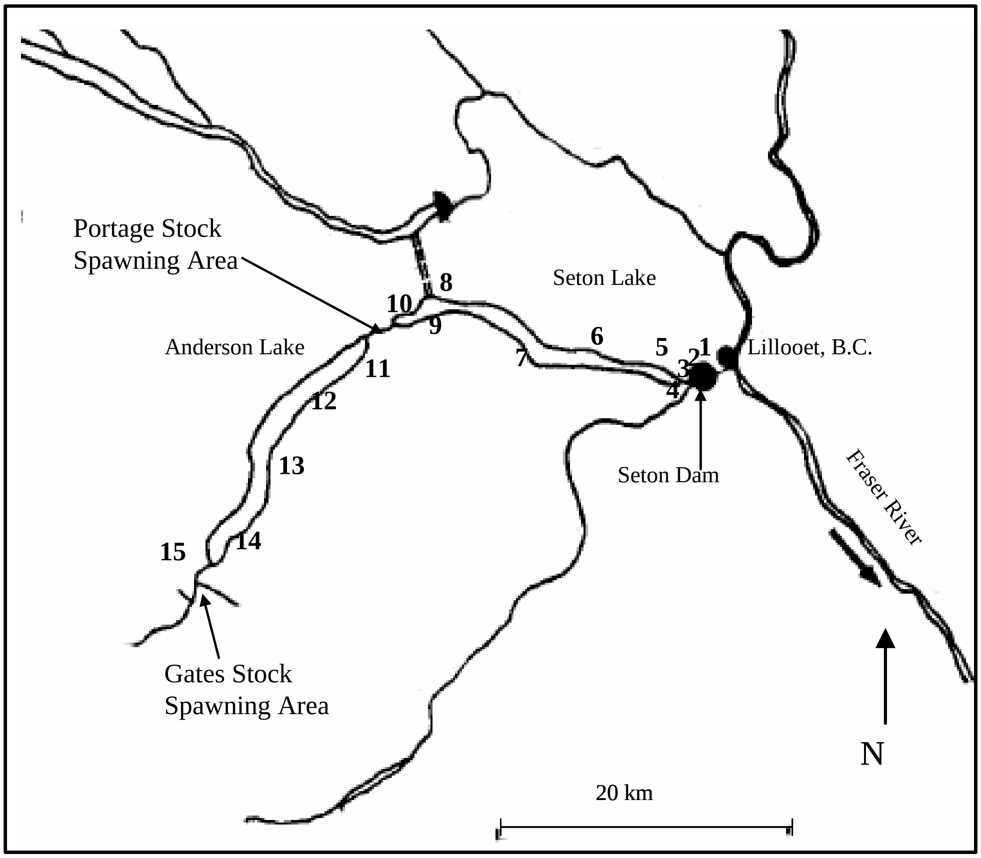

Figure 8 – Pon et al. BCRP project S06-01

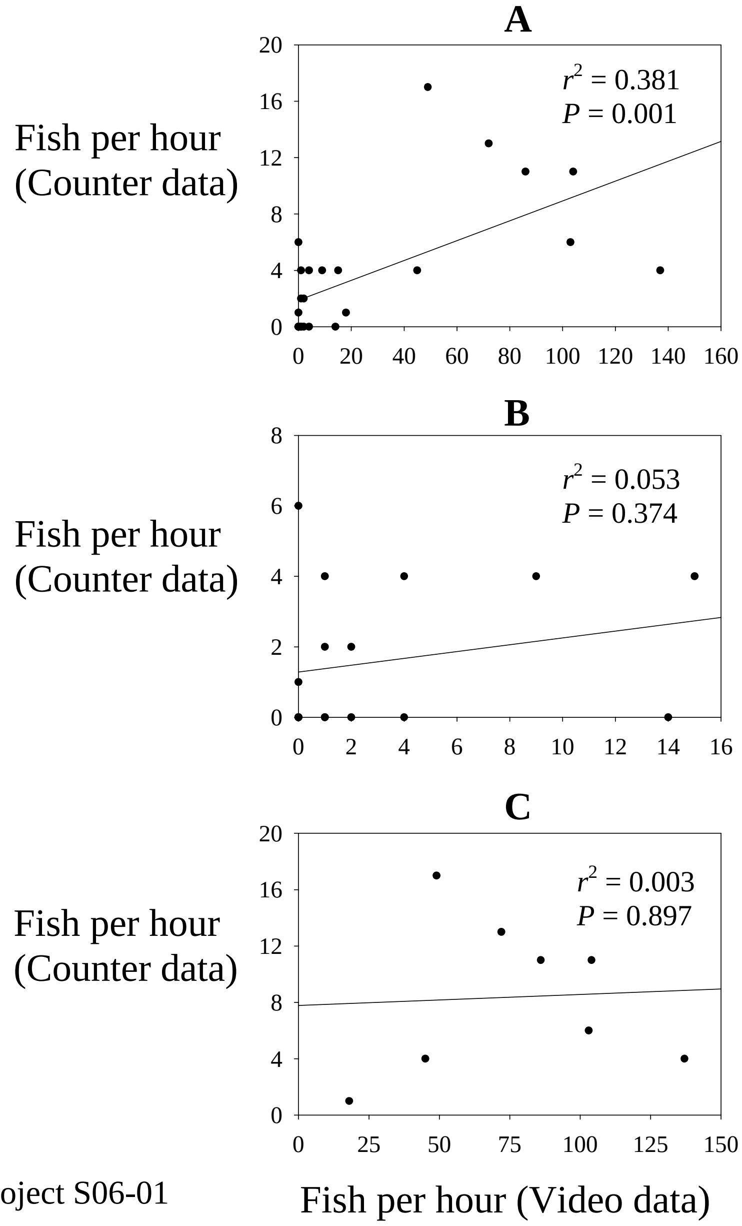

Figure 9 – Pon et al. BCRP project S06-01

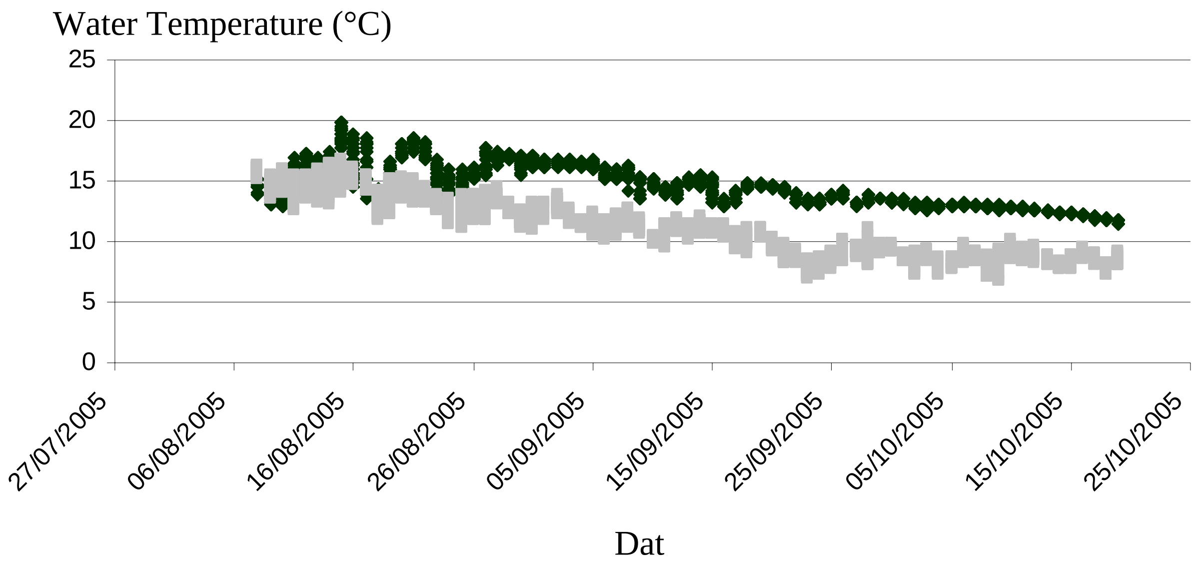

Figure 10 – Pon et al. BCRP project S06-01

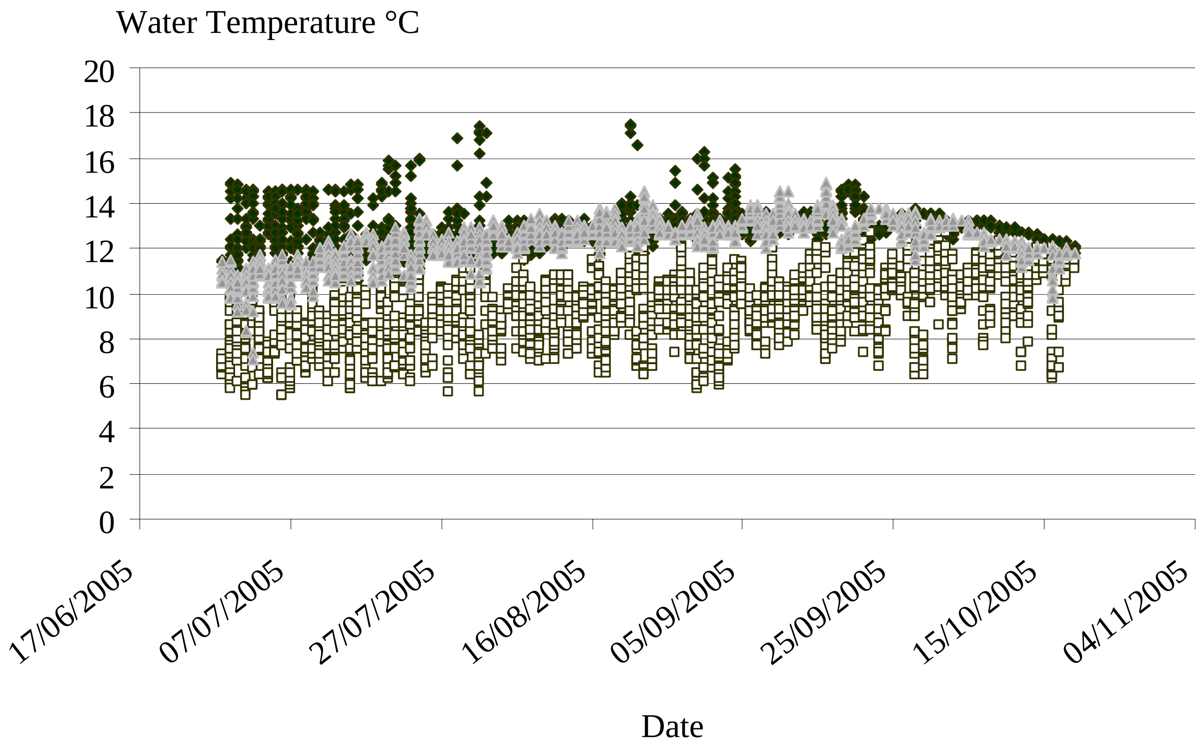

Figure 11 – Pon et al. BCRP project S06-01

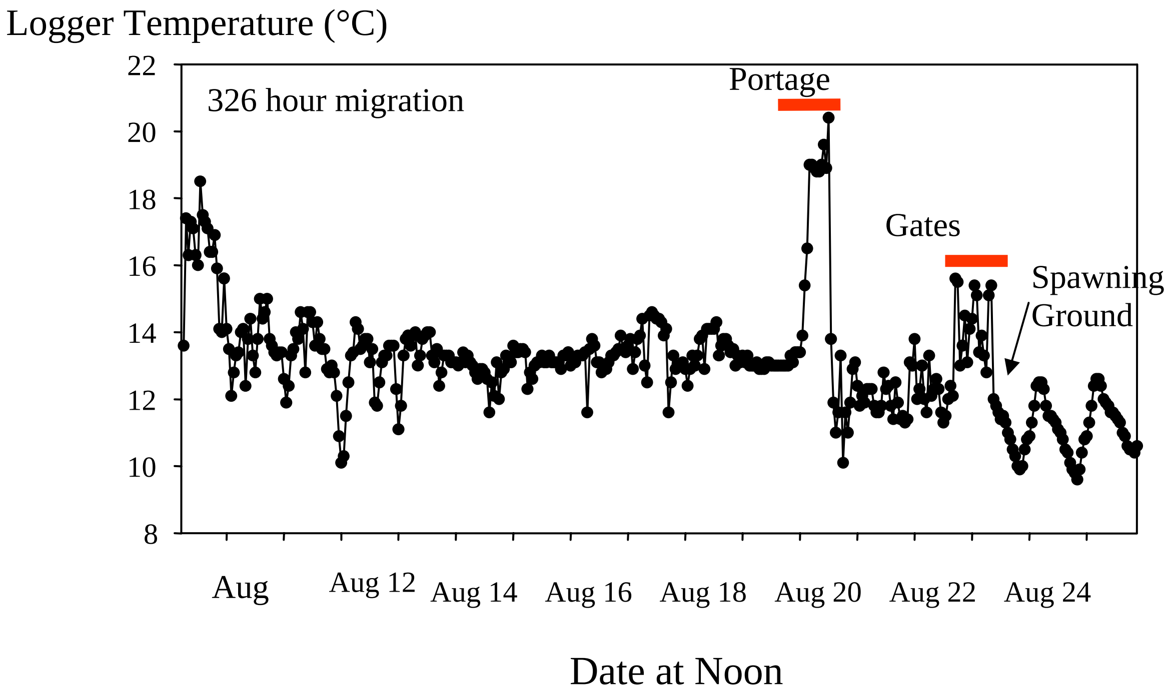

Figure 12 – Pon et al. BCRP project S06-01

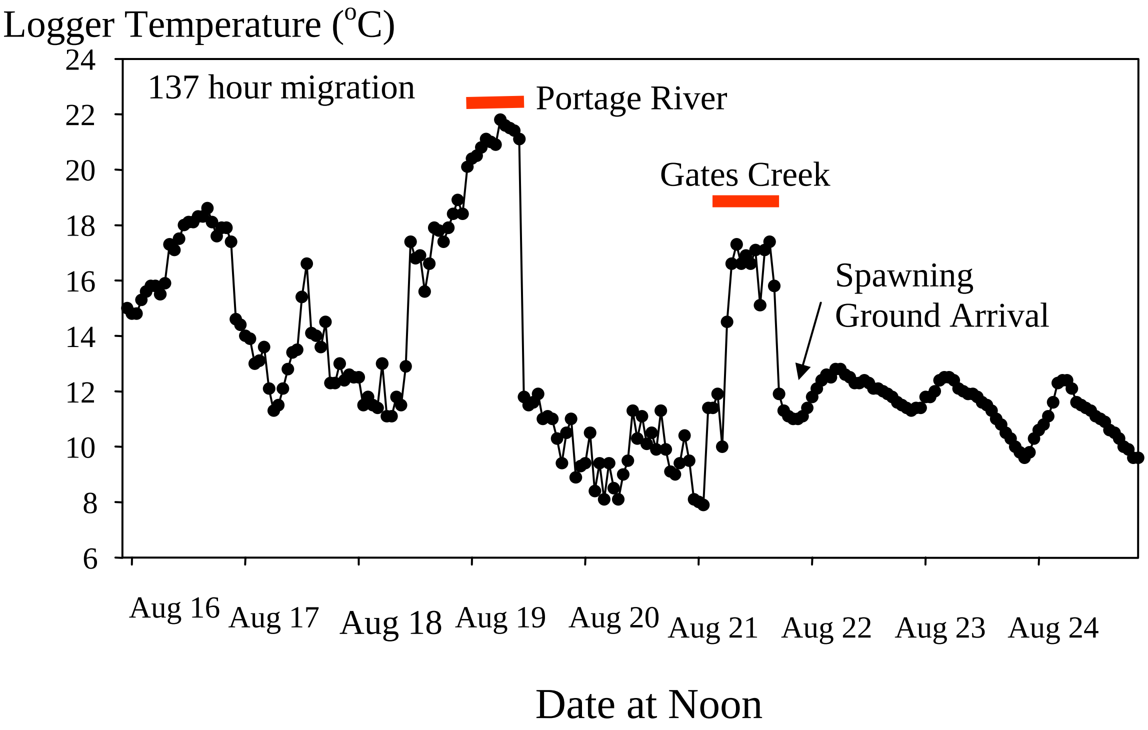

Figure 13 – Pon et al. BCRP project S06-01