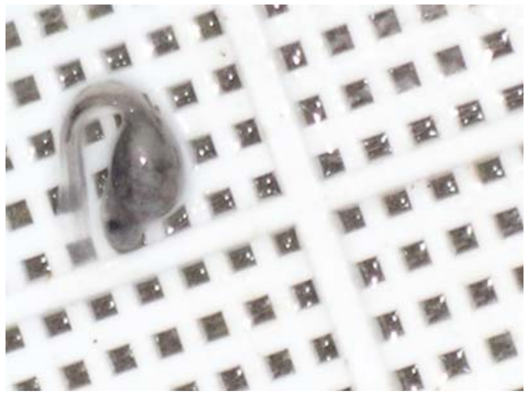
Arrow Lakes Reservoir White sturgeon (*Acipenser transmontanus*) spawning periodicity and embryo and larval development downstream of Revelstoke Dam and estimated effects of river impoundment on the timing of spawning



Prepared by: Mark Tiley, Hydro Impacts Biologist
Canadian Columbia River Inter Tribal Fisheries Commission (CCRIFC)
PO Box 2008, Revelstoke, BC, V0E 2S0
(250) 837-2154

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Top photo: Live recently hatched larval white sturgeon in histological cassette illustrating yolk sac size and early development characteristics.
Bottom photo: Live recently hatched larval white sturgeon dorsal view illustrating relative size of yolk sac.

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The results and recommendations presented in this report do not necessarily represent official positions of ESRF sponsors or funding agencies.

Executive Summary

The Arrow Lakes Reservoir white sturgeon population is believed to have experienced recruitment failure since approximately the mid 1960's to the mid 1970's, coinciding with the construction of two dams on the Columbia River mainstem: Mica Dam which impounds the Columbia River at approximately 140 kilometres (km) upstream of the town of Revelstoke, forming the Kinbasket Reservoir, and Keenleyside Dam which impounds the Columbia River at approximately 226km downstream of Revelstoke, forming the Arrow Lakes Reservoir. The Revelstoke Dam hydroelectric project was later constructed on the Columbia River mainstem between 1977 and 1984 approximately 5km upstream from the City of Revelstoke at RK 232.5 and forms Revelstoke Reservoir. The first documented white sturgeon spawning events within the Arrow Lakes Reservoir system occurred approximately 6km downstream of Revelstoke Dam on July 31 and August 20, 1999, representing the latest known spawning events for the species. Available preliminary comparison of post-regulation and pre-regulation historical temperatures collected downstream from Revelstoke Dam suggested that post-regulation water temperatures at the spawning area are colder from June through August compared to pre-dam conditions. A reduction in water temperature during the spring and summer period may affect: (i) the timing of Arrow Lakes Reservoir white sturgeon spawning; (ii) egg fertilization rate; (iii) embryo development and survival; and (iv) the viability of white sturgeon embryos and larvae. Revelstoke Dam peaking operations may also affect downstream temperature as well as white sturgeon spawning behaviour.

The purposes of this study were to (1) identify potential changes in Columbia River temperature characteristics downstream of Revelstoke Dam since the construction of Mica Dam and Revelstoke Dam which may delay the timing of white sturgeon spawning; (2) identify the influence of water temperature and Revelstoke Dam operations on white sturgeon spawning timing and location; and (3) determine whether the cold hypolimnetic discharges released from Revelstoke Dam have been contributing to Arrow Lakes Reservoir white sturgeon (*Acipencer transmontanus*) subpopulation recruitment failure by causing poor fertilization rate and/or high embryo and larvae mortality.

Water temperature was monitored between March 2003 and December 2003 at potential spawning habitat areas on the Columbia River between Revelstoke Dam and 13 kilometres downstream to determine the temperature range at which white sturgeon spawning currently occurs and to assess changes from historical thermal conditions. Temperature data were compared with available pre-dam temperature records collected between 1955 and 1966 at the former Steamboat Rapids Water Survey of Canada gauging station located on the Columbia River, 1.61km downstream from the current Revelstoke Dam location and 4.5 km upstream from the known Arrow Lakes Reservoir white sturgeon spawning area. Twenty–six artificial substrate mats were deployed in July and August 2003 between RK 231.5 and RK 226.5 by the Columbia Basin Fish and Wildlife Compensation Program (CBFWCP) and Golder Associates in order to identify the timing and approximate location of white sturgeon spawning events.

Thirteen embryos at neurulation were captured on August 7, 2003 and 24 embryos at early cleavage were captured on August 14, 2003 indicating two distinct white sturgeon spawning events. An additional 7 embryos from the August 14 spawning event in later stages of development were subsequently captured on August 22 and August 27, 2003. A total of forty-four fertilized viable embryos were captured between August 07, 2004 and August 27, 2003.

Forty-one embryos were incubated at the location of capture to determine percent hatch, development period and the frequency of external physiological abnormalities of hatched larvae.

Three embryos were preserved and accurately staged in order to perform back calculations to estimate spawning event timing and time to hatch. The two spawning events were estimated to have occurred on August 2 or 3, 2003 and on August 13 or 14, 2003. Columbia River temperatures at the spawning area averaged 9.7^{o}C and 10.6^{o}C during the estimated August 2/3 and August 13/14 spawning periods respectively. Spawning events occurred after a five day period of flows of not less that 245m^{3}s for the August 2/3 spawning event and flows of not less than 268 m^{3}s between August 7, 0500hrs and August 14, 0600hrs for the August 13/14, 2003 spawning event.

Sixty-eight percent of eggs incubated at mean temperatures of 10.1^{o}C (August 2/3 event) and 11.0^{o}C (August 13/14 event) hatched successfully. This hatch rate was roughly comparable to the hatch rates observed at the Wardner Hatchery where embryos are reared in water temperatures ranging between 14^{o}C to 16^{o}C, a temperature range generally considered optimum for white sturgeon spawning. August 2/3 and August 13/14 embryos hatched approximately 16 days and 15 days after the respective estimated spawning dates. Time to hatch was approximately two days later than calculated predictions.

Hatched larvae were sacrificed between 0 to 11 days post hatch and assessed for physiological abnormalities. Twenty-two of twenty-three preserved larvae were physiologically normal.

It was estimated that mean daily temperatures were approximately 2^{o}C colder in early June and approximately 3^{o}C colder from late June through August compared to spot temperature measurements collected in June through August between 1955 and 1966. It was further estimated that such a decrease in spring and summer water temperatures may delay the start of the Arrow Lakes white sturgeon spawning period by approximately two to four weeks if the pre-dam spawning period began when Columbia River minimum daily temperatures generally exceeded 9^{o}C. Results also suggested that peak summer water temperature historically occurred between late July and early August compared to the end of August or early September, 2003. Continued disruption of spawning may occur during the spawning period in August as a result of temperature downstream of Revelstoke Dam periodically dropping to approximately 9^{o}C during that month.

Mean daily water temperature differed by less than 1°C over the entire 13km section of Columbia River mainstem that was monitored, indicating that the Arrow Lakes Reservoir white sturgeon selected spawning habitat based on factors other than water temperature such as depth, substrate and river velocity.

The results obtained from this study suggested that water temperature conditions downstream of Revelstoke Dam do not result in poor fertilization rate, increased rates of sturgeon embryo mortality or external physiological abnormalities of larvae, further suggesting that post dam temperature alterations have not directly contributed to the recruitment failure of the Arrow Lakes Reservoir white sturgeon subpopulation. However, the probable delay in the Arrow white sturgeon spawning season may affect larval and juvenile sturgeon overwintering survival following hatching between mid August to early September, as the reduced available growing season in combination with the low productivity of the mid Columbia River may not allow for sufficient physiological development and growth by the onset of winter.

Acknowledgments

CCRIFC would like to acknowledge the efforts of Westslope Fisheries for capturing and accurately determining the reproductive developmental stage of prespawning female white sturgeon PIT tagged 4214321D and sonic tagged 3-3-4 in August 2002 and in June 2003. Without this earlier success, it is doubtful that an egg/embryo monitoring program and this *in-situ* embryo incubation study would have been conducted in 2003. CCRIFC would like to acknowledge Karen Bray of the Columbia Basin Fish and Wildlife Compensation Program (CBFWCP) who directed the substrate mat monitoring project and assisted with fieldwork. Thank you to Golder Associates who conducted the egg mat monitoring program, provided equipment and substrate mat UTM coordinates, provided advice regarding the deployment of the incubation capsules and provided CCRIFC with temperature data collected in 2003.

Many thanks to Dr. Serge I. Doroshov of the University of California Davis who provided invaluable expert advice and helpful literature relevant to this project. Many thanks also to Joel Van Eenennaam, also of the University of California Davis, who volunteered his expertise in sturgeon physiology to assess the larvae hatched during this study for physiological abnormalities. We appreciate the assistance of Molly Webb, Faculty Associate of Oregon State University who provided advice and confirmed the developmental stages of preserved embryos. Thank you also to Kevin Cappenman of the Columbia River Inter-tribal Fish Commission (CRITFC), based in Portland Oregon, who also voluntarily staged the preserved embryos.

CCRIFC would like to thank wildlife biologist John Woods of Parks Canada for giving CCRIFC the use of his dissecting microscope for embryo staging. Thank you to Steve McAdam of the BC Ministry of Environment and Lynne Campo of the Water Survey of Canada who provided pre-dam historical temperature data. Thank you Eaglevision for your fine GIS map work and to Josh Korman of Ecometrics for providing us with a digital map template. Thank you also to Colin Spence (BC Ministry of Environment) for his support for this study and providing CCRIFC with the necessary sampling permits.

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1.0 Introduction

The Arrow Lakes Reservoir white sturgeon subpopulation of the Upper Columbia River in British Columbia, Canada, has experienced recruitment failure since approximately the mid 1960's to early 1970's (i.e. RL&L, 2000c), coinciding with the construction of two dams on the Columbia River mainstem: Mica Dam which impounds the Columbia River at approximately 140 kilometres (km) upstream of the town of Revelstoke, forming the Kinbasket Reservoir, and Keenleyside Dam which impounds the Columbia River at approximately 226km downstream of Revelstoke, forming the Arrow Lakes Reservoir. Revelstoke Dam was later constructed on the Columbia River mainstem between 1977 and 1984, approximately 6km upstream of the town of Revelstoke (RL&L, 2000a), forming Revelstoke Reservoir. Revelstoke and Mica dams are barriers to upstream fish passage. Fish passage occurs through the Keenleyside Dam boat lock system, but no white sturgeon upstream movement into the Arrow Lakes Reservoir has been documented to date.

The only known white sturgeon spawning location for the Arrow Lakes Reservoir subpopulation is located 6km downstream of Revelstoke Dam. The turbine intakes for both Mica and Revelstoke Dams withdraw water from the hypolimnion, possibly resulting in a reduction in river temperature downstream of Revelstoke Dam from June to late August. RL&L (2000c) observed a spot surface temperature range of 7.2^{o}C from July 05, 1999 to 10.8^{o}C through to August 22, 1999. Limited (n=19) historic spot temperature data collected by the Water Survey of Canada (WSC) between 1955 and 1966 for the June through August summer period (data provided by McAdam, 2001, WSC, 2006) indicated temperatures of approximately 9^{o}C to 11^{o}C from mid to late June and approximately 12^{o}C to 14^{o}C by late July and early August.

Subsequent monitoring of water temperature at the Arrow Lakes Reservoir sturgeon spawning location during the post-dam June to September period has indicated that temperatures generally increase from approximately 7^{o}C in June to approximately 12^{o}C by late August. Revelstoke Dam tailrace temperatures remained at or slightly above 10^{o}C from early August to early November in 2003 and 2004 (Tiley, 2004; 2005a).

The reported minimum temperature indicated for white sturgeon spawning elsewhere in the Columbia River system varies. For the lower Columbia River, the spawning period begins when temperature increases to 10^{o}C in late April or early May (Parsley and Beckman, 1993; McCabe Jr. and Tracy, 1994) with the spawning period ending with temperatures at 19^{o}C or 20^{o}C. RL&L (1996; 1998) observed the onset of white sturgeon spawning at 14^{o}C in late June at the Pend d' Oreille/Columbia River confluence. The timing of spawning of wild white sturgeon males held captive for conservation aquaculture programs could temporarily be suspended by reducing temperatures to approximately 9.0^{o}C (UCWSRI, 2005). Spawning in the Kootenay River 106km to 124km downstream of Libby Dam begins in late May (Paragamian et al. 2003; Paragamian et al 2002) and has occurred at mean daily temperatures of as low as 7.5^{o}C to a high of 14.0^{o}C, although the majority of spawning in the Kootenay River occurs at temperatures between 9.5^{o}C to 12^{o}C (Paragamian et al 2002), similar to the 9.2^{o}C to 11.6^{o}C temperature range observed in August 1999 when white sturgeon spawning downstream of Revelstoke Dam was first confirmed (RL&L, 2000c). No evidence of juvenile recruitment from the August 1999 spawning events downstream of Revelstoke Dam was observed based on gillnet sampling completed in July and August 2001 (personal observation).

The confirmed spawning events for the Arrow Lakes Reservoir white sturgeon population has occurred between July 31 and August 20 (Tiley, 2004, RL&L, 2000c), with a mean incubation temperature of 10.1^{o}C to 11.0^{o}C (Tiley, 2004). The Arrow Lake Reservoir white sturgeon population displays the latest spawning period known for any white sturgeon population and the coldest embryo incubation temperature range; temperatures at which successful hatching from natural spawning events has not previously been documented.

The post dam reduction in Columbia River temperature observed during the Arrow white sturgeon spawning and incubation period was identified as a potential cause for recruitment failure in which cold temperature conditions may result in the disruption of adult spawning behaviour, low fertilization rate, low embryo survival rate and poor larval fitness. The purpose of the following study was to determine whether the cold hypolimnetic discharges released from Revelstoke Dam have been contributing to Arrow Lakes Reservoir white sturgeon (*Acipencer transmontanus*) subpopulation recruitment failure and the potential effects of post-dam temperature conditions on the timing of spawning.

The objectives of this project were as follows:

1. Identify potential changes in Columbia River temperature characteristics downstream of Revelstoke Dam since the construction of Mica Dam and Revelstoke Dam which may delay the timing of white sturgeon spawning;
2. Identify the influence of Revelstoke Dam operations on water temperature which may affect white sturgeon spawning timing, spawning location and incubation;
3. Determine whether the cold hypolimnetic discharges released from Revelstoke Dam have been contributing to Arrow Lakes Reservoir white sturgeon (*Acipencer transmontanus*) subpopulation recruitment failure by causing poor fertilization rate and/or high embryo and larvae mortality.

2.0 Methods

2.1 Study Area

White sturgeon egg and embryo monitoring was conducted from approximately 1 km downstream of Revelstoke Dam (RK 231.5) to the Revelstoke Golf Course and immediately upstream of the Jordan River inflow between RK 226 and RK 227 (Figure 2). For the purpose of this study, eggs are defined as unfertilized ovum. Embryos are defined as fertilized ovum, distinguishable from unfertilized ovum by evidence of embryonic development within the ova casing. Larvae are defined here as the post-hatch early free-swimming stage immediately following emergence from the egg casing to the onset of lateral scute formation at approximately 25mm total length (TL)(Beer, 1981; Conte et al. 1988). Early larval stages are also defined as free embryos (Cambridge dictionary of Biology, 1989) and pre-larvae between stages 35 to 45 as defined in Dettlaff et al. (1993). Embryo incubation was conducted at the site of embryo capture between RK 226 and RK 227.

Figure 1. The Canadian Columbia River Watershed illustrating the geographic relationship of Revelstoke Dam to Keenleyside Dam, Arrow Lakes Reservoir, Mica Dam, and Kinbasket Reservoir. Map courtesy of the Columbia Basin Trust.

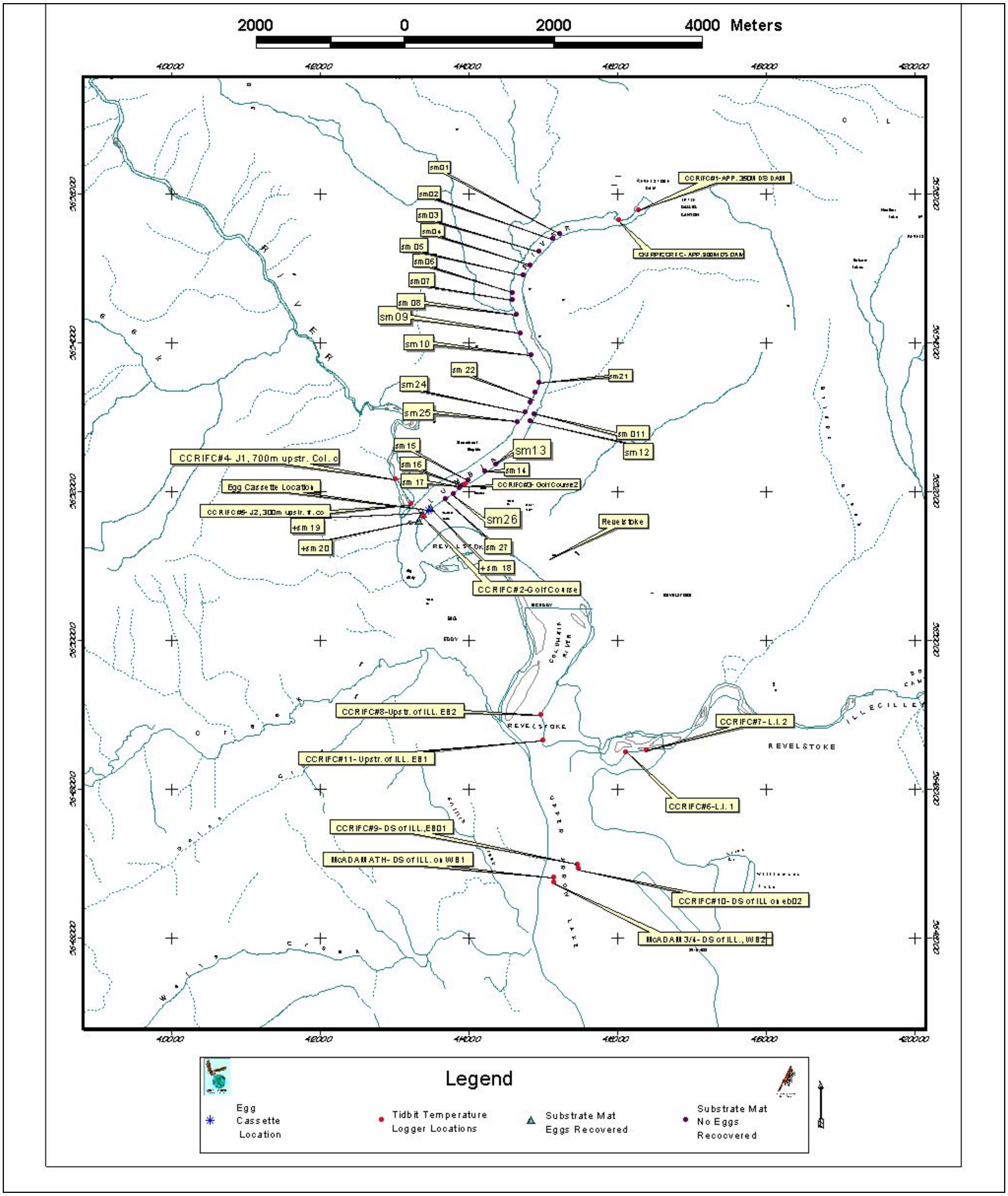

Figure 2. Study area indicating artificial substrate mat sampling sites, egg incubation sites and June to December 2003 temperature logger monitoring locations.

2.2 Spawning Area Temperature Monitoring

To determine how ambient water temperature may relate to spawning site selection, five temperature monitoring stations were established with assistance from the Upper Columbia River White Sturgeon Recovery Team (UCWSRT) within sections of the Columbia River mainstem considered to have habitat characteristics suitable for white sturgeon spawning including main channel depths greater than 2 meters, coarse substrates and velocities that are sufficiently high to facilitate the dispersal of embryos and prevent the siltation of course substrates. Mainstem temperature monitoring stations were established no more than 6 km apart to ensure that temperature data would accurately represent that of the 2003 spawning location.

Hourly temperature data was also collected from the lower Jordan and Illecillewaet Rivers, both significant tributaries of the Columbia River within the spawning area that could have a potential affect on mainstem temperature conditions which may influence sturgeon spawning timing and site selection. Tributary and Columbia River catchment (watershed) areas, WSC station years of operation and station coordinates were obtained from the WSC website www.wsc.ec.gc.ca.

The mouth of the Jordan River is located at the west bank immediately opposite and slightly downstream of the spawning area and could therefore influence downstream temperature and affect the development rate of eggs and sperm within the adults and pre-spawning behaviour of staging adults and thus the timing of spawning events. The Jordan River does not affect the east bank of the Columbia River where embryos were collected in 1999. The Jordan River watershed is 272km^2 in area with a SSE orientation and is also influenced by glacial melt; however, water clarity is generally very high (personal observation) suggesting that run off during the June to September period is mainly derived from snowmelt. The Water Survey of Canada (WSC) operated gauging station 08ND014 on the Jordan River approximately 4km upstream from the confluence with the Columbia River at 51^{o}2'40"N and 118^{o}16'9" between 1963 and 1988. Peak flow in 1966 was 79.3m^3/s on June 03. August 01, 1966 discharge was 30.0m^3/s (WSC, 2006). To determine the influence of the Jordan River on Columbia River mainstem temperature, the hourly data obtained from the Revelstoke Dam tailrace temperature logger was compared to the averaged hourly temperature of the two downstream west temperature loggers DSWB1 and DSWB2. Two temperature monitoring stations (J1 and J2) were established on the Jordan River immediately upstream of the Jordan River/Columbia River confluence.

The Columbia River downstream from the mouth of the Illecillewaet River provides comparatively high turbidity levels within the study area during July and August (Tiley, 2005b) due to glacial melt and possibly localized riverine conditions during periods of Arrow Reservoir backwatering. The lower reaches of the Illecillewaet River and Columbia River habitat influenced by the Illecillewaet River were therefore considered to be potential spawning areas.

The watershed area of the Illecillewaet River is 1150km^2 with an approximate WSW orientation. Peak discharge at the WSC station 08ND013 was 214m^3/s on July 08, 1966. Peak Illecillewaet discharge in 2003 was 210m^3/s on June 08. .

To determine the influence of the Illecillewaet River on Columbia River mainstem temperatures, two temperature monitoring stations were established upstream and downstream of the Illecillewaet River/Columbia River confluence. In addition, two temperature monitoring stations were established within the Illecillewaet River approximately 1km upstream from the Columbia River/Illecillewaet River confluence and far enough upstream to ensure that the Columbia River did not affect Illecillewaet temperature readings during periods of Arrow Lakes Reservoir backwatering. RL&L (2001) considered the lower reaches of the Illecillewaet River to provide suitable spawning habitat for white sturgeon. Four substrate mats were deployed in the lower Illecillewaet River but no evidence of spawning was observed (RL&L, 2001).

Water temperature was monitored from June 28, 2003 to December 07, 2003 between the Revelstoke Dam tailrace at river kilometre (RK) 232.5 to RK 219.5 downstream, (approximately 1.5 km downstream of the Columbia River/Illecillewaet River confluence). River kilometre is defined as the number of kilometres upstream of Keenleyside Dam (RL&L 2001). The river bank, river kilometre and site location abbreviations for each of the temperature monitoring station locations were as follows:

1. The west bank within the tailrace of Revelstoke Dam (Sites TAILR1 at RK 232.25 and TAILR2 at RK 232.5)
2. East bank at the 1999 sturgeon embryo collection sites approximately 6 km downstream of Revelstoke Dam adjacent to the Revelstoke Golf Course (GC1 at RK 226.5 and GC2 at 227.0).
3. North bank within the Jordan River 0.3km (J2) and 0.7 km (J1) upstream of the Columbia River confluence (confluence at the Columbia River west bank, RK 226.5)
4. The east bank of the Columbia River mainstem immediately upstream of the influence of Illecillewaet discharge (USEB1 at 221.3km and USEB2 at 221.7km (confluence at the Columbia River east bank at approximately at RK 221.2).
5. The south bank within the Illecillewaet River at 0.7km (ILLEC1) and 1.1 km (ILLEC2) upstream the Columbia River confluence and upstream of the influence of the Arrow Reservoir.
6. The east bank of the Columbia River mainstem downstream of the Illecillewaet River confluence (DSEB1 and DSEB2 at RK 219.5).
7. The west bank of the Columbia River mainstem downstream of the Illecillewaet River confluence (DSWB1 and DSWB2 at RK 219.4).

Onset Stowaway Tidbit temperature loggers programmed to record temperature hourly were deployed at each monitoring site between June 30 and July 02, 2003. Two temperature loggers were deployed at each site in order to determine data precision and as protection against equipment loss. All thermographs were assessed for accuracy against a calibrated mercury thermometer. All thermographs were within +/-0.2^{o}C of a calibrated P63C Miller and Weber T-3755 mercury thermometer. Onset states that Stowaway Tidbit temperature loggers are accurate to within approximately +/- 0.2^{o}C (Onset Computer Corporation, 1998). The UTM coordinates for each temperature monitoring station were collected with a Garmin 12 GPS unit and the immediate area photographed and described to aid in relocating the temperature monitoring site.

Velocity measurements at the embryo incubation sites were not collected as a result of frequent and abrupt changes in Revelstoke Dam discharges on a daily basis and due to the diversity of channel depths, river channel contours and substrates that typically range from gravel to riprap in the egg collection and incubation area. During the 2003 spawner monitoring program, Golder Associates measured surface river velocity during the substrate mat retrieval sessions, which were generally collected during high discharge periods. One surface velocity measurement using the float method similar to Gallagher & Stevenson (1999) was collected during a zero discharge period between approximately 0400 and 0500 hours and was 0.05 m/s on August 15 at approximately 0500hrs at the mat 19 embryo incubation site. Leakage through Revelstoke Dam is believed to be approximately 14 m^3/s.

As Revelstoke Dam operations may affect downstream temperature, it was necessary to determine potential interactions between discharge, temperature and timing of spawning. BC Hydro provided CCRIFC with hourly Revelstoke Dam discharge data. Discharge data from May 31, 2003 to August 16, 2003, the period that would include pre-spawn migration, pre-spawn staging and actual spawning events, is presented. Golf Course temperature logger stations were periodically checked during early morning zero flow discharge periods to ensure that temperature logger dewatering did not occur. Other temperature logger stations were checked opportunistically during normal working hours.

Within site mean hourly temperature differences were calculated using the following equation: $\sum(T_{1i}-T_{2i})/n$ wherebyT_{1i}= Station X logger 1 temperature at hour i; T_{2i} = Station X logger 2 temperature at hour i; n = number of observations. The mean, minimum and maximum temperature differences were calculated for within and between temperature monitoring stations.

2.3 Embryo Incubation

Karen Bray of the Columbia Basin Fish and Wildlife Conservation Program (CBFWCP), Revelstoke, BC and Golder Associates, Castlegar, BC, conducted the Arrow Lakes Reservoir sturgeon spawning monitoring program. CCRIFC provided field assistance on July 03, 2003, July 23, 2003 and August 27, 2003. Twenty-six artificial substrate mats made of latex-covered horsehair mat bolted onto a 0.75m X 0.92m metal frame were checked for unfertilized eggs, embryos and larvae weekly between July 3, 2003 and August 27, 2003. The substrate mats were tied to secure trees, stumps or boulders with approximately 33m of rope.

Substrate mats generally drifted downstream in the current, just below the water surface as the shoreline anchor rope became taut, keeping the mat suspended. The force of the current would cause the substrate mats to then swing towards the bank while still in suspension until the angle of the rope was nearly parallel to the river bank and water velocities were slow enough to allow the substrate mat to sink. This technique has proven effective in collecting eggs in previous sturgeon spawning investigations (i.e. RL&L, 2000c). A float was attached to each substrate mat by a tether rope, allowing the mat to be retrieved off shore by boat. Egg mats were generally deployed on the side of the river closest to the channel thalweg.

Figure 3. Checking artificial substrate mats for unfertilized eggs, embryos and larvae in the temperature control bath, Revelstoke Golf Course spawning area, Columbia River, August 2003. Photo by Mark Tiley, CCRIFC.

The substrate mats were handled as gently as possible during their retrieval in order to minimize the amount of mechanical stress unfertilized eggs, embryos and larvae might be subjected to. Mats were immediately placed into a bath receiving water pumped directly from the river via an external pump to minimize exposure to air, warm air temperatures and direct sunlight. Differences between incubation bath temperature and river water temperature were monitored during the substrate mat assessment with an environmentally safe Easy-Read pocket thermometer. The Easy Read Pocket Thermometer measurement bias was –0.5^{o}C. As the Easy Read thermometer is in whole degree increments, measurements were rounded to the nearest degree.

In some cases substrate mats were briefly stood on end out of the bath water to reduce the likelihood of missed eggs, embryos or larvae prior to substrate mat redeployment. Several embryos were collected using this technique. Collected embryos were quickly staged live in the field into one of the following generalized developmental categories: cleavage, neurulation, early pre-hatch, pre-hatch or late pre-hatch. Approximately one in 15 embryos were randomly selected for fixing in 10% buffered formalin for later determination of precise developmental stage. Embryo stages were used to determine the timing of spawning events through back-calculations and to predict hatch dates.

Embryos used in the incubation experiment were placed in one plastic histological cassette each to avoid mechanical damage during the incubation period and to reduce the spread of fungal contamination between embryos. White histological cassettes with a compartment volume of 3.9cm^3 (measuring 3.1cm in length X 2.5cm in width X 0.5cm in depth) were used. Embryos were approximately 4mm in diameter immediately prior to hatching. Cassettes were placed in a salmonid egg vial 26.0cm tall and 15.6cm in diameter (volume of 4,970 cm^3) and deployed at the same locations that they were captured. One egg vial was used for each substrate mat on a given date whenever embryos were captured. For example, embryos captured on Mat 20 on August 7 would each be placed in their own cassette with all cassettes from Mat 20 being placed into a salmonid egg vial labelled mat 20.7. The embryos were allowed to incubate generally undisturbed in cassettes until hatching or until they became fungussed indicating that the embryo had died. Mat 18.14 embryos were re-located to the incubation site on August 22 after being checked for fungus and were rechecked for hatching on August 27. Larvae were reared in salmonid egg incubators from 0 to 11 days post hatch.

2.4 Estimated Timing of Spawning Events from Back Calculation

The author staged all preserved embryos with a Heerbrugg Wild M3 dissecting microscope at the Parks Canada field laboratory in Revelstoke, BC. As the author was new to embryo staging, Molly Webb, Faculty Associate of the Department of Fish and Wildlife at the University of Oregon and Kevin Kappenman, fishery biologist for the Columbia River Inter-Tribal Fish Commission (CRITFC), provided quality control using a Motic Digital Stereo Microscope Model DM143 and confirmed each of the preserved embryo stages. Embryos were staged according to the embryo classifications described in Dettlaff et al. (1993). Temperature data obtained from the CCRIFC Golf Course temperature monitoring station 1 (GC1), the station located closest to the 2003 embryo capture sites, were used to back-calculate spawning dates and predict hatching dates using the model equations described in Wang et al. (1985).

2.5 Fitness of Hatched White Sturgeon Larvae

Larval fitness was defined as the frequency of external morphological abnormalities. Larvae hatched from incubated embryos were reared from one to eleven days and assessed live in the field by the author. The author qualitatively assessed live larvae using fin development, body shape, head development and swimming behaviour as indicators of fitness. Quantitative assessment was not conducted in the field to minimize damage and stress to the larvae as a result of handling. All larvae were preserved in 95% ethanol alcohol by September 1, 2003. Daily river stage fluctuations at the incubation location reached approximately four meters by September 1 due to the absence of a mid-summer reservoir backwatering effect. These flow (and stage) changes ranging from 0 m^3/s to 1650m^3/s made continued rearing of larvae unfeasible. Joel Van Eenennaam of the University of California, Davis, assessed all preserved larvae for external physiological abnormalities.

The length/weight relationship of live larvae was not determined due to the fragility of larvae. The total lengths of two live larvae hatched from the August 02/03 spawning event was determined on August 27 and in one case one succumbed larvae was determined opportunistically. Larvae from the August 13/14 spawning event were measured live on August 29, 2003. Any larvae that survived the September 01, 2003 dewatering event were anaesthetized and sacrificed with clove oil on September 01, 2003 and preserved in 95% ethanol and later measured on October 16, 2003.

2.6 Assessment of Timing of Spawning, Location of Spawning

Temperature ranges at the time of spawning events were documented at each of the five CCRIFC temperature monitoring station on the Columbia River mainstem to identify any potential influence of temperature on spawning location. The Golf Course temperature station (loggers GC1 and GC2) located in the immediate area of the1999 embryo capture locations, were compared with the temperature ranges of the other four mainstem monitoring stations. Between-site comparisons used average hourly differences using the following equation:

$$\sum(X_{avgi}-Y_{avgi})/n$$

Whereby, X_{avgi} = Station X average temperature at hour i ($T_{1i}+T_{2i}/2$); Y_{avgi} = Station Y average temperature at hour i; n = number of observations.

The data from the Revelstoke Dam Tailrace 1 temperature logger were lost during the downloading procedure so a comparison between average Golf Course temperatures vs Revelstoke Dam Tailrace 2 raw data was performed.

The mean, minimum and maximum temperature differences were calculated for each comparison. Temperature readings that were clearly influenced by exposure to air during stranding events were not included for within site and between site comparisons. Daily mean temperatures collected at the Revelstoke Dam tailrace and the embryo capture locations were compared to pre-dam temperature data.

Spring temperature data collected by Golder Associates using the same equipment at the Revelstoke Dam tailrace between March 14, 2003 and June 03, 2003 and from June 10 to June 30, 2003 were added to the CCRIFC Golf Course 1 mean hourly temperature dataset, collected from July 01, 2003 to September 02, 2003. In addition, temperature collected by Golder from September 03, 2003 to February 01, 2004 was also used to compare historic pre-dam temperatures during this period. The difference between average hourly temperatures obtained at the CCRIFC Golf Course monitoring station and the Golder Associates Tailrace 1 monitoring station between July 1, 2003 and September 1, 2003 was generally within the +/-0.2^{o}C sensor measurement error with a mean difference of 0.21^{o}C. It was therefore concluded that temperature differences between the

Revelstoke Dam tailrace and the Golf Course area were negligible and that the two sites could be treated as equal in regards to temperature characteristics. The spring to late July data from one of the Golder Associates loggers deployed at the Golf Course site were not used as the data included unusual temperatures and were considered less reliable than data collected from the Golder Associates Tailrace site.

Comparisons of data from two CCRIFC Golf Course 1 and Golf Course 2 loggers and the Golder Associates logger at the Golf Course site indicated a negligible mean difference of 0.09^{o}C between August 27 and September 1 at this site, less than the +/- 0.2^{o}C Tidbit measurement error.

2.7 Comparison between Contemporary and Historic, Pre-dam Columbia River Temperature Conditions at the Arrow Lakes Reservoir Spawning Area

Water Survey of Canada (WSC) hydrometric survey notes included documented spot temperature pre-dam (1955 to 1966) measurements for the Steamboat Rapids gauging station (station # 08ND011) and were provided to CCRIFC by WSC in February 2006. Temperature data was measured at the gauging station and recorded to the nearest ^{o}F with hand-held thermometers. Between 1955 and 1966, the WSC Steamboat Rapids gauging station was located on the east bank of the Columbia River 4.53km upstream of the Jordan River mouth and 1.61km downstream from the present day Revelstoke Dam location at RK 230.9 (WSC, 1983; 1979). WSC staff generally recorded temperature once each time the gauging station was surveyed. Between 1955 and 1966, a total of 66 pre-dam temperature measurements were documented between 0730hrs and 2120hrs. The time at which temperature was measured was documented for 6 of the 66 measurements between 1964 and 1966 with five of the 6 measurements being measured at the end of the survey and one measurement being taken at the beginning of the survey. The historic temperature data was converted to the nearest 0.1^{o}C.

Diurnal temperature range at Steam Boat Rapids prior to Mica Dam construction may have been a factor in the timing of the historic spawning period. The limited pre-dam historic data is insufficient to estimate diurnal temperature ranges at the former Steam Boat Rapids gauging station. Diurnal temperature range at the Stream Boat Rapids temperature gauging station was estimated based on unregulated diurnal temperature trends collected from the Jordan River and Illecillewaet River temperature data as well as temperature collected upstream of Kinbasket Reservoir near Donald in 2002 and the mouth of the Akolkolex River in 2005.

The temperature monitoring station near Donald was located on the north bank of the Columbia River approximately 1 km downstream of the Bluewater Creek campsite (approximately RK 483, or approximately 120km upstream from Mica Dam), the furthest downstream site located on the unregulated section of Columbia River. The Columbia River catchment area upstream of Donald is 9,710km^{2} and is influenced by several tributaries including Bluewater Creek and the Blaeberry, Kicking Horse and Spillimacheen Rivers all of which appear to be heavily influenced by glacial melt as evidenced by suspended glacial silt (personal observation). The WSC Donald station, located on the south bank of the Columbia River at 51^o 29' 0"N and 117^{o}10'45"W, has been in operation since 1944. Peak flow at Donald in 1966 was 680m^3/s on July 20, representing approximately 24% of the 2890m^3/s peak flow at the WSC Steamboat Rapids station on July 09, 1966. August 01,1966 discharge at Donald was 419m^3/s. August 01, 1966 discharge at Steamboat Rapids was 2020m^3/s. Peak flows at Donald in 2002 and 2003 were 908m^3/s on June 30 and 609m^3/s on June 21 respectively. Discharge on August 01, 2002 and 2003 were approximately 373m^3/s and 314m^3/s respectively. The Columbia River upstream of Donald has an approximate NW orientation, shifting to a SSE orientation 120km downstream at Mica Dam.

The Akolkolex River has a drainage area of 394km^2 and an approximately south orientation upstream of the Akolkolex Waterfall after which the river flows in a west-north-westerly (WNW) direction. The Akolkolex River flows into the Columbia River at RK 200 on the east bank of the latter (the Akolkolex River is not included in figure 2). The WSC station 08ND001, located at 50^o 49' 28"N and 118^{o}1'44"W, monitored Akolkolex River discharge between 1913 and 1922 and from January 01 to August 31, 1954. Peak discharge in 1922 was 110m^3/s on June 04, falling to 38.8m^3/s by August 01, 1922. One Onset Stowaway Tidbit temperature logger was placed on the south bank (AKOLK1) and one on the north bank (AKOLK2) of the Akolkolex River approximately 0.10km and 0.15km downstream from Akolkolex Falls and approximately 1.4km upstream from the Akolkolex River/Columbia River confluence on June 08, 2005. The dewatering of AKOLK1 necessitated that the logger be moved downstream approximately 0.2km to the north bank on August 05, 2005. There was no backwatering effect of Arrow Lakes Reservoir at the temperature monitoring stations due to low reservoir elevations in 2005.

Bi-weekly temperature trends for each tributary for June, July and August was determined by pooling all temperature measurements from the unregulated tributaries and the temperature monitoring site near Donald collected between a specific hour over the two-week period. For example, temperature data collected between 00:00hrs to 00:59hrs; 01:00 to 01:59hrs; 02:00 to 02:59hrs etc for a given bi-weekly period was averaged for each hour interval and plotted over time. Plus/minus 1 standard deviation was also plotted for each mean mean temperature observation to indicate temperature variability for a given hour and the time at which mean daily temperature was generally observed (See Appendix A4)**.**

Based on available data for contemporary diurnal trends for the unregulated temperature monitoring locations, daily mean temperature typically occurred between 1200 and 1300 hours at Donald and in the Jordan River, 1400 and 1500hrs in the Illecillewaet River and 1300 to 1400 hrs in the Akolkolex River. Mean daily temperature for all unregulated sample locations combined occurred between approximately 1200hrs and 1500hrs. Historic temperature measurements collected between 0730 hours and 1130 hrs, 1131hrs to 1530 hrs and 1531hrs to 2120hrs were therefore categorized as daily minimum, daily mean and daily maximum temperature periods respectively. As temperature at 1500hr to 1530hr at Donald was in some periods similar to daily maximum temperature, it should be noted that of the five temperature measurements categorized as a mean daily temperature that may have been collected between 1500 and 1530 hours, only the 10°C measurement collected on June 10, 1961 occurred during the June to August period. The four other measurements possibly collected between 1500hrs to 1530hrs were collected in the months of December, January, February and April, a time of year when sturgeon were likely not present. The average daily temperature range was calculated for bi-weekly periods from June 01 to August 31 to estimate the time at which spawning may have occurred assuming the daily minimum temperature necessary for spawning is 9°C. The assumptions of this method are as follows:

1. The former WSC Steamboat Rapids gauging station temperature data for the 1955 - 1966 period is representative of temperatures in which the Arrow Lakes white sturgeon historically spawned.
2. The onset of the pre-dam Arrow Lakes white sturgeon spawning period was determined by temperature and began when daily minimum temperatures generally exceeded 9.0°C.
3. The contemporary seasonal and diurnal temperature characteristics for the Jordan River, the Illecillewaet River, the Akolkolex River and the Columbia mainstem at Donald have not changed since the 1955 to 1966 pre-dam period;
4. The combined average Illecillewaet River, Jordan River, Akolkolex River and Columbia River mainstem (Donald) diurnal minimum and maximum temperatures for a given two week period is representative of the pre-dam diurnal temperature range at the Steamboat Rapids gauging station and downstream;
5. Inter-annual temperature differences in sampled tributaries and the Columbia River near the Donald station do not significantly differ;
6. The mercury thermometers used to collect the historic temperature data were accurate and representative of Columbia mainstem temperatures;
7. The pre-dam temperature measurements were collected at the end of the gauging station survey unless specified in the historic data;
8. The locations where both the pre-dam and contemporary temperature data were collected did not create sample bias.

A regression plot was performed in Microsoft Excel to determine temperature trend for the 1955 to 1966 data and 2003 daily mean temperature data between March 21 and August 08. In order to perform the regression analysis, pre-dam measurements collected on June 10, (10°C in 1961 and 8.9°C in 1963) were averaged as were the 7.8°C and 8.3°C measurements collected on May 28, 1956 and May 28, 1964 respectively. The regression equations for the 1955 to 1966 data and diurnal temperature trends were used to estimate the approximate week in which pre-dam white sturgeon spawning period could have begun, assuming Arrow Lakes Reservoir white sturgeon spawn when daily minimum temperatures exceed 9°C. The level of correlation between temperature and day of year and the level of significance of the temperature/time relationship was determined using JMP 5.1 statistical software.

3.0 Results

3.1 Spawning area Temperature Monitoring

3.1.1 Within site hourly temperature comparisons

Within site comparisons between Columbia mainstem stations indicated that mean differences were all less than the +/-0.2°C measurement error of the temperature loggers, indicating proper equipment function and insignificant equipment bias.

Table 1. Summary of within-site hourly temperature comparisons at the 2003 Columbia River mainstem temperature monitoring sites.

Temperature Comparison	GC1-GC2	USEB 1-USEB 2	DSEB 1-DSEB 2	DSWB 1-DSWB 2
Mean difference (°C) July 01 to Sept 01, 2003	0.12	0.02	-0.05	0.14
Max -ve difference (°C) July 01 to Sept 01, 2003	-0.94	-0.67	-1.15	-0.14
Max +ve difference (°C) July 01 to Sept 01, 2003	2.48	1.81	0.72	1.42

GC = the 1999 egg deposition area adjacent to the Revelstoke Golf Course, **USEB** = the temperature monitoring stations upstream of the Illecillewaet River located on the East bank, **DSEB** = the temperature monitoring stations downstream of the Illecillewaet River located on the East bank, **DSWB** = the temperature monitoring stations downstream of the Illecillewaet River located on the West bank.

3.1.2 Between-site hourly temperature comparisons

Revelstoke Dam Tailrace 2 station temperatures were on average 0.3°C cooler than mean temperatures at the DSWB stations between July 02, 2003 and August 31, 2003. Similarly Revelstoke Dam Tailrace 2 station temperatures were on average 0.23°C cooler than the DSWB mean temperature during the July 31, 2003 to August 14, 2003 spawning period. Sudden increases and decreases in hourly temperature up to 2.5°C, particularly noticeable for the DSWB sites, are likely caused by Revelstoke Dam operations.

Between site comparisons indicated that mean differences between the embryo capture and incubation sites (Golf Course location), differed by less than the sensor measurement error from all other mainstem locations except for the site located immediately downstream of the Illecillewaet River on the east bank (DSEB). The mean difference between the GC site and the DSEB site was -0.47°C from July 01, 2003 to September 01, 2003 and -0.72°C between the observed July 31, 2003 to August 14, 2003 sturgeon spawning period. Differences of approximately1°C or less between the GC site and the DSEB site were assumed to be biologically insignificant; thus no inferential statistical comparisons were performed.

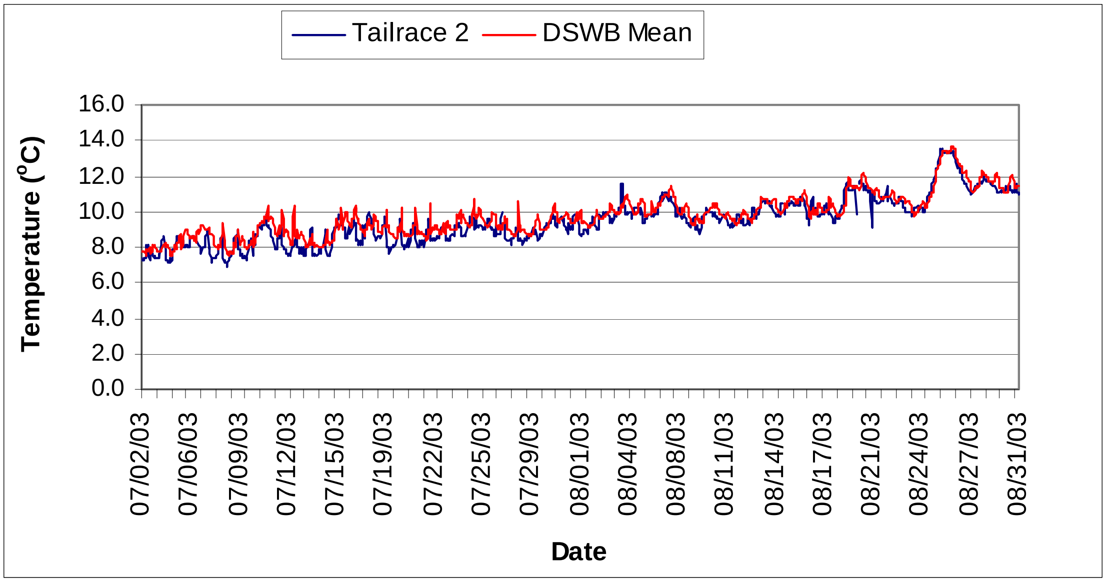

Figure 4. Graphic comparison of Mid Columbia water temperature collected at the Revelstoke Dam tailrace (Tailrace 2) and DSWB mean temperature between July 02, 2003 to August 31, 2003.

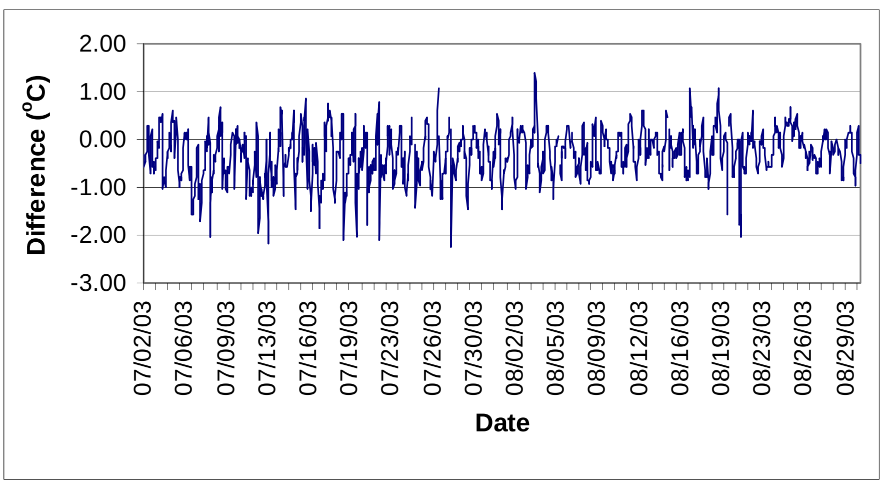

Figure 5. Hourly temperature difference between Revelstoke Dam tailrace 2 temperature logger and DSWB mean hourly temperature, July 02, 2003 to August 31, 2003.

Table 2. Summary of hourly temperature comparisons between the egg deposition area at the Revelstoke Golf Course and upstream and downstream Columbia River mainstem temperature monitoring stations.

Temperature Comparison	GC mean VS Tailrace 2	GC mean VS USEB mean	GC mean VS DSEB mean	GC mean VS DSWB mean
Mean difference (°C) July 01 to Sept 01, 2003	0.13	-0.08	-0.47	-0.17
Max -ve difference (°C) July 01 to Sept 01, 2003	-1.45	-1.42	-2.11	-2.40
Max +ve difference (°C) July 01 to Sept 01, 2003	1.88	1.23	1.09	0.78
Mean difference (°C) July 31 to August 14, 2003	0.13	-0.07	-0.72	-0.10
Max -ve difference (°C) July 31 to August 14, 2003	-1.45	-0.57	-1.88	0.77
Max +ve difference (°C) July 31 to August 14, 2003	1.18	0.45	0.45	0.39

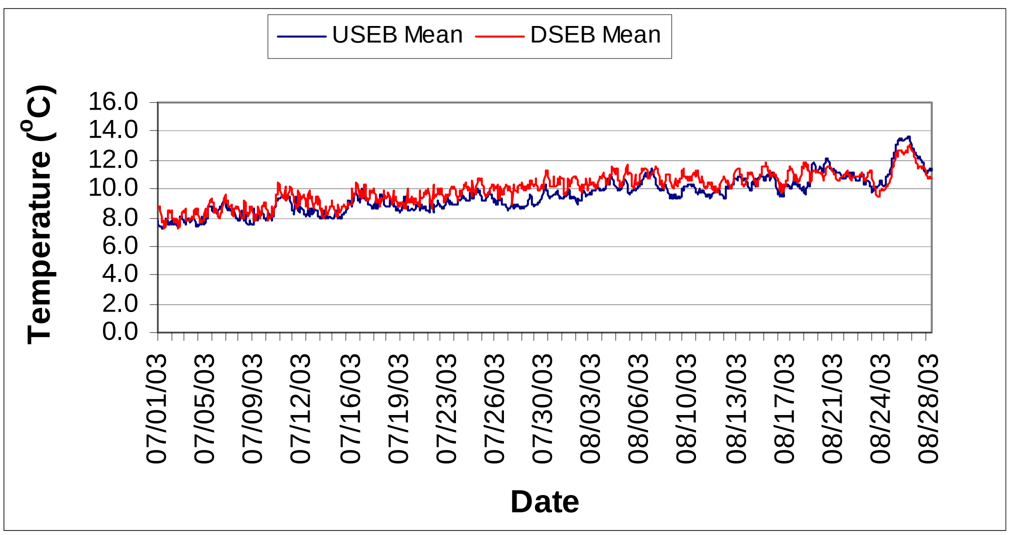

Figure 6. Comparison of Columbia River USEB mean hourly temperature and DSEB mean hourly temperature between July 01, 2003 to August 28, 2003.

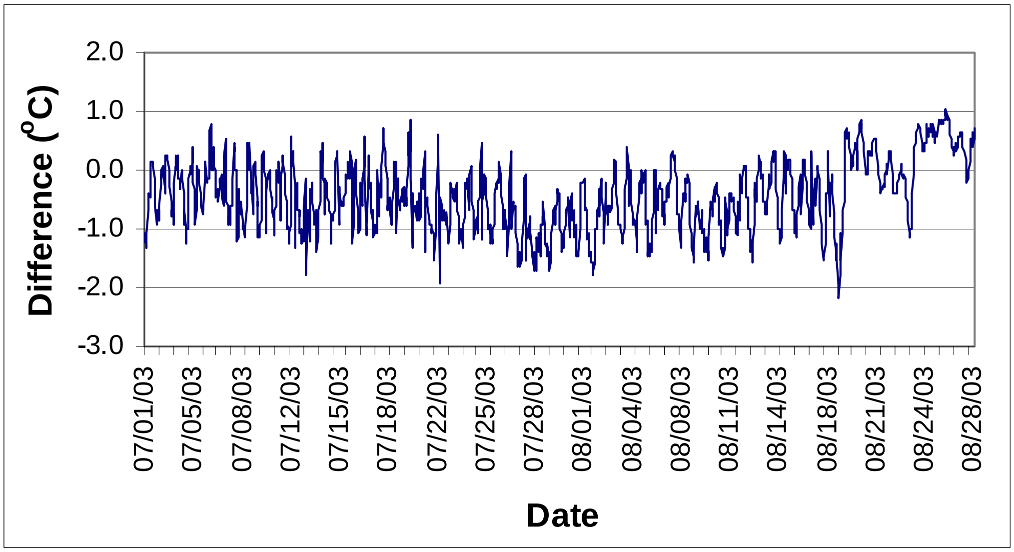

Figure 7. Hourly temperature difference between the USEB mean temperature and the DSEB mean temperature from July 01, 2003 to August 28, 2003.

Illecillewaet temperatures consistently remained above 10°C from July 28 to August 12, 2003 indicating that suitable temperatures for white sturgeon spawning was available during the period spawning events occurred at the Revelstoke Golf Course, suggesting the Illecillewaet River may not provide suitable depth, velocity, clean substrate or other habitat conditions which may be necessary for white sturgeon spawning.

There was a sudden drop in Illecillewaet River temperature beginning on August 12, 2003 with daily minimum temperature falling from 10.39 to 6.50°C on August 15. Jordan River water temperature also declined at this time, possibly due to cold air temperature influence or increased rates of glacial melt.

3.2. Embryo Incubation

3.2.1. Embryo capture Summary

Seven live embryos were captured on substrate mat 19 and six live embryos were captured on substrate mat 20 on August 7, 2003. All 13 embryos captured were in a similar stage of neurulation indicating that a single spawning event had occurred. As each embryo displayed a similar developmental stage, only one embryo from substrate mat 19 was preserved for staging to estimate the time of spawning and time to hatch time.

Twenty-four live embryos were captured on August 14, 2003 on substrate mats 18, 19 and 20, all displaying a similar level of development to the cleavage stage, indicating that a second separate spawning event had occurred. One embryo from substrate mat 18 and one embryo from substrate mat 20 were preserved for laboratory embryo staging.

Four embryos were captured at an early pre-hatch stage on substrate mat 19 and one pre-hatch embryo was captured on substrate mat 20 on August 22. One late pre-hatch embryo was captured on each of substrate mats 18 and 19 on August 27. A portion of a damaged embryo, considered to be at a pre-hatch stage, was captured on mat 20 on August 27 but was not included in the data due to uncertainty regarding embryo viability. The seven embryos captured on August 22 and August 27 had reached a similar stage of development as the embryos captured on August 14 had by the same date. The August 22 and 27 embryos were therefore considered to have been fertilized during the August 13/14 spawning event and were likely subsequently captured after becoming dislodged from riverbed substrate.

A total of 44 live embryos were captured between RK 226.4 and 226.6, or within a distance of approximately 200m in length along the east bank of the Columbia River adjacent to the Revelstoke Golf Course. No unfertilized eggs were captured although approximately 5 fungused eggs were captured on substrate mats that may not have been fertilized. Based on qualitative observation, the substrate at the embryo capture locations consisted of clean, course substrate ranging in size from gravel to large riprap boulders. Approximately 80% of the substrate was comprised of cobbles. Submerged riprap occurred at the toe of the rip rapped section of bank only. River velocity downstream of Revelstoke Dam is dependent on dam operations. During mid-day to early evening hours, surface velocity was estimated to be approximately 1 meter per second (m/s). Velocity at zero discharge was 0.05m/s on August 15 at approximately 0500hrs. RL&L (2000c) reported up to nearly 8.0m depths at the egg capture sites.

3.2.2 Incubation Period

The incubation periods, and therefore embryo development rate, were similar to incubation period predictions calculated using the developmental model described in Wang et al. (1985). The observed hatch period of approximately 16 days for the August 2/3 spawning event was approximately two days longer than the 13.7 day incubation period predicted from the model for embryos reared at 10.1^{o}C mean temperature. Similarly, for the August 13/14 spawning event, time to hatch at 14 to 15 days was approximately two days longer than the 12.2 day incubation period predicted by the model for embryos reared at 11^{o}C mean temperature. As embryos were checked once daily at or following the estimated incubation period, exact hatch times for most larvae were not determined. However, two of five Mat 19, August 7 larvae hatched at 1450 hrs on August 19 during assessment. One embryo from the August 13/14 spawning event hatched on August 27 at 1530 hrs but this embryo likely hatched as a result of the handling that resulted in its' membrane being torn. Precise determination of developmental rates based on time of hatch was difficult due to uncertainty regarding the estimated timing of spawning events.

3.2.3 Influence of low Revelstoke Dam discharge events on Columbia River Temperature.

Zero flow discharges occurred almost daily in July with temperature increasing by up to 2.5°C (two events) in shallow water as recorded by the GC1 temperature logger during night time or early morning hours when zero discharge events occurred. There appeared to be no effect of low discharges on deep water temperature based on GC2 temperature data. There also appeared to be a warming effect in shallow water, most noticeable at approximately 1300hrs presumably due to the effect of sun exposure and/or air temperature as shallow water temperature was generally 0.5°C above that of deeper water. The effect of zero discharge on shallow water temperature is illustrated for the week of July 13 to July 20, 2003 as an example.

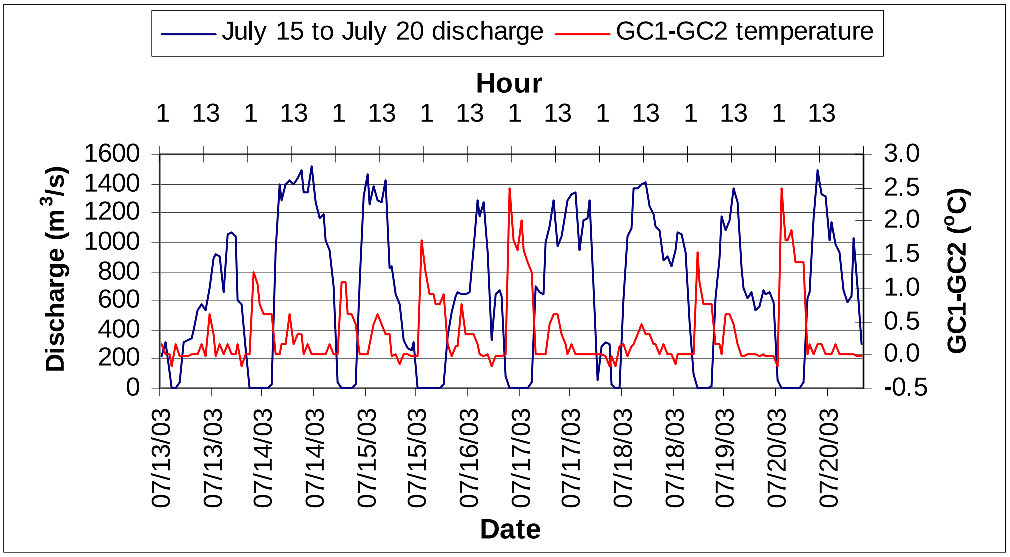

Figure 8. Difference in temperature between shallow water temperature (GC1) and deep water temperature (GC2) recorded at the 2003 embryo capture and incubation location from July 13, 2003 to July 20, 2003.

Of the 10 zero discharge events that occurred between the August 02 to August 29 incubation period, eight events (August 5,6,15,16,20,21 and 22) lasted for a period of approximately 1 to 2 hours with temperatures generally increasing by less than 0.3°C. The zero discharge event that occurred on August 18 lasted for a period of 3 hours and shallow water temperature increased by 0.3°C to 10.5°C at 0600hrs; however, at the same time, deepwater temperature at GC2 fell from 10.4°C at 1300hrs to 8.6°C at 0600hrs, a net difference of 1.8°C. Deep water temperature increased to 10.3°C and shallow water temperature remained stable at 9.4°C on August 16/17 between 1200 and 0100hrs indicating that temperatures collected by loggers within close proximity can still be affected by subtle differences in location and depth. Zero discharge events that occurred on August 4 and August 17 resulted in temperature increases of 0.92°C and 0.94°C respectively. Mean temperature difference between GC1 and GC2 during the incubation period was 0.02°C.

For the majority of the study period, the GC1 logger was located at similar depths to substrate mats 18, 19 and 20 and at a similar depth to the salmonid egg canisters in which the embryos were incubated. Based on these results, it appears unlikely that zero discharge events during August 2003 had a significant effect on the rate of embryo development, embryo survival or the time to hatch.

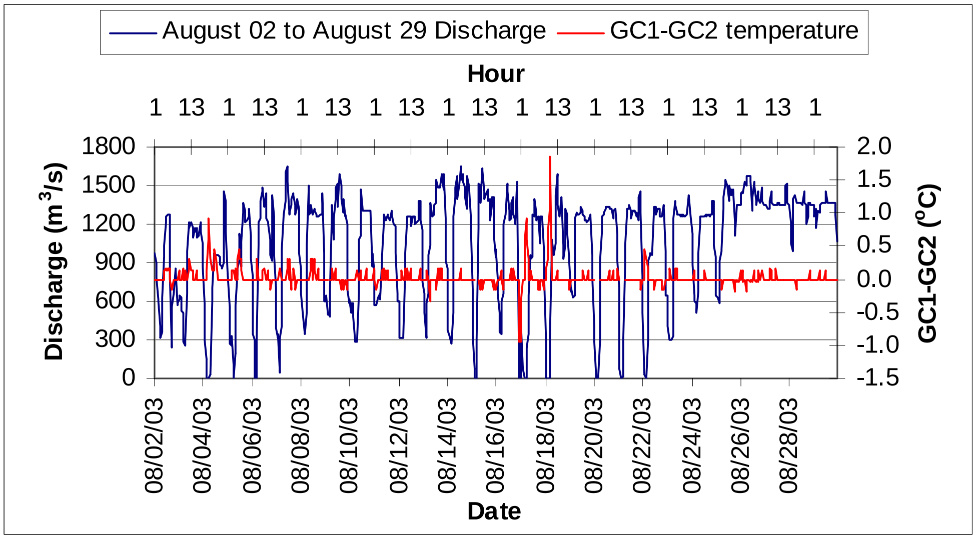

Figure 9. Difference in temperature between shallow water temperature (GC1) and deep water temperature (GC2) recorded at the 2003 embryo capture location during the August 02, 2003 to August 29, 2003 incubation period.

3.2.4 Percent Hatch

The hatch rate for embryos incubated between August 7 and August 19 was 75.0% (9 successfully hatched larvae out of 12 embryos incubated). The mean temperature during the incubation period for the August 2/3 spawning event was 10.1°C and ranged from 9.1°C to 11.9°C. Of the 29 embryos incubated between August 14 and August 27, 65.5 % (19 of 29 embryos) hatched successfully. The mean temperature during the incubation period for the August 13/14 spawning event was 11.0°C and ranged from 9.4 to 13.6°C. Overall, 68.3% of the 41 incubated embryos hatched successfully. The observed hatch rates compared favourably to the 50% hatch rate objective used for the white sturgeon conservation aquaculture program at the Kootenay Trout Hatchery in Wardner, BC (Ron Ek, personal communication).

All Mat 19, August 7 embryos hatched on or before 1450 hours on August 19, 2003. Two of the five embryos hatched during handling and differed in total length by less than 1mm TL from the three previously hatched larvae (personal observation). It is likely that all Mat 19, August 7 embryos hatched on August 19.

The Mat 20, August 7 canister was deployed too far off shore to be retrieved from shore without risking the canister getting stuck in a shallow area of river susceptible to dewatering. The Mat 20, August 7 canister was therefore retrieved by boat during the egg-monitoring program on August 22. Four of six larvae had hatched by August 22 with one embryo still at pre-hatch. This embryo did not hatch and subsequently became heavily overgrown with fungus by August 28. The sixth embryo had become infected with fungal growth by August 22. All but one of the 19 embryos captured on or after August 14 hatched on either August 28 or August 29. One embryo hatched on August 27 likely as a result of its' membrane being torn while being handled during assessment.

The estimated time of spawning and the observed time of hatch may have corresponded to increases in temperature as illustrated in figure 10. Temperature increased on August 19 hatch date from 9.96°C at approximately 0153hrs to 11.82°C at 1253hrs. Similarly, temperature increased from 11.28°C at approximately 0200hrs to 12.03°C at 1200hrs on August 28. Complete hatching may have occurred prior to the temperature dropping by 0.62°C between approximately 2100hrs on August 28 and August 29 at 1900hrs.

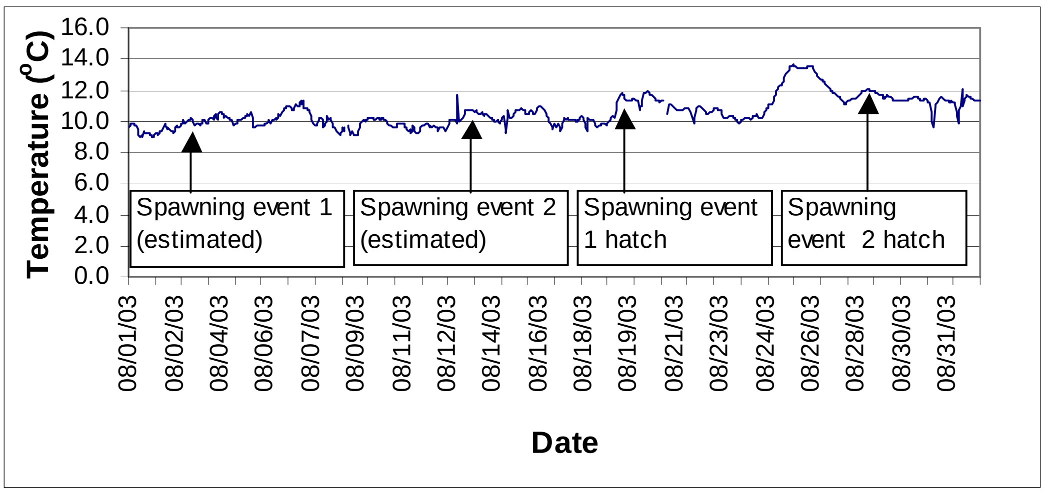

Figure 10. Golf Course (GC1 and GC2) mean hourly temperature data in relation to the August 02/03 and August 13/14 2003 estimated time of spawning events and the respective time at observed hatching.

3.3 Estimated timing of spawning Events - Back Calculations

Molly Webb and Kevin Kappenman confirmed the stage of embryo development necessary for back-calculations used to estimate the approximate time of the spawning events. The author considered the August 7 embryo to have developed to stage 24 (Stage of appearance of eye protrusions and thickening of the anterior end of the excretory system rudiments) which differed from the stage 20 (stage of broad neural plate) identified by Molly Webb and Kevin Kappenman (Figure 12). The author, Molly Webb and Kevin Kappenman considered the substrate mat 18, August 14 embryo to be at stage 10 (late cleavage) and the substrate mat 20 August 14 embryo to be at stage 11 (early blastula). As stage 22 (late neurula) was used to back-calculate the timing of spawning from eggs captured on August 7, the estimated time of spawning did not differ between stages 20 (Molly Webb, Kevin Kappenman) or stage 24 (author).

Figure 11. Preserved white sturgeon embryo at neurulation, stage 20 (Dettlaff et al. 1993), captured on substrate mat 19, August 7, 2003. Photo by Mark Tiley, CCRIFC.

Back-calculated spawning events were based on embryo stage as described above and temperature data collected at the CCRIFC Golf Course 1 temperature monitoring station. The calculated timing of the first spawning event was at August 02 at approximately 2400hrs. Given that the embryo stage used for the calculation (stage 22) differed slightly from the observed embryo stage (stage 20 or stage 24), spawning was estimated to have occurred at night on August 02 or early in the morning on August 03. Similar to the first spawning event, embryos from the second spawning event were captured at stage 9 and stage 10 or 11 for which equation coefficients are not available. Coefficients for stage 6 were used and the calculated timing of the second spawning event was at approximately 0600hrs on August 14, 2003.

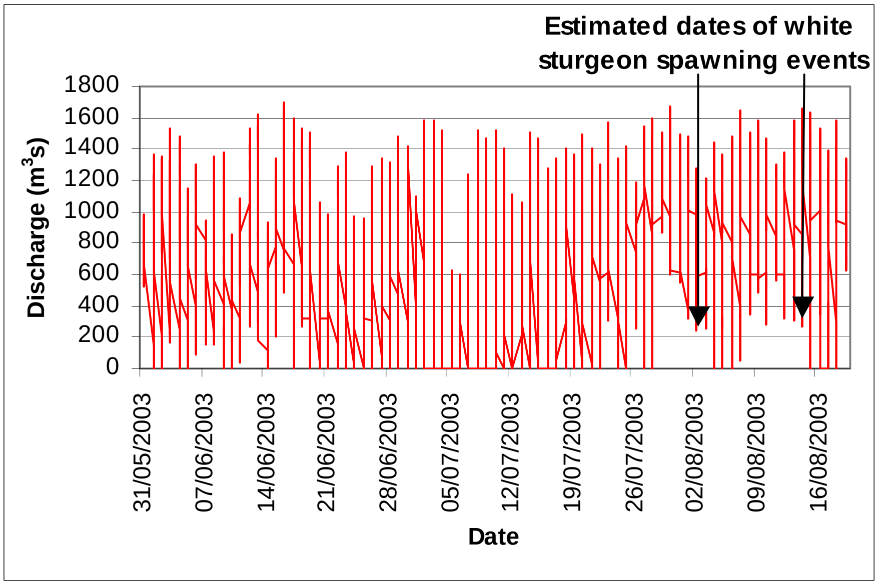

Figure 12. Timing of white sturgeon spawning events in relation to Revelstoke Dam daily discharge range, from May 31, to August 19, 2003. Discharge data courtesy of BC Hydro.

Spawning is estimated to have occurred during the night of August 13, 2003 or during the early morning of August 14, 2003. The mean temperature for August 2 and 3 (48hr period) was 9.7°C and ranged from 9.1°C to 10.2°C. The mean temperature for August 13 and 14 (48hr period) was 10.6°C and ranged from 10.5°C to 10.8°C.

Spawning events occurred after a five day period of flows of not less that 245m^{3}s for the August 2/3 spawning event and flows of not less than 268 m^{3}s between August 7, 0500hrs and August 14, 0600hrs for the August 13/14, 2003 spawning event (Figure 12). These observations suggest that the 2003 Arrow sturgeon spawning events may have been triggered by sustained flow periods. Revelstoke Dam operations may have therefore contributed significantly to the timing of the 2003 spawning events.

3.4 Larval fitness assessment

All larvae were assessed for physiological abnormality in the field and shortly after preservation. Five larvae were assessed qualitatively in the field and were considered to be normal by the author prior to their escape between August 29 and September 1, 2003. Twenty-three larvae were sent to the University of California, Davis for physiological assessment work conducted by Joel Van Eennenaam, a highly experienced sturgeon researcher.

Figure 13. Larval white sturgeon hatched on August 14 and reared in the Columbia River immediately adjacent to the Revelstoke Golf Course east river bank, August 2003, displaying a notochord abnormality. Photo by Mark Tiley, CCRIFC.

The assessment found all larvae to be normal. However, the author observed what appeared to be a notochord abnormality in one larva (Figure 13), resulting in an inability of the larva to swim normally. This observation was communicated to Joel Van Eennenaam who then agreed with the authors' original assessment.

As a small number of embryos were collected in 2003, the total lengths of newly emerged larvae were generally not measured to avoid stressing or injuring the larvae. The larvae that had its' embryo membrane torn and hatched in the presence of the author during assessment on August 27 was 11.3mm TL. The mean total length of live larvae hatched between August 27 and 29 (n=12) was 13.4mm TL at the time of measurement (SD= 0.5mm). The growth rate for larvae reared to up to 11 days post hatch was not determined as the majority of measurements were obtained 6 weeks after preservation in ethanol from which specimens would have likely experienced some shrinkage. Several larvae succumbed to the September 01 dewatering event and may have experienced post mortem shrinkage. The rearing of larvae within histological cassettes may have also affected growth rate.

3.5 Comparison between Contemporary and Historic, Pre-dam Columbia River Temperature Conditions at the Arrow Lakes Reservoir Spawning Area

Both the 1999 and 2003 spawning events suggest that the minimum temperature threshold for natural Arrow white sturgeon spawning is between approximately 9^{o}C and 10^{o}C for sustained periods. Sustained periods of 9^{o}C to 10^{o}C did not occur in the Revelstoke Golf Course area until late July-early August, despite 2003 being a comparatively warm, drought year.

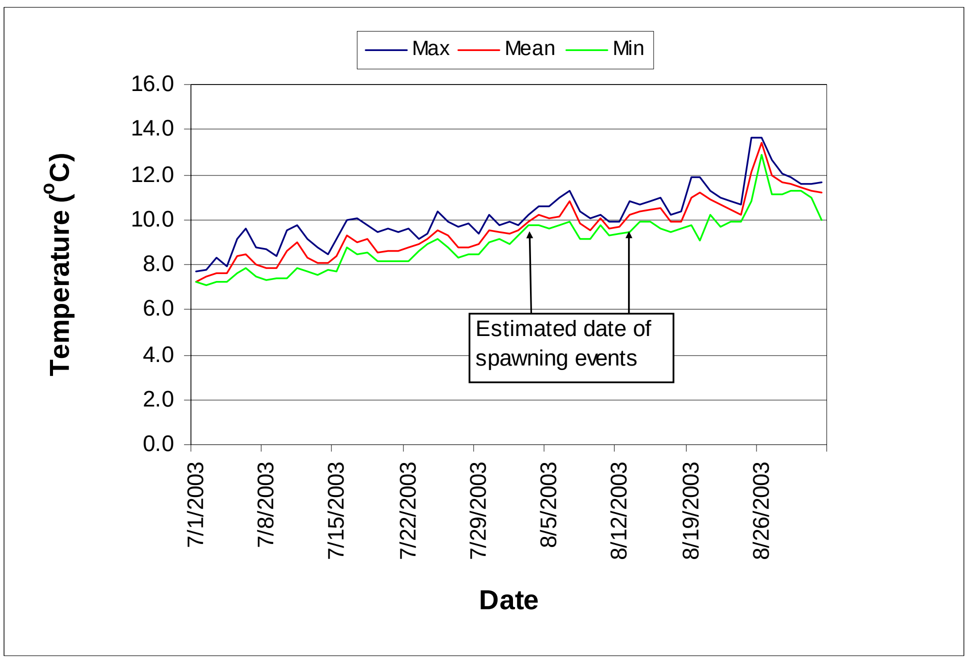

Figure 14. Daily maximum, mean and minimum temperatures collected at the CCRIFC GC1 and GC2 temperature monitoring stations between July 1 and September 1, 2003 in relation to estimated white sturgeon spawning events.

Diel temperature fluctuation in 2003 at the 1999 and 2003 spawning area averaged 2.10^{o}C between March 14, and mid June. Mean diel temperature range was 1.66^{o}C in July, 1.09^{o}C in August and 1.05^{o}C in September. Diurnal temperature range downstream of Revelstoke Dam was approximately 1^{o}C to 3^{o}C lower than the sampled unregulated tributaries. The diurnal temperature pattern downstream of Revelstoke Dam was irregular (i.e. Figure 11) unlike the daily oscillating temperature patterns evident in the hourly temperature plots (provided in Appendix A6) of the sampled unregulated tributaries and the Columbia River mainstem near Donald.

Tables 3 and 4 provide a summary of the number and percentage of historic measurements collected during the daily minimum, mean and maximum time periods.

Table 3. The number and percentage of all pre-dam temperature measurements collected during the daily minimum, mean and maximum temperature time periods.

Diurnal period	Number of observations	Percent of observations
Min	10	15.2
Mean	40	60.6
Max	16	24.2

Table 4. The number and percentage of pre-dam temperature measurements collected during the daily minimum, mean and maximum temperature time periods in June, July and August.

Diurnal period	Number of observations	Percent of observations
Min	3	15.8
Mean	11	57.9
Max	5	26.3

To obtain the most meaningful comparison between historic and contempor4ary temperatures, historical spot temperature data collected between 1955 and 1966 was plotted against 2003 daily mean temperature data.

Figure 15 below graphically illustrates the probable affect of impoundment and regulation on Columbia River water temperature at the white sturgeon spawning area. Although the 1955 to 1966 temperature data were collected opportunistically over an eleven-year period, the pooled historic data illustrates a low level of variability for a given week between years, providing what is likely an accurate representation of an average pre-dam temperature trend.

Late May, 2003 daily mean temperatures were between approximately 1.0^{o}C and 4.5^{o}C colder than historic pre-dam temperatures. Late June 2003 temperatures were colder compared to historic temperatures by a range of approximately 1^{o}C to 4.0^{o}C.

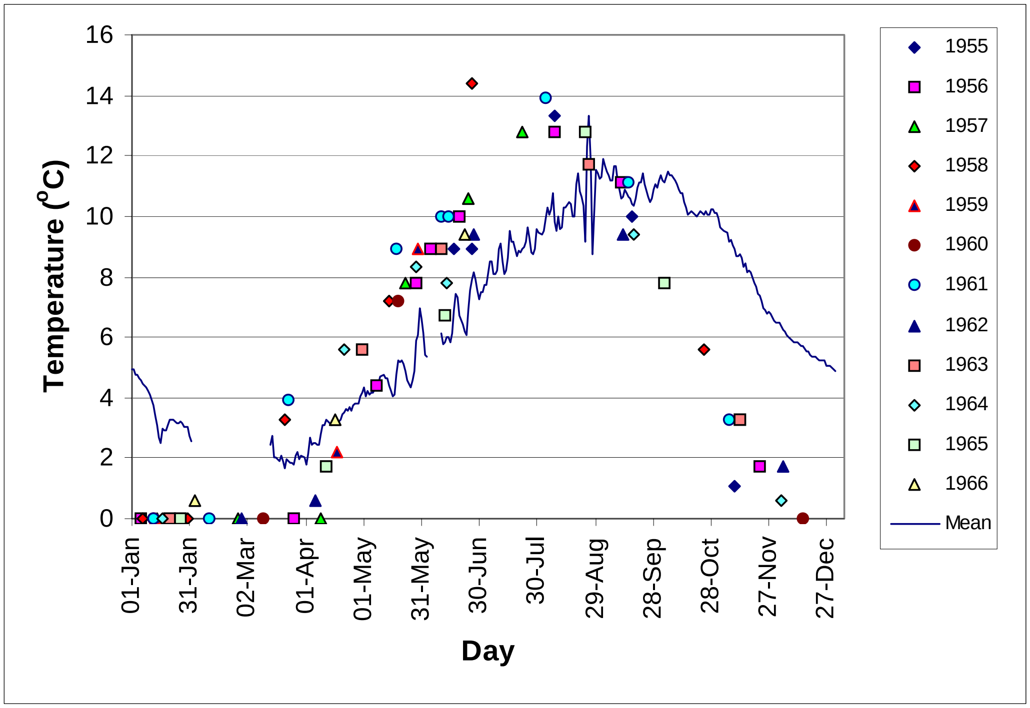

Figure 15. Water Survey of Canada pre-dam temperature measurements collected at Steamboat Rapids in comparison with 2003 daily mean temperature collected at the Golf Course spawning location.

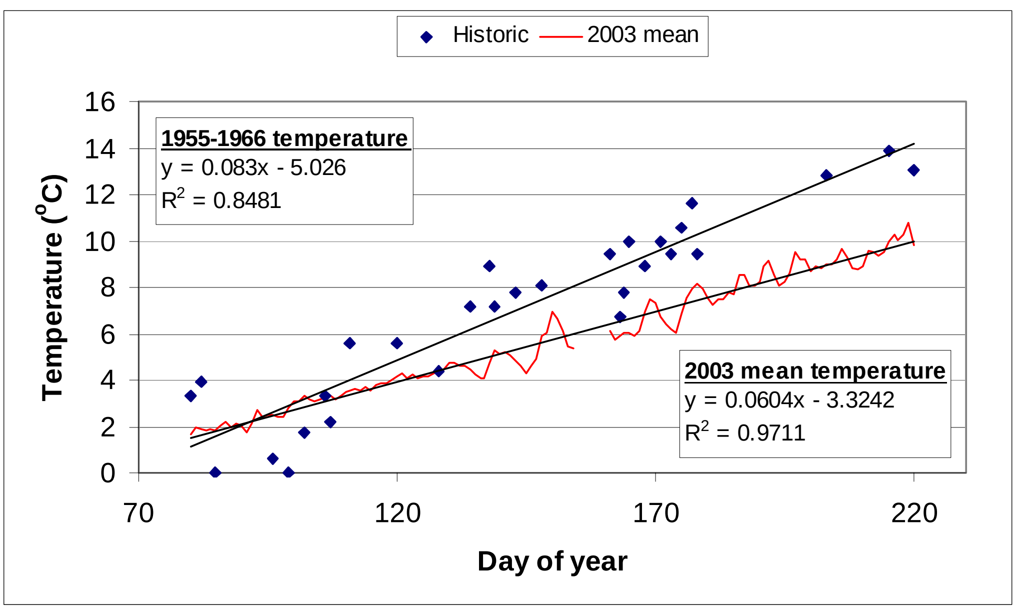

Figure 16. Linear regressions for 1955 to 1966 spot temperature data and 2003 daily mean temperature data from March 21 to August 08. y = temperature; x = day of year.

Similarly, a linear regression comparison estimated that 2003 mean daily temperatures were approximately 2^{o}C colder in June and by early August approximately 3^{o}C colder than pre-dam temperatures. The pre-dam temperature data suggested that mainstem Columbia River temperature reached a maximum in late July to early August followed by a steady decline in temperature until reaching 0^{o}C by approximately mid December.

The correlation between the day of year and 1955-1966 spot temperature and 2003 daily mean temperature between March 21 and August 08 was highly significant: $r = 0.93$, $p<0.0001$; $r = 0.99$, $p<0.0001$ respectively. The rate of temperature increase from March 21, to August 08 for the 1955 to 1966 period was estimated to be 1^{o}C every 12.0 days or 0.08^{o}C/day, whereas the rate of temperature increase from March 21, 2003 to August 08, 2003 was estimated to be 1^{o}C every 16.6 days or 0.06^{o}C/day. Results indicate that the Columbia River downstream of Revelstoke Dam now warms at a slower rate during the spring and summer than occurred prior to impoundment. The regression equation for the 1955 to 1966 temperature was used to estimate the time at which white sturgeon could have spawned prior to Mica Dam construction. The modified equation is as follows:

$$x=(y+5.026)/0.083$$

Mean daily temperature ranges over the bi-weekly periods defined in Table 5 ranged from 2.70^{o}C to 4.71^{o}C. Combined average bi-weekly diel temperature ranged between 3.21^{o}C and 3.98^{o}C. Based on the data from the four unregulated temperature monitoring sites, the most likely mean diel temperature range at Steamboat Rapids prior to regulation was between 3^{o}C and 4^{o}C during June, July and August.

A diel temperature range between 1^{o}C to 5^{o}C, an approximate daily minimum and maximum diurnal temperature range observed in the temperature data for unregulated locations, was used to estimate the approximate timing of the start of the white sturgeon spawning period prior to regulation (Table 6). .

Table 5. Mean daily temperature range over bi-weekly periods between June 01 and August 31 for the Columbia River mainstem at Donald, Jordan River, Illecillewaet River and the Akolkolex River.

Bi-weely time period	Columbia River Donald Stn 2002 Diel temp range (°C)	Jordan River 2003 Diel temp range (°C)	Illecillewaet River 2003 Diel temp range (°C)	Akolkolex River 2005 Diel temp range (°C)	Combined average Diel temp range (°C)
June 01 to June 15	3.97	NA	NA	2.45	3.21
June 16 to June 30	3.98	NA	NA	3.03	3.51
July 01 to July 14	3.92	3.68	2.92	2.80	3.33
July 15 to July 31	4.00	4.71	3.23	3.96	3.98
August 01 to August 15	3.65	3.38	2.70	4.32	3.51
August 15 to August 31	4.30	NA	NA	NA	NA

The estimated timing at the start of the Arrow Lakes white sturgeon period ranged between June 24 to July 18. If it is assumed that water temperature is the primary trigger for initiating white sturgeon spawning, available data suggests that the Arrow Lakes white sturgeon most likely began spawning during the first or second week of July. These study results suggest that Arrow Lakes Reservoir white sturgeon spawning period currently begins approximately two to four weeks later than the spawning period prior to river impoundment.

Table 6. Estimated timing of the beginning of the pre-dam Arrow Lakes white sturgeon spawning period based on temperatures representative of 1999 and 2003 spawning events and a diurnal temperature range suitable for spawning assuming a 9.0°C minimum spawning temperature threshold.

Mean daily temperature (°C)	Estimated date/ Day of year	Diurnal temperature range (°C) suitable for white sturgeon spawning assuming a 9.0°C minimum spawning temperature threshold
9.5	June 24 / 175	1.0 (+/-0.5)
10.0	June 30 / 181	2.0 (+/-1.0)
10.5	July 06 / 187	3.0 (+/-1.5)
11.0	July 12 / 193	4.0 (+/- 2.0)
11.5	July 18 / 199	5.0 (+/-2.5)

4.0 Discussion

4.1 Spawning Area Temperature

The 9.1°C to 11.9°C temperature ranges observed throughout the August 2/3, 2003 spawning event incubation period, a drought year, was almost identical to the 9.2°C to 11.6°C temperature range observed by RL&L (2000c) in August 1999, a high water year. The temperatures observed during the majority of the incubation period following the estimated August 13/14 2003 spawning event which ranged from 9.4°C to 13.6°C, were similar to the temperatures observed in 1999 except for the two-day period between August 25 and August 27, 2003 when temperatures generally ranged between 12.0°C and 13.6°C. Hourly temperature data collected at the 1999 and 2003 spawning area in 1999, 2003, 2004 and 2005 have been similar during the July/August spawning period, although compared to 2003 temperatures, July and August 2004 temperatures were 0.67°C and 0.31°C warmer respectively and from July 25 to September 01, 2005, 0.2°C cooler (Tiley 2005b). The 2003 temperatures are likely representative of temperatures that generally occur downstream of Revelstoke Dam during July and August.

The Jordan River does not influence water temperature at the embryo capture area as discharge from the Jordan River flows into the Columbia River at RK 226.5 immediately downstream and at the opposite (west) bank to the spawning area. Discharge from the Jordan River likely flows downstream along the west bank, shortly thereafter becoming well mixed with Columbia River water in the Big Eddy 0.5km downstream. It is unknown whether the Jordan River had an influence on temperature within Big Eddy where tagged adult sturgeon have consistently been located in July and August. However, the relatively small amount of discharge from the Jordan River (i.e. peak flow of 79.3m^3/s in 1966) is likely not sufficient to have a detectible effect on Columbia River mainstem temperature except possibly along the west bank of the Columbia immediately downstream of the Jordan River inflow.

The Illecillewaet River had a mean warming effect of 0.47^oC between July 01 and August 31 and a mean 0.72^oC warming effect during the 2003 July 31 to August 14 spawning period, but regularly provided temperature over 1^oC warmer than the mainstem during the evening and night hours when the Illecillewaet River was often at daily peak temperature. Prince (2004) located pre-spawning female PIT tagged 4158636864 at RK 220 holding approximately 1km downstream from the Illecillewaet River on June 19, 2003 possibly to hold in warmer temperatures. RL&L (2001) located one male and one female sturgeon in the mouth of the Illecillewaet River on July 11, 2000 and later one male on August 10, 2000. The warmer Illecillewaet water may provide a benefit to prespawning sturgeon by increasing the rate of egg and sperm development. The higher turbidity levels and possibly higher food availability may also attract sturgeon to the Columbia River/Illecillewaet River confluence area. The available tracking data (Tiley, 2005b; Golder Associates, 2004a) suggests that adult sturgeon use of the Columbia River immediately downstream of the Illecillewaet River/Columbia River confluence is likely irregular as opposed to the comparatively consistent use of the Big Eddy area.

Frequent stranding of temperature loggers occurred in the Jordan and Illecillewaet Rivers during the summer and in the Columbia mainstem in the autumn and early winter when Arrow Lakes Reservoir elevations continued to drop. In order to avoid temperature logger stranding, the deployment of temperature loggers from a boat into deep water mainstem locations and in tributaries by foot during very low flow periods is mandatory in order to avoid logger dewatering. However, high discharge can displace the cinder blocks used to anchor temperature loggers to shallow areas subjected to dewatering, so periodic inspection of temperature monitoring stations should be conducted shortly after peak freshet in order to reduce the frequency of dewatering in shallow river sections.

Future monitoring of temperature at the spawning area adjacent to the Revelstoke Golf Course should include both deep water thalweg and near-shore locations in order to ensure that the potential effects of Revelstoke Dam operations on temperature and therefore embryo incubation are documented. Temperature loggers could be attached to incubation arrays and deployed at similar depths as substrate mats to ensure that temperatures most representative of incubation temperatures are collected. Substrate mats generally sink close to the river bank in near shore locations and shallower water than maximum thalweg depth. In one instance, a substrate mat deployed upstream of the embryo capture area was observed partially dewatered at low flow.

For practical and budgetary reasons, future incubation studies will likely be conducted close to shore as deep water deployment would require the frequent use of a boat. This study has illustrated that the rate of embryo development in near-shore habitats could be affected by Revelstoke Dam operations if zero discharge events of two or more hours occur on a regular basis. Zero discharge events in August are generally infrequent in comparison to June and July, but year to year variation in Revelstoke Dam operations, the timing of spawning events and Arrow Lakes Reservoir elevations may result in dam operations having a significant effect on incubation temperatures.

Considerable effort was made to select locations that had limited access to the public. However, several loggers were still pulled to shore and in one case the concrete block and logger was cut from the cable. The temperature loggers deployed within the Jordan River were consistently vandalized by movement to shallow slack water areas or by placement on the riverbank and were subjected to dewatering in late summer and fall. One of the loggers deployed on the east bank downstream of the Illecillewaet River was lost to the public. This area is used regularly for fishing, dog walking, horseback riding and all-terrain vehicle recreation. It is recommended that less accessible tributary sites located further upstream from the Columbia River confluence be selected in future temperature monitoring studies.

4.2 Embryo Capture

Due to the small embryo sample size obtained (n=44), embryos could not be sacrificed to determine the exact time to a given embryo developmental stage. It was not feasible to monitor developmental rate of live embryos due to the potential effects of handling stress and exposure to elevated temperatures on percent egg hatch and time to hatch. Future efforts to confirm spawning efforts may increase embryo capture efficiency by placing more artificial substrate mats in the 1999 and 2003 embryo capture area. If feasible, efforts should be attempted to sample for embryos in deeper sections of the channel thalweg. This may be achieved by deploying substrate mats during early morning, low flow periods to prevent high river velocities from pushing the substrate mats towards the river bank. However, substrate mats placed along eddy lines adjacent to shore such as those that occur along the rip rapped section of Golf Course may also increase embryo capture rate as embryos may have a higher tendency to settle to the substrate in these areas.

4.3 Embryo Incubation and Survival

During this study, temperature did periodically fall below 10^{o}C during the August 02/03 incubation period to as low as 9.1^{o}C on August 09. Embryo survival in cold temperatures (below 9^{o}C or 10^{o}C) may be influenced by the duration of exposure to low temperature and the developmental stage and fitness of the embryo. There is currently no documentation of prolonged incubation of embryos and subsequent survival to hatch in the wild at temperatures averaging below 10^{o}C. Temperature ranged between 9.2^{o}C to 11.6^{o}C at the Golf Course during the August 1999 white sturgeon incubation and spawning periods (RL&L, 2000c), and therefore would not have been inconsistent with the 2003 temperature data, suggesting that successful hatching in 1999 would have been possible.

The incubation period for both of the 2003 Arrow white sturgeon spawning events was longer than predicted by the Wang et al. (1985) model by approximately two days. Wang et al. (1981) determined the development rate of Sacramento white sturgeon using six temperature treatments ranging between 11.0^{o}C and 26^{o}C, with each temperature being held almost constant (+/- 0.5^{o}C) under laboratory conditions. Genetic differences between the Sacramento River and Arrow white sturgeon populations may explain some of the discrepancy between the predicted and observed Arrow and Sacramento white sturgeon incubation periods. In addition, the Wang et al. (1985) model may not be able to predict incubation period with the same level of accuracy for incubation studies conducted under natural conditions in which temperature typically fluctuate. The mean temperature during the incubation period for the August 2/3 spawning event was 10.1^{o}C and ranged from 9.1^{o}C to 11.9^{o}C. The mean temperature during the incubation period for the August 13/14 spawning event was 11.0^{o}C, with a temperature range between 9.4^{o}C and 13.6^{o}C. The 4.2^{o}C temperature range may have slowed embryo development rate enough to explain the difference between the observed time to hatch and the predicted time to hatch.

The minimum temperature necessary for white sturgeon embryo survival to hatch is currently unknown, but based on the available literature it is likely between 8^{o}C and 9^{o}C, with a possible exception being the Kootenay River population. Buddington et al. (1993) transferred newly fertilized embryos from three white sturgeon females from 14^{o}C to 8^{o}C water following a -1^{o}C/15 minute acclimation period. The embryos from only one of the three females survived to neurulation and then at a low rate of 13%. Of the 13% of the surviving embryos, only 14% survived to hatching following incubation at 8^{o}C and many of the larva were small and/or deformed (Buddington et al. 1993). Paragamian et al., 2002 collected white sturgeon embryos in the Kootenay River that were spawned in mean daily temperatures of as low as 7.5^{o}C, but the survival rate of embryos was not determined. Incubation experiments conducted by Nikol’skaya & Sytina (1978) observed that of the embryos of four Russian sturgeon species incubated at 9^{o}C, only Beluga sturgeon (*Huso huso*) embryos survived beyond stage 11 (early blastula) of which only a percentage survived to hatch.

The stage at which the embryos were captured and examined could have been a factor in embryo survival. Embryos become far more tolerant to handling and movement once they reach the neurulation stage (Ron Ek, personal communication). The early embryonic stages of cleavage, in particular gastrulation, are much more sensitive to handling and mechanical stress than embryos that are at or beyond neurulation (Ron Ek, Molly Webb, personal communication). The lower hatch rate observed downstream of Revelstoke dam compared to that reported in Wang (1985) may have been the result of egg retrieval and handling.

The numerous factors that may contribute to embryo mortality limit the ability to draw elaborate conclusions regarding the effects of temperature on embryo survival. However, the primary objective of the *in-situ* study was to determine whether contemporary temperature conditions downstream of Revelstoke Dam were resulting in significant sturgeon embryo mortality or low larval fitness and thus be contributing to the observed Arrow white sturgeon recruitment failure.

The controlled laboratory experiment conducted by Golder Associates was unsuccessful in rearing embryos to hatch due to fungus infection of embryos. Golder Associates used the staging classification used by the Kootenay Tribe of Idaho that differs from that described in Beer (1981) or Detlaff et al. (1993), so accurate comparisons of embryo development rate between the *in-situ* study and the laboratory study were difficult.

Golder Associates (2004b) reared embryos up to the closure of the neural tube (stage 23 in Detlaff et al.1993) prior to total mortality. Golder Associates (2004b) observed that 80% of embryos reared at a mean temperature of 14.8^{o}C had developed to the early neurulation stage (stage 19, Detlaff et al, 1993) in 5 days. This observation is in close agreement, but still at a slower rate of development, with estimated time of spawning for the August 2/3 spawning event in which embryos captured on August 07 and exposed to a mean temperature of 10.1^{o}C had developed to stage 20 (stage of broad neural plate, Detlaff et al, 1993) over an estimated 4 to 5 day period. Interestingly, 80% of embryos reared at a mean temperature of 8.7^{o}C reached early neurulation at 8 days following fertilization. However, fungal infection may have slowed the rate of embryo development prior to embryo mortality (Golder Associates, 2004b). Furthermore, the small sample size obtained in the field would have limited the ability to conduct statistical comparisons between this *in situ* experiment and the controlled laboratory experiment.

All embryos that failed to hatch became heavily covered with fungus, thought to be *Saprolegnia sp*. It is uncertain whether the fungus caused the embryo mortality or whether fungus colonization occurred post mortem. Reports of white sturgeon embryos becoming fungus-infected have been documented in field (i.e. RL&L, 2000c) and laboratory studies (i.e. Wang, 1981; Golder Associates, 2004b). Factors contributing to embryo susceptibility to fungal attack are unknown, but experienced hatchery personal generally believe that adequate flow must be maintained to prevent or reduce fungal attack of incubating embryos (Ron Ek, personal communication).

4.4 Timing of 2003 spawning events

The timing of spawning may be induced by rising water temperatures as both of the 2003 spawning events were estimated to have occurred at a time when temperatures increased by approximately 1^{o}C (Figure10, Figure 14). RL&L (2000c) observed a spawning event on August 20, 1999, immediately following a temperature increase from 9.5°C on August 15 to 11.5°C on August 20. Paragamian and Wakkinen (2002) observed that spawning events in the Kootenay River downstream of Libby Dam occurred during periods of rising temperatures and ceased if temperatures dropped by 0.8°C or more. This study also observed embryo hatching when temperature increased by approximately 1°C to 2°C.

The influence of photoperiod on the diurnal occurrence of white sturgeon spawning is also unknown. Daytime spawning has been observed by Parsley et al. 1993 in the Lower Columbia River downstream of McNary Dam and daytime spawning in the Nechako River, a tributary to the Fraser River in central British Columbia, has also been documented. Both night time and daytime spawning has been documented for lake sturgeon (*Acipencer fluvenscens*) both at natural and dam tailrace spawning areas (Bruch and Binkowski, 2002). The back calculations from this study estimated that spawning likely occurred under darkness. The very clear water conditions downstream of Revelstoke Dam may be a deterrent to daytime spawning. However, back calculated estimates do not provide the high level of accuracy needed to identify the precise time at which spawning events occur.

4.5 Larval Fitness

Low frequencies of physiological abnormalities are observed in larvae when either hatchery or wild brood are spawned in hatchery environments with notochord abnormalities being the most commonly observed deformity (Joel Van Eennenaam, personal communication). Abnormalities are likely attributable to egg quality, timing of spawning or environmental factors not associated with handling (Joel Van Eennenaam, personal communication). All embryos were exposed to unavoidable physical stress when the substrate mats were retrieved from the river substrate as well as very brief exposure to elevated temperatures during their transfer from the substrate mats to the histological cassettes and salmonid egg vials. Considerable effort was made to reduce such stresses as much as possible; nonetheless, there is a slight chance that handling could have been a factor in the single observed deformity.

Wang (1981) observed that white sturgeon larvae reared at 11°C and 20°C contained less muscle and supporting tissue and more fat compared to larvae reared at 14°C to 17°C, the latter temperature range being identical to the temperature range at which spawning was observed in the Sacramento River by Schaffter (1997). Wang (1981) postulated that larvae reared at 14°C to 17°C may be better competitors owing to the observed higher muscle and tissue content. Stock differences between populations may affect metabolism and nutrient utilization, with cold water stocks such as the Arrow Lakes Reservoir and Kootenay River populations being better adapted to colder incubation temperatures. Future studies on Arrow Lakes Reservoir white sturgeon should consider examination of relative fitness in relation to embryo incubation and larval rearing temperatures.

4.6 Estimate of pre-dam spawning period

The July 31 to August 20 spawning events observed in 1999 and 2003 downstream of Revelstoke Dam represent the latest white sturgeon spawning period observed in the wild anywhere thus far for any white sturgeon population. The spawning periods of other Columbia River Basin white sturgeon populations studied have occurred from late May to late June in the Kootenay River (Paragamian et al. 2001), late April to early July in the Lower Columbia River (McCabe Jr. and Tracy, 1994; Parsley et al. 1993; Sprague, 1992) and from late June to late July downstream of the Pend d' Oreille/Columbia River confluence (i.e.; RL&L, 1997 & 1998).

Assuming 2003 temperatures are representative of post impoundment temperatures in general, a delay in the beginning of the Arrow Lakes white sturgeon spawning period by two to four weeks is probable and likely caused by the reduced rate of warming resulting in the approximate 1°C to 4°C cooler temperatures from mid-May to late August, and the delay in the time to the proposed minimum spawning temperature threshold range of 9°C to 10°C. Perrin et al. (2003) observed a two to three week later Fraser River white sturgeon spawning period in 1999, a flood year in which water temperatures were 3°C to 4°C cooler during the spring and summer compared to 1998. Based on back calculations from captured embryos, Perrin et al. (2003) estimated that the 1999 spawning period occurred from July 04 to August 08, also a comparatively late spawning period which may have been delayed due to the colder water temperatures observed in 1999.

Arrow Lakes white sturgeon spawning in late June or early July may have been possible considering that Columbia River discharge at Steamboat Rapids in 1966 was approximately 4 to 70 times greater during the 1966 peak flow discharge recorded at the in the Donald, Jordan and Illecillewaet WSC gauging stations. Diel temperature range at Steamboat Rapids may have therefore been less than the estimated 3°C or 4°C if the influence of air temperature and exposure to sunlight became increasingly less as mainstem discharge increased with distance downstream.

Prespawn female 3-3-4 was located and recaptured in the Revelstoke Airport area 1 to 2 km downstream of the Illecillewaet River inflow at river km 220 on June 17, 2003 (Prince, 2004). Egg diameters of 3.4mm indicated that female 3-3-4 was ripe and likely to spawn within a few weeks (Prince, 2004) providing suggestive evidence that the Arrow white sturgeon subpopulation may have spawned in June or July under pre-dam conditions. It is also possible that Columbia River temperatures may play an important role in the egg development of prespawning female sturgeon and therefore the timing of spawning, percent hatch and larval fitness.

Female 3-3-4 was tracked several times in the Illecillewaet River/Columbia River confluence area where she likely remained for approximately six weeks although undocumented forays to upstream and downstream habitats could have occurred. She was located upstream in the Big Eddy at river km 225-226 on July 30, 2003 (Golder Associates, 2004a). Based on tracking and artificial substrate mat data, female 3-3-4 may have been involved in the August 2/3 2003 spawning event.

There is no way to estimate how long the pre-impoundment spawning period continued. The available literature on white sturgeon spawning periodicity indicates that all documented white sturgeon spawning periods occur during the spring and summer warming trend and prior to peak temperature period. The end of the Arrow Lakes white sturgeon spawning period may have therefore coincided with peak temperature which, based on extremely limited pre-dam data and pre-dam temperature trend, appears to have occurred in late July or early August. The spawning period of the Arrow white sturgeon may have spanned from early or mid July to late July or early August, a period of approximately three to four weeks and similar to the spawning periods observed downstream of Revelstoke in 1999, downstream of the Pend d' Oreille River (RL&L, 1997; 1998) in the Kootenay River (Paragamian et al., 2002; Paragamian et al., 2003), in the Fraser River (Perrin et al., 2003) and in the Sacramento River (Schaffter, 1997).

It is reasonable to assume that temperature sampling at the Steamboat Rapids WSC gauging station was conducted adjacent to the river bank in which surface temperature was measured that potentially resulted in a slight sampling bias towards warmer temperature readings. A significant sample bias is unlikely as the river water within this canyon location would have been swift moving and well mixed. GC logger 1 temperature data suggested that temperature increases exceeding 0.3^{o}C occurred only during zero flow periods lasting several hours. A sample bias of approximately +0.5^{o}C was also observed around mid day at the general location where substrate mats 18 to 20 were deployed. Although GC logger 2 may be more representative of temperatures in the channel thalweg, GC logger 1 data is likely more comparable to the 1955 to 1966 temperature data.

The method used to determine daily mean temperature and diurnal temperature range could be improved upon by incorporating additional temperature data from major tributaries upstream such as Downie Creek and the Goldstream River. However, the biological significance of a two to four week delay in the onset of spawning is uncertain and may not be a contributing factor to recruitment failure. Of more importance may be the continued temperature reductions to as low as approximately 9^{o}C through August which may continue to delay spawning events throughout the spawning period, perhaps explaining the very late timing of the August 20, 1999 spawning event.

Paragamian et al. (2003) has suggested that the ideal temperature range for Kootenay spawning is 9.5^{o}C to 12^{o}C in late May to early June, a temperature range that is highly similar to that at which Arrow white sturgeon spawning and incubation has been observed post regulation. The Arrow Lakes Reservoir white sturgeon population may have a similar temperature preference to the Kootenay River population which would further suggest that historical spawning could have occurred as early as late June. If embryo incubation to hatch historically occurred within a two week period, hatch could have occurred in mid July to early August. A post regulation delay in hatch by four to six weeks could affect larval survival if prey availability becomes increasingly limited in the late summer and fall despite warmer fall and winter temperatures post dam.

The similarity observed in temperatures between sites and the apparent high fidelity for the section of mainstem river upstream of the RK 226.4 to 227.0 embryo collection area as the selected spawning area indicated that the Arrow white sturgeon subpopulation is selecting spawning locations based on factors other than temperature. The Arrow white sturgeon subpopulation may be selecting for a combination of river velocity, channel depth and clean, course substrate characteristics. However, sampling for sturgeon embryos has not been conducted downstream of the Revelstoke Golf Course in other potentially suitable spawning mainstem site locations that provide habitat characteristics similar to that observed adjacent to the Revelstoke Golf Course. Two areas where channel constrictions occur that provide similar velocities, depths and course substrate observed adjacent to the Revelstoke Golf Course is downstream of the mouth of Begbie Creek and Mulvehill Creek (Tiley, 2005b). However, Arrow Lakes Reservoir inundation may make these areas unsuitable for white sturgeon spawning. Sampling immediately downstream of the former Steamboat Rapids located approximately 1.6km upstream of the embryo capture area and other upstream sections of channel that provide greater depths, velocities and turbulence should also be undertaken. Two or three substrate mats were deployed downstream of two such potential spawning areas in 2003 (Golder, 2004a); however, sampling likely occurred very close to the river bank and may have prevented the ability to detect spawning events in these areas.

4.7 Timing of Spawning and Revelstoke Dam discharge

The zero flow events that frequently occurred in June through most of July 1999 and 2003 may also delay sturgeon spawning events by disrupting sturgeon spawning behaviour or creating depth and velocity conditions unsuitable for spawning. 1999 and 2003 are the only two years in which spawning events have been confirmed, with periods of sustained flow occurring in August in both years.

As Revelstoke is a peaking facility that discharges zero to 1700m^3s of water depending on local inflow and power demand, zero flow events occur frequently in June and July. Three of four sturgeon spawning events documented downstream of Revelstoke Dam have occurred following several days of sustained flows with the exception being the estimated spawning date of July 31, 1999, which was estimated to have occurred at approximately 1 to 1.5 days after a zero flow event that occurred between 0200hrs and 0500hrs on July 30, 1999. In 1999, zero flow events occurred almost daily during the first, second and third weeks of June, and almost daily until late July. There was a two-day sustained flow period between July 28 and 29 1999 during which flows of over 1500 m^3s were released for the majority of that two-day period. Discharges briefly dropped to just over 500 m^3s on July 28 (RL&L, 2000c). The August 20, 1999 spawning event was preceded by seventeen days without an occurrence of a zero discharge event with flows generally exceeding 500m^3/s from August 05 to the August 20 spawning event (RL&L,

2000c). Spawning events occurred after a five day period of flows of not less that 245m^3s for the August 2/3 spawning event and flows of not less than 268 m^3s between August 7, 0500hrs and August 14, 0600hrs for the August 13/14, 2003 spawning event.

Paragamian and Wakkinen (2002) provided evidence to suggest that cessation in spawning could be attributable to either a drop in temperature and/or discharge. Paragamian and Wakkinen (2002) did not observe spawning downstream of Libby Dam at flows less than 141m^3/s. Similarly, Schaffter (1997) did not observe spawning at flows of less than 180m^3/s but did detect spawning 1 to 3 days after flows were increased above that level. These studies and the results from this study suggests that a spawning threshold flow which determines river stage (depth) and velocity, may exist, and may vary depending upon channel morphology and hydrology in order to achieve the required minimum depth and/or velocity requirements.

5.0 Recommendations

The hatching of embryos on August 19 and August 28/29, 2003 raises questions regarding the ability of hatched larvae to obtain sufficient growth and energy reserves and reach complete physiological development before the onset of winter. Benthic invertebrate biomass is low in the 12 km stretch of river between Revelstoke Dam and 1 km downstream of the Illecillewaet River confluence due to peaking operations that result in the frequent dewatering of streambed (RL&L, 1995). Other factors that likely contribute to the low invertebrate biomass downstream of Revelstoke Dam, including thalweg areas wetted during zero discharge events, include low nutrient availability (RL&L, 1995; Perrin et al. 2004), cold temperatures (RL&L, 1995) and highly embedded substrates in some areas (Tiley, 2005b, personal observation). The competitive dominance of the benthic invertebrate community by the cnidarian *Hydra* within artificial substrate baskets downstream of Revelstoke Dam (Perrin et al. 2004) suggests that *Hydra* could also contribute to the low benthic productivity through displacement and/or predation upon other benthic organisms. It is currently believed that fish do not predate upon *Hydra*. Invertebrate biomass is also likely to be low between the Illecillewaet River and the Arrow Lakes Reservoir due to reservoir inundation up to the Revelstoke Golf Course by late July in an average water year.

This study has been successful in identifying the need for further research to determine the effects of temperature conditions observed downstream of Revelstoke Dam on larval and juvenile white sturgeon survival. As large quantities of embryos are difficult to obtain downstream of Revelstoke Dam, a controlled *in-situ* and laboratory experiment involving artificially spawned embryos to determine larval and age 0 juvenile overwintering survival exposed to Revelstoke reach temperatures is recommended.

There has been some debate as to whether the confirmed spawning events that occurred in 1999 were chance events, unlikely to be regularly repeated at the same location. As a result, the Columbia River adjacent to the Revelstoke Golf Course was not necessarily considered to be a viable spawning location. 71 of the 82 embryos captured in 1999 were collected at substrate mat sites 18, 19 and 20 (RL&L, 2000c) between RK 226.4 and 226.6 or a distance of approximately 200m. RL&L (2000c) also captured 11 embryos on substrate mats 16 and 17 deployed between RK 226.8 to 227.0. Substrate mat sites 18, 19 and 20 accounted for all of the captured embryos in 2003. White sturgeon throughout the Columbia River system generally spawn in fast-flowing sections of mainstem river, often found in dam tailraces (i.e. RL&L, 1997; 1998; 2000c, Parsley et al. 1993) probably due to the availability of higher water velocity and clean, course substrate as was observed for the Arrow white sturgeon population in 1999 (RL&L, 2000c). The results of the 1999 and 2003 substrate mat and telemetry monitoring investigations strongly suggest that the area between RK 226.4 and upstream is a spawning area of choice based on four spawning events, emphasizing the need to investigate the physical habitat characteristics of this area further.

Dams have often been built at river constrictions where river velocity and turbulence was comparatively high and substrates typically coarse (pre-dam); thus, many Columbia River dam sites may have been constructed at or within close proximity to historic sturgeon spawning locations. Revelstoke Dam construction resulted in the removal of Steamboat Rapids, historically located approximately 1.5 km upstream of the 1999 and 2003 embryo capture locations. Given that all of the 1999 and 2003 embryo capture locations were within a 600m section of river and in close proximity to the former location of Steamboat Rapids, the area upstream may be an historic spawning habitat that is still being utilized. The remaining Arrow Lakes Reservoir white sturgeon may have been imprinted on this location, possibly explaining why all four spawning events have occurred at or near this specific section of river. There is also substantial biotelemetry data that indicates consistent use of the Big Eddy and habitat slightly upstream from the embryo capture area. It is therefore recommended that the section of Columbia River between river kilometre 226 and Revelstoke Dam be considered a viable spawning habitat area for the Arrow Lakes Reservoir white sturgeon subpopulation and should be managed as such. However, other areas should also be monitored for evidence of spawning such as immediately downstream of the Begbie and Mulvehill Creek confluences where constrictions in the historic river channel occur and depth and velocity characteristics at certain reservoir elevations are similar to the depth and velocity characteristics observed adjacent to the Revelstoke Golf Course spawning area.

Photo documentation of river stage changes in response to Revelstoke Dam peaking operations was conducted during site visits throughout the study. It was determined that a large cobble bar (approximately 150,000m^2 in area) located approximately 100 meters downstream of the embryo capture area, becomes dewatered almost daily to a varying extent depending on Revelstoke Dam discharge and Arrow Lakes Reservoir elevation.

Figure 17. The upstream portion of a cobble bar, approximately 150,000m^2 in total area, dewatered at 685m^{3}s, August 9, 2003. The orange float marking the tether rope used to retrieve substrate mat 20 is barely visible off the right bank at treeline. Photo by Mark Tiley, CCRIFC.

Figure 18. The downstream portion the cobble bar, approximately 150,000m^2 in total area, dewatered at 685m^{3}s, August 9, 2003. Big Eddy is to the immediate right of the bedrock outcropping in the upper right of the photo. Photo by Mark Tiley, CCRIFC.

The risk of embryo and post hatch larval stranding immediately downstream of both the 1999 and 2003 embryo capture site was considered to be high. A recommendation was made by the Columbia Water Use Plan (WUP) Consultative Committee to implement a monitoring program to quantify the magnitude and frequency of sturgeon embryo and larval stranding downstream of the spawning area. It is anticipated that the proposal will be recommended for funding under the Water Use Plan monitoring program.

The 68.3% sturgeon embryo hatch rate and the potential significance of sustained flow periods in regards to sturgeon spawning has contributed to the support of an annual minimum flow requirement of 142m^{3}s (5000cfs) from Revelstoke dam under the Columbia River Water Use Planning Process. However, a threshold flow may be necessary to stimulate spawning events. The 2003 spawning events occurred during flows that were at or above 245m^{3}s for the August 2/3 spawning event and flows of not less than 268 m^{3}s for the August 13/14, 2003 spawning event. The results from this study also helped gain support for the recommendation to release sturgeon augmentation flows of up to 30,000cfs. The precise determination of the timing and location of spawning is necessary to identify the relationship between Revelstoke Dam discharge and the timing of sturgeon spawning. The draft Columbia WUP has proposed to implement a videography program in hopes of identifying the flow conditions in which the Arrow Lakes Reservoir sturgeon population is selecting for. If a minimum threshold flow is determined, operations could then be implemented that may enable white sturgeon to spawn uninterrupted by low flow conditions, resulting in earlier spawning than might otherwise occur.

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