Duncan Dam Project Water Use Plan

Lower Duncan River Water Quality Monitoring

Reference: DDMMON-7

Year 2 Synthesis Report

Study Period: March 2011- May 2012

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FINAL
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Year 2 Report

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EXECUTIVE SUMMARY

The Duncan Dam (DDM) Water Use Planning (WUP) project was initiated to address flow management issues with respect to impacts on competing resources in the area. The DDM WUP Consultative Committee recommended that temperature and TGP monitoring studies be carried out to determine if water temperature or TGP levels in the Lower Duncan River are affected by operations (BC Hydro 2005). Regulated discharges at DDM have been shown to impact fish species in the lower Duncan River (e.g., Porto and van Dishoeck 2008, Porto et al. 2009, Thorley et al. 2010). Use of low level outlet gates (LLOG) or spillway operating gates (SPOG) may influence water quality (i.e., total dissolved gas pressure (TGP) and water temperature). Because water temperature and TGP have been shown to influence freshwater fish, DDM operations may affect fish in the LDR, particularly at critical times of the year. Water temperatures may affect spawn timing or larval emergence timing and survival while TGP can lead to the development of gas bubble trauma (GBT), which can cause effects ranging from reduced swimming ability to death. The current state of knowledge with respect to BC Hydro's management questions for DDMMON-7 is provided in the following table.

Management Question and Hypotheses	Status
What is the relationship between water discharge through the DDM spillway and the production of TGP? H1: Total gas pressure concentrations in the LDR are correlated with DDM spillway discharges	- Total gas pressure is strongly predicted by the amount of discharge from Duncan Dam spillway gates. - TGP concentrations exceeded 110% at spill discharges greater than ~60 m^3/s during the 2010 and 2011 monitoring periods. TGP concentrations exceeded 115% at spill discharges greater than ~100 m^3/s during the 2010 monitoring period and ~110 m^3/s during the 2011 monitoring period.
How does the operation of the DDM low-level gates and the spillway affect the water temperature regime in the LDR? H2: Water temperature in the LDR supports the productivity of fish species of interest H3: Water temperature in the LDR is correlated with DDM operations.	- Water temperature in the LDR is influenced by the operation of the DDM low level outlet gate (LLOG) and spillway gate (SPOG) discharge structures as well as tributary inflows, predominantly the Lardeau River. Factors that influence the temperature of the DDM releases include: ambient temperatures, reservoir elevation and thermal stratification. - Water temperatures, specifically along the left downstream bank (River Left) throughout the length of the LDR are correlated to DDM discharges. The spatial extent and intensity of this correlation is dependent on the discharges from the various inputs. - SPOGs generally release water from the upper, warmer layers of the Duncan Reservoir during the main spill period (summer) while LLOGs release cooler, hypolimnetic water at this time. - The operation of the LLOGs influence water temperature daily variability and mean levels. For example, high LLOG discharge reduces daily temperature variability. - The LDR is generally warmer than the Lardeau River during the winter period when moderate/high flows are released from the LLOGs. - Modeling of mixing at a point in the LDR at km 2.55 below

	the zone where DDM and Lardeau River discharges meet, indicates that at DDM discharges <50 m^3/s, 80-100% mixing of the two water bodies is predicted at all Lardeau discharge levels modeled. As DDM discharge increases (80-250 m^3/s) there is 0-20% mixing when discharge from the Lardeau River is low (<50 m^3/s) or high (>175 m^3/s), but when the Lardeau River is between these two levels, there is some mixing predicted (20-40%). At DDM discharge >225 m^3/s with mid-range Lardeau River discharges, 40-60% mixing is predicted. - The LDR generally supports the productivity of fish species of interest (kokanee, rainbow trout and mountain whitefish), since these species have been observed performing different life history functions. Some critical life history periods may be negatively influenced by water temperature within the LDR as mentioned in the points below. - The influence of the LDR water temperature regime on kokanee (*Onchorhynchus nerka*) may affect the abundance of spawners present, spawning distribution, as well as timing of peak spawn and fry emergence. - Water temperature was one environemental variable that potentially decreased rainbow trout (*Onchorhynchus mykiss*) egg survival during periods of dewatering in the DDM tailout spawning area, but observed temperatures were not outside optimal preferences for other life history stages of this species. - The influence of DDM operations on water temperatures in the LDR may affect mountain whitefish (*Prosopium williamsoni*) spawn and emergence timing, since water temperatures were observed to be higher than optimal at the commencement of the observed spawning and incubation period.

1.0 INTRODUCTION

Duncan Dam (DDM) was built in 1967 as a storage facility under the Columbia River Treaty (CRT). Flow management in the lower Duncan River (LDR) below DDM is dictated by seasonal operating targets set by the CRT and, to a lesser degree, water level requirements for Kootenay Lake set by the International Joint Commission. A number of competing flow management priorities (e.g., CRT, fisheries, and recreational uses) impose significant constraints for DDM operations. The Duncan Dam Water Use Planning (WUP) process was initiated to address these flow management issues with the intention of striking an optimal balance between competing resource interests.

Discharges at DDM normally flow through two low level outlet gates (LLOG1 and LLOG2), which can operate in unison or separately depending on flow priorities and the time of year. In addition to the LLOGs, two spillway gates (SPOG1 and SPOG2) also exist on the east-side of DDM and have typically been used from mid-July to September, when reservoir elevations are highest (BC Hydro 2005, AMEC 2010, Lawrence et al. 2011). Like the LLOGs, the spillway gates can be operated separately or together. DDM spillway gates may also be used outside this period (e.g., SPOG1 was used October 4, 2010; Lawrence et al. 2011).

The relationship between the Duncan Reservoir temperature profile, the location and volume of discharge and the resulting water temperature and total gas pressure (TGP) levels in the LDR was uncertain because monitoring of water temperature and TGP during spill events at DDM had been limited. Therefore, in order to address potential impacts of DDM operations on LDR fish resources, BC Hydro required a clear understanding of the relationship between operational conditions at DDM and downstream water temperature and TGP. Specifically, a water quality monitoring program was commissioned “to determine if a relationship exists between water temperature and TGP levels and DDM operations and decide if/how each of these water quality parameters affects fish species downstream of DDM using TGP as a performance measure (there is no performance measure for water temperature)” (BC Hydro 2010). The water quality monitoring program consisted of continuous water temperature monitoring at locations throughout the LDR, Duncan Reservoir and tributaries to the LDR from May 2010 to May 2012 as well as spot and continuous TGP monitoring during the summer months in 2010 and 2011 (Lawrence et al. 2011).

Water quality factors, specifically water temperature and TGP, can influence the life history of various fish species (AMEC 2010). For example, water temperatures can influence kokanee hatch and emergence timing and survival (AMEC 2012), as well as the spawn-timing and staging behaviour of Gerrard rainbow trout and mountain whitefish (e.g., Thorley et al. 2011; McPhail 2007; Wang et al. 2010). High levels of TGP can lead to the development of gas bubble trauma (GBT), with effects ranging from bubbles in the gills, to reduced swimming ability, to death (Weitkamp and Katz 1980). Tolerance of elevated TGP levels varies with species and life stage (Weitkamp and Katz 1980). Relatively narrow ranges for both water temperature and TGP define optimal growth conditions for fish species (e.g., Thorley et al. 2011). Conditions outside these optimal ranges can reduce fish growth and affect long term survival, or can be directly fatal (e.g., Coleman and Fausch 2007, Inhat and Bulkley 1984, Currie et al. 1998, Selong et al. 2001).

Preliminary information collected during Year 1 of the current study suggested that water released from DDM can variably affect downstream water temperatures according to the time of year and discharge structure used (Lawrence et al. 2011). As a result of thermal stratification in the Duncan Reservoir and differences in the elevations of the two gate types at the dam, the temperature of water released into the LDR can vary depending on whether the LLOGs or SPOGs are used. Temperatures of the water entering the LDR during spillway operation are generally most similar to the warmer, epilimnetic (upper) layer of the reservoir during periods of reservoir thermal stratification. Releases from the LLOGs can be drawn from a range of depths in the reservoir depending on the reservoir elevation, but generally are drawn from the cooler, hypolimnetic (bottom) layer when the reservoir is stratified.

In addition to affecting water temperatures, DDM releases also affect TGP levels in the LDR (Lawrence et al. 2011). Limited monitoring of spill events at DDM prior to the current study indicated that spillway discharge >115 m^3/s, coupled with LLOG discharge of 142 m^3/s, results in TGP levels above 115% (BC Hydro 2010). Modeling conducted during the present program has updated this finding. TGP levels above 115% are harmful to fish if exposure continues for a period of 4 to 5 days, and fish can die within hours if exposed to levels above 130% (Fidler and Miller 1994).

Temperature and TGP conditions in the LDR are also affected by discharge from the Lardeau River which flows into the LDR immediately downstream of DDM (Lawrence et al. 2011). Three additional tributaries (Meadow, Hamill and Cooper creeks) may also influence water quality in lower sections of the LDR.

1.1 DDM WUP & Operating Orders

During the DDM WUP process, an analysis was conducted to “determine how operation of Duncan Dam low-level operating gates and the spillway affect temperature and total gas pressure (TGP) in the lower Duncan River and their potential implications to fish” (BC Hydro 2005). This analysis reviewed unpublished BC Hydro reports (i.e., 2003c, 2003d in BC Hydro 2005), which provided a “spill versus TGP production relationship, indicating that TGP events occur when spills exceed 115 m^3/s” (BC Hydro 2005). Therefore, water quality-related performance measures developed during the WUP process included the number of Total Gas Pressure Days >115%, but a performance measure for water temperature was not included (Table 1, BC Hydro 2005).

The Total Gas Pressure Days/Events performance measure is defined as “the number of days when TPG levels are greater than 115% through spilling and the number of events where consecutive days exceed 115%” (BC Hydro 2005). This performance measure was developed to estimate the quantity of TGP under different operating alternatives (BC Hydro 2005).

The Duncan WUP Consultative Committee (CC) also developed a Total Gas Pressure procedure which states:

“When Duncan Dam discharges are nearing 285 m^3/s, ensure that flows through one low level outlet are near the maximum flow of 170 m^3/s to restrict spill volumes to 115 m^3/s (in the spillway) and therefore, limit Total Gas Pressure levels downstream” (BC Hydro 2005).

The TGP procedure for DDM was developed based on operations that allow for the passage of bull trout migrating up into the Duncan Reservoir (BC Hydro 2005). This operation is achieved by co-ordinating flows through the two LLOGs from May to mid-September, restricting flow volumes to 140 m^3/s from the LLOGs and using the spillway to release any additional flow (BC Hydro 2005). As mentioned above, TGP levels begin to adversely affect fish downstream once spillway flows increase above 115 m^3/s, and this risk increases with higher spillway discharges (BC Hydro 2010). Therefore, once the reservoir is near full pool and natural inflows are above 255 m^3/s, there is a trade-off between aiding bull trout migrations into the reservoir versus TGP effects on fish downstream.

Uncertainties still remained, therefore the CC recommended that temperature and TGP monitoring studies be carried out to collect baseline monitoring to further refine performance measures and determine if temperature is an issue (BC Hydro 2010).

Table 1: Fish Performance Measures Developed During DDM WUP for the Lower Duncan River (BC Hydro 2005). Those pertaining to DDMMON-7 are shaded.

Location	Performance Measure	Units of Measure
LDR Sidechannel	Kokanee Effective Spawning Habitat Lost	Hectares of effective spawning habitat lost
	Kokanee Effective Rearing Habitat Lost	Hectares of effective rearing habitat lost
	Rainbow Trout Effective Rearing Habitat	Hectares of effective rearing habitat
	Rainbow Trout Effective Rearing Habitat Lost	Hectares of effective rearing habitat lost
LDR Mainstem	Whitefish Effective Spawning Habitat	Hectares of effective spawning habitat
	Whitefish Effective Spawning Habitat Lost	Hectares of effective spawning habitat lost
	Kokanee Effective Spawning Habitat	Hectares of effective spawning habitat
	Rainbow Effective Rearing Habitat Lost	Hectares of effective spawning habitat lost
	Total Gas Pressure Days	Number of days TGP >115%
	Total Gas Pressure Events	Number of events TGP >115%
	Significant Events	Number of significant operational changes >0.20 m; number of significant operational changes > 0.45 m

1.1.1 Operational Range

The target flow protocol outlines the flows that must be provided below the confluence of the Duncan and Lardeau Rivers under the current LDR WUP (Table 2). Flows can be within 5% of the minima and maxima outlined in the protocol as long as the 3 day average meets the target levels (BC Hydro 2005). There are no formal stipulations in the target protocol about which gates should be used to meet these flows. However, operations may be modified to accommodate seasonal needs (e.g., Stark et al. 2011). For example, operations are modified slightly during the bull trout transfer period (May to September) to allow fish to pass up one of the discharge tunnels (Stark et al. 2011; AMEC 2010).

Table 2: Target flow protocol for flows below the confluence of the Duncan and Lardeau Rivers as per DDM Water Use Plan (BC Hydro 2005).

Dates	Cubic Metres per Second (m^3/s)	
	Minimum	Maximum
August 1- August 24	73	400
August 25 – September 24	73	250
September 25-27	73	190
September 28-30	73	130
October 1-21	73	76
October 22 – December 21	73	110
December 22 – April 9	73	250
April 10- May 15	73	120
May 16 – July 31	73	400

The LLOGs are the preferred means of discharging water and the SPOGs are only to be used to pass the surcharge inflows when the reservoir is full (BC Hydro 2005). The SPOGs have typically been used from mid-July to September to control reservoir elevations. SPOGs have also been used outside this period to lower the reservoir elevation for facility maintenance purposes and other needs (e.g. SPOG 1 was used October 4, 2010 to facilitate removal of the bull trout weir below LLOG2; BC Hydro unpublished data). The target flows as outlined in the protocol (Table 2) and the actual flows for 2008-2011 are shown in Figure 1.

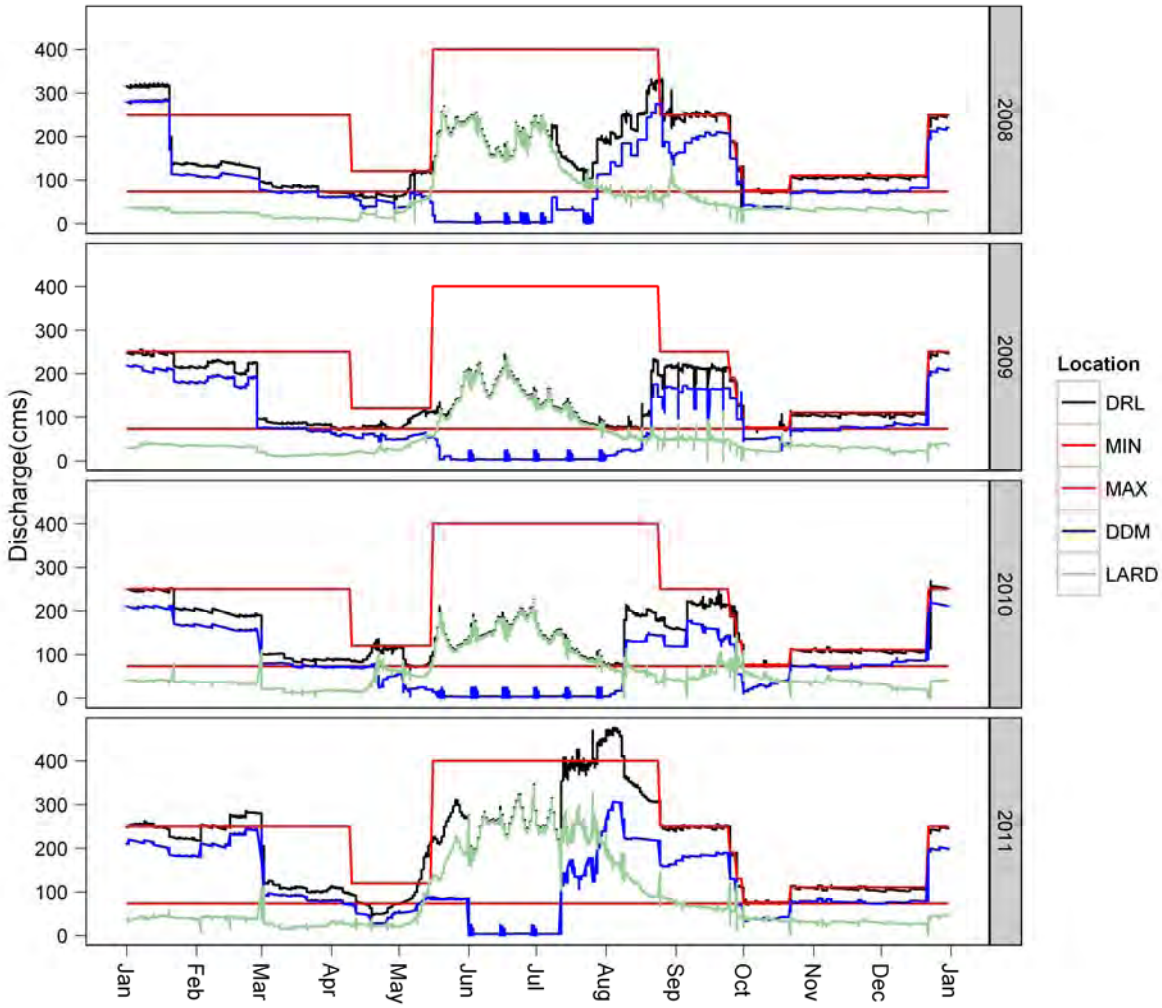


Figure 1: **Annual hydrographs for the lower Duncan River with the Water Use Plan operational targets identified. Hourly discharge levels are presented for the Duncan Dam (DDM) outflow (spill and low-level gates combined), the Lardeau River (LARD) alone and the LDR and LARD combined at the Water Survey Canada Gauge (WSC08NH118 - DRL).**

1.2 Study Objectives & Key Management Questions

The primary **management questions** to be addressed by this program include (TOR):

1. What is the relationship between water discharge through the DDM spillway and the production of TGP?; and,
2. How does the operation of the DDM low-level gates and the spillway affect the water temperature regime in the LDR?

In addition, the following **hypotheses** are to be tested (TOR):

H_1: Total gas pressure concentrations in the LDR are correlated with DDM spillway discharges.

H_2: Water temperature in the LDR supports the productivity of fish species of interest; and,

H_3: Water temperature in the LDR is correlated with DDM operations.

2.0 METHODS

2.1 Study Area

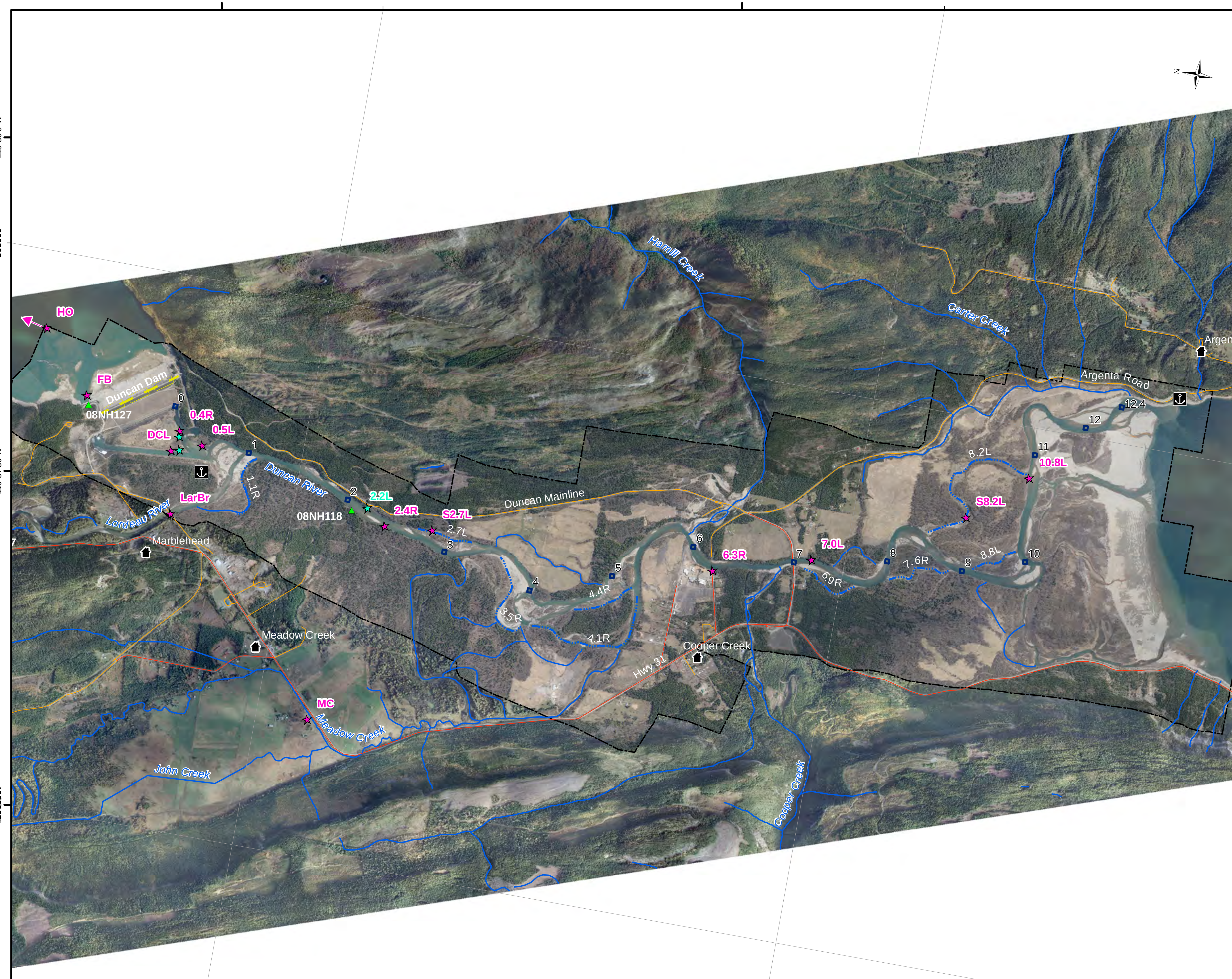
The study area encompassed the approximately 12 km section of the lower Duncan River from Duncan Dam to its confluence with Kootenay Lake as well as forebay areas of DDM in the Duncan Reservoir and one location each in the Lardeau River and Meadow Creek (Figure 2). Further information on study area habitats and water conditions for the LDR and Duncan Reservoir is provided under DDMMON-2 (Porto et al. 2009) and DDMMON-10 (Masse, Poisson and Redfish 2011). Further information on site locations is provided below.

2.2 Site Locations

Temperature and TGP monitoring station locations were selected based on their fulfillment of at least one of the following requirements:

- Site was specified in the TOR for this project;
- Site has historically been used as a water temperature or TGP monitoring location; and/or,
- Collection of data from this location was required for other Duncan WUP programs.

Sampling locations included both continuous temperature and TGP monitoring stations and discrete TGP sample locations (Figure 2). TGP monitoring stations were deployed in the LDR at locations similar to those used during previous monitoring completed by BC Hydro (2002-2004) as specified in the TOR. Site descriptions and GPS coordinates for continuous monitoring stations of which there were two locations in the Duncan Reservoir, nine in the LDR (including eight temperature and three TGP stations, two of which were the same as temperature monitoring locations), one in the Lardeau River, one in Meadow Creek, and one air temperature location are included in Appendix A.



Legend

- Continuous Temperature Monitoring Location and Name
- Continuous TGP Monitoring Location
- WSC Gauge
- Boat launch
- Communities
- River km (AMEC, 2009)
- Dam

Roads

- Paved
- Unpaved
- Named Sidechannel
- Streams
- Extent of May 2009 Orthophotography

Scale:1:35,000

500 250 0 500 1000

Meters

Reference

Ortho Date: April 30, 2009
Discharge at DRL: 73 - 74cms

Disclaimer

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CLIENT: BC Hydro

PROJECT: DDMMON#7- LDR Water Quality Monitoring

Temperature and
TGP Monitoring Locations
on the Lower Duncan River

JOB No: VE51974	COMPILATION DATE: 2011/04/05	Figure
GIS FILE: study_sites_year_1_v3.mxd	REVISION DATE: 2012/05/29	
PDF FILE: study_sites_year_1_v3.pdf	PRINTING DATE: 2012/05/29	
PROJECTION: UTM Zone 11 / DATUM: NAD83 / ANALYST: EO	QA/QC: CL / REQ: LP	amec

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2.3 Study Schedule & Timing

Field data collection for this program commenced on May 15, 2010 and ended on May 17, 2012. A summary of temperature and TGP monitoring and download sessions in Year 1 is provided in Lawrence et al. (2011). A summary of these activities in Year 2 (2011) is provided in Table 3.

Table 3: Summary of dates and field activities completed in Year 2 (May 2011 to May 2012) to facilitate water temperature and total gas pressure (TGP) monitoring in the lower Duncan River system.

Action	Date	Notes
Temperature Download	25-May-11	All stations downloaded. SC8.2L and Howser stations removed, MC relocated to near Hwy 31 bridge, station 6.3R added.
Temperature Download	5,8,18,19 Aug 11	All stations downloaded. Air logger removed. Added loggers to FB array at 10, 15 and 20 m.
TGP Spot Measurements	5-Aug-11	Spot measurements at vehicle access sites throughout LDR
Install TGP Continuous Station	8-Aug-11	Install station 2.2L
TGP Spot Measurements	18-Aug-11	Spot measurements via boat every 2 km throughout LDR on the left, right and middle river banks as well as in the DDM FB and Lardeau River.
TGP Station Download	19-Aug-11	Download 2.2L station
TGP Station Removal	2-Sep-11	Remove 2.2L station
Temperature Download	22 and 28 Nov 11	All stations downloaded. FB array shortened to 1 and 5m prior to winter months.
Temperature Download	7-Feb-12	All locations downloaded except FB array due to ice cover.
Temperature Station Removal	17-May-12	All stations downloaded and removed.

* TGP Downloads included downloading data from TGP datalogging device, replacement of batteries, calibration of the TGP probe and comparison of initial readings with an additional spot measuring TGP probe. L= Left downstream bank, R= Right downstream bank, S= Sidechannel, DCL= Discharge channel left bank station, FB= Forebay array station, LDR= Lower Duncan River, MC= Meadow Creek

As noted in Table 3, two temperature monitoring stations were removed in May 2011 (side channel 8.2L and Duncan Reservoir at Howser), one station was added (LDR at Km 6.3R) and one station was relocated (Meadow Creek) following Year 1 recommendations (Lawrence et al. 2011).

2.4 LDR Discharge

Hourly discharge records were obtained for DDM and the Water Survey of Canada (WSC) gauge (DRL; No: 08NH118) below the Lardeau and Duncan rivers confluence from BC Hydro's Access database for the period of record from 1995 to 2012. From 1995 until 2003 the data provided by BC Hydro Power Records distinguished between flow released through the low level outlets (LLOGs) and the spill gates (SPOGs), but did not distinguish between flows from each gate. From 2003 onwards, hourly discharge data delineated flow from each of the four gates (LLOG1, LLOG2, SPOG1, SPOG2). The pre-WUP period was defined as operations up until the implementation of the WUP flows after the order was received in December 2007 from the Water Comptroller. For two years prior to the receipt of the order, that is, since December 2005, WUP flow targets were opportunistically implemented, but these years were still considered as pre-WUP. The post-WUP period was considered to commence in January 2008.

2.5 Water Quality Parameters

In order to address the Management Questions for this program (Section 1.1), TGP data were collected in 2010 and 2011 and water temperature data was collected from 2010 through 2012 throughout the LDR as described below.

2.5.1 TGP

A memorandum summarizing the TGP component of this program was finalized in April 2012 at the request of the BC Hydro contract authority (Trevor Oussoren, Natural Resource Specialist, BC Hydro, Castlegar). Methods associated with TGP monitoring are provided below though all data analysis methods, study results and discussion are provided in that memorandum (Appendix B).

2.5.1.1 Continuous Monitoring

Two TGP continuous sampling locations were specified in the TOR for this program (i.e., DCL and LDR 2.2L; Appendix A). However, BC Hydro requested that a third station also be included (i.e., LDR 0.4R; Appendix A). Continuous monitoring TGP stations were installed in the LDR at these three stations in Year 1, from July 7 to October 6, 2010 (Appendix A, Figure 2). In Year 2, continuous TGP monitoring occurred only at the LDR 2.2L station from August 8 to September 3, 2011 (Appendix B).

Monitoring at DCL and 2.2L (Figure 2) was conducted using a Point Four Systems, Inc. (Coquitlam, BC) PT4 Tracker Total Gas Pressure Smartprobe outfitted with PT4 Tracker Multi Probe Meter Long Term Deployment Units (herein referred to as PT4). This unit was housed in a pelican case and included 30 m (100 feet) of cable connecting the TGP probe. The battery life for the two PT4 units was estimated between 3 and 4 weeks, depending on the logging interval used. The third unit installed in the spillway channel (0.4R, Figure 2) was supplied by BC Hydro, which was also developed by Point Four Systems, Inc. This unit was also housed in a pelican case and included a Lumi4 DO/TGP Probe outfitted with PT4 Tracker Multi Probe Meter Long Term Deployment Units (herein referred to as Lumi4) with 30 m of cable and a battery life estimated at 7 days. The two TGP Smartprobe units had been factory calibrated for all parameters prior to use. Calibration was confirmed by allowing the units to run side-by-side for approximately 1 hour at the office in Nelson, BC. The Lumi4 meter provided by BC Hydro was also run during this period to confirm correct readings of all parameters. Barometric pressure readings were also compared with those reported on the Environment Canada website for Nelson, BC at that time (www.weatheroffice.gc.ca). Additional battery packs were purchased for all three meters which allowed a direct swap of pelican cases in the field and therefore no unit downtime while batteries were recharged.

All TGP units (PT4 and Lumi4) and additional battery cases were deployed inside a locked aluminum case, fixed to a nearby tree (Figure 3). The cable was run from these cases, along with a backup and strain relief cable, to the river. Housings were made for the TGP probes to protect their membranes while deployed in the LDR. Each housing consisted of 1.5” or 3” black PVC tubes, perforated to allow adequate water flow across the membrane, cabled to two railroad plate anchors with a combined weight of approximately 11.5 kg (25 lbs) (Figure 3). Cable ties were used on either side of the tube to ensure the membrane stayed in place during deployment. The probes were deployed as deep as wading allowed, which generally meant a deployment depth of approximately 1.5 m.

Figure 3: Lock-case used to protect PT4 Tracker and batteries such as that deployed near the WSC station at 2.2L (left). Perforated PVC tubes attached to weights were used to house the TGP probes while deployed in the LDR (right).

Continuous monitoring stations took measurements every 15 minutes to maximize the amount of data collected. Parameters measured included barometric pressure (mmHg), total gas pressure (mmHg), deltaP (mmHg), percent saturation of TGP (%), water temperature (°C) and date/time. Station servicing included: i) downloading data from the PT4 Tracker Meter to a laptop computer; ii) battery replacement; iii) TGP membrane replacement with a dry membrane; and, iv) calibration, redeployment and comparison of readings with a TGP spot measurement device. The calibration procedure involved leaving the probe with a dry membrane exposed to air and ensuring TGP readings were equal to barometric pressure readings (i.e. 100% saturation). If required, TGP pressure values (in mmHg) were entered manually to ensure they were equivalent with barometric pressure, thus calibrating the meters. Data was reviewed in the field for errors prior to redeployment. Servicing for the PT4 units was required every 14 to 21 days, whereas the Lumi4 units required servicing every 4 to 7 days.

2.5.1.2 Spot Measurements

Spot TGP measurements were taken with either a PT4 TGP Smartprobe or Lumi4 meter during station servicing to compare with TGP levels recorded by continuous stations during the Year 1 and 2 continuous TGP monitoring periods (Table 2, Lawrence et al. 2011). Additional spot measurements were also taken during spill events to determine the downstream transmission of

TGP at vehicle accessible locations. Spot measurements were taken by deploying the probe at approximately 1.5 m depth and allowing readings to stabilize. Once stabilized, readings of TGP (mmHg and % saturation), deltaP (mmHg), and barometric pressure (mmHg) and water temperature (°C) were collected. Locations where spot TGP measurements were taken included the Lardeau River, Duncan Reservoir, DDM tailrace (in the discharge and spillway channels) and the LDR at Km 2.2R, Km 6.3R, Km 7.0L, Km 7.0R, Km 10.8L and Km 11.5L.

In order to determine the TGP dissipation pattern during a spill event, one boat-based spot measurement survey occurred on August 18, 2011. TGP spot measurements were collected following the same methods outlined above at left bank, right bank and middle river locations approximately every 2.0 kms from the DDM tailrace to Km 11.0 (Appendix B). Spot measurements were also collected in the Lardeau River and Duncan Reservoir at this time.

2.5.1.3 2010 Spill Gate Testing

A review of spillway operations between 2004 and 2009 was conducted to determine 'typical' spill operations that may occur at DDM. Information reviewed included:

- Minimum, mean, and maximum discharge from each LLOG and SPOG when spillway gates have been in use;
- Time period and duration of SPOG use; and,
- Percentage of the total river flow that has historically been comprised of spill flow versus LLOG flow (%LLOG1, %LLOG2, %SPOG1, %SPOG2).

Results were provided to T. Oussoren (BC Hydro contract authority) and a spill program was developed in August 2010 in conjunction with DDM operations. The final DDM gate testing plan developed by BC Hydro is provided in Lawrence et al. (2011) and spill gate testing occurred between August 23 and 27, 2010. Spill gate testing was not required in 2011 as spill gates were in use throughout August.

2.5.2 Water Temperature

A total of 12 continuous water temperature monitoring stations were deployed in the study area, which included two stations in the DDM forebay (vertical arrays), eight stations in the LDR, one in Meadow Creek and one in the Lardeau River (Figure 2, Appendix A). Site locations were based on the project's information review (AMEC 2010) and as specified by the TOR. In addition to these 12 temperature monitoring stations, TGP stations also continuously logged water temperature every 15 minutes during the period when these stations were operating (i.e., July to October 2010 and August 2011; Section 2.5.1).

Onset TidBiT v2 temperature loggers (hereafter referred to as TidBiTs) measured temperature every 30 minutes. Two TidBiTs were deployed at each temperature monitoring station to provide back-up in case of logger failure. Data was downloaded quarterly (Section 1.3) using the HOBOware Pro Version 2.x for Windows software. Data was inspected in the field for erroneous readings (e.g., possible dewatered time periods as indicated by diurnal temperature fluctuations similar to those recorded in air at that time) prior to TidBiT redeployment.

TidBiTs were housed in PVC tubes weighted by 1 to 2 railroad plate anchors (~6.5 kg each), similar to the anchoring system used for the TGP probes (Section 2.5.1). TidBiTs were fixed within the PVC tube by either stainless steel wire or heavy duty cable ties. The weighted unit was affixed to a nearby tree or boulder onshore with 5 mm aircraft cable enclosed in a plastic sheath. Water temperature monitoring stations were deployed during the lowest flow period of the year in 2010 and specific locations were chosen that were not anticipated to dewater.

Two water temperature arrays were also established in Duncan Reservoir. One array was located in DDM forebay (hereafter referred to as the DDM forebay array), which consisted of an array of TidBiTs deployed along a nylon rope at depth intervals of 1, 5, 10, 15, 20 and 25 m to adequately capture surface temperatures and any thermal stratification within the reservoir during the summer months. The DDM forebay array was fixed to the DDM forebay boom immediately upstream of the DDM LLOGs (Figure 4). The configuration of the DDM forebay array allowed for continuous temperature monitoring at specified depths as reservoir elevations fluctuated seasonally, as measured from the reservoir surface. For example, TidBiTs were added at the 15 m, 20 m and 25 m depth intervals as water elevation increased in July 2010, whereas in November 2010 the 20 m and 25 m loggers were removed so that they did not sit at the bottom of the reservoir during low pool. In August 2011, the 20 m logger was again added to the forebay array and in November 2011 all loggers except the 1 m and 5 m loggers were removed due to the previously described timing of isothermic conditions and in anticipation of ice cover preventing access until the following May at which time the reservoir would be at low pool.

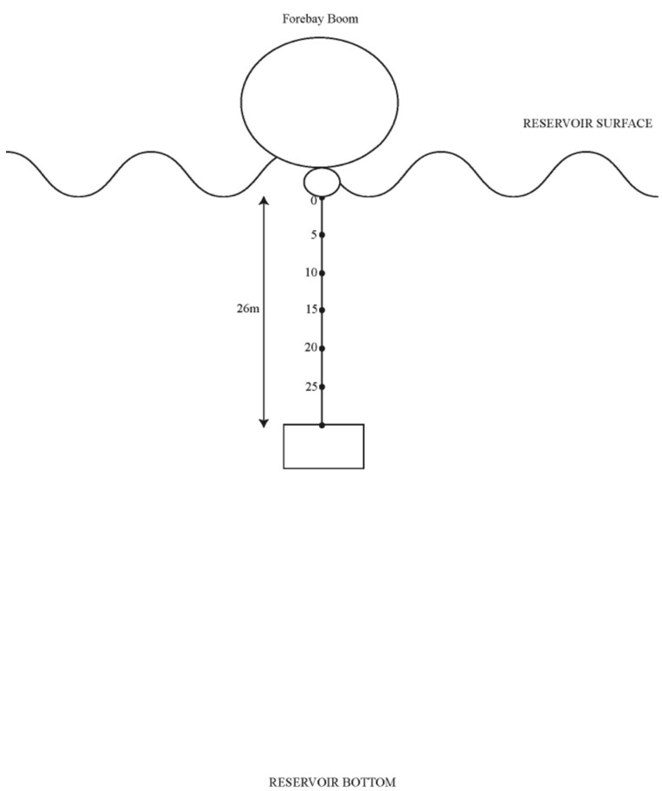

Figure 4: Schematic diagram of the Duncan Reservoir forebay water temperature array.

A second water temperature array was located off-shore from the Howser boat launch (hereafter referred to as the Howser array) from May 2010 to May 2011. This array was set up to monitor hypolimnetic releases from the reservoir and consisted of TidBiTs set at the elevation at which the LLOGs draw water (541.63 m) and just above the bottom of the reservoir (Figure 5). Therefore depths intervals of 1 m and 13 m, measured from the reservoir bottom were used. This array was removed following recommendations from Year 1 as the hypolimnetic temperature information by collected by the forebay temperature array better represented what was entering the LLOGs compared to that measured near Howser, approximately 5 km away from DDM (Lawrence et al. 2011).

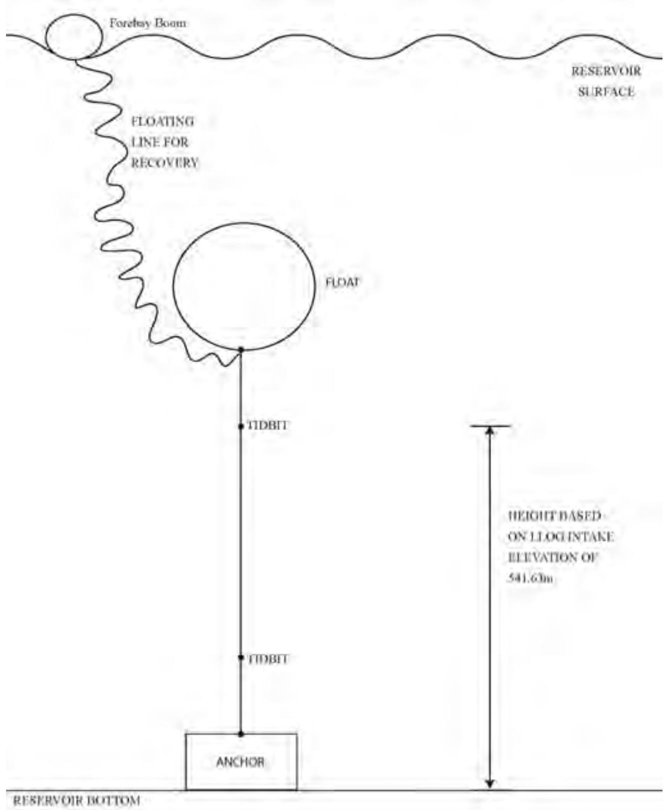

Figure 5: Schematic diagram of the Howser water temperature array in Duncan Reservoir.

2.5.3 Air Temperature

Reliable continuous air temperatures were initially required for modelling and analyses for this program. Therefore, one TidBiT was initially deployed at the BC Hydro staff house in a discreet area to obtain a continuous recording of air temperature. Service and calibration of the air temperature station was the same as that for the water temperature stations. This site was relocated on September 21, 2010 to the DDM Tailrace Boat Launch due to access issues. The logger was fixed to a tree in an inconspicuous location out of direct sunlight. The air temperature logger was removed in August 2011 as BC Hydro had installed a station capable of monitoring air temperature at the DDM tailrace.

2.6 Data Management

Data was immediately backed-up on a portable USB storage device following all TGP and water temperature station downloads. All data were entered into an MS Access database developed specifically for this program. Data was reviewed for errors before being imported or entered into the database.

Historical TGP and water temperature data provided by BC Hydro and other contractors were assessed for continuity and applicability to the current study. Applicable data was included in the database in raw form (i.e. hourly individual readings and not precompiled daily averages). Historical data included: i) unpublished BC Hydro TGP data (2003 and 2004); ii) unpublished water temperature data collected under DDMMON-3 (2008 and 2009); and iii) unpublished BC Hydro water temperature data (summer and fall months for 2002-2004).

2.7 Data Analyses

The data exploration and analyses in this final year of the DDMMON-7 study program assessed the spatial and temporal patterns of water temperature in the LDR and examined the relationship between DDM operations and water temperature. These analyses provided the information to address Management Question 2 and Hypotheses H2 and H3 (Section 1.2). As mentioned previously, methodology pertaining to TGP analyses is provided in Appendix B. TGP analyses were required to address Management Question 1 and Hypothesis H1.

2.7.1 Discharge

Hourly discharge records for low level outlet gates (LLOGs), spillway gates (SPOGs) and the gauging station at DRL were extracted from the BC Hydro database. Lardeau River discharge was estimated by subtracting the total discharge at DDM from that measured at DRL. The target flow levels from the Order Table for Duncan Dam were plotted for comparison to the discharge values (Figure 1). Due to the time lag between changes in flows at DDM and the registering of the change at DRL, on occasion, there were times when a large step change was shown to be occurring in the Lardeau River when it was just an artifact. To eliminate these erroneous changes, any change in Lardeau River discharge greater than 25 m^3/s in one hour was removed from the data prior to modeling and analysis.

A Bayesian state-space polynomial proportional mixing model was applied to discharge and temperature data to assess the influence of DDM operations on water temperature in the LDR. The model was fitted using the software package R 2.15.0 (R Development Core Team 2012), which interfaced with JAGS (Just Another Gibbs Sampler) 3.2 using the rjags package (Plummer 2003). The models assumed low information (Ntzoufras 2009) uniform and normal prior distributions. The posterior distributions were estimated from a minimum of 1,000 Markov Chain Monte Carlo (MCMC) simulations thinned from the second halves of three MCMC chains of 800 iterations in length. Model convergence was confirmed by ensuring that R-hat (the Gelman-Rubin Brooks potential scale reduction factor) was less than 1.1 for each of the parameters in the model (Gelman & Rubin 1992; Brooks & Gelman 1998; Gelman et al. 2004).

The statistical significance of particular parameters was assessed from their two-sided Bayesian p-values (Bochkina and Richardson 2007; Lin et al. 2009). Plots of model estimates were produced using the ggplot2 R library (Wickham 2009). Key assumptions of the Bayesian state-space polynomial proportional mixing model included:

- The lag between changes in temperature and discharge at Lardeau River, LLOG and SPOG and 2.7 Km down the LDR is less than one hour;
- The hourly discharge in the Lardeau River is the discharge from DRL minus the total discharge from DDM;
- The temperature at DCL is the water temperature from the LLOG release;
- The temperature at 0.4R is the water temperature from the SPOG release;
- The temperature at side channel station S2.7L is the water temperature down the left bank of the LDR;
- The temperature at 2.4R is the water temperature down the right bank of the LDR;
- The water temperature from DDM is the weighted average of the water temperatures from LLOG and SPOG where the temperatures are weighted by the relative discharge proportions;
- With no mixing, the water temperature down the left bank of the LDR is the water temperature from DDM and the water temperature down the right bank of the LDR is the water temperature from the Lardeau River;
- The model estimates the mixing of the output from DDM and the Lardeau River at one point on the LDR at approximately river km 2.55 (midway between instrumentation at river kms 2.7 and 2.4)
- With 100% mixing there is no difference in the water temperature down the left or right banks of the LDR at river km 2.55 and the temperature at river km 2.55 is the weighted average of the water temperatures from the Lardeau River and DDM weighted by the relative discharge proportions;
- The percent mixing depends on the discharge from the Lardeau River and DDM and is adequately described by third-order polynomials with full second-order interactions; and,
- The residual variation in hourly water temperature is adequately described by a normally distributed first-order autoregressive process.

A description of the data variables, model parameters and the JAGS model code (Gilks et al. 1994) are provided in Appendix C. For information on JAGS distributions and functions see the JAGS Version 3.1.0 user manual (Plummer 2011), which is available at http://sourceforge.net/projects/mcmc-jags/files/Manuals/3.x/].

2.7.2 TGP

Information pertaining to TGP analyses is provided in Appendix B.

2.7.3 Water Temperature

Hourly water temperature data measured at DRL was obtained from the BC Hydro database for the period from December 2003 until April 30, 2012 and the mean, maximum and minimum hourly temperatures were plotted for the pre-WUP and post-WUP (January 2008 onwards) periods to get an overview of the water temperature patterns in the last nine years.

Water temperature data collected during the two years of this study program were the primary data used in the present analyses. Prior to analysis, all data were plotted extensively and inspected for outliers. Outliers were initially identified by visual assessment, then compared through a series of queries to determine if any mechanistic reason could be found for the disparity between that datum and other proximal data. After cross-referencing with field records the data were corrected or removed prior to analysis. The one exception to this was the water temperature data from the Water Survey of Canada station (WSC Station No. 08NH118; herein referred to as DRL) located at Km 2.1R. There were certain anomalies in the DRL data that were not explicable when compared to variation in other water temperature data from the same time period and proximal locations. Since DRL is the longest historical data set available for water temperature in the LDR and the extent of the errors is unknown, the DRL water temperature data were used where necessary and the limitations and concerns with the potential errors in this data are further described in the results section where relevant. Water temperature files for each TidBiT logger were also tested with a Microsoft Access query to determine and exclude any loggers that deviated beyond 1ºC from its replicate. Water temperature was also collected during spot and continuous TGP measurements during the spill period of 2011. Continuous water temperature was collected from August 8 to September 2, 2011 at 2.2L by the TGP probe. Spot measurements collected between August 5, 2011 and August 18, 2011 were used to assess the downstream spatial extent of any water temperature effects of DDM in the LDR during spill gate use.

The range of effects of DDM operations on downstream water temperatures can include: i) no effect; ii) a cooling effect; or, iii) a warming effect, relative to Lardeau River temperatures which are considered a surrogate for pre-impoundment Lower Duncan River temperatures for the purposes of this study. The cooling and warming effects are assumed to reflect the effects of impoundment and flow regulation at Duncam Dam. The Lardeau River is used in this study as the best available comparison to natural temperatures that may have occurred in the LDR without the construction and operation of DDM, since no historical records exist for water temperature in the LDR prior to construction of DDM (AMEC 2010).

Water temperatures as measured by the DDMMON-7 loggers were averaged to hourly levels to allow comparison to the discharge levels and were plotted by location and through time along the length of the LDR. On the plots, water temperatures were related to the BC Water Quality Guidelines (2001) for temperature requirements specific to freshwater aquatic life. Further information on these guidelines is provided in AMEC (2010) and in Tables 4 and 5. The hourly rate of change in water temperature was also calculated and plotted through time for data collected in the LDR and Duncan Reservoir to compare to the BC Water Quality Guidelines (2001; Table 4). The stratification in the reservoir forebay was assessed by plotting the temperature through time at each depth (1, 5, 15, 20 and 25 m below surface) relative to the logger at 10 m. The 10 m logger was selected as the reference point, since it was most likely to be at the threshold of the thermocline (Lawrence et al. 2011).

Table 4: Summary of water quality guidelines for temperature specific to freshwater aquatic life as presented in BC Water Quality Guidelines 2001. Guidelines most applicable to the LDR or Duncan Reservoir are italicized.

Water Use	Recommended Guideline
Freshwater Aquatic Life (streams with bull trout and/or Dolly Varden)	*Maximum Daily Temperature is 15°C Maximum Incubation Temperature is 10°C Minimum Incubation Temperature is 2°C Maximum Spawning Temperature is 10°C*
Freshwater Aquatic Life (streams with known fish distribution)	*+/- 1°C change beyond optimum temperature range for each life history phase of the most sensitive salmonid species present. Hourly rate of change not to exceed 1°C*
Freshwater Aquatic Life (streams with unknown fish distribution)	Mean Weekly Maximum Temperature (MWMT) = 18°C (Maximum daily Temperature = 19°C) Maximum Incubation Temperature = 12°C (in the spring and fall) Hourly rate of change not to exceed 1°C
Freshwater Aquatic Life (lakes and impoundments)	*+/- 1°C change from natural ambient background*

Table 5: Optimum water temperature (°C) ranges for specific life history stages of salmonids and other coldwater fish species found in the LDR as per BC Water Quality Guidelines (Oliver and Fidler 2001).

Species	Incubation	Rearing	Migration	Spawning
Sockeye*	4.0 – 13.0	10.0 – 15.0	7.2 – 15.6	10.6 – 12.8
Rainbow	10.0 – 12.0	16.0 – 18.0	---	10.0 – 15.5
Bull Trout	2.0 – 6.0	6.0 – 14.0	---	5.0 – 9.0
Brook Trout	1.5 – 9.0	12.0 – 18.0	---	7.1 – 12.8
Mountain Whitefish	< 6.0	9.0 – 12.0	---	< 6.0
Burbot	4.0 to 7.0	15.6 – 18.3	---	0.6 – 1.7
White Sturgeon	14.0 – 17.0	---	---	14.0

*As kokanee were not included in review by Oliver and Fidler (2001), sockeye (anadromous kokanee salmon) information has been included.

2.7.3.1 Water Temperature Modeling

Water temperature modeling following the methodology described in Section 2.7.1, with the following considerations. There were two questions assessed with the water temperature data. The first was what water temperatures resulted downriver from water coming out of the LLOGs and the SPOGs. This was modeled with a proportional mixing model as described in 2.7.1. The TidBiT logger placed at station DCL in the tailrace channel was considered the best data representing the output from the LLOG before it is affected by the influence of the Lardeau River and the spillway. For temperature plots and modelling purposes, the DCL station was referred to as 'LLOG' for that reason. The logger at station 0.4R was considered the best data representing water temperatures associated with SPOG and was plotted as the station 'SPOG'.

The second question included what was the relationship between water flowing out of DDM and what was present within the reservoir. This question was addressed by interpolating the water temperatures throughout the reservoir water column and comparing the water coming out of the dam with the depth in the reservoir at which that temperature occurred. The water temperature in the Duncan Reservoir at 1 m intervals from 1 m to 40 m in depth was estimated from the temperature logger array data at Howser (when available) and in the forebay for each hourly interval by linear interpolation. Based on the observed water temperatures at the Howser site in 2010, the interpolation assumed that the water temperature at 40 m was 7°C to provide a boundary for interpolation; this temperature was considered a constant during the stratified period. For each hourly interval in which a SPOG or LLOG was discharging, the 1 m depth increment in the reservoir that was closest to the temperature recorded at 0.4R and DCL, respectively, was identified and plotted as a point on a thermal profile of the reservoir by depth and date.

3.0 RESULTS

3.1 Discharge

Discharge for DDM low level outlet gates (LLOGs), spillway gates (SPOGs) and the Lardeau River from 2003 to 2011 is provided in Figure 6. The duration and frequency of spill events is generally shorter and lower, respectively, during the post-WUP period, which commenced in 2008, as compared to pre-WUP conditions (Figure 6). However, in 2011 the spill period was of longer duration than other pre- and post-WUP years.

Detailed discharge plots for the LLOGs, SPOGs and the Lardeau River for the DDMMON-7 study period are presented in Figure 7. Discharge levels at all stations reflect much higher inflows in 2011 than in 2010 (Figure 7). This also resulted in a much shorter period of low discharge from the LLOG gates in 2011 (Figure 7). In 2010, SPOG discharge occurred during scheduled tests in the third week of August and in three other SPOG discharge events in the autumn of 2010. The autumn events were relatively small and of short duration (Figure 7). The single spill event in 2011 ran from July 29 to August 25 (Figure 7).

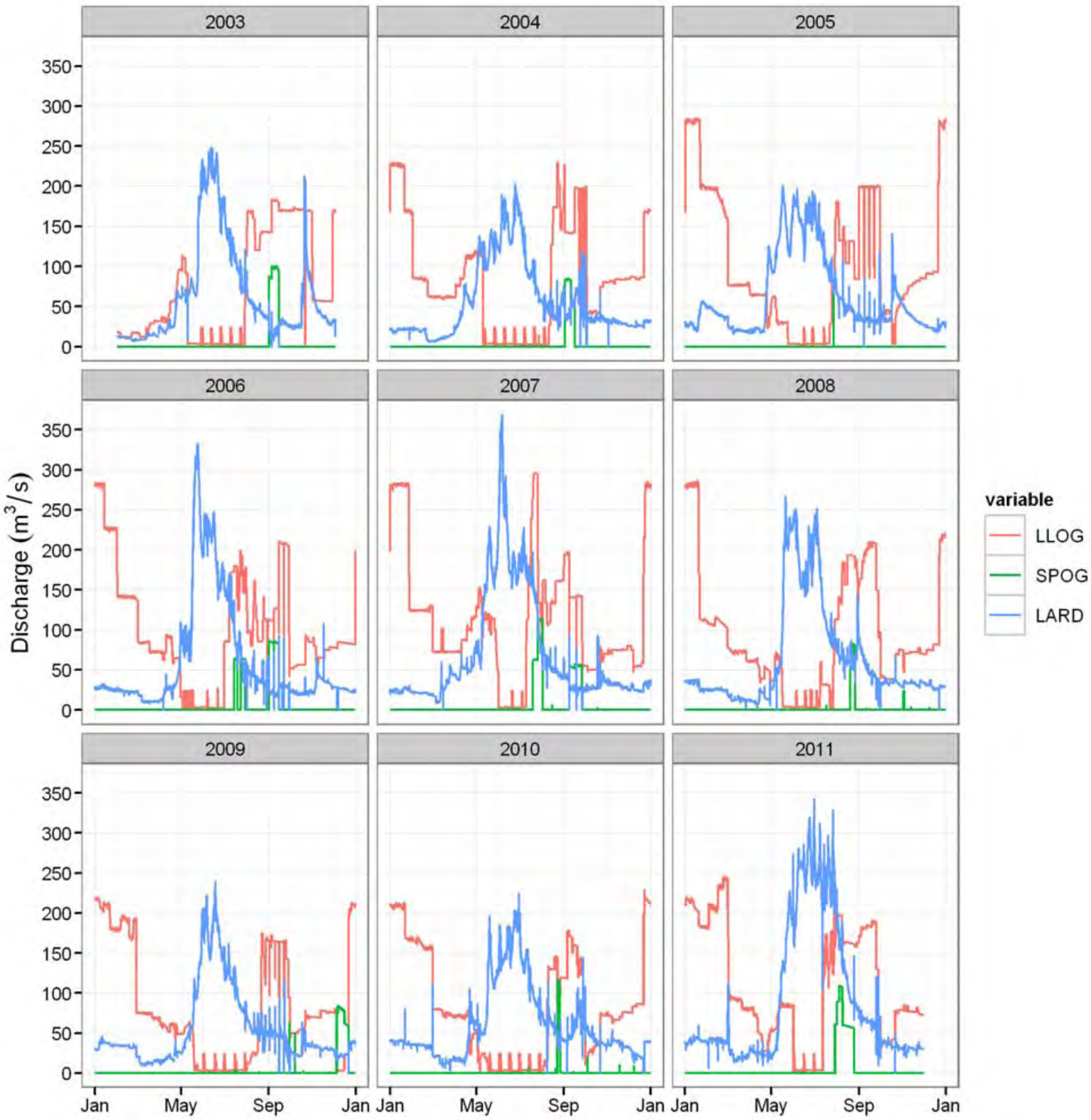

Figure 6: Hourly discharge levels through time from Duncan Dam low-level outlets (LLOG), spill gates (SPOG) and Lardeau River (LARD), 2003 to 2011.

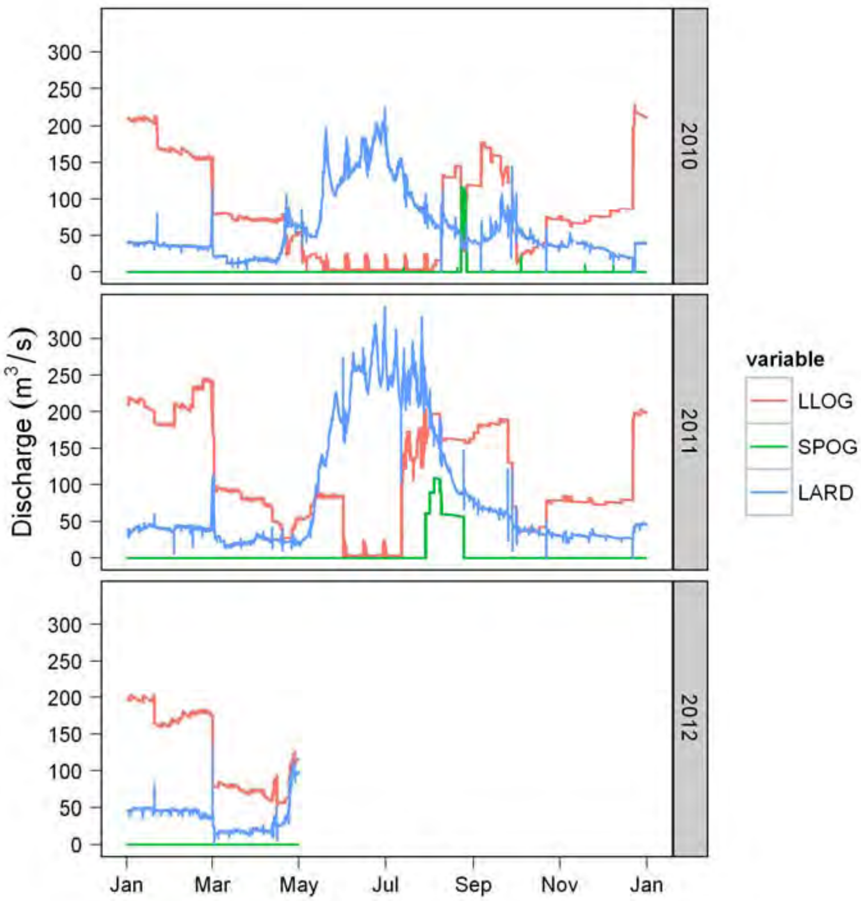

Figure 7: Hourly discharge levels through time from the Duncan Dam low-level outlets (LLOG), spill gates (SPOG) and Lardeau River (LARD), January to December 2010 and January to May 2012.

3.2 TGP

TGP results are provided in Appendix B.

3.3 Water Temperature

The variability (width of the grey band) is greater in the post-WUP period throughout the year with notable increases in the November to December period and in the spring months from March to June (Figure 8). However as previously mentioned, there is some uncertainty in the reliability of this data. Since data provided by BC Hydro power records is not verified for data quality, errors in discharge, stage, elevation and temperature data recorded at DRL are always a possibility. The anomalies in the DRL data appear to be unexplained spikes and higher than expected water temperatures, so the errors appear to bias temperature estimates in an upwards direction (Figure 9). The inexplicable spikes are most evident in July 2010 where the temperature recorded reached 20°C, while no other stations in the river at that time register this same pattern, including the DDMMON-7 study logger 300 m downstream on the same side of the river (2.4R; Figure 9).

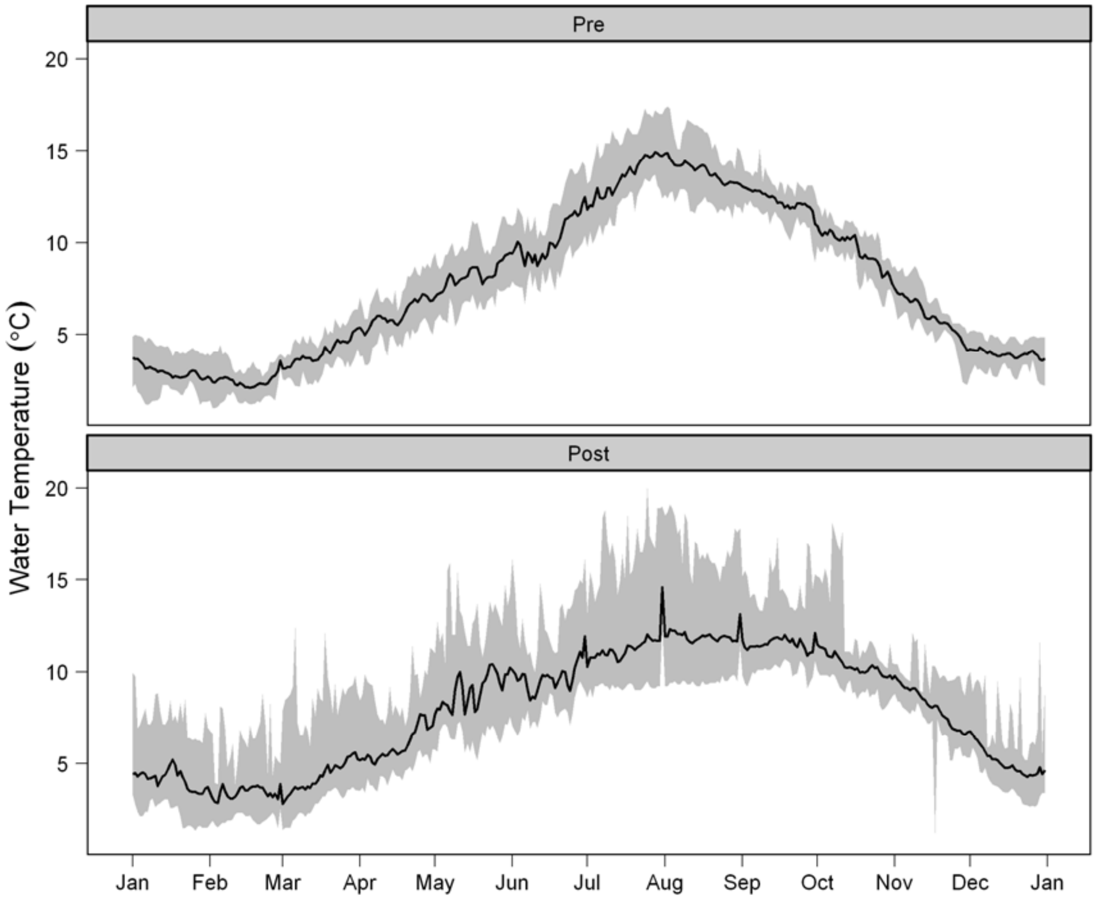

Figure 8: Mean hourly water temperature (black line) and minimum and maximum hourly temperatures (grey band) as measured at the WSC gauge at Km 2.1 (DRL) for Pre-WUP (2003-2007) and Post-WUP (2008-2012) periods.

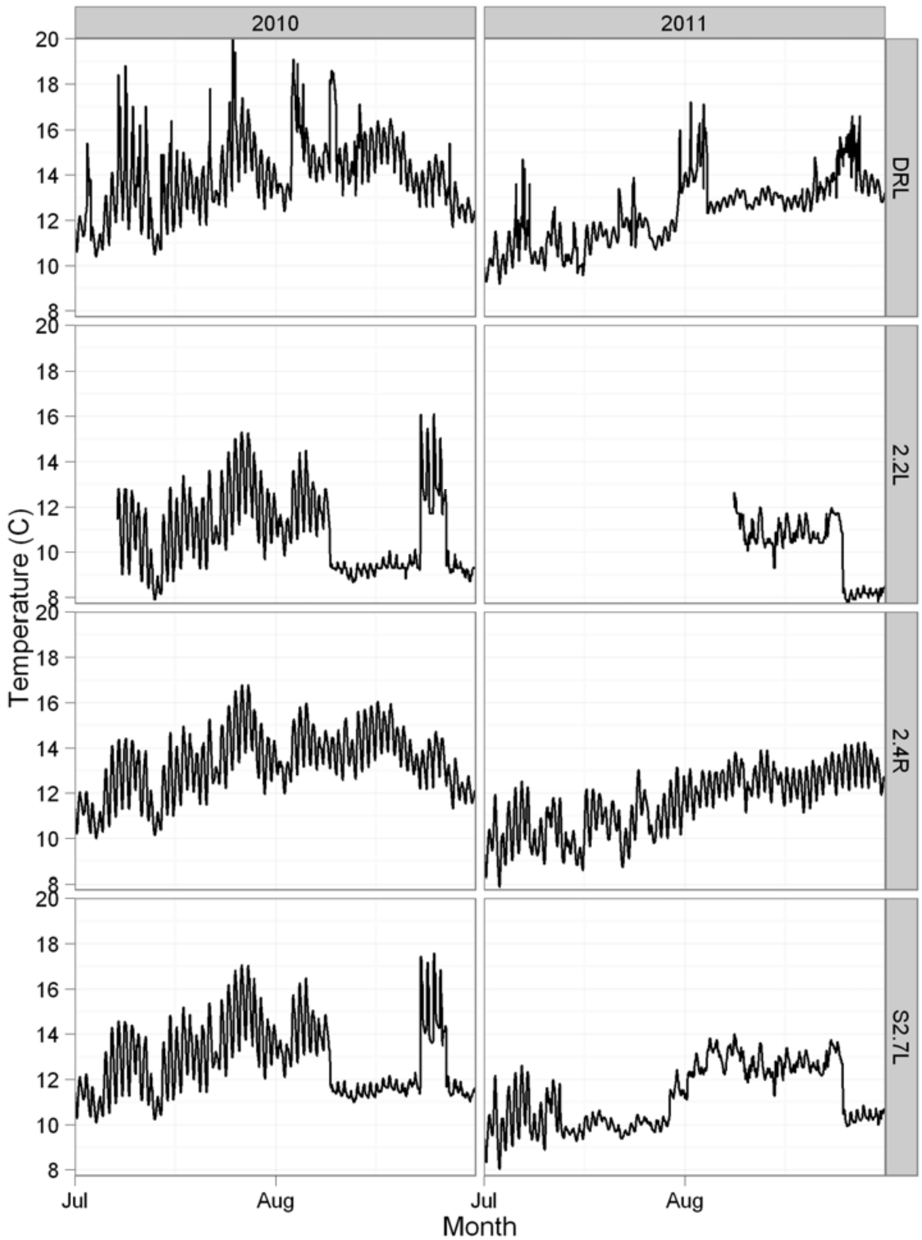

Figure 9: Mean hourly water temperature during July and August 2010 and 2011 as measured at DRL (WSC Station No.08NH118) and DDMMON-7 stations 2.4R (River Right, 300 m downstream of DRL), 2.2L (River Left across from DRL) and S2.7L.

Mean hourly temperature collected at all DDMMON-7 monitoring stations was plotted through time from January 2010 to May 2012 (Figures 10 and 11). Water temperatures were occasionally above the 15 ºC threshold for bull trout streams at stations 0.4R and 0.5L (Figure 10). Water temperatures in the surface of the reservoir also exceeded 15ºC at certain times of the year and this would affect meeting the BC Water Quality Guidelines at some of the river left sites in the LDR if the flow through the dam drew from the top 10 m of the reservoir (Figure 11).

The BC Water Quality Guideline states that for streams with known fish distributions the rate of water temperature change should not exceed ±1ºC / hour (Table 4). This rate was exceeded during the June through late August period in 2010 and 2011 at LDR stations 0.4R, 0.5L, 2.4R and S2.7L as well in late August 2010 at stations 7.0L and S8.2L (Figure 12).

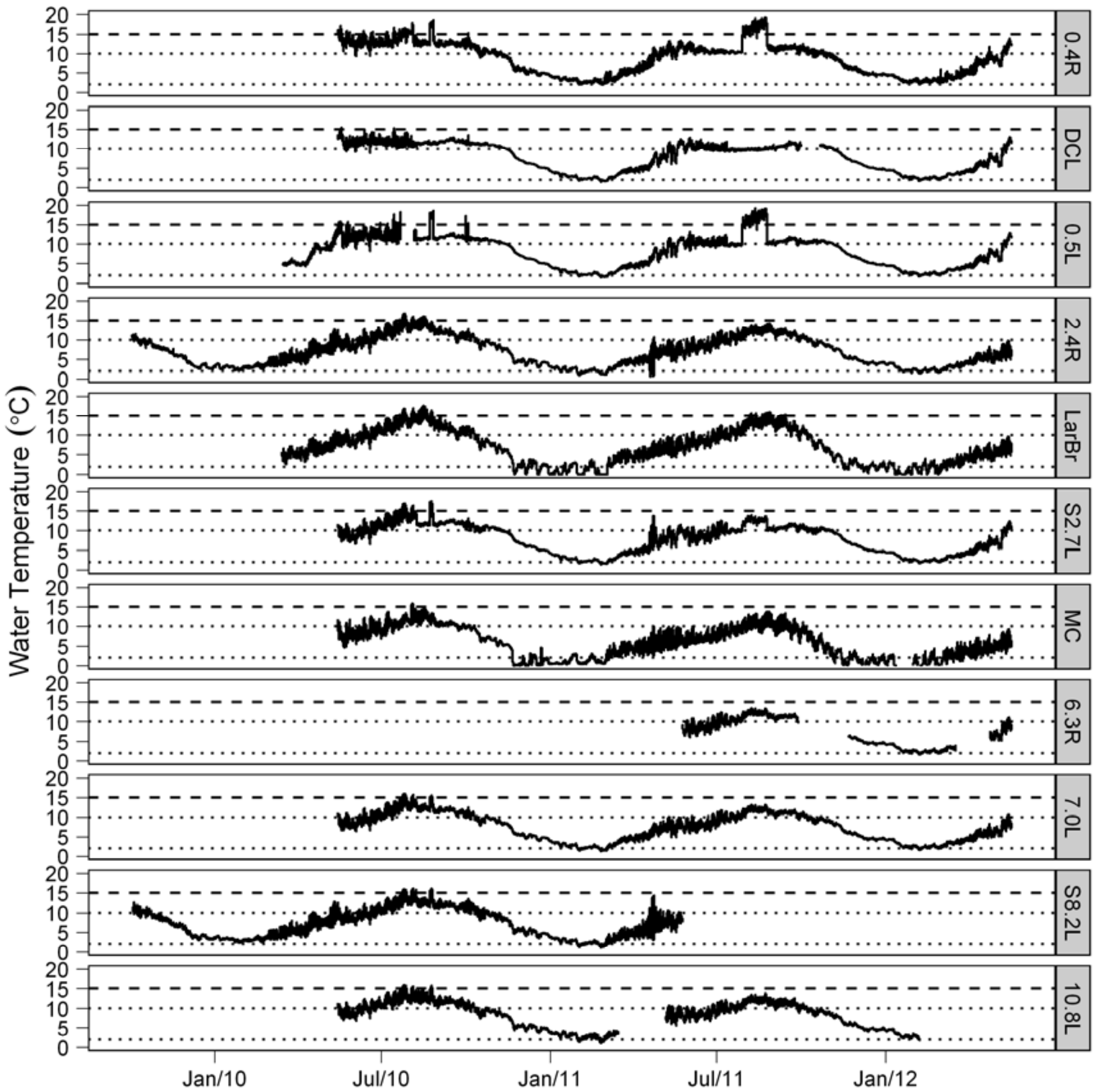

Figure 10: Mean hourly water temperature (solid line) at logger stations in LDR and tributaries with 15ºC maximum temperature guideline (dashed line) and 2ºC and 10ºC minimum and maximum spawning and incubation temperature guidelines for streams containing bull trout. Gaps in the data occurred when loggers were not-yet installed, removed, dewatered or malfunctioned.

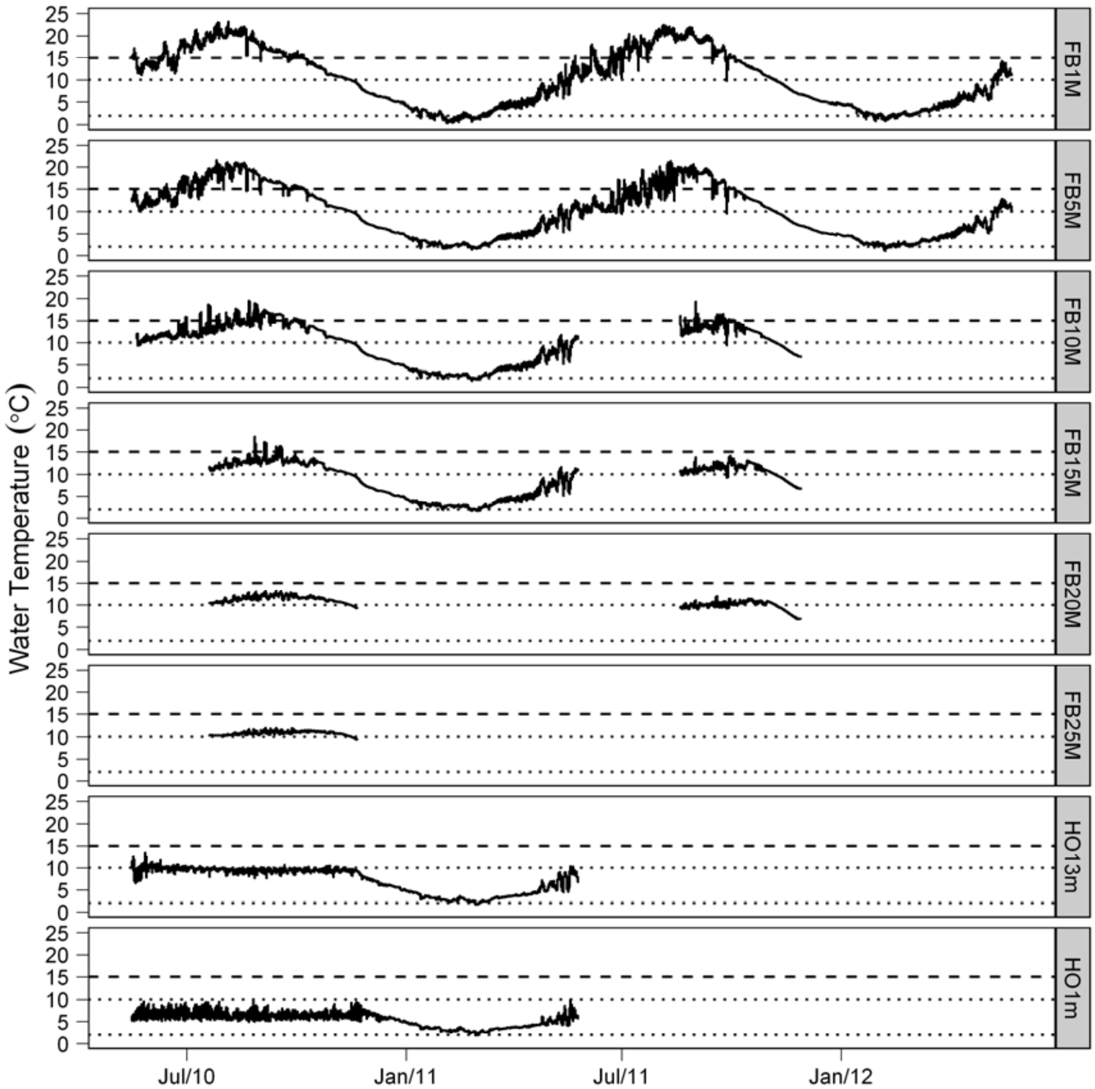

Figure 11: Mean hourly water temperature (solid line) at logger arrays in Duncan Reservoir with 15ºC maximum temperature guideline for rivers (dashed line) and 2ºC and 10ºC minimum and maximum spawning and incubation temperature guidelines for streams containing bull trout.

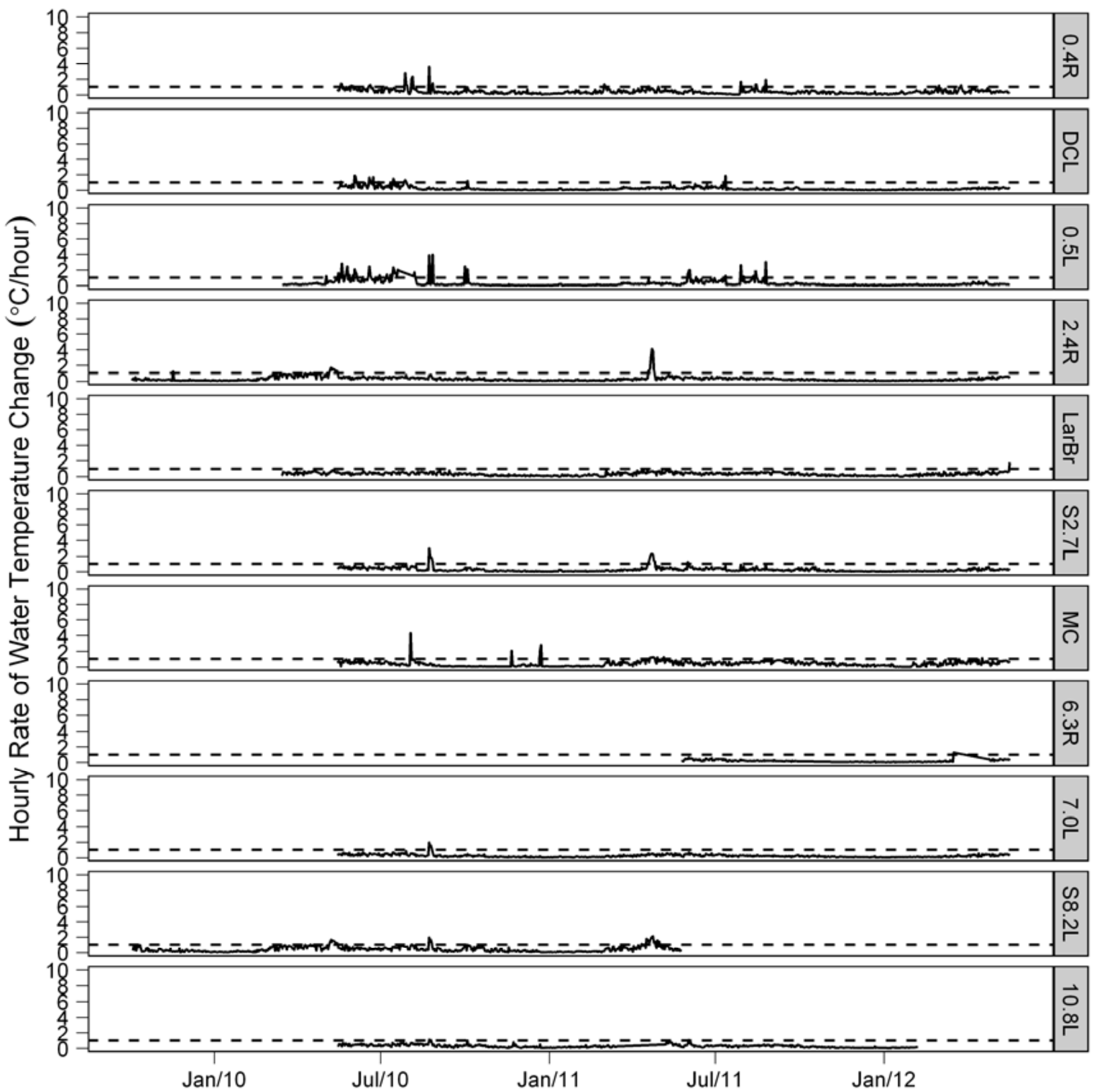

Figure 12: Hourly rate of water temperature change through time (solid line) at logger stations in the LDR for 2010-2012. The BC Water Quality Guideline for aquatic life in streams with known fish distributions (i.e., +/- 1ºC per hour) is depicted by the dashed line.

Discharge during the period from January 2010 to April 2012 and the temperature at logger stations downstream of DDM were examined in more detail in order to relate DDM operations to LDR temperatures from field data (Figure 13).

Once spilling began, water temperature was distinctly elevated above temperatures measured immediately before spill (i.e., background levels) in August 2010 and July through August 2011 at logger station S2.7L whereas this was not observed at station 2.4R (Figure 13). These time periods coincided directly with periods of SPOG use (Figure 13). Loggers on both sides of the river did show a fluctuation in temperature during late April 2011 when LLOG discharge dropped to below 50 m^3/s and the Lardeau River discharge was still low (Figures 7 and 13).

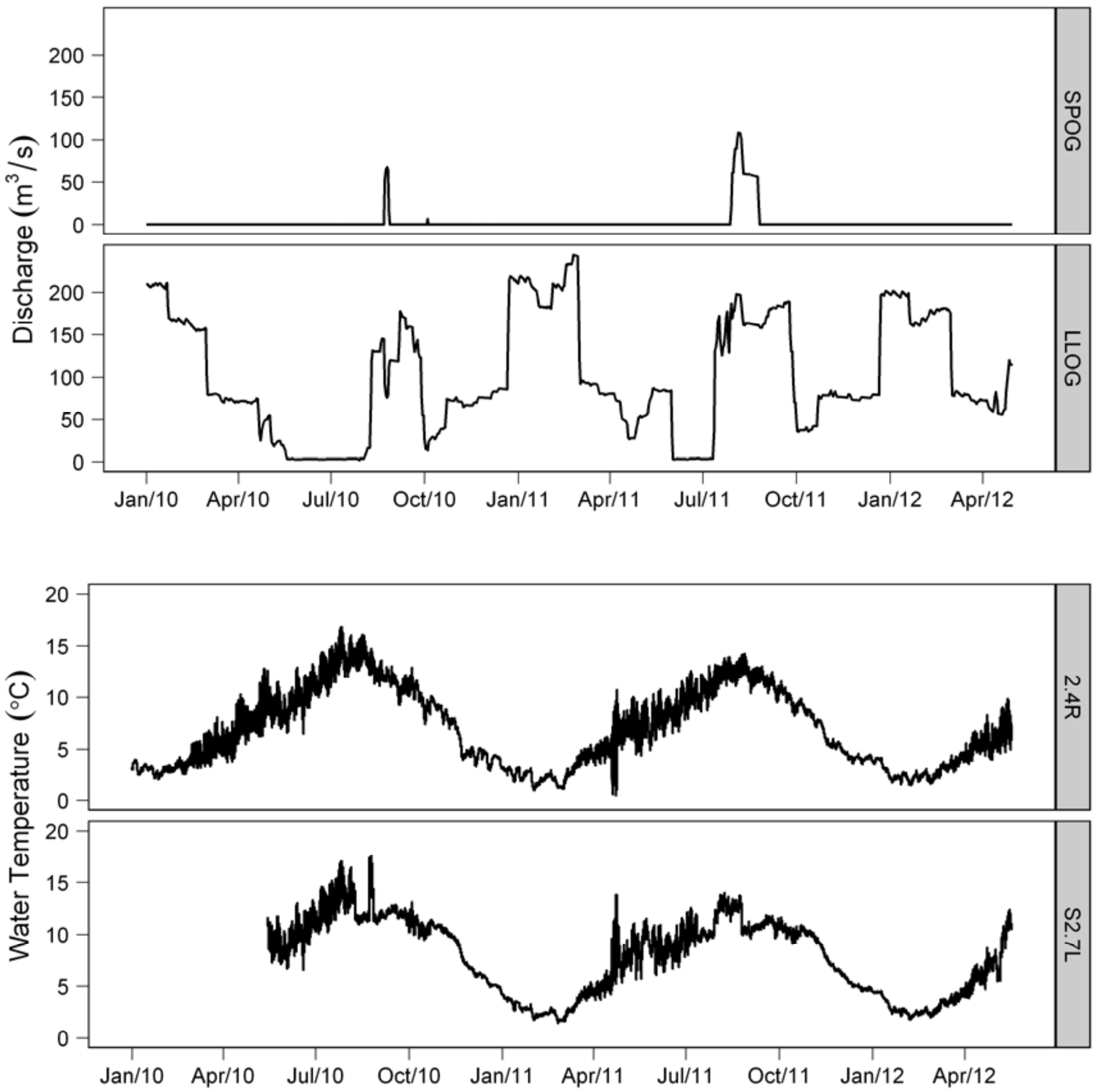

Figure 13: Mean hourly discharge level (top two plots) from spill gates (SPOG) and low-level outlets (LLOG)). Mean hourly water temperatures at logger stations 2.4R and S2.7L (bottom two plots), January to April 2012.

In 2010, water temperature measurements in the reservoir showed isothermal temperatures in the winter and stratification during the summer with the thermocline estimated to form at 10-12m deep in the reservoir (Masse, Redfish and Poisson 2011). The isothermal state of the reservoir from November 2010 to May 2011 is distinguished by the fluctuation around the zero difference line for the loggers at 5 and 15 m below surface (Figure 14). The logger at 1 m depth from surface shows little difference, but is colder than that at 10 m for January and February as shown by the fluctuations below the zero effect line (Figure 14). In the summer months, where data were available due to reservoir elevations and the quarterly station service schedule defined for the project, the stratification is clearly seen by the positive differences in temperature at the 1 and 5 m depths and the negative differences (cooler temperatures than recorded at 10 m depth) recorded at 15, 20 and 25 m depths (Figure 14).

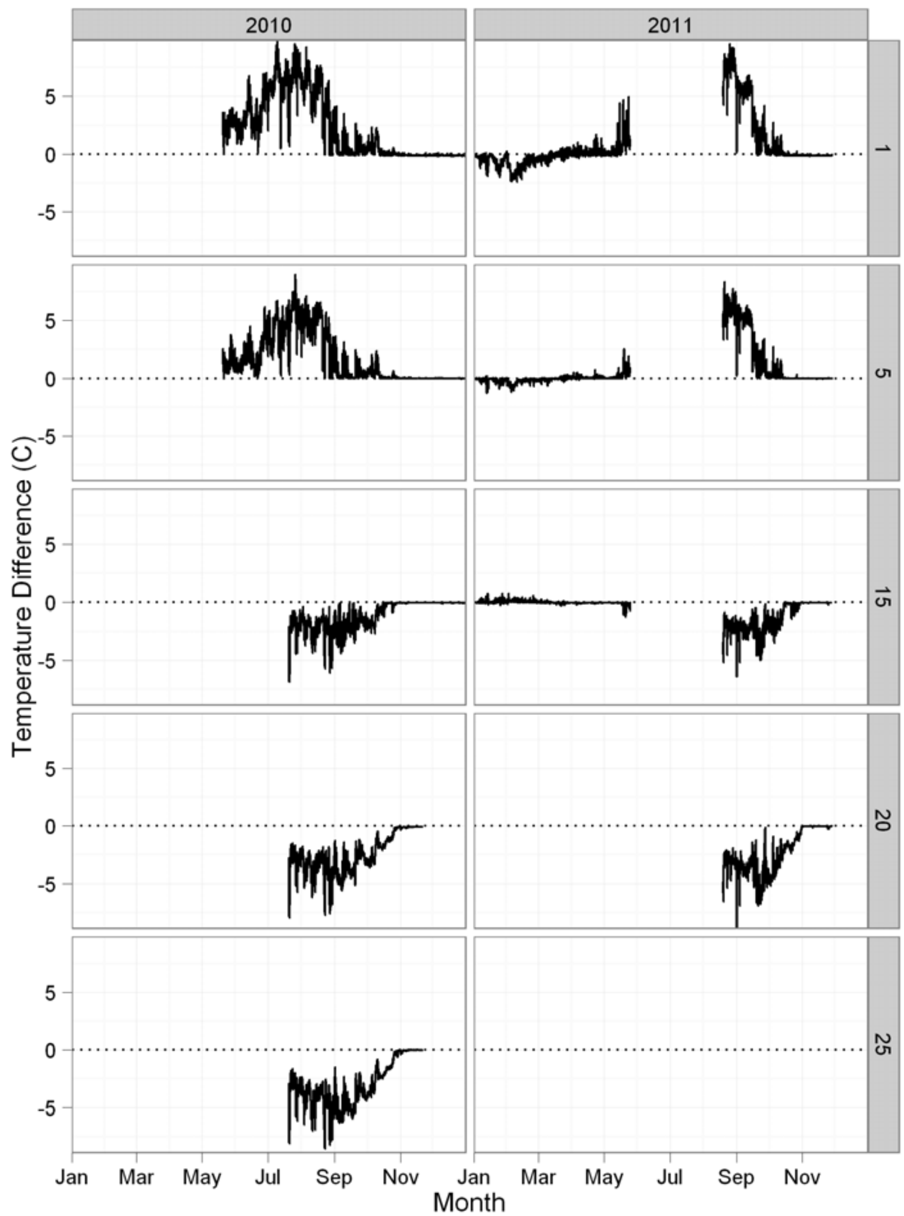

Figure 14: Differences in Duncan Dam forebay mean hourly water temperature at 1, 5, 15, 20 and 25 m in relation to the logger located at 10 m, as measured vertically from the water surface, for periods that records are available in 2010 and 2011.

The isothermal state of the reservoir forebay can be observed from November to May (where data exist) and the stratification can most clearly be observed in August. When the reservoir is stratified, temperatures are markedly cooler at stations below 10 m depth from the surface (Figure 15).

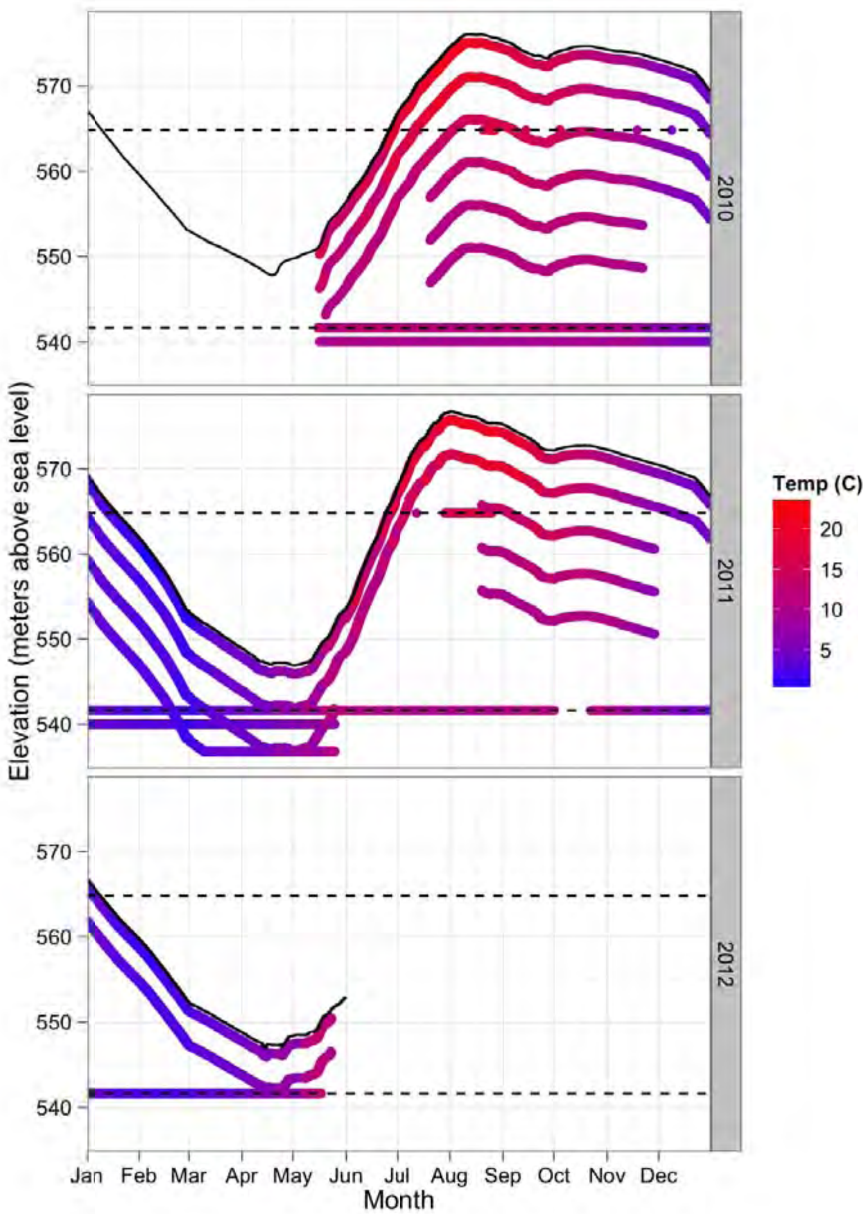

Figure 15: Water temperatures at various depths in the Duncan Reservoir relative to surface elevation, 2010-2012. Dashed lines indicate elevations of the low level outlet gate (LLOG; 541.63 m) and spillway gate (SPOG; 564.8 m) sills. The solid black line indicates Duncan Reservoir surface elevation as measured at the DDM forebay. Coloured bands overlaying the gate elevation dotted lines show the water temperature discharged from the LLOGs and SPOGs while that plotted below the LLOG elevation line is that recorded at the absolute LLOG sill elevation (541.63 m) as measured at station HO13m.

Spot measurements taken at river Km 2.2L on August 5, 2011 indicated that water temperature on the left bank was approximately 2°C warmer compared to the right bank. There were insufficient data throughout the remainder of the LDR due to limited river access on this date to determine if the pattern for warmer temperatures persisted throughout or disappeared and reappeared as a result of other tributary contributions (Figure 16). Comprehensive left, middle and right bank sampling on August 18, 2011 showed minimal left/right bank water temperature difference, which did not persist past river Km 3.5 (Figure 16). These readings were obtained after spill had been ongoing for 3 weeks.

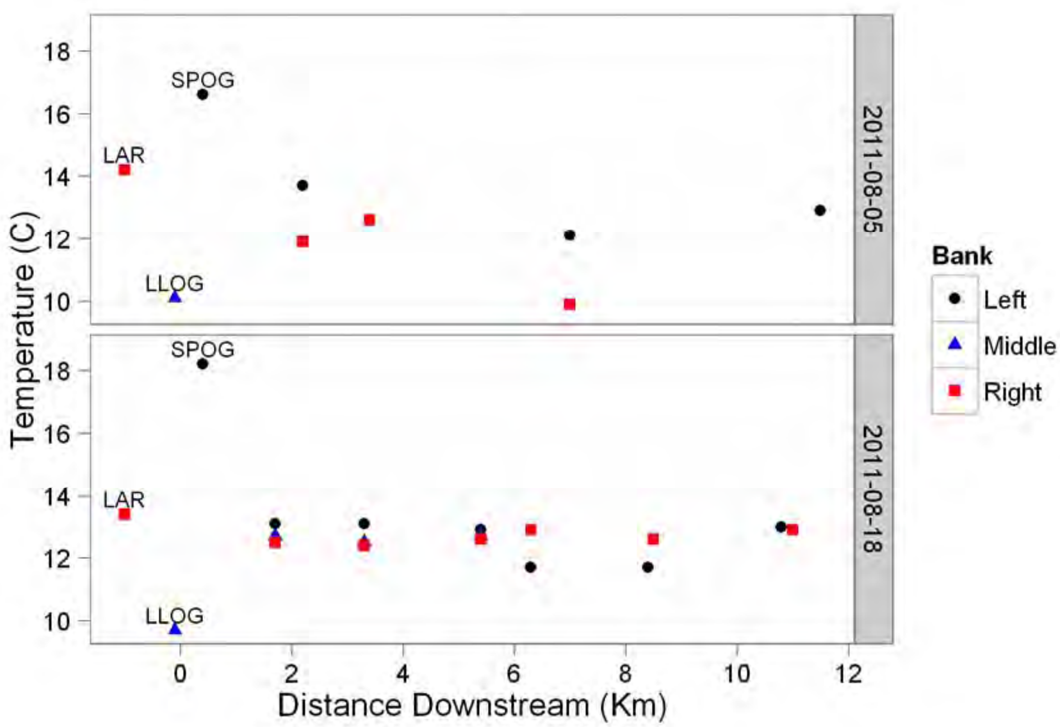

Figure 16: Water temperatures taken as spot measurements throughout the lower Duncan River on August 5, 2011 (top plot) and August 18, 2011 (bottom plot).

Water temperature discharged through the LLOGs (as measured at station DCL, the discharge channel) and the SPOGs (as measured at station 0.4R, the spillway channel) gradually increased between January and May, as did water temperature in the Lardeau River (Figure 17). During the period from October to March, however, the DDM tailrace at both the discharge channel and the spillway are warmer than the Lardeau River by up to 5°C (Figure 18). This trend, though slightly moderated, was also observed 2-3 km downstream on both river banks (Figure 18).

The LLOG discharge channel and spillway sites remained relatively warmer until July when the tailrace became cooler as the LLOGs began discharging hypolimnetic water once the reservoir stratified (Figure 18). When spill events occurred, the spillway rapidly became 5-10°C warmer than the discharge channel and about 5°C warmer than the Lardeau River (Figures 17 and 18).

This trend was also observed at station S2.7L in 2010; in 2011, however, water temperature at S2.7L was very similar to the Lardeau River and only slightly warmer (2-3°C) than the discharge channel. Once spill was completed, water temperature in the tailrace was briefly about 3°C cooler than the Lardeau River, but during the winter period the LDR was relatively warmer than the Lardeau River (Figures 17 and 18).

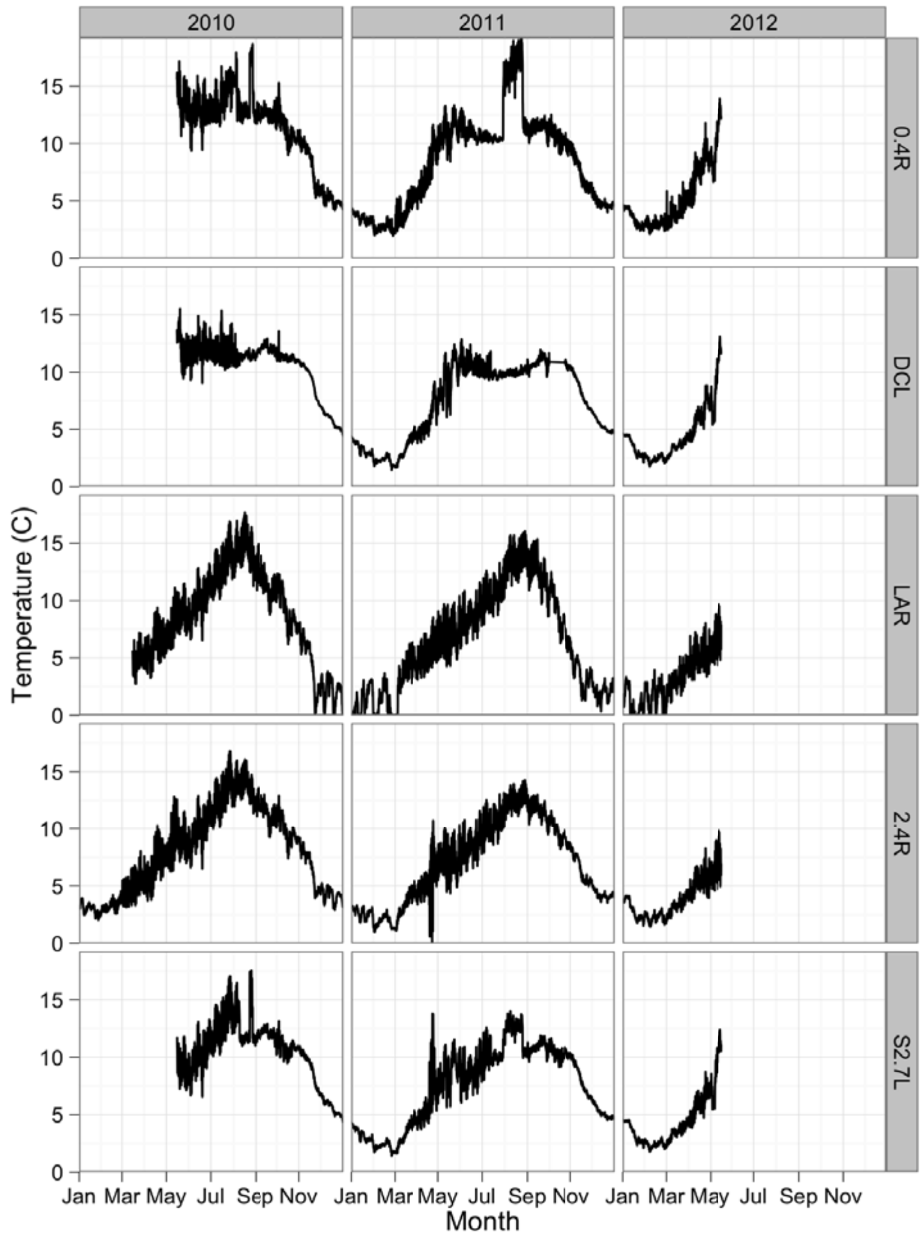

Figure 17: Mean hourly water temperature measured in the Duncan Dam (DDM) spillway channel (0.4R), the DDM discharge channel (DCL) below the low level outlet gates, the Lardeau River (LAR) at the DDM bridge, and the lower Duncan River at Km 2.4R and S2.7L, 2010-2012.

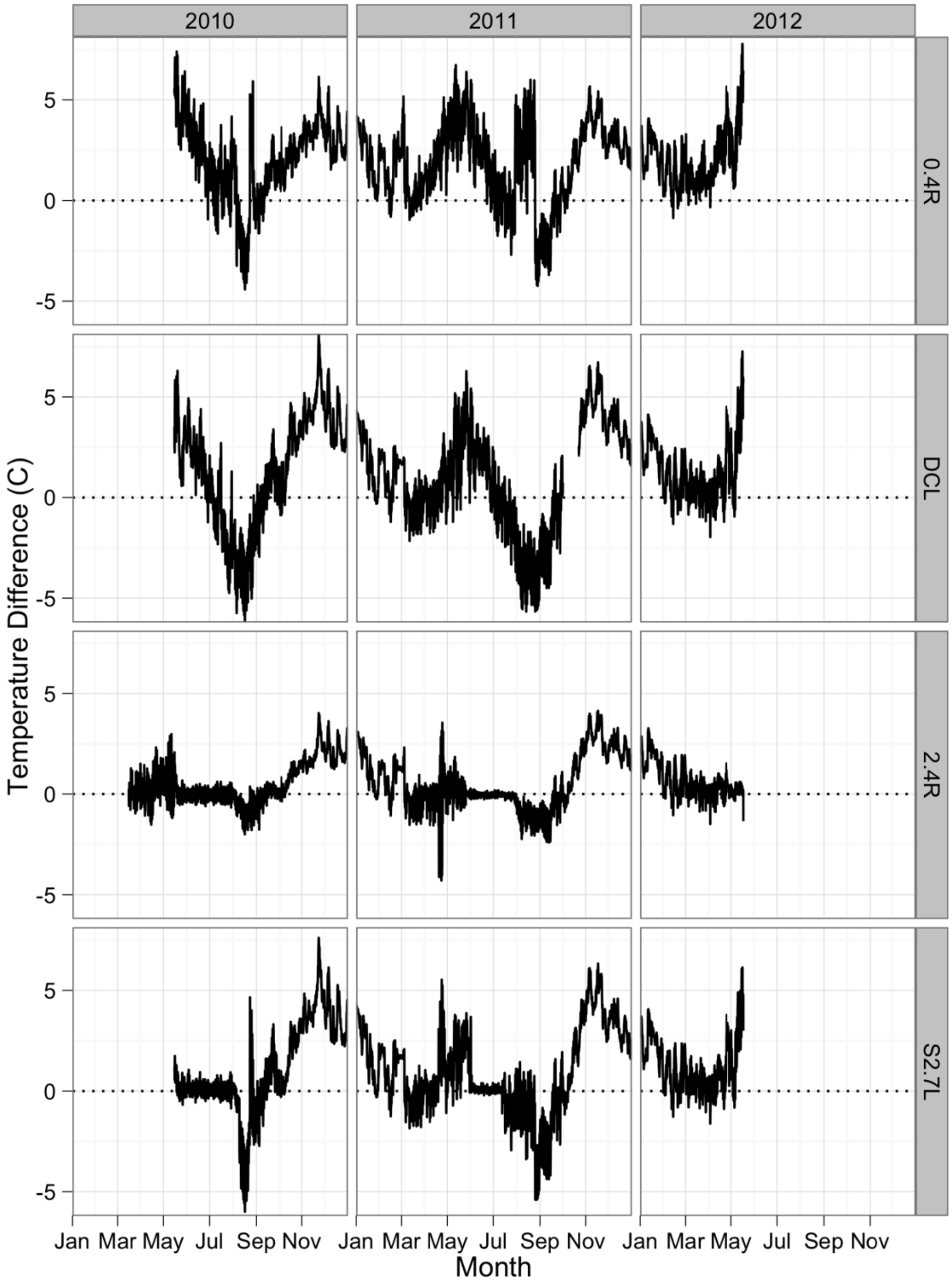

Figure 18: Mean hourly water temperatures relative to the Lardeau River in the Duncan Dam (DDM) spillway channel (0.4R), the DDM discharge channel (DCL) below the low level outlet gates, and the lower Duncan River at Km 2.4R and S2.7L, 2010-2012. Values on the zero line show no difference in water temperature between the recording station and the Lardeau River. Values above the line show that the station is warmer and values below show that the station is cooler at that point in time.

Water temperatures at downstream locations (6.3R, 7.0L and 10.8L) were generally within 1°C of what would be predicted as water temperatures from upstream inputs were completely mixed (Figure 19). This indicates that the LDR was fully mixed during most of the monitoring period in these downstream locations. The only time period when water temperatures were not as predicted based on upstream discharge and temperature was during SPOG use in August 2010 where the time lag in water moving downstream caused an anomalous decrease in predicted water temperature (Figure 19). Water temperature at river Km 7.0L was slightly cooler than predicted during each season except winter, when it was slightly warmer (Figure 19). Greater variation in water temperature was observed from that predicted at river Km 10.8; a greater influence of diel heating may occur at this location (Figure 19).

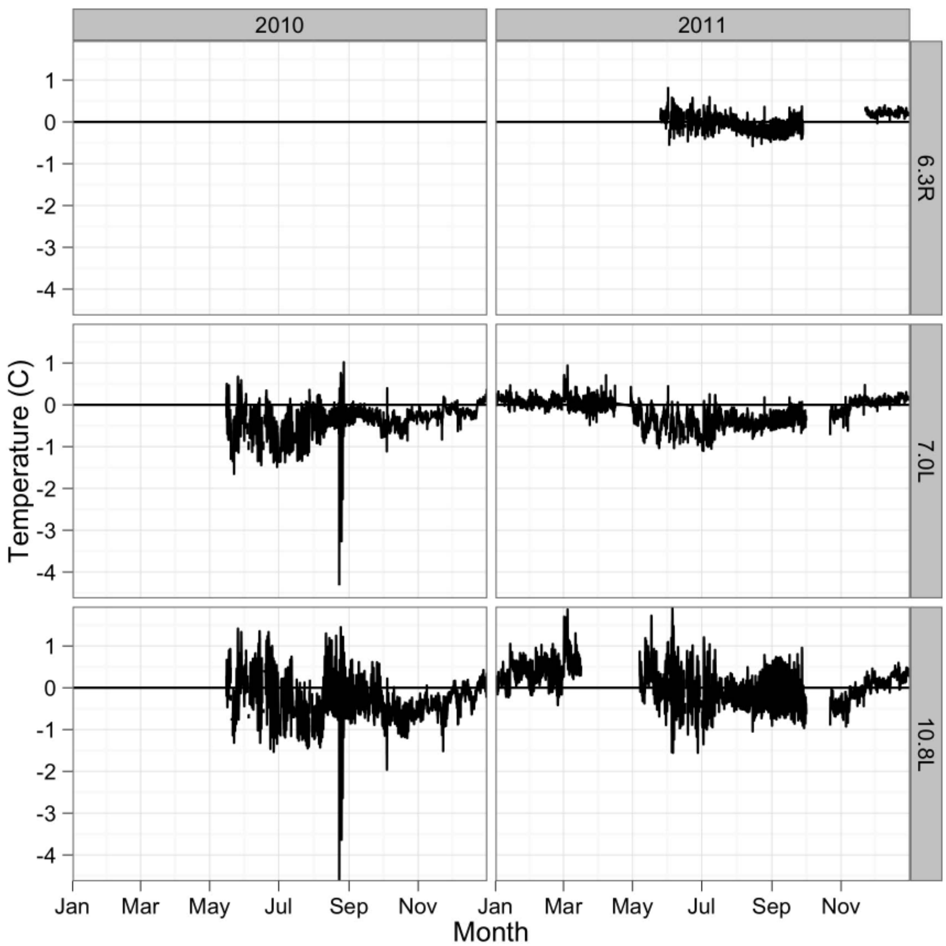

Figure 19: Mean hourly water temperatures relative to those predicted by the current water temperature and the proportion of discharge originating from Duncan Dam (DDM) and the Lardeau River at Km 6.3R, 7.0L and 10.8L, 2010-2011. Values on the zero line show no difference in water temperature from those predicted by proportional mixing. Values above the line show that the station is warmer and values below show that the station is cooler than predicted at that point in time.

Based on water temperatures observed in the LDR tailrace (i.e., at the LLOG discharge channel), the interpolated reservoir temperatures were assessed to see what depth of the forebay it was most likely that water was withdrawn from throughout the year. For example, in 2010, water temperatures below the LLOG outlet were most similar to the water temperatures found in the reservoir forebay at depths between 10 and 25 m in August, whereas in September this deepened to 20-25 m and ranged widely in the possible depths from which it was drawing in October when the reservoir thermal stratification lessened (Figure 20). In November, the average temperature of the withdrawn water through the LLOGs was most similar to that found at the 25-35 m depths in the reservoir forebay. In 2011, a similar pattern was observed throughout the late summer and fall as in 2010 (Figure 20). The average temperature of water withdrawn through the spillway was most alike that found at depths between 5 and 7 m in the reservoir at the start of spilling. After spilling had occurred for some time, however, withdrawn water was most similar to that found at depths of 15 m in the reservoir (Figure 21).

The mixing model did not extrapolate below 73 m^3/s at DRL, since there were very few observations at these discharge levels for the Lardeau River and DDM; this is also the target minimum (Table 1; Figures 22 and 23). The mixing model was derived to describe patterns of mixing between DDM and Lardeau at a point on the LDR at approximately river km 2.55. The description that follows discusses the various levels of mixing that were predicted at river km 2.55.

At low discharge levels from DDM, 80-100% mixing was predicted with the range of modeled Lardeau River discharges. This degree of mixing decreased as DDM discharge increased (between 80-250 m^3/s) until there was 0-20% mixing when discharge from the Lardeau River was either very low or very high (<50 m^3/s or >175 m^3/s) (Figure 22). With intermediate Lardeau River discharges over the mid-range of DDM, there was some mixing predicted between approximately 20 and 40% and at very high DDM values (>225 m^3/s) with midrange Lardeau River discharges, it was predicted that there was between 40 and 60% mixing (Figure 22).

The next phase of the modeling exercise brought temperatures into the mixing predictions with the assumed starting point of warm water (25°C) flowing out of DDM, as would occur during spill, and cooler water (10°C) discharging from the Lardeau River. The model assessed the mixing that would occur on the left and right bank of the LDR with varying flow levels from the combined SPOG and LLOG flows (DDM) and the Lardeau River. At low levels of discharge from DDM (<50-80 m^3/s depending upon Lardeau discharge), the left bank was influenced by the cooler water from the Lardeau River. At mid-range discharges for both DDM and the Lardeau River, there was mixing on the left bank with the temperature from DDM lowered by the influence of the Lardeau River (Figure 23) and at very high discharges from DDM, higher water temperatures were observed as the volume of warmer water overwhelmed the cooling influence of the Lardeau discharge (Figure 23). In contrast, the right bank remained cooler until either the Lardeau River discharge dropped below 100 m^3/s or DDM discharge was above 50 m^3/s. That is, as higher discharge outflows were observed from DDM, the more mixed water temperatures were along the right bank. However, theoretically if there was no flow from the Lardeau River and high DDM flows then water temperatures remained at the model start point of 25°C. Alternatively, if Lardeau River flows were high, mixing was less and the volume of cooler water high so water temperatures remained lower near the model start point of 10°C. Generally, however, the two streams of water mix and result in an averaged temperature range over most of the flow ranges observed (Figure 23).

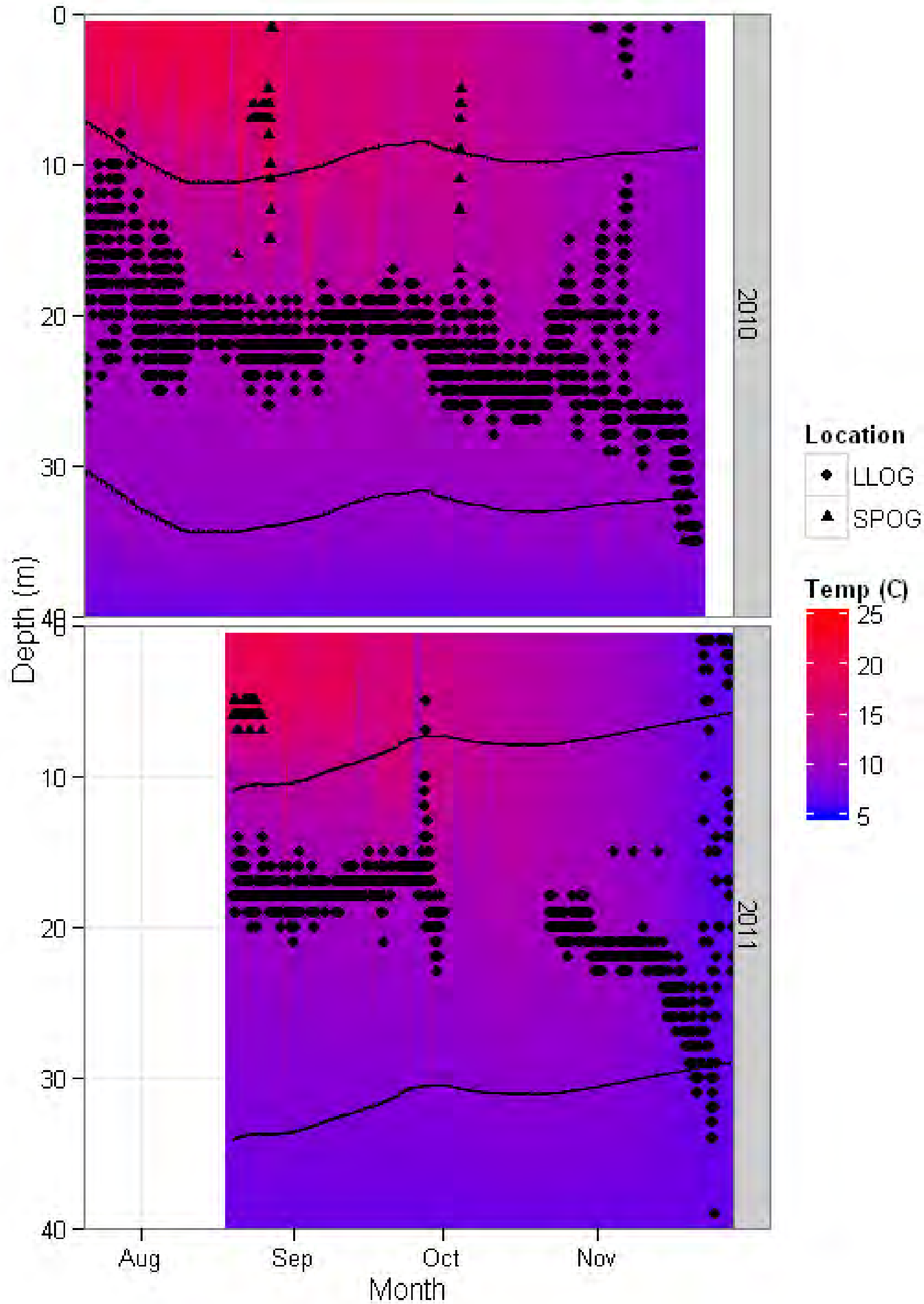

Figure 20: Water temperatures for flows passing through the LLOGs and SPOGs, July to November 2010 and 2011. Water temperatures in the spillway below the dam (SPOG) are represented by black triangles and water temperatures below the low level outlet gates (LLOG) are represented by black circles. Black lines represent the depth of the LLOG and SPOG sills relative to the reservoir surface.

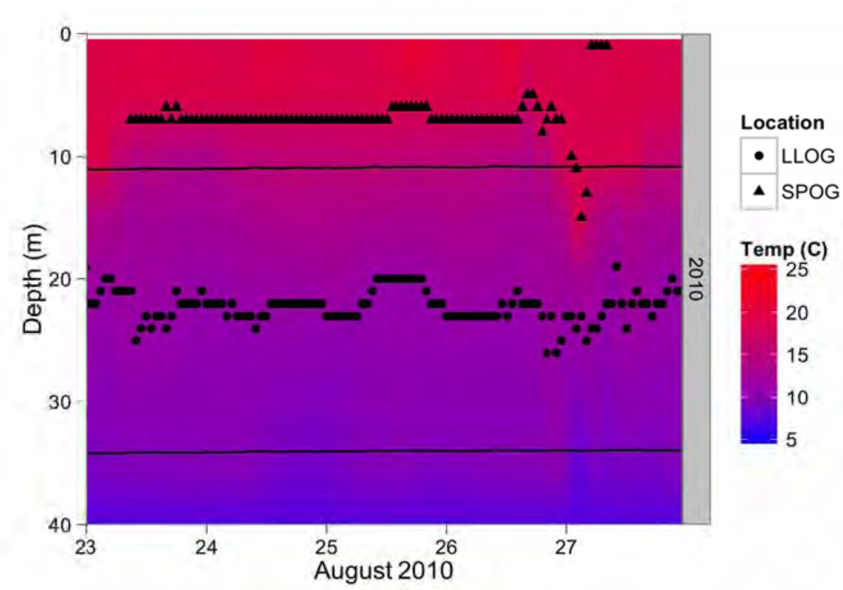

Figure 21: Water temperatures as spill testing progressed in August 2010. Water temperatures below the spillway (SPOG) are represented by black triangles and water temperatures below the low level outlet gates (LLOG) are represented by black circles. Black lines represent the depth of the LLOG and SPOG sills relative to the reservoir surface.

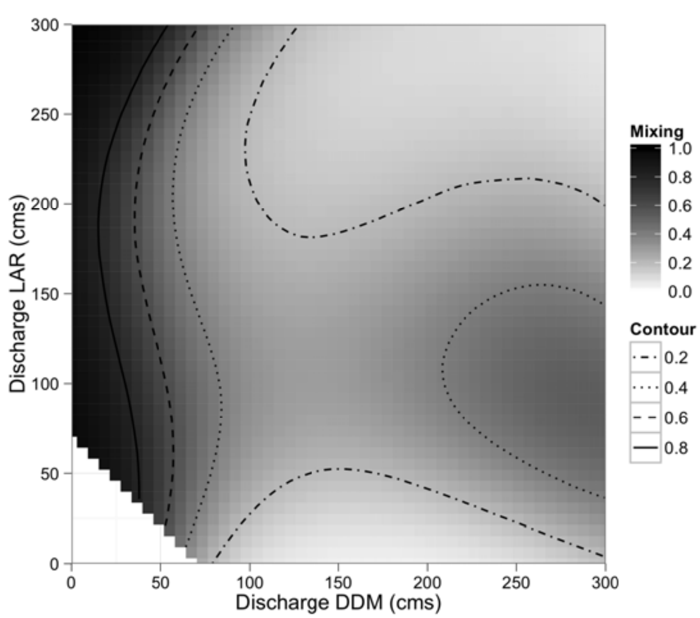

Figure 22: Mixing model for total Duncan Dam (DDM) and Lardeau River discharge with one hundred percent mixing set to equal 1.0 and zero percent mixing to equal zero. Contour lines show the transition between levels of mixing and the model is predicting mixing at a point on the LDR approximately at river km 2.55 (between instrumentation at river km 2.4 and 2.7).

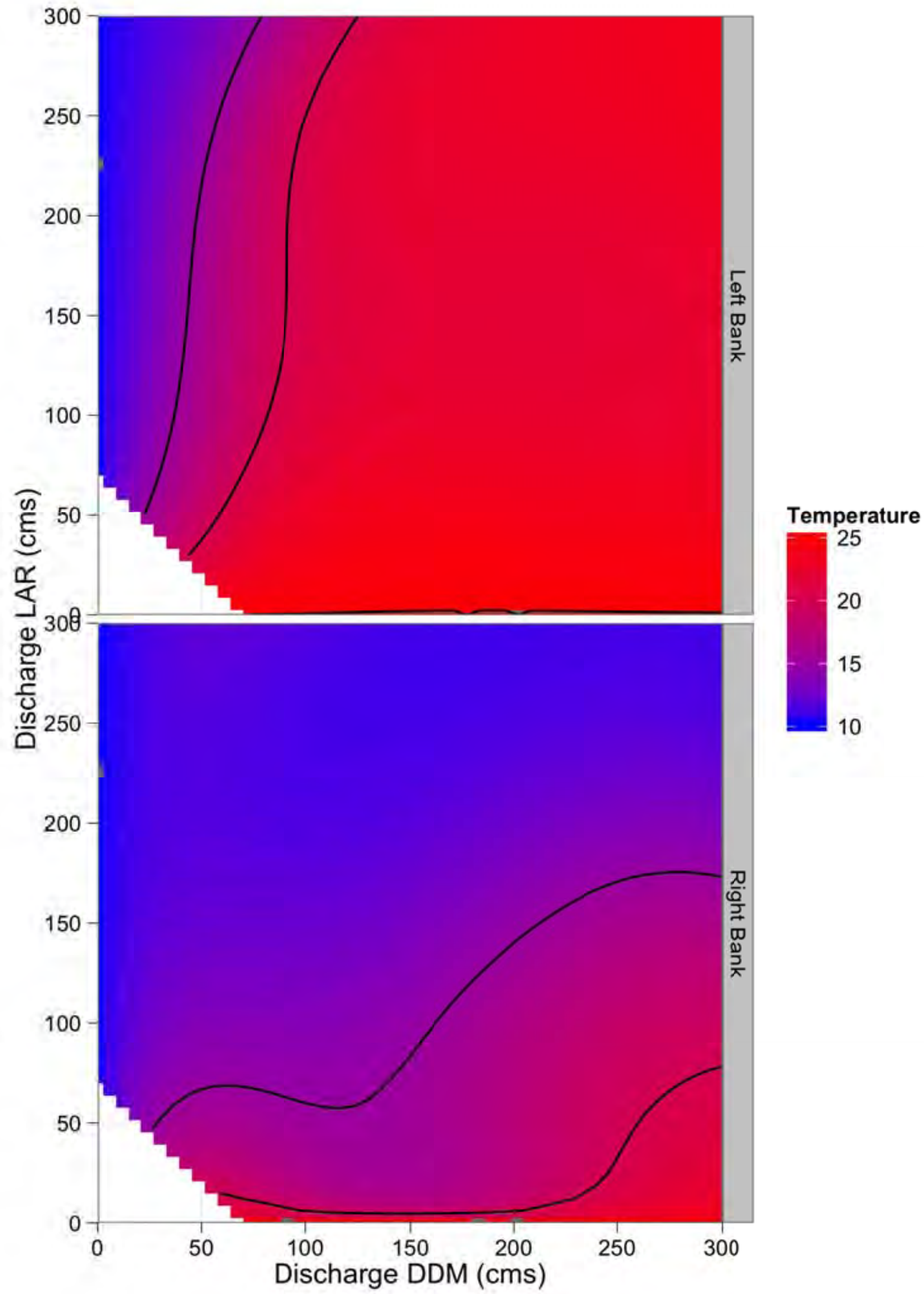

Figure 23: Mixing model for total Duncan Dam (DDM) and Lardeau River discharge with one hundred percent mixing set to equal 1.0 and zero percent mixing to equal zero with input from DDM set at 25°C and from the Lardeau at 10°C. Contour lines show the transition between levels of mixing.

4.0 DISCUSSION

The following discussion is structured in terms of the two management questions and three hypotheses for DDMMON-7. Findings presented herein may be used to determine adaptive strategies for water management at DDM.

4.1 Management Question 1

What is the relationship between water discharge through the DDM spillway and the production of TGP?

Discussion of Management Question 1 is provided in Appendix B.

4.1.1 Hypotheses 1

H1: Total gas pressure concentrations in the Lower Duncan River are correlated to Duncan Dam spillway discharges

Answer: Supported (Fail to Reject)

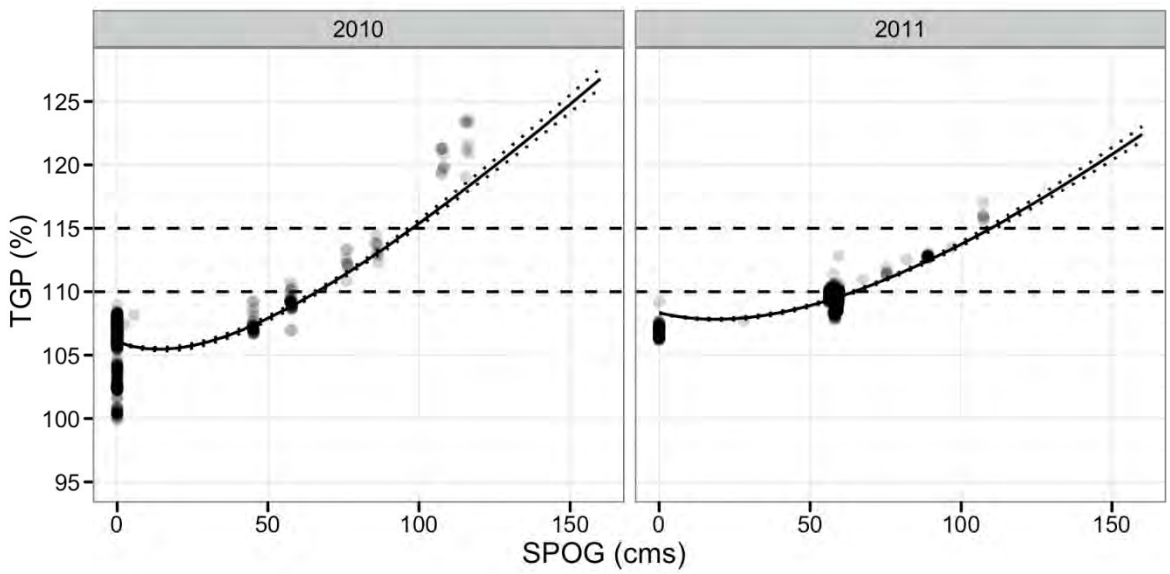

Figure 24: State space model output of the relationship between %TGP and SPOG discharge at sampling station 2.2L. Dashed lines represent federal (115%) and provincial (110%) TGP guidelines. Dotted lines around the model prediction line are 95% credibility intervals.

TGP data collected in 2010 and 2011 support the hypothesis that TGP levels in the LDR are correlated with DDM spillway discharges. TGP levels rise above background levels at locations along the left downstream bank during SPOG use. However, TGP levels along the right downstream bank remain similar to background levels during SPOG use likely as this bank is dominated by inflows from the Lardeau River rather than water discharged by DDM. Based on spot TGP measurements collected across the river every 2 km on August 18, 2011, it would be conservative to assume that the influence of spillway TGP is dissipated and mixed with Lardeau River and LLOG discharge by river Km 5.4 at the discharge conditions sampled.

Spillway operations modeled in relation to %TGP for the two years of data showed that the provincial water quality guideline of 110% TGP is exceeded when spillway outflows are greater than 60 m^3/s (Figure 24). The next benchmark for guidelines is 115% which is the DFO level that cannot be exceeded for 4-5 days and the discharge level at which the SPOG outflows intersects this line varies somewhat from year to year based on the slope of the relationship between SPOG and %TGP. In 2010, SPOG flow of 100 m^3/s corresponded to the 115% TGP guideline, whereas in 2011 this flow value was slightly higher at 110 m^3/s.

Low level outlet gate (LLOG) discharge did not result in TGP concentrations exceeding any guidelines during the TGP monitoring period. It was predicted that the BC provincial guidelines of 110% TGP could be exceeded in the tailrace area due to LLOG operations when discharge from the low level outlet gates reaches or is greater than 225 m^3/s. During the May-September period, this level of discharge from the LLOGs is very unlikely given the constraints of the bull trout transfer program.

4.2 Management Question 2

How does the operation of the DDM low-level gates and the spillway affect the water temperature regime in the LDR?

There are two broad ways in which DDM operations can affect water temperatures. The first is to increase or decrease the hourly variability in water temperature and the second is to change the overall mean hourly water temperature level to make it warmer or colder than the Lardeau River, which has been used to represent the conditions in a natural system. Both types of change can be observed in the water temperature data collected between 2010 and 2012 for this program. These types of change can result from either LLOG operation or SPOG operation though the use of the spill gates is far less frequent than the use of the low-level outlet gates. In discussing these effects, comparisons have been made to both the Duncan Reservoir and Lardeau River. The thermal regime of the Duncan Reservoir is discussed as it plays a role in determining how various DDM operations influence water temperature in the LDR, while the Lardeau River is discussed as it is the largest tributary to the LDR and presumed to be roughly similar to the thermal regime of the LDR prior to impoundment and flow regulation.

The patterns observed in water temperature fluctuation downstream of DDM points to the complex relationship between reservoir elevation, discharge from each of the gate types (LLOG and SPOG) as well as the mixing that occurs with inflows from the Lardeau River and other tributaries further downstream such as Meadow, Cooper and Hamill creeks.

4.2.1 Low-Level Gates (LLOGs)

The temperature of the water that is drawn through the LLOGs varies according to reservoir surface elevation and extent of thermal stratification. Water released from the LLOGs is predominantly most similar to the forebay water from depths below the thermocline (10 to 25 m as measured from the surface) during time periods when the Duncan Reservoir is stratified (July through October). During spill gate use in August 2010, the temperature of water discharged through the LLOGs was most alike that found at depths between 19 and 25 m where water was at times up to 10°C cooler than the surface.

In general, during the high LLOG flow months in early fall and winter, mean hourly water temperatures differed in the LDR compared to the Lardeau River and daily variability in water temperature in the LDR was quite low. When LLOG flows were reduced in October and early March, water temperature variability increased and was similar to the daily variability observed in the Lardeau River.

Changes to the LDR temperature regime resulting from variation in LLOG discharge (as displayed in Figure 7) from March 2011 to May 2012 are discussed below in terms of step changes in discharges and compared observations in 2010 (Lawrence et al. 2011):

- <u>March to June 2011 (Low to Moderate LLOG discharge)</u>: Mean hourly water temperature throughout the LDR gradually increased from seasonal lows of approximately 2°C to 14°C during this period. In April, water temperatures at some of the LDR stations varied by up to 10°C daily at a given location for a short period of time. This corresponded to a period of low discharge (~50 cms at DRL), the lowest observed during the study period, and the variable temperatures observed may have resulted from diel warming patterns in shallow locations. In comparison, the Lardeau River exhibited the same gradual warming trend with mean hourly water temperatures that ranged between 0 to 3°C in March and up to to 12°C in June. Daily variability in water temperature was similar between the LDR and Lardeau River at this time, except for locations in the DDM tailrace where minimal variability was observed. Water temperature in the DDM tailrace (DCL, 0.4R and 0.5L) was elevated above what was observed in the Lardeau River between April and June by up to 7°C. This led to a slight left/right bank temperature differential which was observed at the nearest station downstream (S2.7L), though this was not observed further downstream. The mixing model predicted variable levels (20-100%) of mixing during this period of low DDM and low to moderate Lardeau River discharges. Mixing levels during periods of low Lardeau River discharge are more influenced by small changes in DDM discharge than during moderate to high Lardeau River discharge.

  The patterns observed between March and May 2012 were similar to 2011. The water temperature differential between the DDM tailrace and the Lardeau River was greater in 2012 (up to 10°C warmer water in the tailrace) and this again persisted to the nearest downstream monitoring location (S2.7L).

- <u>Early June to middle of July 2011 (Low LLOG discharge):</u> During freshet, all locations monitored in the LDR downstream of the Lardeau River were similar to what was measured in the Lardeau River at this time. Typical temperatures were between 8 and 13°C. Exceptions were observed at stations located in the DDM tailrace that were not backflooded by high Lardeau River water levels (DCL and 0.4R), which were warmer than the Lardeau River at the beginning of this period and then cooler at the end. The mixing model predicted full mixing (80-100%) during this period of negligible DDM discharge and high Lardeau River discharges.

  This period of low LLOG flow was much shorter than that observed in 2010, though temperatures patterns were similar. In addition, Lardeau River discharge during freshet was nearly twice that observed in 2010.

- Late July to October 1, 2011 (High LLOG discharge): Differences between the left and right banks of the LDR were observed for mean hourly variability in water temperatures during this period. Water temperature was higher along the right than left bank during the month of August, but this temperature dichotomy was related to operation of the spill gates and is discussed in Section 4.2.2. In the LDR, mean hourly water temperatures along the left downstream bank decreased and very little daily variability was observed when spill gates were not in use between late July and October. This trend was evident at upstream stations only (0.5L and S2.7L) and water temperatures were similar on the left and right bank at stations further downstream (e.g.,. 6.3R and 7.0R). In contrast, mean hourly water temperature measured along the right bank at Km 2.4R remained similar to that of the Lardeau River (though about 1°C cooler), which exhibited a general cooling trend during this period with more hourly variability compared to the left bank of the LDR. Spot measurements taken during spillway use in August suggested the location of complete mixing between DDM and Lardeau River waters varied with respective discharge. The mixing model also suggested low to moderate mixing (0-40%) when both DDM and Lardeau River discharge was high (as was the case July through August) and that mixing remained moderate (20-40%) when both DDM and Lardeau River discharge dropped to a moderate level (as it did through September).
- October 2 to late December 2011 (Low to Moderate LLOG discharge): During this period, mean hourly water temperatures in the LDR steadily declined from approximately 12°C to 5°C. The temperature of the Lardeau River was also decreasing, though more rapidly, during this period and lows of near 0°C were recorded by the end of December. Throughout this period, water temperatures were observed to be warmer and less variable in the LDR compared to the Lardeau River. For example, mean hourly water temperatures in the LDR discharge channel gradually decreased to about 5°C in December, while mean hourly water temperatures in the Lardeau River dropped to near freezing at this time. The mixing model predicted a moderate level (20-80%) of mixing during this period of low DDM and low to moderate Lardeau River discharge. This time period consisted of a discharge and temperature regime similar to the March to June 2011 (though water temperatures were increasing instead of decreasing at that time) and the pattern of warmer and less variable temperatures in the LDR compared with the Lardeau River were similar between these two seasons.

  In 2010, the LDR was warmer than the Lardeau River only at locations upstream of the confluence of the two rivers and variability downstream of the confluence followed a pattern similar to the Lardeau River; Lardeau River discharge was higher during this period in 2010, which may have caused this yearly difference.
- Late December 2011 to March 2012 (High LLOG discharge): Mean hourly water temperatures in the LDR at all locations were higher than that observed in the Lardeau River during the first half of this period of high LLOG discharge; values converged with those observed in the Lardeau River in late February. In addition, water temperatures closely followed the subtle cooling trend observed in the Duncan Reservoir from 5°C in late December to 2°C by March. Mean hourly water temperatures were observed to be similar on the left and right banks of the LDR with very little daily variability. The

exception to this was the right bank station at 2.4R which showed slightly higher daily variability than the nearest left bank station (S2.7L) suggesting some influence of the Lardeau River though this trend was absent further downstream a 6.3R where no daily variation was observed. The mixing model predicted that at the high DDM and lmoderate Lardeau River discharge values there was approximately 20% mixing.

The trend was similar in 2010 and 2011, though locations downstream of the Lardeau River showed more daily variability along the right bank than the left during this period suggesting a slightly greater influence of the Lardeau River.

4.2.2 Spillway Gates (SPOGs)

DDM spillway gates (SPOGs) have been used in various seasons since the instatement of WUP flows but are usually operational for greater durations during the summer months when the Duncan Reservoir is at full pool and completely stratified. Water released from the reservoir via the SPOGs has a water temperature that is most similar to the forebay water at depths between 0 and 15 m as measured from the water surface. In 2010, when the full range of forebay temperatures were monitored for the entire spill period, water in the spillway was most alike the forebay water at 7 m depth until the end of the spill period when water temperature was similar to that found at a greater range of depths of up to 12 m. There are a number of factors which may have deepened the thermocline at this time including warmer climatic conditions heating the surface water or hydrologic forces within the reservoir redistributing the warmer water entering the SPOGs. Whatever the reason for this change, the SPOGs continued to release warm surface water which led to water elevated by approximately 6°C above water temperatures observed within DDM tailrace areas downstream of the spillway plunge pool. Water temperatures remained elevated above those observed before and after spill gate use (background levels) at all stations along the left bank as far as Km 10.8, though the effect was less substantial than at upstream stations (2-3°C).

SPOGs were in operation from July 29 to August 25, 2011. As in 2010, release of water via the SPOGs resulted in left/right bank thermal differences in the LDR with water temperatures along the left bank being warmer than those along the right. Water temperature was elevated by approximately 3-4°C above those observed at S2.7L on the left downstream bank for the duration of SPOG use. The warming effect during SPOG use damped out fairly quickly along the left bank with very limited increases in temperature at river Km 7.0L and 10.8L. Water temperature along the right bank (at DRL and river Km 2.4) remained similar to the Lardeau River for the duration of SPOG use over the temperatures and discharges monitored. However, at river Km 6.3R, water temperature patterns were very similar to what was recorded at Km 7.0L. These locations were likely influenced by Meadow and Hamill creeks and the variance from what was observed upstream indicates greater, nearly complete mixing of SPOG, LLOG and Lardeau River at this point. Additional spot measurements collected on the left and right bank during SPOG use indicated that left/right bank temperature differentials were present at downstream locations under certain discharge conditions (i.e., 2°C warmer on the left than right banks at river Kms 2.2 and 7.0 on August 5, 2011 when SPOG discharge was 108 m^3/s) though this effect was muted or absent under other discharge conditions (i.e., very limited temperature difference which did not persist past river Km 3.5 on August 18, 2011 when SPOG discharge was 58 m^3/s). This information is provided based on direct field measurements. The modeling effort cannot predict the level of mixing by discharge as a function of downstream location and it only predicts mixing at Km 2.55 in relation to discharge.

In August 2010, SPOG testing operations resulted in rapid elevation of water temperature along the left bank of the LDR from the spill channel to the furthest downstream monitoring location and exceeded the accepted ±1°C with respect to hourly rate of change in water temperature (BC Water Quality Guidelines 2001). This trend was not observed at the onset of SPOG operation in 2011, which was a 'normal' spillway gate operation as compared to the 5-day testing that occurred in 2010. In 2011, SPOGs were opened less at the onset of use (30 m^3/s then 60 m^3/s) than they had been in 2010 (116 m^3/s). In addition, Lardeau River discharges were higher than what were observed during spillway operation in 2010.

In 2010, the release of water from the surface of the Duncan Reservoir during spillway testing elevated downstream water temperatures along the left bank as far downstream as Km 10.8 above 15°C, which is the maximum temperature recommended in rivers with bull trout present. In 2011, however, this elevation above 15°C was only observed in the two tailrace stations (0.4R and 0.5L) immediately downstream of the spillway plunge pool and upstream of the Lardeau River; all downstream locations did not exceed this guideline.

The mixing model, which considered overall DDM discharge, highlighted the influence of Lardeau River discharge on the extent that SPOG water is mixed through the LDR at Km 2.55 only. During periods of high DDM discharge (such as during the spill period), the level of mixing can be low (20-40%) when Lardeau River discharge is low as was observed in 2010, or it can be greater (20-60%) with higher Lardeau River discharge as was observed in 2011. The mixing model reiterated that mitigation for the sometimes dramatic increases in downstream LDR water temperatures during SPOG operation can come from both water entering the system by the DDM LLOGs as well as the Lardeau River.

4.2.3 Influence of LDR Water Temperature on Fish

Some influences of water temperature on various fish species were summarized in AMEC (2010) and were focused on 5 key functional properties of temperature acting on fish, which include temperature as a: i) lethal agent; ii) stressing factor; iii) controlling/limiting factor; iv) directing agent; and, v) masking factor. Responses to sub-optimal water temperatures vary by fish species, age, condition and avoidance ability (AMEC 2010). McCullough et al. (2009) indicated that studies on the influence of cumulative exposure to adverse high temperatures have demonstrated that accumulated stress from consecutive thermal cycles resulted in mortality. Diel fluctuations and localized cold water refuges may provide respite from elevated daily maximum temperatures if there is sufficient time to repair protein damage resulting from exposure (McCullough et al. 2009). Studies on salmonids have demonstrated an avoidance reaction to high temperatures by seeking deep pools, ground water, cooler tributaries and headwater reaches (Oliver and Fidler 2001).

The differences in temperature observed between the two banks of the LDR during elevated water temperatures resulting from spillway use suggest that at certain times and discharge levels, fish have a potential refuge from intolerable temperatures by moving toward the Lardeau-influenced right bank, or alternatively when Lardeau River water temperatures reach seasonal highs the left bank of the LDR is dominated by cooler hypolimnetic reservoir water providing the same potential as a refuge. However, during fall/winter, the influence of the Lardeau River is minimal due to low flows and warmer water from the reservoir keeps the LDR elevated above what has been observed in the Lardeau River (see implications on target species below).

It appears that an important issue for acute fish health in the LDR is the rapid increase in temperature observed as a result of initial spillway use. Research indicates that stress from temperature changes (both increases and decreases) can induce selective predation on stressed fish to lose swimming function and predator perception as well as confuse the spawning periods of various fish species (AMEC 2010). However, if discharge is limited (i.e., to 30 or 60 m^3/s) at the onset of SPOG use, this potential stressor may not be observed. Directing spillway use away from the time periods when the reservoir's thermocline is well established may be an additional means of reducing the stressing influence of rapid temperature changes on fish in the LDR. Use of the SPOGs in October 2009 did not generate the same spikes in left bank water temperatures as measured by DDMMON-3 level loggers as those observed in 2010. However, there is limited practicality to this as use of the spill gates is more likely when the reservoir is at full pool and stratified.

The influence of the water temperature regime of the LDR system has been further discussed below for LDR target fish species of interest (BC Hydro 2005). These species include kokanee (*Onchorhynchus nerka*) studied under DDMMON-4 (AMEC 2012) LDR Kokanee Spawning Monitoring and rainbow trout (*Onchorhynchus mykiss*) and mountain whitefish (*Prosopium williamsoni*) both studied under DDMMON-2 LDR Habitat Use Monitoring (Thorley et al. 2011).

4.2.3.1 Kokanee

The influence of the water temperature regime on kokanee may affect the abundance of spawners present, spawning distribution, as well as timing of peak spawning and fry emergence in the LDR. These are discussed further below.

Studies on salmonids have demonstrated an avoidance reaction to high water temperatures by seeking deep pools, ground water, cooler tributaries and headwater reaches (as cited in Oliver and Fidler 2001). This may be one reason the abundnace of kokanee spawning in the Duncan River system is lower in the LDR (3%) compared to Meadow Creek (66%) and the Lardeau River (32%; AMEC 2012) because spawners may be seeking out cooler water that has been observed in the other systems at this time. Additional reasons for differences in abundance between the three systems may also be the quality of spawning habitat available (AMEC 2012).

Kokanee have been observed spawning in LDR side channels earlier than LDR mainstem habitats likely because they are seeking out low velocity, cooler (shaded) areas to minimize energy expenditure as has been observed for kokanee in Meadow Creek (Morbey and Ydenberg 2003). In addition, the distribution of kokanee spawners may be influenced by discharge (and associated water temperatures that result) as a higher proportion of kokanee are observed on the right bank after discharge is reduced in late September during kokanee spawning protection flows (Appendix D, AMEC 2012). The right bank is likely influenced by Lardeau River flows and may generally be cooler compared to the left bank, thus kokanee spawners may be actively seeking out areas of cooler water for spawning.

Although, spawn run timing in the LDR, Meadow Creek and the Lardeau River was found to be similar and occurred from late August to late October (AMEC 2012), preliminary trends based on four years of study suggest that peak spawning may be influenced by water temperatures with kokanee spawning later when early September temperatures are warmer (Appendix D). Oliver and Fidler (2001) indicated that sockeye salmon, a close relative of kokanee, spawn between 10.6°C and 12.8°C. Water temperatures in the LDR during the peak kokanee spawning period (September 23 to October 13) have been, at times, observed over these preferred temperatures during the four year enumeration period (AMEC 2012, Appendix D).

Egg incubation, embryonic development, and fry emergence timing are dependent on water temperature (i.e., ATUs), which are influenced by DDM operations (AMEC 2012). Fry emergence was approximately 3 months earlier in the LDR than that estimated for the Lardeau River and Meadow Creek (AMEC 2012)[1]. For example, LDR water temperatures from October 2010 through January 2011 were higher than those measured in the Lardeau River during this time period. This may explain earlier fry emergence timing estimated for the LDR, since warmer water temperatures would promote faster egg development, earlier hatch times, more rapid alevin development and yolk sac absorption, which would lead to earlier emergence of fry. It is unknown whether early emerging fry are at a disadvantage compared to fry that emerge later. A temporary disadvantage for early emerging fry has been observed within the hatchery environment with embryos noted as being 'weaker' and having a larger yolk sac in relation to their body size compared to embryos that hatch later (Becker et al. 1983). However, early emerging sockeye salmon fry were not observed to be at a disadvantage when entering Lake Washington (WA) up to three months earlier than peak abundance of their preferred prey because they were able to feed on other prey available at that time (Beauchamp et al. 2004). Survival of early emerging fry from the LDR may be dependent on predation and food availability in Kootenay Lake. It is unknown at this time whether LDR fry entering Kootenay Lake in late winter would have adequate food resources for growth and survival because zooplankton sampling has not been conducted during this period (E. Schindler, Limnologist, Ministry of Environment, pers. comm., 2012).

Dewatering of kokanee spawning habitats may also cause increased water temperatures to occur in isolated pools where kokanee redds are present, but it is unknown at this time what proportion of egg mortality occurs in areas that remain wetted that are cut-off from the mainstem during lowered October LDR flows (AMEC 2012). Upper water temperature tolerances allowing >50% egg survival for sockeye are 15.5°C (Oliver and Fidler 2001). Water temperatures above this thermal tolerance have been observed infrequently during the kokanee spawning period in the LDR in 2009, 2010 and 2011 (Appendix D), but it is unknown whether these brief temperature increases are experienced by embryos buried in redds and if they are affected by them (AMEC 2012).

4.2.3.2 Rainbow Trout

Changes to water temperatures in the LDR related to DDM operations may affect the rainbow trout population by potentially impacting egg survival during periods of flow reduction and

[1] Although DRL water temperatures were used to calculate emergence timing for kokanee and errors have been associated with this station (see above), incubation studies conducted during one cohort year confirmed that emergence timing was earlier than that compared to the other systems (AMEC 2012).

dewatering in the DDM tailout spawning area (Thorley and Baxter 2011), but other life history components were not outside optimal preferences. Further discussion is provided below.

Rainbow trout have been observed spawning in the tailout area of the DDM discharge channel from mid-March to mid-May (Thorley and Baxter 2011). Water temperatures during the spawning period did not differ from the Lardeau River by more than 1°C until mid- to late April (Thorley and Baxter 2001) nor did water temperatures increase above the optimal spawning temperature of 20°C (Oliver and Fidler 2001) during this period. Thorley and Baxter (2011) indicated that early arriving fish were staging and spawning in the tailout area for reasons other than water temperature, but these additional reasons were not provided.

Redd dewatering observed during DDM operations during the bull trout transfer period in April/May caused surface water temperatures to exceed 15°C in the spawning area on several occasions in two of the past three years (Thorley and Baxter 2011). Preliminary studies demonstrated that low egg survival may be caused by low water velocity, fine sediment intrusion and warm water temperatures, which could contribute to low dissolved oxygen levels and egg mortality (Thorley and Baxter 2011). Oliver and Fidler (2001) indicated that 0% egg survival occurs for rainbow trout at water temperatures exceeding 18.5°C or below 3°C, but these water temperatures were not observed during the spawning period at the tailrace spawning area (Figure 17). However, temperatures did exceed those optimal for rainbow trout egg incubation (12°C) in the DDM tailrace spawning area for extended periods in 2009 and 2010 and sporadically in 2011 during the incubation period.

Emergence was estimated to be completed by the end of June in the LDR (Thorley and Baxter 2011). It is not known at this time how this timing compares with the Lardeau River (J. Thorley, Fish Biologist, Poisson Consulting Ltd., pers. comm., 2012). Information on rainbow trout emergence timing compared to the Lardeau River will be provided under DDMMON-2 (Poisson et al. In prep). The rate of temperature change measured in the upper LDR (e.g., 0.5L) during the end of the rainbow trout incubation period (June) was observed to exceed the BC Water Quality guidelines for rate of water temperature change from 2009-2011 when DDM discharge is near zero with sporadic, short duration increases; it is not known whether this affected egg/fry development and emergence timing.

The LDR was observed to have optimal growth temperatures for juvenile rainbow trout during most of the growing season (10-14°C; Oliver and Fidler 2001), but water temperatures were observed between 15°C and 20°C during the July-August spill periods in 2010 and 2011 in the upper portions of the LDR. However, other areas of the LDR such as areas more influenced by the Lardeau River (right bank), tributary confluences and the Lardeau River itself would have provided cooler refuge areas for rearing fish to move into at these times. Upper incipient lethal temperatures for juvenile rainbow trout (24.0-29.4°C; Oliver and Fidler 2001) were not observed to occur throughout the LDR during this study program; water temperatures did not exceed 20°C within the study area other than at the reservoir surface during summer.

4.2.3.3 Mountain Whitefish

Water temperatures in the LDR may affect mountain whitefish spawn and emergence timing in the LDR, since water temperatures were observed to be higher than optimal at the commencement of the spawning and incubation period.

The following are observations for mountain whitefish with respect to water temperature that have been reported in the literature: i) selected summer temperatures for adult mountain whitefish range from 11 to 20ºC; ii) most reported spawning temperatures are below 5 - 6ºC (Brown 1952; Thompson and Davies 1976); iii) optimal egg incubation temperatures are 4-6ºC (Rajagopal 1979; Brinkman and Vieira 2009); and, iv) optimum temperatures for growth of early juvenile MW range from 9 to 12ºC (Stalnaker and Gresswell 1974). Later stage juveniles have been sampled in habitat with temperatures ranging from 12.2 - 20.6ºC (Mullan 1976).

In the lower Duncan River, water temperatures at the start of the spawning period (October) were approximately 10ºC and maintained an average temperature higher than the optimum of 6ºC until the first week of December (near the end of spawning). These temperatures are overly warm for the most successful fertilization and complete incubation of the eggs possible (Rajgopal 1979; Brinkman and Veira 2009). Later spawners may have an advantage over early spawners with respect to egg survival due to water temperature. Based on water temperature data from the period of record, water in the fall is slightly warmer in the post-WUP years than prior to the ordering of the WUP flows (more variability in LLOG discharge prior to WUP flows) though there are few years of data on which to base this observation at this time. However, water temperature within the LDR during the egg incubation period was observed to be within the tolerance temperatures reported for mountain whitefish (0-12°C; Oliver and Fidler 2001).

Fry emergence of eggs spawned in the early warm period was estimated to occur in early January, based on water temperatures observed in autumn (Poisson, AMEC and Mountain Waters et al. 2012) with emergence of late spawners occurring until early May with peak emergence in March and April. Optimal temperatures for early juvenile mountain whitefish growth were not usually observed in the LDR until May creating a potential disadvantage to the eggs that are spawned early in the LDR (Figure 17). Further information on spawn timing and emergence will be provided under DDMMON-2 (Poisson et al. In prep).

4.3 Hypotheses 2

H2: Temperature in the Lower Duncan River supports the productivity of fish species of interest.

<u>Answer</u>: Inconclusive

The following is based on the definition that productivity represents the maximum growth of organisms under optimal conditions (Wetzel 2001 as cited in Randall 2003), with optimal conditions describing the habitat or ecosystem (in this case water temperature of the LDR). However, this measure of productivity is difficult to measure even after extensive investigation and fish biologists usually define productivity as the maximum survival rate of a population of fish based on recruitment and spawners (e.g., Randall 2003, Chilcote 2004). Productivity of a fish species is inherently related to its life history strategy, but productivity can also vary with populations over time because of changes in environmental conditions (Randall 2003).

The LDR generally provides environmental conditions to support the productivity of fish species of interest, since target species have been observed performing different life history functions during many years of study (e.g., Thorley et al. 2011, AMEC 2012). Although the present study did not directly measure fish productivity, several complimentary studies conducted in the LDR have determined that some critical life history periods may be negatively influenced by environmental parameters experienced within the LDR as discussed in Section 4.2.3. Therefore, because some life history stages may be affected by water temperatures in the LDR, while others do not seem to fall outside 'optimal' conditions, it cannot be definitively concluded at this time whether water temperature in the LDR completely supports (or fails to support) the productivity of fish species of interest.

4.4 Hypotheses 3

H3: Temperatures in the Lower Duncan River are correlated to Duncan Dam operations

Answer: Supported (Fail to Reject)

Water temperature monitoring in the LDR, Duncan Reservoir and Lardeau River between 2010 and 2012 supports the hypothesis that that there was a correlation between temperature in the LDR and DDM operations. There are two broad ways in which DDM operations can affect water temperature. The first is to increase or decrease the hourly variability in water temperature and the second is to change the overall mean hourly water temperature level to make it warmer or colder compared with natural conditions as measured in the Lardeau River.

The following two examples support this hypothesis:

- High LLOG discharge during the winter (November to March) resulted in similar water temperatures in the LDR and Duncan Reservoir. The trends in water temperature at this time follow those measured in the DDM discharge channel rather than those measured in the Lardeau River.
- SPOG use released epilimnetic water from the Duncan Reservoir between July and October. This operation resulted in water temperature increases at locations along the left downstream bank. In 2010, this was observed as far downstream as river Km 10.8 (though moderated by flow mixing compared with upstream locations), while in 2011, when Lardeau River discharge was higher during the spill period, this was observed until approximately river Km 3.5

The influence of DDM operations on water temperature was observed predominantly along the left downstream bank of the LDR possibly to about 5 km downstream from DDM, while the water temperature regime along the right downstream bank was more similar to that observed in the Lardeau River depending on the relative discharge levels of the tributary and DDM operations. The exception to this is during periods of low Lardeau River discharge and high DDM discharge (generally December to May) when water temperatures throughout the LDR were similar on both river banks and variation due to climatic conditions was reduced as well as during periods of low DDM discharge and high Lardeau discharge during freshet (June-July) when water temperatures in the LDR downstream of the Lardeau are similar.

5.0 RECOMMENDATIONS

1. Restrict spillway flows to less than 60 m^3/s if the more conservative provincial TGP guidelines are to be followed (110%), and if the DFO guidelines of 115% TGP are followed, a spillway limit of 100 m^3/s would be required based on the two years of data collected during the present program. See Appendix B for further details.

2. Collect spot TGP measurements during spill events in the DDM forebay, discharge channel, spillway channel, in the LDR at river Kms 2.2 and 7.0 on the left and right banks and in the Lardeau River. These measurements can confirm the validity of the model developed from the two years of modeling data. Additionally, it is unclear if repairs and upgrades to the DDM spillway gates in 2011/2012 will change the TGP patterns observed during the 2010/2011 monitoring period and further reiterates the requirement for TGP monitoring during spill events.
3. At the onset of SPOG use, gradually open SPOGs to reach the desired discharge through the spillway. Stepped discharge increases will limit rapid increases in water temperature which can negatively impact fish.
4. Consider an alternative source of water temperature data than that available from DRL (WSC No. 08NH118). Water temperatures collected at DRL contained a number of erroneous and unexplained readings throughout the monitoring period. Additionally, the influence of DDM operations was predominantly observed at left bank locations in the LDR where real-time and continuous water temperatures are not collected.
5. Consider modifying the DDM Local Operating Orders (LOO) and General Operating Orders (GOO) to incorporate temperature, TGP and discharge predictions from the models to minimize impact on the LDR with regards to these variables.

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APPENDIX A
Site Location Descriptions and UTMs

LDR- DDM Discharge Channel- DCL

This site is located on the left downstream bank of the discharge channel, approximately 50 m upstream of the confluence with the spillway channel. Location included continuous water temperature monitoring from May 2010 to May 2012 and seasonal continuous total gas pressure (TGP) monitoring from July to October 2010. TGP spot measurements were also collected here in August 2011. This monitoring location was specified in the BC Hydro TOR, was similar to that used to collected water temperature data from the discharge channel in 2009 and TGP spot measurements in the mid 90s (AMEC 2010).

LDR- Spillway Channel- 0.4R

This site is located on the right downstream bank of the spillway channel approximately 50 m upstream of the confluence with the DDM discharge channel. Location included continuous water temperature monitoring from May 2010 to May 2012. Seasonal continuous TGP monitoring occurred here from July to October 2010 though this data was not included in TGP analyses due to equipment malfunctions (AMEC 2011). TGP Spot measurements were taken here between July and October 2010 and in August 2011. This location was selected to capture water temperature and TGP changes that may occur during use of the SPOG's. Discrete TGP measurements have been taken below the spillway gates sporadically in 1976, 1996, 2000, and 2009 (AMEC 2010). This location was selected due to easy access to the spillway, proximity to discharge channel location and to minimize any damage to equipment during spill events.

LDR- Tailrace- 0.5L

This site is at river km 0.5 on a mid-channel island located along the left bank across from the DDM tailrace boat launch. Location included continuous water temperature monitoring from May 2010 to May 2012. This location was previously used in 2009 to collect water temperature data at the only known Gerrard rainbow trout spawning area in the LDR, which is directly influenced by DDM operations and at times by back flooding of the Lardeau River. In 2010, temperature monitoring began in March at the beginning of the rainbow trout spawning period.

LDR- DRL- 2.2R

Water temperatures are currently monitored by the Water Survey Canada (WSC) staff gauge (WSC No: 08NH118) located at river km 2.2 on the right bank and data has been collected continuously at 1 hr intervals since 2003. Spot TGP measurements were collected at this location between July and October 2010 and in August 2011.

LDR- 2.2L

This site is located at river km 2.2 on the left bank, just downstream of the concrete blocks and overhead pulley associated with the WSC station. Location included continuous water temperature and TGP monitoring from July to October 2010 and during August 2011. BC Hydro monitored TGP levels continuously during spill events in 2002, 2003, and 2004 near this location and discrete measurements were also taken in 2000, 2002, and 2009. This site provided a downstream location where outputs from the LLOG's, SPOG's and possibly the Lardeau River have mixed.

LDR- 2.4R

This site is located at river km 2.4 on the right bank, about 200 m downstream of the WSC station. Location included continuous water temperature monitoring from October 2009 to May 2012. Water temperature monitoring commenced at this location in October 2009 in association with kokanee spawning studies (DDMMON-4).

LDR- Sidechannel 2.7L- S2.7L

This site is located midstream in sidechannel 2.7L, approximately 60 m downstream of the log jam at the inlet to the sidechannel. Location included continuous water temperature monitoring from May 2010 to May 2012.

LDR- 6.3R

This site is located between Hamill and Cooper creeks and was added as a continuous temperature monitoring location from May 2011 to May 2012. The site was added in Year 2 to better clarify left/right bank thermal regimes.

LDR- Argenta Bridge- 7.0L

This site is located just downstream of the Argenta Bridge at river km 7.0 on the left bank. Location included continuous water temperature monitoring from May 2010 to May 2012 and spot TGP measurements from July to October 2010 and in August 2011. Water temperature was continuously monitored from 2003 to 2004 by BC Hydro near this location.

LDR- Sidechannel 8.2L- S8.2L

This site is located midstream in sidechannel 8.2L, 300 m downstream of inlet. Location included continuous water temperature monitoring which began in October 2009 during DDMMON-4 kokanee spawning surveys and ended in May 2011. The location is situated in the thalwag of the sidechannel in a location which was not anticipated to dewater.

LDR- 10.8L

This site is located at river km 10.8 on the left bank just downstream of the outlet of sidechannel 8.2L. This location represents the most downstream continuous temperature monitoring location from May 2010 to May 2012; no suitable locations were found in the remaining 1.5 km of the LDR as the river banks were too unstable to install a monitoring station. This location was also accessible by foot and spot TGP measurements were collected here during spill events in August 2010 and August 2011.

Duncan Reservoir- Forebay- FB1M, FB5M, FB10M, FB15M, FB20M, FB25M

An array of temperature loggers was installed from May to July 2010 on a portable log boom approximately 200 m upstream of the LLOGs in the Duncan Reservoir forebay, then relocated to the forebay booms immediately in front of the LLOGs on 20 July 2010 where it remained for the rest of the monitoring period. Continuous water temperature monitoring occurred in the forebay at depths of 1 m, 5 m, 10 m, 15 m, 20 m and 25 m, measured from the surface downward. However, depending on current forebay water level elevations, some of these loggers were removed or data not included in analysis as the loggers may have been located on the bottom of the reservoir, especially during low pool. As a result, continuous water temperature records are available at 1 and 5 meters depth from May 2010 to May 2012 while those for deeper depths are available for the July to November period in those years. Water temperature was recorded for a one month period at this location in 2002.

Duncan Reservoir- Across from Howser- HO1M, HO13M

An additional temperature logger array was installed from May 2010 to May 2011 across from the Howser boat launch, in what was the original Duncan Lake basin prior to impoundment. Loggers were located at two depths; 1 m and 13 m from the bottom of the reservoir. The logger at 13 m is at the same elevation as the sill of the LLOGs.

Lardeau River- Lardeau Bridge- LarBr

This site is located approximately 75 m downstream of the DDM access bridge on the left bank of the Lardeau River. A thermologger was installed directly under the bridge for the duration of Gerrard rainbow trout spawning surveys in 2009 and 2010, then relocated to the downstream location in September 2010 as backup to the logger installed there the previous May. This site therefore includes continuous records from March 2010 to May 2012. The Lardeau is the largest tributary to the LDR and water temperatures have historically been collected by MOE at a site designated '50 km downstream of Gerrard'. Spot TGP measurements were also collected here between July and October 2010 and during August 2011.

Meadow Creek- MC

This site was located approximately 60 m upstream of the confluence of Meadow Creek (MC) and LDR sidechannel 4.1R on the left bank from May 2010 to May 2011. These loggers were relocated to a new location 225 m upstream on Hwy 31 Bridge over Meadow Creek where it logged data from May 2011 to May 2012. Location included continuous water temperature monitoring. Historically, MOE collects water temperature data in MC but downloads are not completed regularly and this location supplements their data when it is not available.

Air Temperature

Continuous air temperature was collected initially in the woods behind the BC Hydro staff house, then relocated to a treed area near the DDM tailrace boat launch on 18 August 2010. The logger was removed in August 2011 as BC Hydro had installed a monitoring station in the DDM tailrace which included air temperature monitoring capabilities.

Table A1. GPS coordinates of DDMMON-7 temperature and TGP continuous sampling locations

Waterbody	Location	UTM_Easting	UTM_Northing
Duncan Reservoir	DDM Forebay	503763	5567021
Duncan Reservoir	Howser	504668	5572334
Lower Duncan River	Spillway Channel (0.4R)	503458	5566059
Lower Duncan River	0.5L	503493	5565904
Lower Duncan River	2.2L	503270	5564447
Lower Duncan River	2.4R	503080	5564160
Lower Duncan River	6.3R	503223	5561159
Lower Duncan River	7.0L	503452	5560449
Lower Duncan River	10.8L	503452	5560449
Lower Duncan River	Discharge Channel (DCL)	503413	5566069
Lower Duncan River	Sidechannel 2.7L	503115	5563806
Lower Duncan River	Sidechannel 8.2L	504050	5559050
Lardeau River	Lardeau Bridge	502930	5566030
Meadow Creek (2010-11)	MC	502282	5561874
Meadow Creek (2011-12)	MC	501046	5564286
Air	DDM Tailrace Boat Launch	503363	5565862

APPENDIX B
DDMMON-7 TGP Memorandum Report April 10, 2012

DDMMON-7: Lower Duncan River Water Quality Monitoring

TGP Memorandum Report

April 10, 2012

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Introduction

The Duncan Dam Water Use Plan (DDM WUP) has an overarching goal of maximizing fish productivity in the lower Duncan River (LDR) within the operating constraints of Duncan Dam (DDM). Regulated discharges at DDM have been shown to impact fish species in the lower Duncan River (Porto *et al.* 2009; Irvine and Porto 2010; Thorley *et al.* 2010).

Use of the low level outlet gates (LLOG) or spillway operating gates (SPOG) may influence water quality through alterations in total dissolved gas pressure (TGP) and water temperature. Water temperatures may affect spawn timing or egg emergence timing and survival as well as other processes, while TGP can lead to the development of gas bubble trauma (GBT), which can cause effects ranging from reduced swimming ability to death (Weitkamp and Katz 1980).

At a meeting with the BC Hydro contract authority on October 29, 2011, it was requested that a memorandum be submitted by January 30, 2012 discussing the results of TGP monitoring and updated analyses for data collected in 2010 and 2011. This memorandum focuses particularly on the level, duration and spatial extent of TGP observed in the LDR under different operational regimes: i) gate testing conducted in 2010; and ii) actual operations that occurred in 2011. This information is related to provincial and federal regulations pertaining to %TGP in aquatic systems. In brief, the guidelines from the province state that TGP should be less than or equal to ΔP 76mm Hg (110% saturation at sea level) to prevent onset of gas bubble trauma (BC Ministry of Environment 2004) and DFO states that TGP saturation >115% can be harmful if maintained for 4-5 days. Levels of TGP greater than 130% can be lethal in a matter of hours (Weitkamp and Katz 1980). The full regulatory context for TGP is outlined in the DDMMON-7 information review (Porto and Lawrence 2010).

The intention of this memorandum is to supply information to allow the refinement of operating orders at DDM in order to minimize potential effects of TGP on fishes in the LDR.

Management Questions and Hypotheses

The primary management questions to be addressed by this program include (BC Hydro 2010):

1. What is the relationship between water discharge through the DDM spillway and the production of TGP?

2. How does the operation of the DDM low-level gates and the spillway affect the water temperature regime in the LDR?

In addition, the following hypotheses are to be tested (BC Hydro 2010):

H1: Total gas pressure concentrations in the LDR are correlated with DDM spillway discharges.

H2: Water temperature in the LDR supports the productivity of fish species of interest; and,

H3: Water temperature in the LDR is correlated with DDM operations.

This memo uses data from the DDMMON-7 2010 and 2011 field programs to provide answers and recommendations for management question 1 and hypothesis 1. Through discussions with the BC Hydro contract authority, management question 1 has been expanded to effectively read 'What is the relationship between discharge through DDM and the production of TGP?' so this memo includes the additional focus of modeling the effects of the low level outlet gate operations on the production of TGP as well as the effect of the spill gates on TGP production.

This memo therefore assesses the potential relationships between:

1) spill gate operations and TGP in the LDR;

2) low level outlet gate operations and TGP in the LDR; and,

3) the spatial extent of the influence of elevated TGP within the LDR.

The management questions and hypotheses concerning water temperature will be addressed in the final report to be submitted in June, 2012.

Methods

Data

TGP monitoring occurred during two field seasons, 2010 and 2011. During both of these years the DDM spillway was used to release water from the reservoir into the LDR during the summer months; this occurred from August 23 to 27, 2010 and July 29 to August 25, 2011. A TGP monitoring field program had not been scheduled for the 2011 potential spill period as the focus of the Year 2 of the program was refined to focus on the analysis and predictive outcomes of the relationships between TGP generation and the operations of DDM. Following the initiation of spillway use at the end of July 2011, TGP spot measurements were requested followed shortly thereafter by the installation of a continuous TGP monitoring station.

In 2010, continuous measurements of TGP were taken from July 7 until October 6 at three locations: 2.2L (river km 2.2 on the left downstream bank), DDM tailrace (also referred to as the DDM discharge channel or DCL) and 0.4R (DDM spillway channel) (Appendix 1). The TGP meter at 0.4R was excluded from the analysis as spot measurements showed it to be unreliable for measuring TGP. In 2011, continuous measurements of TGP were taken from August 8 until September 2 at site 2.2L. Water temperature was also recorded at each continuous TGP monitoring site.

In 2010, TGP spot measurements were also taken in conjunction with meter calibration (July/August) and during spill activities (August) (Lawrence *et al.* 2011). Spot measurements were taken from the DDM forebay to river km 10.8 in 2010. TGP spot measurements were also taken on August 5, 2011 during initiation of spill from several road accessible points ranging from the DDM forebay to river km 7.0. TGP spot measurements were taken from a boat on August 18, 2011 at left, right and mid-channel locations from the DDM forebay to river km 11.0 in order to determine the TGP dissipation pattern during a spill event. TGP spot measurements taken during calibration in both 2010 and 2011 in the spillway are the only TGP data for this area that are included within this analysis. Within all available TGP data, 11 spot measurements have been taken in the DDM forebay, with all data obtained at this station measured during the months of July, August or September. Historical continuous TGP measurements were obtained during the months of July-October inclusive in 2002, 2003 and 2004 (not all months had data in all years). These data were not used in the present analysis because data comparability was uncertain, and since historical data were all measured at one location (500m downstream of the Lardeau confluence) at river km 1.5, they were unable to be used to address the management questions assessing the spatial extent of the TGP effects in the LDR. Inter-annual variability appears high so comparing the data from these years to the other years to assess dissipation or spatial extent of TGP would be ineffective.

Discharge data from the low-level outlet gates and the spill gates were obtained from the BC Hydro DDM MS Access database that is populated with data obtained from BC Hydro's Power Records department. Discharge from the Lardeau River was estimated by subtracting the sum of discharge passing through DDM from the discharge recorded at the Water Survey of Canada gauge (08NH118) at river km 2.1 on the LDR, which is approximately one km downstream of the confluence of the LDR and Lardeau rivers. If the value was negative, a zero value for Lardeau River discharge was assumed.

The percent TGP was averaged hourly prior to analysis to reduce the autocorrelation inherent in time series data. The autocorrelation functions were plotted after averaging and there was still remnant positive autocorrelation. This was factored into the model design.

Percent TGP was also plotted to display the results versus regulatory thresholds as outlined in Porto & Lawrence (2010). Provincial guidelines state that TGP should not exceed 110%, whereas federal guidelines use 115% as the threshold that can harm fish if they are maintained for a period of 4 to 5 days. The federal guideline of 130% TGP (fish can be killed at this level within hours) is not included because values did not reach this level and the addition of the 130% line compressed the graphs so plotting details were obscured. The highest TGP recorded from continuous monitoring in the LDR was 124.1% on 23 August 2010 at 11:35h.

Analysis

Hourly discharge and TGP data were analyzed using a Bayesian state-space regression analysis. A state space analysis explicitly models underlying processes using observed data when the observed data does not directly measure the parameters of interest. A model is generated to represent how the processes work with the stated assumptions and is estimated by linking the observed data with the assumed processes to obtain estimates of the parameters of interest. Key assumptions of the Bayesian state-space regression analysis included:

- TGP increases linearly with discharge above 25 m^3/s;
- The TGP at DCL represents the TGP from the lower level outlet gates;
- The TGP at 2.2L represents the TGP on the left bank of the LDR;

- The TGP on the left bank of the LDR is proportional to the discharge and TGP from the lower level outlet and spill gates;
- The lag between a change in discharge at the lower level outlet or spill gates and a change in the TGP at 2.2L is less than one hour;
- The residual variation is adequately described by a normally distributed first-order autoregressive process with a coefficient of 0.4.

The analyses was performed using R 2.14.0 (R Development Core Team 2011) which interfaced with JAGS 3.1.0 (Plummer 2003) using the rjags library. BUGS distributions and functions as implemented in JAGS are defined in Table 1. The Bayesian state-space regression analysis assumed low information (Ntzoufras 2009) uniform prior distributions. The posterior distributions, which were estimated using Gibbs sampling (Ntzoufras 2009), were derived from 1,500 Markov Chain Monte Carlo (MCMC) simulations thinned from the second halves of three MCMC chains of $1 \text{x} 10^4$ iterations in length. Model convergence was confirmed by ensuring that R-hat (the Gelman-Rubin Brooks potential scale reduction factor) was less than 1.05 for each of the primary parameters in the analyses (Gelman and Rubin 1992; Brooks and Gelman 1998; Gelman *et al.* 2004). Model adequacy was checked through examination of the residuals. Throughout the report, plots were produced using the ggplot2 library (Wickham 2009).

Table 1. BUGS distributions and functions used in the Bayesian state-space regression analysis

Distribution/Function	Definition	Description
$\text{dnorm}(\mu, \tau)$	$\sqrt{\tau/(2\pi)}\exp(-\tau(x-\mu)^2/2)$	Normal distribution
$\text{dunif}(a, b)$	$1/(b-a)$	Uniform distribution
$\text{pow}(x, z)$	x^z	Power function

Key variables and model parameters in the analysis are listed in

Table 2. The prior probability distributions are listed in BUGS-style syntax in

Table 3 and the dependencies (both stochastic and deterministic) between variables and parameters are listed in BUGS-style syntax in Table 4. Taken together, Tables 2 to 4 provide a full description of the analysis.

Table 2: Key variables and parameters in the Bayesian state-space regression analysis

Variable/Parameter	**Definition**
σ^{L}	The standard deviation of the TGP at the L^{th} location
β_0^L	The intercept of the relationship between TGP and discharge at the L^{th} location
β_1^L	The slope of the relationship between TGP and discharge at the L^{th} location
μ_i^L	The expected TGP at the L^{th} location
ρ_i^{SPOG}	The proportion of the discharge on the left bank of the LDR from the spill gates
DIS_i^L	The discharge (m^3/s) at the L^{th} location
TGP_i^L	The total gas pressure at the L^{th} location

Table 3: Key prior probability distributions in the Bayesian state-space regression analysis

Parameter	**Prior Distribution**

σ^{L}	dunif(0,10)
β_0^L	dunif(50,150)
β_1^L	dunif(−10,10)

Table 4: Key relationships between the variables and parameters in the Bayesian state-space regression analysis

Variable/Parameter	Relationship
μ_i^L	$\beta_0^L + \beta_1^L * DIS_i^L$
ρ_i^{SPOG}	$DIS_i^{SPOG}/(DIS_i^{SPOG} + DIS_i^{LLOG})$
μ_i^{LDR}	$\mu_i^{LLOG} * \rho_i + \mu_i^{SPOG} * (1 - \rho_i)$
θ_i^L	$\mu_i^L + 0.4 * (TGP_{i-1}^L - \mu_{i-1}^L)$
TGP_i^L	$\mathrm{dnorm}(\theta_i^L, \mathrm{pow}(\sigma^{\mathrm{L}}, -2))$

Results

Discharge levels from each gate type are shown for the pre-WUP period (2003-2007) and the post WUP implementation (2008 to 2011) in Figure 1. In the years for which there is hourly discharge data for all parameters (2003-2011), the spillway was never used during the January to May period and spill (SPOG) typically occurred between July and December. However, some spills occurred in late June 2007 and 2008, (Figure 1).

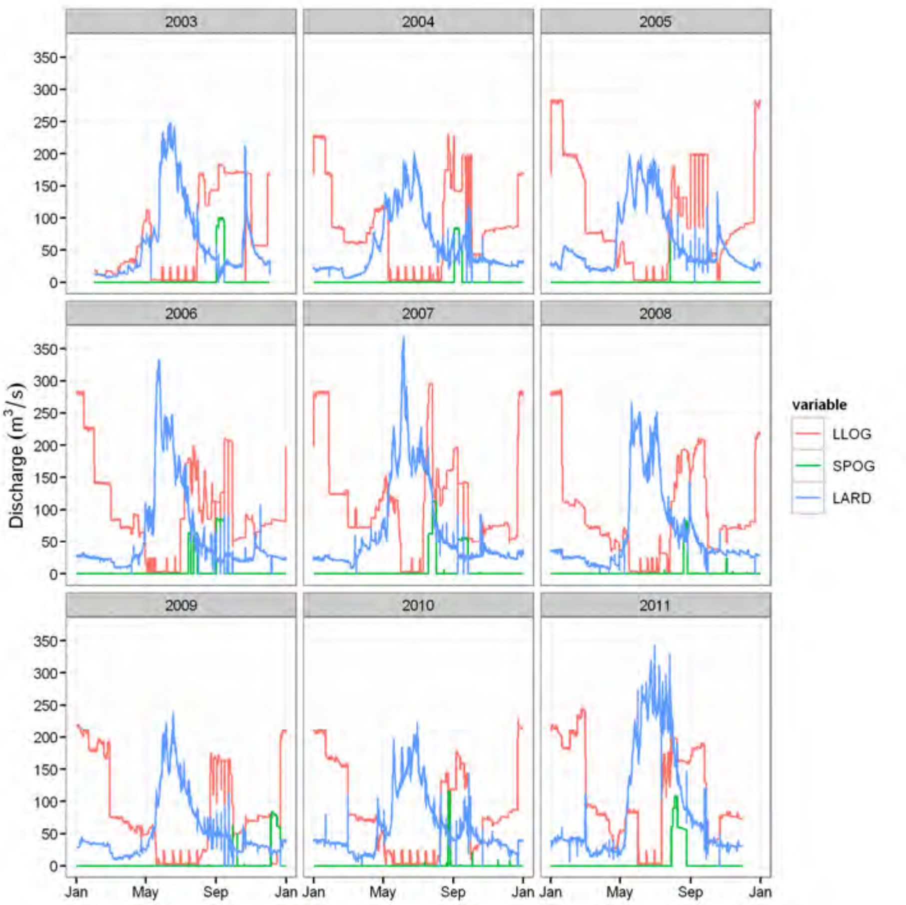

Figure 1 – Discharge (m^3/s) from low level outlet gates (LLOG), spill gates (SPOG) and the Lardeau River, 2003-2011. WUP flow targets were ordered by the Comptroller of Water Rights in 2008.

The spill events that were monitored as part of DDMMON-7 over the past two years were associated with the use of the spill gates in the August-September periods of each year (Figure 2). The low level outlet gates' discharge levels for each year of the WLR project are shown in Figure 3.

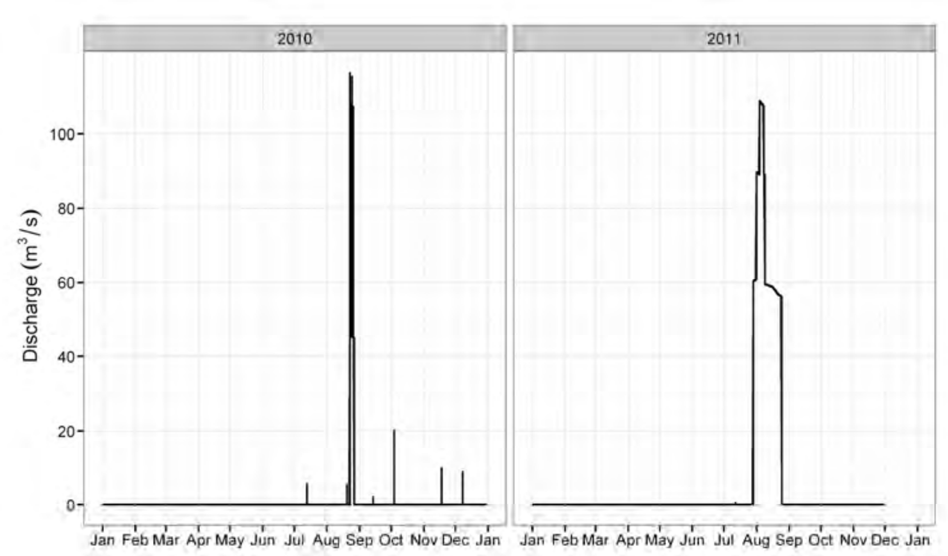

Figure 2 – Discharge (m^3/s) from the spill gates (SPOG) in 2010 and 2011.

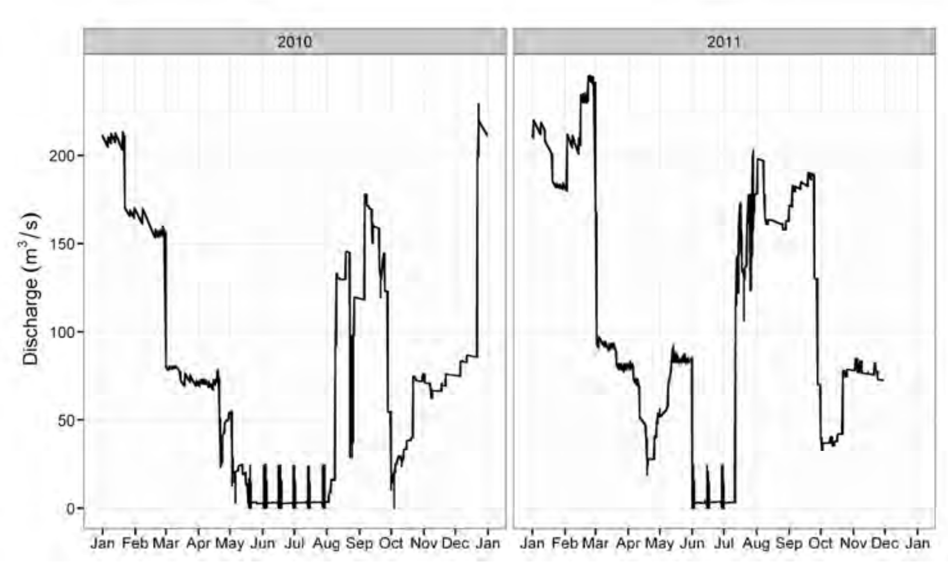

Figure 3 – Discharge (m^3/s) from low level outlet gates (LLOG) in 2010 and 2011.

The relationships between discharge from the spill gates, the low level outlet gates and the Lardeau River and the continuously measured percent total gas pressure are plotted in Figures 4-6. There were no reliable continuous data from the spillway channel during spill periods in either year, so only the two locations (DCL – tailrace, and 2.2L) for which there were data are shown.

The pattern of %TGP in relation to spill discharge shows a wide range of %TGP values at the zero discharge level and then a positive linear relationship with increasing %TGP associated with increased spill discharge when looking at site 2.2L during both years (Figure 4, top panel). The continuous TGP monitoring that occurred in the tailrace (DCL) in 2010 showed no indication of increased TGP with increased spill discharge (Figure 4, bottom panel).

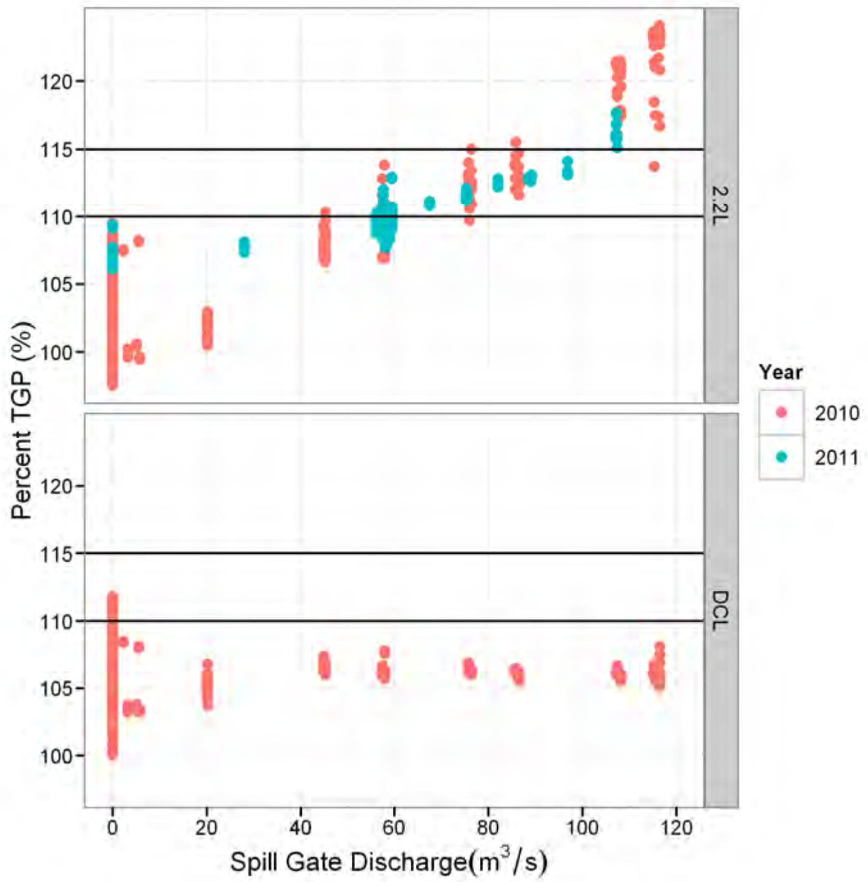

Figure 4 – Percent total gas pressure (TGP) in relation to spill discharge (m^3/s) from DDM spill gates. Two monitoring stations were included in 2010 (DCL and at Km 2.2L), whereas in 2011 only one station was monitored (Km 2.2L). The horizontal black lines denote the provincial TGP guideline of 110% and the federal guideline of 115%.

The patterns between LLOG discharge and percent TGP monitored at DCL in 2010 are less clear. A weak positive trend between increased discharge and increased TGP values can be seen

(Figure 5, bottom panel). A positive linear trend is also seen at 2.2L between increased LLOG discharge and increased %TGP (Figure 5, top panel). In 2011, the meter recorded TGP levels over a small range of discharge values, but there was a strong positive trend between LLOG discharge and %TGP in the 2011 data (Figure 5, top panel). The high %TGP values seen at monitoring station 2.2L occur when the spill gates were operational (Figure 5, top panel).

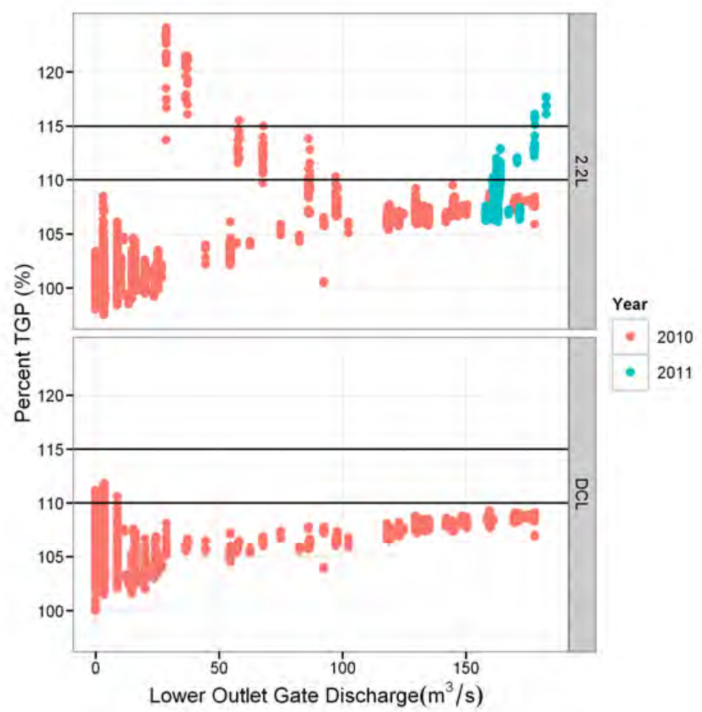

Figure 5 – Percent total gas pressure (TGP) in relation to lower level outlet gate discharge (m^3/s) measured at two monitoring stations in 2010 (DCL and at Km 2.2L), and at one station in 2011 (Km 2.2L). The horizontal black lines denote the provincial TGP guideline of 110% and the federal guideline of 115%.

There were no continuous TGP monitoring data points in the Lardeau River so %TGP was plotted in relation to the discharge from the Lardeau River at the two continuous sampling stations. The %TGP levels were high when Lardeau River discharges were at the extreme ends of their range (station 2.2L; Figure 6). Although the Lardeau River can backwater the confluence and tailrace area when DDM flows are low, there was no discernable pattern between %TGP and discharge at the DCL station (Figure 6).

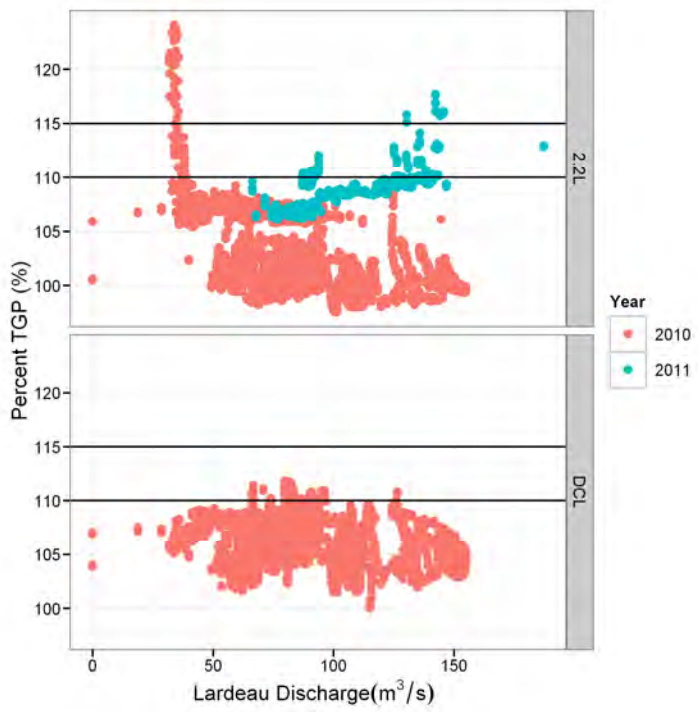

Figure 6 – Percent total gas pressure (TGP) in relation to Lardeau River discharge (m^3/s) measured at two monitoring stations in 2010 (DCL and at Km 2.2L), and at one station in 2011 (Km 2.2L). The horizontal black lines denote the provincial TGP guideline at 110% and the federal guideline of 115%.

The hourly average %TGP measured at station 2.2L in 2010 and 2011 were plotted in relation to SPOG and LLOG discharge to assess the interaction between the two gate types and the resultant %TGP (Figure 7). When LLOG discharge was at low levels and SPOG discharge was high, %TGP reached its highest maximum value of approximately 125%. When LLOG discharge was high while SPOG discharge was high, %TGP was still at or above 110%, but was reduced compared to the situation where there was little outflow from the low-level outlet gates mixing with the spill discharge. This pattern held at moderate and high levels of LLOG output - as long as SPOG output was high, %TGP was high (Figure 7). Any symbols in bright orange or red are above the provincial or federal guidelines.

The model for the relationship between LLOG output and %TGP in the tailrace when discharge is over 25m^3/s shows that discharge levels must be 225m^3/s in order to exceed 110% TGP (Figure 8). It would extend the data beyond reasonable extrapolation to state when it would exceed 115%. The maximum discharge values in the pre-WUP period for both low-level outlet gates combined was 299 m^3/s and in the post-WUP period was 286 m^3/s.

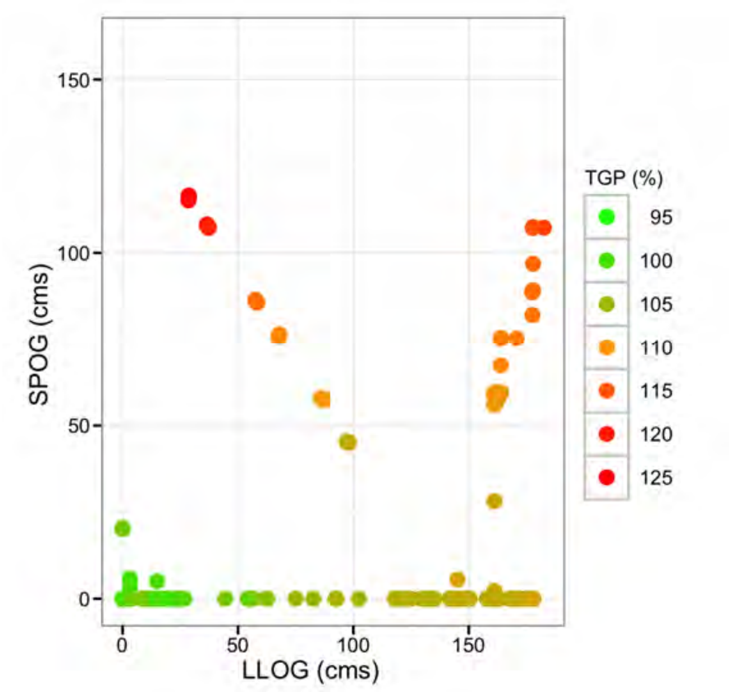

Figure 7 – Spill discharge vs. low level outlet gate discharge as measured at sampling station 2.2L for 2010 and 2011. Hourly averaged percent TGP is denoted by colours with orange and red indicating levels above provincial and federal guidelines.

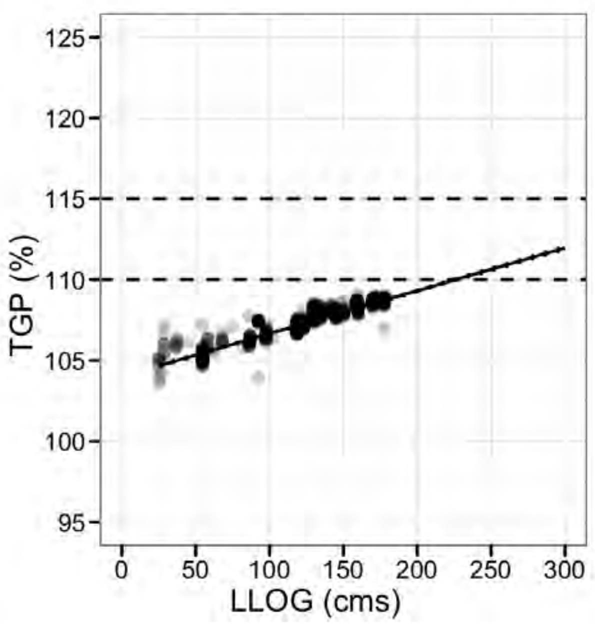

Figure 8 – State space model output of the relationship between %TGP and LLOG discharge. Dashed lines represent the %TGP levels of the provincial and federal guidelines.

The state space model used data from the tailrace monitoring station and the station at 2.2L to estimate the relationship for the spillway between %TGP and SPOG (Figure 9 therefore has no raw data plotted around the line). The model commenced when flow through the spillway was greater than 25 m^3/s to avoid the daily variation patterns in %TGP seen at very low flows. Within the spillway, it is predicted that 110% TGP would be exceeded at 50 m^3/s and 115% TGP would be exceeded at 70 m^3/s (Figure 9). Spot measurements taken within the spillway in 2011 correlate well with this prediction; 58 m^3/s produced 113%TGP and 108 m^3/s produced 122%TGP.

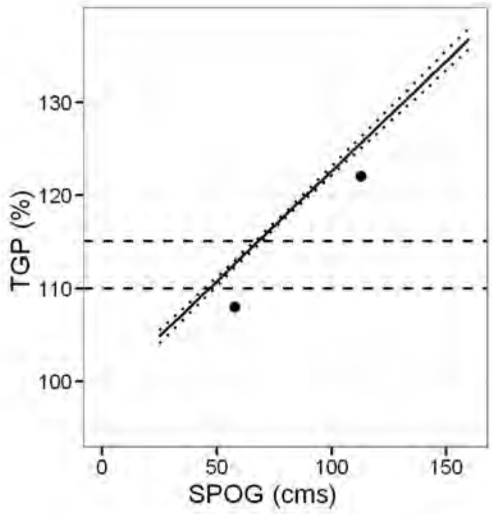

Figure 9 – State space model output of the relationship between %TGP and SPOG discharge. Spot measurements of %TGP from August, 2011 are the plotted points. Dashed lines represent the %TGP levels of the provincial and federal guidelines. Dotted lines around model prediction are 95% credibility intervals. Plotted points are spillway spot TGP measurements.

The model output for assessing the relationship between SPOG outflow and % TGP at 2.2L in the LDR was completed for each year since there were substantially different flow conditions in 2010 and 2011 (Figure 1). The model takes the modeled relationship from the spillway (Figure 9), the modeled relationship from the tailrace (Figure 8) and infers the mixing of the two water sources to be proportional to the discharge from each in order to model the total gas pressure at 2.2L (Figure 10). In both years, 110% TGP was exceeded at 60 m^3/s from SPOG and 115% TGP was exceeded at 100 m^3/s in 2010 and 110 m^3/s in 2011 (Figure 10).

Figure 11 incorporates the flow levels from LLOG and SPOG in a predictive, colour coded format so that %TGP is green when below all regulatory thresholds, and is bright orange ranging to red when above any regulatory thresholds (Figure 11).

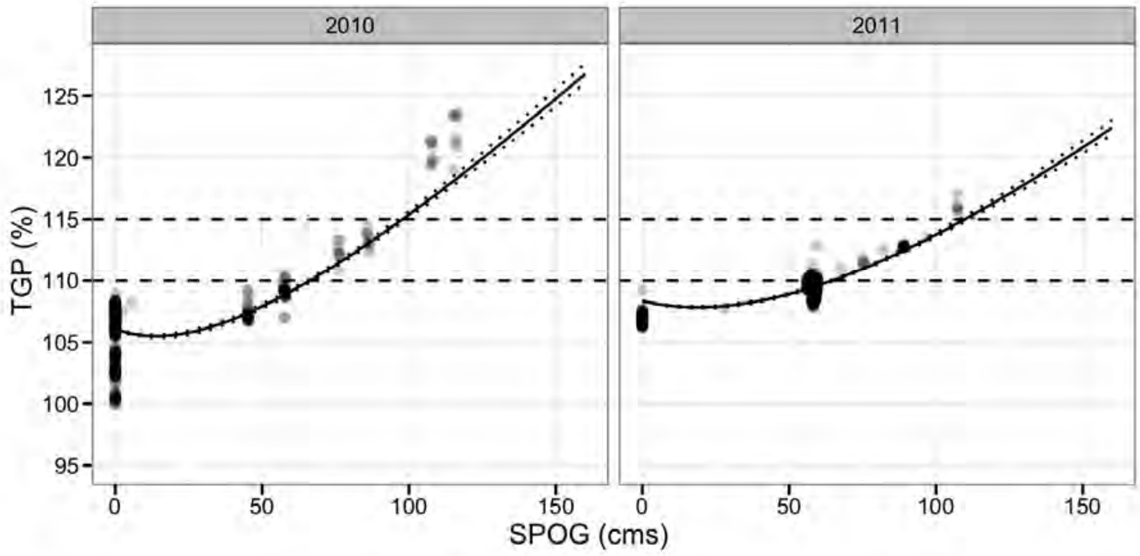

Figure 10 – State space model output of the relationship between %TGP and SPOG discharge at sampling station 2.2L. Dashed lines represent federal and provincial TGP guidelines. Dotted lines around the model prediction line are 95% credibility intervals.

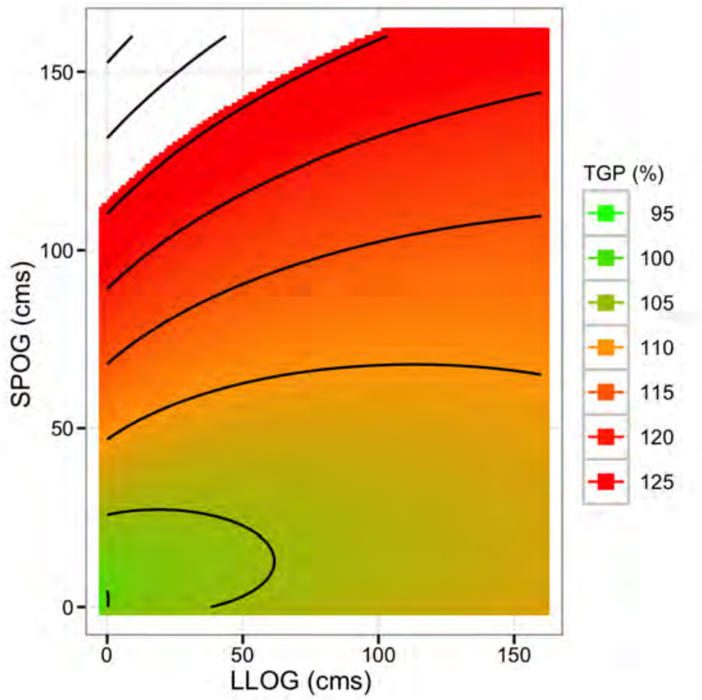

Figure 11 – Model outcomes with %TGP levels for gate operations from LLOG and SPOG. Colours that are bright orange or warmer are higher than regulatory guidelines for %TGP.

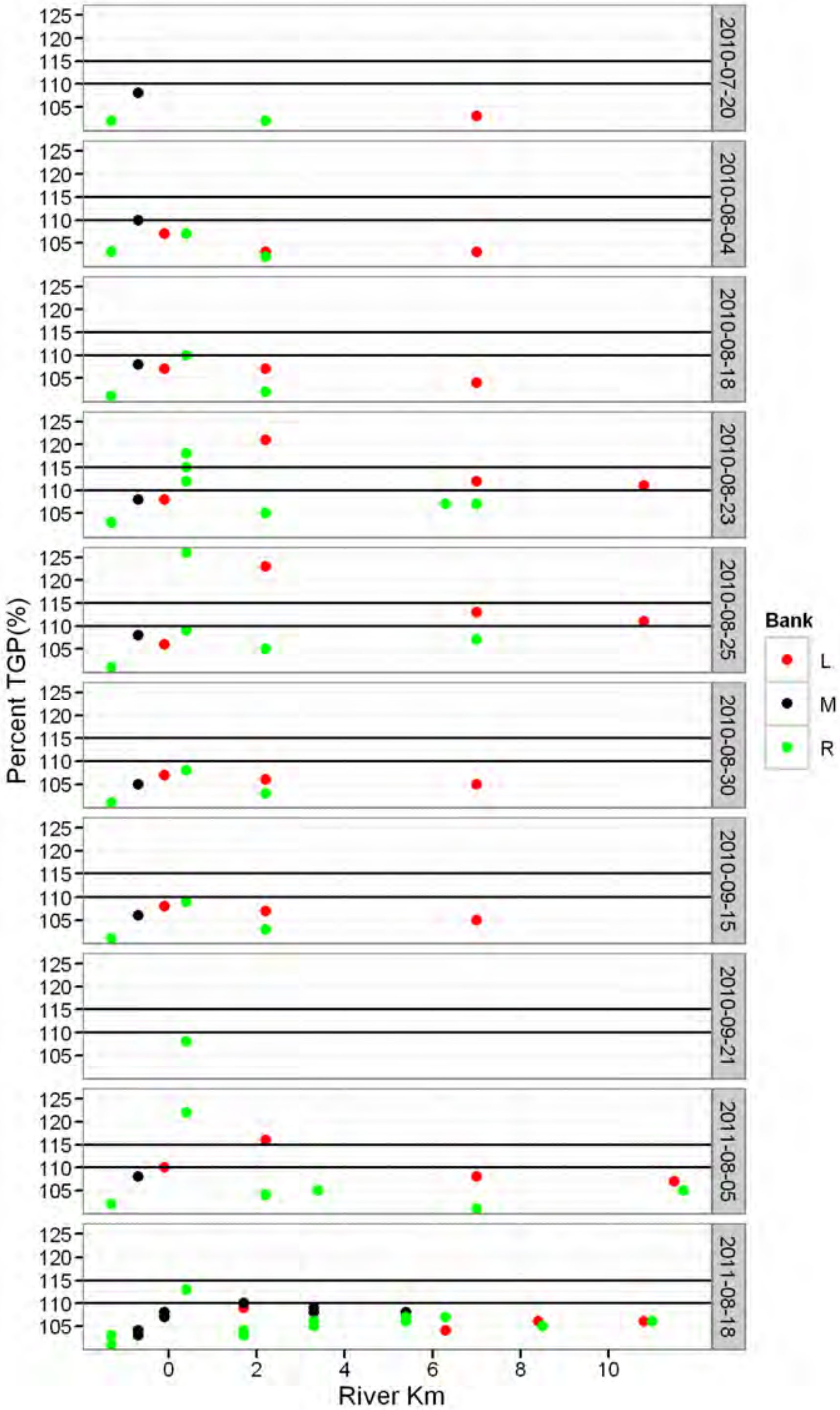

Figure 12 – Percent total gas pressure (%TGP) vs. river km on the LDR. Negative values for river km denote sampling sites at the Lardeau River Bridge (-1.3), Duncan Reservoir Forebay (-0.7) and the tailrace (Station DCL, Km-0.1). The river bank of each sample site's influence is coded by colour. Horizontal lines mark the provincial and federal TGP guidelines (110% and 115%).

TGP spot measurements taken in 2010 and 2011 were grouped by sampling date in order to assess the spatial extent of the influence of elevated TGP coming from the low level outlet gates and the spill gates as well as the influence of the Lardeau River (Figure 12). The Lardeau River bridge (the far left, green symbol on each panel at -1.7 river km) sampling point had %TGP ranging from 100-105 (Figure 12). The most complete data set was from August 18, 2011 (lowest panel, Figure 12) where many sites at mid, left and right bank were sampled from the boat along the length of the LDR. There appeared to be full mixing somewhere between river km 3.3 (where the left bank value was 109%, the middle value was 109% and the right bank value was 106%) and km 5.4 where the values for left, middle and right banks were 107, 108 and 107% respectively. Below river km 5.4, the values diverged again, likely due to the influence of Hamill Creek entering the LDR at km 5.9 and the entrance of Cooper Creek at km 6.9.

Discussion

The level, duration and spatial extent of elevated gas pressure combine with time of year and species and life stages present to create a level of risk for fish within the LDR. Each factor pertaining to TGP is discussed in this report in relation to the data from 2010 and 2011 and the modeling outcomes. The results presented here are considered conservative since the monitored spills occurred during months with highest reservoir temperatures (i.e., July, August and September) and therefore present the worst case scenario for generating high levels of TGP. The risk levels for fish species and life stages will be discussed in the final report for this project.

Spillway operations modeled in relation to %TGP for the two years of data showed that the provincial water quality guideline of 110% TGP is exceeded when spillway outflows are greater than 60 m^3/s. The next benchmark for regulations is 115% which is the DFO level that cannot be exceeded for 4-5 days and the discharge level at which the SPOG outflows intersects this line varies somewhat from year to year based on the slope of the relationship between SPOG and %TGP. In 2010, SPOG flow of 100 m^3/s elicited the 115% TGP and in 2011, the flow value was slightly higher at 110 m^3/s.

The BC provincial guidelines of 110% TGP would be exceeded in the tailrace area due to LLOG operations when discharge from the low level outlet gates reaches or is greater than 225 m^3/s. During the May-September period, this level of discharge from the LLOGs would be impossible given the constraints of the bull trout transfer program. Given the range of data available, extrapolation to where the line would cross the 115% TGP level is uncertain and therefore not discussed further. It is also important to note that the model of the relationship between %TGP and LLOG discharge was based on data collected during the time of year when discharge is restricted to one low-level outlet gate by the bull trout transfer requirements; the predictive relationship may change if water was released from both low-level gates.

During the DDM WUP process, a review was conducted to assess how operations of DDM low-level gates and spillway affected temperature and total gas pressure (TGP) in the lower Duncan River and their potential implications to fish (BC Hydro 2005). The review outlined a predictive relationship between spill and TGP production that indicated that TGP events occur when spills from DDM exceed 110 m^3/s. Therefore, TGP related performance measures included the number of Total Gas Pressure Days >115%, and the total number of TGP Events, where events were defined as occasions where consecutive days exceeded 115% (BC Hydro 2005).

The DDM WUP CC also developed a Total Gas Pressure procedure which states: "When Duncan Dam discharges are nearing 285 m^3/s, ensure that flows through one low level outlet are near the maximum flow of 170 m^3/s to restrict spill volumes to 115 m^3/s (in the spillway) and therefore, limit Total Gas Pressure levels downstream" (BC Hydro 2005) and this was restated in the Terms of Reference where risk of adverse effects of TGP were considered to be increasing with spillway flows above 115 m^3/s (BC Hydro 2010).

Based on the results of this study, it appears that if the more conservative provincial guidelines are followed, the spillway flows would need to be restricted to less than 60 m^3/s, and if the DFO guidelines of 115% TGP are followed, a spillway limit of 100 m^3/s would be required based on the two years of data. The directive to maintain LLOG flows as high as possible given bull trout transfer constraints should be maintained to help in lowering TGP levels.

The number of 'TGP events' where 115% TGP persisted over consecutive days (BC Hydro 2005) was not assessed for 2010 since the tests were of short duration (3 day period) with ramp up and ramp down in each day. In 2011, %TGP at the only continuously monitored station of 2.2L exceeded 115% on August 8, but since it had dropped below 112% by the next day, this would not have been considered an event. The percent TGP measured at this meter went above 110% numerous times after that date, but never exceeded 115% again until its removal on September 2, 2011.

The areal extent of the elevated TGP is also relevant for determining the risk level to fishes in the LDR. The Lardeau River is considered a natural hydrograph and its inflows dominate the flow down the right side of the LDR until full mixing with the dam and spillway inflows is attained. The TGP spot measurements taken throughout the LDR on both banks and mid-river show the extent of mixing spatially among the Lardeau River, the tailrace (LLOG) outflows and the spillway (SPOG) outflows. Based on the available data, it would be conservative to assume that the influence of spillway TGP is dissipated and mixed with Lardeau River and LLOG discharge by river km 5.4 at the discharge conditions sampled on August 18, 2011. The extent of elevated TGP across the width of the river is unknown, but the spot measurements do indicate that it is predominantly the left bank that is affected. If the area within the tailrace is eliminated from the calculation and we assume that the left half of the river is affected, approximately 22.5% of the 24 lineal kms of wetted usable area along the banks of the LDR may be affected by elevated TGP levels. This affected areal percentage was obtained by taking the ~12km of the LDR below DDM, multiplying by two to obtain the lineal distance for both mainstem banks, then taking the approximately 5.4 km of the left bank that was affected divided into 24 lineal km to obtain the percentage of affected area. Although this is an approximation, it allows the consideration of risk levels to fishes in the LDR to have an estimate of the spatial extent of the risk.

There are some limitations to these conclusions due to the changes in the scope that occurred mid-program and the limited data available to parameterize models to address the modified management questions. In 2010, the study design incorporated monitoring TGP at two locations historically monitored by BC Hydro: DCL and Km 2.2L. A third station, located below the spillway, was also included to monitor TGP. The original study design reflected the management questions set out in the TOR. TGP monitoring was not planned for 2011 as it was determined that if additional data were required following a comprehensive analysis of the 2010 data then a TGP monitoring program would be considered for 2012 (T. Oussoren and A. Leake, pers. comm., 2011). However, due to climactic conditions, a spill event occurred in July/August 2011 and it was determined that TGP monitoring would be useful during typical DDM spillway operation since only gate testing was conducted in 2010. Due to the malfunction of the TGP meter in the spillway in 2010, and the skeleton TGP program in 2011, the data set available to determine the relative contribution of LLOGs and SPOGs and estimate variation through space and time is sparse. Without data from the DCL station in 2011, there is little that can be said about the relative influence of the spill sill elevations vs. the low level outlet gate elevations from the reservoir and how they affect the TGP downstream. The modeling effort partially compensates for the missing spillway data from 2010 by using the state space model to estimate the relationship between SPOG and %TGP at the spillway location by back-calculating from the known values at 2.2L and at DCL. With the current model, the outflows from the spillway and the low level outlet gates are assumed to be proportional to the amount of discharge from each part of the dam whereas additional data from different years with different flow regimes would allow empirical investigation of the mixing processes. Two very different flow regimes occurred in each of the two years of sampling. In 2011 actual operations were monitored as compared to 2010 when spill gate tests were conducted. The additional influence of the Lardeau River was not modeled because a continuous monitoring station was not included in the study design and only spot measurements were available. If additional certainty or complexity is required, the existing data set may not be sufficient.

Closure

This report is to the best of our knowledge accurate and correct. If you have any questions regarding its contents please contact one of the undersigned.

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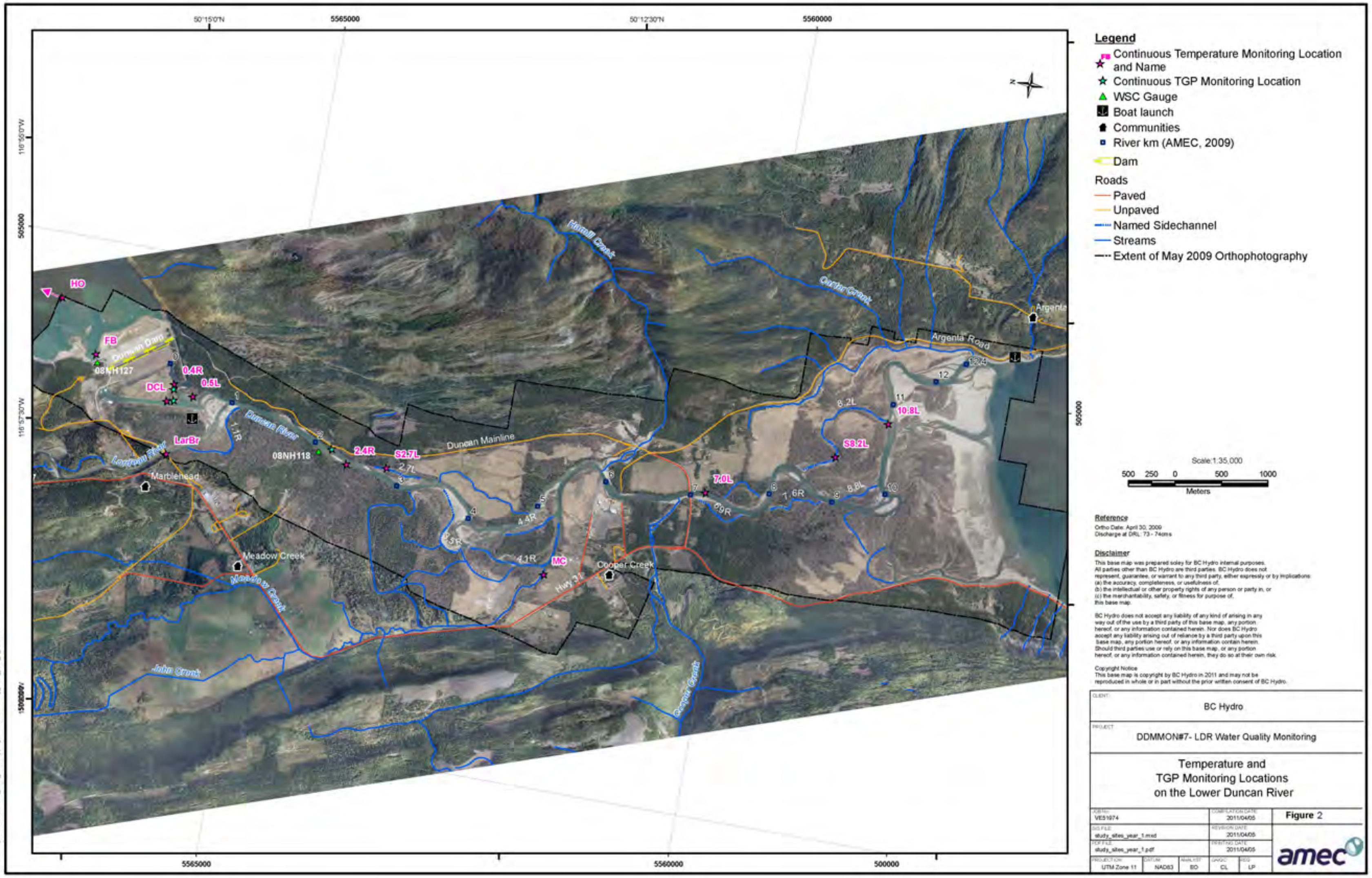
Appendix 1
Map of Lower Duncan River Temperature and TGP Data Monitoring Locations


Legend
Continuous Temperature Monitoring Location and Name
Continuous TGP Monitoring Location
WSC Gauge
Boat launch
Communities
River km (AMEC, 2009)
Dam
Roads
Paved
Unpaved
Named Sidechannel
Streams
Extent of May 2009 Orthophotography
Scale 1:35,000
500 250 0 500 1000
Meters
BC Hydro
DDMMON#7- LDR Water Quality Monitoring
Temperature and
TGP Monitoring Locations
on the Lower Duncan River
Figure 2
amec
HO
FB
Duncan Dam
08NH127
0.4R
0.5L
DCL
LarBr
08NH118
2.4R
S2.7L
Duncan River
Duncan Mainline
Marblehead
Meadow Creek
MC
Cooper Creek
Hwy 31
John Creek
7.0L
S8.2L
10.8L
Argenta Road
Argenta
Hamill Creek
Carter Creek

APPENDIX C
Temperature Model Code

Table 1: Variables in the mixing analysis.

Variable	Description
Discharge.DDM[i]	Discharge at Duncan Dam at the i^{th} time
Discharge.LAR[i]	Discharge in the Lardeau River at the i^{th} time
Temperature.DDM[i]	Temperature at Duncan Dam
Temperature.LAR[i]	Temperature in the Lardeau River at the i^{th} time
Temperature.S2.7L[i]	Temperature at S2.7L at the i^{th} time
Temperature.2.4R[i]	Temperature at 2.4R at the i^{th} time
Time[i]	Number of hours from the start of the time series of the i^{th} time

Table 2: Parameters in the mixing analysis.

Parameter	Description
bMixIntercept	Proportion mixing at origin
bMixDDM – bMixDDM3	First to third order polynomials of the effect of discharge from DDM on the proportion mixing
bMixLAR – bMixLAR3	First to third order polynomials of the effect of discharge from LAR on the proportion mixing
bMixDDM.LAR – bMixDDM.LAR3	Interactions between effects of discharge from DDM and LAR on the proportion mixing
bCor	Autoregressive correlation coefficient
eMixing[i]	Expected proportion mixing at the i^{th} time
eThetaTemperature.RightBank[i]	Expected temperature on the right bank of the LDR at the i^{th} time after adjusting for autocorrelation
eThetaTemperature.LeftBank[i]	Expected temperature on the right bank of the LDR at the i^{th} time after adjusting for autocorrelation
eTemperature.RightBank[i]	Expected temperature on the right bank of the LDR at the i^{th} time
eTemperature.LeftBank[i]	Expected temperature on the left bank of the LDR at the i^{th} time
sTemperature	Standard deviation of the residual variation in water temperature

```
model {
  sTemperature ~ dunif(0, 1)
  bMixIntercept ~ dnorm(0, 1^-2)
  bMixDDM ~ dnorm(0, 1^-2)
  bMixDDM2 ~ dnorm(0, 1^-2)
  bMixDDM3 ~ dnorm(0, 1^-2)
  bMixLAR ~ dnorm(0, 1^-2)
  bMixLAR2 ~ dnorm(0, 1^-2)
  bMixLAR3 ~ dnorm(0, 1^-2)
  bMixDDM.LAR ~ dnorm(0, 1^-2)
  bMixDDM2.LAR ~ dnorm(0, 1^-2)
  bMixDDM.LAR2 ~ dnorm(0, 1^-2)
  bMixDDM2.LAR2 ~ dnorm(0, 1^-2)
  bCor ~ dunif(0, 1)
  eThetaTemperature.LeftBank[1] <- eTemperature.LeftBank[1]
  eThetaTemperature.RightBank[1] <- eTemperature.RightBank[1]
  for(i in 2:nrow) {
    eThetaTemperature.LeftBank[i] <- eTemperature.LeftBank[i] + bCor^(Time[i]-Time[i-1]) * (Temperature.S2.7L[i-1] - eTemperature.LeftBank[i-1])
    eThetaTemperature.RightBank[i] <- eTemperature.RightBank[i] + bCor^(Time[i]-Time[i-1]) * (Temperature.2.4R[i-1] - eTemperature.RightBank[i-1])
  }
  for (i in 1:nrow) {
    dDDM[i] <- cDischarge.DDM[i]
    dLAR[i] <- cDischarge.LAR[i]
    logit(eMixing[i]) <- bMixIntercept  * dDDM[i]^0 * dLAR[i]^0 +
```

```
bMixDDM * dDDM[i]^1 * dLAR[i]^0 +

bMixDDM2 * dDDM[i]^2 * dLAR[i]^0 +

bMixDDM3 * dDDM[i]^3 * dLAR[i]^0 +

bMixLAR * dDDM[i]^0 * dLAR[i]^1 +

bMixLAR2 * dDDM[i]^0 * dLAR[i]^2 +

bMixLAR3 * dDDM[i]^0 * dLAR[i]^3 +

bMixDDM.LAR * dDDM[i]^1 * dLAR[i]^1 +

bMixDDM2.LAR * dDDM[i]^2 * dLAR[i]^1 +

bMixDDM.LAR2 * dDDM[i]^1 * dLAR[i]^2 +

bMixDDM2.LAR2 * dDDM[i]^2 * dLAR[i]^2 +

    eTemperature.LeftBank[i] <- (Temperature.DDM[i] * Discharge.DDM[i] + Temperature.LAR[i] * Discharge.LAR[i] * eMixing[i]) / (Discharge.DDM[i] + Discharge.LAR[i] * eMixing[i])

    eTemperature.RightBank[i] <- (Temperature.DDM[i] * Discharge.DDM[i] * eMixing[i] + Temperature.LAR[i] * Discharge.LAR[i]) / (Discharge.DDM[i] * eMixing[i] + Discharge.LAR[i])

    Temperature.S2.7L[i] ~ dnorm(eThetaTemperature.LeftBank[i],sTemperature^-2)

    Temperature.2.4R[i] ~ dnorm(eThetaTemperature.RightBank[i],sTemperature^
```

APPENDIX D
Water Temperature & Discharge Related to Kokanee Spawning in the LDR - Memo

Questions

1) Do water temperature and discharge influence spawn timing of Kokanee?
2) Do water temperature and discharge affect spawning distribution of Kokanee within the LDR?

Methods

Water temperature and discharge data were extracted from the BC Hydro temperature, elevation and discharge database for the Water Survey of Canada station at DRL and from the DDDMMON-7 database for the water temperature stations at S2.7L and 2.4R.. The spawn timing was extracted from the Area Under the Curve (AUC) analysis completed by Poisson Consulting Ltd. in 2012 (AUC memo needs to be cited for .4 and .5.) and compared correlatively with the discharge and temperature to assess any trends in influence of water temperature or discharge on the timing. Four years of kokanee spawner abundance data were extracted from the DDMMON-4 database. Only those fish that were determined by observers to be in spawning condition were used (i.e., not those fish moving or staging as defined in AMEC 2012).

Results

The discharge levels at DRL are high at the start of the spawning and staging period for kokanee with a range of discharge values over the four years (2008-2011) from 200-250m^3/s (Figure 1). The discharge then drops near the end of September usually in 2-4 drops to the 73-76 m^3/s level. As was seen in the plotting and analysis for DDMMON-7, the DRL water temperature appears unreliable with large variation from the patterns seen at other temperature loggers nearby for the same period of time (Figure 2). This leaves us with three years of reliable water temperature data to compare to kokanee spawners from the stations installed at S2.7L and 2.4R as part of DDMMON-7 (Figure 3). The water temperature gradually decreases over the kokanee spawning period with a slight step change downwards in about the third week of September (Figure 3).

The drop in discharge that occurs in the LDR in late September may have an effect on the distribution of spawning kokanee as this large decrease in discharge is affiliated with the change in proportion of kokanee observed on the left and right banks (Figure 3); after the drop occurs, more kokanee are proportionally seen on the right bank than before the drop. There is no pattern whatsoever between the discharge at DRL assessed from September 1-14th and the timing of the kokanee spawn timing (Figure 4). Spawn timing suggests that kokanee spawn later when early September temperatures are warmer (Figure 5). It must be emphasized for both the comparison to the discharge and to water temperature that three or four years is not adequate to determine any relationship between environmental variables and spawn timing, though it provide preliminary trends. In addition, the analyses completed for DDMMON-7 illustrate how complex the mixing trends in temperature streams from the spillway, low-level outlet gates and tributaries may be.

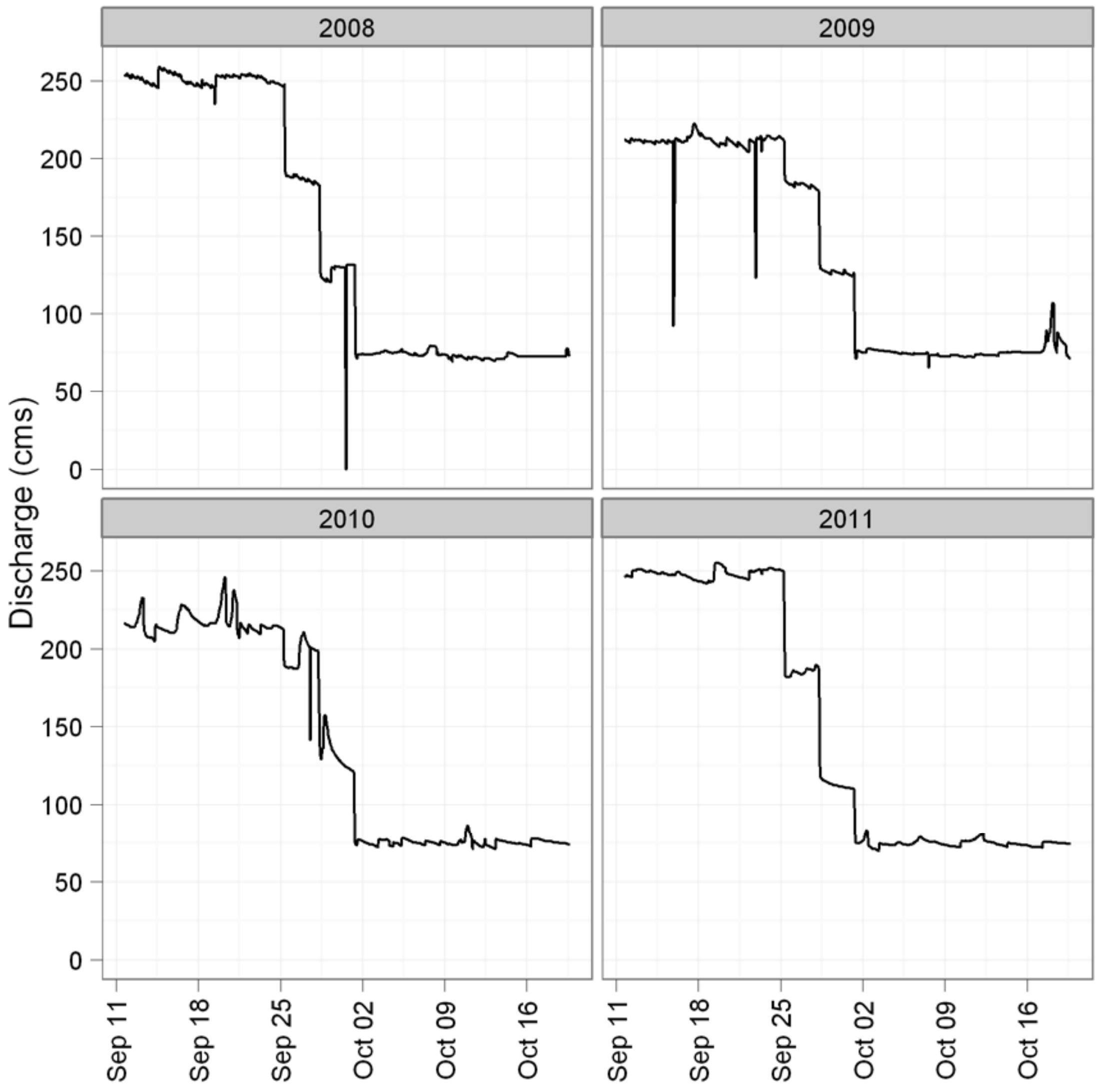


Figure 1 – Hourly discharge from DRL during the Kokanee spawning period from 2008 to 2011.

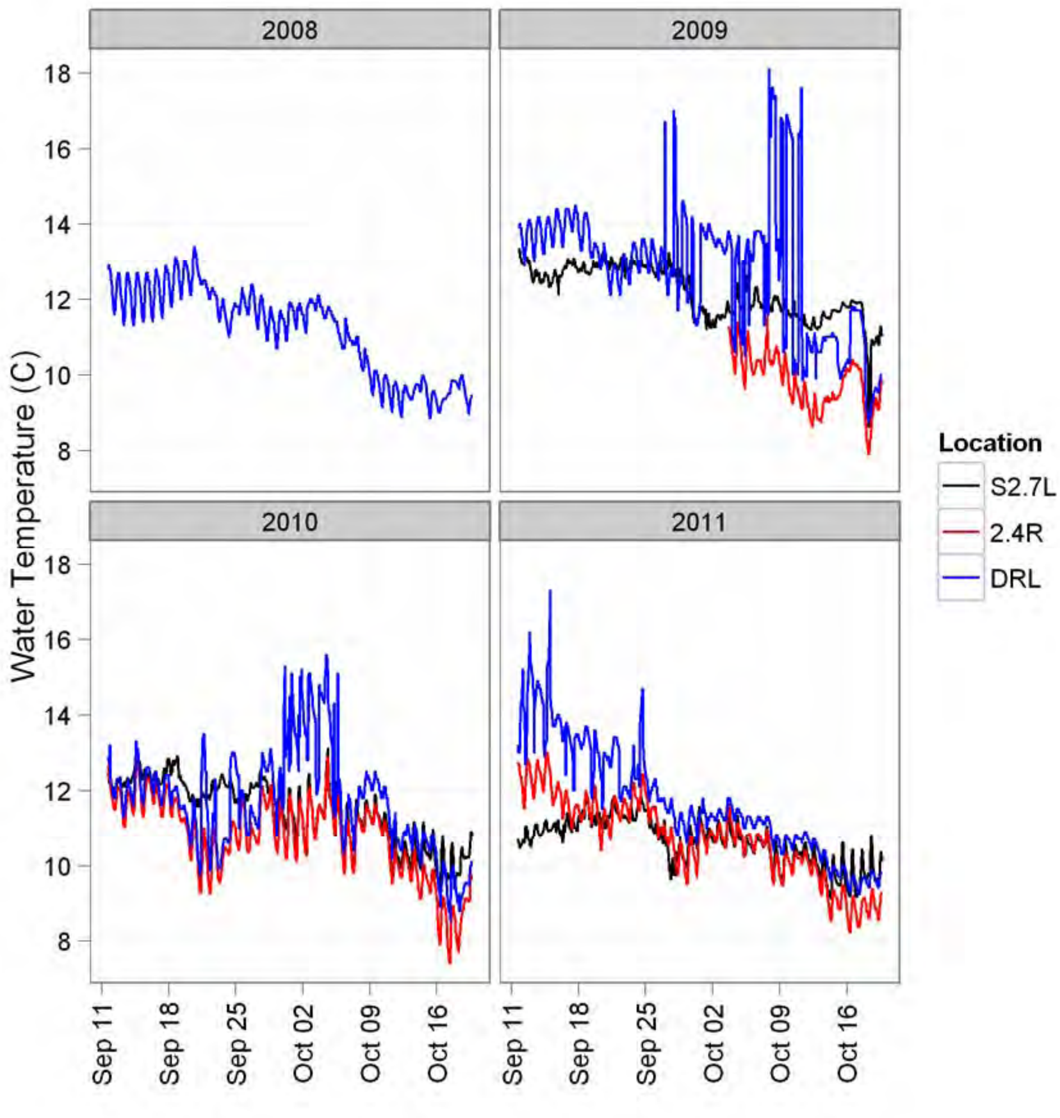


Figure 2 - Hourly water temperature at Water Survey of Canada station DRl, 2.4R and S2.7R. by date and year during the kokanee spawning period from 2008 to 2011.

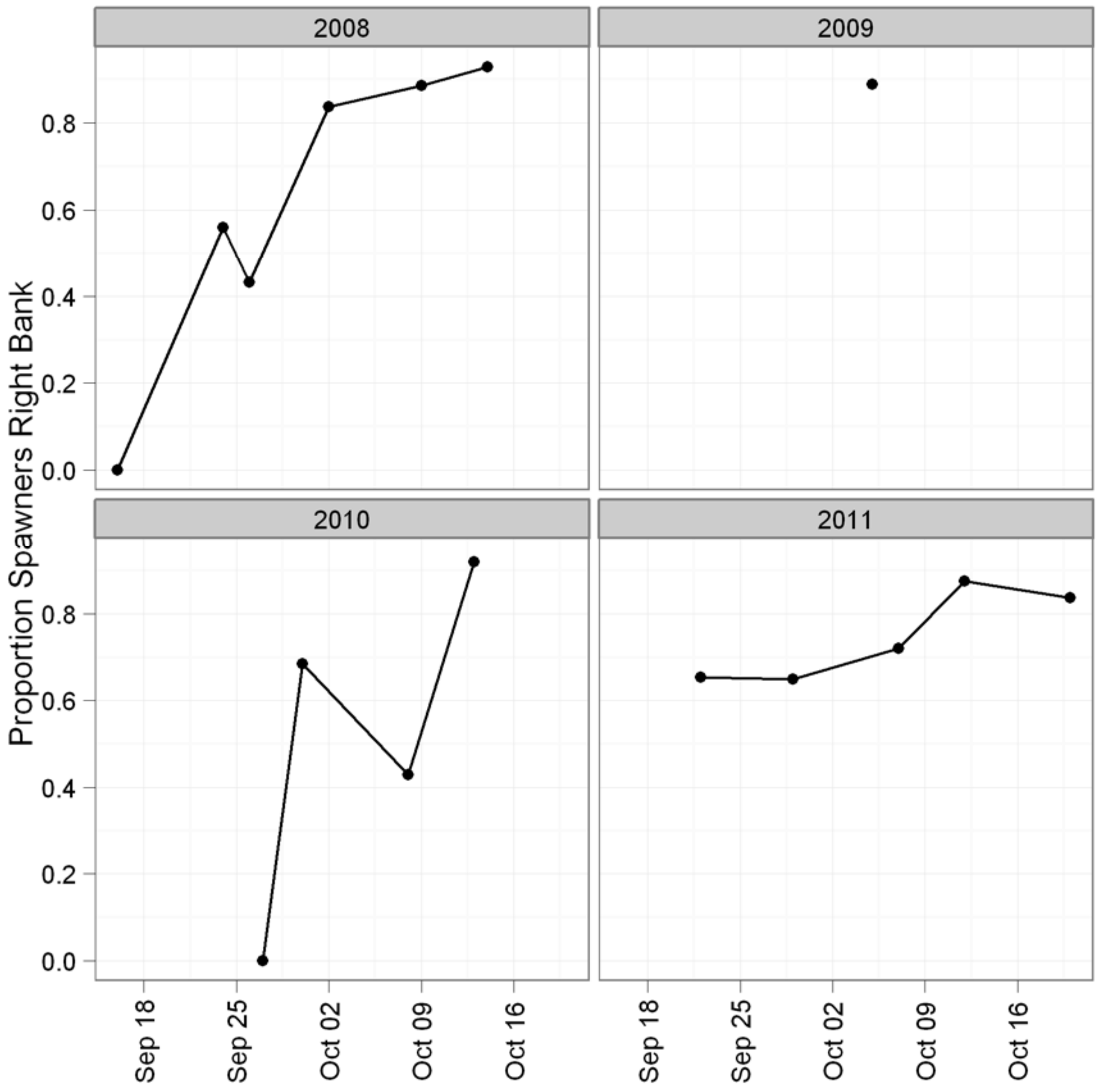


Figure 3 – Proportion of kokanee spawners in the upper 3.5 km of LDR on the right downstream bank versus the left downstream bank. The proportions are based on helicopter surveys and include the mainstem plus sidechannel 2.7L which is classified as the downstream left bank. Only counts for more than 100 spawners are shown.

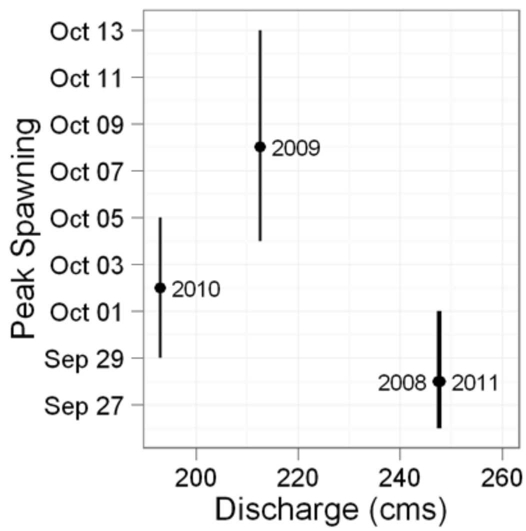


Figure 4 – Discharge at DRL from September 1-14 vs. estimated peak timing for kokanee spawners with 95% credibility intervals.

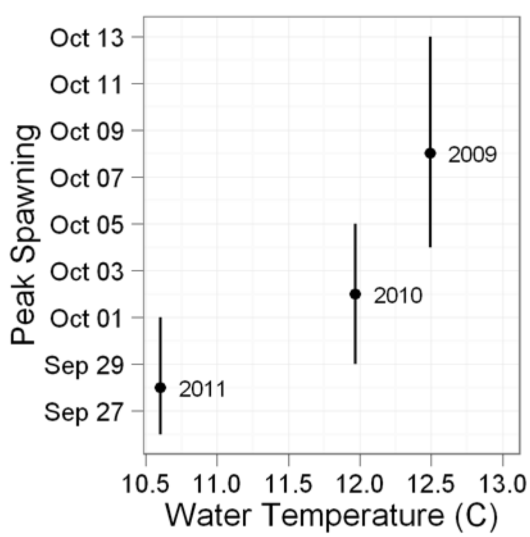


Figure 5 – Water temperature from September 1-14 at S2.7L vs. estimated peak timing for kokanee spawners with 95% credibility intervals.