Columbia River Project Water Use Plan

Revelstoke Flow Management Plan

Mid-Columbia Physical Habitat Monitoring

Implementation Year 11 (Final Synthesis Report)

Reference: CLBMON-15a

Study Period: 2007-2018

Prepared by:
E. Plate[2], M. Zimmer[1], A. Duncan[1], Y. Bychkov[2], E. Smith[1], and N. Wright[3]

[1]Okanagan Nation Alliance
#101-35353 Old Okanagan Highway
Westbank, BC, V4T 3J6

[2]LGL Limited
9768 Second Street
Sidney, BC, V8L 3Y8

[3]Ecofish Research Limited
Suite F – 450 8th Street
Courtenay, BC, V9N 1N5

April 2019

Mid-Columbia Physical Habitat Monitoring Project

Implementation Year 11 (2017)

Reference: CLBMON-15a

Study Period: 2007-2018

Prepared by:
E. Plate[2], M. Zimmer[1], A. Duncan[1], Y. Bychkov[2], E. Smith[1], and N. Wright[3]

[1]**Okanagan Nation Alliance**
#101-3535 Old Okanagan Highway
Westbank, BC, V4T 3J6

[2]**LGL Limited**
9768 Second Street
Sidney, BC, V8L 3Y8

[3]**Ecofish Research Limited**
Suite F – 450 8th Street
Courtenay, B.C. V9N 1N

April 2019

Suggested Citation:

E. Plate[2], M. Zimmer[1], A. Duncan[1], Y.Bychkov[2], E.Smith[1], and N. Wright[3]. 2019. CLBMON-15a Mid-Columbia River Physical Habitat Monitoring Project, 2017 (Year 11). Prepared for: BC Hydro, Burnaby, BC. Prepared by: Okanagan Nation Alliance[1], LGL Limited[2] and Ecofish Research Limited[3]:

Cover Photo:

Jet boat at Station 1 on the MCR with Revelstoke Dam in the background (2013 Elmar Plate LGL Limited).

List of acronyms

ALR	Arrow Lakes Reservoir
CC	Consultative Committee
HLK	Hugh L. Keenleyside Dam
HEC-RAS	Hydrologic Engineer Center River Analysis System
masl	meters above sea level
MCR	Middle Columbia River
REV	Revelstoke Dam
REV5	Revelstoke Dam fifth unit
RFMP	Revelstoke Flow Management Plan
TGP	Total Gas Pressure
TSS	Total Suspended Solids
WUP	Water Use Plan

EXECUTIVE SUMMARY

As part of the Columbia Water Use Plan (WUP) a year-round minimum flow release of 142 m^3/s from Revelstoke Dam (REV) was implemented in December, 2010 to enhance fish habitat in the Middle Columbia River (MCR) which is bordered by Revelstoke Dam at the upstream end and Arrow Lakes Reservoir on the downstream end. On the same date the fifth turbine in Revelstoke Dam (REV5) was commissioned and increased the diel maximum flows (the combination of minimum flows and REV5 is hencefoth named new flow regime). To assess the effects of the increased minimum and maximum flows, BC Hydro initiated the CLBMON-15a program in 2006 and the monitoring of the physical environment of the MCR started in 2007 (Implementation Year 1). The 2007 start allowed for four years of data collection pre-minimum flow implementation and four and a half years of post-flow implementation data collection from December 2010 to May of 2015. The post-flow implementation regime was characterized by an increase in minimum flows (from 8.5 m^3/s seepage flows during zero generation to 142 m^3/s flow) and in increase in maximum flows (from 1,700 m^3/s to 2,124 m^3/s) when discharge from previously four turbines was complemented by discharge run from Turbine 5. In this report, a short summary of overall results from 2007 to 2018 (end of project) is provided. For results of earlier Implementation Years, the reader is referred to Plate et al. (2014, 2015, 2016), Golder (2014) and Golder summary reports from 2008 to 2012[1].

As defined in the WUP (BC Hydro 2007 and revised in BC Hydro 2015), the objective of CLBMON-15a was to provide empirical information on the response of key physical habitat variables to the implementation of minimum flow releases from Revelstoke Dam and operation of REV 5. Physical habitat data such as stage and temperature combined with water quality data are required to test hypotheses about the observed changes in large river habitat conditions and to support the logical chain of inference for explaining observed changes in key ecological productivity indicators in each of the monitoring programs of the Revelstoke Flow Monitoring Program. To gather the necessary data stage and temperature were monitored continuously at six stations in MCR and two tributaries complimented by seasonal monitoring of water quality.

Given the dynamic and complex nature of the regulated flow regime, and the geographic extent of the MCR study area, a hydraulic model (HEC-RAS) was required to describe the hydraulics of the MCR within the study area, by calibrating the model parameters using the monitoring data obtained during this study.

A HEC-RAS model was developed to correlate and predict stage, current and wetted area information with REV discharges before and following the implementation of the new flow regime. It was based on water stage, water level and temperature information collected at 4 stations in the MCR: Reach 2 (~20 km downstream of REV), Reach 4 (~4 km downstream of REV) and one station each in the Illecillewaet and Jordan rivers.

[1]available at *www.bchydro.com/about/sustainability/conservation/water_use_planning/southern_interior/ columbia_river/revelstoke-flow.html*

As of the end of the May 2015 monitoring period, the HEC-RAS model was adequately calibrated and predicted stage and wetted area for the MCR well for Reach 4 (closest to REV) throughout all seasons and discharges. For the lower reaches of the MCR (Reaches 2 and 3) the model has high predictive power when the Arrow Lakes do not back water into the MCR (winter and spring) and less predictive power when the MCR's flow and wetted area are affected more by Arrow Lakes backwatering than REV discharges (summer and fall). Arrow Lakes Reservoir (ALR) at full pool backwaters the MCR into reaches 3 & 4, and thus buffers effects of the REV discharge.

In addition, the HEC-RAS model output was used to provide data for the prediction of wetted area, stage or flows for all flow releases from Revelstoke Dam at different elevations of Arrow Lake Reservoir. Based on these data, inundation maps were produced for different discharge and backwatering scenarios.

Stage, Water Levels and Temperature Monitoring Results

Based on the stage data collected by Golder from 2007–2012 and confirmed by the data collected as part of the 2013 collection (Plate et al. 2014, 2015), the implementation of the new flow regime, as expected, led to a greater range of amplitude in diel water levels and flows. There was no evidence that the new flows changed the seasonal variations in flows or water levels. Diel variation in water temperature was significantly smaller post flow implementation based on the data by Golder (2014), Plate et al. (2014, 2015, 2016), and no changes in water temperature were detected on a seasonal basis. Although statistically significant, the changes in the diel range of water temperatures were very small ranging from 0.1–0.4 °C and do not appear to be ecologically significant.

Seasonal Water Quality Monitoring

In past years, physical and nutrient water parameters were collected as point samples up to three times per year, to be used as indicators of trophic status for a particular year. Due to low sample size, these results could not be judged representative of long-term conditions and be used to draw conclusions about effects of the implementation of the new flow regime. Following a review of all results, the monitoring and analysis of nutrient parameters were therefore terminated in May of 2014. In general, all physical and nutrient water parameters were typical of highly oligotrophic systems and in line with the results obtained in earlier studies (Golder 2014, Plate et al. 2014, 2015).

Table 1 CLBMON-15a status of objectives, management questions and hypotheses (Year 11, 2017 no changes in 2018).

Objectives	**Management Question 1: How does the 142m³/s minimum flow and the increased flow based on REV 5 affect…**	**Management Hypothesis: Implementation of a 142m³/s minimum flow release from REV will not significantly…**	**Final Status**
Measure differences in the daily and seasonal river water temperature regimes between pre- and post-implementation of the 142 m³/s minimum flow regime	…water temperature in the flowing reach of the MCR	…alter the water temperature regime of the MCR • Ho 1a: diel variation of water temperature • Ho 1b: seasonal pattern of mean water temperature	Based on continuous temperature data sampling, diel variation of water temperature following implementation of the new flow regime was 0.1-0.4 °C smaller than before. The ecological significance of such a small change is questionable. The seasonal pattern of mean water temperatures does not appear to be affected by the new flow regime.
Measure spatial and temporal differences in the daily and seasonal range of river level fluctuations between pre- and post-implementation of the 142 m³/s minimum flow regime	**Management Question 2: How does the 142m³/s minimum flow and the increased flow based on REV 5 affect……** … the range and variability in river level fluctuations in the MCR	… range and variability of river level fluctuations in the MCR • Ho 2a: diel variation of river levels in MCR • Ho 2b: seasonal pattern of mean river fluctuations in the MCR	Based on continuous stage logger measurements from 2008 to spring of 2015, diel variation in water levels following the new flow regime was larger following the new flow regime while the seasonal pattern of mean river fluctuations did not appear to be affected.

Collect seasonal nutrient and electrochemistry data at the reach scale to spatially characterize water quality conditions	**Management Question 3: Does the 142m³/s minimum flow and the increased flow based on REV 5 affect…** …water quality in terms of electrochemistry and biologically active nutrients	(no hypothesis)	Based on three individual annual samples from 2008 to spring of 2015 for nutrients, physical parameters and electrochemistry the sampling frequency was deemed to be too low to determine any differences between the pre- and post-new flow regime conditions. This decision was made as part of a a discussion during a RFMP (Revelstoke Flow Management Plan) workshop in February of 2014. Little to no difference before /after new flow regime was found in the MCR stations (within and among years). A subsequent literature search on on the effects of flows on water quality did not yield any comparable study.
Estimate changes in the quantity and spatial distribution of permanently inundated river channel resulting from 142 m^3/s minimum flow releases	**Management Question 4: How does the 142m³/s minimum flow and the increased flow based on REV 5 affect…** …total area of river channel that is permanently wetted …are there biologically significant differences in velocity and depth …if so where do these occur	…increase the area of river channel that is continuously inundated in the MCR • Ho 3a: does not increase the minimum total wetted channel area in the MCR • Ho 3b: does not increase the ecologically productive' area in the MCR	The estimates based on Golder 2014 and the HEC-RAS model show that the wetted river bed area at minimum flows increased by 32% after implementation of the new flow regime, but only when Arrow Lake Reservoir is below 425 masl. When ALR is higher, the effect is lessened in the reaches close to REV where the MCR is backwatered by high Arrow Lakes elevations, and non-existent in the MCR reaches further from REV and below the elevation of Arrow Lakes Reservoir.

TABLE OF CONTENTS

TABLE OF TABLES

TABLE OF FIGURES

ACKNOWLEDGEMENTS

This project was funded by BC Hydro. The opportunity to carry out the interesting field work and desk-top analysis for this project was much appreciated by all three member organizations of the project team. For BC Hydro, Trish Joyce as the project manager was very helpful with finding data, requesting low flow levels through Revelstoke Dam and keeping the project team on track. Robert Pimer (BC Hydro Sr. Applications Engineer) kept the field crews in touch with the Revelstoke Dam operator and the Power Supply Operating Shift Engineer (PSOSE) for low flow requests and up-to-date discharge information. Guy Martel was the BC Hydro reviewer for this report and Karen Bray (BC Hydro) provided Station 3 stage data.

1. INTRODUCTION

1.1. Background

The Revelstoke Dam (REV) is located on the middle Columbia River (MCR) in British Columbia, Canada, approximately 8 km upstream from the City of Revelstoke. Discharges from the dam flow down the MCR and into the Arrow Lakes Reservoir (ALR), which is impounded by the Hugh L. Keenleyside Dam (HLK) approximately 250 km downstream of the REV. The MCR is defined as the flowing portion of the Columbia River, which varies in length, depending on the water level in the ALR. The Revelstoke Generating Station is the second largest power plant in BC Hydro's hydroelectric power generation system, providing approximately 20% of BC Hydro's total system capacity (BC Hydro 2017).

As part of the BC Hydro implementation of the Columbia Water Use Plan (WUP) for its hydroelectric and storage facilities on the Columbia River in 2007, the Columbia River Water Use Plan Consultative Committee (WUP CC) recommended the establishment of a year round 142 m^3/s minimum flow release from REV to enhance fish habitat in the MCR. The 142 m^3/s minimum flows replaced previous minimum flows of 8.5 m^3/s (seepage flows during zero generation). To reduce uncertainties about the environmental benefits of the proposed minimum flow releases it was recommended to develop and implement programs under the Revelstoke Flow Management Plan (RFMP) to measure changes in the MCR abiotic and biological aquatic environments in response to minimum flow releases. In 2007, BC Hydro commissioned the MCR Physical Habitat Monitoring Program to collect physical habitat and water quality information on the MCR. The potential changes in the biological aquatic environment were investigated as part of other studies carried out under the RFMP umbrella and are informed by the CLBMON-15a results presented here.

The recommended 142 m^3/s minimum flow release from REV was implemented at the same time when BC Hydro also added a fifth generating unit (REV 5) to the Revelstoke Generating Station. REV 5 was commissioned on December 20, 2010 and added 500 MW to the station's generating capacity. This increase in power generation also increased the peak discharge from 1,700 m^3/s to 2,124 m^3/s. Therefore, the impacts of the operation of REV 5 and the implementation of the 142 m^3/s minimum flow (henceforth called the new flow regime) were assessed in one program.

The monitoring of the physical habitat carried out in this study developed logical linkages between REV operations (including REV 5) and physical changes in fish habitat that can be used to inform the other biological studies carried out in the Columbia River.

1.2. Study area

The MCR has a total length of approximately 48 km (Figure 1); its riverine section increases in length at low ALR levels and shortens in length when the ALR is high. ALR levels can fluctuate between 420.0 m and 440.2 m, and can cause a backwater effect into the MCR during times of high reservoir levels (Plate et al. 2014, 2015). The highest ALR levels can backwater the MCR to about 8 km from REV right into the town of Revelstoke in late summer and early fall. The MCR-ALR interface zone is located in the town of Revelstoke at high ALR levels in the summer or downstream of Revelstoke airport at low ALR levels in winter and spring.

The study area for CLBMON-15a Physical Habitat Monitoring Program encompasses the 32-km section of the MCR from the outlet of REV downstream to the confluence with the Akolkolex River, and two major tributaries and is divided as follows (Figure 1):

- MCR Reach 4 (Rkm 238–231.8) – REV downstream to the Jordan River confluence;
- MCR Reach 3 – (Rkm 231.8–226.8) the Jordan River confluence downstream to the Illecillewaet River confluence;
- MCR Reach 2 – (Rkm 226.8–203.5) the Illecillewaet River confluence downstream to the Akolkolex River confluence; and
- Two tributaries – the Illecillewaet (Station 7 at Greely Bridge) and Jordan (Station 8, 6 km from mouth).

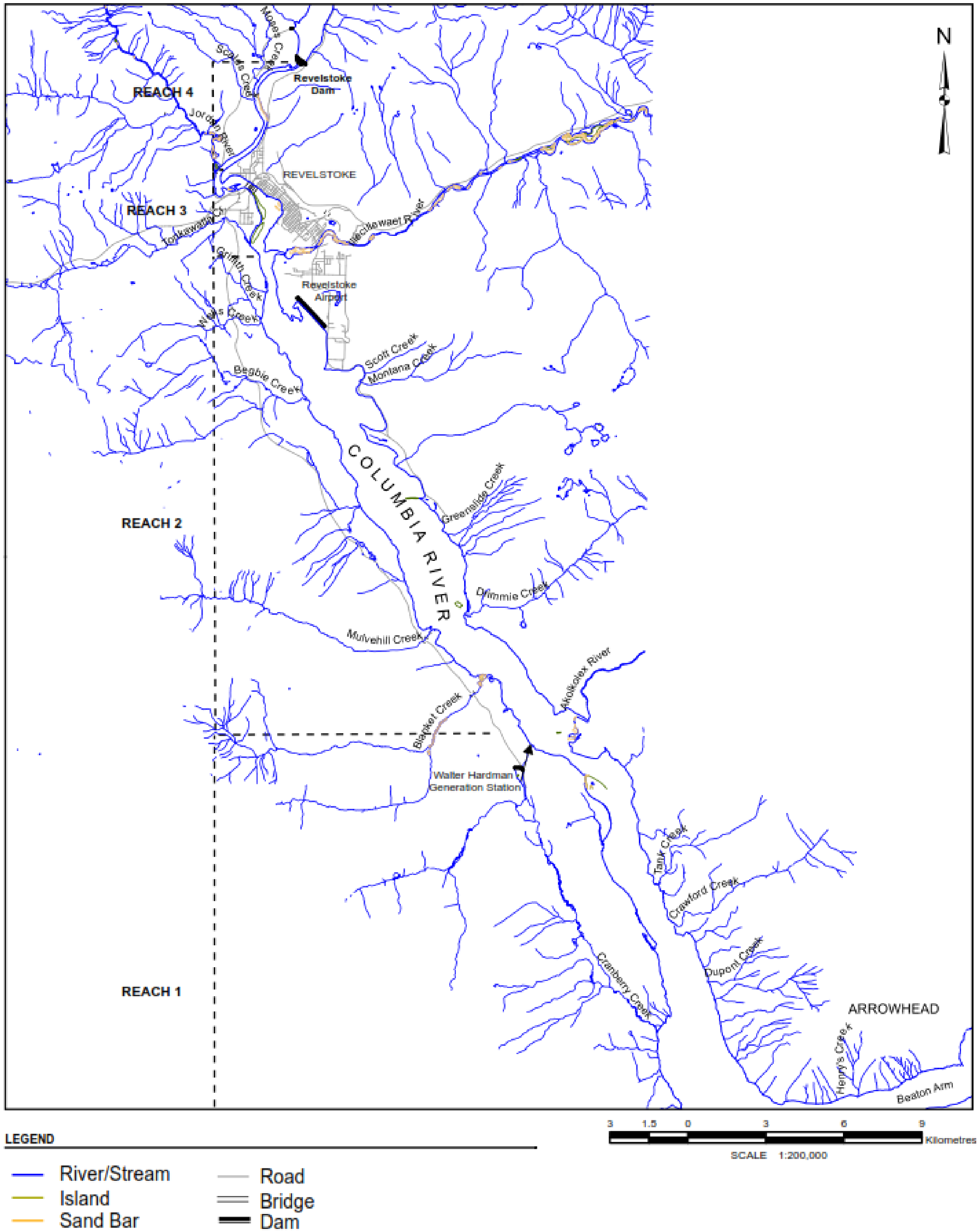


Figure 1 Map showing an overview of the CLBMON-15a study area and the reach naming conventions (Source: Golder 2012, Figure 1, Page 2).

1.3. Monitoring Program Overview and Objectives

The objective of CLBMON-15a was to provide empirical information on the response of key physical habitat variables to the implementation of minimum flow releases from Revelstoke Dam and operation of REV 5 (BC Hydro 2015). Physical habitat data are required to test hypotheses about the observed changes in large river habitat conditions and to support the logical chain of inference for explaining observed changes in key ecological productivity indicators in each of the monitoring programs of the Revelstoke Flow Monitoring Program (BC Hydro 2015).

The objectives of the Middle Columbia River Physical Habitat Monitoring Program are (BC Hydro 2015):

1) To measure spatial and temporal differences in the daily and seasonal river water temperature regimes between current operations and the 142 cms minimum flow regime.
2) To measure spatial and temporal differences in the daily and seasonal range of river level fluctuation between current operations and the 142 cms minimum flow regime.
3) To estimate changes in water quality (nutrient and electrochemistry) resulting from 142 cms minimum flow releases at the reach scale.
4) To estimate changes in the quantity and spatial distribution of permanently inundated river channel resulting from Revelstoke Dam flow releases.

The scope of the Middle Columbia Physical Habitat monitoring program is (BC Hydro 2015):

1) To continuously monitor water temperature and river stage at index monitoring stations focusing on the upper two reaches of the Middle Columbia River (Reaches 3 and 4), and in key tributaries (Jordan and Illecillewaet Rivers).
2) To use existing water quality data and data available from other sources to assess the importance of minimum flow releases in affecting water quality in the Middle Columbia River, Reaches 3 and 4.
3) To use stage data collected during the monitoring program to calibrate existing 1-d steady and unsteady hydraulic models for the Middle Columbia River and to use those models to estimate total area, locations of and changes in inundated river channel.
4) To use the empirical data and hydraulic modeling results to test hypotheses about the influence of minimum flow releases on hydraulic characteristics and temperature of the Middle Columbia River.
5) To develop an electronic data base system for systematic storage and retrieval of physical habitat data for the Middle Columbia.

The geographic scope of the Middle Columbia River is the ~30 km long section from the Akolkolex River to the tailrace of Revelstoke Dam (Reaches 4, 3 and 2; Table CLBMON-15a-1).

While not excluding Reach 2 where possible and applicable, the upper two reaches (3 and 4) are the main focus of sampling and modeling.

1.4. General Approach and Monitoring Program Components

Stage and water temperature monitoring: All details with regards to the deployment, maintenance and operation of the fixed monitoring stations previously installed can be found in Golder (2008, 2009, 2010, 2011, 2012) and Plate et al. (2014, 2015, 2016).

Hydraulic model calibration and application:

Given the dynamic and complex nature of the regulated flow regime, and the geographic extent of the MCR study area, a hydraulic model (HEC-RAS) was required to describe the hydraulics of the MCR within the study area. We calibrated the model parameters using the monitoring data obtained during this study.

The HEC-RAS one-dimensional (1D) backwater hydraulic model, developed by the U.S. Army Corps of Engineers, performs both steady and unsteady state flow analyses in river systems. A HEC RAS model of the MCR was developed by Korman et al. (2002) and calibrated by Golder (2011, 2012, 2014) and Ecofish Research Ltd. (Dashti et al. 2015a and 2015b, Imam et al. 2014).

Ecofish Research Ltd. (Ecofish) was retained by Okanagan Nation Alliance (ONA) to work together with LGL Limited (LGL) to calibrate the existing unsteady state HEC RAS model of the MCR for the 2014/2015 monitoring period. Additional tasks included the QA and processing of the stage and temperature data collected during the monitoring period, and an analysis of local inflows from three MCR tributaries. These data were used for calibration of the HEC RAS model of the MCR.

All details with regards to the development, application and calibration of the HEC-RAS model for both steady and unsteady states can be found in Korman et al. (2002) and calibrated by Golder (2011, 2012, 2013) and Ecofish Research Ltd. (Dashti et al. 2015a and 2015b, Imam et al. 2014).

Seasonal water quality sampling: Based on recommendations resulting from a RFMP workshop in February of 2014, sampling of non-physical and electrochemistry data was not carried out from 2015 to 2018 because point samples could not be deemed representative of long-term conditions. Once the collection of water quality data was terminated, a literature review was carried out to determine potential effects on water chemistry based on changes in discharge from dams in British Columbia and elsewhere. The results of the review can be found under the discussion of Management Question 3 (Does the implementation of the 142 m^3/s minimum flow affect water quality in terms of electrochemistry and biologically active nutrients?) later in this report.

Nevertheless, physical and electrochemistry data were collected once in 2015 at the four index stations in the MCR and in the Jordan River. The physical and electrochemistry data were recorded *in situ* using a handheld multimeter. Detailed methods and results of these water quality measurements can be found in Plate et al. (2015).

Physical data storage and quality assurance: All data collected from 2015 to 2018 were entered into a project MS Access database established by Golder Associates and updated by LGL Ltd. in 2015.

Stage and water temperature monitoring station removal:

In 2017 and 2018, only MCR stations Station 2 and 4 remained functional and were downloaded annually in May for the addition of stage and temperature data to the database without additional HEC-RAS model runs. In May 2018 the remaining loggers at Stations 2 and 4 were removed. In the fall of 2018, the attempt to demobilize the standpipes for all stations was abandoned due to safety concerns and the remaining standpipes will be left in place subject to the development of site-specific demobilization plans that will require work in very steep terrain and on rock faces by specialized technicians secured through rock climbing safety equipment.

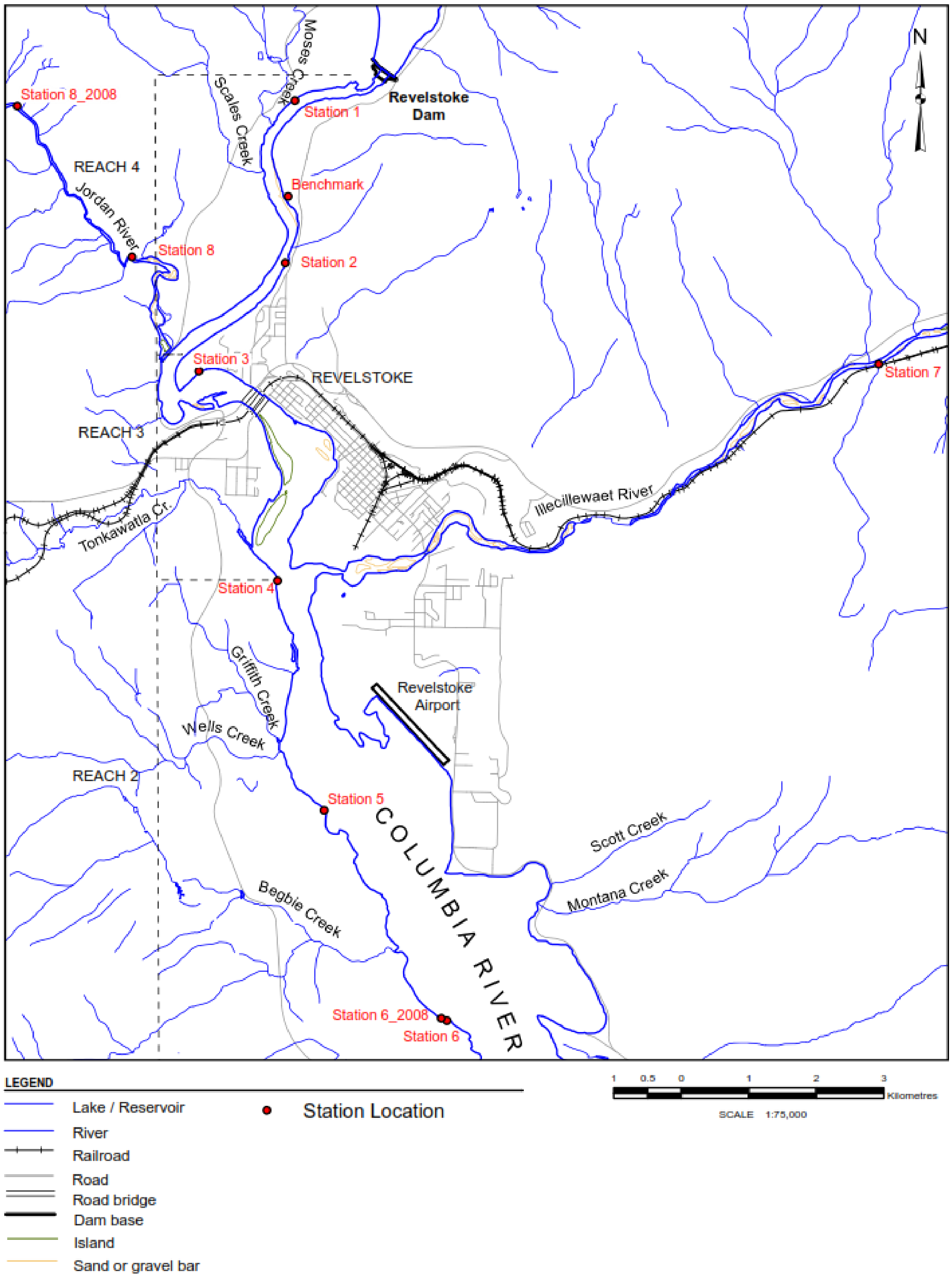


Figure 2 Map showing an overview of the MCR study area and the location of all monitoring index stations (Source: Golder 2012, Figure 2, Page 5).

1.5. **Key CLBMON-15a Management Questions and Hypotheses**

The key management questions addressed by CLBMON-15a are (BC Hydro 2015):

1. How does the implementation of the 142 m^3/s minimum flow affect water temperature in the flowing reach of the Middle Columbia River? What is the temporal scale (diel, seasonal) of water temperature changes? Are there spatial differences in the pattern of water temperature response?
2. How does the implementation of the 142 m^3/s minimum flow affect the range and variability in river level fluctuation in the Middle Columbia River? Are there temporal (seasonal scale) or spatial (reach scale) differences in the pattern of response?
3. Does the implementation of the 142 m^3/s minimum flow affect water quality in terms of electrochemistry and biologically active nutrients?
4. How do flow releases from Revelstoke Dam affect the total area of river channel that is permanently wetted? Are there biologically significant differences in changes in velocity and depth of large river habitats? Where and when do those hydraulic changes occur?

The hypotheses based on the management questions are (BC Hydro 2015):

Hypothesis 1. Implementation of a 142 m^3/s minimum flow release from Revelstoke Dam will not significantly alter the water temperature regime of the MCR.

- Hypothesis 1A: The implementation of a 142 m^3/s minimum flow release from Revelstoke Dam does not significantly change the diel variation of water temperature of the MCR; and
- Hypothesis 1B: The implementation of a 142 m^3/s minimum flow release from Revelstoke Dam will not significantly alter the seasonal pattern of mean water temperature of the MCR.

Hypothesis 2. The implementation of a 142 m^3/s minimum flow release from Revelstoke Dam will not significantly change the magnitude (i.e., range and variability) of river level fluctuations in the MCR.

- Hypothesis 2A: The implementation of a 142 m^3/s minimum flow release from Revelstoke Dam does not reduce the diel variation of river levels in MCR;
- Hypothesis 2B: The implementation of a 142 m^3/s minimum flow release from Revelstoke Dam will not alter the seasonal pattern of mean river level fluctuations in the MCR.

Hypothesis 3. The implementation of a 142 m^3/s minimum flow release from Revelstoke Dam will not significantly increase the area of river channel that is continuously inundated in MCR.

- The implementation of a 142 m^3/s minimum flow release from Revelstoke Dam does not increase the minimum total wetted channel area in Middle Columbia River.
- The implementation of a 142 m^3/s minimum flow release from Revelstoke Dam does not increase the 'ecologically productive' area (minimum total wetted channel area inundated daily for a minimum of 21 days) in Middle Columbia River.

2. METHODS

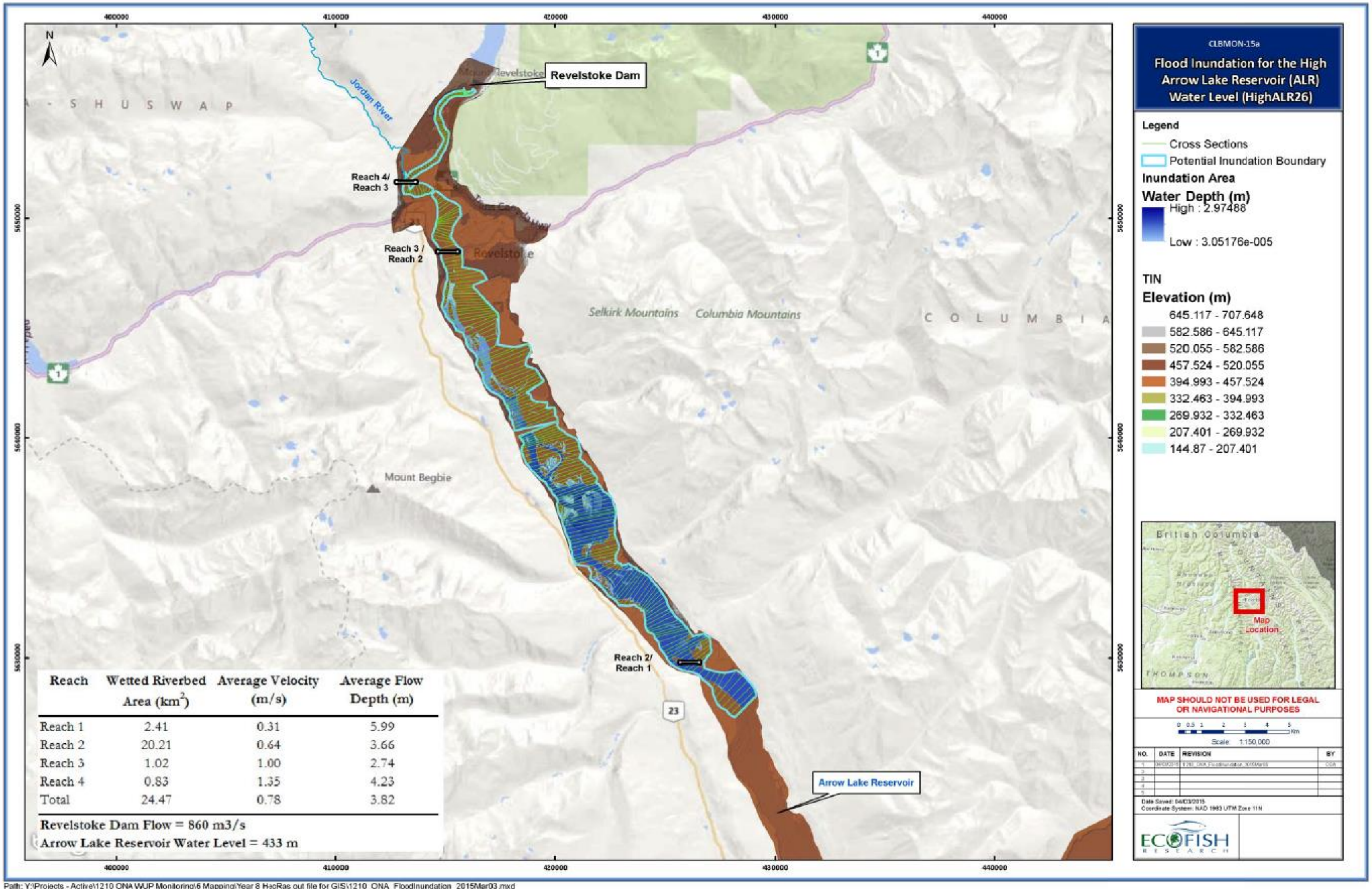
Detailed methods for:

1. River stage and temperature logging in the MCR and the two tributaries (Illecillewaet and Jordan Rivers) can be found in Golder (2014) and Plate *et al.* (2014);
2. Hydraulic model calibration and application for the MCR can be found in Korman et al. (2002) and specific to CLBMON-15a in the MCR in Golder (2011, 2012, and 2014) and Ecofish Research Ltd. (Dashti *et al.* 2015a and 2015b, Imam *et al.* 2014); and
3. Water quality monitoring can be found in Plate *et al.* (2014, 2015, 2016) and Golder (2014).

3. RESULTS

3.1. HEC-RAS Modeling

The MCR-specific HEC-RAS model is most accurate in its prediction of water depth, current velocity and wetted width for the MCR Reaches closest to (7 km) REV. For distances > 7 km from REV and under periodical influence of backwatering from the Arrow Lakes Reservoir, the modelled HEC-RAS values are only accurate in the winter and spring when the Arrow Lakes are at a level that does not create backwatering of the MCR. During the summer and fall at Arrow Lakes high elevations, backwatering has a larger effect on hydraulic parameters of the MCR than REV discharge and consequently a model based on REV discharge has less predictive power for the lower reaches of the MCR. One possible output of the HEC-RAS model was a series of maps that visualized wetted river bed and water depth throughout the MCR at different REV discharge scenarios. One example of these maps is shown in Figure 3.



Reach	Wetted Riverbed Area (km^2)	Average Velocity (m/s)	Average Flow Depth (m)
Reach 1	2.41	0.31	5.99
Reach 2	20.21	0.64	3.66
Reach 3	1.02	1.00	2.74
Reach 4	0.83	1.35	4.23
Total	24.47	0.78	3.82

Figure 3 Example of HEC-RAS model output visualizing wetted river bed and water depth throughout the MCR for a flow of 860 m^3/sec. The three decimals are based on calculated model output while the model is accurate to approximately ± 1 m.

3.2. **Water Temperature**

Overall, daily water temperature fluctuations were greater in the two naturally fed tributaries (Jordan River and Illecillewaet River) than in the MCR (Plate *et al.* 2014, 2015, 2016 and 2015, Golder 2014). The annual and monthly temperature patterns in the MCR remained consistent pre- and post-minimum flow application (Plate *et al.* 2014, 2015, 2016 and 2015, Golder 2014). It is therefore concluded that the minimum discharge did not affect the general temperature pattern over the whole study period and in all reaches.

Water temperature analyses post-implementation of the new flow regime assessed the effect of flow fluctuations on daily temperature variations and showed a decrease in diel variation of 0.1–0.4 °C (Golder 2014). Models to assess the hourly water temperature variations in response to discharge pre- and post-minimum flow implementation had poor fit and predictive ability and did not show any effect (Golder 2014).

3.3. **Seasonal Water Quality Monitoring**

No flow regime-based changes in water quality were detected throughout the study period and based on the low sampling frequencies for physical and chemical parameters, a statistical analysis of the potential effects of the WUP flows was not advisable. In general, water quality for the tributaries and the MCR was indicative of oligotrophic systems (Golder 2007-2014, Plate et al. 2014-2016) (Table 2).

Table 2 Water quality parameter values measured as part of CLBMON-15a in the MCR compared with typical values for oligotrophic systems.

Parameter	Value in MCR	Typical Value Range for Oligotrophic Systems or Systems in Temperate Climate
Total Dissolved Solids	5 - 100 mg/L (average = 60 mg/L)	60-70 Ultraoligotrophic lakes in the U.S.[1]
Dissolved Oxygen	11 - 13 mg/L (96-102 % saturation)	6 – 13 mg/L[2]
Temperature	2 °C winter-spring to 10 °C summer	0-10 °C[3]
Total Nitrogen	100 - 500 µg/L	0 – 700 µg/L[4]
Total Phosphorus	0 - 25 µg/L (majority > 10 µg/L)	0 – 25 µg/L[4]

[1] http://www.lakesuperiorstreams.org/understanding/param_ec.html

[2] BC Ambient water quality guidelines for dissolved oxygen. https://www2.gov.bc.ca/assets/gov/environment/air-land-water/water/waterquality/wqgs-wqos/approved-wqgs/dissolvedoxygen-tech.pdf

[3] BC Hydrometric Stations. On the Internet: https://wateroffice.ec.gc.ca/google_map/google_map_e.html?map_type=real_time&search_type=province&province=BC

[4] Dodds, W.K., Jones, J.R. and E.B. Welch. 1998. Suggested classification of stream trophic state. Water Research, 32 (5): 1455-1462.

4. DISCUSSION

4.1. Management Question 1

How does the 142m^3/s minimum flow and the increased flow based on REV 5 affect water temperature in the flowing reach of the MCR? What is the temporal scale (diel, seasonal) of water temperature changes? Are there spatial differences in the pattern of water temperature response?

Hypothesis 1: Implementation of a 142 m^3/s minimum flow release from Revelstoke Dam did not significantly alter the water temperature regime of the MCR.

Hypothesis 1 is supported by data collected from 2007 to 2015, which showed that diel variation of water temperature following implementation of the new flow regime was 0.1-0.4 °C lower than before (addressing Hypothesis 1A in Section 1.4. *Key CLBMON-15a Management Questions and Hypotheses*), however the ecological significance of this variation is questionable. Similarly, the seasonal pattern of mean water temperatures does not appear to be affected by the new flow regime (addressing Hypothesis 1B in Section 1.4. *Key CLBMON-15a Management Questions and Hypotheses*).

4.2. Management Question 2

How does the implementation of the 142 m^3/s minimum flow affect the range and variability in river level fluctuation in the Middle Columbia River? Are there temporal (seasonal scale) or spatial (reach scale) differences in the pattern of response?

Hypothesis 2: Implementation of a 142 m^3/s minimum flow release from Revelstoke Dam increased diel variation in water levels but did not affect seasonal patterns of mean river fluctuations in the MCR.

Hypothesis 2 was partially supported by data collected from 2012 to 2015. Diel variation in water levels (old flow regime range: 8.5 – 1,750 = 1,741.5 m^3/s; new flow regime range: 142 – 2.150 = 2,008 m^3/s) was larger following the new flow regime (addressing Hypothesis 2A in Section 1.4. *Key CLBMON-15a Management Questions and Hypotheses*), while the seasonal pattern of mean river fluctuations was not affected (addressing Hypothesis 2B in Section 1.4. *Key CLBMON-15a Management Questions and Hypotheses*).

4.3. Management Question 3

Does the implementation of the 142 m^3/s minimum flow affect water quality in terms of electrochemistry and biologically active nutrients?

Little to no difference in electrochemistry and biologically active nutrients were found based on three individual annual samples collected from 2012 to 2015. However, the sampling frequency was deemed to be too low to determine any differences between the pre- and post-new flow regime conditions.

Instead, the literature was reviewed in 2018 to find studies on the effects of minimum flows on hydrological and water quality parameters below dams. As a general result of this review it was determined that many studies have been published on water quality and hydrology below dams, however few were found that test the effects of minimum flows on water quality parameters. Effort was expended in reviewing literature sources using the keywords and search engines outlined in Table 3. In addition, BC Hydro's Water Use Plan studies for all locations (Southern Interior, Northern Interior, Vancouver Island and Lower Mainland) were reviewed.

Table 3 Search engines and keywords used in literature review for CLBMON-15A.

Search Engine	**Keywords**
Google	Effect of minimum flows below dams
	Effect of minimum flows on physical parameters below dams
	Minimum flow effects at dams
	Minimum flows Bull River
	Minimum flows Bow River
	Minimum flows Kananaskis
Bing	Effect of minimum flows below dams
	Minimum flows below dams
	Effect of minimum flows downstream
	Minimum flow effects below dams
	Effects of environmental flows below dams

4.3.1 Results of the Literature Review

The results of the literature search are summarized in Table 4. The most common parameter measured below dams and affected by minimum flow was water temperature (McArthur et al. 2010, Perrin and Bennett 2011, Callisto et al. 2012, Morrone and Triton 2014, Golder and WJ Gazey Research 2015). Few studies included comparisons of pre- and post-treatment data. Perrin and Bennett (2011) conducted a study similar to CLBMON15A on the Coquitlam River and collected long-term data on the following parameters: flow (cms), mean daily water temperature (°C), turbidity, conductivity and pH; the Coquitlam minimum flows varied monthly throughout the year (as did the flows in the MCR) and averaged 3.44 m^3/s in that study, much lower than REV minimum flows and in a smaller system. On average Coquitlam minimum flows ranged between 0.25 – 7 m^3/s, which is far less than the 142 m^3/s implemented at REV.

Table 4 Literature search summary table. Shaded cells represent results for the present study.

Year	Location	Title	Author	Min Flow Level	Study Period	Parameters Measured	Main Results
2016	**BC, Canada**	**Mid Columbia Physical Habitat Monitoring - CLBMON15A**	**Dashti et al. 2016**	**142 cms**	**2012 - 2015**	**water stage, water temperature, water level, wetted area, temperature, conductivity, DO, pH, turbidity**	**Following minimum flows: - diel temp variations reduced by 0.1-0.4°C; - diel variation in water level is larger but the seasonal pattern of river levels is not affected; - no difference in water quality; -wetted river bed area estimated to increase by 32%**
2011	BC, Canada	Coquitlam River Periphyton and Benthic Invert Monitoring	Perrin and Bennett	3.44 cms average	Oct 2008 - ?	flow (cms), mean daily temperature, turbidity, conductivity, pH	Minimum flows increased productivity. While temperature decreased by 1°C after minimum flows were implemented, biodiversity was more affected by riparian inputs and turbidity.
2015	BC, Canada	Peace River Fish Index - Peace River WUP	Golder and WJ Gazey Research	*250 cms	2008 - 2015?	temperature	No comparison between pre- and post-implementation of alternate minimum discharge regime
2015	AB, Canada	Physical habitat below a hydropeaking dam: Examining progressive downstream change (Pocaterra Dam Kananaskis)	Winterhalt	0.5 cms	Summer 2011	velocity, depth, TSS	Changes in depth and velocity between low and high flow releases from dam; increased total suspended solids (TSS) during high flow releases
2014	BC, Canada	Walter Hardman Temperature Effects Monitoring	Morrone and Triton	0.1 cms	2007-2012	temperature	Implementation of minimum flows did not affect water temperatures
2012	Brazil	Minimum flow effects on benthic invertebrates as bioindicators downstream of hydroelectric dams	Callisto et al. 2012	7 cms	June/Oct 2005; June/Dec 2008	temperature, turbidity, alkalinity, oxygen, conductivity, total N and P	Lower conductivity, decreased turbidity, reduced nutrient levels and increased water temperature as a result of reduced flows

* Estimated minimum flow level based on graphs provided in the report.

4.3.2 Discussion

Many challenges were identified which restricted the results of the literature review. In order to effectively evaluate and compare the effects of implementing minimum flows on downstream habitats at different dam locations, the measured parameters (type, sampling frequency, seasonality) would have to be standardized. In addition, the standardized parameters such as stage or temperature were not monitored pre- and post-flow change implementation. In summary, an in-depth discussion of results on the effects of minimum flows / environmental flows on water quality parameters from different dams was not possible based on the identified literature.

4.4. Management Question 4

How do flow releases from Revelstoke Dam affect the total area of river channel that is permanently wetted? Are there biologically significant differences in changes in velocity and depth of large river habitats? Where and when do those hydraulic changes occur?

Implementation of a 142 m^3/s minimum flow release from Revelstoke Dam increased the total area of river channel that is permanently wetted in MCR by 32 % when the Arrow Lakes Reservoir is below 425 masl. Changes in velocity and depth have not affected accrual rates of periphyton within the permanently wetted channel, however peak flows from REV 5 and other high-water events appear to reduce periphyton accrual rates and standing crop in permanently submerged habitats (Schleppe et al. 2018). The implementation of the minimum flow releases increased periphyton accrual rates at elevations which were previously dewatered but have not affected habitats above the minimum flow line (Schleppe et al. 2018).

Data from November 2013 – October 2014 indicated that wetted area of the river ranged between 9.9 km^2 and 28.3 km^2 (average 15.5 km^2 representing an increase of 32% from pre-NFR) while the average flow depth ranged between 2.1 m and 6.8 m (average 2.7 m representing an increase of 30% from pre-NFR), and the average flow velocity ranged between 0.12 m/s and 1.64 m/s (Plate et al. 2015) (Table 5).

Hypothesis 3 (The implementation of a 142 m^3/s minimum flow release from Revelstoke Dam will not significantly increase the area of river channel that is continuously inundated in MCR) was rejected based on Golder 2014 and the HEC-RAS model containing data from 2012 – 2015, and additional calibration data collected from 2016 – 2018 (Stations 2 and 4; Figure 3). At higher reservoir elevations the effect of the new flow regime is lessened beyond 7 km from Revelstoke Dam (addressing Hypothesis 3A and 3B in Section 1.4. *Key CLBMON-15a Management Questions and Hypotheses*).

Table 5 Parameter comparison between conditions before the implementation of the New Flow Regime (NFR) and after its implementation (Source: Before NFR: Golder 2014; Post NFR: Plate et al. 2016).

Parameter	Before (NFR)	Post (NFR)
Wetted Area (Average)	11.8 km^2	15.5 km^2 (32% increase)
Flow Depth (Average)	2.1 m	2.7 m (30% increase)
Flow Velocity (Average)	Was not reported	1.01 m/s

4.5. **Original Management Question 2 (from 2010 Terms of Reference)**

The original Management Question 2 in the 2010 terms of reference (ToR) was: "**How does the implementation of the 142 m^3/s minimum flow affect total gas pressure (TGP) in the flowing reach of the Middle Columbia River?"** This management question was dropped in the 2015 ToR because of the unpredictable nature of the spillway and synchronous condense operations at the Revelstoke Dam could not be monitored within the scope of CLBMON 15a. Instead, BC Hydro's Total Dissolved Gas Strategy (BC Hydro 2014) will assess operational risks and identify opportunities for mitigation at all facilities (including Revelstoke Dam).

4.6. **Shiny App**

In 2017 and 2018 and in consultation with BC Hydro, a web-based application was developed that can be used to download and graph physical data collected as part of CLBMON-15a. The R-based Shiny App developed for the CLBMON-15a currently operates on a combined stage/elevation/flow dataset for the period of 2003-2018. It allows users to explore the dataset in the following views:

1. Elevation (m) by date;
2. Flow (m^3/sec) by date;
3. Stage (m) by date;
4. Level (m) by date; and
5. Temperature (°C) by date.

All views can be filtered for a date range. A curve (or a set of curves – one per station) can be fitted to the selected data for views 2-5. Views 3-5 show the data for individual stations and the set of displayed stations can be filtered individually by station name and for a range of river kilometers.

The App can be accessed via:[2]

[2] Please conctact BC Hydro for access to the App.

- URL: [redacted]
- Password: [redacted]

The following graphs are sample output from the Shiny App that can be saved to a PDF or jpeg file format for immediate pasting into reports (Figure 4, Figure 5).

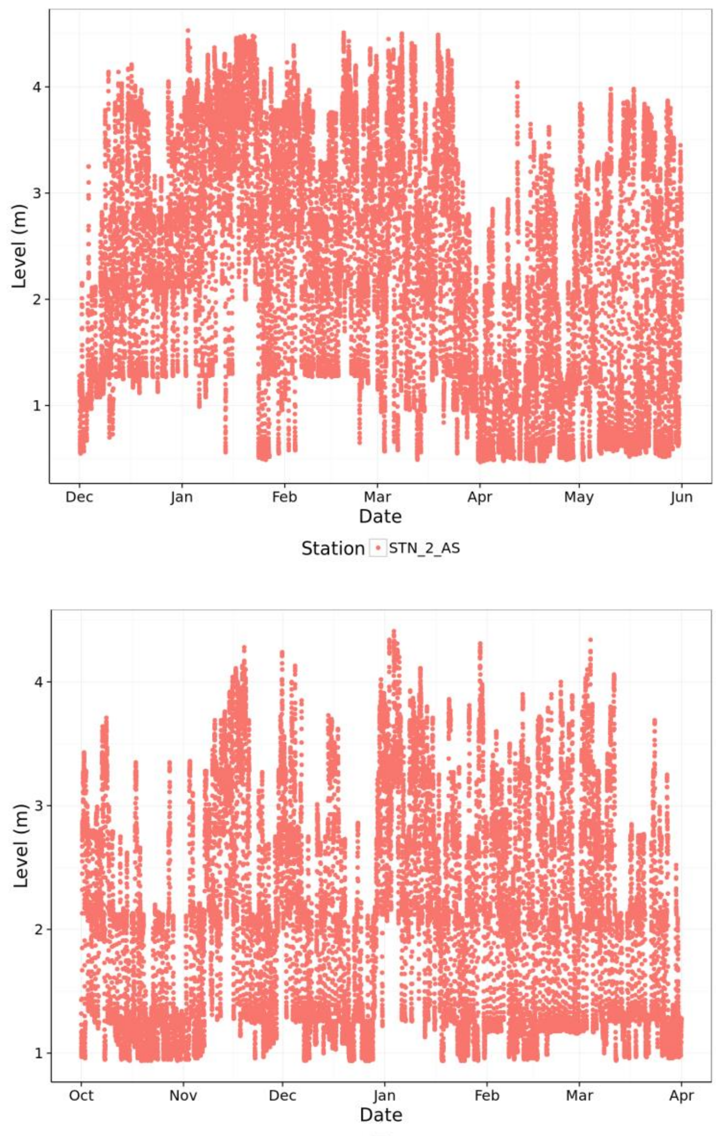


Figure 4 png output from CLBMON-15a Shiny App. In this example, water level at Station 2 Anchor Station (Stn_2_AS) is plotted from December 2012 to June 2013 in the top plot, while the information is plotted for the period from October 2014 to April 2015 in the bottom plot. Note that the water level at this station did not drop below the 1 m level after the new flow regime was implemented in 2014.

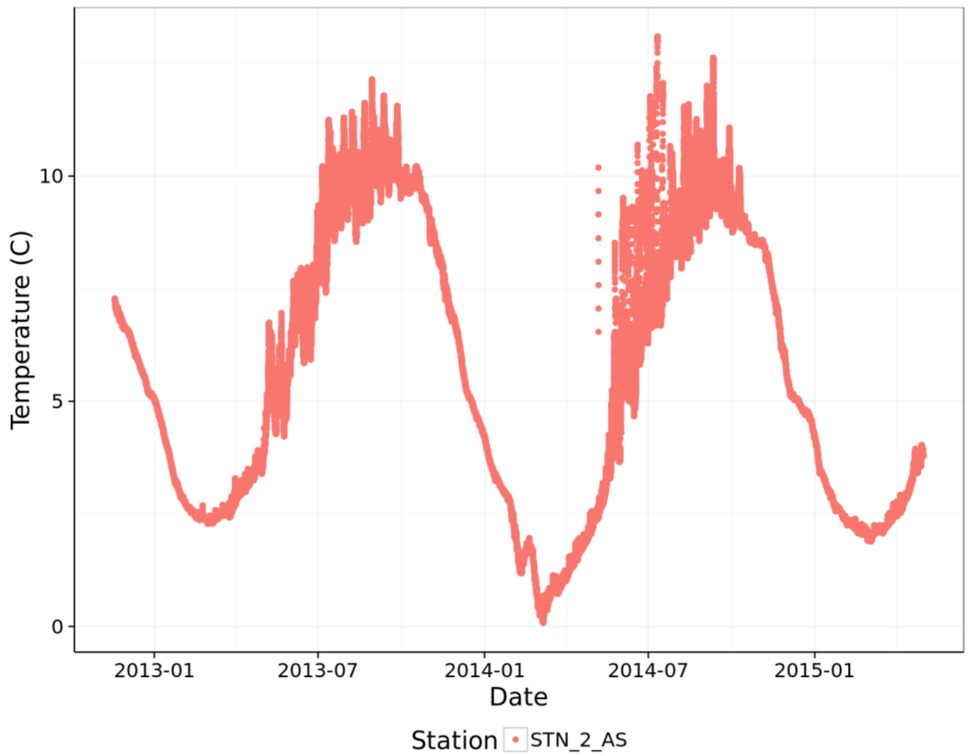


Figure 5 Screenshot of example output from CLBMON-15a Shiny App. In this example, water temperature at Station 2 Anchor Station is plotted from August 2012 to April 2015. Note that the water temperature at this station is always fluctuating in the summer and fall when the air temperatures affect water temperatures and not in winter when they are not.

6. REFERENCES

BC Hydro. 2007. Columbia River Project Water Use Plan. Revised for Acceptance by the Comptroller of Water Rights. On the internet: https://www.bchydro.com/content/dam/hydro/medialib/internet/documents/environment/pdf/wup_columbia_water_use_plan_revised_for_acceptance_by_th.pdf

BC Hydro. 2010. Columbia River Project Water Use Plan. Revelstoke Flow Management Plan. Monitoring Program Terms of Reference. CLBMON-15a Middle Columbia River Physical Habitat Monitoring. On the internet: https://www.bchydro.com/content/dam/hydro/medialib/internet/documents/planning_regulatory/wup/southern_interior/2010q3/web_clbmon-15_tor.pdf

BC Hydro. 2014. BC Hydro Total Dissolved Gas Strategy. Prepared for BC Hydro Environmental Risk Management, Burnaby, BC.

BC Hydro. 2015. Columbia River Project Water Use Plan. Revelstoke Flow Management Plan. Monitoring Program Terms of Reference. CLBMON-15a Middle Columbia River Physical Habitat Monitoring. Revision January 29, 2015. On the internet: https://www.bchydro.com/content/dam/BCHydro/customer-portal/documents/corporate/environment-sustainability/water-use-planning/southern-interior/clbmon-15a-tor-revision-2015-01-29.pdf

BC Hydro. 2017. Quick facts. Available at bchydro.com/quickfacts

Dashti, S., K. Healey, Imam, Y., L. Walker, and N. Wright. 2015 a. CLBMON-15a Middle Columbia River, Physical Habitat Monitoring – River Stage Monitoring and Hydraulic Model Calibration and Application for 2013/2014. Memo to Elmar Plate, LGL Limited., Sidney, BC. May 04, 2015.

Dashti, S.[3], K. Healey, Y. Imam[3], L. Walker[3], N. Wright[3] E. Plate[2] and M. Zimmer[1]. 2015 b. CLBMON15 Mid-Columbia River Physical Habitat Monitoring Project, 2015 (Year 9). Prepared for BC Hydro, Revelstoke, BC. Prepared by: Okanagan Nation Alliance[1], LGL Limited[2] and Ecofish Research Limited[3]: 99 pp. On the Internet: https://www.bchydro.com/content/dam/BCHydro/customer-portal/documents/corporate/environment-sustainability/water-use-planning/southern-interior/clbmon-15a-yr9-2016-12-01.pdf

Golder Associates Ltd. (Golder). 2008. Columbia River Water Use Plan Monitoring Program: Physical Habitat Monitoring Study Period: 2007. Prepared for BC Hydro CLBMON#15a. 23 p + app. On the Internet: https://www.bchydro.com/content/dam/hydro/medialib/internet/documents/environment/pdf/wup_-_columbia_may.pdf

Golder Associates Ltd. (Golder). 2009. Columbia River Water Use Plan Monitoring Program: Physical Habitat Monitoring Study Period: Year 2 – 2008. Prepared for BC Hydro, Castlegar, BC. Golder Report No. 08-1480-0035. 23 p + app. On the Internet: https://www.bchydro.com/content/dam/hydro/medialib/internet/documents/environment/pdf/wup_-_columbia_clbmon-15a.pdf

Golder Associates Ltd. (Golder). 2010. Columbia River Water Use Plan Monitoring Program: Physical Habitat Monitoring Study Period: Year 3 – 2009. Prepared for BC Hydro, Castlegar, BC. Golder Report No. 09-1480-0024. 33 p + app. On the Internet: https://www.bchydro.com/content/dam/hydro/medialib/internet/documents/planning_regulatory/wup/southern_interior/2010q3/clbmon-15a_yr3__no.pdf

Golder Associates Ltd. (Golder). 2011. CLBMON-15a Mid Columbia River Physical Habitat Monitoring. Annual Technical Report – 2010. Prepared for BC Hydro, Castlegar, BC. Golder Report No. 10-1492-0084. 40 p. + 6 app. On the Internet: https://www.bchydro.com/content/dam/hydro/medialib/internet/documents/planning_regulatory/wup/southern_interior/2011q2/clbmon_15a_yr4_2011-06-01.pdf

Golder Associates Ltd. (Golder). 2012. CLBMON-15a Mid Columbia River Physical Habitat Monitoring. Annual Technical Report – 2011. Prepared for BC Hydro, Castlegar, BC. Golder Report No. 11-1492-0084. 44 p. + 6 app. On the Internet: https://www.bchydro.com/content/dam/BCHydro/customer-portal/documents/corporate/environment-sustainability/water-use-planning/southern-interior/mid-columbia-physical-habitat-monitoring-project-water-use-plan-clbmon-15a.pdf

Golder Associates Ltd. (Golder). 2014. CLBMON-15a Mid Columbia River Physical Habitat Monitoring. Annual Technical Report – 2012. Report prepared for BC Hydro, Castlegar, BC. Golder Report No. 12-1492-0084. 44 p. + 6 app. On the Internet: https://www.bchydro.com/content/dam/BCHydro/customer-portal/documents/corporate/environment-sustainability/water-use-planning/southern-interior/clbmon-15a-yr6-2014-01-27.pdf

Imam, Y., S. Dashti, L. Walker, and N. Wright. 2014. CLBMON-15a Middle Columbia River, Physical Habitat Monitoring – River Stage Monitoring and Hydraulic Model Calibration and Application for 2012/2013. Memo to Elmar Plate, LGL Limited., Sidney, BC. February 28, 2014.

Korman, J., L. Lan, L. Hildebrand, and L. Failing. 2002. Fish Habitat Performance Measures to Evaluate Minimum Discharge Requirements for Revelstoke Canyon Dam. Appendix Q. Prepared for Columbia WUP Fisheries Technical Committee. Consultative Committee Report Columbia River Water Use Plan.

Plate, E.M.[2], Y. Imam[3], S. Dashti[3], L. Walker[3], N. Wright[3] and M. Zimmer[1]. 2014. CLBMON-15a Mid-Columbia River Physical Habitat Monitoring Project, 2013 (Year 7). Prepared for BC

Hydro, Revelstoke, BC. Prepared by Okanagan Nation Alliance[1], LGL Limited[2] and Ecofish Research Limited[3]: 95 pp. On the Internet: https://www.bchydro.com/content/dam/BCHydro/customer-portal/documents/corporate/environment-sustainability/water-use-planning/southern-interior/clbmon-15a-yr7-2014-04-01.pdf

Plate, E.M.[2], Y. Imam[3], S. Dashti[3], L. Walker[3], N. Wright[3] and M. Zimmer[1]. 2015. CLBMON15a Mid-Columbia River Physical Habitat Monitoring Project, 2014 (Year 8). Prepared for BC Hydro, Revelstoke, BC. Prepared by: Okanagan Nation Alliance[1], LGL Limited[2] and Ecofish Research Limited[3]: 99 pp. On the Internet: https://www.bchydro.com/content/dam/BCHydro/customer-portal/documents/corporate/environment-sustainability/water-use-planning/southern-interior/clbmon-15a-yr8-2015-06-01.pdf

Plate, E.M.[2], Y. Imam[3], S. Dashti[3], L. Walker[3], N. Wright[3] and M. Zimmer[1]. 2016. CLBMON15a Mid-Columbia River Physical Habitat Monitoring Project, 2014 (Year 9). Prepared for BC Hydro, Revelstoke, BC. Prepared by: Okanagan Nation Alliance[1], LGL Limited[2] and Ecofish Research Limited[3]: 69 pp. On the Internet: https://www.bchydro.com/content/dam/BCHydro/customer-portal/documents/corporate/environment-sustainability/water-use-planning/southern-interior/clbmon-15a-yr9-2016-12-01.pdf

Schleppe, J., R. Plewes, H. Larratt, A. Duncan. 2018. CLBMON-15b Middle Columbia River Ecological Productivity Monitoring, Annual Report 2016. Okanagan Nation Alliance with Ecoscape Environmental Consultants Ltd. & Larratt Aquatic Consulting Ltd. 71 pp. On the Internet: https://www.bchydro.com/content/dam/BCHydro/customer-portal/documents/corporate/environment-sustainability/water-use-planning/southern-interior/clbmon-15b-yr11-2018-12-01.pdf

Literature Cited Specific to Literature Review

Callisto, M., Tupinambas, T., Castro, D., and Maroneze, D. 2012. Minimum flow effects on benthic macroinvertebrates as bioindicators downstream of hydroelectric dams. 9th ISE 2012, Vienna. 8 p.

Golder Associates and WJ Gazey Research. 2015. GMSMON-2 Peace River Fish Index – 2014 Investigations. Peace Project Water Use Plan. Prepared for BC Hydro. 202 p.

McArthur, M., Martel, G., Berdusco, J., and Leake, A. 2010. Monitoring of Winter Habitat Maintenance Flows – Implementation Year 1. Aberfeldie Project Water Use Plan. 65 p.

Morrone, K., and Triton Environmental Consultants. 2014. Lower Cranberry Creek Temperature Effects Monitoring. Walter Hardman Project Water Use Plan. Prepared for BC Hydro. 51 p.

Perrin, C., and Bennett, S. 2011. Coquitlam River Periphyton and Benthic Invertebrate Monitoring. Coquitlam River Project Water Use Plan. Developed for BC Hydro. 87 p.

Winterhalt, L.M. 2015. Physical habitat below a hydropeaking dam: Examining progressive downstream change. MSc Thesis – University of British Columbia. 86 p.