Columbia River Project Water Use Plan

Revelstoke Flow Management Plan

Mid-Columbia Physical Habitat Monitoring

Implementation Year 9

Reference: CLBMON-15a

Study Period: 2015

Prepared by:
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EXECUTIVE SUMMARY

To enhance fish habitat in the Middle Columbia River (MCR) and 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 2010. At the same time the fifth turbine in Revelstoke Dam (REV5) was commissioned and increased the diel maximum flows. 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 was started in 2007 or Implementation Year 1. The 2007 start allowed for four years of data collection pre-minimum flow implementation and four years of post WUP flow implementation data collection to May of 2015. In this report, the physical monitoring results from November 2014 to the end of May 2015 (Implementation Year 9) are summarized. For results of earlier Implementation Years, the reader is referred to Plate et al. (2014, 2015), Golder (2013) and Golder summary reports from 2008 to 2012[1].

The main reason for the 2015 CLBMON-15a data collection, was the addition of stage and temperature data for the last calibration run of the HEC-RAS model that also considered data for Station 3 provided by BC Hydro. To this end, water stage, water level and temperature at four stations in the MCR reaches 2 to 4 and one station each in the Illecillewaet and Jordan rivers was collected with data loggers and downloaded in May of 2015. In addition, a fifth station in the MCR (Station 3) was operated, maintained and downloaded by BC Hydro. In previous years, stage data was also collected at Station 1 closest to the dam. Since the correlation between discharge and stage for this location was well established in 2014, Station 1 was demobilized and no data was collected for this station between November 2014 and the end of May 2015. Within the remaining five MCR stations, Station 2 was located closest (~4 km downstream of REV) to REV while Station 6 was located the farthest (~20 km downstream of REV) from REV. Stage data from the five MCR and the two tributary stations were used to calibrate a HEC-RAS model for the MCR. As of the end of May 2015 monitoring period, the HEC-RAS model has been adequately calibrated and can predict 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 the MCR in 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 in summer and fall. Arrow Lakes Reservoir (ALR) at full or close to full pool backs up the MCR well into the CLBMMON-15a monitoring area and thus buffers effects of the REV discharge on stage at Stations 4–6 in MCR reaches 1–3. 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.

Parallel to the stage and temperature logging, other physical parameters were sampled for the one downloading site visit in May, 2015 at the index stations in the MCR as well as the Jordan River tributary.

Stage and Water Monitoring Results

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

Based on the stage data collected by Golder from 2007–2012 and confirmed by the data collected as part of the 2013 (Plate et al. 2014) and this study, the implementation of the 142 m^3/s minimum flows and the increase in maximum flows at the end of 2010, as expected, led to a greater range of amplitude in diel water levels and flows. Currently, there is no evidence that the WUP flows have changed the seasonal variations in flows or water levels. Similarly, diel variation in water temperature was significantly smaller post WUP flow implementation based on the data by Golder (2013), Plate et al. (2014, 2015) and this study, but no changes to 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 to be used as indicators of trophic status for a particular year. Due to low sample size, these results could not be used to draw conclusions about effects of the implementation of the increased WUP minimum and the increased Revelstoke Dam turbine 5 maximum flow discharges from Revelstoke Dam. The analysis of nutrient parameters was 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 2013, Plate et al. 2014, 2015).

Table 1 CLBMON-15a status of objectives, management questions and hypotheses (Year 9, 2015).

Objectives	**Management Question: 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…**	**Year 9 (2015) Status**
Measure differences in the daily and seasonal river water temperature regimes between pre- and post-implementation of the 142 m^3/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 2012 to 2014 data (only one download in the spring of 2015), diel variation of water temperature following implementation of the 142 $m^3/$ minimum flows and REV 5 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 WUP flows and REV 5.

Measure spatial and temporal differences in the daily and seasonal range of river level fluctuations between pre- and post-implementation of the 142 m^3/s minimum flow regime	…range and variability in river level fluctuations in the MCR	…change the magnitude (i.e., range and variability) of river level fluctuations in the MCR • Ho 3a: diel variation of river levels in MCR • Ho 3b: seasonal pattern of mean river fluctuations in the MCR	Based on 2012 to 2014 data (only one download in the spring of 2015), diel variation in water level following WUP flows and REV 5 is larger because of the new flow regime while the seasonal pattern of mean river fluctuations does not appear to be affected.
Collect seasonal nutrient and electrochemistry data at the reach scale to spatially characterize water quality conditions	…water quality in terms of electrochemistry and biologically active nutrients	…alter the water quality in terms of electrochemistry and biological active nutrients of the MCR • Ho: spatial variation in water quality parameters	Based on 2012 to 2014 data (only one download in the spring of 2015), the sampling frequency (three times per year) for nutrients, physical parameters and electrochemistry is too low to determine any differences between the pre- and post-WUP flows and REV5 conditions. Little to no differences were found in the MCR stations among stations and years. Tributaries consistently showed slight differences when compared with the MCR with regards to nutrients and electrochemistry.
Estimate changes in the quantity and spatial distribution of permanently inundated river channel resulting from 142 m^3/s minimum flow releases	…total area of river channel that is permanently wetted	…increase the area of river channel that is continuously inundated in the MCR • Ho 4a: does not increase the minimum total wetted channel area in the MCR	The estimates based on Golder 2013 and the HEC-RAS model show that the wetted river bed area at minimum flows will increase by 32% when compared with pre-WUP flows and REV 5 when Arrow Lake Reservoir is below 425 masl. When ALR is higher, the effect is lessened.

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Suggested Citation: Dashti, S.[3], K. Healey[3], Y. Iman[3], N. Wright[3], E. Plate[2] and M. Zimmer[1]. 2016. CLBMON-15a 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]:

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, Jason Watson 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.

Evan Smith and Amy Duncan (both ONA) were valuable members of the 2015 field crew.

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 16% of BC Hydro's total system capacity (BC Hydro 2000).

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 address the uncertainty about the environmental benefits of the proposed minimum flow releases it was further recommended to develop and implement programs under the Revelstoke Flow Management Plan (RFMP) to measure changes in the MCR non-physical aquatic environment in response to minimum flow releases. These potential changes in the non-physical aquatic environment were investigated as part of other studies carried out under the CLBMON umbrella and are informed by the CLBMON-15a results presented here.

The recommended 142 m^3/s minimum flow release from REV was implemented in 2010, 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 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 under the CLBMON program.

The MCR has a total length of approximately 48 km and its flowing section increases in length at low ALR levels (Figure 1) 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 daily REV discharge fluctuations significantly affect the availability and suitability of MCR aquatic habitat between the REV and the MCR-ALR interface zone. In 2007, BC Hydro commissioned the MCR Physical Habitat Monitoring Program to collect physical habitat and water quality information on the MCR. 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).

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.

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, 2013) and Ecofish Research Ltd. (Dashti et al. 2015, Imam et al. 2014).

Ecofish Research Ltd. (Ecofish) was retained by 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.

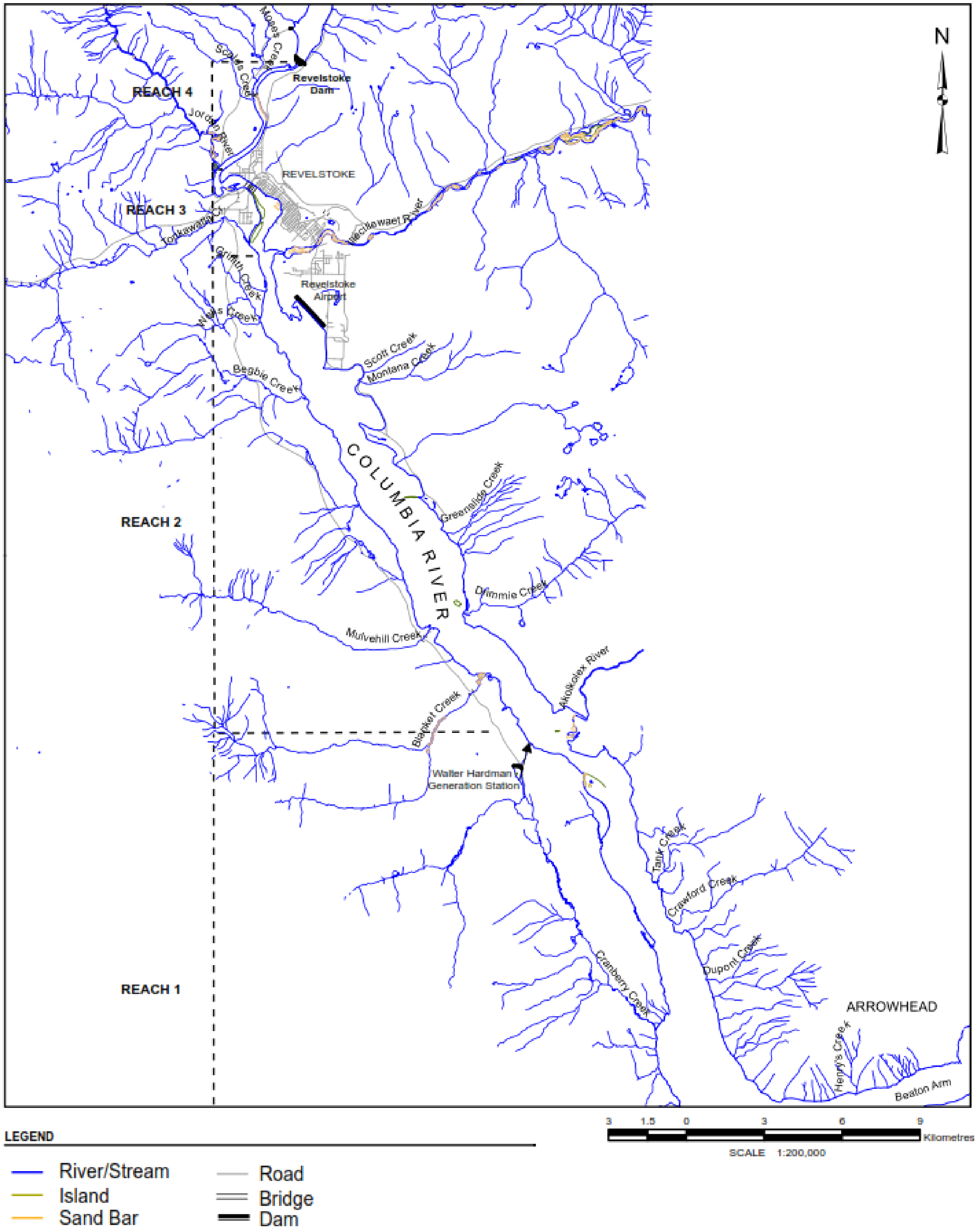


Figure 1 Map showing an overview of the CLBMON-15a study area and the reach naming conventions (Source: Golder 2012).

1.2. Monitoring Program Overview and Objectives

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 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.

1.3. General Approach and Monitoring Program Components

In general, previously installed (Golder 2008, 2009, 2010, 2011, 2012) fixed index monitoring stations continuously recorded river stage and water temperature information while physical water quality was sampled once in 2015 at index site (Figure 2). The monitoring program was divided into the following main data collection and analysis tasks.

- Stage and water temperature monitoring: Stage and temperature data were collected with six time-synchronized data loggers at four stations in the MCR and one station in the Jordan River, a major tributary (Table 2). Data were provided by outside sources for the stage of the Illecillewaet River (Environment Canada automated stream gauging station 08ND013 – Illecillewaet River at Greeley). Stage and temperature data for Station 3 was provided by BC Hydro. All continuous data loggers were deployed in stainless steel standpipes bolted to rock faces or coarse substrate or deployed on anchor systems, and collected data over the large vertical range of possible river stages. MCR data loggers were downloaded and maintained once in 2015. In general, data were collected at 10-minute intervals (Jordan River, 30-minute intervals). On May 6, 2014, and based on the recommendations coming out of a Revelstoke Flow Management Plan (RFMP) interim review workshop in February of 2014, the two stage and temperature loggers at Station 1, closest to REV, were demobilized. The HEC-RAS model predictions for stage at this station predicted the empirical data collected by the stage loggers with high precision. Therefore it was decided that logger data from Station 1 was no longer needed to calibrate the model.
- Hydraulic model calibration and application: A HEC-RAS model was developed for both steady and unsteady states (depending on river section and temporal operation patterns of interest) and calibrated with empirical river stage data collected under this monitoring program. The calibrated model was then used to estimate the quantity and spatial distribution of permanently wetted river channel due to changes in REV operations and backwatering of the ALR. 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, 2013) and Ecofish Research Ltd. (Dashti *et al.* 2015, Imam *et al.* 2014).

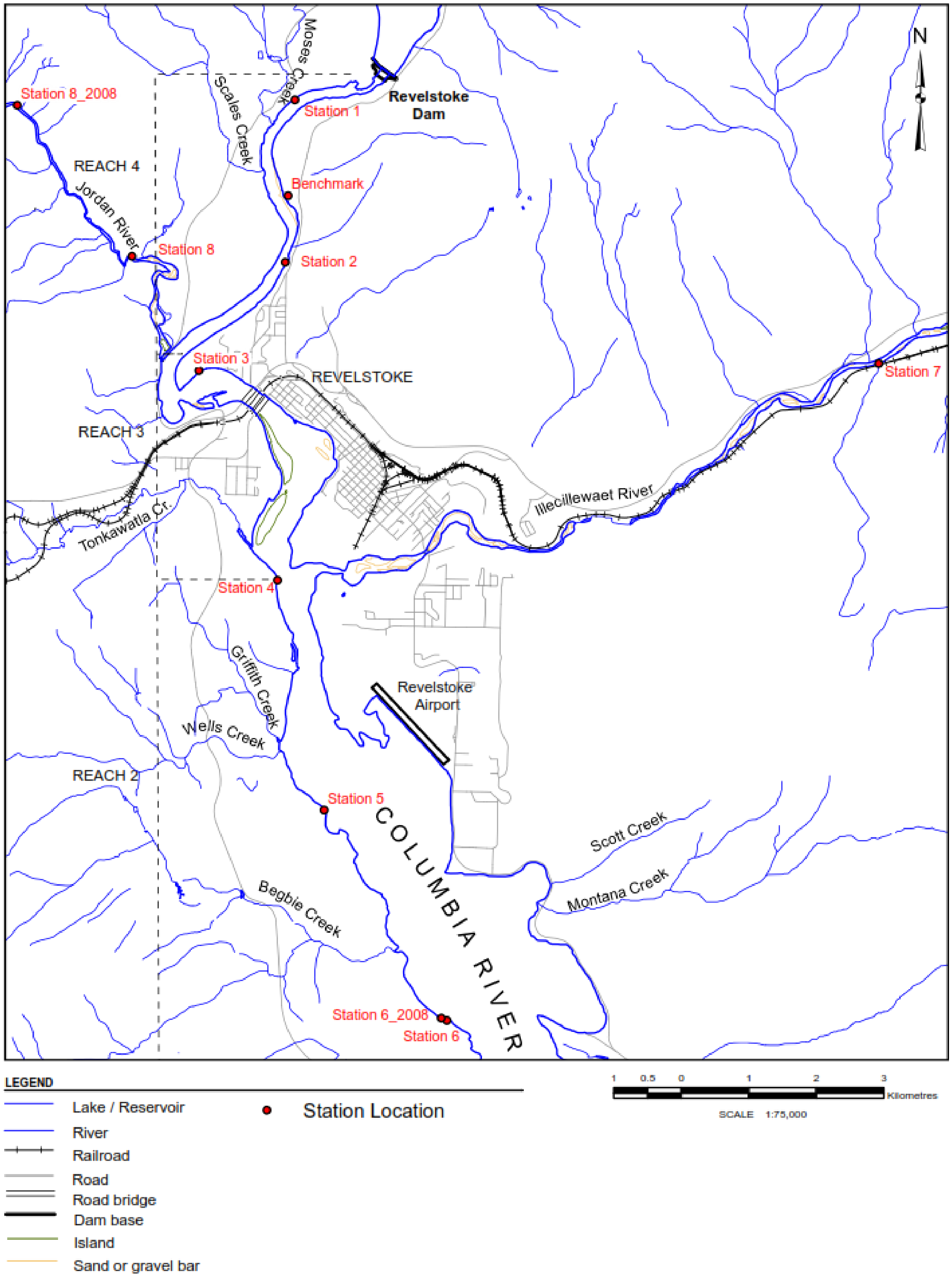


Figure 2 Map showing an overview of the MCR study area and the location of all monitoring index stations (Source: Golder 2012).

- Seasonal water quality sampling: Sampling of non-physical and electrochemistry data was not carried out in 2015 based on recommendations coming out of a RFMP workshop in February of 2014. 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.
- Physical data storage and quality assurance: All data were entered into a project MS Access database established by Golder Associates and improved by LGL Ltd. in 2015.

1.4. 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. STAGE AND WATER TEMPERATURE MONITORING

2.1. Stage and Temperature Monitoring Methods

River Stage and Temperature Loggers – Locations, Surveying and Maintenance

For the purposes of this monitoring program, stage and temperature data were obtained from the following monitoring stations and sources:

- MCR Monitoring Stations 2, 2AS, 4, 5 and 6 (stage and temperature loggers) – (Figure 2) in Reaches 2 through 4;
- MCR Monitoring Station 3 – data provided by BC Hydro;
- Tributary Inflows Study Internal Sources – a stage and temperature logger in the Jordan River and a temperature logger in the Illecillewaet River;
- Tributary Inflows External Sources – an automated stage logger in the Illecillewaet River (Environment Canada automated stream gauging station 08ND013 – Illecillewaet River at Greeley).
- Revelstoke Dam Discharge – hourly and 10-minute (data provided by BC Hydro; note that for the purposes of this monitoring program, the Winter-Kennedy method is used to determine an accurate flow rate through Units 1 to 4 of the REV turbines based on Golder 2013);
- ALR Elevations – as measured at Nakusp in metres (data provided by BC Hydro).

The five river stage data loggers (deployed in four standpipes and one anchor station) were installed on the MCR by Golder (2013). These loggers were attached to wire cables of known length for retrieval and enclosed in standpipes that are attached to steep banks or vertical rock faces. The wire cables were attached to a bolt inside the standpipe with known elevation as a fixed elevation reference point. One additional river stage data logger was installed on an anchor at the standpipe station in Reach 4 (Station 2). The anchor-based monitoring station (Stations 2_AS) was used in calibrating the hydraulic model in previous years. To maintain consistency between years, stations 2_AS were used in model calibration and application for the 2014/2015 monitoring year. Installation and location details for all river stage data loggers are described in Golder (2008; 2013).

In 2015, the HEC-RAS model was also calibrated using data from Station 3 (labelled by BC Hydro as REV 'TR2' or 'Tailrace-7km'), maintained by BC Hydro and located within Reach 3 of the MCR. Station 3 data for November 2012 to August 2013 were made available for the 2014/2015 model runs completed by Ecofish. However, the simulated stages at Station 3 were on average 1 m higher than observed stages. Given that the cause of this difference could not be discerned (i.e., whether this stage difference was the result of a shift in the sensor, or hydraulic control, or whether it was due to model inaccuracy), we did not calibrate the model with Station 3 data last year (Dashti *et al.* 2015).

Station 3 hourly stage data for October 2014 to August 2015 were made available for the 2014/2015 model runs. Simulated water levels were again, on average, 1 m higher than observed level data. BC Hydro determined that an offset correction of +0.44 be applied to the data due to movement of the sensor upon re-installation in October 2014. To account for the additional difference in simulated and observed water levels, an additional offset of +0.54 was applied to the Station 3 water levels. The offset is likely required due to a difference in datum or errors in surveying Station 3, the MCR index stations, and MCR bathymetry. Golder (2012) indicated that the accuracy of bathymetry data is around 0.5 m.

Station 7 discharge measurements for the Illecillewaet River are recorded by Water Survey of Canada (WSC Station No. 08ND013). Data from this station were used to determine inflows to the MCR from this tributary.

Water stage and temperature data at the MCR index and Jordan River stations were obtained using a Solinst Levelogger Gold F300 data logger (accuracy for water level ±0.5 cm; temperature ±0.05 °C). Two barometric data loggers (Solinst Barologgers: accuracy ±0.1 cm) were also installed at Stations 2 and 4. The barometric data loggers were enclosed in separate 1 m (approximate length) standpipes, located ~1-2 m above high water mark on rock outcrops. Data from the barologgers were used for barometric compensation of the water level data.

Water stage and temperature at each of the index stations were recorded at 10-minute intervals, with the exception of the Jordan River Station (Station 8), where data were collected at 30-minute intervals. The 30-minute intervals were sufficient for monitoring changes of water stage and temperature in the tributaries and allowed for additional storage of data in the event the site could not be accessed and downloaded during spring freshet.

The collected water elevation data were corrected by adjusting the values using the surveyed orthometric datum (elevation described above sea level; obtained during the April 30, 2013 field visit), so that all station water elevations were reported using identical metrics. UTM coordinates, elevations (masl), data available, and logging interval are provided for all stations in Table 2.

Table 2 Logger information of the hydrometric gauges installed at MCR for the 2013–2015 monitoring period.

Station Name	System	Solinst Logger Type	UTM Zone 11		Start Date (PST)	End Date (PST)	Duration (Days)	Logging Interval (min)	Elevation (masl)
			Easting	Northing					
CLB-Station 1	MCR	Level	415049	5655566	07-Nov-2013 03:00	06-May-2014 22:30	180	10	438.26
CLB-Station 1_AS	MCR	Level	415049	5655566	07-Nov-2013 02:20	06-May-2014 22:50	180	10	437.38
CLB-Station 2	MCR	Level & Baro[1]	414925	5653213	07-Nov-2013 00:10	26-May-2015 11:00	565	10	436.66
CLB-Station 2_AS	MCR	Level	414925	5653213	07-Nov-2013 00:50	27-May-2015 2:10	566	10	436.83
CLB-Station 4	MCR	Level & Baro[1,2]	414807	5648490	06-Nov-2013 13:30	26-May-2015 12:10	566	10	432.16
CLB-Station 5	MCR	Level	415490	5645100	06-Nov-2013 13:20	26-May-2015 13:05	566	10	430.79
CLB-Station 6	MCR	Level	417171	5642074	06-Nov-2013 13:50	26-May-2015 13:45	566	10	429.36
CLB-Station 8	Jordan R.	Level	410904	5655521	05-Nov-2013 14:00	26-May-2015 17:30	567	30	534.29

[1] No specific coordinates available; located at the gauging station.

[2] Data file used for barometric pressure compensation of stage at all stations. The barologger at Station 2 was back-up.

Station maintenance in 2015 was carried out as part of the one station visit and consisted of the following measures:

- Reviewing the downloaded data to ensure that at least one station at each location had been immersed continuously in water and measuring river stage.
- Checking and potentially reinforcing standpipe support structures.
- Checking the condition of aircraft cables connecting the stage and temperature loggers to the bolt of known elevation on the inside of the standpipe. None of the aircraft cables needed to be replaced in 2015.
- Checking for sediment build up inside the standpipes and flushing out sediment. Sediment had built up in the standpipe at all stations in 2015 and was cleaned out of the standpipes at Stations 2 and 4, the only stations where stage and temperatures gauges were left in place. The stage and temperature gauges for the other stations were removed while the standpipes were left in place for potential future instrument deployment.
- Checking all data loggers for proper operations and exchange them if necessary. All data loggers operated as expected in 2015 and therefore the two data loggers left in the field at Stations 2 and 4 were not exchanged. Two new back-up data loggers were taken into the field in 2015.

2.2. Index Station Elevation Synchronization and Orthometric Correction

Following a re-survey of all stations on April 30, 2013 for position and elevation (Plate et al. 2014), no further surveying of station elevations or position was carried out in 2014.

2.3. Tributary inflows

Tributary inflows were included as inputs to the HEC-RAS hydraulic model for six tributaries to the MCR. Unsteady (variable) flows were estimated for the three largest tributary inflows to the MCR: the Illecillewaet River, the Jordan River, and the Akolkolex River. Steady (constant) flows were used for the three smaller tributaries (Begbie Creek, Drimmie Creek, and Mulvehill Creek), as seasonal variations on these creeks are assumed to have a negligible effect on the model results. Table 3 summarises the methods used to estimate tributary inflows to the MCR, for each of the six tributaries included in the HEC-RAS model.

Flow data for the Illecillewaet, Jordan, and Akolkolex Rivers were hourly averages which is suitable for applying in HEC-RAS model; the annual-average flow for these rivers is an order of magnitude smaller than the annual-average mean discharge from REV.

In general, inaccuracies in the estimated hourly flows for Illecillewaet, Jordan, and Akolkolex Rivers have minor effect on the HEC-RAS model results; the annual-average flow for these rivers is an order of magnitude smaller than the annual-average mean discharge from REV.

Table 3 Methods of estimating tributary inflows to the MCR.

Tributary	Mean Annual Discharge[1] (m^3/s)	Method of estimating inflow to MCR
Illecillawaet River	43	Drainage area proration
Jordan River	17	Ranked regression; Drainage area proration
Akolkolex River	14	Ranked regression
Begbie Creek	3.4	Steady (constant) inflow
Drimmie Creek	5.5	Steady (constant) inflow
Mulvehill Creek	2.8	Steady (constant) inflow

[1] Taken from Golder 2013, Appendix B; estimated from BC Hydro (1985 to 2000)

2.4. Illecillewaet River

The Illecillewaet River is the largest tributary included in the model, with an active WSC gauging station (Illecillewaet River at Greeley: WSC 08ND013) located approximately 10 km upstream of its confluence with the MCR. WSC provided provisional flow data for this station for the modelled period (2013-2014). Illecillewaet inflows to the MCR were estimated by applying a drainage area proration factor to these daily average flow data, to account for the additional inflows to the Illecillewaet River between the WSC station (08ND013) and the confluence with the MCR.

2.5. Jordan River

Station 8, Station 8_2008, and Station 8_2011 were established on the Jordan River with the intention of collecting stage data and discharge measurements, enabling a rating curve to be developed and flow data to be collected for the Jordan River. Four discharge measurements have been collected on the Jordan River during the 2013/2014 monitoring period (Table 4). Three of these measurements were taken under similar flow conditions, and as such, do not yet provide a reliable stage-discharge rating curve for the low (<4.5 m3/s) and high flow range (>14.7 m3/s). No additional discharge measurements were made during the 2014/2015 monitoring period. Thus, tributary inflows from the Jordan River have been estimated using a correlation based on ranked regression analysis between historic data from two WSC Stations: Illecillewaet River at Greeley (WSC 08ND013) and Jordan River above Kirkup (WSC 08ND014).

Table 4. Jordan River discharge measurement results for the monitoring period, May 2013 to September 2014 (no discharge was carried out in May of 2015 due to flooding conditions).

Date	Start and End Time (PST)	Method	Stage (m)	Stage (masl)	Discharge (m^3/s)
01-May-13	13:22-14:21	Wading/Price AA	1.16	535.45	14.6
28-Sep-13	15:28-17:07	Wading/Price AA	1.08	535.37	12.2
05-Nov-13	10:51-12:20	Wading/Price AA	0.93	535.22	4.5
08-Sep-14	17:00-18:35	Wading/Price AA	1.04	535.33	10.2

Available concurrent records of mean daily discharge from the two stations (over 25 years of data between November 1963 and December 1988) were filtered to remove unreliable data, and the remaining datasets were ranked and correlated. The best-fit relationship between the ranked flows was tested by applying it to the unranked data. A comparison of estimated against actual flows at the WSC Jordan River station (1963-1988) resulted in a Nash Sutcliffe Efficiency (NSE) of 0.90, showing the equation to have excellent predictive power. Further details of this ranked regression analysis are provided in Table 5.

Table 5. Details of the ranked regression analyses and resultant correlations developed for the Jordan and Akolkolex Rivers.

Tributary:	Jordan River	Akolkolex River
Stations used	Illecillewaet River at Greeley (WSC 08ND013); Jordan River above Kirkup (WSC 08ND014)	Illecillewaet River near Revelstoke (WSC 08ND003); Akolkolex River near Revelstoke (WSC 08ND001)
Period of concurrent record	November 1963 - December 1988	May 1913 - December 1916
Length of concurrent record	25.1 years	3.7 years
No. cases	8592	1109
Type of equation	4th order polynomial	3rd order polynomial
Equation	$y = 9.17768E\text{-}09x^4 - 6.52058E\text{-}06x^3 + 1.74521E\text{-}03x^2 + 1.91278E\text{-}01x + 9.65814E\text{-}01$	$y = -1.75858E\text{-}06x^3 + 1.71844E\text{-}03x^2 + 1.73827E\text{-}01x + 3.02360E+00$
r^2	0.9992	0.9964
NSE	0.90	0.74

The relationship was then applied to the provisional flow data from the Illecillewaet River at Greeley (WSC 08ND013) station for the period required for the HEC-RAS model (2012-2013), in order to estimate concurrent flows at the Jordan River above Kirkup (WSC 08ND014) station over the same period.

As an additional check, these data were compared with available level data from Station 8_2011 (November 6, 2013 to October 31, 2014), resulting in a correlation with an r^2 value of 0.874.

Finally, the estimated flows for the Jordan River at the WSC station location (WSC 08ND014) were scaled by drainage area proration, to estimate Jordan River flows at its confluence with the MCR.

2.6. Akolkolex River

There has been no active gauging station on the Akolkolex River during the HEC-RAS modelling period (2001-2014), therefore no flow data are available to use as inputs to the hydraulic model. As with the Jordan River, tributary inflows have therefore been estimated using a correlation based on ranked regression analysis between historic data from two WSC Stations: Illecillewaet River near Revelstoke (WSC 08ND003) and Akolkolex River near Revelstoke (WSC 08ND001).

Available concurrent records of mean daily discharge from the two stations (3.7 years of data between May 1913 - December 1916) were filtered to remove unreliable data, and the remaining datasets were ranked and correlated. The best-fit relationship between the ranked flows was tested by applying it to the unranked data. A comparison of estimated against actual flows at the WSC Akolkolex River station (1913-1916) resulted in a Nash Sutcliffe Efficiency (NSE) of 0.74, showing the equation to have reasonable predictive power. Further details of this ranked regression analysis are also provided in Table 5.

The relationship was then applied to the provisional flow data from the Illecillewaet River at Greeley (WSC 08ND013) station (adjusted by drainage area pro-ration to represent flows near the Illecillewaet River near Revelstoke (WSC 08ND003) station) for the period required for the HEC-RAS model (2013-2014), in order to estimate concurrent flows at the Akolkolex River near Revelstoke (WSC 08ND001) station over the same period. No further adjustment to the flow data was required, as the Akolkolex River near Revelstoke (WSC 08ND001) station is located within a few hundred metres of the confluence with the MCR. Further, errors in the estimated flow for Akolkolex River likely have negligible effect on the HEC-RAS model results; Akolkolex River flows into MCR near the downstream boundary of the modelled domain.

3. HYDRAULIC MODEL CALIBRATION AND APPLICATION

3.1. Introduction

Given the dynamic and complex nature of the regulated flow regime, and the geographic extent of the MCR study area, the Hydrologic Engineering Centers - River Analysis System (HEC-RAS), a hydraulic model 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. 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, and 2013) and Plate et al. (2014, 2015).

Ecofish Ltd. (Ecofish) was retained by 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.

3.2. Scope

Ecofish updated the existing HEC-RAS model provided by BC Hydro and calibrated by Ecofish in 2014 and 2015, entered new flow data into the model, ran unsteady-state simulations with the model, and exported the results to MS Excel. Validation periods were selected and for each validation period Ecofish compared model predictions to stage data to determine if further model calibration was necessary. At the request of BC Hydro, model performance was assessed to determine its ability to resolve habitat conditions at different flows. The model results were used to estimate hydraulic parameters that are important to fish habitat. In addition, 30 steady-state simulations ran during the low ALR water level and 30 steady-state simulations ran during the high ALR water level; the results were exported to MS Excel and as GIS data files. Among the 60 steady-state simulations, 20 simulation results were chosen to produce flood maps.

3.3. Methods

Model Setup

The HEC-RAS model was used to simulate the period between November 01, 2014 and May 31, 2015. For this period, data were generally available for Revelstoke Dam, stations along MCR, Arrow Lakes Reservoir, and major tributaries. Short gaps in the data records were filled using linear interpolation. For all simulated periods, a time step of 10 minutes was used. This short time step ensured the accuracy of the model results, in particular during rapid changes in REV discharge.

The modelled domain extended 37 km downstream of Revelstoke Dam (REV). Discharge from REV was applied at the upstream boundary of the domain. Six tributary inflows were accounted for in the model including flows from the major tributaries Illecillewaet, Jordan, and Akolkolex Rivers and the smaller tributaries Begbie, Drimmie, and Mulvehill Creeks. At the downstream boundary of the domain, ALR water level was applied.

Except for Jordan River, tributaries were accounted for in the model using lateral inflows and the geometry of the tributaries was not included explicitly. For Jordan River, a 0.6 km reach consisting of three cross-sections was used to represent this tributary (this reach is described in Plate *et al.* 2014, 2015).

Model Calibration

Preliminary runs with the HEC-RAS model indicated that model calibration was required. Calibration of the model involved comparing observed and simulated stages at five stations. These stations were 2_AS, 3, 4, 5, and 6 (Table 2). To account for the difference in simulated and observed water levels, an offset of +0.99 was applied to Station 3 data.

Model results for Stations 2, 3 and 4 indicate that the model underestimates water level for low flows in the MCR. To resolve this, the roughness coefficients were increased at low flows and reduced at high flows for cross sections between 168 -182 and (Table 6).

To improve the model results, slight adjustments to the cross-section elevations around Station 5 were also made. These adjustments were consistent with the accuracy of the bathymetry data used for developing the model and were smaller than previous elevation adjustments of 0.5 m done by Golder (2012).

Table 6. Calibrated flow roughness coefficients used in the unsteady-state hydraulic model for cross sections between 168-182 and 167-124 (see Table 7).

Flow	**Model Cross Section Range**	
(m^3/s)	**182-168**	**167-124**
0	1.25	1.2
400	1.15	1.1
600	1.1	1.05
800	1	1
1000	1	1
1200	0.9	0.9
2200	0.85	0.85

To improve the model results, slight adjustments to the cross-section elevations were considered. These adjustments were consistent with the accuracy of the bathymetry data used for developing the model and were smaller than previous elevation adjustments of 0.5 m done by Golder (2012).

Model Performance Assessment

The model performance determines its ability to resolve habitat conditions at different flows. The resolution of the model was evaluated for each station as follows:

1. We approximated the relationship between simulated stage and discharge using the model output time series, considering moving averages of width 50 m^3/s to 350 m^3/s.
2. We assumed that these relationships reflect the true relationships between stage and discharge.
3. Over the range of model flows (~142 to 2100 m^3/s) we calculated the difference in stage corresponding to flow intervals of 50 m^3/s, 100 m^3/s, 150 m^3/s, 200 m^3/s, 300 m^3/s and 350 m^3/s.

4. We compared these stage differences to the model errors (i.e., difference between simulated and observed stage) for the model output time series.
5. For each time series data point, if the model error was greater than the stage differences corresponding to a given flow interval, we assumed that the model would be unable to resolve that flow difference under the conditions present. If the model error was less than the stage difference corresponding to the flow interval, then the model would be able to resolve that flow difference.
6. The time series data were binned by flow in increments of 50 m^3/s for summary purposes.
7. For each flow bin, the number of data points where the model error was less than the stage differences was determined. This number was divided by the total data points in the bin to estimate the probability of being able to resolve each flow difference at different flows.

Note that the above evaluations are provided for the low ALR water level conditions at Stations 5 and 6, and for the whole period for Stations 2, 3 and 4.

Analysis of Simulated Hydraulic Parameters

Model results for November 2014 to May 2015 were used to estimate hydraulic parameters that are important to fish habitat. The estimated parameters were wetted bed area, average flow velocity, and average flow depth. These parameters were estimated for reaches 1 to 4 and also for the entire modelled domain.

Wetted bed area was calculated for each reach using,

$$A_i = \sum_{j=2}^{n_i} \left(\frac{P_{j-1} + P_j}{2} \right) \Delta x_{j-\frac{1}{2}} \tag{1}$$

where $A_i(t)$ is the wetted bed area for reach $i = 1,2,3,4$ at time t; P_{j-1} and P_j are the wetted perimeters of the adjacent cross-sections $j - 1$ and j, respectively; and $\Delta x_{j-\frac{1}{2}}$ is the distance between cross-sections; and n_i is the number of cross-sections in reach i. For the modelled domain, the wetted bed area A was set to the sum of wetted areas for the four reaches,

$$A = \sum_{i=1}^{4} A_i \tag{2}$$

The average flow depth for each reach was estimated using,

$$d_i = \frac{\forall_i}{s_i} \tag{3}$$

where d_i, $\forall_i$, and s_i are the average flow depth, volume, and surface area for reach i, respectively. The average flow depth for the entire domain was computed using,

$$d = \frac{\sum_{i=1}^{4} \forall_i}{\sum_{i=1}^{4} s_i} \tag{4}$$

where $\sum_{i=1}^{4} \forall_i$ is the total volume of water in the domain at time t and $\sum_{i=1}^{4} s_i$ is the corresponding surface area.

The average flow velocity for each reach was estimated using the distance-weighted mean,

$$\overline{U}_i = \frac{1}{L_i} \sum_{j=2}^{n_i} \left(\frac{U_{j-1} + U_j}{2} \right) \Delta x_{j-\frac{1}{2}} \tag{5}$$

where $\overline{U}_i$ is the average flow velocity for reach $i = 1,2,3,4$; U_{j-1} and U_j are the average flow velocities through cross-sections $j-1$ and j, respectively; $\Delta x_{j-\frac{1}{2}}$ is the distance between cross-sections $j-1$ and j; $L_i = \sum_{j=2}^{n_i} \Delta x_{j-\frac{1}{2}}$ is the length of reach i; and n_i is the number of cross-sections in reach i. For the modelled domain, the average flow velocity was also calculated using a distance-weighted mean,

$$\overline{U} = \sum_{i=1}^{4} \overline{U}_i \frac{L_i}{L} \tag{6}$$

where $L = \sum_{i=1}^{4} L_i$ is the length of the modelled domain.

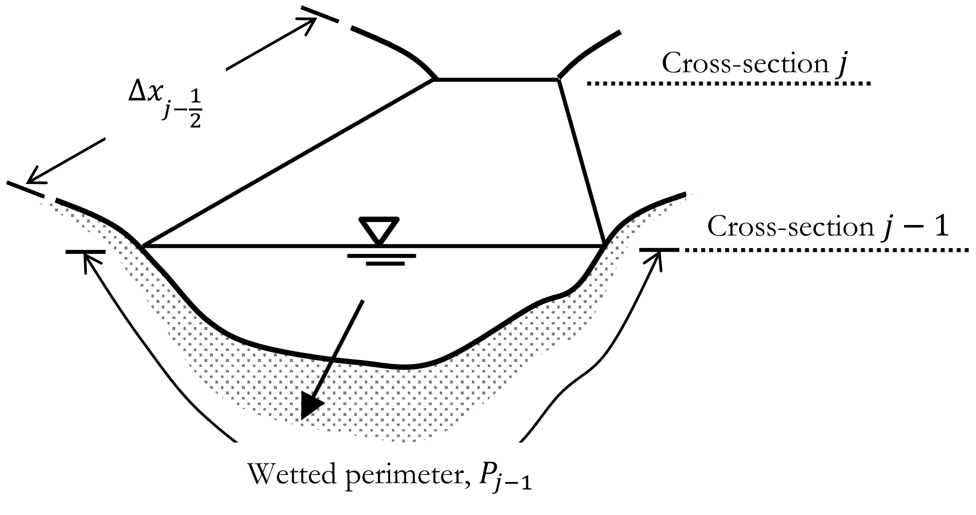


Figure 3. Schematic of stream cross-sections showing variables used in calculating wetted area.

Steady-State Simulations

To produce inundation maps and provide the average hydraulic characteristics of each river reach for low and high ALR water levels and different flows conditions, 30 steady-state simulations ran during the low ALR water level and 30 steady-state simulations ran during the high ALR water level; the results were exported to MS Excel and as GIS data files. Among the 60 steady-state simulations, 20 simulation results were chosen to produce flood maps that best represented the change in flood area under different flow conditions and ALR levels.

BC Hydro supplied a Digital Terrain Model (DTM) covering the Columbia River from Revelstoke Dam to the Arrow Lakes Reservoir. The DTM consisted of various data sources collected over multiple years:

1. 2007 data compiled from stereo collection at low water conditions;
2. 2011 data supplied by a subcontractor from a small format camera;
3. July 2012 LiDAR coverage during high water conditions.

The data collected in 2007 extended from reach 4 to almost the end of reach 2 (or cross-section 243 to cross-section 37), and was collected at low water conditions. The 2011 data covered the full extent of the Columbia River from the Revelstoke Dam to the Arrow Lakes Reservoir; the accuracy of this data is unknown. The 2012 data overlapped the above two sets of data, but was not an exact match. The coverage of this file extended from reach 4 to the middle of reach 2 (or cross-section 243 to cross-section 125), and was most accurate for high flow conditions.

The three DTM layers were combined into one Triangulated Irregular Network (TIN) file and used as the underlying terrain map. For each steady-state simulation the water elevation data over the Columbia River was exported from HEC-RAS as a GIS file. HEC-GeoRAS was used to compute the difference between the terrain elevations and water surface elevations to produce the flood inundation maps. Areas with positive elevations (meaning water surface is higher than the terrain) are flood, while areas with negative elevations are dry.

3.4. Hydraulic Model Calibration and Application Results

Model Calibration

For the model calibration period, November 01, 2014 to May 31, 2015, the Manning roughness coefficients for the cross sections between 168 -182 and 124-167 were increased at low flows and reduced at high flows using the flow roughness factor (Table 7). A well calibrated model has small differences between simulated and observed water levels, and from the 2014/2015 model calibration results (Table 8), it appears that the MCR model is well calibrated.

Table 7 Calibrated Manning roughness coefficients for the unsteady-state hydraulic model. Shown are the calibrated roughness coefficients for the previous versions of the model (Plate et al. 2014 and 2015, and Golder 2013) and the current version of the model. Also shown is the expected range of roughness coefficients based on channel morphology and bed type (Golder 2013). The roughness coefficients did not require adjustment in 2013/2014 from those used in the previous 2012/2013 MCR model.

Model Cross Section Range[1]	**Expected Range**	**Manning Roughness Coefficient**		
		Golder (2013)	**Ecofish (2014)**	**Ecofish (2016)**
243-201	0.03 to 0.035	0.035	0.030	0.030
200-183	0.03 to 0.035	0.03	0.030	0.030
182-168	0.035 to 0.08	0.045	0.080	-[2]
167-124	0.035 to 0.08	0.038	0.030	-[2]
123-116	0.017 to 0.04	0.028	0.017	0.017
115-1	0.017 to 0.04	0.02	0.020	0.020

[1] Cross-section 243 is at the upstream end of the modelled domain (i.e., at REV). Cross-section numbers decrease in the downstream direction.

[2] The flow roughness factor is applied for these model cross section ranges.

Table 8 Agreement between simulated and observed stages at the MCR stations. Given are the root mean square error (RMSE), bias, and bounds for differences between simulated and observed stages. Results are shown for the previous versions of the model (Imam et al. 2014 and Dashti et al. 2015) and for the validation runs done with the current version of the model.

Validation Period	Parameter	Station 1_AS	Station 2_AS	Station 3	Station 4	Station 5	Station 6
Ecofish(2014)	Upper Bound(m)	0.86	0.62		0.16	0.26	0.41
18-Nov-12	Lower Bound(m)	-1.75	-2.12		-1.14	-1.27	-0.42
to 10-Feb-2013	BIAS(m)	0.09	-0.06		-0.06	-0.05	-0.03
	RMSE(m)	0.22	0.26		0.15	0.22	0.12
Ecofish(2014)	Upper Bound(m)	0.72	0.52		0.2	0.12	0.56
11-May-13	Lower Bound(m)	-1.24	-1.38		-1.03	-1.26	-0.8
to 06-Nov-2013	BIAS(m)	0.05	-0.14		-0.19	-0.37	-0.06
	RMSE(m)	0.19	0.29		0.23	0.39	0.19
Ecofish(2015)	Upper Bound(m)	0.6	1.86		1.18	0.67	0.5
06-Nov-13	Lower Bound(m)	-0.33	-1.47		-0.74	-0.76	-0.43
to 30-Oct-2014	BIAS(m)	0.12	0.02		-0.07	-0.09	0.06
	RMSE(m)	0.18	0.23		0.18	0.23	0.14
Ecofish(2015)[*]	Upper Bound(m)	0.6	1.86		1.18	0.67	0.5
06-Nov-13	Lower Bound(m)	-0.33	-1.47		-0.69	-0.76	-0.39
to 30-Oct-2014	BIAS(m)	0.12	0.02		-0.07	-0.09	0.06
	RMSE(m)	0.18	0.23		0.17	0.23	0.14
Ecofish(2016)	Upper Bound(m)		0.66	1.09	0.35	0.29	0.42
01-Nov-14	Lower Bound(m)		-0.6	-0.67	-0.25	-0.43	-0.22
to 31-May-2015	BIAS(m)		0.04	0.1	0.05	-0.1	0.1
	RMSE(m)		0.14	0.24	0.09	0.15	0.14

[*] The goodness-of-fit measures were revised after correcting for an error in time zone for Station 4, 5 and 6 data.

The following section provides an evaluation of the model performance at different flows for each station.

Model Performance Assessment

The data points shown in Figure 4 and Figure 5 represent the stage and flow time series data simulated by the MCR model. The solid colored lines represent the stage discharge rating curves for the average flow intervals from 50–300 m³/s. Aside from extreme low or high flows conditions, where data are sparse, the relationships are similar for all averaging intervals. These relationships are valid for low ALR water level conditions at Station 5 and 6, and for all conditions at Stations 2, 3 and 4.

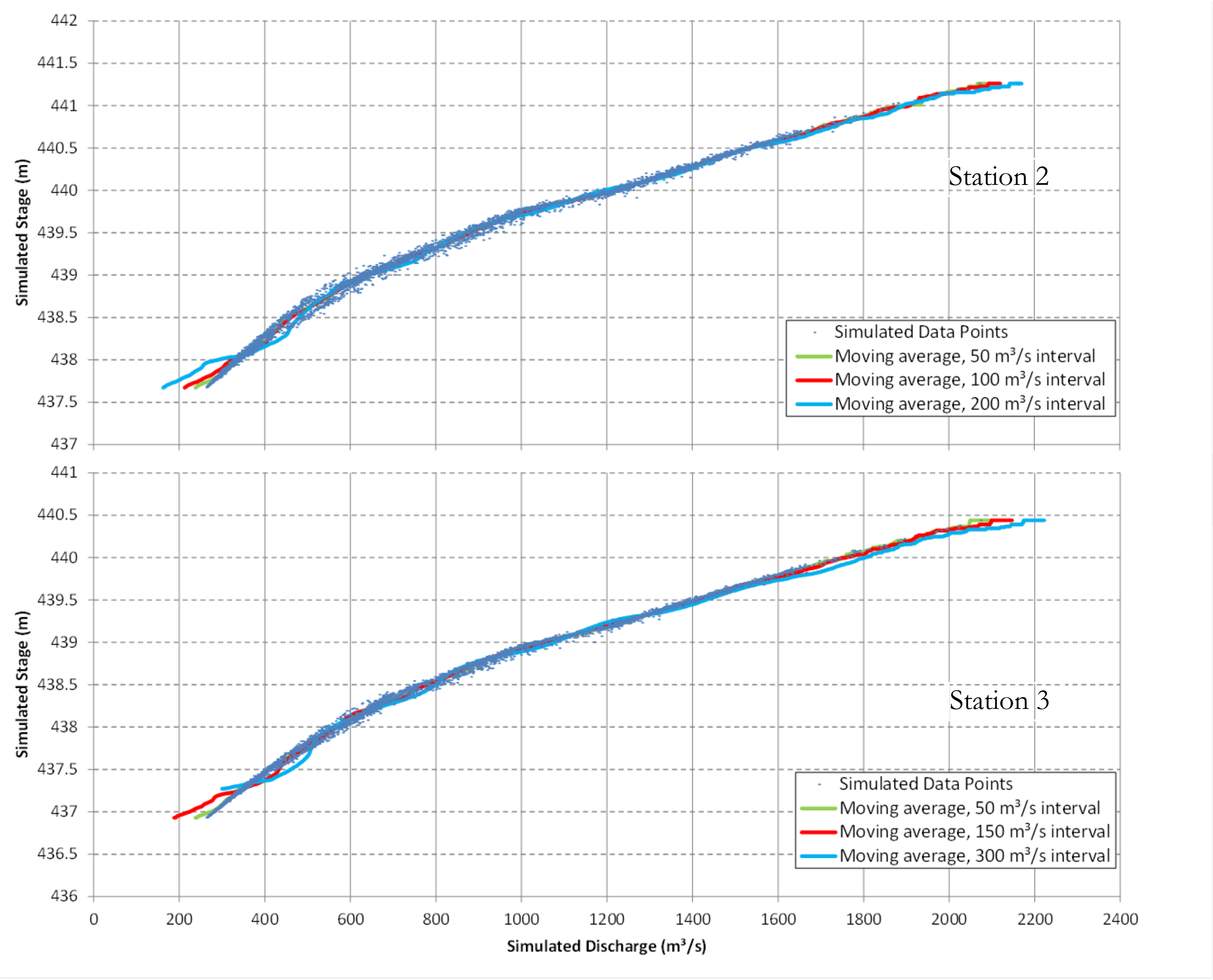


Figure 4 Relationship between stage and discharge at MCR stations 2 and 3 simulated by the model (data points) and calculated via moving average across flow intervals ranging from 50- 300 m^3/s.

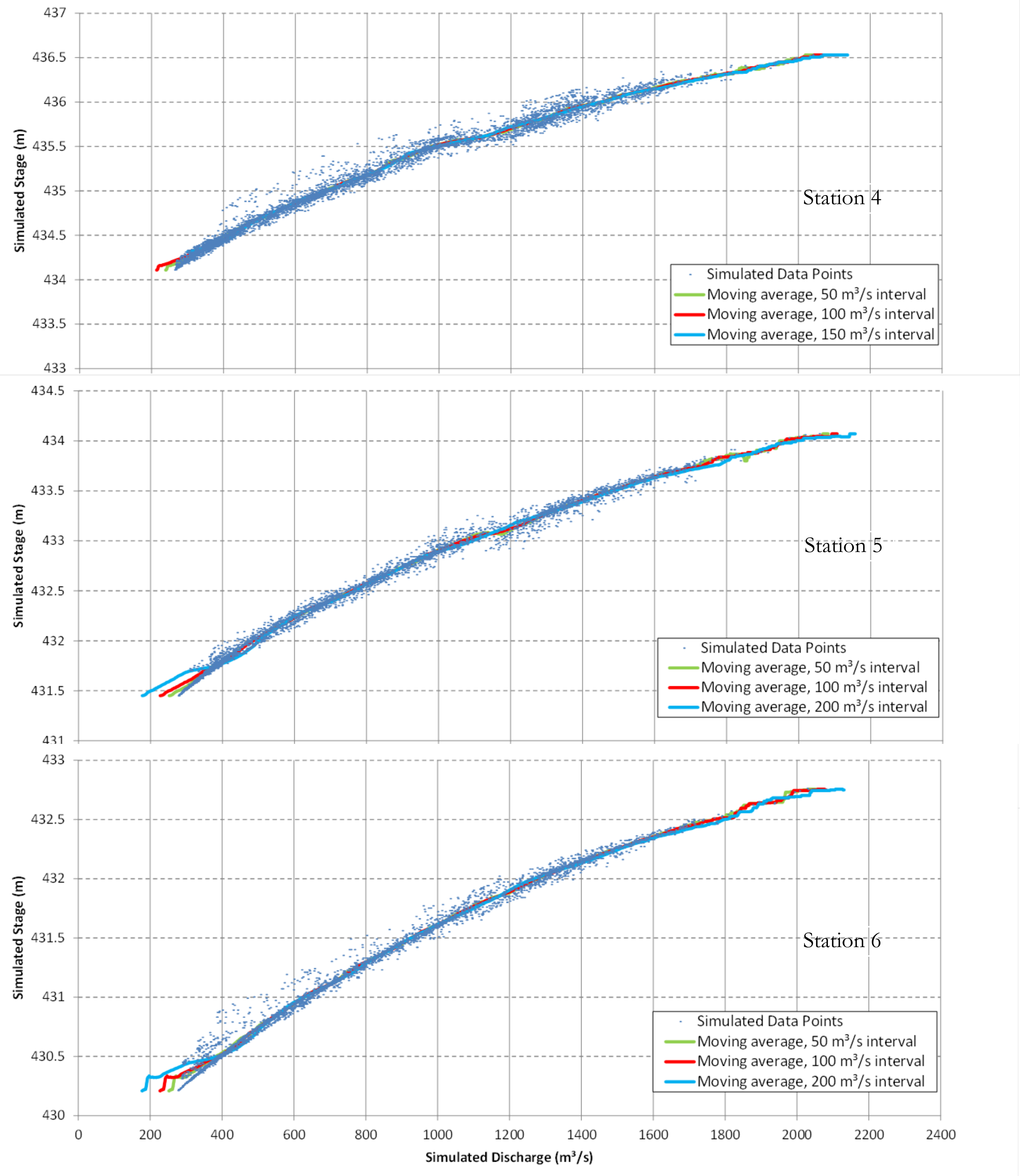


Figure 5 Relationship between stage and discharge at MCR stations 4, 5 and 6 as simulated by the model (data points) and calculated via moving average across flow intervals ranging from 50 m^3/s to 200 m^3/s.

The model performance assessment is further summarized in Figure 6 that shows the estimated probability of resolving flow differences of 50, 100 and 200 m^3/s for five MCR Stations.

For Station 2, the model can resolve differences of 200 m^3/s with ~ 100% probability at all flow conditions. Between ~1200 and 1700 m^3/s, the model can reliably resolve differences of ~ 100 m^3/s, and below 400 m^3/s, the model can reliably resolve differences of ~ 50 m^3/s.

For Station 3, the model can resolve differences of 150 m^3/s with near 100% probability between roughly 300 and 800 m^3/s. The model resolution is poorer (150 to 300 m^3/s) outside of this flow range.

For Station 4, the model can resolve differences of 100-150 m^3/s with near 100% probability at all flow conditions. The model can resolve differences of ~200 m^3/s at Station 5 and Station 6.

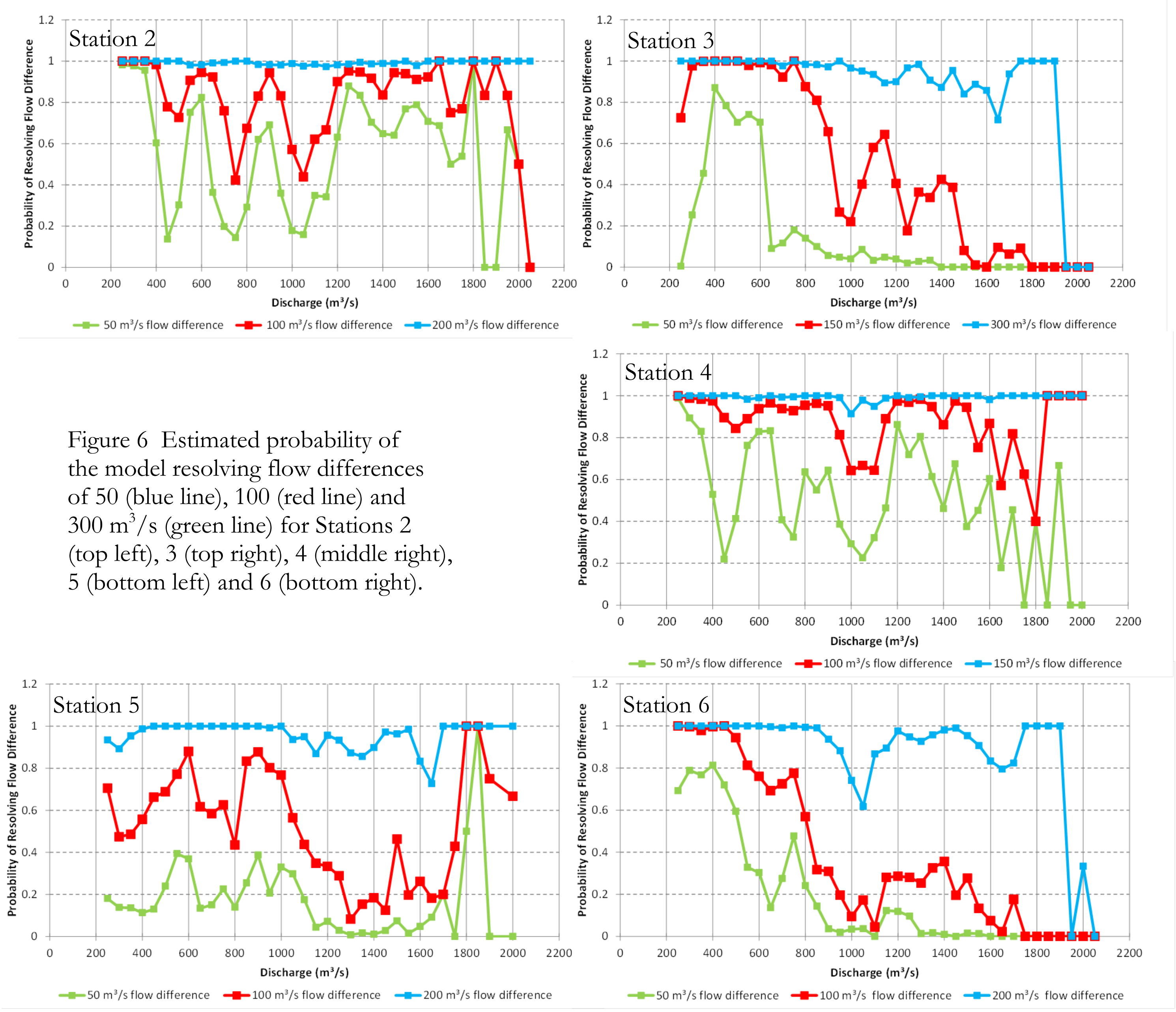


Figure 6 Estimated probability of the model resolving flow differences of 50 (blue line), 100 (red line) and 300 m^3/s (green line) for Stations 2 (top left), 3 (top right), 4 (middle right), 5 (bottom left) and 6 (bottom right).

3.5. Model Validation, Water Stage and Discharge

Figure 11 in Appendix C, shows results of the simulations using the Manning roughness coefficients for November 01, 2014, to May 26, 2015. In general, there was good agreement between the simulated and observed stages at Stations 2_AS, 3, 4, 5, and 6.

Quantitative measures of agreement are summarized in Table 9 which gives error bounds (i.e., the maximum positive and negative difference between observed and modeled elevations over the validation period), bias (i.e., the average difference between observed and modeled elevation for each validation period), and root mean square error. For the simulation covering November 01, 2014, to May 31, 2015, the model gives a bias between -0.1 m and +0.10 m and a root mean square error (RMSE) between 0.09 m and 0.24 m. These values are improved compared to those for the previous version of the model which gave a bias between -0.37 m and +0.12 m and a RMSE between 0.12 m and 0.39 m (Plate *et al.* 2014, 2015).

Table 9. Agreement between simulated and observed stages at the MCR stations. Given are the root mean square error (RMSE), bias, and bounds for differences between simulated and observed stages. Results are shown for the previous versions of the model (Imam et al. 2014 and Dashti et al. 2015) and for the validation runs done with the current version of the model.

Validation Period	Parameter	Station 1_AS	Station 2_AS	Station 3	Station 4	Station 5	Station 6
Ecofish(2014)	Upper Bound(m)	0.86	0.62		0.16	0.26	0.41
18-Nov-12	Lower Bound(m)	-1.75	-2.12		-1.14	-1.27	-0.42
to 10-Feb-2013	BIAS(m)	0.09	-0.06		-0.06	-0.05	-0.03
	RMSE(m)	0.22	0.26		0.15	0.22	0.12
Ecofish(2014)	Upper Bound(m)	0.72	0.52		0.2	0.12	0.56
11-May-13	Lower Bound(m)	-1.24	-1.38		-1.03	-1.26	-0.8
to 06-Nov-2013	BIAS(m)	0.05	-0.14		-0.19	-0.37	-0.06
	RMSE(m)	0.19	0.29		0.23	0.39	0.19
Ecofish(2015)	Upper Bound(m)	0.6	1.86		1.18	0.67	0.5
06-Nov-13	Lower Bound(m)	-0.33	-1.47		-0.74	-0.76	-0.43
to 30-Oct-2014	BIAS(m)	0.12	0.02		-0.07	-0.09	0.06
	RMSE(m)	0.18	0.23		0.18	0.23	0.14
Ecofish(2015)*	Upper Bound(m)	0.6	1.86		1.18	0.67	0.5
06-Nov-13	Lower Bound(m)	-0.33	-1.47		-0.69	-0.76	-0.39
to 30-Oct-2014	BIAS(m)	0.12	0.02		-0.07	-0.09	0.06
	RMSE(m)	0.18	0.23		0.17	0.23	0.14
Ecofish(2016)	Upper Bound(m)		0.66	1.09	0.35	0.29	0.42
01-Nov-14	Lower Bound(m)		-0.6	-0.67	-0.25	-0.43	-0.22
to 31-May-2015	BIAS(m)		0.04	0.1	0.05	-0.1	0.1
	RMSE(m)		0.14	0.24	0.09	0.15	0.14

* The goodness-of-fit measures were revised after correcting for an error in time zone for Station 4, 5 and 6 data.

It should be noted that the validation runs for the 2012/2013, 2013/2014 and 2014/2015 models were considerably longer than those carried out by Golder (2013) for the previous version of the model. The total duration of validation runs in Golder (2013) was ~30 days. For the updated 2012/2013 and 2013/2014 models validation runs amounted to 270 days each (excluding the simulation for February 11 to May 10, 2013). Even the duration for the 2014/2015 model validation run was 187 days. From these long validation runs, shorter periods with remarkable agreement between model results and observations can be identified and those shorter periods were used by Golder (2013). These shorter periods give lower RMSE and bias but do not take advantage of data having been collected for the whole year.

3.6. Hydraulic Characteristics of the MCR

REV Discharge: Before REV 5 went online in 2010, discharge from REV fluctuated from 8.5 m^3/s to approximately 1,750 m^3/s with a total range of 1,741.5 m^3/s between highest and lowest seasonal discharge (Figure 7). Following the start-up of REV5 and the implementation of 142 m^3/s minimum flows at the end of 2010, the total range of discharges increased by 266.5 m^3/s to 2,008 m^3/s and ranged from 142–2,150 m^3/s in 2011 and 2012 (Figure 7). This pattern continued in 2013–2015, when discharges fluctuated from 142 m^3/s to 2,150 m^3/s (Figure 12 in Appendix D).

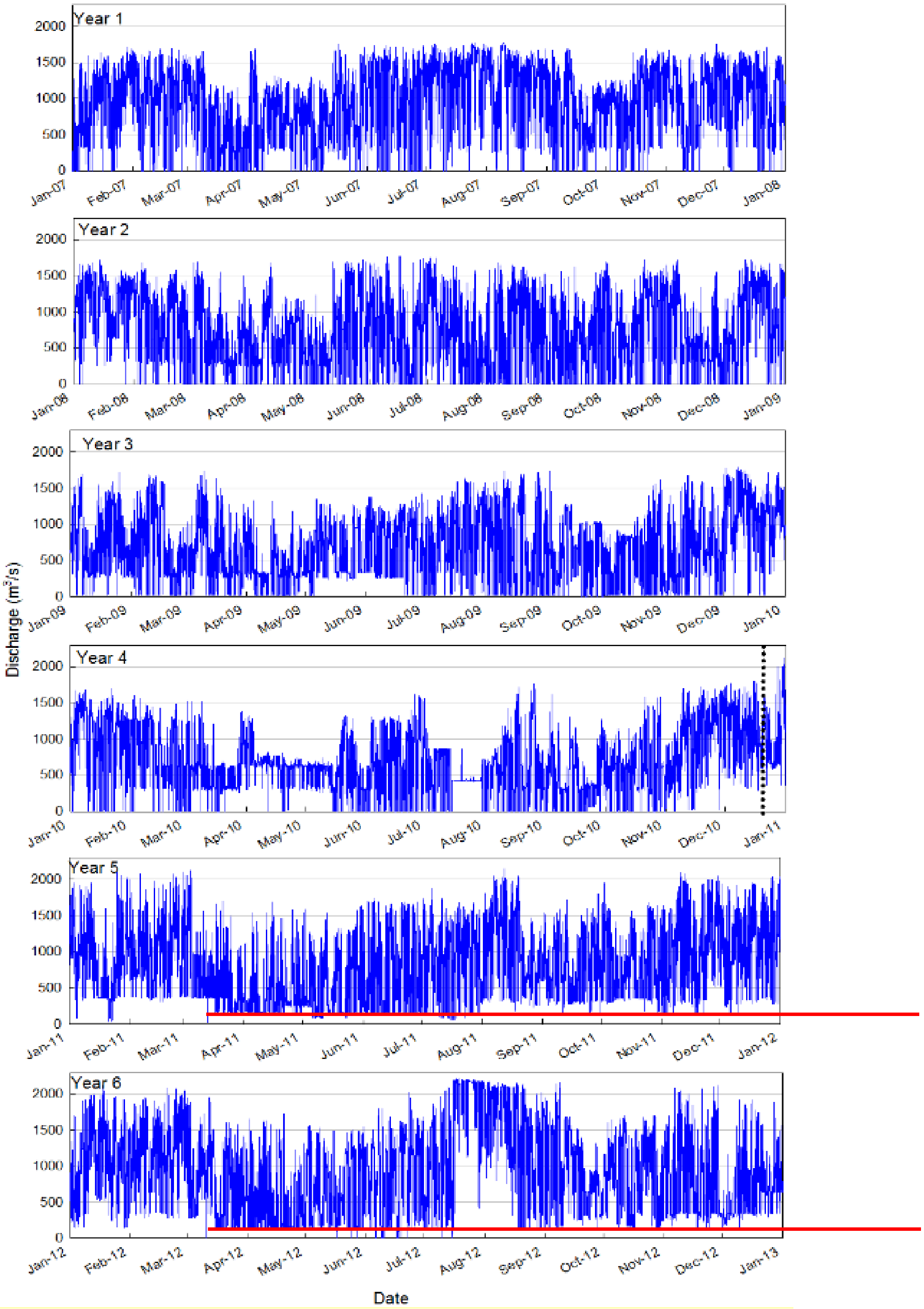


Figure 7 Revelstoke Dam generating stations hourly discharge 2007–2012. REV 5 came online and 142 m^3/s minimum flows (red solid line) were implemented at the end of 2010 (Year 4, black dotted line (Source: modified from Golder 2013). Hourly discharge data from REV for 2015 are shown in Figure 12.

Whole Study Fluctuations of Wetted Area, Flow Depth and Flow Velocity

Over the period November 01, 2014 to May 31, 2015, the wetted bed area for the modeled domain ranged between 10 km^2 and 23.7 km^2, the average flow depth ranged between 2.2 m and 3.7 m, and the average flow velocity ranged between 0.66 m/s and 1.27 m/s (Table 13 to Table 19 in Appendix E

Table 19, and Figure 12 in Appendix D).

Over the period of simulation, the largest mean flow depth for the reaches of the domain was 5.7 m in reach 1, while the smallest mean flow depth was 1.9 m in reach 2. For reaches 3 and 4, the mean flow depths were 2.8 m and 3.9 m, respectively. The largest mean flow velocity for the reaches of the domain was 1.53 m/s in reach 4, while the smallest mean flow velocity was 0.23 m/s in reach 1. For reaches 2 and 3, the mean flow velocities were 0.99 m/s and 0.85 m/s, respectively.

Over the period November 01, 2014 to May 31, 2015, the mean wetted area, flow depth, and flow velocity were 15.5 km^2, 2.7 m, and 1.01 m/s, respectively. The mean wetted area differences between reaches are influenced by their length and ALR backwatering. About 79% of the mean wetted area of the domain was in reach 2 which had a length of 12.2 km and a mean wetted perimeter of 0.4 km. Reach 1 had ~10% of the mean wetted area with a reach length of 1.5 km and a mean wetted perimeter of 0.37 km. Reach 3 had ~6.0 % of the mean wetted area with a reach length of 1.0 km and a mean wetted perimeter of 0.2 km. Finally, reach 4 had ~5% of the mean wetted area with a reach length of 0.8 km and a mean wetted perimeter of 0.2 km.

Table 10 summarizes the modeled variations in hydraulic characteristics parameters discussed in the previous paragraphs.

Diurnal Fluctuations in Flow Depth, Flow Velocity and Wetted Area

In addition to seasonal variations, there were diurnal fluctuations in the average flow depth, average flow velocity, and wetted area of the domain (Figure 12, Appendix D)

Over the period of simulation (November 01, 2014 to May 31, 2015), the mean diurnal fluctuation in the wetted area of the domain was 0.6 km^2 which amounts to 3.9% of the mean wetted area. The smallest diurnal fluctuations in wetted area occurred in late November 2014 with a minimum of 0.001 km^2. The largest diurnal fluctuations in wetted area occurred again in late January 2015 with a maximum of 3.9 km^2. Relative to the mean wetted area for each reach, diurnal fluctuations in wetted area were largest for reach 2 (affected most by ALR fluctuations) where the mean diurnal fluctuation in wetted area was 5.9% of the mean wetted area for this reach. For reaches 4, 3 and 1 (in order of closest to largest distance from REV), the mean diurnal fluctuations in wetted area were 2.6%, 1.2% and 2.1%, respectively.

Over the period of simulation, the mean diurnal fluctuation in the flow depth of the domain was 0.11 m which amounts to approximately 4.0% of the mean flow depth. The maximum diurnal fluctuation in flow depth was 0.6 m. Relative to the mean flow depth for each reach, diurnal fluctuations in flow depth were modelled with increasing distance from REV as follows: Reach 4 (closest to REV) had large diurnal fluctuations with a mean diurnal fluctuation in flow depth of 8.8% of the mean flow depth for this reach. In Reach 3, the mean diurnal fluctuation in flow depth was 10.2% of the mean flow depth for this reach was also large. For reaches 2 and 1, the mean diurnal fluctuations in flow depth were much smaller with 2.9% of the mean flow depths for both of these reaches.

Over the period of simulation, the mean diurnal fluctuation in the velocity of the domain was 0.11 m/s which amounts to 10.8% of the mean velocity. The maximum diurnal fluctuation in velocity was 0.45 m/s. Relative to the mean velocity for each reach, diurnal fluctuations in velocity were modelled with increasing distance from REV as follows: In general, , diurnal fluctuations in velocity were quite similar and between 10-15% between all reaches from Reach 4 to Reach 1. For Reach 4, Reach 3, Reach 2, and Reach 1 the mean diurnal fluctuations in velocity were 12.2%, 11.4%, 9.9% and 14.2%, respectively, of the mean velocity for each reach.

Monthly Fluctuations in Wetted Area and Flow Depth

The maximum monthly average wetted area for the whole study domain was 26.5 km^2 and occurred in May 2015 when the ALR water level was high (428.5 masl to 434.2 masl) (Figure 12). The maximum monthly average flow depth was 4.2 m and also occurred in May 2015 due to high ALR water level. The minimum monthly average wetted area was 8.3 km^2 and occurred in February and March 2015 when the ALR water level was low (424.6 masl to 425.3 masl in February and 424.0 masl to 424.9 masl in March). The minimum monthly average flow depth was 2.1 m and also occurred in February and March 2015 due to low ALR water level (Figure 12).

Table 10 Summary of HEC-RAS modeled variations in wetted area, flow depth and velocity for the November, 2014 to May 26, 2015 period.

Hydrological Parameter	**Whole**	**Min**	**Max**
Diurnal Fluctuations			
Wetted Area	Whole Period: 0.6 km²	June-July: 0.001 km²	Feb-March: 3.9 km²
Flow Depth	Whole Study Area: 0.11 m	Reach 1 & 2: 0.003 m (or 2.9% of mean flow depth)	Reach 3: 0.6 m (or 10.2% of mean flow depth)
Velocity	Whole Study Area: 0.11 m/s	Reach 2: 9.9% of mean velocity	Reach 1: 0.45 m/s (or 14.2% of mean velocity)
Fluctuations over the Whole Study Period (All Reaches)			
Wetted Area	15.5 km²	8.3 km²	26.5 km²
Flow Depth	2.7 m	1.8 m	4.2 m
Velocity	1 m/s	0.39 m/s	1.72 m/s
Monthly Average Min and Max of Wetted Area & Flow Depth (All Reaches)			
Wetted Area		Feb-Mar 2015 (low ALR): 8.3 km²	May 2015 (high ALR); 26.5 km²
Flow Depth		Feb-Mar 2015 (low ALR); 2.1 m	May 2015 (high ALR): 4.2 m

3.7. HEC-RAS Model Summary and Recommendations

The HEC-RAS hydraulic model for the Mid-Columbia River was updated to include new data for November 2014 to May 2015. The Manning roughness coefficients for cross sections between 168 -182 and 124-167 has been increased for low flows and reduced for high flows using a flow roughness factor. The performance of the model was validated by running the model for the length of the data record from November 2014 to May 2015. The performance of the updated model is improved compared to the previous versions (Imam *et al.* 2014 and Dashti *et al.* 2015).

Station 3 hourly stage data for October 2014 to August 2015 were made available for the 2014/2015 model runs. However, simulated water levels were on average +0.54 m higher than observed level data. This offset was applied to the Station 3 water levels for the 2014/2015 model runs. The offset is likely required due to a difference in datum or errors in surveying Station 3, the MCR index stations, and MCR bathymetry. Golder (2012) indicated that the accuracy of bathymetry data was around 0.5 m.

The model was calibrated against water level data for seven months from November 2014 to May 2015. These data included high and low water levels in the Arrow Lakes Reservoir (ALR). During low ALR water levels, the water level at the gauges in the Mid-Columbia River decreased in the downstream direction as would be expected and the errors in the surveyed elevations for the gauges had minor effect on model calibration compared to the fluctuations in water level at these gauges. Nevertheless, the accuracy of the model is only as good as the input data. The 2012-2013 model calibration suggests that, in the initial version of the model (Golder 2012), the elevation of cross-sections between Station 2 and Station 4 is inaccurate or is changing with time; this confirmed in the model 2013-2014 and 2014-2015 model runs. The 2014-2015 model calibrations suggest that the elevation of cross-sections around Station 5 may also be changing with time. To maintain model reliability, cross-section surveys are recommended for the reach between Station 2 and Station 4, and around Station 5.

3.8. Temperature Variation Results and Discussion

Since assumptions made with regards to temperature are based on seasonal variations and the 2014-2015 study period was limited to the cooler temperatures from November to May we are presenting 2013-2014 data in Figure 8.

When comparing the annual water temperature variations between index stations in the MCR and index stations in two of its tributaries for the 2013-2014 period, a clear trend is apparent (Figure 8). The water discharged through REV is taken from the hypolimnetic layer of the water column in Revelstoke Reservoir and is therefore less fluctuating in temperature between seasons than the naturally fed Jordan and Illecillewaet rivers in the winter and spring and colder in summer and fall (Figure 8). In 2014, winter water temperatures from January–March ranged from 2–4 ˚C at the MCR stations but only 0–2 ˚C in the tributaries. Temperatures from July–September at the tributary index stations ranged from 10–14 ˚C and from 10–12 °C at the MCR index stations.

In the spring and summer, the day and night temperature differences were more pronounced than in fall and winter. This phenomenon can be seen in little diurnal temperature variation in the MCR stations in the fall and winter when compared to spring and summer (Figure 8).

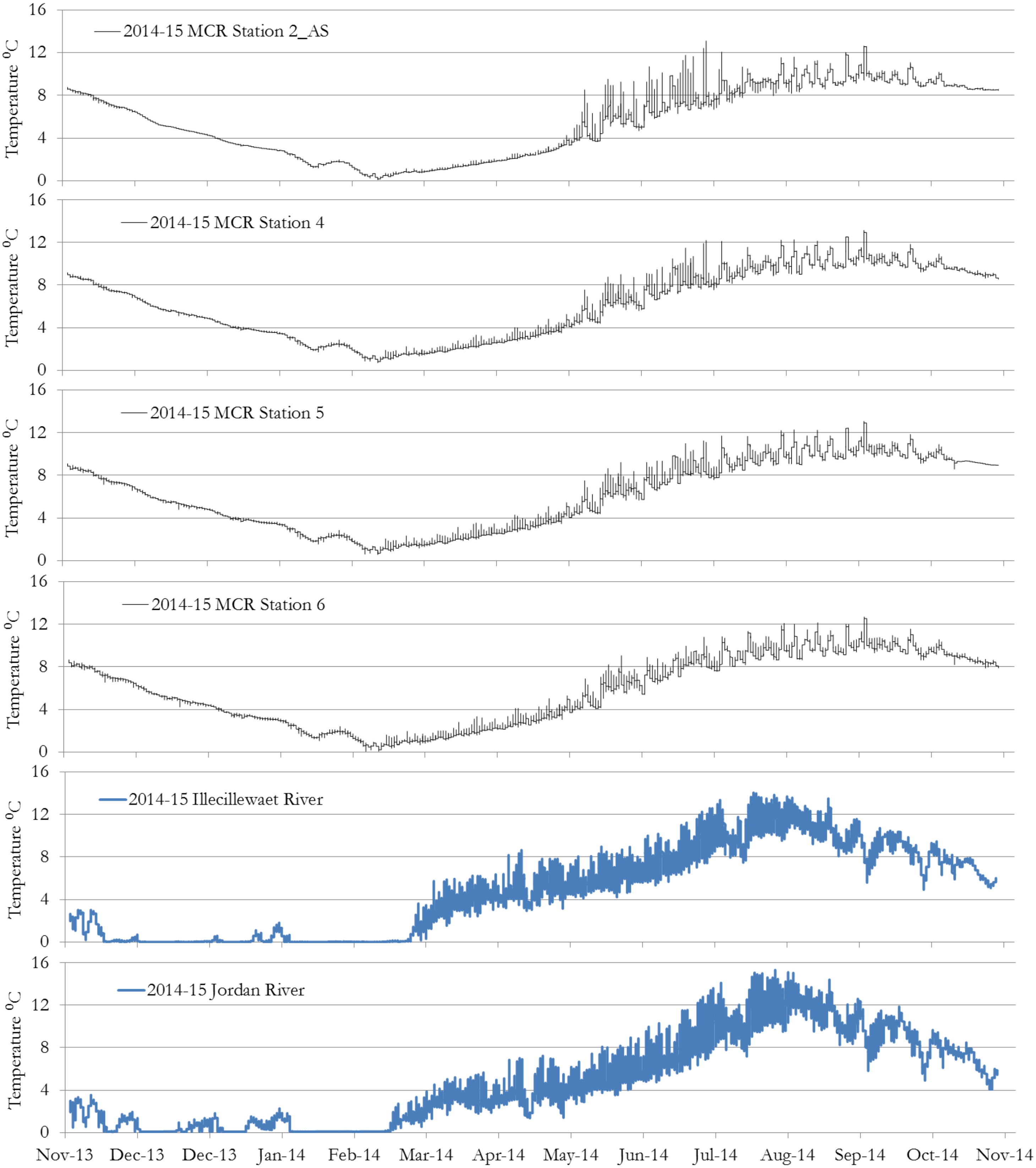


Figure 8 Water temperatures at 4 MCR (Station 1 was dismantled in May 2014) and 2 tributary (Illecillewaet and Jordan Rivers) index stations from Nov 2013–Nov-2014.

Overall, daily water temperature fluctuations were also greater for the two naturally fed tributaries The temperature patterns found in 2014 closely resembled temperature patterns from 2007–2013 and stayed consistent pre- and post-minimum flow application (this study, Plate et el. 2014 and 2015, Golder 2013). It is therefore assumed that the WUP implemented minimum discharge did not affect the general temperature pattern over the whole study period and all reaches.

Water temperature analyses post-implementation of the WUP minimum flow of 142 m^3/s assessed the effect of flow fluctuations on daily temperature variation and showed a decrease in diel variation of 0.1–0.4 ˚C (Golder 2013). 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 an effect (Golder 2013). Other programs initiated under the WUP may show whether such a small change in diel temperature variation will have ecological effects.

4. SEASONAL WATER QUALITY MONITORING

The seasonal water quality sampling program was meant to give an indication of the general annual productivity trends in the MCR and its two tributaries Illecillewaet and Jordan Rivers based on three annual samples in the spring, summer and fall. This low sampling frequency made it highly questionable that annual trends in productivity could be observed or that pre- and post-minimum flow differences could be detected. Nevertheless, water quality sampling and analysis were carried out during all previous years (2007-2013, Golder 2013, Plate et al. 2014 and 2015) of CLBMON-15a and until May of 2014 and were terminated after that.

Nevertheless, physical water parameters were measured *in situ* for the three download dates in 2014 and the one download date in 2015.

4.1. Physical Water Quality Parameters

Physical parameters were measured *in situ* as part of every field visit in 2014 and 2015 to calibrate the temperature of the deployed stage and temperature loggers. Table 11 shows the schedule for the 2014 and 2015 physical parameter measurements (Table 12).

Table 11 Field schedule of the 2014 and 2015 *in situ* physical water parameter measurements (2014 and 2015 dates) and water sample collections for laboratory analysis (only spring 2014).

Date dd-mmm-yy	Arrival Time (24h)	Location Name
5-May-14	16:13	Jordan River Station #8
5-May-14	18:41	Illecillewaet River Station #7
6-May-14	10:12	MCR Station #6
6-May-14	11:07	MCR Station #5
6-May-14	12:01	MCR Station #4
6-May-14	13:23	MCR Station #2
8-Sep-14	19:39	Jordan River Station #8
9-Sep-14	11:32	MCR Station #2
9-Sep-14	12:36	MCR Station #6
9-Sep-14	13:15	MCR Station #5
9-Sep-14	13:45	MCR Station #4
9-Sep-14	15:54	Illecillewaet River Station #7
9-Sep-14	23:35	MCR Station #2
31-Oct-14	15:24	Jordan River Station #8
31-Oct-14	17:19	Illecillewaet River Station #7
1-Nov-14	10:57	MCR Station #2
1-Nov-14	12:40	MCR Station #4
1-Nov-14	15:15	MCR Station #5
1-Nov-14	15:40	MCR Station #6
26-May-15	11:00	MCR Station #2
26-May-15	12:10	MCR Station #4
26-May-15	13:05	MCR Station #5
26-May-15	13:45	MCR Station #6
26-May-15	17:30	Jordan River Station #8
27-May-15	2:10	MCR Station #2

Table 12 Physical parameters measured (for all 2014 and 2015 field visits).

Physical Parameters: In-Situ Measurement
Temperature (°C)
Conductivity. (μS/cm)
Specific Conductivity (μS/cm)
Total Dissolved Solids (mg/L)
Dissolved Oxygen Saturation (%)
Dissolved Oxygen Absolute (mg/L)
pH
Turbidity (NTU) (only fall 2014)

4.2. Physical Water Quality Parameters Data Analysis Methods

In the context of CLBMON-15a, the physical parameter results sampled in-situ at the index stations are used as indicators of the general status on a certain date. Physical parameter values are therefore graphically presented without statistical analysis or statistical comparisons to previous years, other stations or changes in discharge from REV.

4.3. Seasonal Water Quality Results and Interpretation

In Situ Measurements of Physical Parameters

Comment: Based on the low sampling frequencies for physical parameters, a statistical analysis of the potential effects of the WUP flows was not advisable. As described above, physical parameters were sampled to provide a very general indication of seasonal values and did not represent an accurate representation of the range in values within each season.

Temperature: In general, *in situ* temperature measurements in 2015 were carried out to calibrate the installed stage and temperature loggers. In all instances, the *in situ* measurements were within 0.2 °C of the logger measured temperatures and calibrations were not necessary.

Conductivity: The conductivities in the four MCR index stations and the Illecillewaet River throughout 2014 and in May of 2015 were similar and ranged from 0.11–0.15 µS/cm (Figure 9, top panel, Figure 10, top panel). The conductivity measured in the very nutrient poor Jordan River was lower and ranged from 0.025–0.04 µS/cm throughout 2014 and in May 2015 (Figure 10, top right panel).

Total Dissolved Solids (TDS): Over the three seasons in 2014, TDSs values were low and stable in the four MCR index stations and the Illecillewaet River. TDS values in the Jordan River were lower throughout 2014 and in late May of 2015 and did not change much over this period ranging from 0.018–0.027 mg/L(Figure 9, second from top row, right panel, Figure 10, second from top row right panel).

Dissolved Oxygen (DO): DO saturation and total DO values were typical of oligotrophic riverine systems and ranged from 95–105 % and 10–13 mg/L, respectively over the three seasons in 2014, May 26, 2015 and all stations (Figure 9, third from top row, left and right panel). Over the three seasons in 2014 and on May 26, 2015, DO saturation and total DO values in the Illecillewaet and Jordan rivers ranged from 82–101 % and from 10–12 mg/L, respectively with similar values for Jordan River and Illecillewaet River (Figure 10, third from top row, left and right panel).

pH: pH Values for the five MCR Index stations and the Illecillewaet River in 2014 and 2015 were quite consistent and ranged from pH 7.7–8.1 (Figure 9, bottom centre panel, Figure 10, bottom centre panel). These slightly alkaline values were similar to the pH values measured by Golder (2013) in 2012 and appear to be typical for MCR and its tributaries. The pH values for Illecillewaet River measured in 2014 ranged from 7.8–9.15 (Figure 10, bottom centre panel) and were slightly higher than in Jordan River where they ranged from pH 6-8–7.6 in 2014 and in May of 2015.

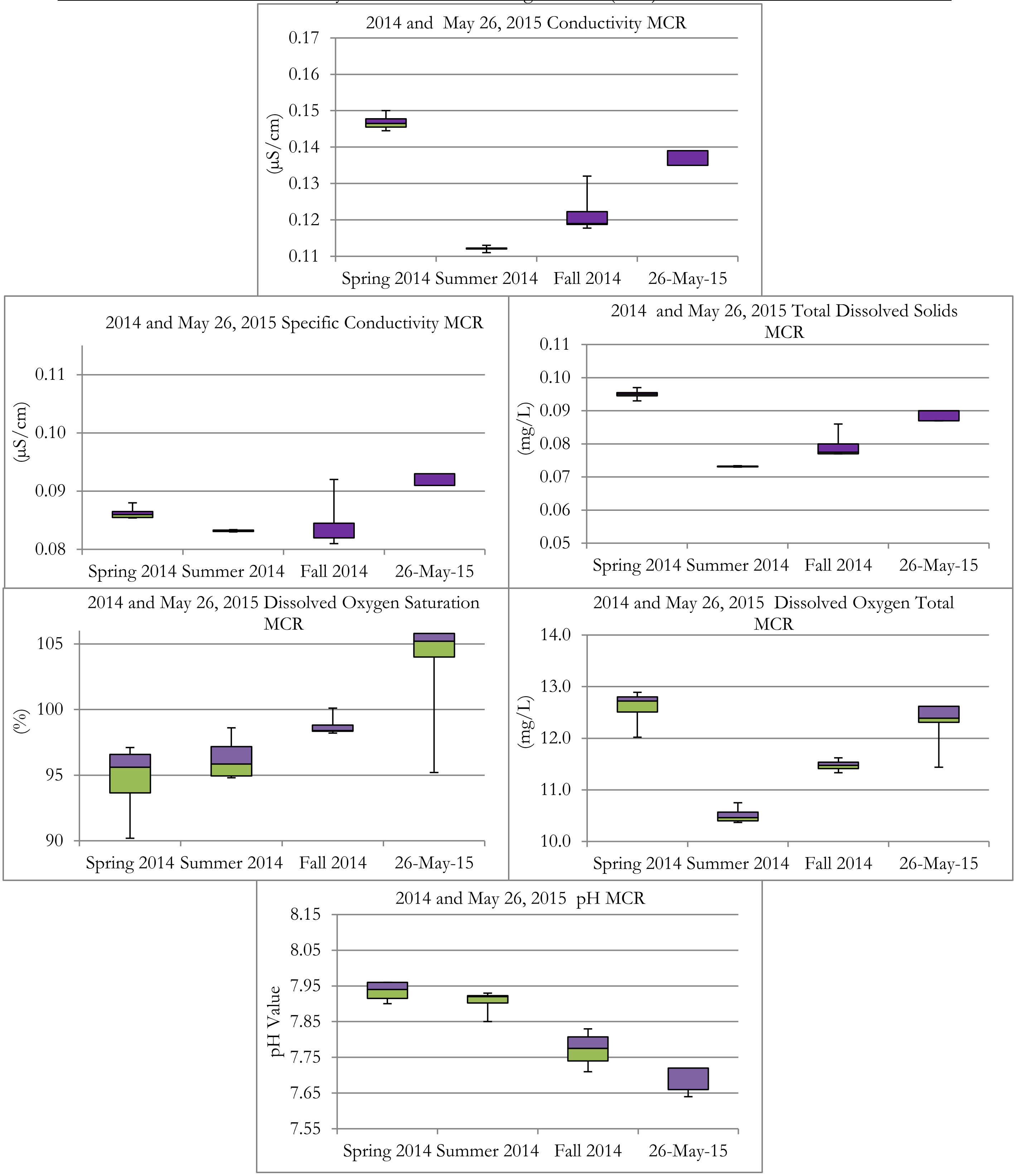
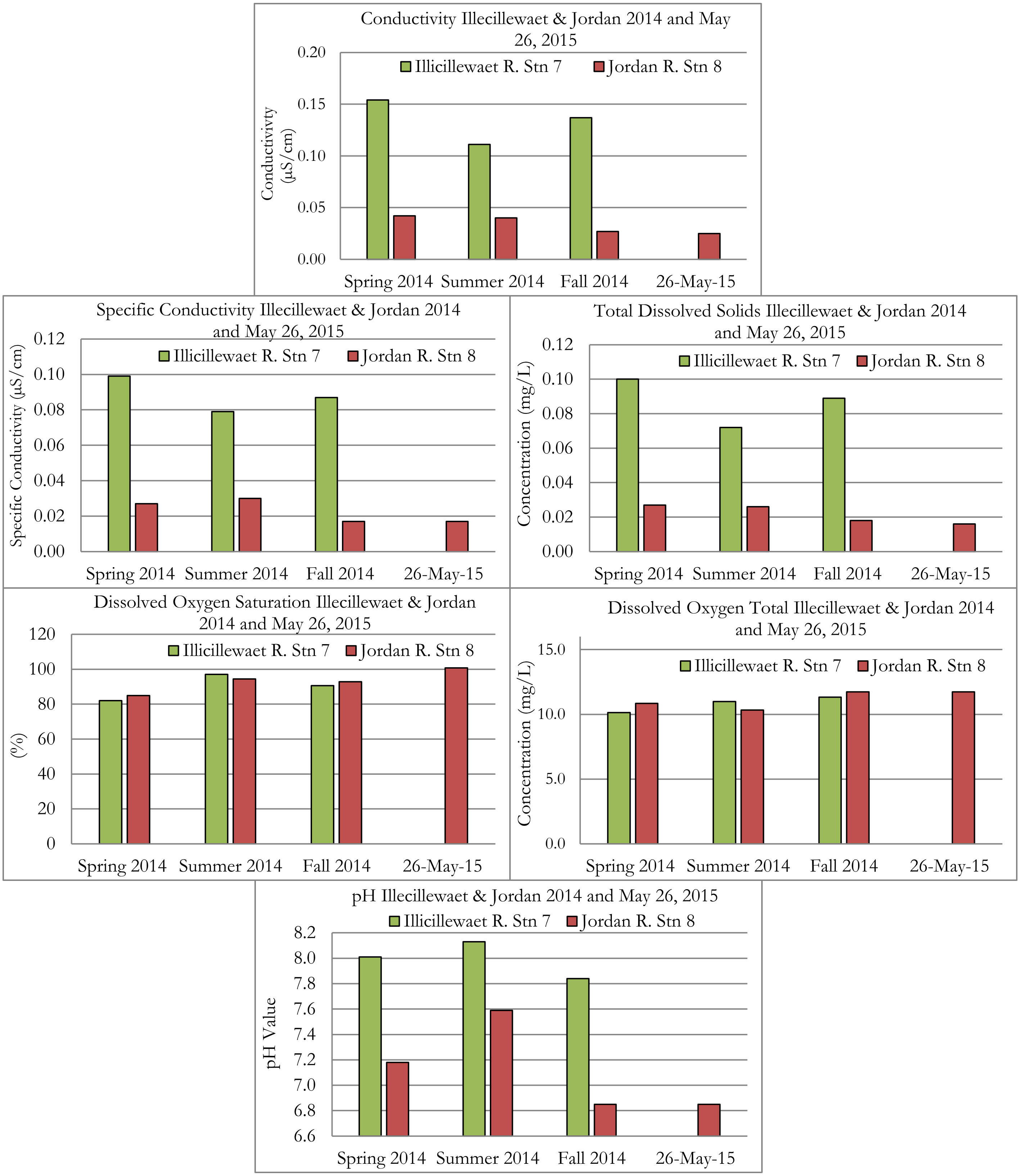


Figure 9 Results for physical parameters measured *in situ* at four MCR index stations in 2014 and May 26, 2015 (lower bar = minimum–25% percentile; green = 25%–median, purple = median–75percentile, upper bar = 75% percentile–maximum).



Conductivity Illecillewaet & Jordan 2014 and May 26, 2015

Specific Conductivity Illecillewaet & Jordan 2014 and May 26, 2015

Total Dissolved Solids Illecillewaet & Jordan 2014 and May 26, 2015

Dissolved Oxygen Saturation Illecillewaet & Jordan 2014 and May 26, 2015

Dissolved Oxygen Total Illecillewaet & Jordan 2014 and May 26, 2015

pH Illecillewaet & Jordan 2014 and May 26, 2015

Figure 10 Results for physical parameters measured *in situ* at the Illecillewaet and Jordan River index stations in 2014 and May 26, 2015.

5. CHANGES IN 2015 AND RECOMMENDATIONS FOR FUTURE WORK

On February 19, 2014, BC Hydro held a review meeting with all consultants working within the Revelstoke Flow Management Plan (RFMP) program and solicited suggestions for scope changes to the program for the final three years, from 2015 to 2017. As part of CLBMON-15a, stage data collected in the MCR, Illecillewaet and Jordan River index stations over the last eight years were used to calibrate a HEC-RAS model to predict flows, water depths and wetted width for the MCR Reaches 2–4. Based on this extended calibration phase, it appears that the predictive power of the HEC-RAS model is now high enough to reduce field measurements to two stations in the MCR that are downloaded once per year. Stage and level data from these data loggers will only be downloaded but not used for additional calibration runs of the HEC-RAS model in 2016 and 2017 unless rationale for additional calibration will be provided. It was therefore recommended that the focus of CLBMON-15a should be shifted from *in situ* data collection to calibrate the HEC-RAS model to the application of the HEC-RAS model to produce information for the other programs under the CLBMON-15 umbrella. The following technical changes were suggested at the review meeting:

1. The HEC-RAS model is highly accurate in its prediction of water depth, current velocity and wetted width for the MCR Station 1, the closest index station to REV. This is not surprising since the MCR at this station only receives regulated discharge from REV without any unpredictable tributary contributions. Therefore, no further calibration of the HEC-RAS model output for Station 1 is necessary and the standpipe and anchor stations at Station 1 were dismantled and removed in May 2014.

2. For all other stations, a process to test for the predictive power of the HEC-RAS model was applied and it was decided that the model is sufficiently calibrated to predict stage for all MCR stations in relation to REV discharge. Therefore all MCR stations were downloaded for the last time in May of 2015 and the stage loggers at Stations 5 and 6 were removed. The remaining two stage loggers and two barometric loggers at Stations 2 and 4 were left in place and their sampling frequency was changed from 10 min intervals to 30 min intervals to reduce the number of download and maintenance visits from the current three times to one time per year. Stage and temperature loggers at Stations 2 and 4 will now be used to continue temperature measurements. Stage data will be collected as well but not be analyzed unless further HEC-RAS model calibration will be required. The standpipes and anchor stations at Stations 2 and 4-6 in the MCR and the additional station in the Jordan River will be left in place to accommodate potential future logger deployment if so desired.

3. In 2013 and 2014, the data from Station 3 in Reach 4 of the MCR was not accessible for calibration of the HEC-RAS model. In the last model calibration that is described in this report, all Station 3 data was made accessible by BC Hydro and a portion of the Station 3 (the station is serviced and data is downloaded by BC Hydro) could be used for model calibration.

4. The HEC-RAS model was used to produce a table and maps that correlate the discharge from REV, MCR tributaries and the stage data for ALR with the wetted width and precise

extent of the MCR in Reaches 2–4. This geo-referenced information can be used as input to models that estimate daily amount of instrument or fish habitat submergence throughout the year or a particular sampling season.

5. As part of the 2015-2016 project year, we updated and streamlined an easily searchable database for all information that was collected as part of the CLBMPN-15a project to allow for streamlined information exchange between CLBMON-15a and other projects.
6. For 2016 and 2017 and in consultation with BC Hydro we are envisioning the development of a web based application that can be used to download and graph physical data collected as part of CLBMON-15a.
7. We are also hoping that we can work together with the other CLBMON component investigators to provide physical data that can be integrated into habitat, fish and productivity studies to show discharge and stage related effects.

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7. APPENDICES

APPENDIX A:
2015 SITE VISIT AND MAINTENANCE DATA

2015	26-May	11:00	MCR Station #2	2	414925	5653213	11:00	11:45	98	26	+00:48	11:00	11:45	100	26	-04:43	Temp Check OK
2015	26-May	12:10	MCR Station #4	4	414807	5648490	12:12	12:50	98	26	+00:48	12:10	12:53	97	26	+01:08	Temp Check OK
2015	26-May	13:05	MCR Station #5	5	415490	5645100	13:05	out	97	26	+1:04						Temp Check OK
2015	26-May	13:45	MCR Station #6	6	417171	5642074	13:45	out	97	26	+00:53						Temp Check OK
2015	27-May	2:10	MCR Station #2 Anchor	2	414925	5653213	2:50	out	99	26	+00:53						Temp Check OK

APPENDIX B:
2015 *IN SITU* PHYSICAL WATER QUALITY PARAMETER RESULTS

Year	Date mm/dd	Arrival Time (24h)	Location Name	Station #	UTM Coordinates in UTM Zone: 11		Temperature	Conductivity	Specific Conductivity	Total Dissolved Solids	DO Saturation	DO Total	pH
2015	26-May	11:00	MCR Station #2	2	414925	5653213	7.69	0.139	0.093	0.09	105.8	12.62	7.66
2015	26-May	12:14	MCR Station #4	4	414807	5648490	7.8	0.135	0.09	0.087	107.4	12.76	7.72
2015	26-May	13:04	MCR Station #5	5	415490	5645100	8.01	0.135	0.091	0.087	104	12.31	7.66
2015	26-May	13:47	MCR Station #6	6	417171	5642074	8.18	0.134	0.091	0.087	105.2	12.39	7.76
2015	27-May	1:30	MCR Station #2	2	414925	5653213	7.41	0.141	0.094	0.091	95.2	11.44	7.64
2015	26-May	17:30	Jordan River Station #8	8	410904	5655521	8.68	0.025	0.017	0.016	100.8	11.73	6.85

APPENDIX C:
GRAPHICAL REPRESENTATION OF THE NOVEMBER 2014 TO MAY 26, 2015 MODELLED AND OBSERVED STAGES AT THE MCR STATIONS

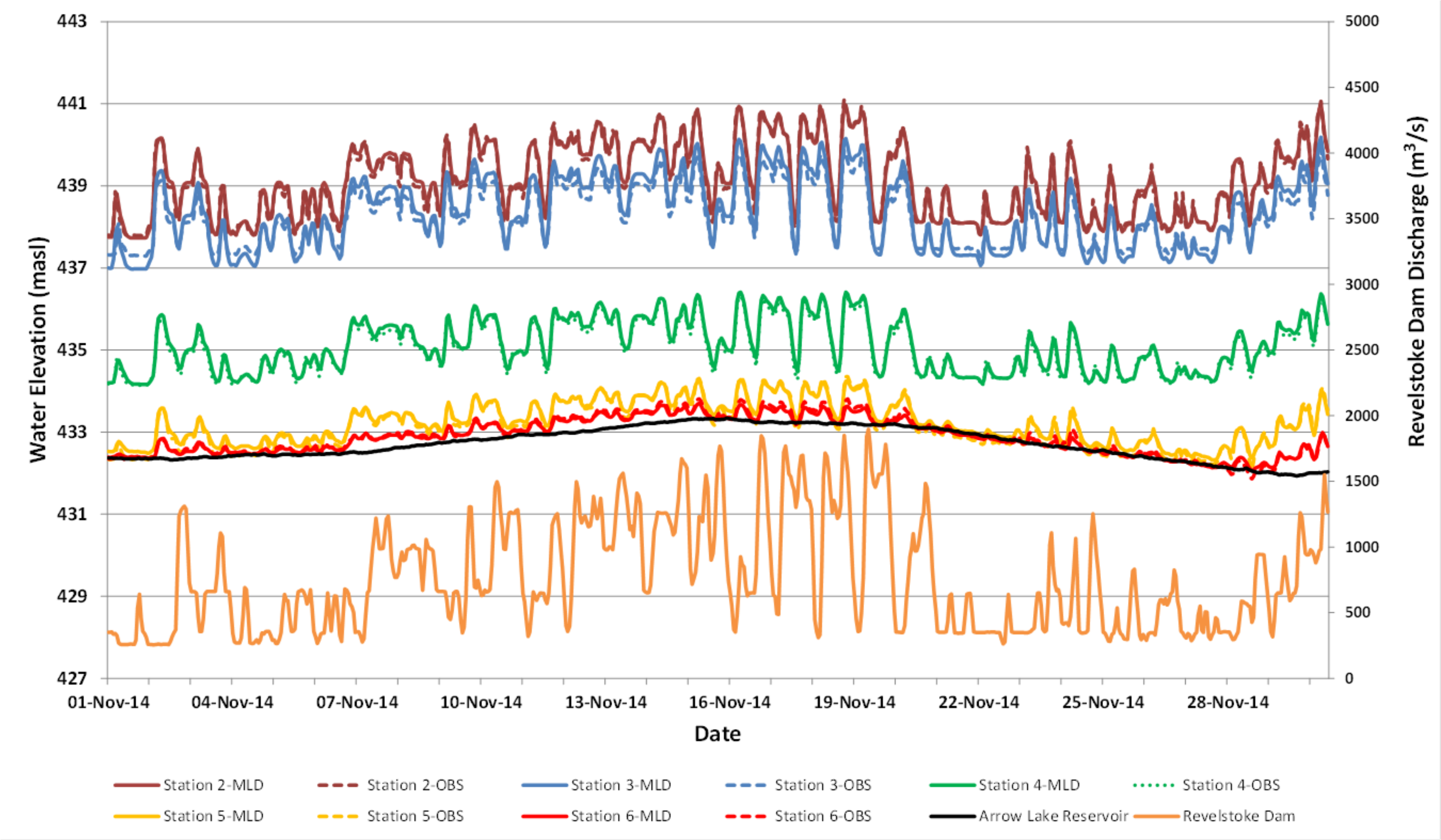


Figure 11 Modelled (MLD) and observed (OBS) stages at the MCR stations for November 1, 2014 to May 26, 2015(y-axis for water elevations for MCR stations on the left, y-axis only for discharge through Revelstoke Dam on the right).

Figure 11 continued.

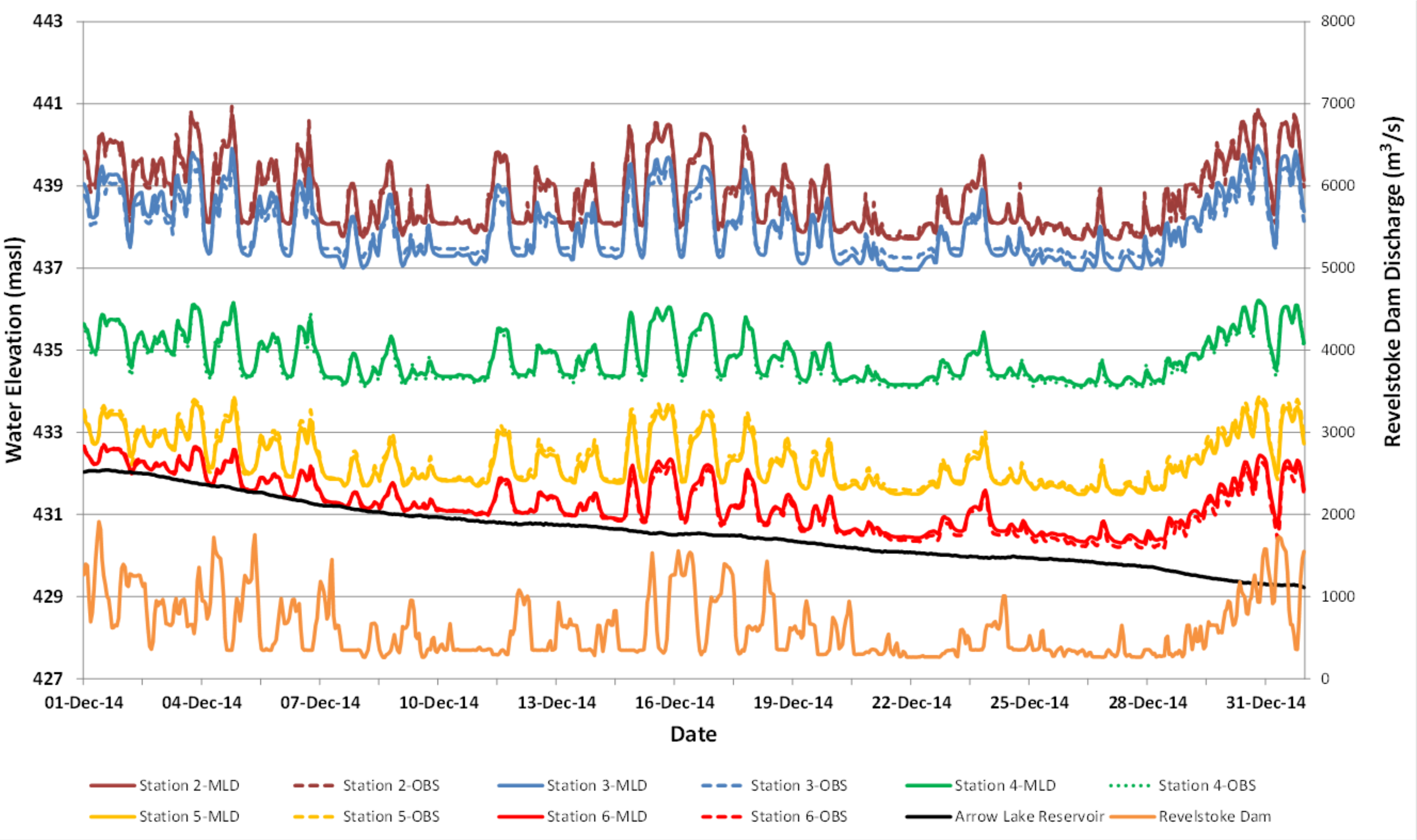


Figure 11 continued.

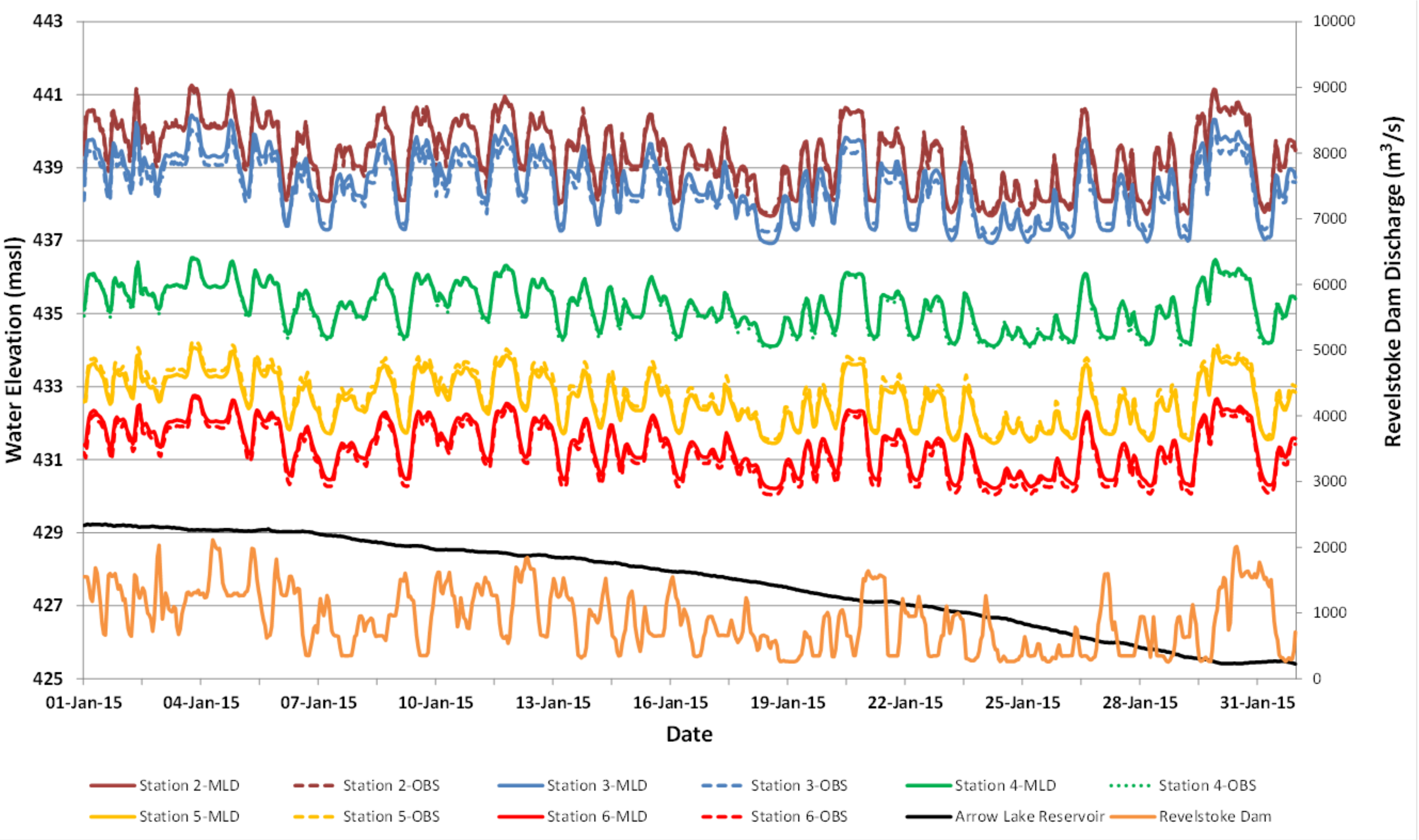


Figure 11 continued.

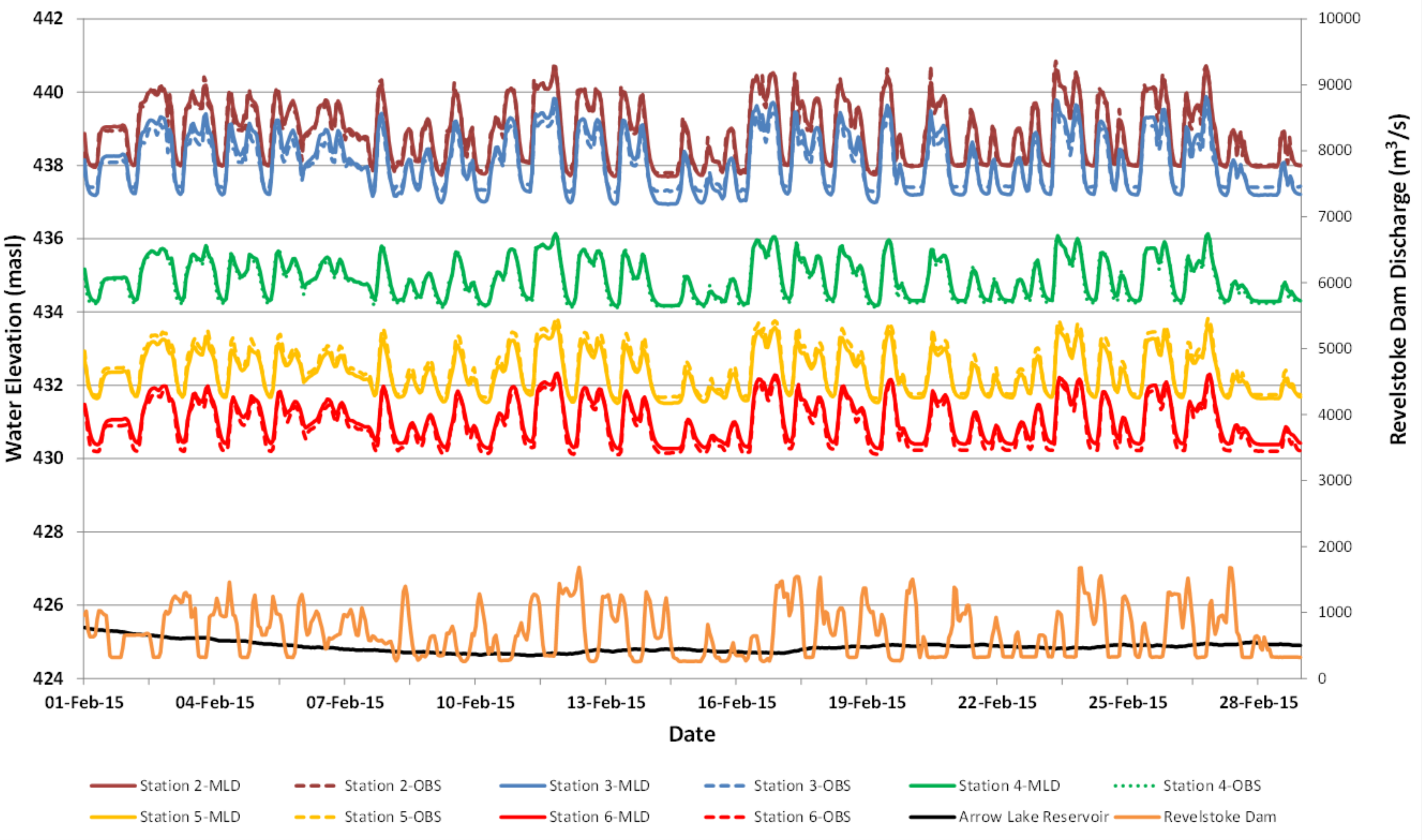


Figure 11 continued.

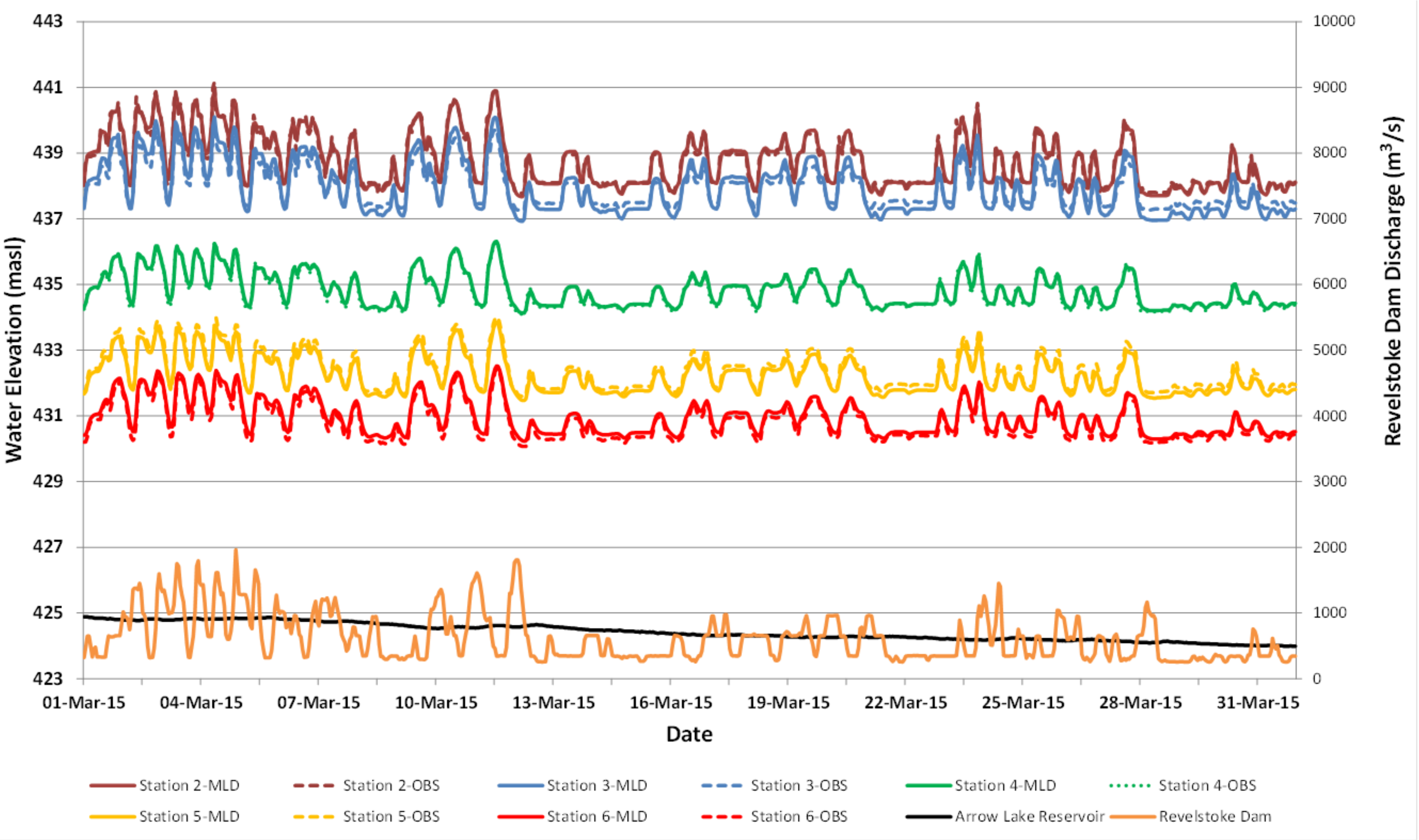


Figure 11 continued.

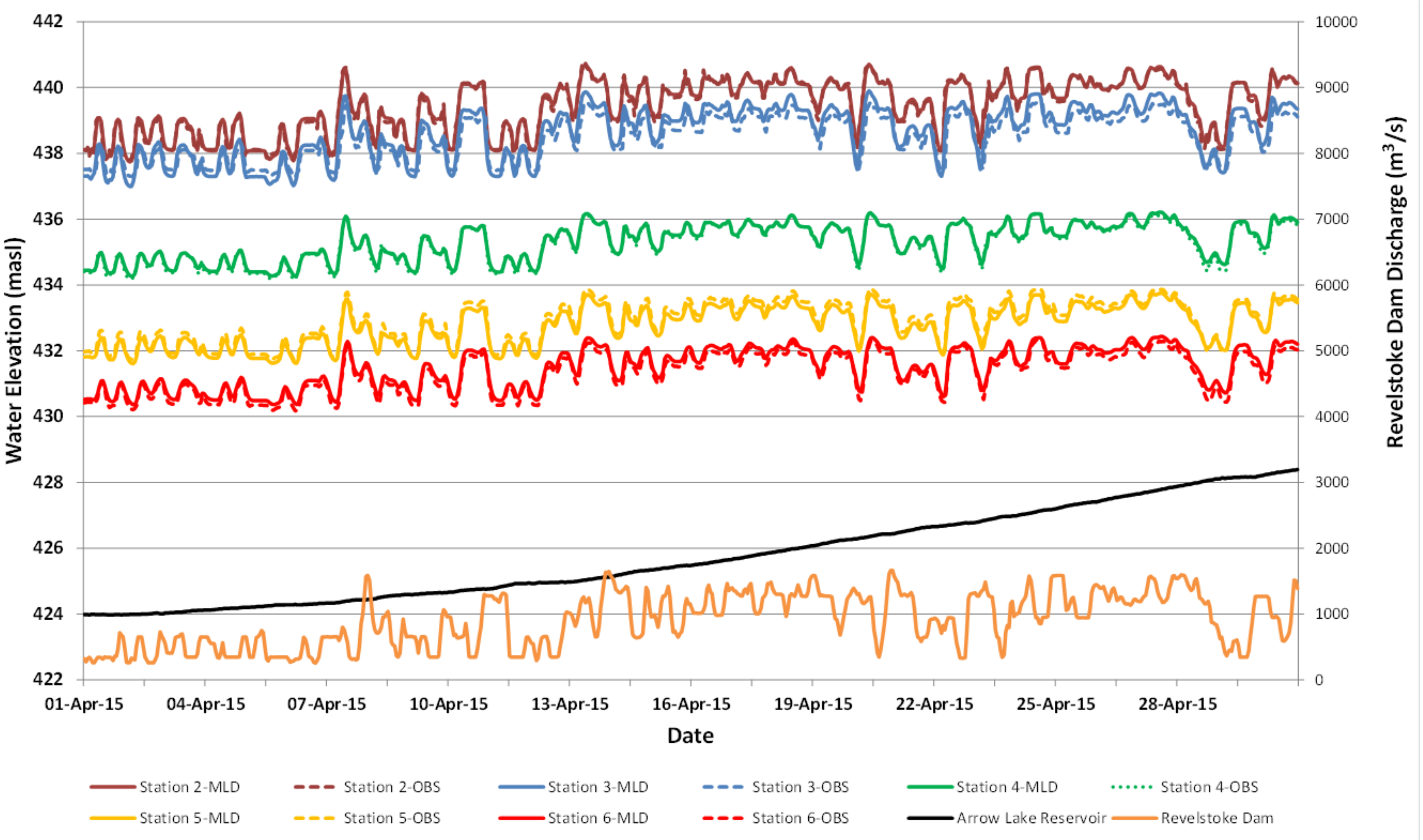
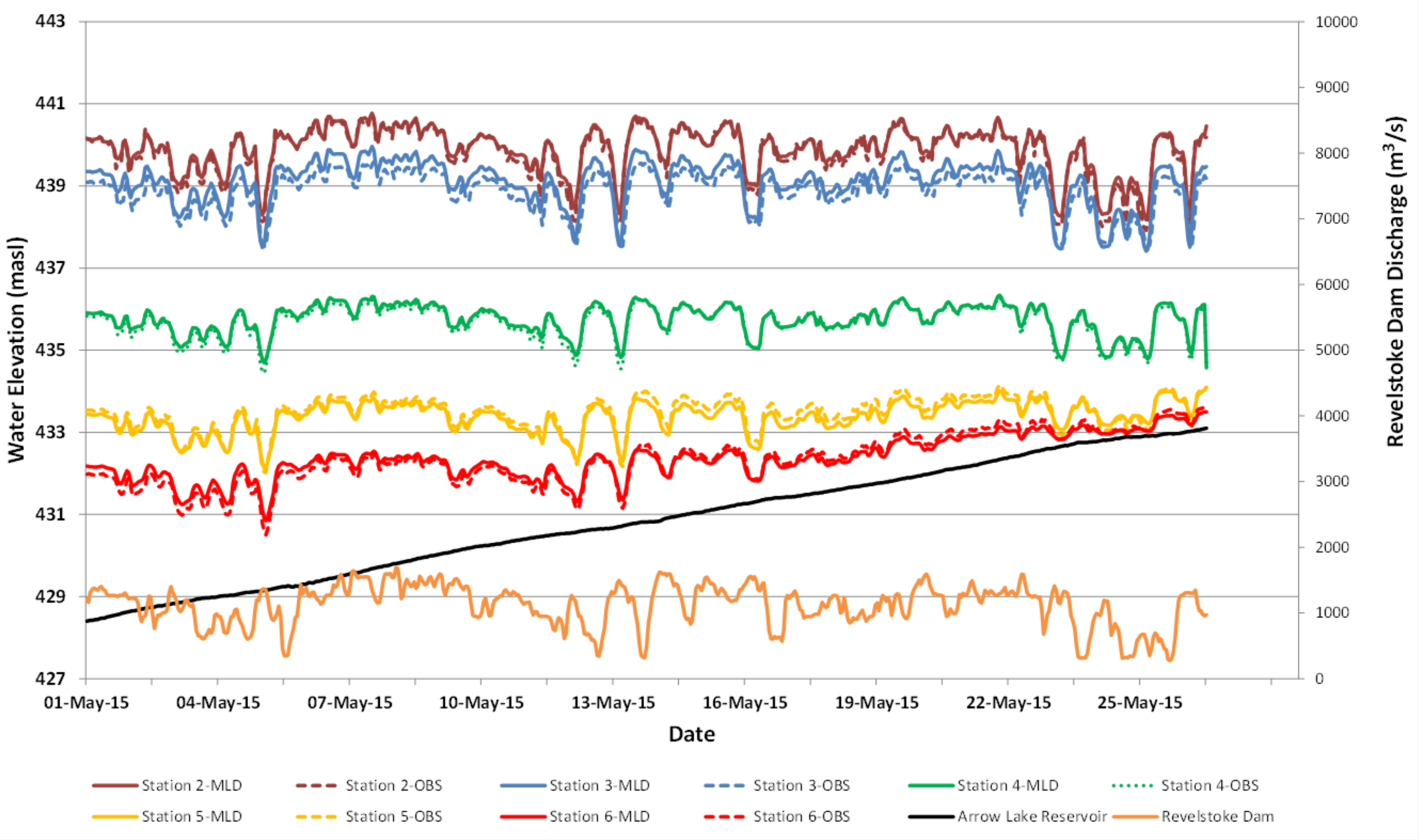


Figure 11 continued.



APPENDIX D:

GRAPHICAL REPRESENTATION OF THE 2014-2015 DISCHARGE FROM REV, WATER LEVEL AT DOWNSTREAM BOUNDARY, SIMULATED AVERAGE FLOW DEPTH, SIMULATED AVERAGE FLOW VELOCITY, AND SIMULATED WETTED RIVERBED AREA.

Figure 12 a) Discharge from REV and water level at downstream boundary of modelled domain; b) simulated average flow depth; c) simulated average flow velocity; and d, e) simulated wetted riverbed area for November 01, 2014 to November 30, 2015.

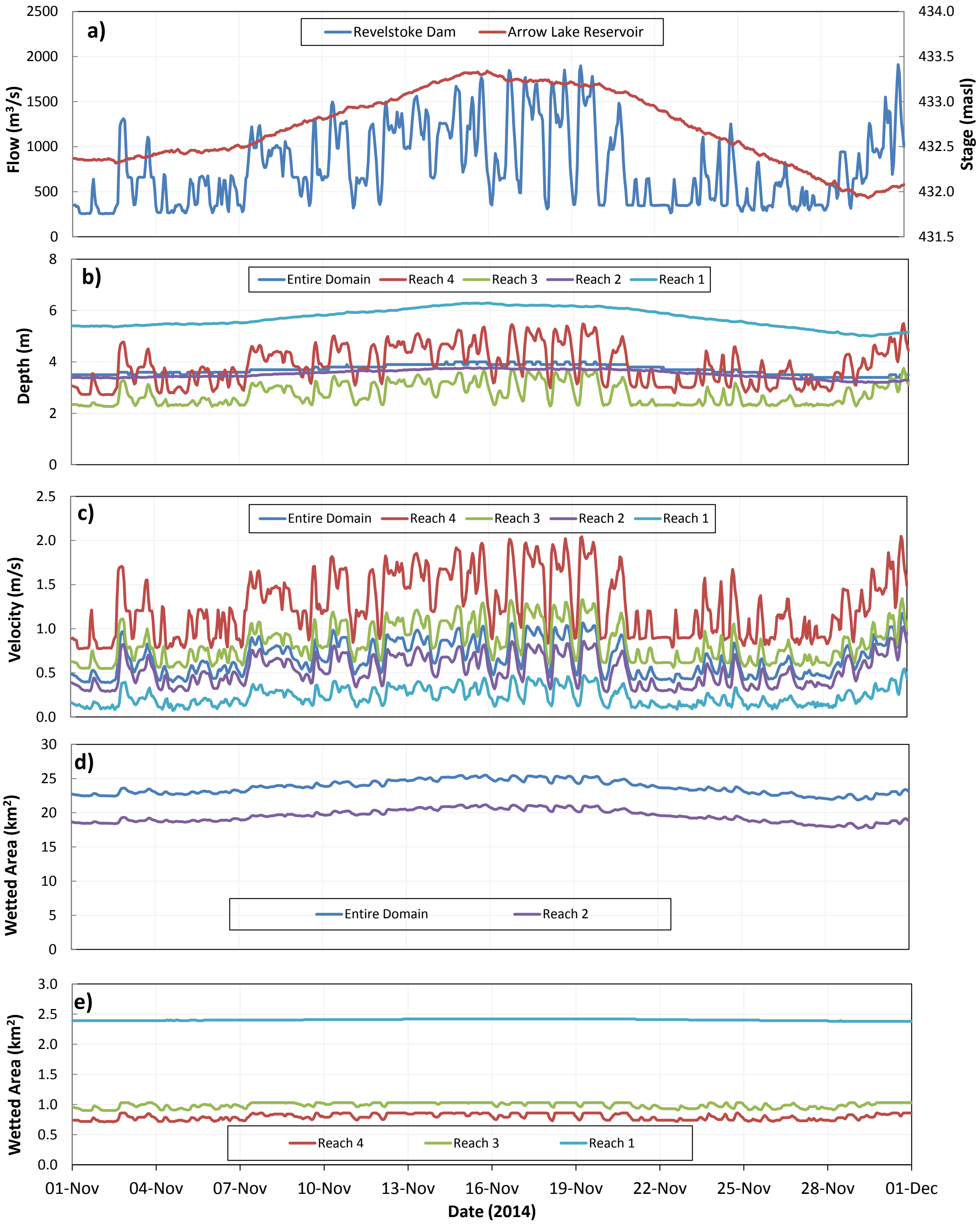


Figure 12 continued for the month of December 2014

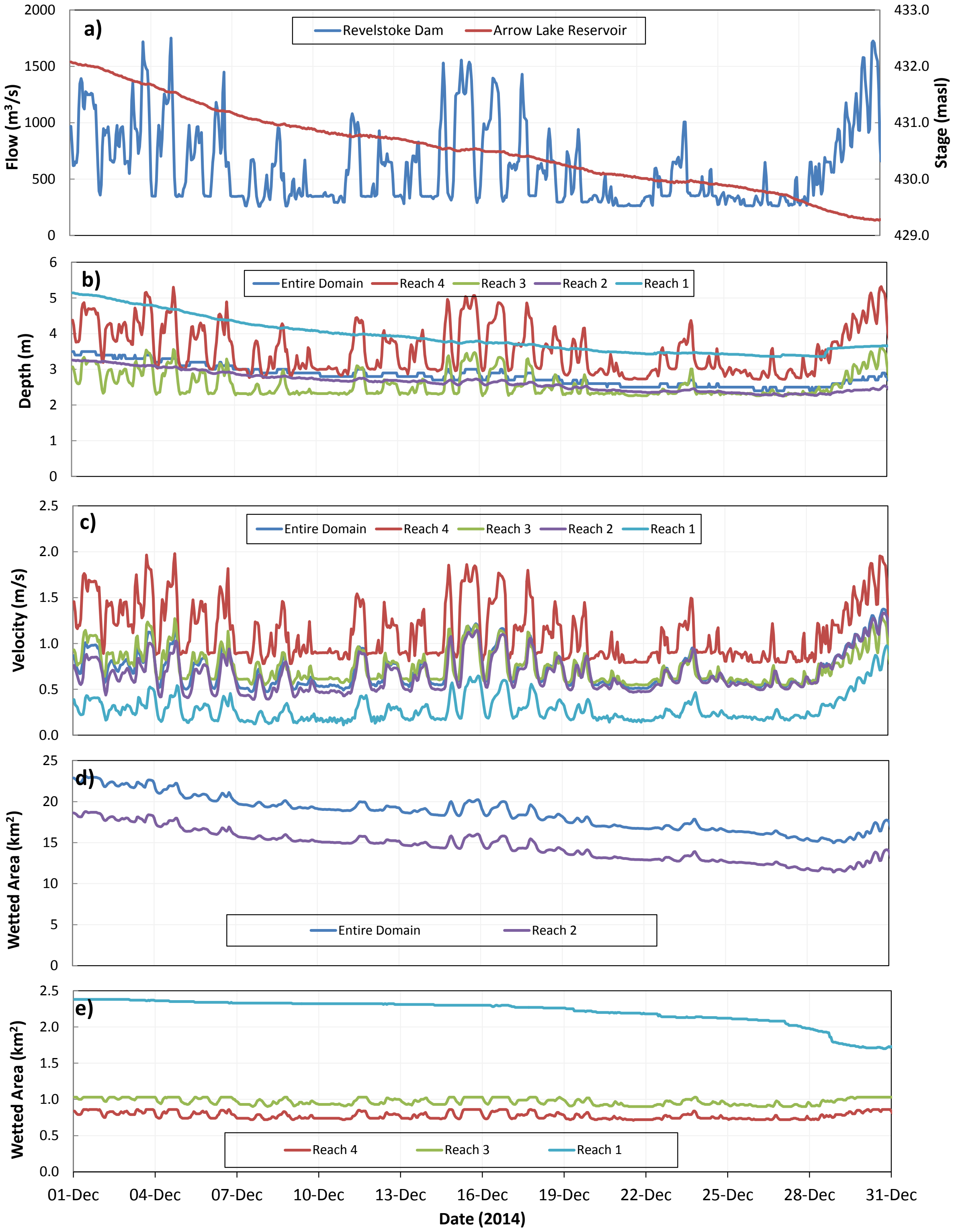


Figure 12 continued for the month of January 2015

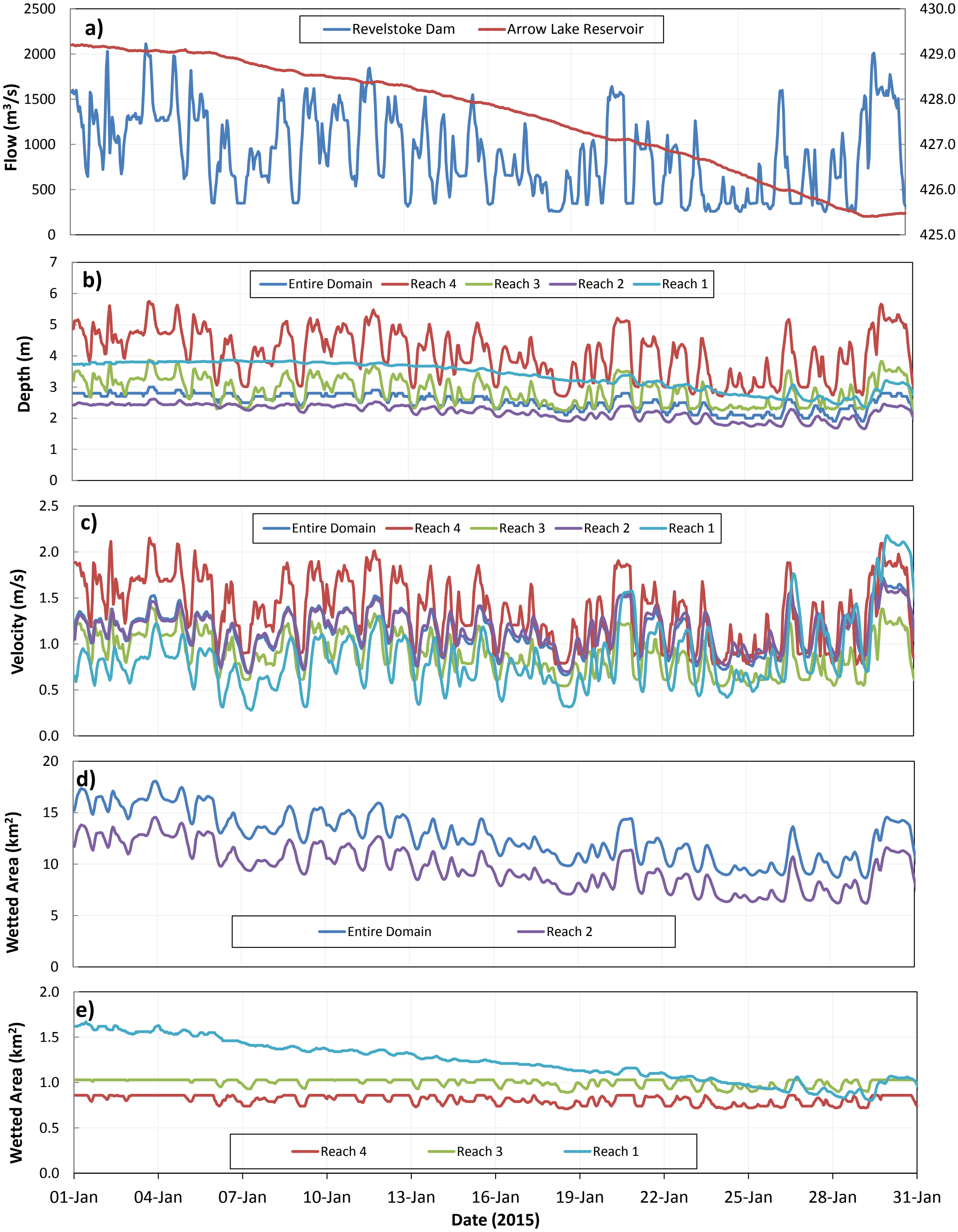


Figure 12 continued for the month of February 2015

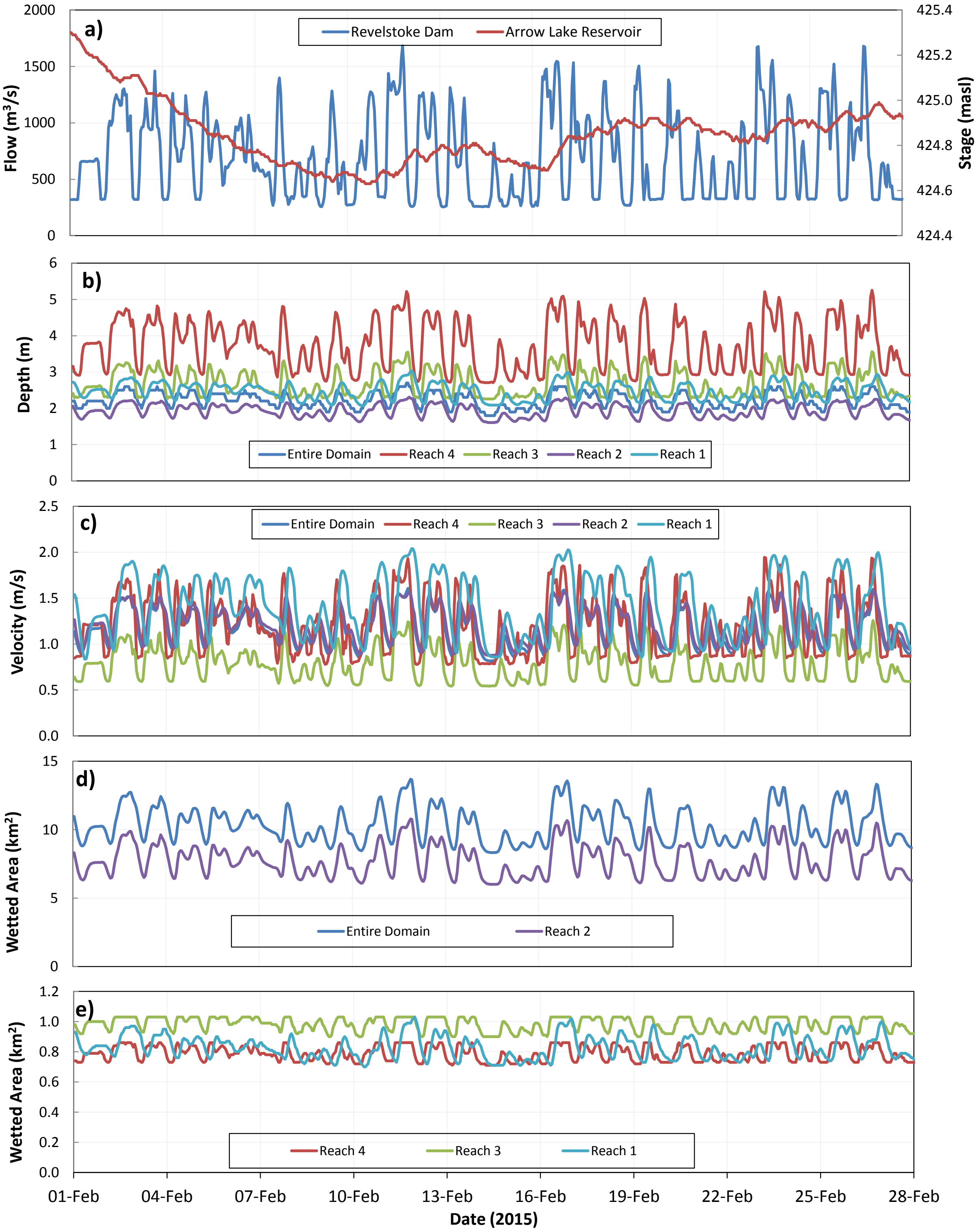


Figure 12 continued for the month of March 2015

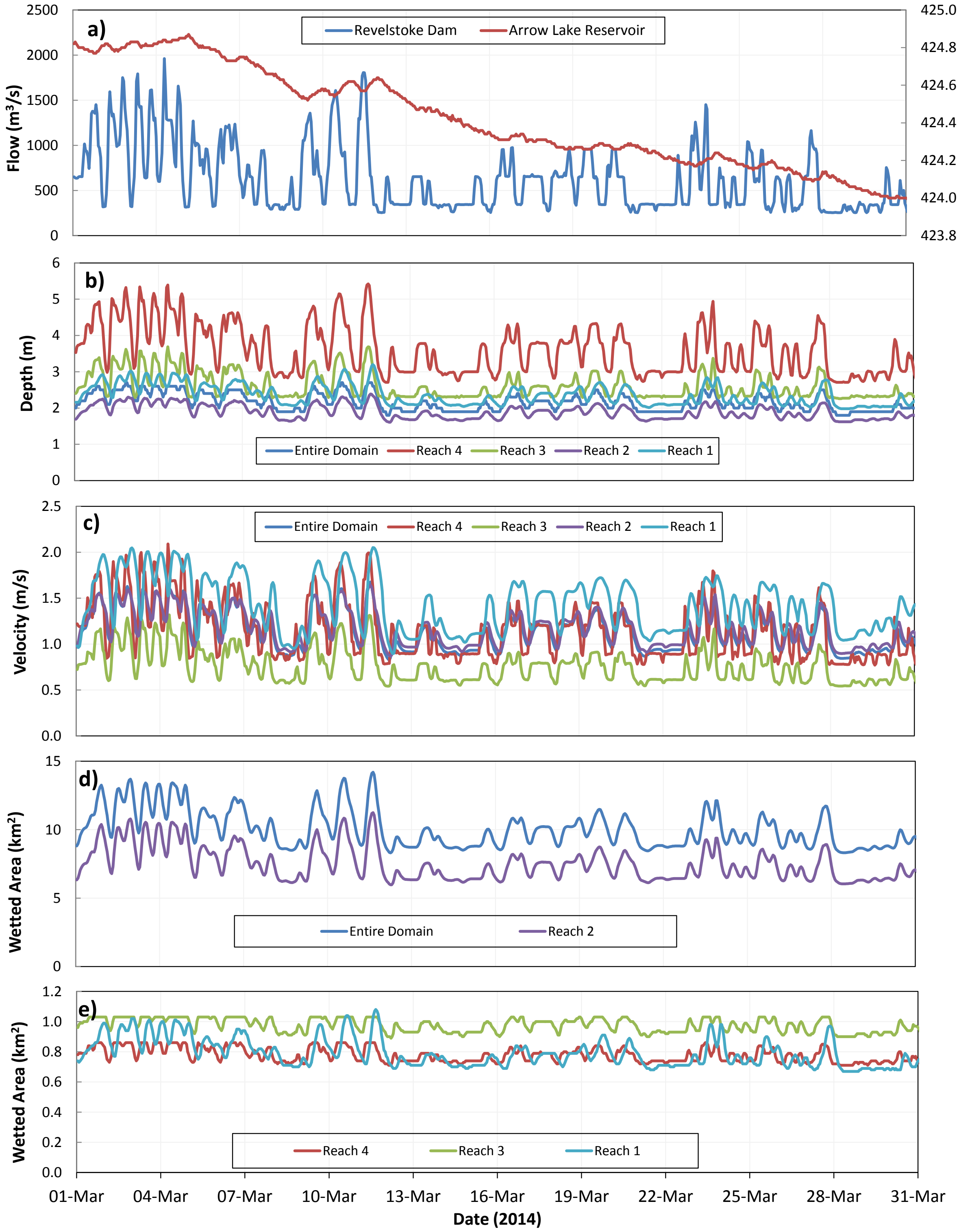


Figure 12 continued for the month of April 2015

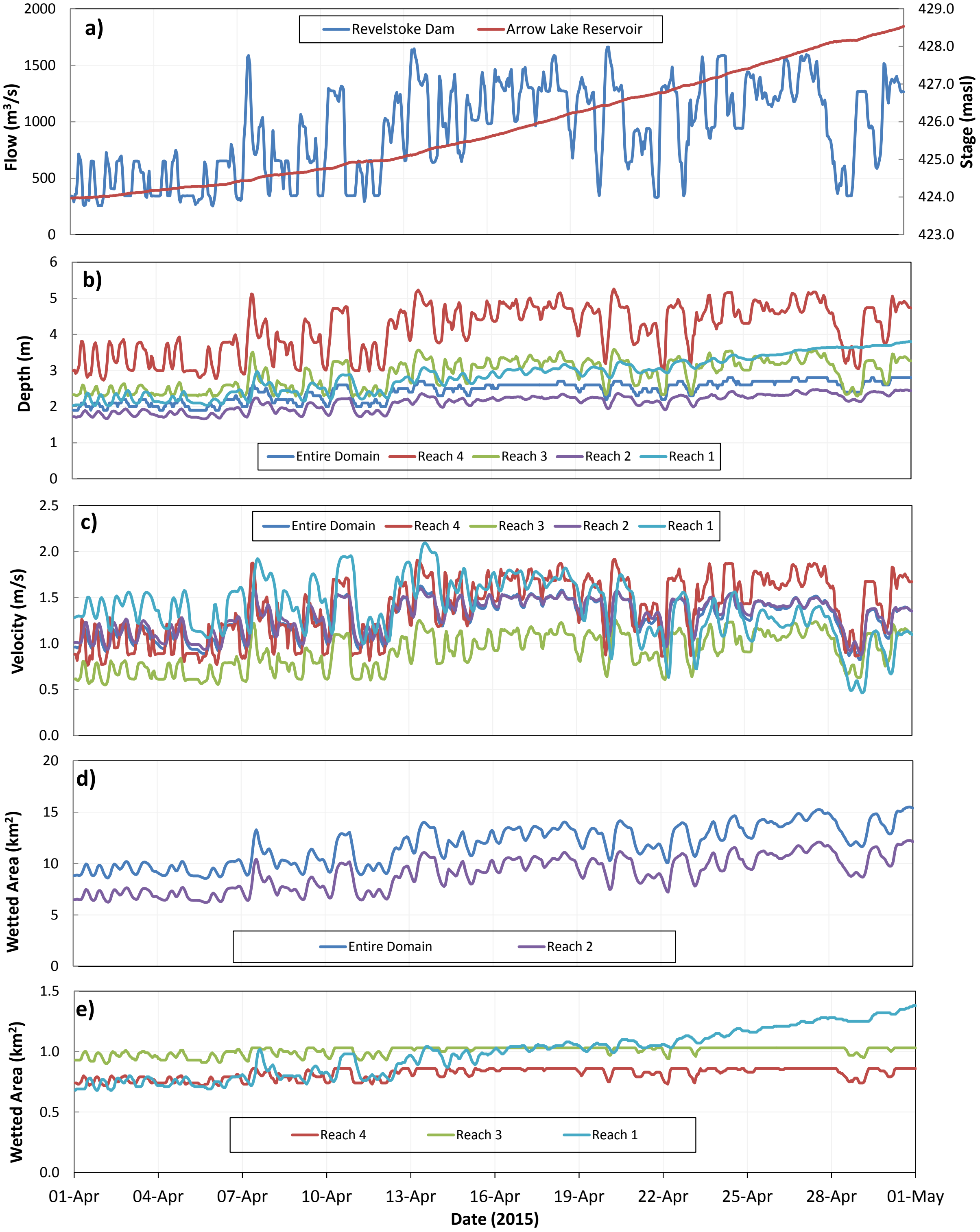
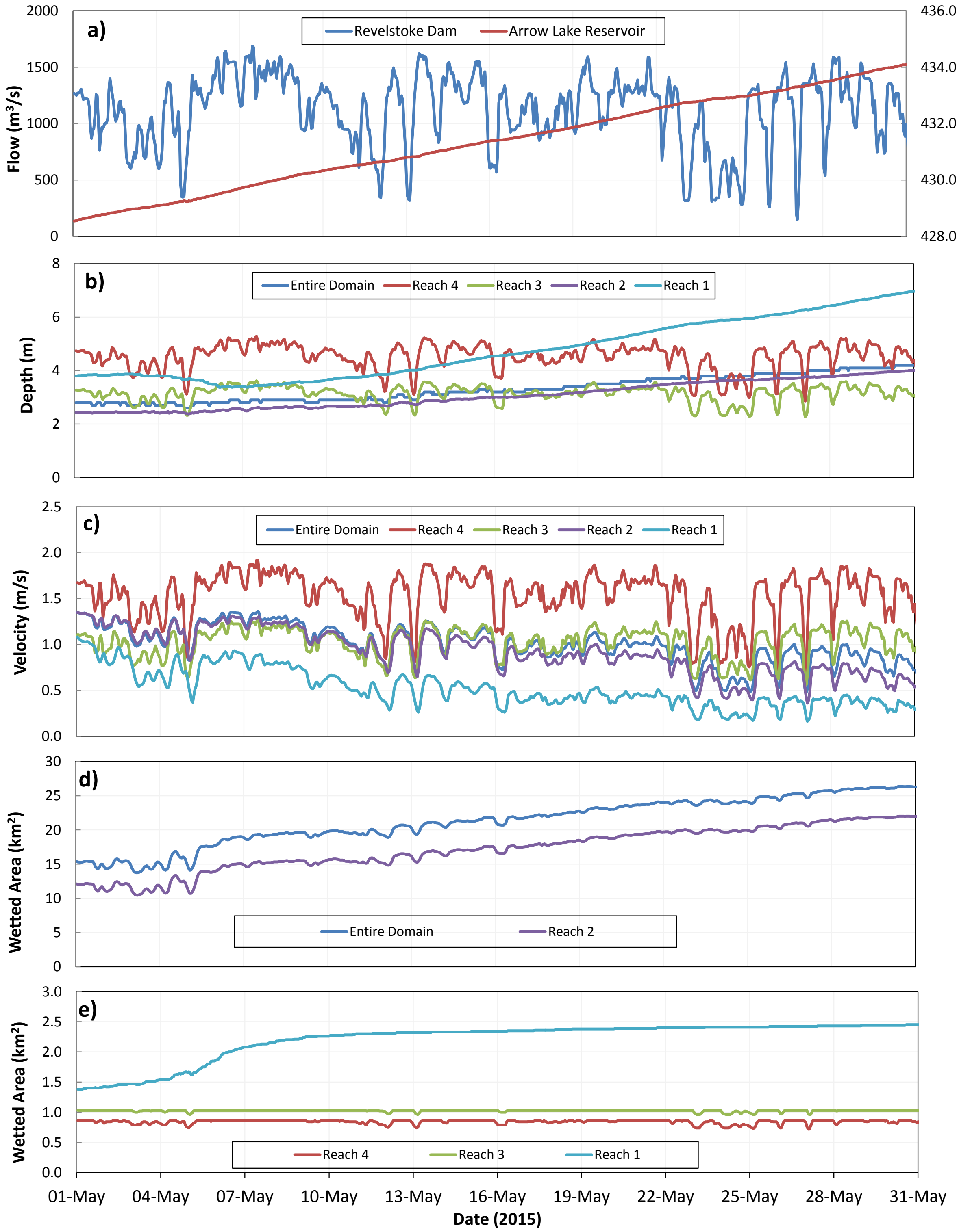


Figure 12 continued for the month of May 2015



APPENDIX E:
TABULAR REPRESENTATION OF THE 2014-2015 WETTED BED AREA, AVERAGE FLOW DEPTH, AND AVERAGE FLOW VELOCITY FOR THE REACHES OF THE MIDDLE COLUMBIA RIVER BY MONTH

Table 13 Wetted bed area, average flow depth, and average flow velocity for the reaches of the Middle Columbia River for November 01 to 30, 2014.

Reach	**Wetted Riverbed Area (km^2)**			**Average Flow Depth (m)**			**Average Velocity (m/s)**		
	Average	**Min**	**Max**	**Average**	**Min**	**Max**	**Average**	**Min**	**Max**
Total Area	23.7	21.8	25.5	3.7	3.3	4.0	0.66	0.39	1.17
Reach 4	0.8	0.7	0.9	3.9	2.7	5.5	1.26	0.77	2.05
Reach 3	1.0	0.9	1.0	2.7	2.3	3.8	0.83	0.55	1.34
Reach 2	19.5	17.7	21.2	3.5	3.2	3.8	0.52	0.28	1.02
Reach 1	2.4	2.4	2.4	5.7	5.0	6.3	0.23	0.07	0.55

[1] For November 2014, the average, min, and max discharges of Revelstoke Dam were 770, 255, and 1912 m^3/s, respectively.

[2] The average, min, and max ALR water levels during this time period were 432.7, 431.9, and 433.3 m, respectively.

Table 14 Wetted bed area, average flow depth, and average flow velocity for the reaches of the Middle Columbia River for December, 2014.

Reach	**Wetted Riverbed Area (km^2)**			**Average Flow Depth (m)**			**Average Velocity (m/s)**		
	Average	**Min**	**Max**	**Average**	**Min**	**Max**	**Average**	**Min**	**Max**
Total Area	18.5	14.1	23.1	2.8	2.4	3.5	0.74	0.47	1.38
Reach 4	0.8	0.7	0.9	3.6	2.7	5.3	1.14	0.78	1.98
Reach 3	1.0	0.9	1.0	2.6	2.2	3.7	0.75	0.55	1.29
Reach 2	14.5	10.6	18.8	2.6	2.2	3.3	0.68	0.39	1.33
Reach 1	2.2	1.6	2.4	3.9	3.4	5.1	0.30	0.11	0.98

[1] For December 2014, the average, min, and max discharges of Revelstoke Dam were 620, 258, and 1751 m^3/s, respectively.

[2] The average, min, and max ALR water levels during this time period were 430.5, 429.2, and 432.1 m, respectively.

Table 15 Wetted bed area, average flow depth, and average flow velocity for the reaches of the Middle Columbia River for January, 2015.

Reach	**Wetted Riverbed Area (km^2)**			**Average Flow Depth (m)**			**Average Velocity (m/s)**		
	Average	**Min**	**Max**	**Average**	**Min**	**Max**	**Average**	**Min**	**Max**
Total Area	12.7	8.6	18.1	2.5	1.9	3.0	1.13	0.66	1.72
Reach 4	0.8	0.7	0.9	4.1	2.7	5.8	1.36	0.78	2.15
Reach 3	1.0	0.9	1.0	2.9	2.2	4.0	0.89	0.54	1.41
Reach 2	9.6	6.2	14.6	2.2	1.6	2.6	1.15	0.69	1.67
Reach 1	1.2	0.8	1.7	3.3	2.3	3.9	0.88	0.28	2.18

[1] For January 2015, the average, min, and max discharges of Revelstoke Dam were 886, 255, and 2113 m^3/s, respectively.

[2] The average, min, and max ALR water levels at this time period were 427.6, 425.3, and 429.2 m, respectively.

Table 16 Wetted bed area, average flow depth, and average flow velocity for the reaches of the Middle Columbia River for February, 2015.

Reach	Wetted Riverbed Area (km^2)			Average Flow Depth (m)			Average Velocity (m/s)		
	Average	Min	Max	Average	Min	Max	Average	Min	Max
Total Area	10.3	8.3	13.7	2.2	1.8	2.7	1.16	0.82	1.61
Reach 4	0.8	0.7	0.9	3.7	2.7	5.2	1.20	0.77	1.94
Reach 3	1.0	0.9	1.0	2.6	2.2	3.6	0.79	0.54	1.26
Reach 2	7.7	6.0	10.8	1.9	1.6	2.3	1.20	0.88	1.58
Reach 1	0.8	0.7	1.0	2.5	2.1	3.0	1.39	0.84	2.04

[1] For Feburary 2015, the average, min, and max discharges of Revelstoke Dam were 684.6, 255, and 1683 m^3/s, respectively.

[2] The average, min, and max ALR water levels at this time period were 424.9, 424.6, and 425.3 m, respectively.

Table 17 Wetted bed area, average flow depth, and average flow velocity for the reaches of the Middle Columbia River for March, 2015.

Reach	Wetted Riverbed Area (km^2)			Average Flow Depth (m)			Average Velocity (m/s)		
	Average	Min	Max	Average	Min	Max	Average	Min	Max
Total Area	10.0	8.3	14.2	2.2	1.8	2.7	1.13	0.83	1.68
Reach 4	0.8	0.7	0.9	3.6	2.7	5.4	1.14	0.77	2.09
Reach 3	1.0	0.9	1.0	2.6	2.2	3.8	0.75	0.54	1.32
Reach 2	7.5	6.0	11.2	1.9	1.6	2.4	1.17	0.87	1.64
Reach 1	0.8	0.7	1.1	2.4	2.0	3.2	1.42	0.90	2.05

[1] For March 2015, the average, min, and max discharges of Revelstoke Dam were 618.3, 254, and 1961.6 m^3/s, respectively.

[2] The average, min, and max ALR water levels at this time period were 424.4, 424.0, and 424.9 m, respectively.

Table 18 Wetted bed area, average flow depth, and average flow velocity for the reaches of the Middle Columbia River for April, 2015.

Reach	Wetted Riverbed Area (km^2)			Average Flow Depth (m)			Average Velocity (m/s)		
	Average	Min	Max	Average	Min	Max	Average	Min	Max
Total Area	11.8	8.5	15.5	2.4	1.9	2.8	1.27	0.82	1.63
Reach 4	0.8	0.7	0.9	4.1	2.7	5.3	1.39	0.76	1.91
Reach 3	1.0	0.9	1.0	2.9	2.2	3.7	0.91	0.55	1.26
Reach 2	9.0	6.2	12.2	2.1	1.6	2.5	1.30	0.88	1.60
Reach 1	1.0	0.7	1.4	2.9	2.0	3.8	1.38	0.46	2.09

[1] For April 2015, the average, min, and max discharges of Revelstoke Dam were 915.7, 254, and 1661.7 m^3/s, respectively.

[2] The average, min, and max ALR water levels at this time period were 426, 424, and 428.5 m, respectively.

Table 19 Wetted bed area, average flow depth, and average flow velocity for the reaches of the Middle Columbia River for May, 2015.

Reach	**Wetted Riverbed Area (km^2)**			**Average Flow Depth (m)**			**Average Velocity (m/s)**		
	Average	**Min**	**Max**	**Average**	**Min**	**Max**	**Average**	**Min**	**Max**
Total Area	21.4	13.7	26.5	3.3	2.6	4.2	1.00	0.46	1.36
Reach 4	0.8	0.7	0.9	4.5	2.9	5.3	1.53	0.55	1.92
Reach 3	1.0	1.0	1.0	3.2	2.2	3.7	1.02	0.56	1.28
Reach 2	17.3	10.5	22.1	3.1	2.4	4.0	0.91	0.32	1.35
Reach 1	2.2	1.4	2.5	4.8	3.4	7.0	0.51	0.16	1.08

[1] For May 2015, the average, min, and max discharges of Revelstoke Dam were 1107.5, 149, and 1685.7 m^3/s, respectively.

[2] The average, min, and max ALR water levels at this time period were 431.4, 428.5, and 434.2 m, respectively.

Table 20 Discharge from Revelstoke Dam, wetted bed area, average flow depth, and average flow velocity for the reaches of the Mid-Columbia River for the low ALR boundary water level (428 m) downstream of the modelled domain.

Simulation No	Revelstoke Dam Flow (m^3/s)	Arrow Lake Reservoir Low Water Level (m)	Wetted Riverbed Area (km^2)					Average Velocity (m/s)					Average Flow Depth (m)				
			Total	Reach 4	Reach 3	Reach 2	Reach 1	Total	Reach 4	Reach 3	Reach 2	Reach 1	Total	Reach 4	Reach 3	Reach 2	Reach 1
1	262	428	10.44	0.71	0.84	7.66	1.23	0.69	0.84	0.69	0.70	0.3	2.2	2.65	2.04	1.97	3.52
2	300	428	10.61	0.72	0.86	7.80	1.23	0.74	0.89	0.72	0.76	0.3	2.2	2.77	2.13	1.99	3.52
3	328	428	10.71	0.73	0.87	7.88	1.23	0.76	0.92	0.74	0.79	0.3	2.3	2.85	2.19	2.01	3.52
4	350	428	10.80	0.73	0.88	7.95	1.23	0.79	0.95	0.76	0.81	0.3	2.3	2.91	2.22	2.02	3.53
5	370	428	10.86	0.74	0.89	8.00	1.23	0.80	0.97	0.77	0.83	0.3	2.3	2.97	2.25	2.03	3.53
6	401	428	11.02	0.74	0.90	8.14	1.23	0.83	1.00	0.78	0.86	0.4	2.3	3.06	2.31	2.03	3.53
7	426	428	11.14	0.75	0.91	8.25	1.23	0.86	1.03	0.80	0.89	0.4	2.3	3.14	2.34	2.05	3.53
8	445	428	11.22	0.75	0.92	8.32	1.23	0.87	1.04	0.81	0.91	0.4	2.3	3.19	2.36	2.06	3.53
9	479	428	11.33	0.76	0.93	8.41	1.23	0.90	1.08	0.82	0.93	0.4	2.3	3.28	2.35	2.07	3.53
10	488	428	11.38	0.76	0.93	8.46	1.23	0.91	1.09	0.83	0.94	0.5	2.3	3.31	2.36	2.08	3.54
11	520	428	11.49	0.77	0.94	8.55	1.23	0.94	1.12	0.84	0.97	0.5	2.4	3.40	2.39	2.10	3.54
12	555	428	11.62	0.78	0.96	8.66	1.23	0.96	1.15	0.86	1.00	0.5	2.4	3.49	2.40	2.12	3.54
13	575	428	11.68	0.78	0.96	8.71	1.23	0.98	1.16	0.87	1.01	0.5	2.4	3.53	2.40	2.13	3.54
14	605	428	11.78	0.78	0.97	8.79	1.23	1.00	1.19	0.88	1.03	0.6	2.4	3.60	2.37	2.14	3.55
15	625	428	11.86	0.79	0.97	8.87	1.23	1.01	1.20	0.89	1.05	0.6	2.4	3.65	2.39	2.16	3.55
16	650	428	11.93	0.79	0.98	8.93	1.23	1.03	1.22	0.90	1.06	0.6	2.4	3.70	2.41	2.17	3.55
17	670	428	12.00	0.79	0.98	8.99	1.24	1.04	1.24	0.91	1.08	0.6	2.5	3.75	2.44	2.18	3.55
18	701	428	12.12	0.80	0.98	9.10	1.24	1.06	1.26	0.92	1.09	0.6	2.5	3.82	2.46	2.19	3.56
19	750	428	12.28	0.81	0.99	9.24	1.24	1.09	1.30	0.94	1.13	0.7	2.5	3.93	2.53	2.22	3.56
20	775	428	12.35	0.81	1.00	9.30	1.24	1.11	1.31	0.95	1.14	0.7	2.5	3.98	2.56	2.24	3.57
21	791	428	12.39	0.81	1.00	9.33	1.24	1.12	1.32	0.95	1.15	0.7	2.5	4.02	2.58	2.25	3.57
22	801	428	12.42	0.82	1.00	9.37	1.24	1.12	1.33	0.96	1.16	0.7	2.5	4.04	2.60	2.25	3.57
23	823	428	12.49	0.82	1.01	9.43	1.24	1.14	1.35	0.97	1.17	0.7	2.6	4.08	2.63	2.27	3.57
24	850	428	12.56	0.82	1.01	9.49	1.24	1.15	1.37	0.98	1.18	0.8	2.6	4.13	2.66	2.28	3.57
25	875	428	12.65	0.83	1.01	9.58	1.24	1.17	1.38	0.99	1.20	0.8	2.6	4.18	2.70	2.29	3.58
26	903	428	12.75	0.83	1.01	9.67	1.24	1.18	1.40	1.00	1.21	0.8	2.6	4.23	2.72	2.30	3.58
27	926	428	12.84	0.84	1.02	9.75	1.24	1.19	1.42	1.01	1.22	0.8	2.6	4.26	2.74	2.32	3.59
28	950	428	12.91	0.84	1.02	9.81	1.24	1.21	1.43	1.01	1.24	0.8	2.6	4.30	2.76	2.33	3.59
29	975	428	13.08	0.84	1.02	9.97	1.24	1.22	1.45	1.02	1.25	0.9	2.6	4.35	2.80	2.32	3.59
30	1000	428	13.15	0.85	1.02	10.04	1.25	1.23	1.47	1.03	1.26	0.9	2.6	4.39	2.83	2.34	3.60

Table 21 Discharge from Revelstoke Dam, wetted bed area, average flow depth, and average flow velocity for the reaches of the Mid-Columbia River for the high ALR boundary water level (433 m) downstream of the modelled domain.

Simulation No	Revelstoke Dam Flow (m^3/s)	Arrow Lake Reservoir High Water Level (m)	Average Wetted Riverbed Area (km^2)					Average Velocity (m/s)					Average Flow Depth (m)				
			Total	Reach 4	Reach 3	Reach 2	Reach 1	Total	Reach 4	Reach 3	Reach 2	Reach 1	Total	Reach 4	Reach 3	Reach 2	Reach 1
1	160	433	23.79	0.69	0.85	19.84	2.41	0.39	0.62	0.63	0.32	0.1	3.7	2.40	2.05	3.63	5.99
2	180	433	23.81	0.69	0.86	19.85	2.41	0.41	0.66	0.65	0.33	0.1	3.7	2.48	2.09	3.63	5.99
3	200	433	23.77	0.70	0.85	19.80	2.41	0.39	0.69	0.68	0.29	0.1	3.7	2.54	2.07	3.63	5.99
4	225	433	23.89	0.71	0.88	19.89	2.41	0.45	0.72	0.69	0.37	0.2	3.8	2.65	2.19	3.63	5.99
5	255	433	23.92	0.72	0.89	19.90	2.41	0.47	0.77	0.71	0.38	0.2	3.8	2.74	2.23	3.63	5.99
6	280	433	23.83	0.72	0.87	19.83	2.41	0.45	0.84	0.73	0.33	0.1	3.8	2.74	2.17	3.63	5.99
7	300	433	23.94	0.73	0.90	19.90	2.41	0.50	0.84	0.74	0.40	0.2	3.8	2.86	2.28	3.63	5.99
8	330	433	23.98	0.73	0.91	19.92	2.41	0.52	0.87	0.76	0.41	0.2	3.8	2.96	2.33	3.63	5.99
9	350	433	23.96	0.74	0.91	19.90	2.41	0.51	0.91	0.77	0.40	0.2	3.8	2.99	2.32	3.63	5.99
10	380	433	24.01	0.74	0.92	19.93	2.41	0.54	0.94	0.79	0.43	0.2	3.8	3.10	2.34	3.63	5.99
11	410	433	24.02	0.75	0.93	19.93	2.41	0.55	0.98	0.81	0.43	0.2	3.8	3.18	2.34	3.64	5.99
12	440	433	24.05	0.76	0.94	19.95	2.41	0.57	1.01	0.83	0.45	0.2	3.8	3.26	2.36	3.64	5.99
13	470	433	24.10	0.76	0.95	19.97	2.41	0.59	1.03	0.85	0.47	0.2	3.8	3.35	2.39	3.64	5.99
14	500	433	24.12	0.77	0.96	19.98	2.41	0.61	1.06	0.86	0.48	0.2	3.8	3.43	2.40	3.64	5.99
15	530	433	24.14	0.77	0.96	19.99	2.41	0.62	1.09	0.87	0.49	0.2	3.8	3.48	2.40	3.64	5.99
16	560	433	24.18	0.78	0.97	20.02	2.41	0.64	1.11	0.89	0.52	0.2	3.8	3.57	2.39	3.65	5.99
17	590	433	24.19	0.78	0.98	20.02	2.41	0.65	1.14	0.90	0.52	0.2	3.8	3.64	2.41	3.65	5.99
18	620	433	24.24	0.79	0.98	20.06	2.41	0.68	1.16	0.91	0.55	0.3	3.8	3.73	2.44	3.65	5.99
19	650	433	24.23	0.79	0.98	20.04	2.41	0.68	1.20	0.92	0.54	0.2	3.8	3.77	2.45	3.65	5.99
20	680	433	24.29	0.80	0.99	20.09	2.41	0.71	1.21	0.94	0.58	0.3	3.8	3.87	2.53	3.65	5.99
21	710	433	24.30	0.80	0.99	20.09	2.41	0.71	1.24	0.95	0.58	0.3	3.8	3.92	2.56	3.65	5.99
22	740	433	24.37	0.81	1.00	20.14	2.41	0.73	1.25	0.96	0.61	0.3	3.8	4.00	2.61	3.65	5.99
23	770	433	24.38	0.81	1.01	20.15	2.41	0.74	1.28	0.97	0.61	0.3	3.8	4.05	2.64	3.65	5.99
24	800	433	24.41	0.82	1.01	20.17	2.41	0.76	1.30	0.98	0.63	0.3	3.8	4.12	2.69	3.66	5.99
25	830	433	24.43	0.82	1.01	20.19	2.41	0.77	1.33	0.99	0.63	0.3	3.8	4.17	2.72	3.66	5.99
26	860	433	24.47	0.83	1.02	20.21	2.41	0.78	1.35	1.00	0.64	0.3	3.8	4.23	2.74	3.66	5.99
27	890	433	24.46	0.83	1.02	20.20	2.41	0.78	1.37	1.01	0.64	0.3	3.8	4.27	2.75	3.66	5.99
28	920	433	24.44	0.84	1.02	20.17	2.41	0.78	1.40	1.01	0.63	0.3	3.8	4.28	2.77	3.65	5.99
29	950	433	24.59	0.84	1.02	20.32	2.41	0.82	1.41	1.04	0.68	0.3	3.8	4.37	2.85	3.65	5.99
30	1000	433	24.65	0.85	1.02	20.36	2.41	0.83	1.44	1.06	0.69	0.3	3.8	4.46	2.90	3.65	5.99