Columbia River Project Water Use Plan

Revelstoke Flow Management Plan

Mid-Columbia Physical Habitat Monitoring Project

Implementation Year 8

Reference: CLBMON-15a

Study Period: 2014

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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 the end of 2014. In this report, the physical monitoring results from November 2013 to the end of October 2014 (Implementation Year 8) are summarized. For results of earlier Implementation Years, the reader is referred to Plate et al. (2014), Golder (2013) and Golder summary reports from 2008 to 2012[1].

The main task of CLBMON-15a was the monitoring of water stage and temperature at five stations in the MCR reaches 2 to 4 and one station each in the Illecillewaet and Jordan rivers. In addition, a sixth station in the MCR (Station 3) was operated, maintained and downloaded by BC Hydro. Within the six MCR stations, Station 1 was located closest (~1 km downstream of REV) to REV while Station 6 was located the farthest (~20 km downstream of REV) from REV. Stage data from the six MCR and the two tributary stations were used to calibrate a HEC-RAS model for the MCR. As of the end of the 2014 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 during all downloading site visits at the index stations in the MCR as well as the Illecillewaet and Jordan River tributaries.

Stage and Water Monitoring Results

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

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

was significantly smaller post WUP flow implementation based on the data by Golder (2013), Plate et al. (2014) 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

Physical and nutrient water parameters were used as indicators of trophic status for a particular year. Due to low sample size, these results should 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).

Table 1 CLBMON-15a status of objectives, management questions and hypotheses (Year 8, 2014).

Objectives	**Management Question: How does the 142m^3/s minimum flow affect…**	**Management Hypothesis: Implementation of a 142m^3/s minimum flow release from REV will not significantly…**	**Year 8 (2014) 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	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 river water Total Gas Pressure (TGP) levels between pre- and post-implementation of the 142 m^3/s minimum flow regime	…TGP in the flowing reach of the MCR	…alter TGP levels in the flowing reach of the MCR (Ho 2)	TGP values are no longer measured as part of the CLBMON-15a program and therefore a 2014 status update was not possible.

Measure spatial and temporal differences in the daily and seasonal range of river level fluctuations between pre- and post-implementation of the 142 m³/s minimum flow regime	…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	Diel variation in water level following WUP flows and REV 5 is larger because of the greater range of possible discharges. The seasonal pattern of mean river fluctuations does not appear to be affected by WUP flows and REV 5.
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	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 m³/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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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 at low ALR levels (Figure 1) and shortened lengths 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). 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.

In 2007, BC Hydro commissioned the MCR Physical Habitat Monitoring Program (CLBMON-15a) to collect physical habitat and water quality information on the MCR. The study area for CLBMON-

15a encompasses the 32-km section of the MCR from the outlet of REV downstream to the confluence with the Akolkolex River, and is divided as follows (Figure 1):

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

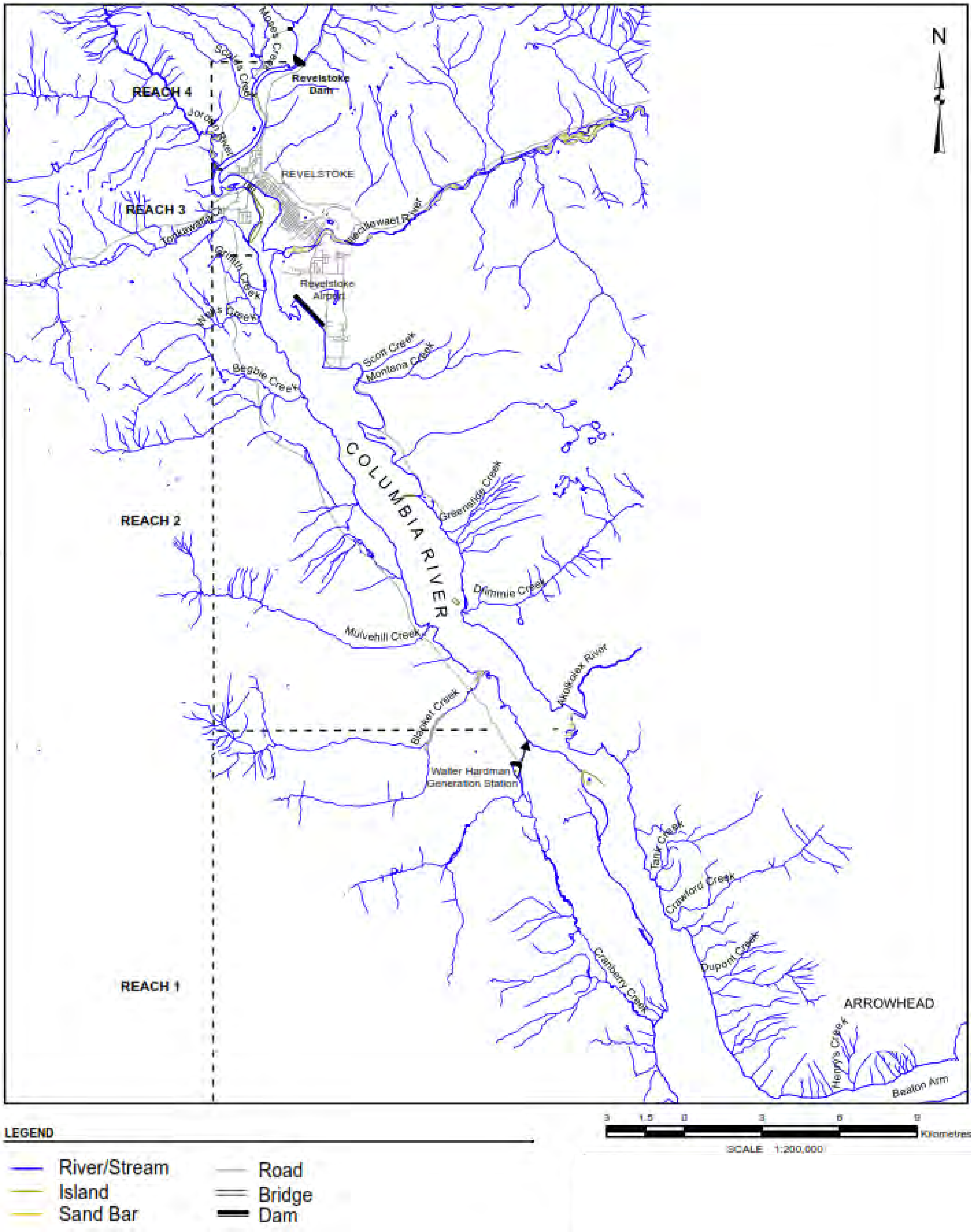


Figure 1 Map showing an overview of the CLBMON-15a study area and the reach naming conventions (Source: Golder 2012).

1.2. Monitoring Program Overview and Objectives

As defined in the WUP (BC Hydro 2005), the objective of CLBMON-15a was to monitor physical parameters for four years pre-REV 5 operations and for up to 10 years of post-REV 5 operations. The year 2014 or Year 8 of the program marked the fourth year of post-REV 5 operations. The physical data gathered as part of CLBMON-15a addresses the following objectives:

1) To measure spatial and temporal differences in the daily and seasonal river water temperature regimes between pre-implementation of the 142 m^3/s minimum flow regime and post-implementation of the 142 m^3/s minimum flow regime (ongoing).
2) To measure spatial and temporal differences in river water TGP levels between pre and post-implementation of the 142 m^3/s minimum flow regime (completed in 2011 and therefore no additional data gathered in 2014).
3) To 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 (ongoing).
4) To collect seasonal nutrient (completed in May 2014 and therefore only data for the first sampling date in May 2014 reported here) and electrochemistry data (ongoing) at the reach scale to spatially characterize water quality conditions.
5) To estimate changes in the quantity and spatial distribution of permanently inundated river channel resulting from 142 m^3/s minimum flow releases (ongoing).

The SCOPE of the MCR Physical Habitat Monitoring Program is:

1) To continuously monitor water temperature and river stage at index monitoring stations focusing on the upper two reaches of the MCR (Reaches 3 and 4), and in key tributaries (Jordan and Illecillewaet rivers) (ongoing).
2) To conduct strategic, non-continuous TGP monitoring at index stations in the flowing reach of the MCR (completed in 2011).
3) To conduct seasonal water quality sampling to analyze for electrochemistry and biologically active micronutrients (completed in May 2014 and therefore only data for the first sampling date in May 2014 reported here) at index monitoring stations with a focus on the upper two reaches of the MCR (Reaches 3 and 4).
4) To use stage data collected during the monitoring program to calibrate existing 1-d steady and unsteady hydraulic models for the MCR and to use those models to estimate locations of and changes in inundated river channel (ongoing).
5) To use the empirical data and hydraulic modelling results to test hypotheses about the influence of minimum flow releases on hydraulic characteristics and temperature of the MCR (ongoing).

6) To develop an electronic database system for systematic storage and retrieval of physical habitat data for the MCR (ongoing).

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 three times per year at index sites and nutrient concentrations were sampled only once in May of 2014 (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 seven time-synchronized data loggers at five stations in the MCR and one station in the Jordan River, a major tributary (Table 2). In addition, only temperature data was collected from the Illecillewaet River. Data were provided by outside sources for the stage of the Illecillewaet River (Environment Canada automated stream gauging station 08ND013 – Illecillewaet River at Greeley). 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 three times per year. 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 CLBMON 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.

- Seasonal water quality sampling: Sampling of non-physical and electrochemistry data was carried out only for the May 2014 date and terminated after that based on recommendations coming out of a CLBMON workshop in February of 2014. Nevertheless, physical and electrochemistry data were collected three times per year (spring, summer and fall) at the five index stations in the MCR and one station each in the Jordan and the Illecillewaet Rivers for a total of 21 samples collected in 2014. 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 earlier by Golder Associates for CLBMON-15a.

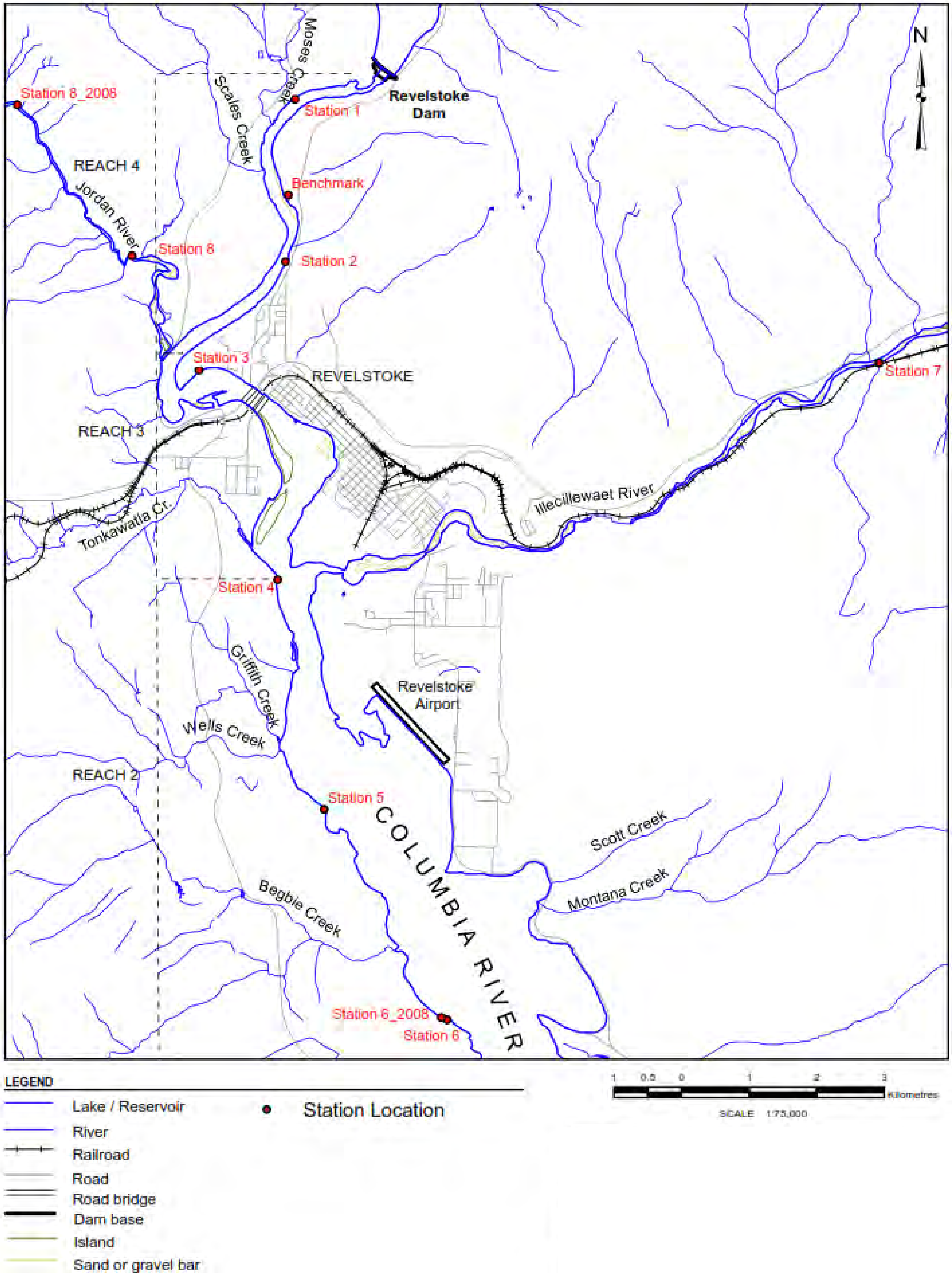


Figure 2 Map showing an overview of the MCR study area and the location of all monitoring index stations (Source: Golder 2012).

1.4. Key CLBMON-15a Management Questions and Hypotheses

The key management questions for CLBMON-15a are:

1. How does the implementation of the 142 m^3/s minimum flow affect water temperature in the flowing reach of the MCR? What is the temporal scale (diel, seasonal) of water temperature changes? Are there spatial differences in the pattern of the water temperature response?
2. How does the implementation of the 142 m^3/s minimum flow affect total gas pressure (TGP) in the flowing reach of the MCR (this management question was not addressed in 2014)?
3. How does the implementation of the 142 m^3/s minimum flow affect the range and variability in river level fluctuation in the MCR? Are there temporal (seasonal scale) or spatial (reach scale) differences in the pattern of response?
4. Does the implementation of the 142 m^3/s minimum flow affect water quality in terms of electrochemistry and biologically active nutrients (biologically active nutrients were only collected on May 6, 2014 and this management question was not addressed after that anymore)?
5. How does the implementation of the 142 m^3/s minimum flow release from Revelstoke Dam affect the total area of river channel that is permanently wetted?

The hypotheses based on the management questions are:

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 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. Implementation of a 142 m^3/s minimum flow release from Revelstoke Dam will not significantly alter TGP levels in the flowing reach of the MCR. (Note that the TGP monitoring program was terminated in 2011 and therefore no data were collected in 2014)

- Hypothesis 2A: The implementation of a 142 m^3/s minimum flow release from Revelstoke Dam will not significantly alter TGP levels.

Hypothesis 3. 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 3A: The implementation of a 142 m^3/s minimum flow release from Revelstoke Dam will not alter the diel variation of river levels in MCR;
- Hypothesis 3B: 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 4. The implementation of a 142 m^3/s minimum flow release from Revelstoke Dam does not increase the minimum total wetted channel area in MCR.

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 1 (terminated on May 6, 2014), 1AS (terminated on May 6, 2014), 2, 2AS, 4, 5 and 6 (stage and temperature loggers) – (Figure 2) in Reaches 2 through 4;
- MCR Monitoring Station 3 – was malfunctioning until September 2014 and was therefore replaced in October of 2014. Once the station elevation has been surveyed by BC Hydro, Station 3 data will be included in the calibration of the next HEC-RAS model calibration run;
- 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 seven river stage data loggers (deployed in five standpipes and two anchor stations) 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. Two additional river stage data loggers were installed on anchors at the standpipe stations in Reach 4 (Stations 1 and 2). The anchor-based monitoring stations (Stations 1_AS and

2_AS) were used in calibrating the hydraulic model in previous years. To maintain consistency between years, stations 1_AS and 2_AS were used in model calibration and application for the 2013/2014 monitoring year. Installation and location details for all river stage data loggers are described in Golder (2008; 2013).

In previous years, 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. However, this station was not functional until September 2014 and was replaced with a new station and logger in October 2014. Station 3 data since October 2014 could not be used for model calibration because the logger elevation has not yet been surveyed. Station 3 stage data is hoped to be included in the next model calibration, once the station elevation has been surveyed by BC Hydro.

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 2013/2014 monitoring period.

Station Name	System	Solinst Logger Type	UTM Zone 11 Easting	UTM Zone 11 Northing	Start Date (PST)	End Date (PST)	Duration (Days)	Logging Interval (min)	Elevation (masl)
CLB-Station 1	MCR	Level	415049	5655566	07-Nov-2013 03:00	06-May-2014 22:30	180.2	10	438.26
CLB-Station 1_AS	MCR	Level	415049	5655566	07-Nov-2013 02:20	06-May-2014 22:50	180.2	10	437.38
CLB-Station 2	MCR	Level & Baro[1]	414925	5653213	07-Nov-2013 00:10	01-Nov-2014 10:50	359.4	10	436.66
CLB-Station 2_AS	MCR	Level	414925	5653213	07-Nov-2013 00:50	01-Nov-2014 10:40	359.4	10	436.83
CLB-Station 4	MCR	Level & Baro[1,2]	414807	5648490	06-Nov-2013 13:30	01-Nov-2014 12:40	360	10	432.16
CLB-Station 5	MCR	Level	415490	5645100	06-Nov-2013 13:20	01-Nov-2014 15:00	360.1	10	430.79
CLB-Station 6	MCR	Level	417171	5642074	06-Nov-2013 13:50	01-Nov-2014 15:30	360.1	10	429.36
CLB-Station 8	Jordan R.	Level	410904	5655521	05-Nov-2013 14:00	31-Oct-2014 16:30	360.1	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 2014 was carried out as part of all three station visits 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. The standpipe at Station 2 was reinforced with new brackets on May 6, 2014.
- 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 2014.
- Checking for sediment build up inside the standpipes and flushing out sediment. Sediment had built up in the standpipe at all stations in 2014 and was cleaned out with a pipe cleaner in October of 2014.
- Cleaning of the water permeable end covers of the standpipes and re-attaching them. End covers were cleaned at all stations in 2014 using a dry-suit and a snorkel. In addition, algae and detritus growth on the outside of all standpipes and the anchor was scraped off. Data logger readings in 2014 appeared accurate and consistent with readings in 2013.
- Checking all data loggers for proper operations and exchange them if necessary. All data loggers operated as expected in 2014 and therefore none of the data loggers were exchanged. Two new back-up data loggers were taken into the field in 2014.

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 daily averages. For application of the HEC-RAS model, these daily-average flows were transformed to hourly flows using linear interpolation. 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 pro-ration
Jordan River	17	Ranked regression; Drainage area pro-ration
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 pro-ration 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). 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.

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 pro-ration, 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).

Ecofish Ltd. (Ecofish) was retained by LGL Limited (LGL) to calibrate the existing unsteady state HEC-RAS model of the MCR for the 2013/2014 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, 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 06, 2013 and October 30, 2014. 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).

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 1_AS, 2_AS, 4, 5, and 6 (Table 2). Data from Station 3 were included in the initial model calibration (Golder 2013). However, data for this station were not available for the 2013/2014 simulation period due to sensor malfunction, and were not used for calibrating the current version of the model.

Station 3 data for November 2012 to August 2013 were made available; these data were not available for the 2012/2013 model runs completed by Ecofish (Imam *et al.* 2014). To check the accuracy of the model in predicting station 3 water levels, this data was input to the previous version of the model (Imam *et al.* 2014). 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 this station 3 data.

The roughness coefficients did not require adjustment from those used in the previous 2012/2013 MCR model (Table 6).

Table 6. Calibrated Manning roughness coefficients for the unsteady hydraulic model. Shown are the calibrated roughness coefficients for the previous versions of the model, (Plate et al. 2014) and (Golder 2013). Also shown is the expected range of roughness coefficients based on channel morphology and bed type (Golder 2013).

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

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

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. We evaluated the resolution of the model 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 300 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, and 200 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 2, 4, 5, and 6, and for the whole period for Station 1.

Analysis of Simulated Hydraulic Parameters

Model results for November 2013 to October 2014 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.

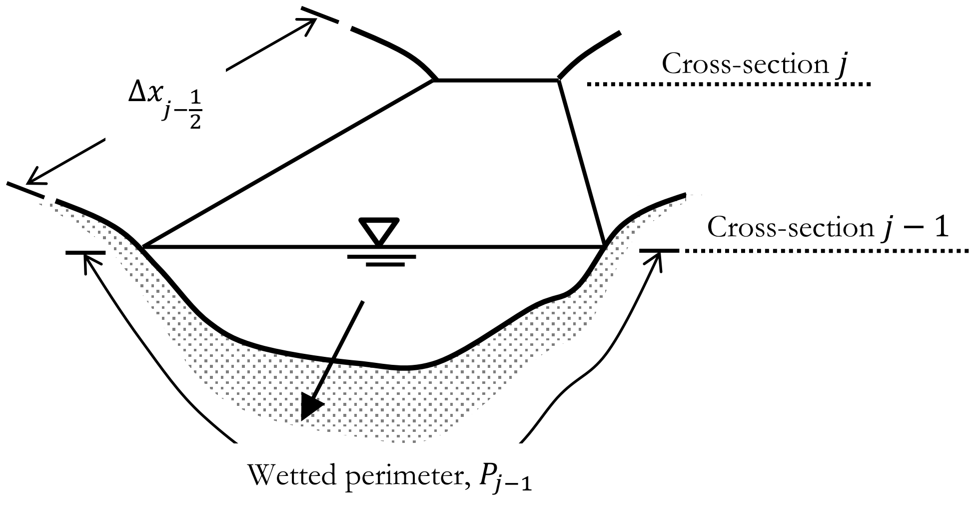


Figure 3. Schematic of stream cross-sections showing variables used in calculating wetted area.

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

Model Calibration for November 06, 2013 to October 30, 2014 used the Manning roughness coefficients from the previous version of the model (Plate et al. 2014, Table 6), as there were no changes in the calibrated roughness coefficients for any of the reaches. A well calibrated model has small differences between simulated and observed water levels, and from the 2013/2014 model calibration results (Table 7, details of Table 7 are explained in 3.5 Model Validation, Water Stage and Discharge), it appears that the MCR model is well calibrated. 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 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 averaging flow intervals from 50 m^3/s to 300 m^3/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 2, 4, 5 and 6 and for all conditions at Station 1.

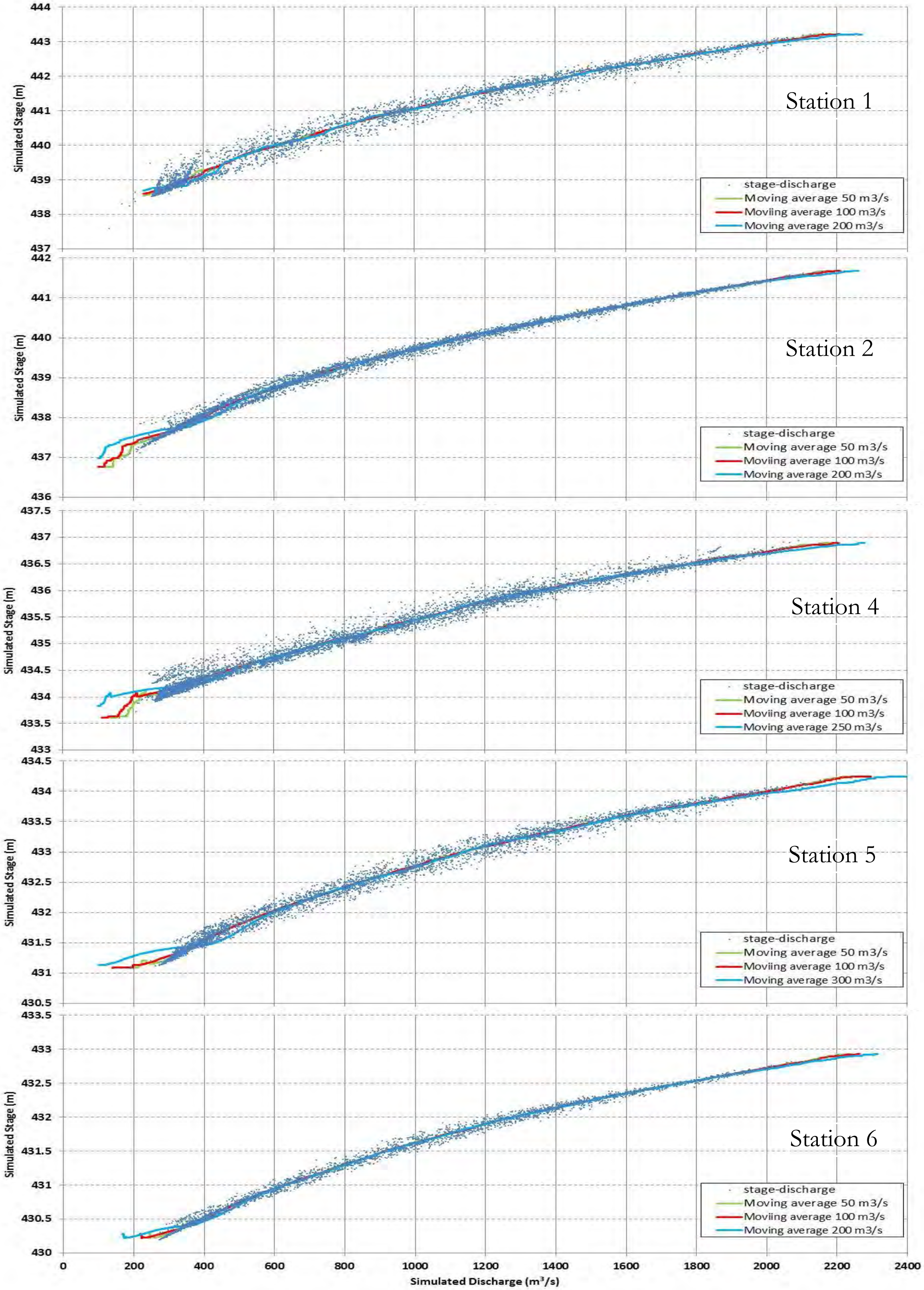
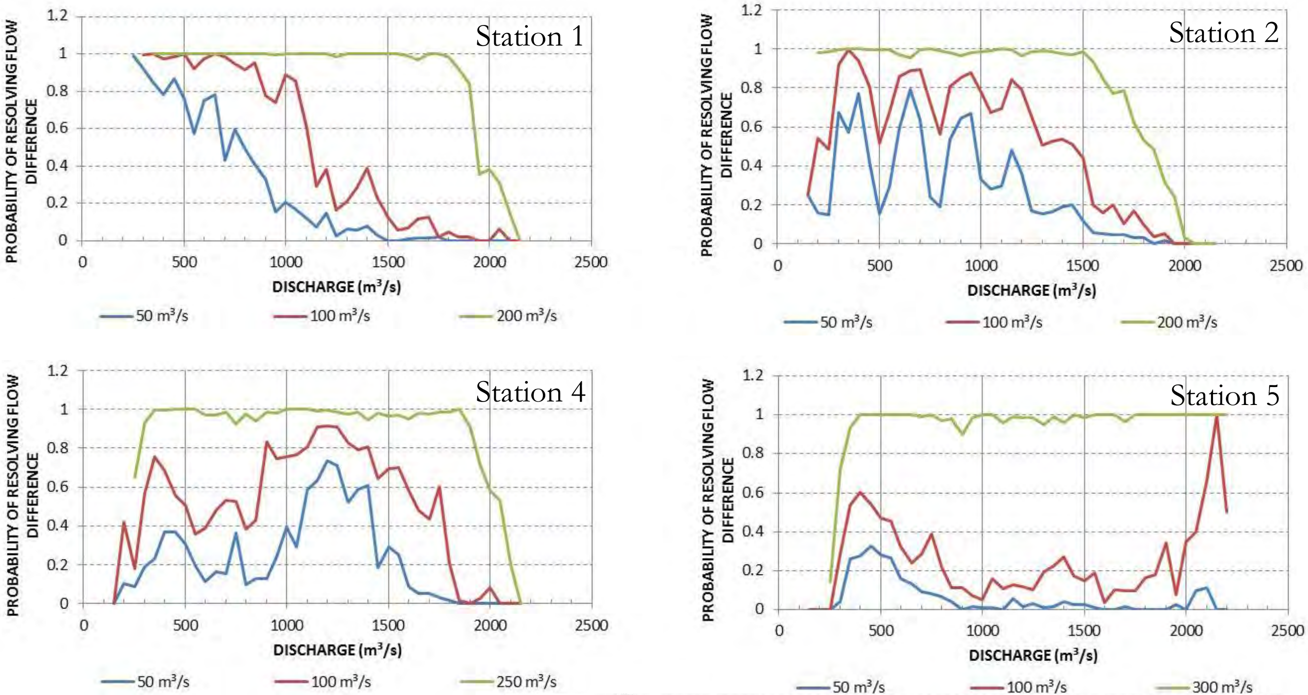


Figure 4 Relationship between stage and discharge at MCR stations 1, 2, 4, 5 and 6 as simulated by the model (data points) and calculated via moving average across flow intervals ranging from 50 m3/s to 300 m3/s.

The lines in the plots shown in Figure 5 represent the model's probability of resolving flow differences. For **Station 1**, the model performs best at low flows: it can resolve differences of 50 m³/s with ~80% probability at flows less than 500 m³/s. Between 500 and 1000 m³/s, the model can resolve differences of approximately 100 m³/s. Between 1000 and ~1800 m³/s, the model can resolve differences of ~ 200 m³/s. The model resolution is > 200 m³/s above 1800 m³/s. For **Station 2**, the model can resolve differences of 200 m³/s with near 100% probability. There is no clear trend for the model's ability to resolve finer flow differences – for example, at ~400 m³/s the model can resolve a difference of 100 m³/s with 100% probability, but this probability is reduced to ~ 50% at 500 m³/s. The model performance for **Station 4** is best at moderate flows: the model can resolve differences of 100 m³/s with 80% probability between ~900 and 1400 m³/s. The model resolution is ~250 m³/s outside of this range. The model resolution is much coarser at **Stations 5 and 6**. The model can resolve differences of 300 m³/s at **Station 5** and 250 m³/s at **Station 6**. Stage changes in response to discharge changes in the order of 50 m³/s are predictable for all stations when the ALR is low and no backwatering occurs. However, when the ALR is high and backwaters the MCR up to station 4, changes in stage at stations 4-6 will be minimal in response to discharge changes of 50 m³/s.



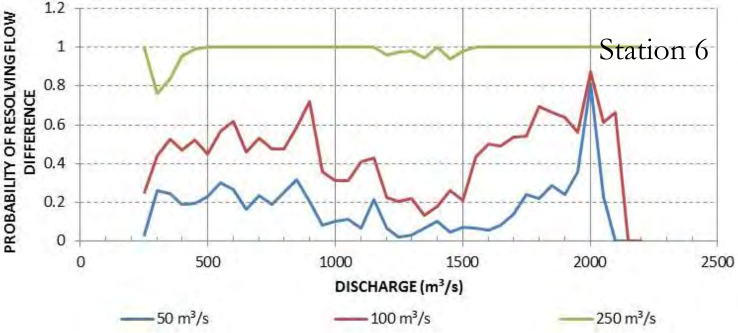


Figure 5 Relationship between stage and discharge at MCR stations 1,2,4,5 and 6 as simulated by the model (data points) and calculated via moving average across flow intervals ranging from 50 m3/s to 300 m3/s

3.5. Model Validation, Water Stage and Discharge

Figure 16 in Appendix D, shows the results of the simulations carried out using the Manning roughness coefficients for November 06, 2013, to October 30, 2014. In general, there is good agreement between the simulated and observed stages at Stations 1_AS, 2_AS, 4, 5, and 6.

Quantitative measures of agreement are summarized in Table 7 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 06, 2013, to October 30, 2014, the model gives a bias between -0.09 m and +0.12 m and a root mean square error (RMSE) between 0.14 m and 0.23 m. These values are improved compared to those for the previous version of the model which gave a bias between -0.37 m and +0.09 m and a RMSE between 0.12 m and 0.39 m (Plate et al. 2014).

Table 7. 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 version of the model (Plate et al. 2014) and for the validation runs done with the current version of the model.

Validation Period	Parameter	Station 1_AS	Station 2_AS	Station 4	Station 5	Station 6
Ecofish(2014)	Upper Bound(m)	0.86	0.62	0.16	0.26	0.41
(18-Nov-2012	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-2013	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

It should be noted that the validation runs for the 2012/2013 and the 2013/2014 models are considerably longer than those done 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 the 2013/2014 models, validation runs amount to 270 days each (excluding the simulation for February

11 to May 10, 2013). 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 6). 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 6). This pattern continued in 2013–2014, when discharges fluctuated from 142 m^3/s to 2,150 m^3/s (Figure 17 in Appendix E).

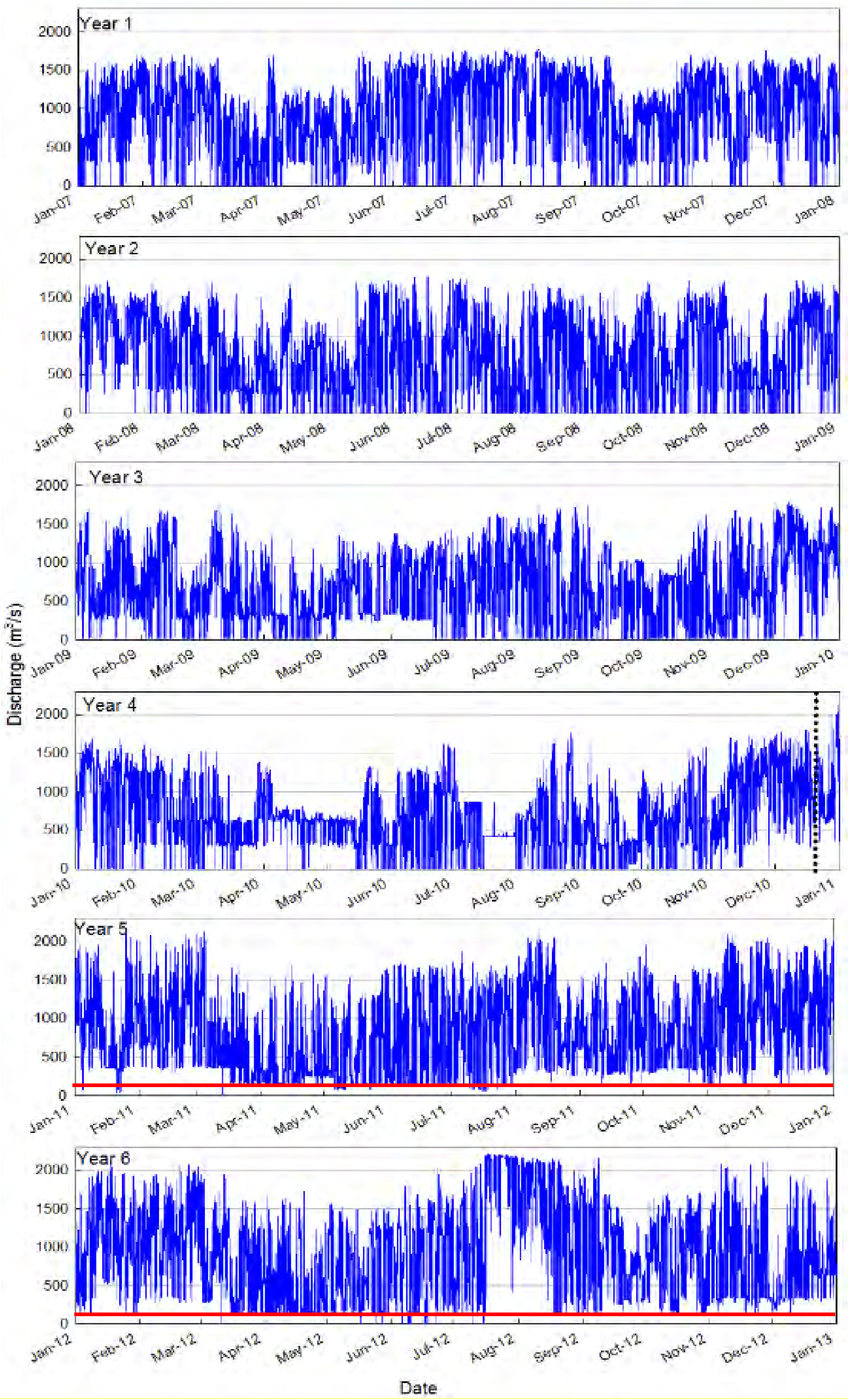


Figure 6 Revelstoke Dam generating stations hourly discharge 2007–2012. REV 5 came online and 142 m^3/s minimum flows (red solid line) were implemented at the end of 2010 (Year 4, black dotted line (Source: modified from Golder 2013).

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

Over the period November 06, 2013 to October 30, 2014, the mean wetted bed area for the modeled domain ranged between 9.9 km^2 and 28.3 km^2 (Figure 7, top panel) the average flow depth ranged between 2.1 m and 6.8 m (Figure 7, centre panel), and the average flow velocity ranged between 0.12 m/s and 1.64 m/s (Figure 7, bottom panel). The detailed data sets that these average values are based on are summarized in Figure 17 and Table 12 to Table 23, Appendices E and F). The mean wetted area, flow depth, and flow velocity were 20.1 km^2, 3.5 m, and 0.8 m/s, respectively.

The mean wetted area differences between reaches are influenced by their length and ALR backwatering and therefore about 81% of the mean wetted area of the domain was in reach 2 which had a length of 23.3 km and a mean wetted perimeter of 0.7 km is and is affected by ALR backwatering. Reach 1 is also affected by ALR backwatering but has a length of only 3.3 km, a mean wetted perimeter of 0.64 km and represents ~10% of the mean wetted area with the domain. Reach 3 had ~5% of the mean wetted area with a reach length of 5.0 km and a mean wetted perimeter of 0.2 km. Finally, reach 4 had ~4% of the mean wetted area

Table 8 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 17 in Appendix E). Over the period of simulation (November 06, 2013 to October 30, 2014), the mean diurnal fluctuation in the wetted area of the domain was 1.3 km^2 which amounts to 6.8% of the mean wetted area. The smallest diurnal fluctuations in wetted area occurred in late June and early July 2014 with a minimum of 0.05 km^2. The largest diurnal fluctuations in wetted area occurred in February and March 2014 with a maximum of 4.8 km^2. Relative to the mean wetted area for each reach, diurnal fluctuations in wetted area were largest for reach 4 where the mean diurnal fluctuation in wetted area was 14% of the mean wetted area for this reach. For reaches 1, 2 and 3, the mean diurnal fluctuations in wetted area were 1.5%, 7.5% and 8.5% of the mean wetted areas for these reaches.

Over the period of simulation, the mean diurnal fluctuation in the flow depth of the domain was 0.2 m which amounts to 5.8% of the mean flow depth. The maximum diurnal fluctuation in flow depth was 0.7 m. Relative to the mean flow depth for each reach, diurnal fluctuations in flow depth were largest for reach 4 where the mean diurnal fluctuation in flow depth was 47% of the mean flow depth for this reach. Reach 3 also had relatively large diurnal fluctuations with a mean diurnal fluctuation in flow depth of 30% of the mean flow depth for this reach. For reaches 1 and 2, the mean diurnal fluctuations in flow depth were 1.3% and 3.8% of the mean flow depths for these reaches.

Over the period of simulation, the mean diurnal fluctuation in the velocity of the domain was 0.4m/s which amounts to 50% of the mean velocity. The maximum diurnal fluctuation in velocity was 0.8 m/s. Relative to the mean velocity for each reach, diurnal fluctuations in flow depth were largest for reach 1 where the mean diurnal fluctuation in velocity was 73% of the mean velocity for this reach. For reaches 2, 3 and 4, the mean diurnal fluctuations in velocity were 48.5%, 53.7% and 63.9% of the mean velocities for these reaches.

Monthly Fluctuations in Wetted Area and Flow Depth

The maximum monthly average wetted area was 28.2 km^2 and occurred in July 2014 when the ALR water level was high (436.6 masl to 439.1 masl) (Figure 17). The maximum monthly average flow depth was 6.2 m and also occurred in July 2014 due to high ALR water level. The minimum monthly average wetted area was 12.9 km^2 and occurred in April 2014 when the ALR water level was low (428.3 masl to 429.3 masl). The minimum monthly average flow depth was 2.5 m and also occurred in April 2014 due to low ALR water level (Figure 7).

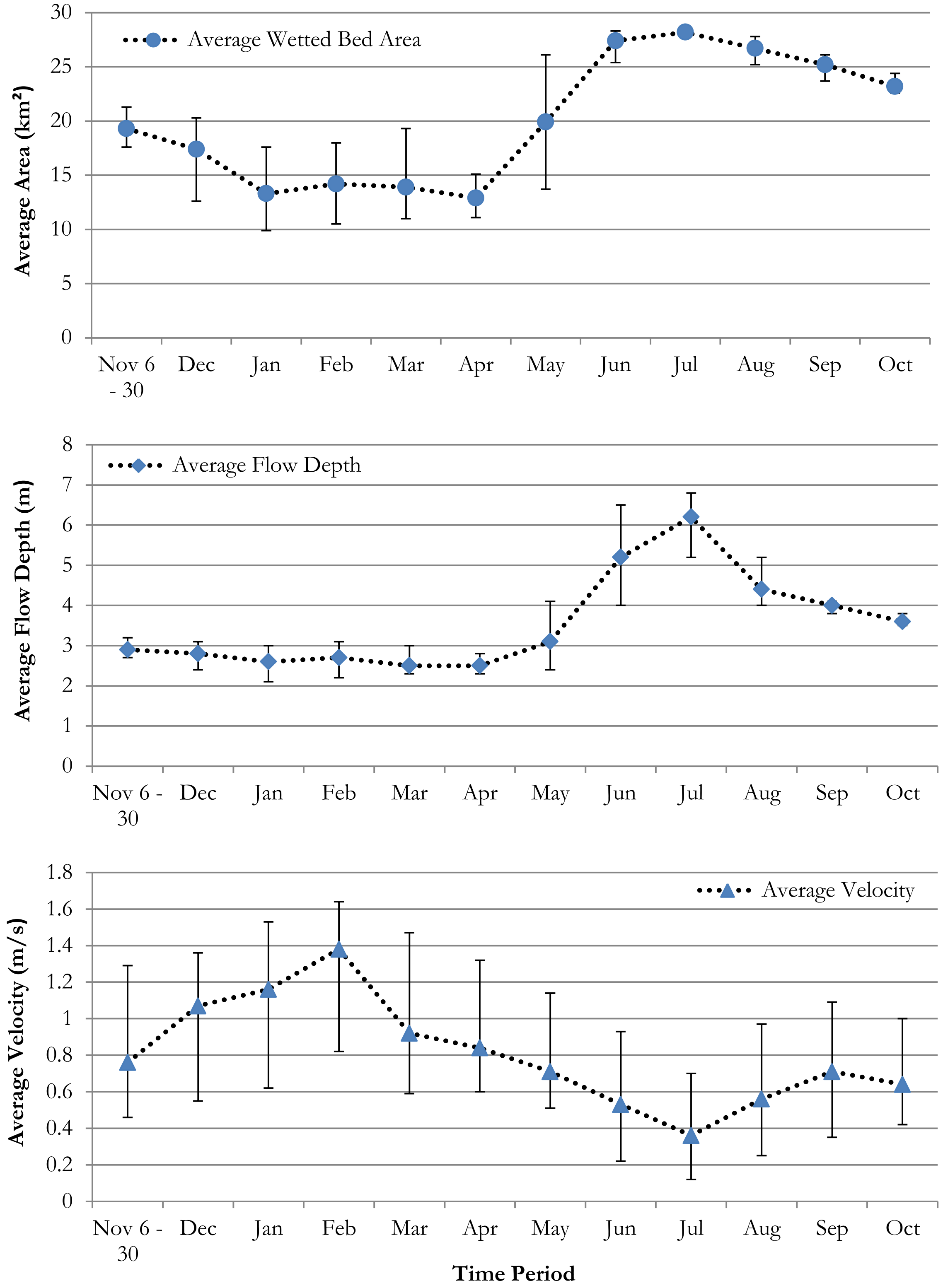


Figure 7 HEC-RAS modeled average wetted bed area (top panel), flow depth (centre panel) and velocity (bottom panel) for MCR reaches 1-4 from November 6, 2013 – October 31, 2014. The error bars stand for the maximum and minimum values for each time period.

Table 8 Summary of HEC-RAS modeled variations in wetted area, flow depth and velocity for the November 6, 2013 to the October 31, 2014 period.

Hydrological Parameter	Whole	Min	Max
Diurnal Fluctuations			
Wetted Area	Whole Period: 1.3 km^2	June-July: 0.05 km^2	Feb-March: 4.8 km^2
Flow Depth	Whole Study Area: 0.2 m	Reach 1: 0.07 m (or 1.3% of mean flow depth)	Reach 4: 1.65 m (or 47% of mean flow depth)
Fluctuations over the Whole Study Period (All Reaches)			
Wetted Area	20.1 km^2	9.9 km^2	28.3 km^2
Flow Depth	3.5 m	2.1 m	6.8 m
Velocity	0.8 m/s	0.12 m/s	1.64 m/s
Reach Average Min and Max of Flow Depth & Velocity (Whole Study Period)			
Flow Depth		Reach 2: 2.3 m	Reach 1: 9.2 m
Velocity		Reach 1: 0.15 m/s	Reach 4: 1.64 m/s
Monthly Average Min and Max of Wetted Area & Flow Depth (All Reaches)			
Wetted Area		July 2014 (high ALR): 28.2 km^2	April 2014 (low ALR); 12.9 km^2
Flow Depth		July 2014 (high ALR); 6.2 m	April 2014 (low ALR): 2.5 m

3.7. Steady-State Simulation Results

For the steady-state simulations, the average ALR water level from January 19 to February 09, 2014 (428 m) was chosen to represent low ALR levels and flows from 262 to 1000 m3/s, and the average ALR water level from June 24 to July 23, 2014 (433 m) was selected to represent high ALR levels and flows from 160 to 1000 m3/s. The minimum flow for the steady-state simulations was set as the minimum flow that occurred during the periods specified to represent the low and high ALR levels. Inflows from tributaries were set as the average tributary inflow for each flow condition. 30 steady-state simulations ran during the low ALR water level (428 m) and 30 steady-state simulations ran during the high ALR water level (433 m).

The average hydraulic characteristics of each reach and the total domain were computed for each simulation, and are provided in Table 24 for low ALR level and Table 25 (both in Appendix F) for high ALR level. For the 30 low ALR simulations, the wetted bed area for the modeled domain ranged from 10.4 km^2 to 13.1 km^2, the average flow depth ranged from 2.2 m to 2.6 m, and the average flow velocity ranged from 0.69 m/s to 1.23 m/s. For the 30 high ALR simulations, the wetted bed area for the modeled domain ranged from 23.8 km^2 to 24.6 km^2, the average flow depth ranged from 3.7 m to 3.8 m, and the average flow velocity ranged from 0.39 m/s to 0.83 m/s (Table 24 and Table 25).

For each simulation, the water elevation data was exported from HEC-RAS, and HEC-GeoRAS was used to compute the difference between the terrain elevations and water surface elevations. The terrain coverage from the TIN file was not always adequate or accurate for all flow conditions. The maps produced from the simulation results are submitted in a separate file as an attachment to this report. These inundation maps showed areas of the riverbed without water that should have been wetted based on the average wetted riverbed area and flow depth, which were positive for all reaches.

The elevations of a few cross-sections were checked by comparing the elevations extracted from the combined TIN file and the HEC-RAS geometry data. In some cases, there was a 10-20 m difference between the cross-section elevations extracted from the TIN file and the elevations extracted from the HEC-RAS geometry data. Water levels extracted from HEC-RAS were lower than the terrain elevations extracted from the TIN file, and as a result those areas are assumed to be dry by HRC-GeoRAS. All flood maps were reviewed and most maps were chosen from the high ALR water level simulations, as these provided a more accurate depiction of inundation on the mid-Columbia River.

3.8. HEC-RAS Model Summary and Recommendations

The HEC-RAS hydraulic model for the Mid-Columbia River was updated to include new data for November 2013 to October 2014. No model calibration or adjustments to the Manning roughness coefficients were required for this modeling period. The performance of the model was validated by running the model for the length of the data record from November 2013 to October 2014. The performance of the updated model is improved compared to the previous version (Plate et al. 2014).

Data from Station 3 (Tailrace-7km) were not available and were not used in calibrating and validating the model for 2013/2014. Station 3 was replaced in November 2014, though it had not been surveyed to a common datum at that time. Once surveyed, it is recommended that running the model with stage data at this station be used for future calibration and validation of the HEC-RAS model. Using the data from this station will improve the calibration results for the model and increase confidence in the calibrated Manning roughness coefficient for reach 3 where the station is located.

The model was calibrated against water level data for about a year. 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. 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 model runs. To maintain model reliability, cross-section surveys are recommended for the reach between Station 2 and Station 4.

The accuracy of the inundation maps would be improved with a more accurate underlying terrain map (TIN file) that covered all of the reaches over both low and high flow conditions.

3.9. Temperature Variation Results and Discussion

When comparing the annual water temperature variations between index stations in the MCR and index stations in two of its tributaries, 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).

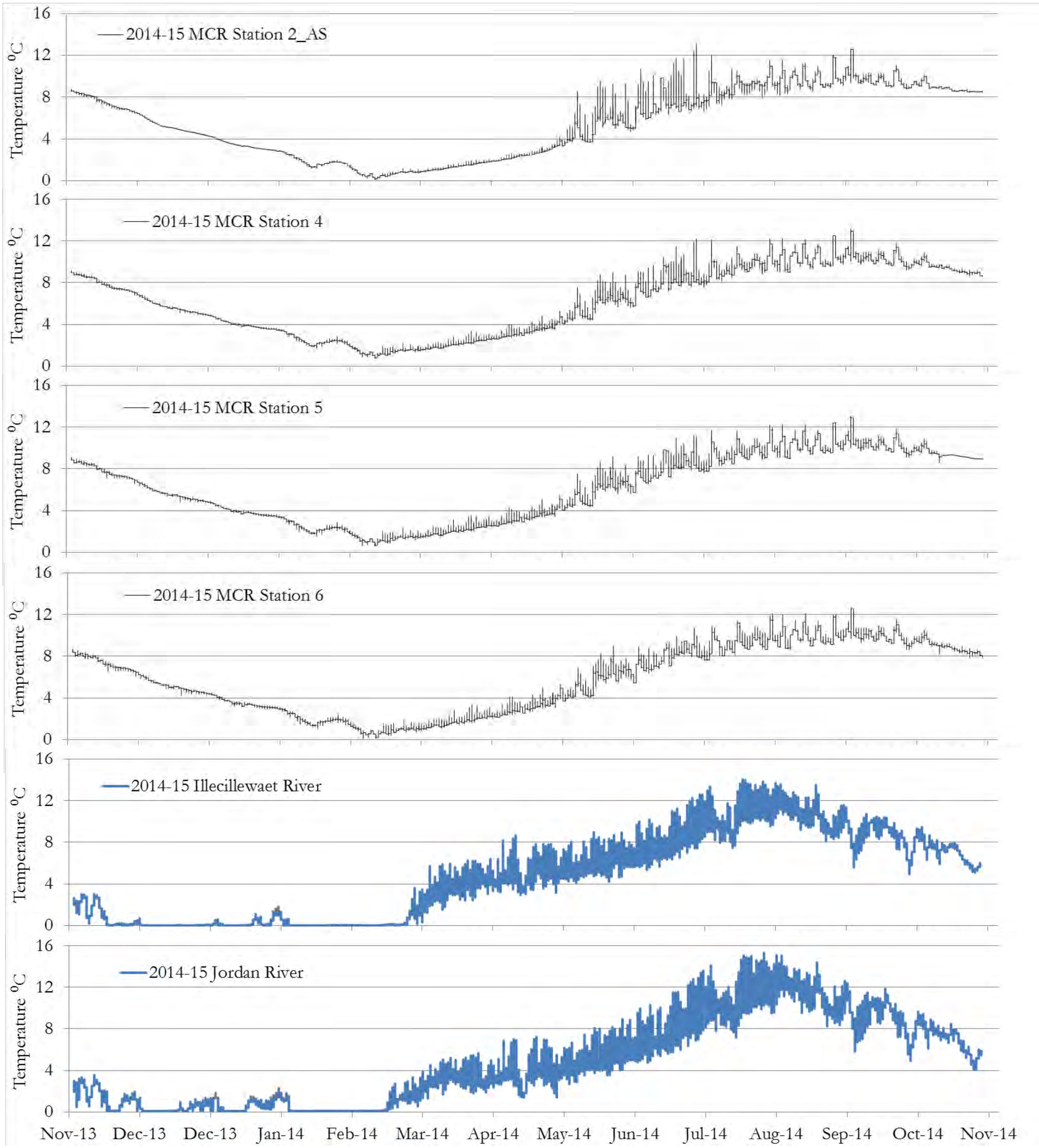


Figure 8 Water temperatures at 4 MCR (Station 1 was dismantled in May 2014) and 2 tributary (Illecillewaet and Jordan Rivers) index stations from Nov 2013–Nov-2014.

Overall, daily water temperature fluctuations were also greater for the two naturally fed tributaries The temperature patterns found in 2014 closely resembled temperature patterns found from 2007–2013 and stayed consistent pre- and post-minimum flow application (this study, Plate et el. 2014, Golder 2013). It is therefore it 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 are tasked to 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 makes it highly questionable that annual trends in productivity can be observed or that pre- and post-minimum flow differences can be detected. Nevertheless, water quality sampling and analysis were carried out during all previous years (2007-2013, Golder 2013, Plate et al. 2014) of CLBMON-15a and until May of 2014 and were terminated after that.

4.1. Water Quality Sampling Stations and Schedule

Water samples for nutrient analysis were taken once, in May of 2014 and the results from this sampling date are shown in context of the 2013 results. Samples were collected from the 5 MCR index sites and the two index sites at the tributaries (Illecillewaet and Jordan Rivers) (Figure 2). No nutrient analysis samples were taken at MCR Station 3 in 2014 because the stage and temperature logger are managed by BC Hydro and were not operational throughout the 2014 field season. MCR Nutrient sampling index locations were chosen to be in close proximity of the periphyton/benthic substrate sites for MCR Ecological Productivity Monitoring CLBMON-15b.

Physical parameters were measured *in situ* as part of every field visit in 2014 to calibrate the temperature of the deployed stage and temperature loggers. Table 9 shows the schedule for the 2014 physical parameter measurements and the collection of water samples for nutrient analysis (Table 10).

Table 9 Field schedule of the 2014 *in situ* physical water parameter measurements and water sample collections for laboratory analysis.

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

Table 10 Physical parameters measured (for all field 2014 visits) and nutrient parameters (only May 2014 field visit) analysed in a laboratory.

Physical Parameters: In-Situ Measurement	Nutrients: Samples Collected for Analysis at Water Chemistry Laboratory
Temperature (°C)	Nitrate
Conductivity. (µS/cm)	Ammonia
Specific Conductivity (µS/cm)	Total Kjeldahl Nitrogen
Total Dissolved Solids (mg/L)	Total Nitrogen
Dissolved Oxygen Saturation (%)	Total Phosphorus
Dissolved Oxygen Absolute (mg/L)	Total Dissolved Phosphorus
pH	Total Soluble Reactive Phosphorus
Turbidity (NTU)	Total Dissolved Solids
	Total Suspended Solids

4.2. Water Quality Sampling Methods

All water samples for laboratory analysis (Table 10, right column) were collected as follows:

1. The 1 L and the 150 mL water sampling bottles were pre-labelled and transported to the sampling locations with tightly closed lids to avoid contamination.
2. The sampling protocol for 1 L and 150 mL bottles was the same.
3. At each site the sampling bottle was opened and rinsed out three times with the sampling water before the actual sample was taken.
4. Samples were always taken upstream of the sampler, boat and all other sampling equipment and in a depth of 30 cm from the surface in steady flow. During sampling it was ensured that no disturbed sediment was collected.
5. Once filled, the sample bottles were immediately closed and stored in a cooler with ice at a temperature of <7 °C.
6. The 150 mL bottle was filled for the analysis of Soluble Reactive Phosphorus and the water for rinsing and the actual sample itself were filtered through a 45 µm filter attached to a Luer-Taper on a 100 mL syringe.
7. While Soluble Reactive Phosphorus was analysed out of the 150 mL filtered sample, all other parameters (Table 10, right column) were analysed out of the 1 L sample.
8. All samples were delivered to CARO Analytical Services in Kelowna, BC (#102-3677 Highway 97N, V1X 5C3) within 48 hours of sampling and kept at a temperature below 7 °C. Upon arrival, CARO contacted LGL Ltd. and confirmed sample temperature and condition.

In the past, the Department of Fisheries and Oceans Cultus Lake Salmon Research Laboratory near Chilliwack, BC was contracted for low level nutrient analysis but this option was not available in 2014. Therefore all samples were analysed by CARO Analytical Services. Lowest possible reporting limits, analysis methods and storage details for all parameters are shown in Table 11.

Table 11 Nutrient parameter sampling, storage and analysis detail.

Parameter	Sampling Jar	Preservation	Storage	Holding Time	Comments	Lowest Possible Reporting Limit	Analysis Method	Method Reference
Nitrate	1 L	No	Under 10 °C	3 days		0.004 mg/L	Colorimetric	EPA 353.2
Ammonia	1 L	No	Under 10 °C	3 days		0.005 mg/L	Colorimetric	APHA 4500-NH3 G
Total Kjeldahl Nitrogen	1 L	No	Under 10 °C	3 days		0.023 mg/L	Colorimetric	EPA 821-R-01-004
Total Nitrogen	1 L	No	Under 10 °C	3 days		0.05 mg/L	Colorimetric	EPA 351 - 351.4
Total Phosphorus	1 L	No	Under 10 °C	3 days		0.001 mg/L	Colorimetric, Kjeldahl Digestion	EPA 365.4
Total Dissolved Phosphorus	1 L	No	Under 10 °C	3 days		0.001 mg/L	Colorimetric, Kjeldahl Digestion	EPA 365.4
Soluble Reactive Phosphorus	150 mL	No	Under 10 °C	3 days	Filter in the field, 45 µm filter	0.002 mg/L	Colorimetric	APHA 4500-P D
Total Dissolved Solids	1 L	No	Under 10 °C	7 days		5 mg/L	Gravimetric	APHA 2540 C
Total Suspended Solids	1 L	No	Under 10 °C	7 days		1 mg/L	Gravimetric	APHA 2540 D

4.3. Water Quality Data Analysis Methods

Three water samples or measurements taken per year can be used to give an indication of the condition of the MCR at the index stations or its two tributaries, but this sampling frequency is too low to determine statistical differences between years, stations or sampling times. This sampling frequency is also too low to pick up any potential effects directly related to the WUP minimum flows combined with a larger range of flows based on REV 5. The low sampling frequency and inherent variability of water quality with climate and hydrologic events also prevents an accurate examination of the variability of water quality concentrations with flows or other factors. For example, water quality in the Jordan River fluctuates following every average precipitation event and is highly dependent on snow run-off. Illecillewaet River water quality is even more variable due to the strong glacial contribution to its flow. During warm and sunny summer days glacial streams typically increase in flow and Total Suspended Sediment and many other parameters fluctuate because of increased glacial run-off. In the context of CLBMON-15a, the water quality and physical parameter results at the index stations are used as indicators of the general status on a certain date. Nutrient and physical parameter values are therefore graphically presented without statistical analysis or statistical comparisons to previous years, other stations or changes in discharge from REV.

4.4. Seasonal Water Quality Results and Interpretation

In Situ Measurements of Physical Parameters

Temperature: Temperatures on each of the three sampling dates in spring, summer and fall in the MCR showed minor differences between the four index stations. In general, temperatures increased from spring to summer and then decreased in the fall of 2014 (Figure 9, top left panel). Temperatures ranged from 3.5 °C in the spring to 11.5 °C in the summer.

Based on the glacial and snow run-off that enters the Jordan River and especially the Illecillewaet River, temperatures measured in those two systems ranged from 5–6.2 °C in the spring, increased to a high of 10–11.6 °C in late summer and decreased to a much lower temperature of ~5.7 °C in the fall (Figure 10, top left panel).

Conductivity: The conductivities in the four MCR index stations and the Illecillewaet River were similar and ranged from 0.11–0.15 µS/cm over the three seasons (Figure 9, top right panel, Figure 10, top right panel). The conductivity measured in the very nutrient poor Jordan River was even lower and ranged from 0.028–0.04 µS/cm (Figure 10, top right panel). The patterns and values with regards to variations by season and among stations were very similar for specific conductivity (Figure 9, second from top row, left panel, Figure 10, second from top row, left panel).

Total Dissolved Solids (TDS): Over the three seasons, TDSs values were low and stable in the four MCR index stations and the Illecillewaet River but lower in Jordan River (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 95–99 % and 10–13 mg/L, respectively over the three seasons and all stations (Figure 9, third from top row, left and right panel). Over the three seasons, DO saturation and total DO values in the Illecillewaet and Jordan rivers ranged from 82–98 % 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 were quite consistent and ranged from pH 7.8–8.1 (Figure 9, bottom left panel, Figure 10, bottom left 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 ranged from 7.8–9.15 (Figure 10, bottom panel) and were slightly higher than in Jordan River where they ranged from pH 6-8–7.6.

Turbidity: Turbidity in the four MCR stations were consistently low in late summer of 2014 (1 NTU) but had a wide range in the fall of 2014 (Figure 9, bottom right panel). The large range of turbidity within the four MCR stations was based on the elevated turbidity values at MCR Stations 5 (13 NTUs) and 6 (16 NTUs) (Figure 11, top panel). MCR Stations 5 and 6 in turn received very turbid water (194 NTUs) from the Illecillewaet River in the fall of 2014 (Figure 11, bottom panel). The authors were later informed that the Illecillewaet River was the site of a large slide that dislodged and mobilized fines in the fall of 2014.

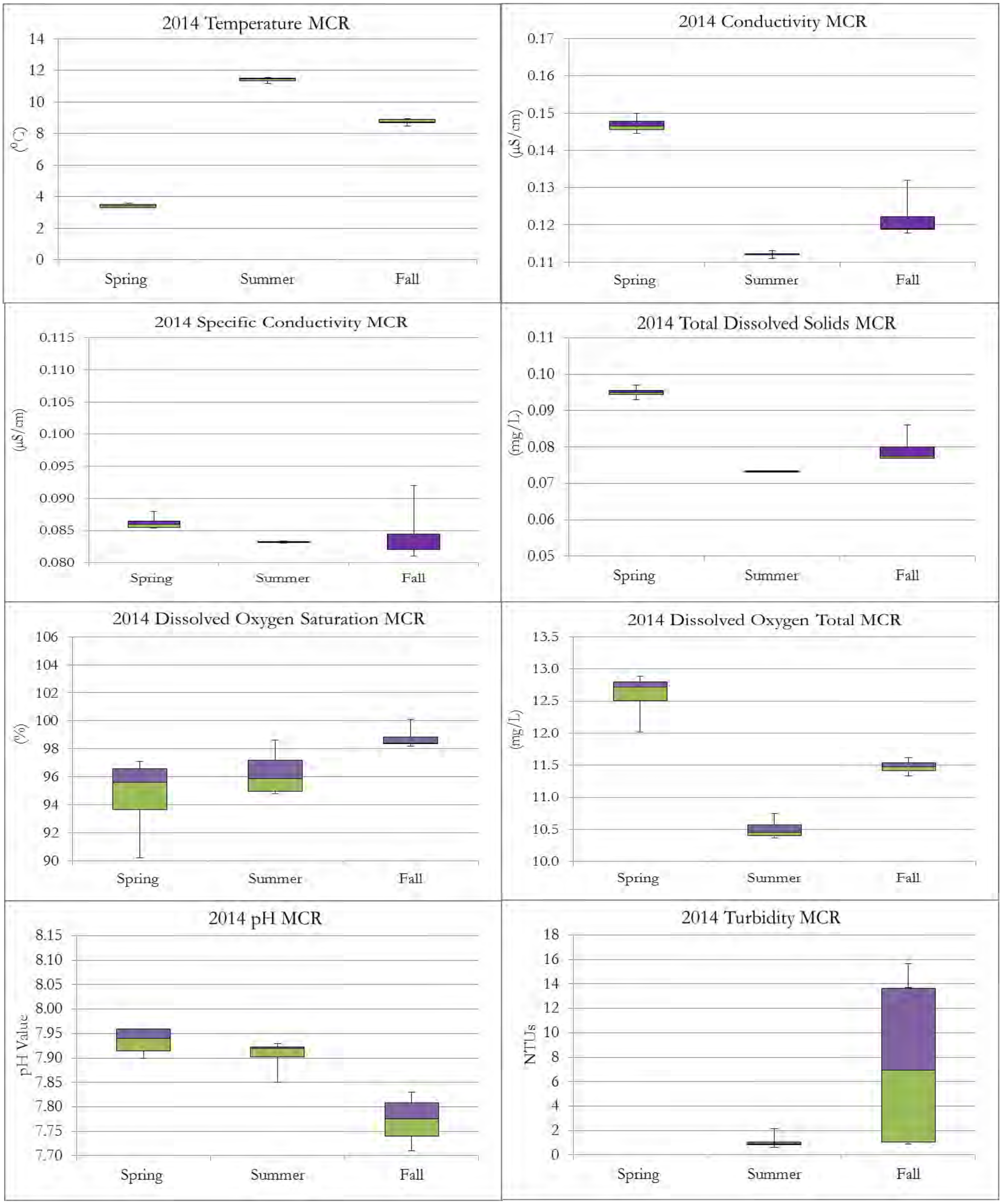


Figure 9 Results for physical parameters measured *in situ* at four MCR index stations in 2014 (lower error bar = minimum–25% percentile, green box = 25%–median, purple box = median–75% percentile, upper error bar = 75% percentile–maximum).

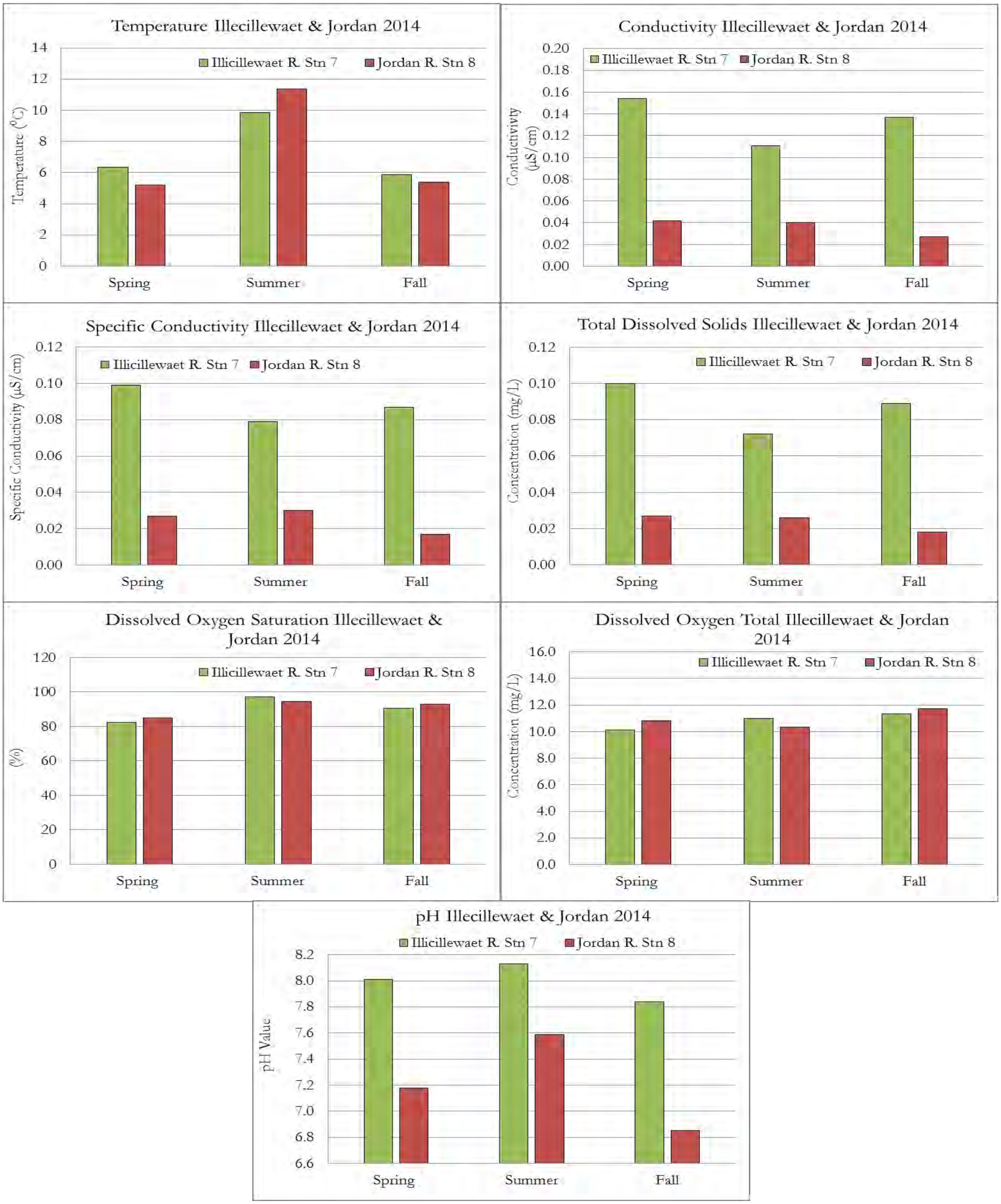


Figure 10 Results for physical parameters measured *in situ* at the Illecillewaet and Jordan River index stations in 2014.

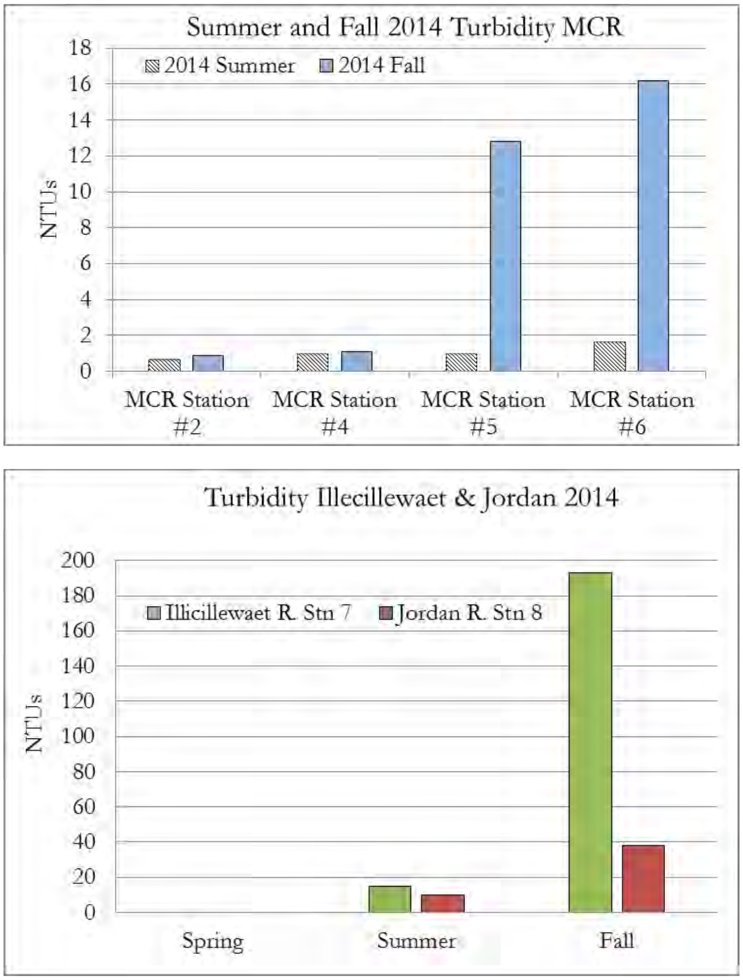


Figure 11 The top panel shows that the large range of measurements in the MCR Station results was based on very high turbidity measurements at Stations 5 and 6 in the fall of 2014 and the bottom panel shows that the Illecillewaet River was the source for the high turbidity.

Laboratory Analysis of Nutrient Parameters

Nitrate: In 2013 Nitrate concentration samples collected at the MCR index stations showed little variability between sampling dates started from low values in the spring (93–103 µg/L) to slightly higher values in late summer (112–121 µg/L) and fall (107–122 µg/L) (Figure 12, top left panel). The spring 2014 values fell into a similar range of concentrations (94-145 µg/L) bud showed slightly higher variability between stations (Figure 12, top left panel). The 2013 Nitrate concentrations in the Illecillewaet and Jordan rivers were higher than in the MCR throughout the year but particularly in the spring (402 µg/L Illecillewaet, 356 µg/L Jordan) (Figure 13, top left panel). The same was true for the spring of 2014 when Illecillewaet (444 µg/L) and Jordan River (551 µg/L) values that were much higher than the MCR station values and the 2013 summer and fall values in the tributaries. In comparison to the combined Nitrate and Nitrite BCWQG (10,000 µg/L) all Nitrate concentrations measured in the MCR and tributaries are very low and typical for nutrient poor or oligotrophic systems

Ammonia: In the spring of 2013 and 2014, Ammonia concentrations were below the detection limits in the MCR, and Illecillewaet and Jordan rivers (Figure 12, top right panel, Figure 13, top right panel). For the late summer 2013 sampling date, the Ammonia concentration rose to a range of 0–44 μg/L in the MCR and stayed below the detection limit in the tributaries. The MCR fall 2013 water samples had Ammonia concentrations ranging from 44–73 μg/L while the concentrations in the Illecillewaet and Jordan rivers rose to 59 and 73 μg/L, respectively. In comparison to the Ammonia BCWQG of 1,000 μg/L, the values measured in the MCR and tributaries were very low and typical for nutrient poor or oligotrophic systems.

Total Kjeldahl Nitrogen (TKN) and Total Nitrogen (TN): In 2013, both forms of Nitrogen in the MCR were higher in the spring (TKN: 164–570 μg/L; TN: 6—480 μg/L) and then decreased in the late summer (TKN: 112–180 μg/L; TN: 0–60 μg/L) and fall (TKN: 195–275 μg/L; TN: 90–160 μg/L) (Figure 12, second row from top). TKN and TN concentrations behaved in a similar pattern in the Illecillewaet and Jordan rivers. TKN and TN concentrations in the Illecillewaet River were high in the spring of 2013 (TKN: 688 μg/L; TN: 290 μg/L) and then decreased in the late summer (TKN: 198 μg/L; TN: 60 μg/L) and fall (TKN: 277 μg/L; TN: 130 μg/L) (Figure 13, second row from top). Similarly, TKN and TN concentrations in the Jordan River were high in the spring of 2013 (TKN: 933 μg/L; TN: 580 μg/L) and then decreased in the late summer (TKN: 417 μg/L; TN: 180 μg/L) and fall (TKN: 305 μg/L; TN: 120 μg/L) (Figure 13, second row from top).

In the spring of 2014, TN (205–309 μg/L) and TKN (110-160 μg/L) concentrations were within the range of concentrations observed in the MCR in 2013 (Figure 12, second row from top). The same was true for the TN and TKN values in the Illecillewaet (TN=380 μg/L; TKN=828 μg/L) and Jordan Rivers (TN=130 μg/L; TKN=681 μg/L) in the spring of 2014. Although total Kjeldahl Nitrogen does not have a BCWQG concentration, the values measured in the MCR and tributaries are very low and typical of an oligotrophic system.

Total Phosphorus (TP) and Total Dissolved Phosphorus (TDP): The BCWQGs for In 2013, TP and TDP in the MCR and the tributaries showed a similar pattern for the three sampling dates. TP and TDP were low in spring, increased in late summer and fell back to spring levels in fall (Figure 12, third row from top, Figure 13, third row from top). Within this pattern, TP concentrations ranged from 2–35 μg/L in the MCR and from 4–47 μg/L in the Illecillewaet and Jordan rivers. TDP concentrations ranged from 0-25 μg/L in the MCR and 2–34 μg/L in the Illecillewaet and Jordan rivers.

The spring 2014 values for TP and TDP in the MCR and the Jordan River (3–7 μg/L) fell into the same range of low concentrations. The spring 2014 TP (21 μg/L) and TDP (19 μg/L) values in the Illecillewaet River were slightly higher but still well within values observed in 2013.

Total Dissolved Reactive Phosphorus (TDRP): In general, the 2013 and spring 2014 TDRP concentrations were low, ranging from 0–14 μg/L in the MCR and 0–6 μg/L in the Illecillewaet and Jordan rivers (Figure 12, bottom panel, Figure 13, bottom panel). The TDRP concentrations for the

MCR and the tributary stations in the fall of 2013 were all below detection limit. The same was true for the spring 2014 TDRP concentrations in the MCR. They are therefore invisible in the graphs. The spring 2014 concentrations for the Illecillewaet (5 µg/L) and Jordan (6 µg/L) Rivers were similar to the spring and summer concentrations observed for these sampling locations in 2013.

All nutrient concentrations measured in 2013 and the spring of 2014 were similar to the range of nutrient concentrations measured in 2012 (Golder 2013). Total dissolved reactive or Ortho-Phosphorus is the only phase of Phosphorus that is readily bioavailable and is therefore also the only state of Phosphorus that has a BCWQG (2,000 µg/L). The values measured in the MCR and tributaries are much lower than this and typical of an oligotrophic system.

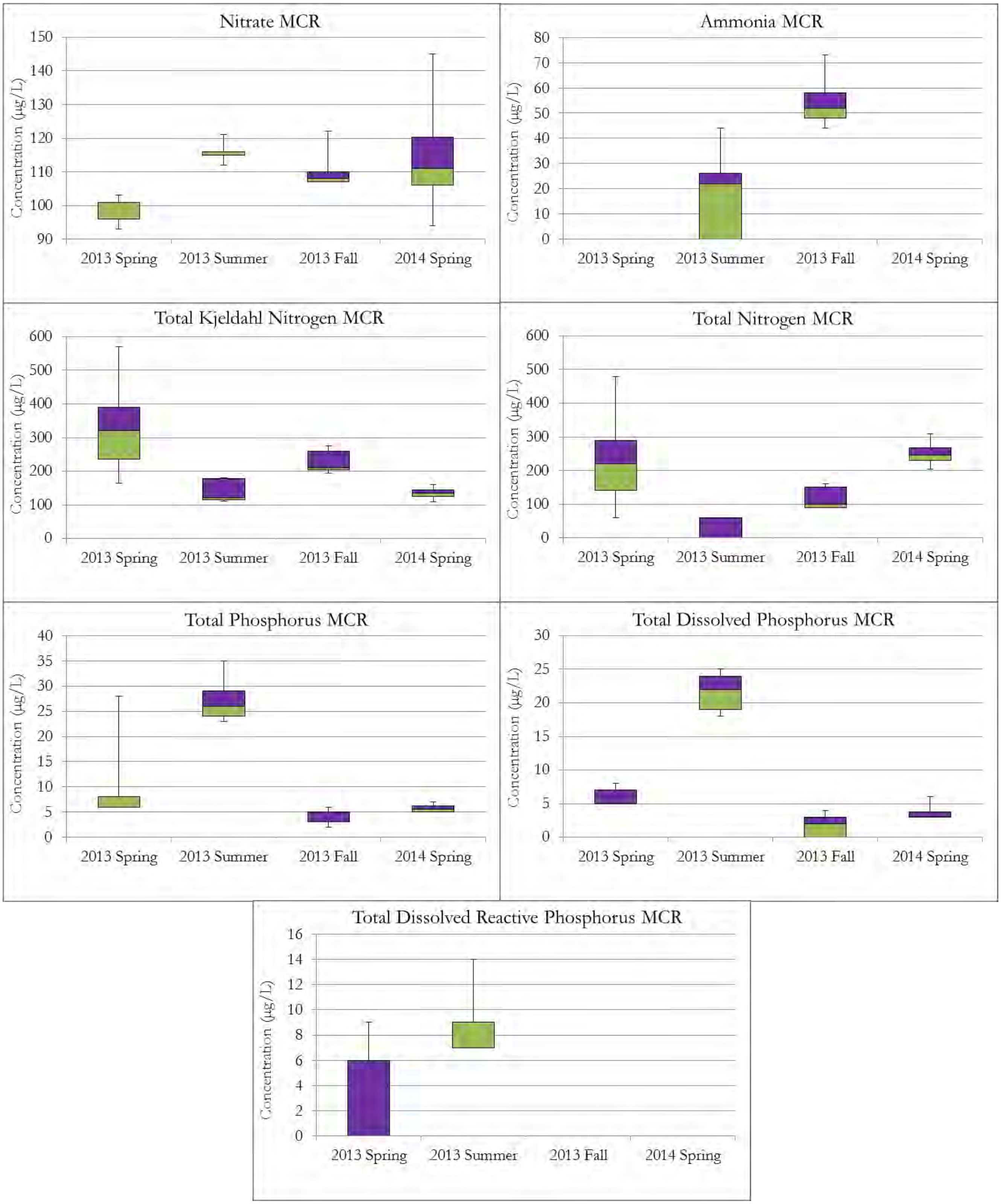


Figure 12 Nutrient concentrations at the five MCR index stations in 2013 and the spring of 2014 (lower error bar = minimum–25% percentile, green box = 25%–median, purple box = median–75% percentile, upper error bar = 75% percentile–maximum).

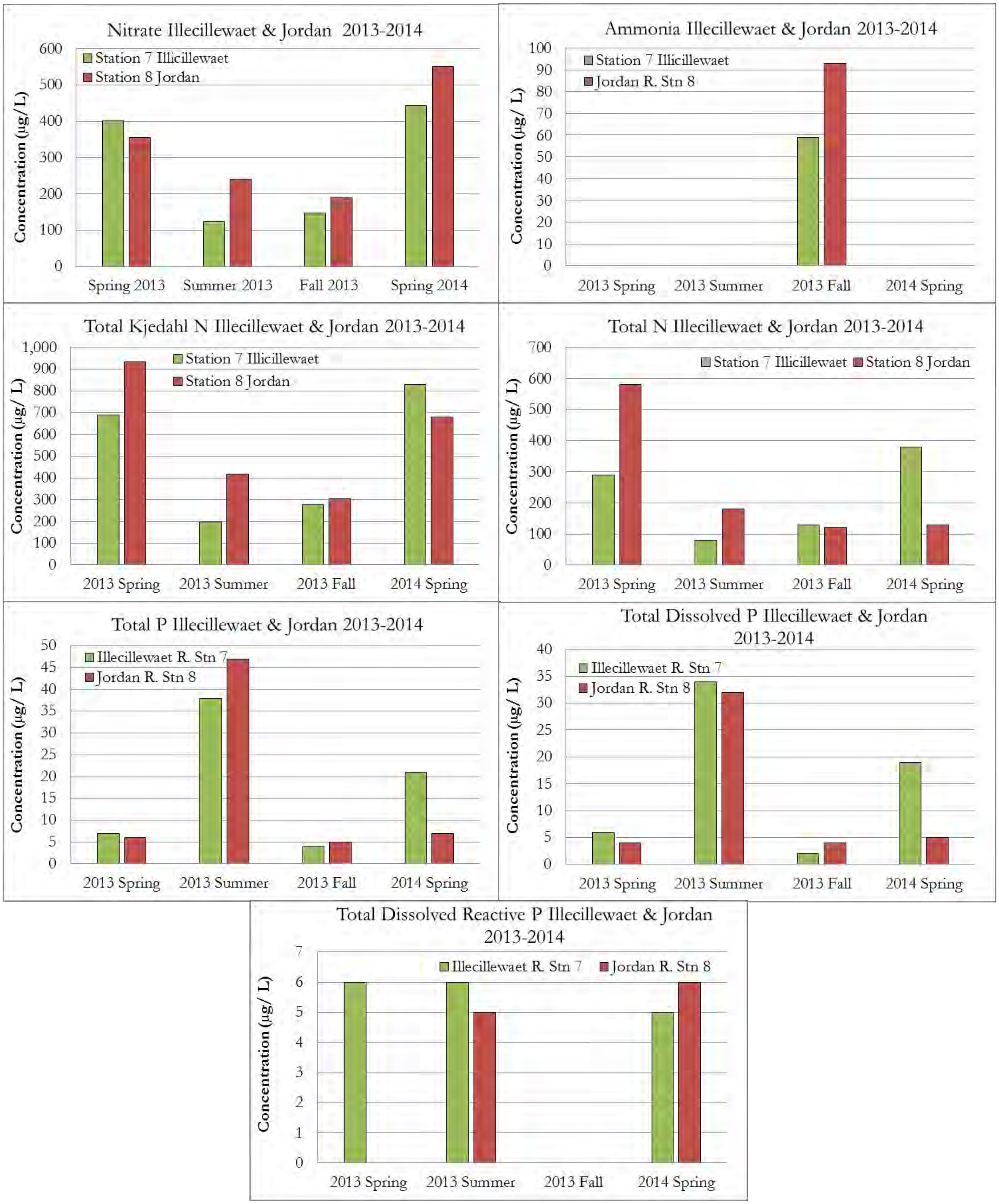


Figure 13 Results for nutrient concentrations in water samples collected at the Illecillewaet and Jordan River index stations in 2013 and the spring of 2014.

Laboratory Analysis of Physical Parameters

Total Dissolved Solids (TDS): 2013 and spring 2014 TDS concentrations at MCR (range: 66–104 mg/L) and Illecillewaet River (range: 82–100 mg/L) stations were similar and did not show great variability within sampling locations or sampling dates (Figure 14 and Figure 15, top panels). TDS concentrations in Jordan River were much lower for the three sampling dates in 2013 and the spring 2014 sampling date and ranged from 15–33 mg/L.

Total Suspended Solids (TSS): TSS values were generally very low throughout all 2013 and 2014 sampling dates and locations and ranged from 0–4 mg/L aside from one sample that was taken in the Jordan River in late summer following a strong overnight rainfall that elevated the TSS concentration to 27 mg/L (Figure 14 and Figure 15, second panel from top).

Turbidity: Turbidity in 2013 and the spring of 2014 samples from the MCR and the tributaries was very low in the spring and fall and higher in the summer (Figure 14 and Figure 15, second panel from bottom). Within this general pattern, turbidity ranged from 0.3–2.1 NTUs in the MCR and from 0.2–7 NTUs in the Illecillewaet and Jordan rivers.

pH: The spring 2014 and the 2013 pH values at the MCR index stations and 2013 Illecillewaet River station were quite stable within locations and seasons and ranged from pH 7.69–7.95 (Figure 14 and Figure 15, bottom panel). In comparison, 2013 pH values for the Jordan River were slightly lower for all sampling dates and ranged from pH 7.23–7.54. These slightly alkaline pH values were also observed as part of the in-situ measurements of this study and in 2013 (Plate et al. 2014) and in 2012 (Golder 2013) and appear to be typical for the MCR area.

In the spring of 2014, the pH value for the Jordan Rivers was slightly lower (pH 6.64) than for all other sampling dates and locations in 2013 but still within the range of values perfectly suitable for aquatic life.

Comments

Based on the low sampling frequencies for physical and nutrient parameters, a statistical analysis of the potential effects of the WUP flows was not advisable. As described above, physical and nutrient 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.

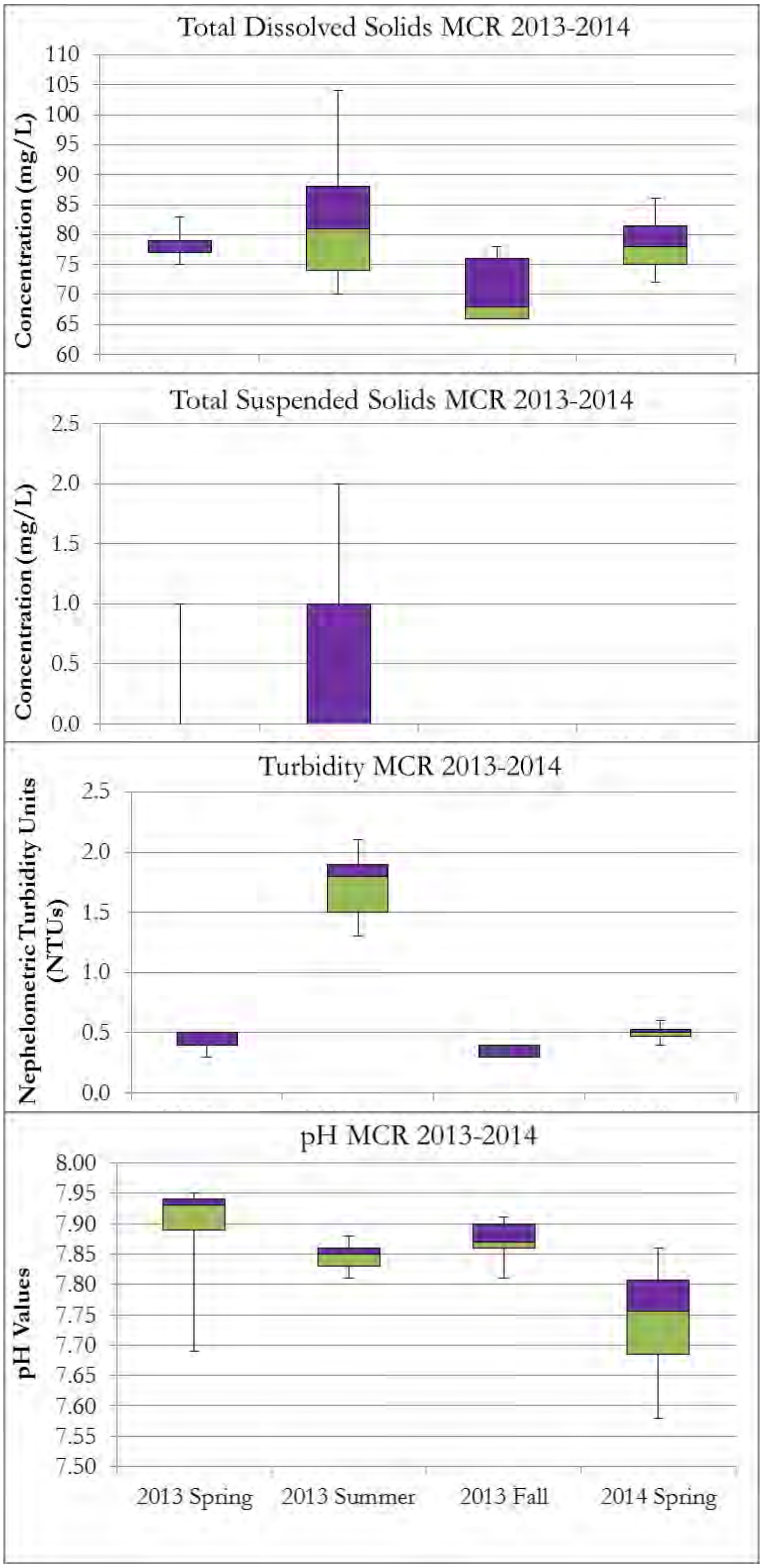


Figure 14 Results for nutrient concentrations in water samples collected at the Illecillewaet and Jordan River index stations in 2013 and the spring of 2014.

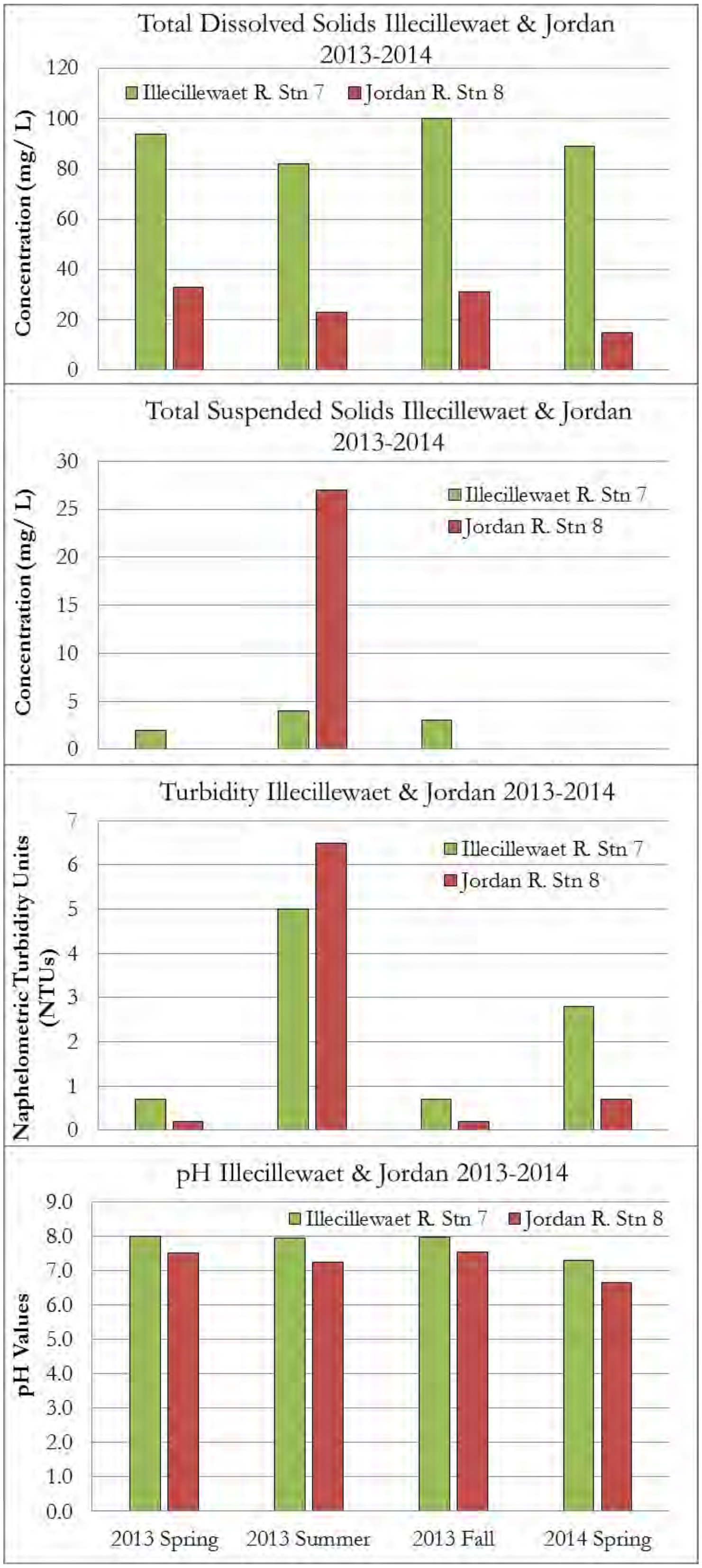


Figure 15 Results for TDS, TSS, turbidity and pH measured in water samples taken at the five MCR index stations in 2013 and the spring of 2014.

5. CHANGES IN 2014 AND RECOMMENDATIONS FOR FURTURE WORK

On February 19, 2014, BC Hydro held a review meeting with all consultants that are working within the Revelstoke Flow Management Plan (RFMP) CLBMON program and solicited suggestions for scope changes to the program for the final 3 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 have been 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 abandon field measurements. 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. If possible and available, data from Station 3 (the station is serviced and data is downloaded by BC Hydro) should be used for future runs of the HEC-RAS model.
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 will produce 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. REFERENCES

BC Hydro. 2000. Making the connection: The BC Hydro electric system and how it operates. 56 p.

Golder Associates Ltd. (Golder). 2008. Columbia River Water Use Plan Monitoring Program: Physical Habitat Monitoring Study Period: 2007. Prepared for BC Hydro CLBMON#15a. 23 p + app.

Golder Associates Ltd. (Golder). 2009. Columbia River Water Use Plan Monitoring Program: Physical Habitat Monitoring Study Period: Year 2 – 2008. Prepared for BC Hydro, Castlegar, BC. Golder Report No. 08-1480-0035. 23 p + app.

Golder Associates Ltd. (Golder). 2010. Columbia River Water Use Plan Monitoring Program: Physical Habitat Monitoring Study Period: Year 3 – 2009. Prepared for BC Hydro, Castlegar, BC. Golder Report No. 09-1480-0024. 33 p + app.

Golder Associates Ltd. (Golder). 2011. CLBMON-15a Mid Columbia River Physical Habitat Monitoring. Annual Technical Report – 2010. Prepared for BC Hydro, Castlegar, BC. Golder Report No. 10-1492-0084. 40 p. + 6 app.

Golder Associates Ltd. (Golder). 2012. CLBMON-15a Mid Columbia River Physical Habitat Monitoring. Annual Technical Report – 2011. Prepared for BC Hydro, Castlegar, BC. Golder Report No. 11-1492-0084. 44 p. + 6 app.

Golder Associates Ltd. (Golder). 2013. CLBMON-15a Mid Columbia River Physical Habitat Monitoring. Annual Technical Report – 2012. Report prepared for BC Hydro, Castlegar, BC. Golder Report No. 12-1492-0084. 44 p. + 6 app.

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

Plate, E.M.[2], Y. Imam[3], S. Dashti[3], L. Walker[3], N. Wright[3] and M. Zimmer[1]. 2014. CLBMON-15a Mid-Columbia River Physical Habitat Monitoring Project, 2013 (Year 7). Prepared for BC Hydro, Revelstoke, BC. Prepared by Okanagan Nation Alliance[1], LGL Limited[2] and Ecofish Research Limited[3]: 95 pp.

APPENDIX A:
2014 SITE VISIT AND MAINTENANCE DATA

Year	Date mm/dd	Arrival Time (24h)	Location Name	Station #	Stage Out	Stage Back In	Stage Batt. Left %	Stage Memory Left %	Time Sync.	Baro Out	Baro Back In	Baro Bat %	Baro Memory %	Time Sync.	TidBit Out	TidBit Back In	TidBit Bat %	TidBit Memory %	Time Sync.	Comments
2014	5-May	15:50	Jordan River Station #8	8	16:03	16:48	99	75	-58.42											all readings off by ~-2.5cm, cable not properly pushed in in November
2014	5-May	18:35	Illicillewaet River Station #7	7											18:37	19:15	93	67	no	S/N 10328108, other TidBit lost, Temperature OK
2014	6-May	10:00	MCR Station #6	6	10:05	10:23	98	33	-58.47											Temp Solinst 3C, Temp YSI 3.3C, cleaned lower end from outside, tightened clamps on standpipe
2014	6-May	11:00	MCR Station #5	5	11:05	11:25	98	33	-58.26											Temp Solinst 3.58C, Temp YSI 3C, cleaned lower end from outside, checked clamps on standpipe
2014	6-May	11:50	MCR Station #4	4	12:00	12:48	98	33	-58.42	11:58	12:40	98	33	-58.31						Temp Solinst 3.61C, Temp YSI 3.54C, cleaned lower end from outside, checked clamps on standpipe
2014	6-May	13:23	MCR Station #2	2	13:15		98	33	-58.45	13:18		100	33	-63.19						Temp Solinst 3.3C, Temp YSI 3.3C, cleaned lower end from outside, added a clamp on standpipe
2014	6-May	22:00	MCR Station #1	1	22:35		98	33												Taken out for good
2014	6-May	22:00	MCR Station #1 Anchor	1	22:56		99	33												Left anchor and Solinst in place for later
2014	7-May	0:00	MCR Station #2 Anchor	2	0:10		99	33	-58.41											Everything clean
2014	8-Sep	19:40	Jordan River Station #8	8	19:46		99	80	-2											river a little high and quite turbid, carried out discharge measurement
2014	9-Sep	11:32	MCR Station #2	2	11:32	11:56	98	55	-1.45	11:46		100	55	-0.18						
2014	9-Sep	12:36	MCR Station #6	6	12:38		98	55	-1:33											
2014	9-Sep	13:15	MCR Station #5	5	13:15		98	55	-1.42											standpipe needs cleaning from inside
2014	9-Sep	13:46	MCR Station #4	4	13:46		98	55	-1.33	13:43	14:06	98	55	-1.36						standpipe needs cleaning from inside
2014	9-Sep	14:35	MCR Station #2	2	14:40	14:53	98	100	0	14:43	14:58	100	100	0						Second visit for the day, re-set baro to 10 min sampling intervall
2014	9-Sep	15:55	Illicillewaet River Station #7	7											16:02	16:35	100	77		Needs second Tidbit
2014	10-Sep	0:50	MCR Station #2 Anchor	2	0:54		99	55	-01:38											waiting for 1.5 hours for low flow
2014	31-Oct	15:30	Jordan River Station #8	8	15:32	16:20	99	93	+00:15											Temp Checked=OK; Time Synched, Cleaned standpipe, checked all fasteners, Too high for discharge measurement
2014	31-Oct	17:10	Illicillewaet River Station #7	7											17:35	19:00				SN: 10328108,T=OK, Synched, data checked, cinder block was burried in mud
2014	31-Oct	17:10	Illicillewaet River Station #7	7											N/A	19:00				SN: 10575960, newly installed TiBit, now back to 2 Tidbits in thst station
2014	1-Nov	10:59	MCR Station #2	2	10:59		98	82	+00:11											Temp Checked=OK; Time Synched, Cleaned standpipe, checked all fasteners
2014	1-Nov	10:59	MCR Station #2 Baro	2						10:59		100	82	+0.21						Temp Checked=OK; Time Synched
2014	1-Nov	11:50	MCR Station #2 Anchor	2	11:50		99	82	+00:07											Temp Checked=OK; Time Synched, Cleaned standpipe, checked all fasteners
2014	1-Nov	12:40	MCR Station #4 Baro	4						12:40	13:05	98	82	+0.14						SN: 034315, Temp Checked=OK; Time Synched
2014	1-Nov	13:10	MCR Station #4	4	12:50	14:55	98	82	+00:12											SN: 1036068, Temp Checked=OK; Time Synched, Cleaned standpipe, checked all fasteners
2014	1-Nov	15:10	MCR Station #5	5	15:10	15:20	98	82	+00:15											SN: 1040334, Temp Checked=OK; Time Synched, Cleaned standpipe, checked all fasteners, lower part of standpipe covered in layer of fines from Illecillewaet Blow-Out
2014	1-Nov	15:35	MCR Station #6	6	15:35	15:52	98	82	+00:12											SN: 1021824, Temp Checked=OK; Time Synched, Cleaned standpipe, checked all fasteners, lower part of standpipe covered in layer of fines from Illecillewaet Blow-Out

APPENDIX B:
2013 *IN SITU* PHYSICAL WATER QUALITY PARAMETER RESULTS

Year	Date mm/dd	Arrival Time (24h)	Location Name	Station #	UTM Zone: 11		Temperature	Conductivity	Specific Conductivity	Total Dissolved Solids	DO Saturation	DO Total	pH	Turbidity
							ºC	µS/cm	µS/cm	mg/L	%	mg/L	pH Units	NTU
2014	5-May	16:13	Jordan River Station #8	8			5.19	0.042	0.027	0.027	84.9	10.84	7.18	
2014	5-May	18:41	Illicillewaet River Station #7	7			6.33	0.154	0.099	0.1	82.1	10.13	8.01	
2014	6-May	10:12	MCR Station #6	6			3.33	0.144	0.084	0.093	96.4	12.77	7.96	
2014	6-May	11:07	MCR Station #5	5			3.5	0.147	0.086	0.095	90.2	12.02	7.96	
2014	6-May	12:01	MCR Station #4	4			3.53	0.146	0.086	0.095	97.1	12.89	7.9	
2014	6-May	13:23	MCR Station #2	2			3.26	0.15	0.088	0.097	94.8	12.67	7.92	
2014	8-Sep	19:39	Jordan River Station #8	8			11.36	0.04	0.03	0.026	94.4	10.33	7.59	10.2
2014	9-Sep	11:32	MCR Station #2	2			11.18	0.112	0.083	0.073	94.8	10.41	7.85	0.6
2014	9-Sep	12:36	MCR Station #6	6			11.62	0.112	0.083	0.073	96.7	10.51	7.92	1.6
2014	9-Sep	13:15	MCR Station #5	5			11.42	0.113	0.083	0.073	95	10.37	7.92	0.9
2014	9-Sep	13:45	MCR Station #4	4			11.5	0.112	0.083	0.073	98.6	10.75	7.93	0.9
2014	9-Sep	15:54	Illicillewaet River Station #7	7			9.86	0.111	0.079	0.072	97.1	10.99	8.13	14.7
2014	9-Sep	23:35	MCR Station #2	2			10.71	0.115	0.083	0.074	94.6	10.5	7.9	0.8
2014	31-Oct	15:24	Jordan River Station #8	8			5.38	0.027	0.017	0.018	92.8	11.74	6.85	38
2014	31-Oct	17:19	Illicillewaet River Station #7	7			5.85	0.137	0.087	0.089	90.6	11.32	7.84	193
2014	1-Nov	10:57	MCR Station #2	2			9.13	0.132	0.092	0.086	98.4	11.33	7.71	0.9
2014	1-Nov	12:40	MCR Station #4	4			8.68	0.118	0.082	0.077	98.4	11.51	7.75	1.1
2014	1-Nov	15:15	MCR Station #5	5			8.8	0.119	0.082	0.078	100.1	11.62	7.83	12.8
2014	1-Nov	15:40	MCR Station #6	6			8.67	0.119	0.082	0.077	98.2	11.44	7.8	16.2

APPENDIX C:
2013 LABORATORY NUTRIENT AND PHYSICAL PARAMETER RESULTS

Year	Date Sampled	Station #	Nitrate	Ammonia	Nitrogen, Total	Nitrogen, Total Kjeldahl	Phosphorus, Total	Phosphorus, Total Dissolved	Phosphorus, Dissolved Reactive	Solids, Total Dissolved	Solids, Total Suspended	Turbidity	pH
			mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	NTU	pH units
2014		STN1											
2014	6-May	STN2	0.094	0	0.205	0.11	0.005	0.003	0	76	0	0.5	7.86
2014	6-May	STN4	0.11	0	0.254	0.14	0.007	0.006	0	80	0	0.4	7.79
2014	6-May	STN5	0.112	0	0.238	0.13	0.006	0.003	0	72	0	0.5	7.72
2014	6-May	STN6	0.145	0	0.309	0.16	0.005	0.003	0	86	0	0.6	7.58
2014	5-May	STN7-ILLI	0.444	0	0.828	0.38	0.021	0.019	0.005	89	0	2.8	7.29
2014	5-May	STN8-JORDAN	0.551	0	0.681	0.13	0.007	0.005	0.006	15	0	0.7	6.64

APPENDIX D:
GRAPHICAL REPRESENTATION OF THE 2014 MODELLED AND OBSERVED STAGES AT THE MCR STATIONS

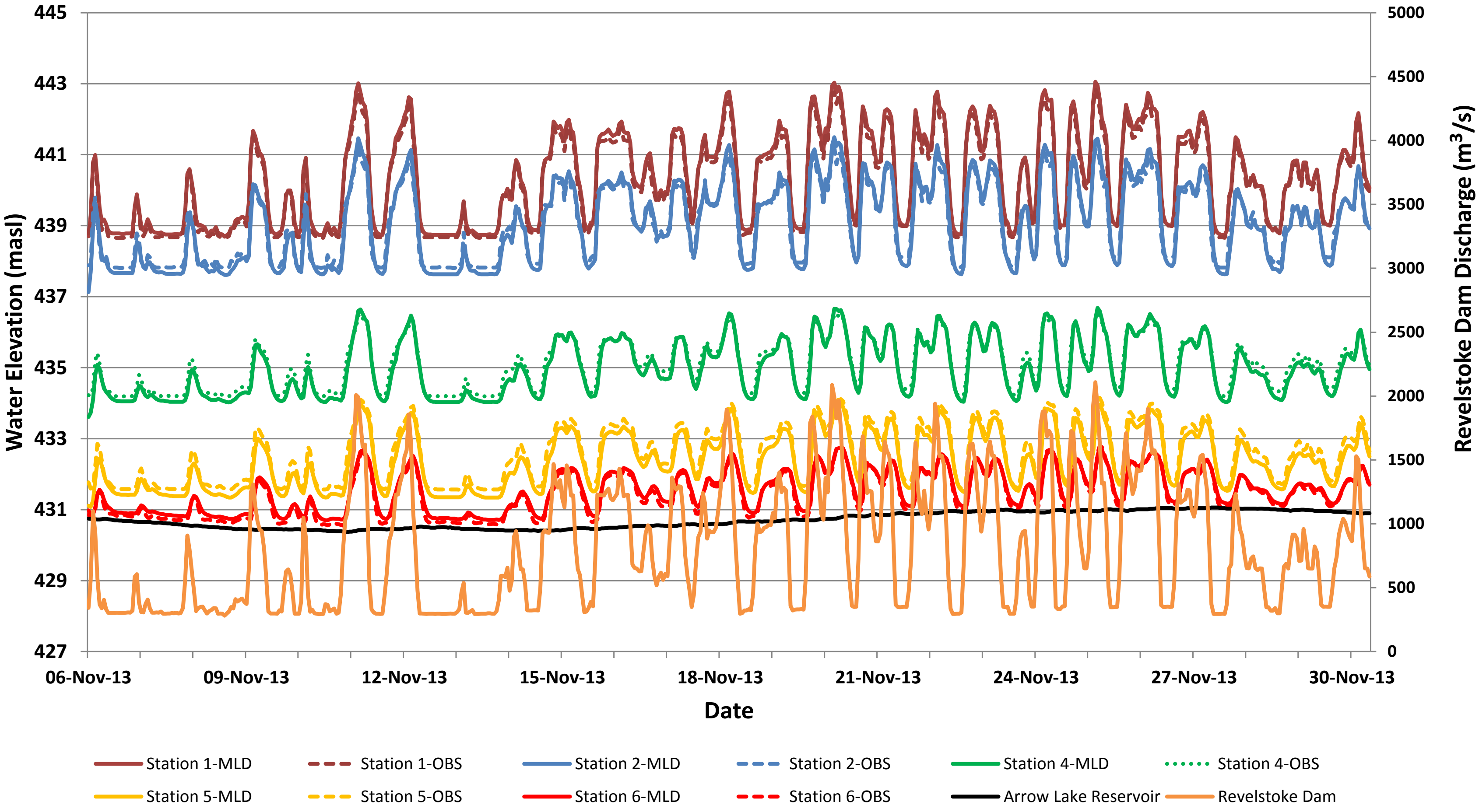


Figure 16 Modelled (MLD) and observed (OBS) stages at the MCR stations for November 18, 2012 to February 10, 2013 (y-axis for water elevations for MCR stations on the left, y-axis only for discharge through Revelstoke Dam on the right).

Figure 16 continued.

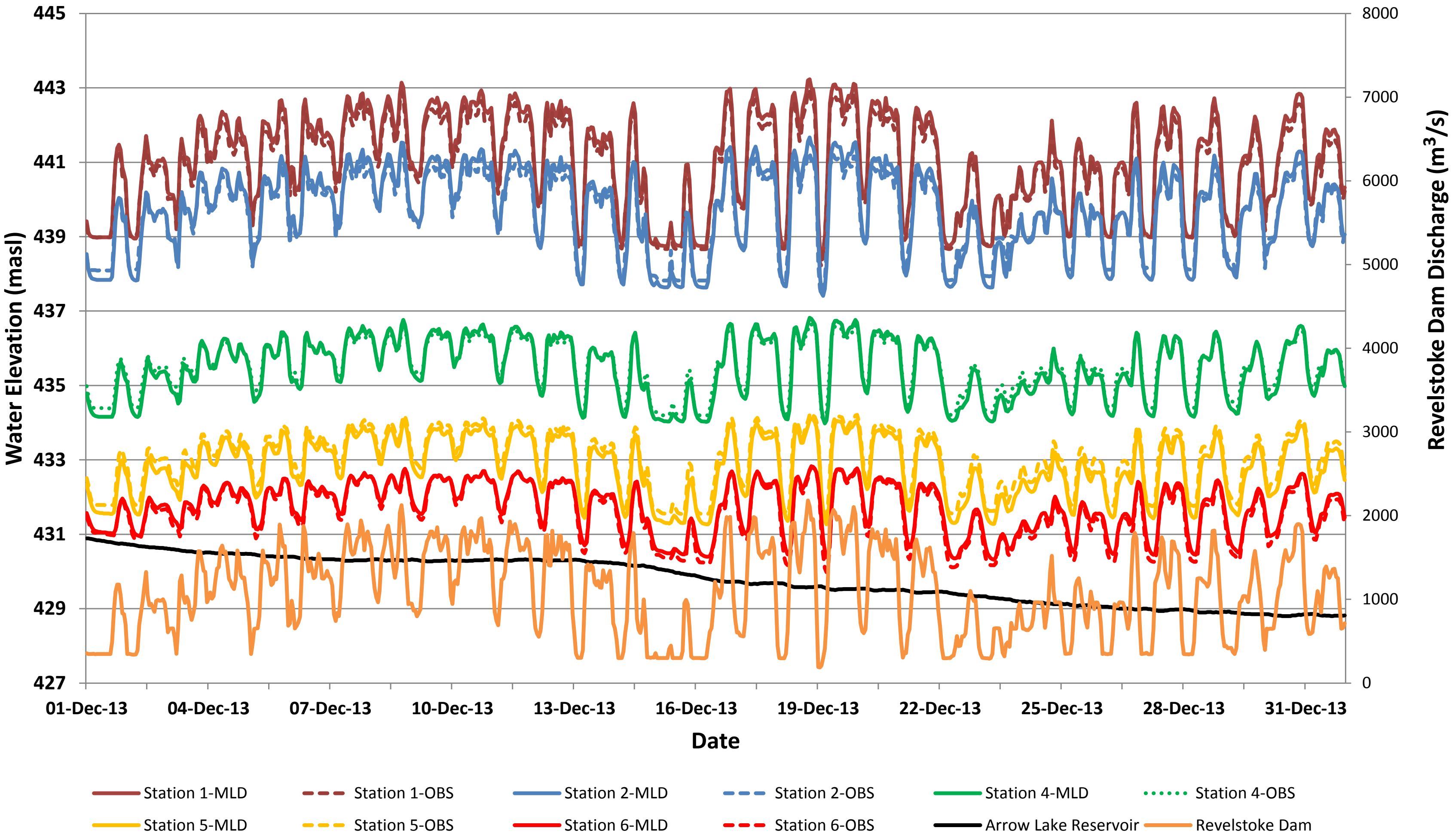


Figure 16 continued.

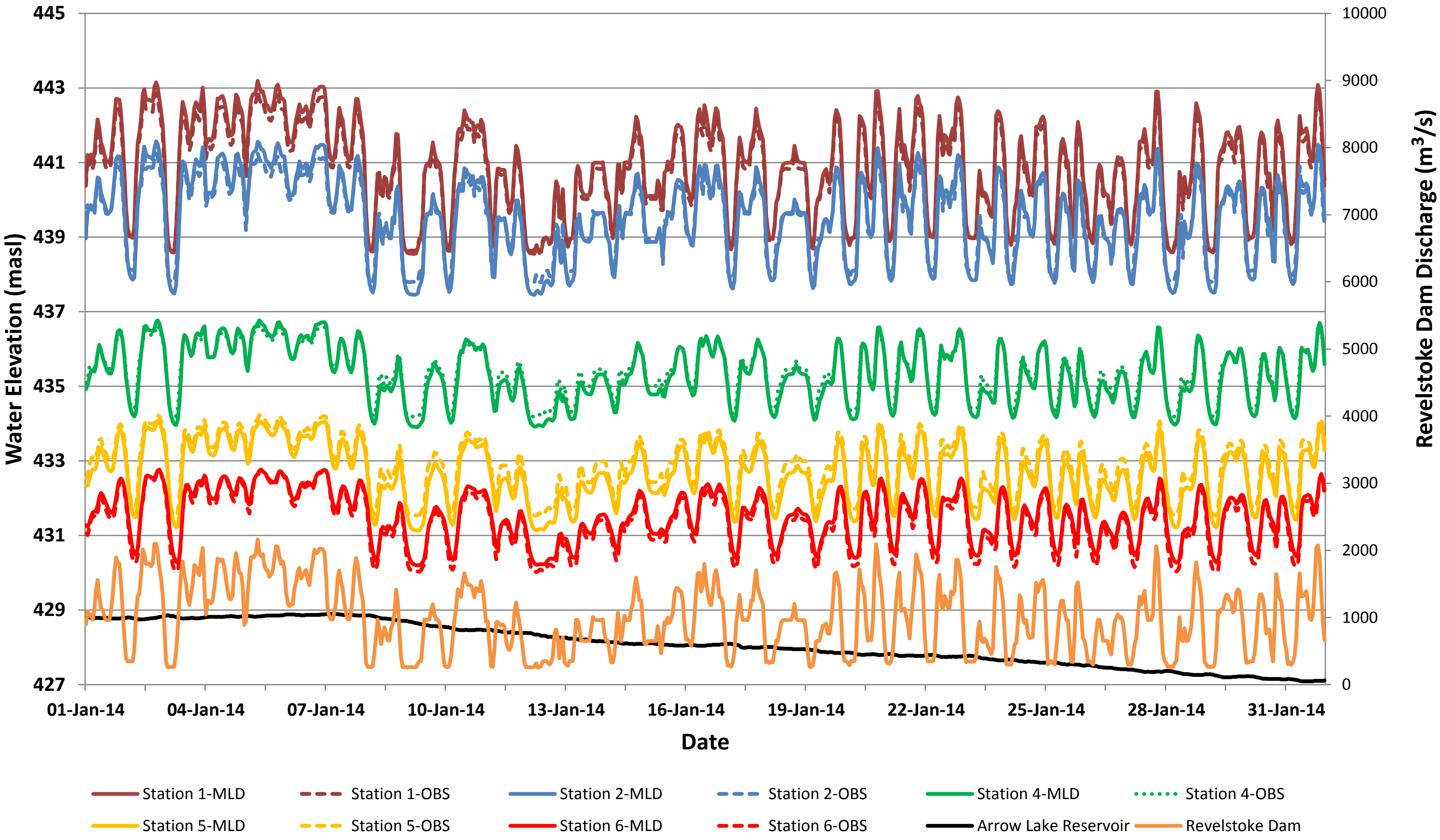


Figure 16 continued.

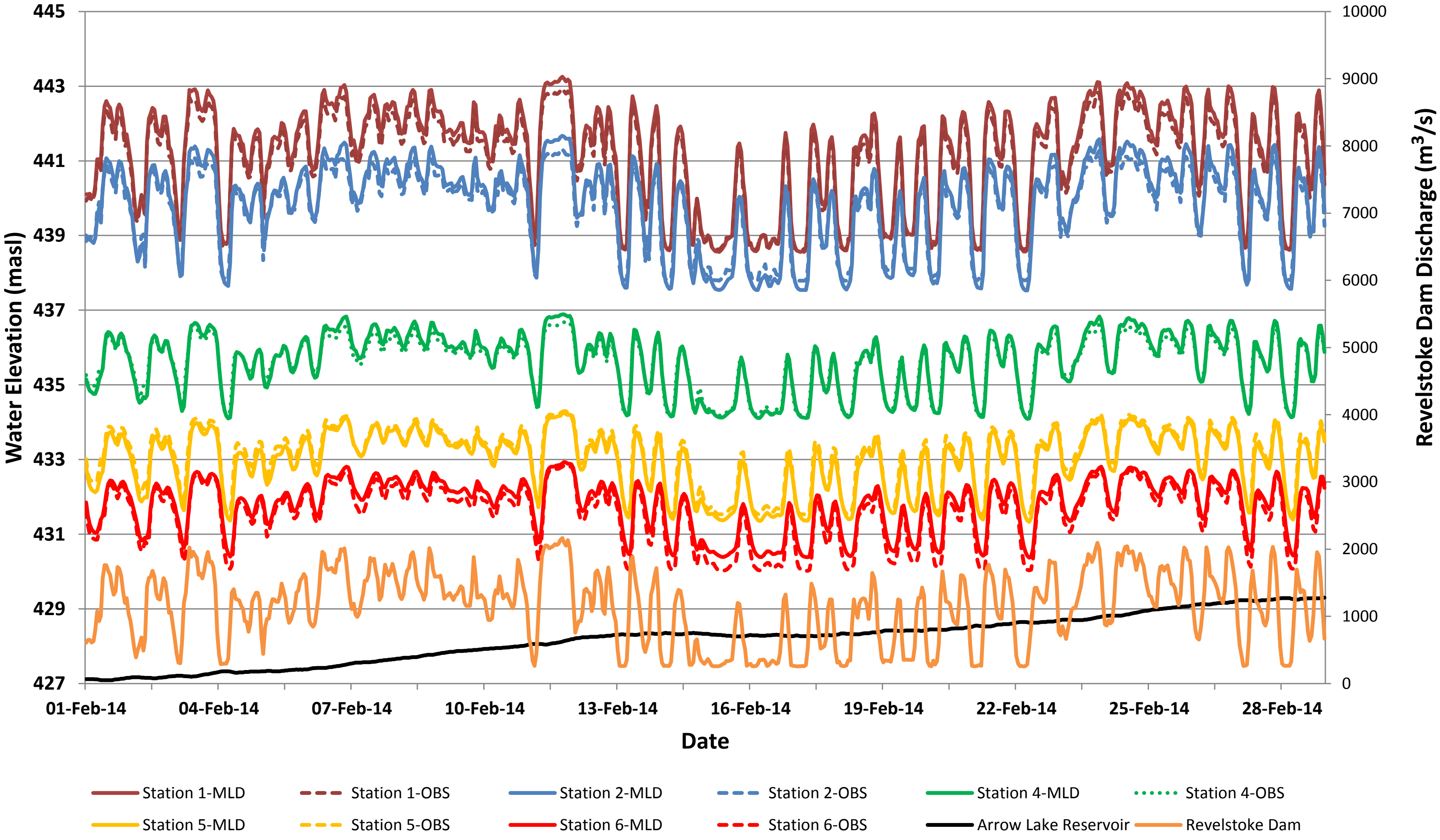


Figure 16 continued.

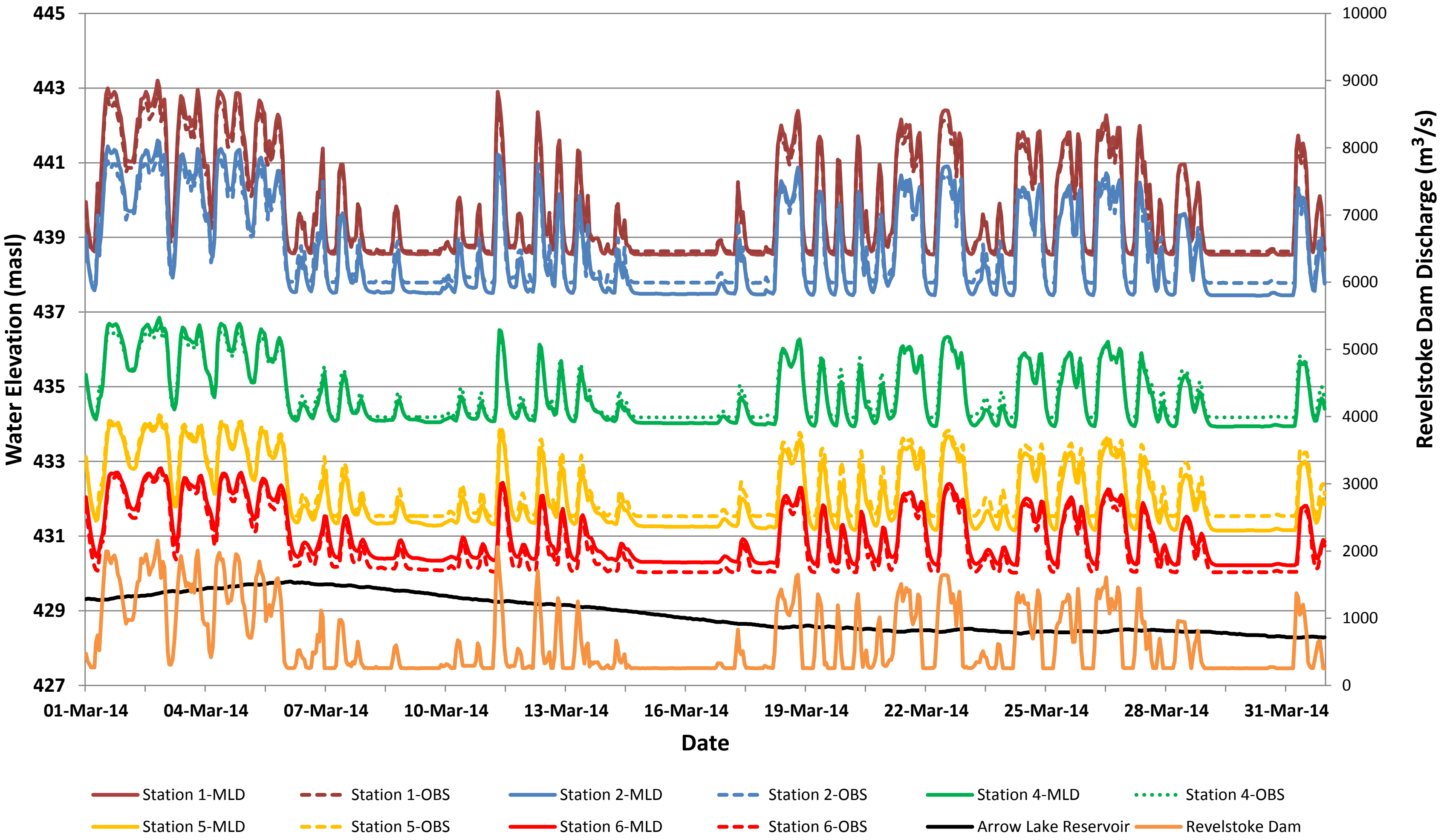


Figure 16 continued.

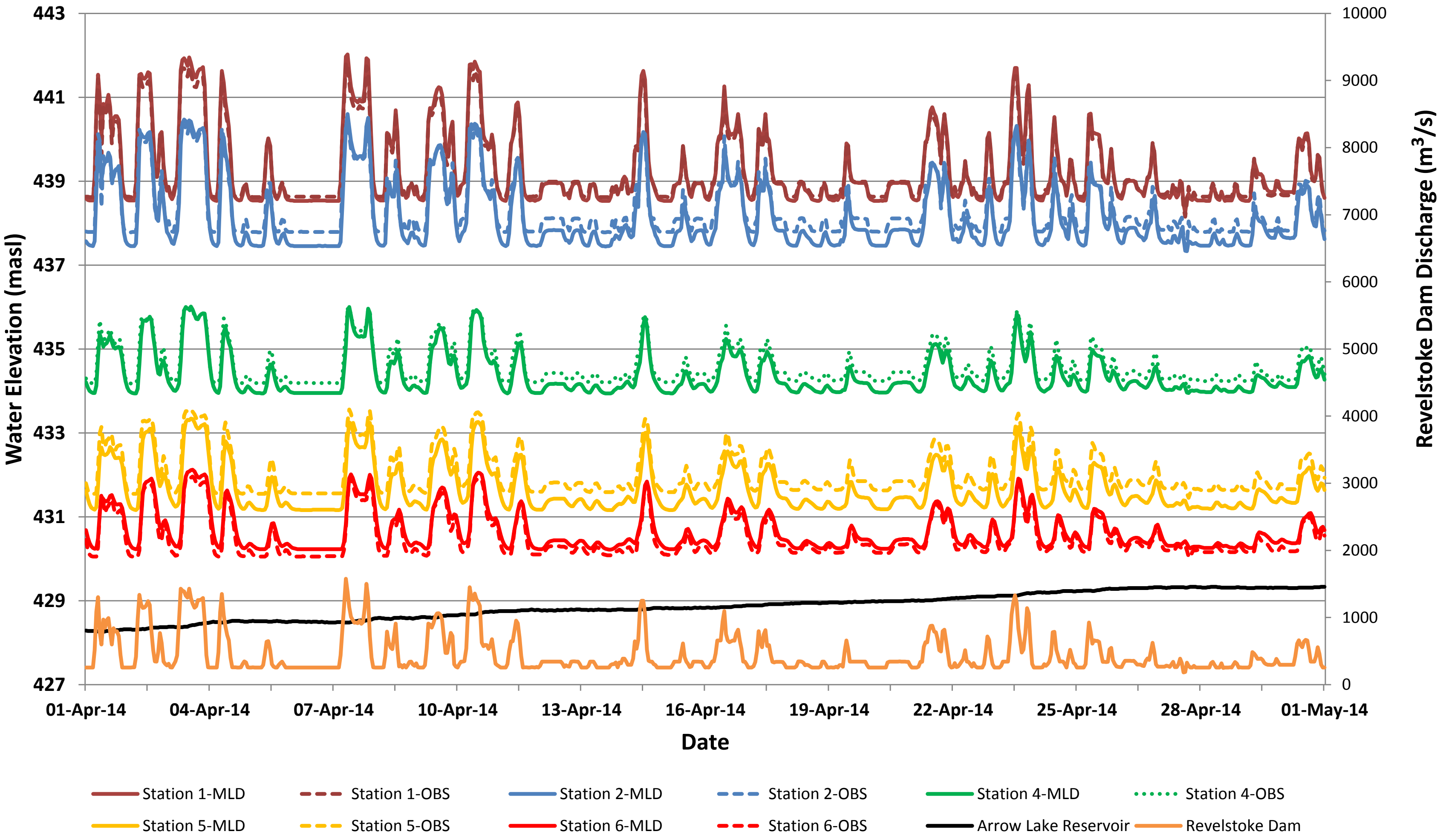


Figure 16 continued.

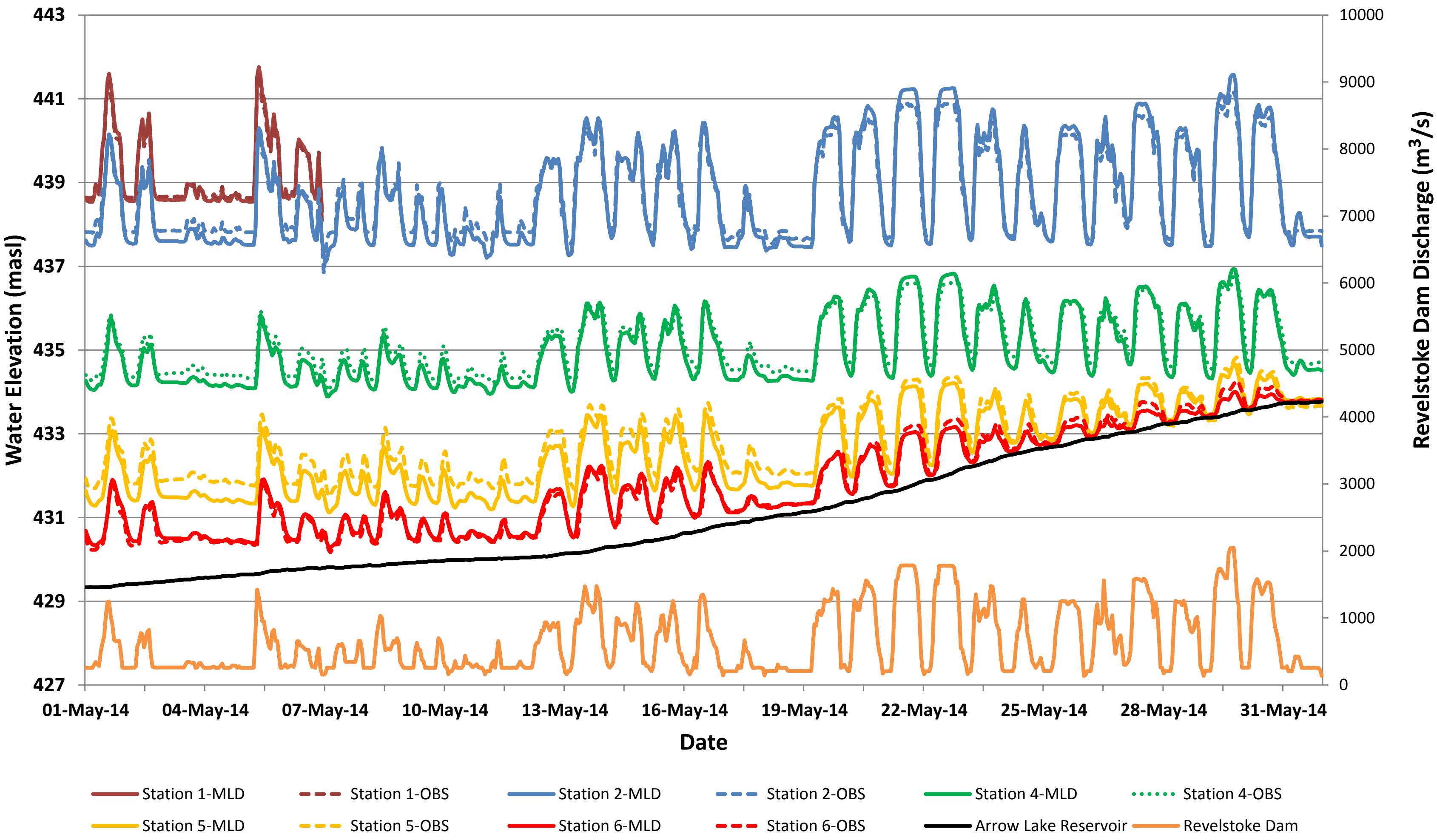


Figure 16 continued.

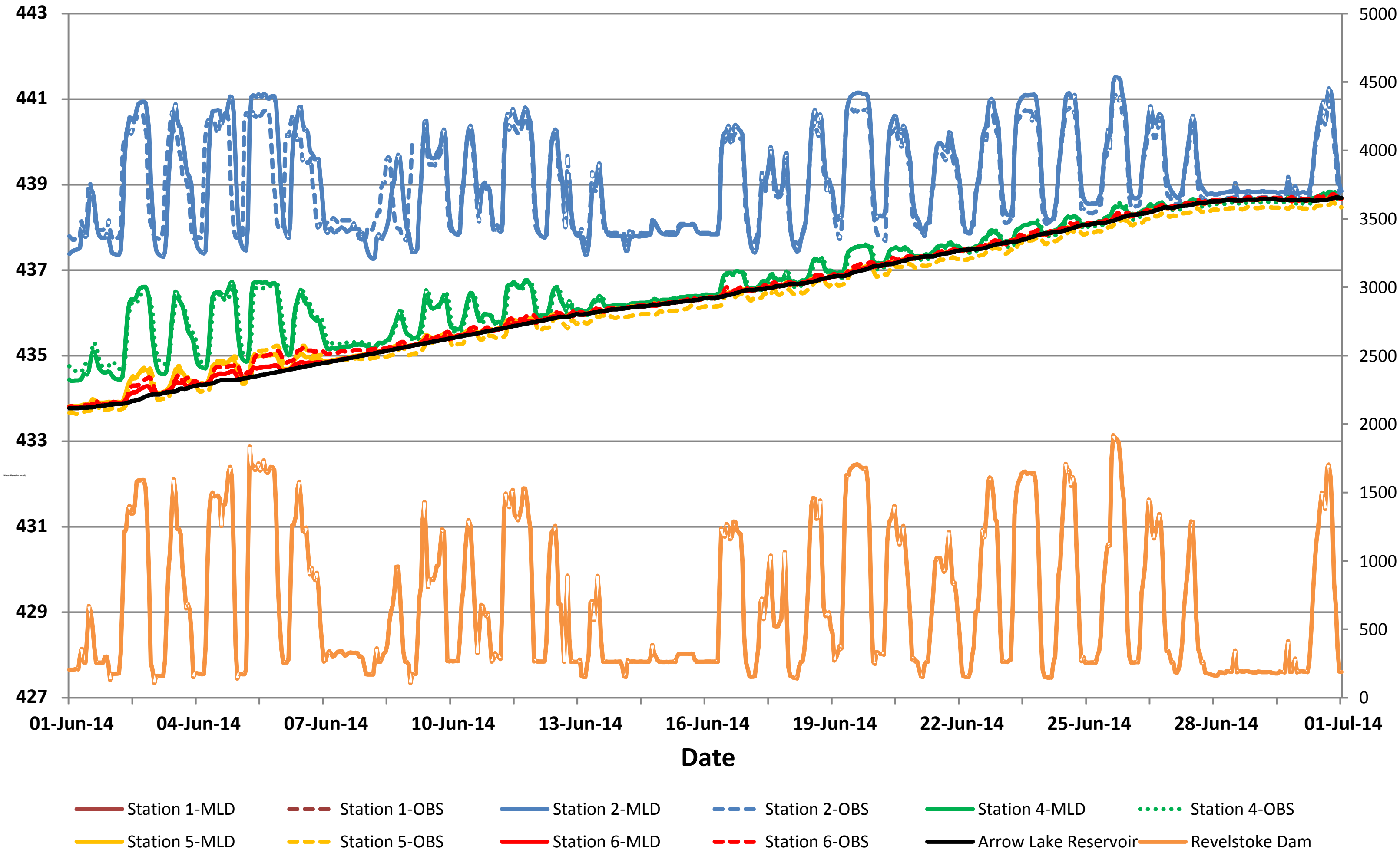


Figure 16 continued.

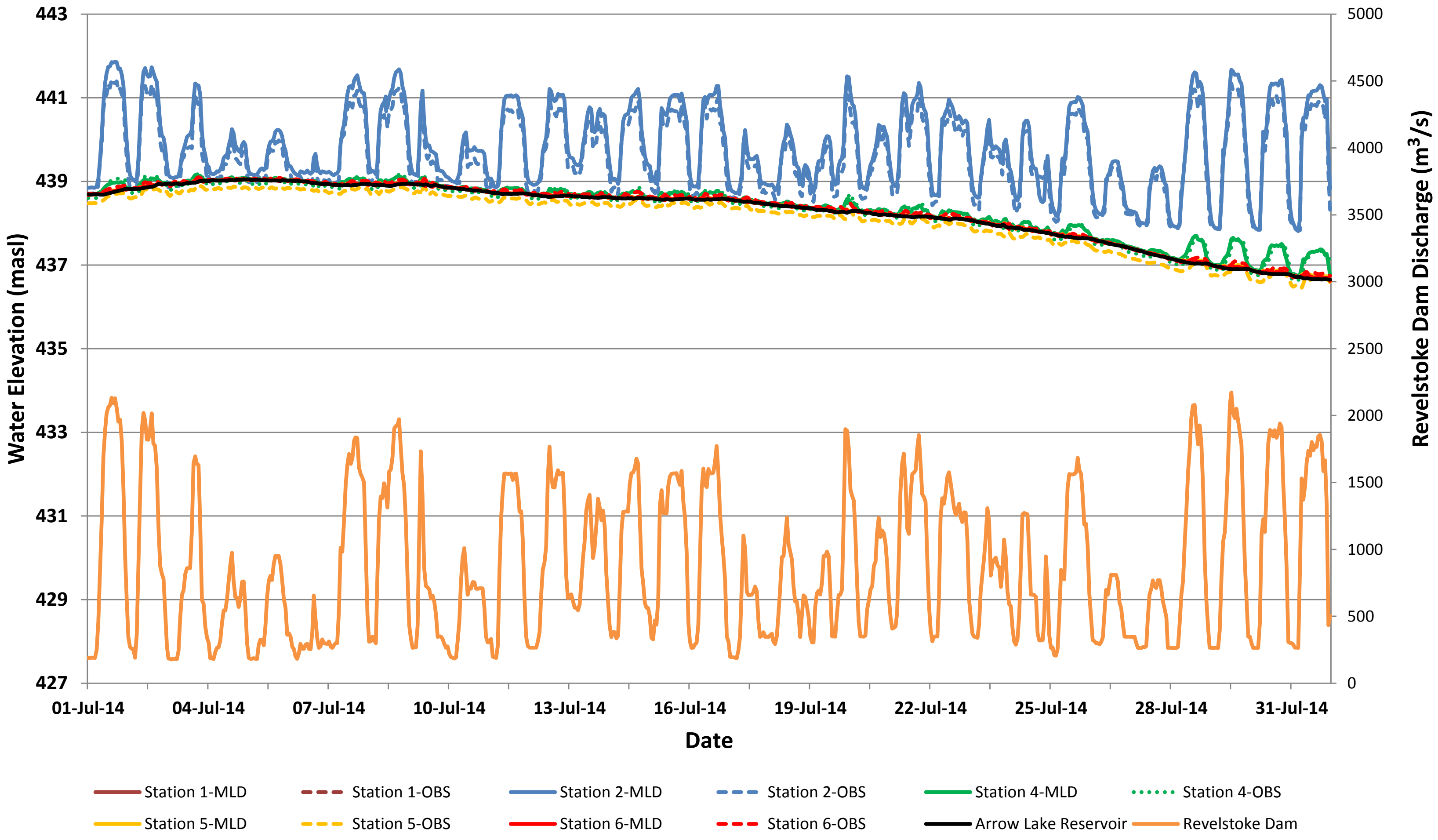


Figure 16 continued.

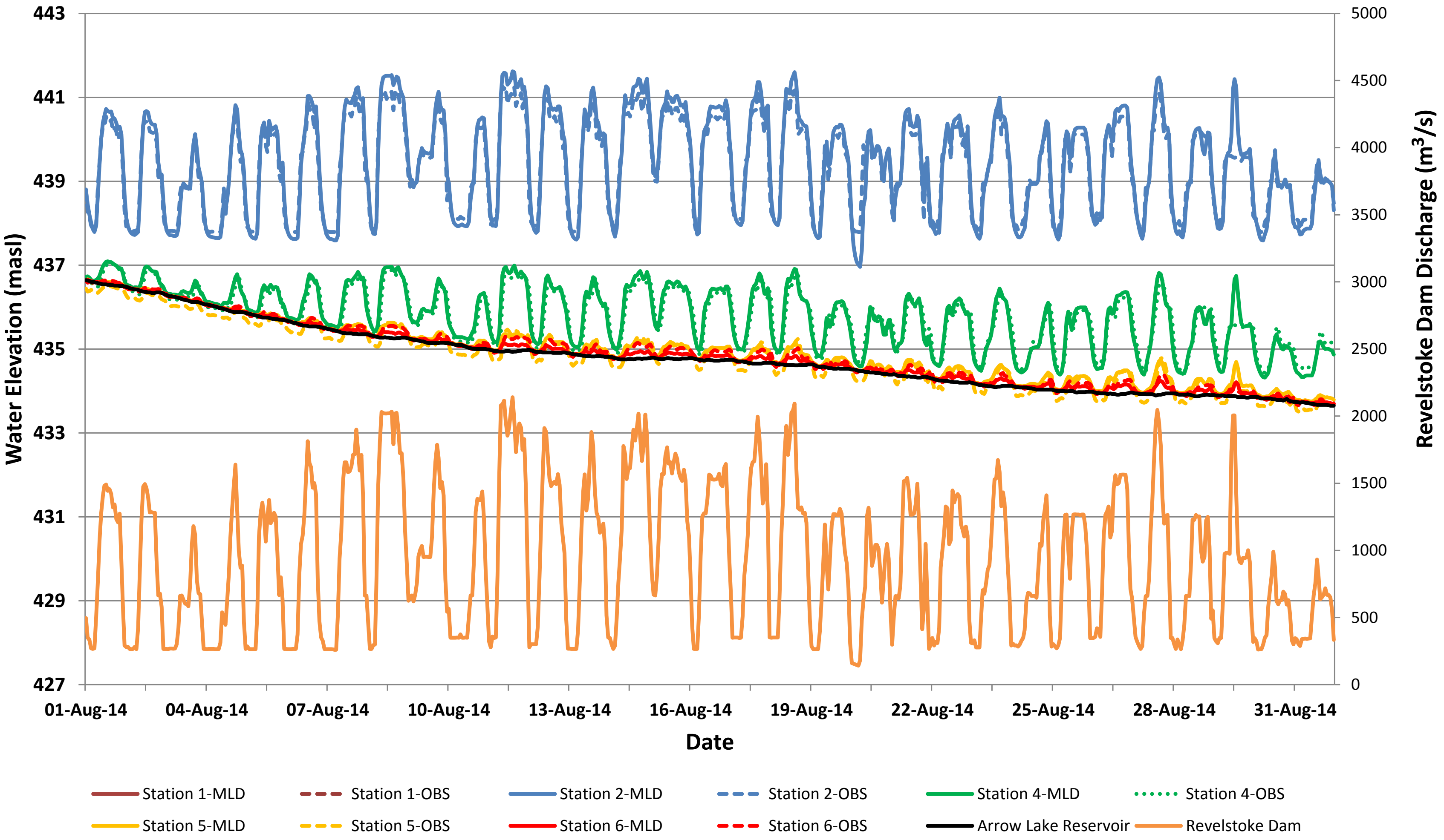


Figure 16 continued.

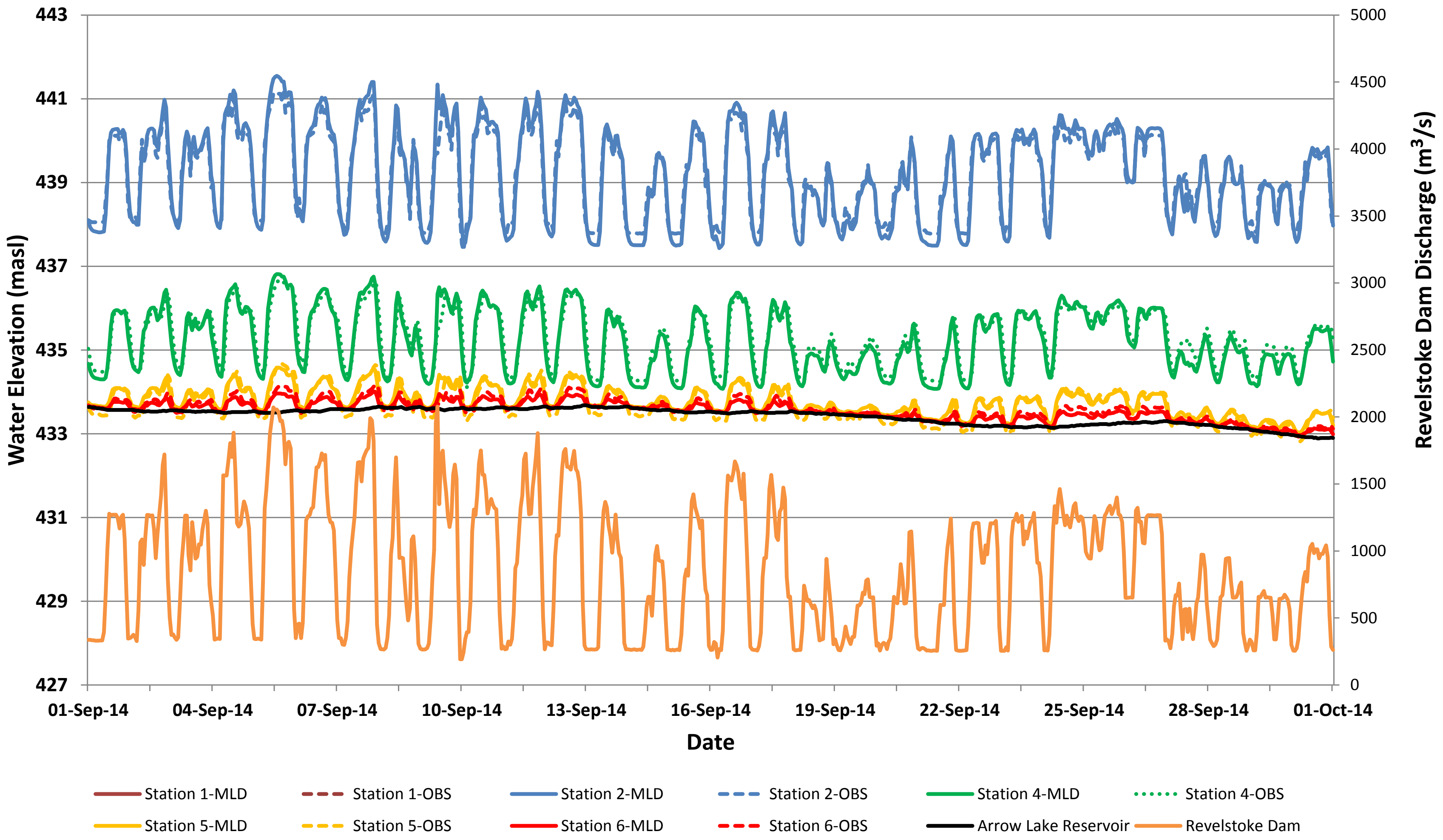
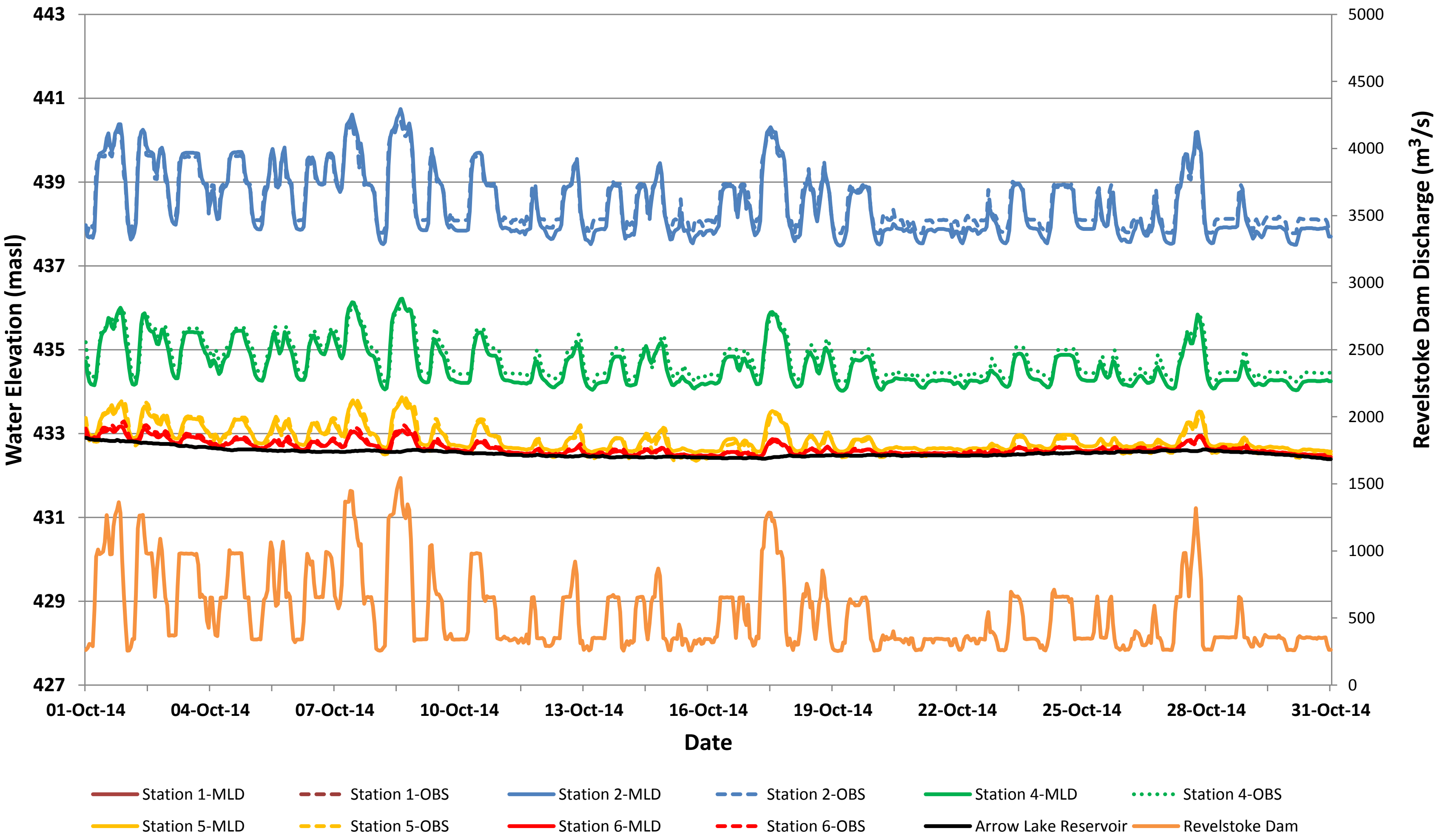


Figure 16 continued.



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

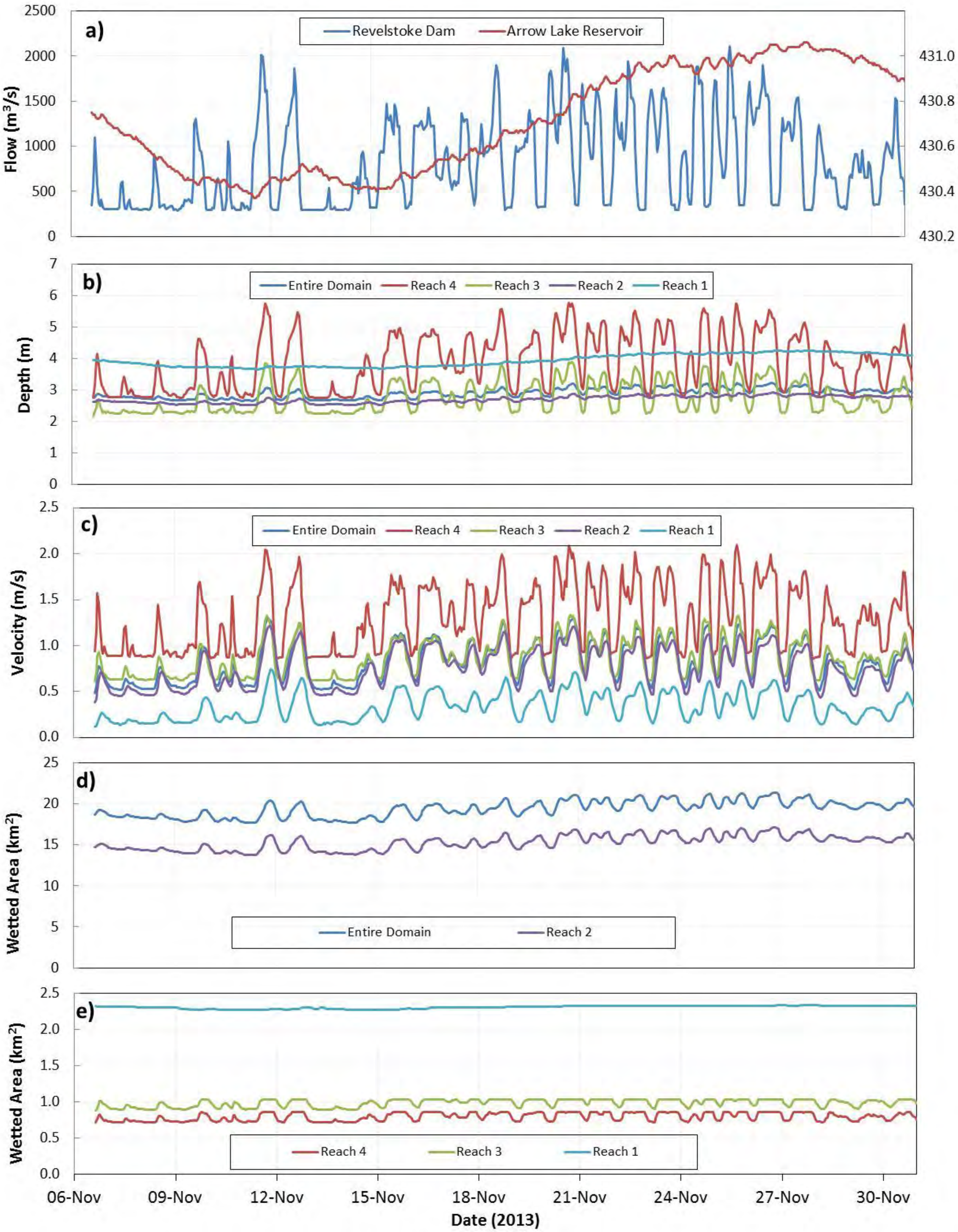


Figure 17 a) Discharge from REV and water level at downstream boundary of modelled domain; b) simulated average flow depth; c) simulated average flow velocity; and d, e) simulated wetted riverbed area for November 06, 2013 to October 31, 2014.

Figure 17 continued for the month of December 2013

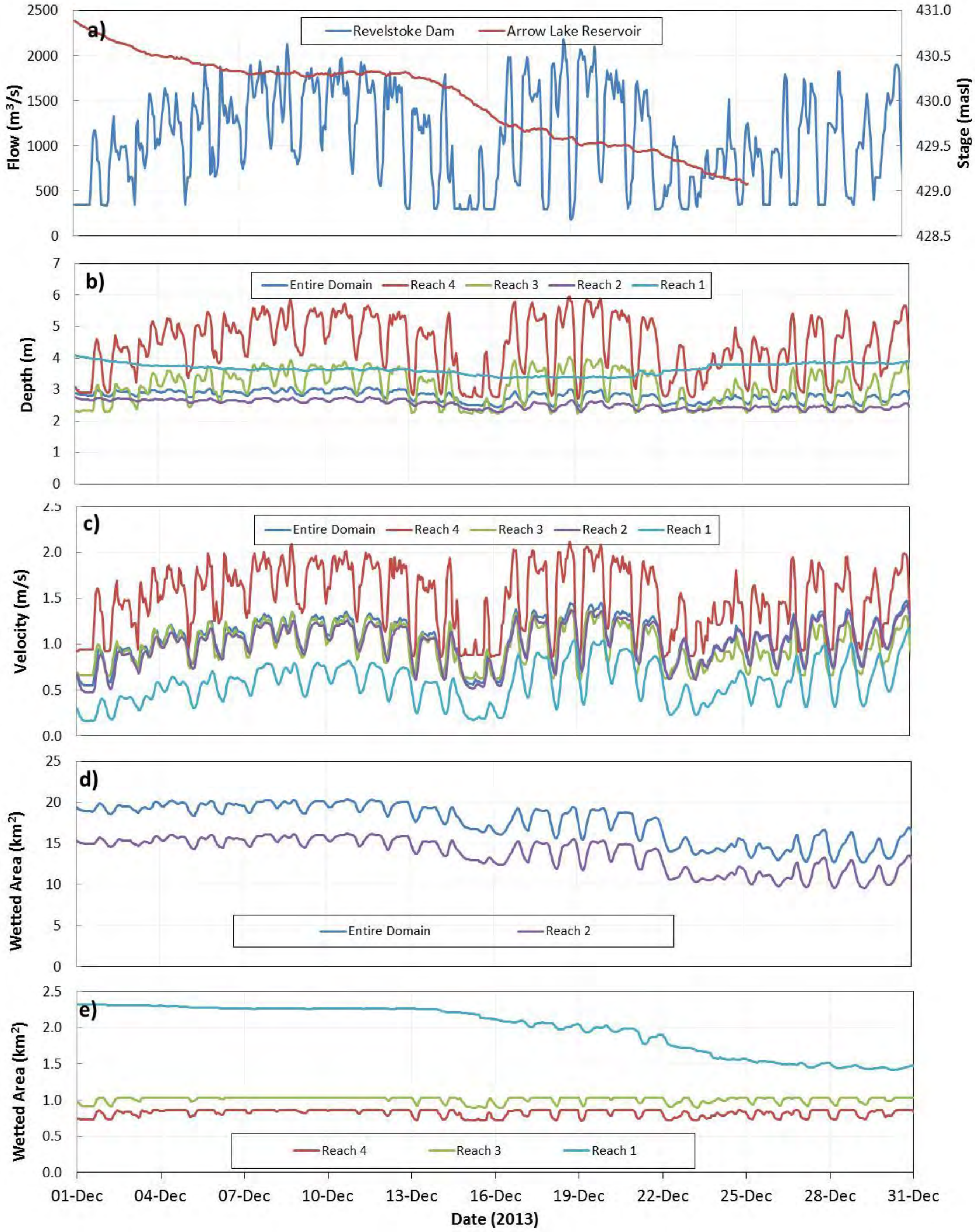


Figure 17 continued for the month of January 2014

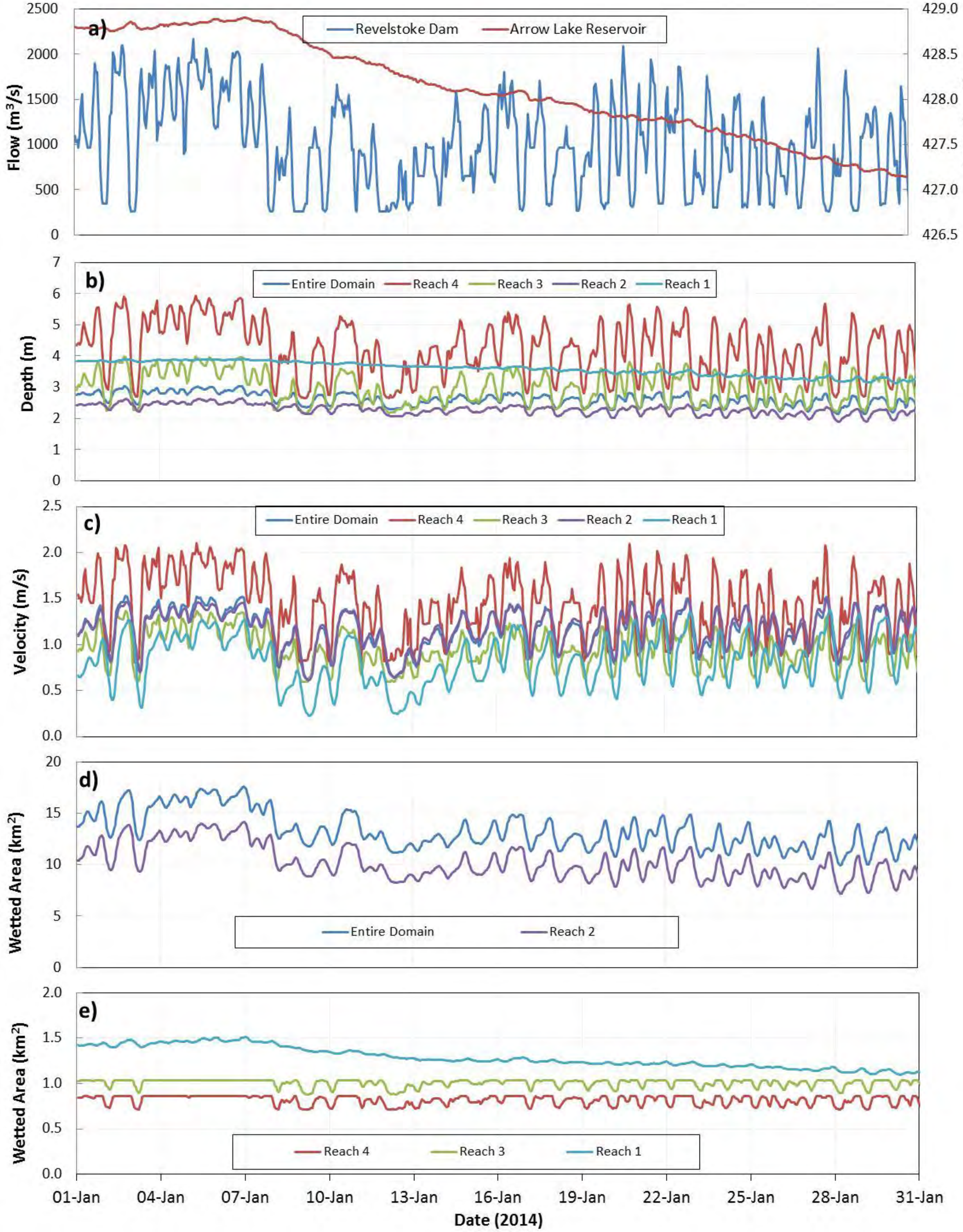


Figure 17 continued for the month of February 2014

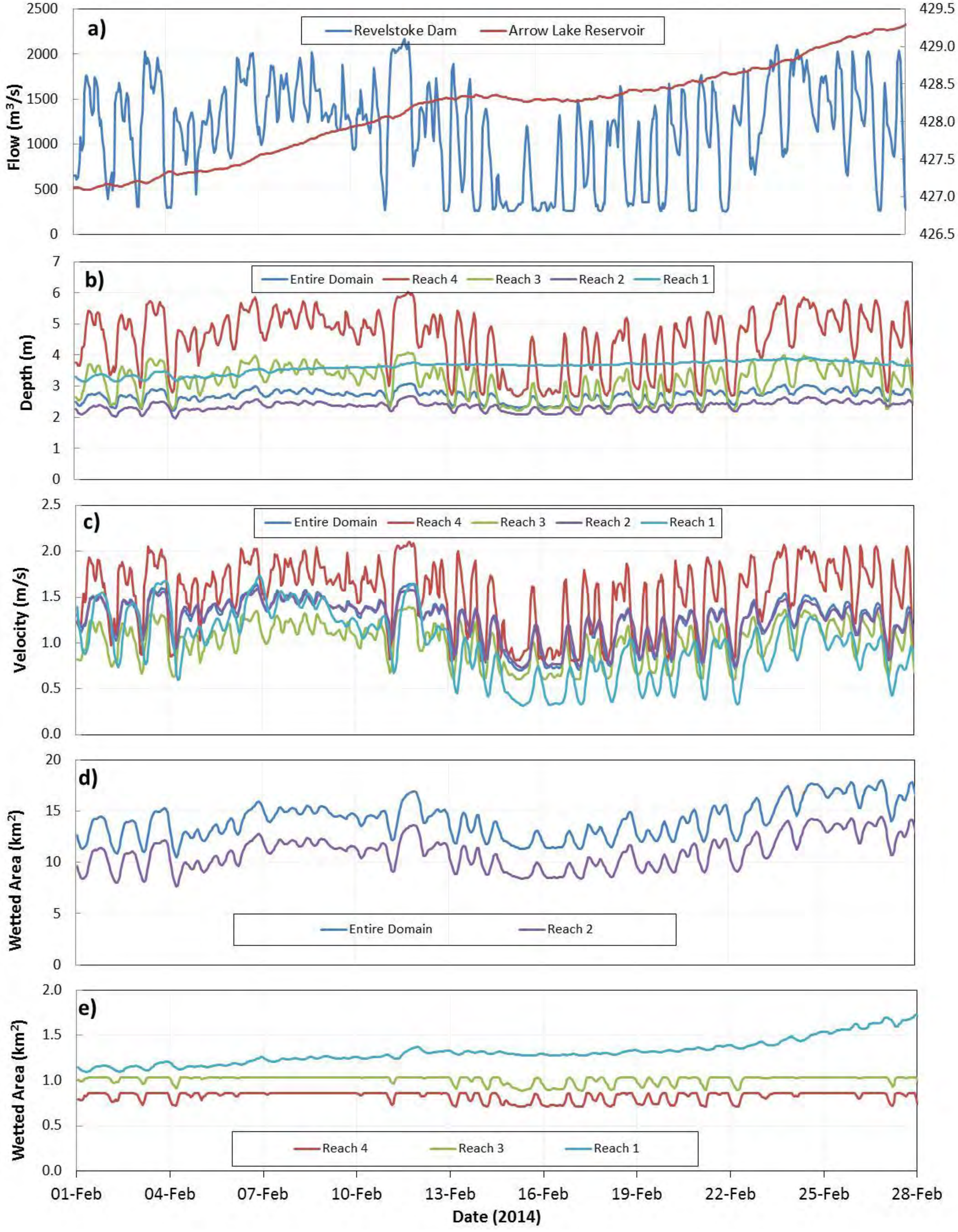


Figure 17 continued for the month of March 2014

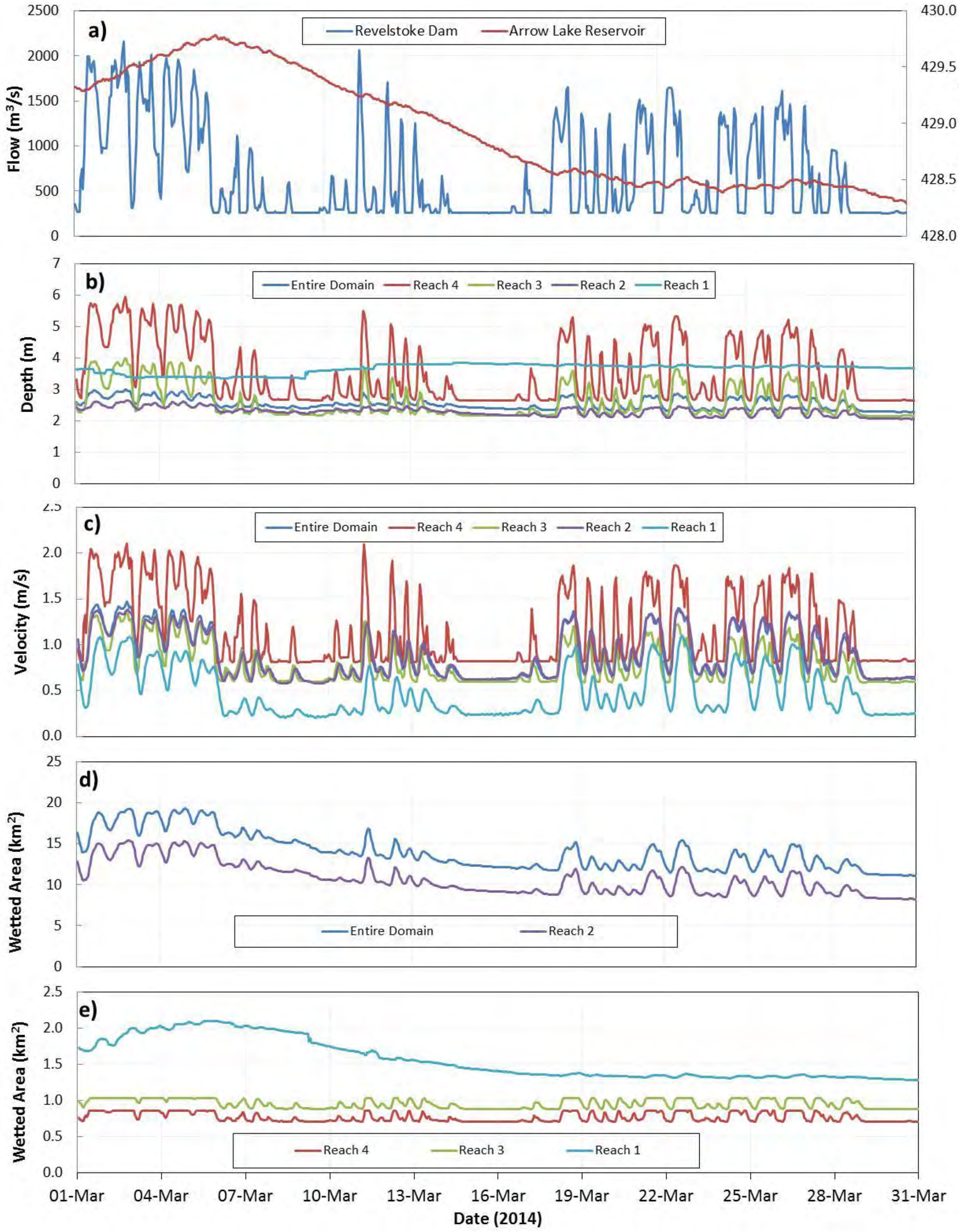


Figure 17 continued for the month of April 2014

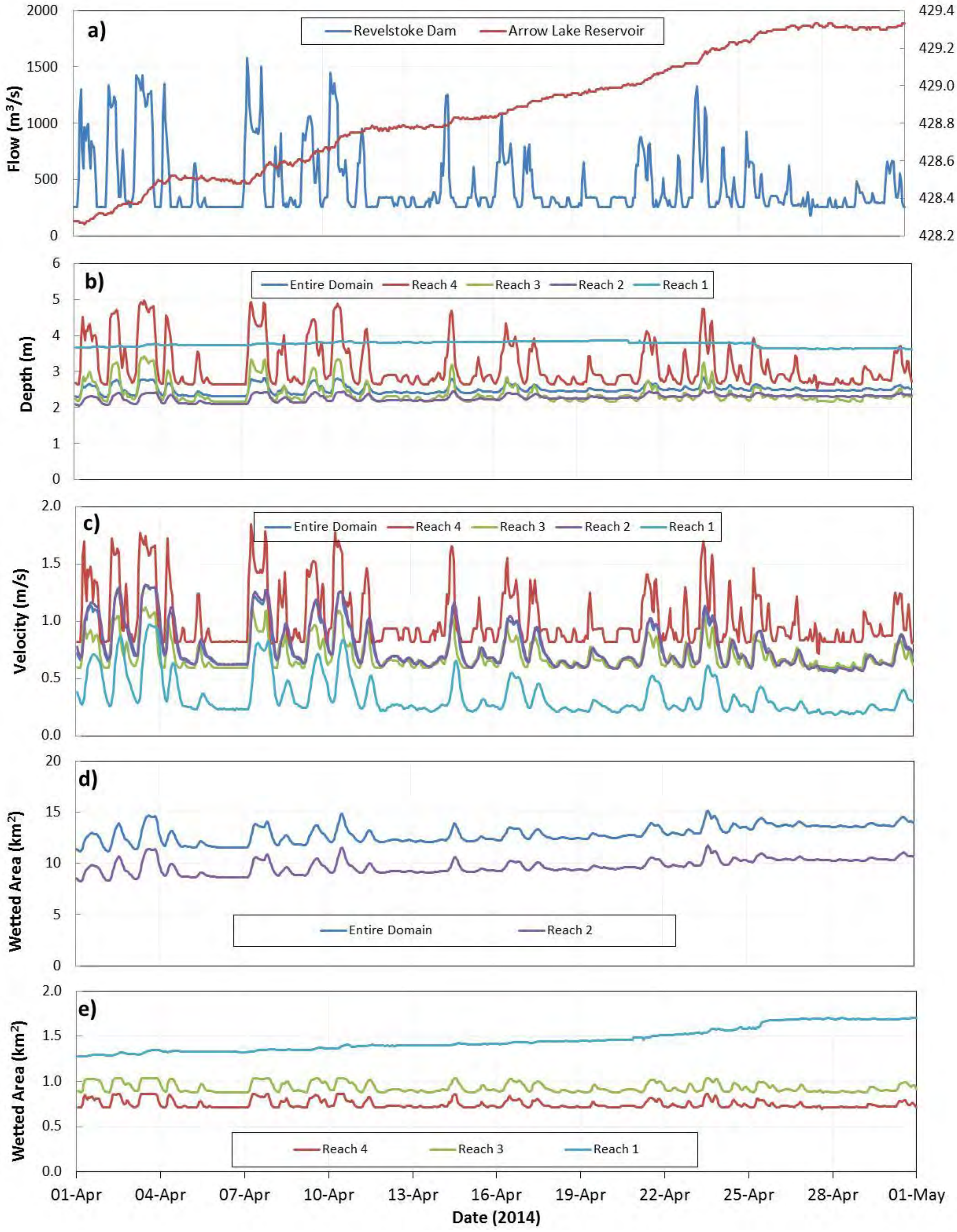


Figure 17 continued for the month of May 2014

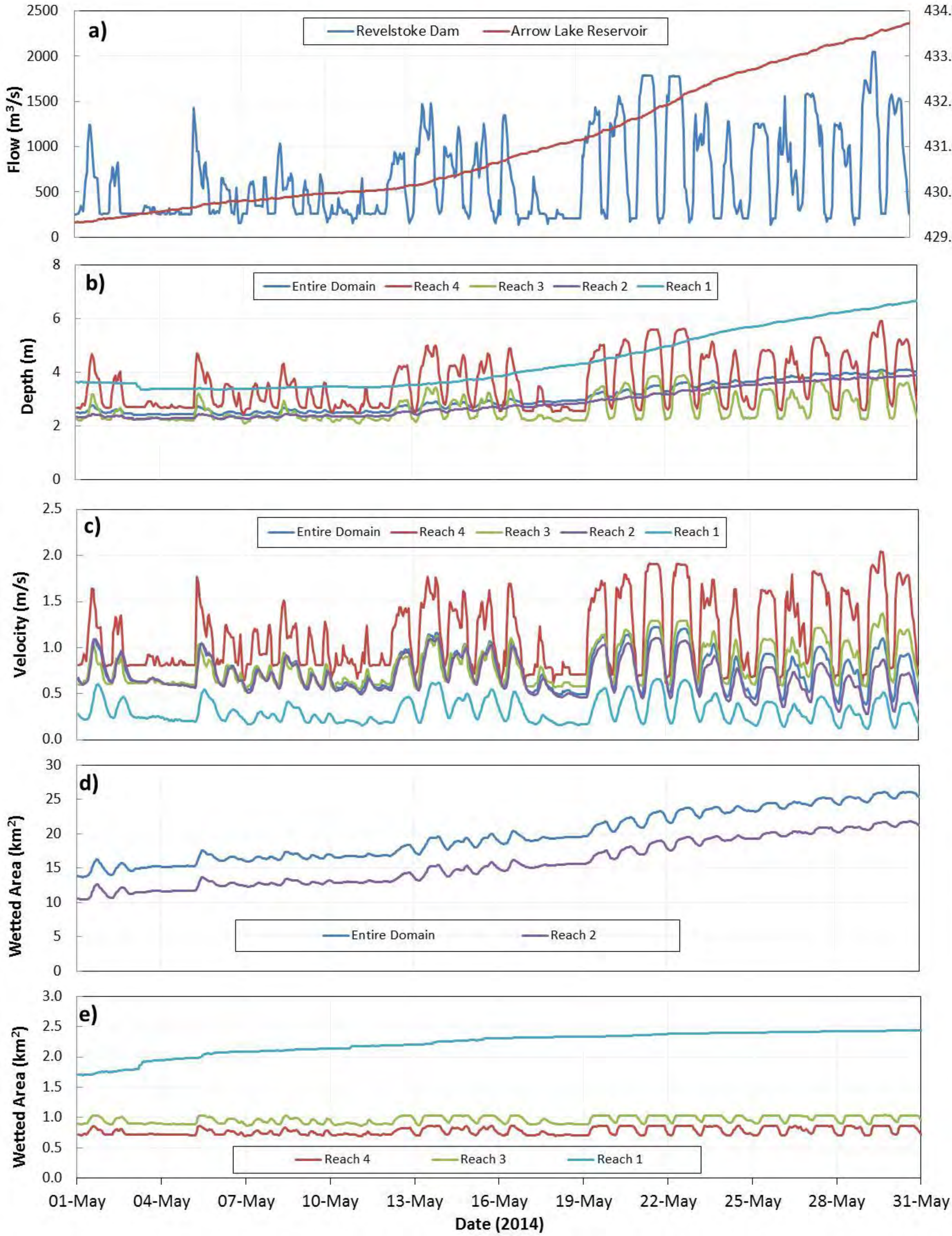


Figure 17 continued for the month of June 2014

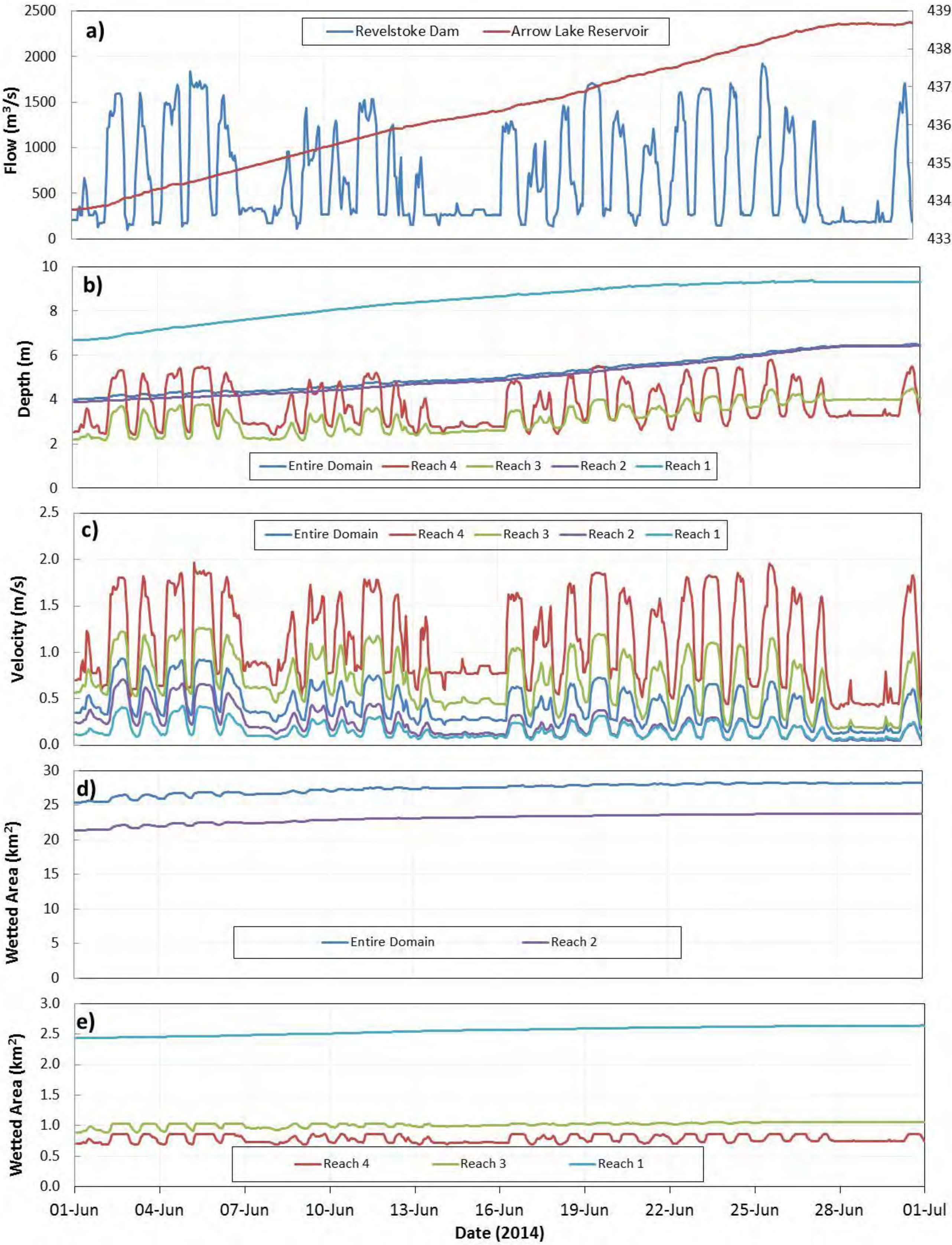


Figure 17 continued for the month of July 2014

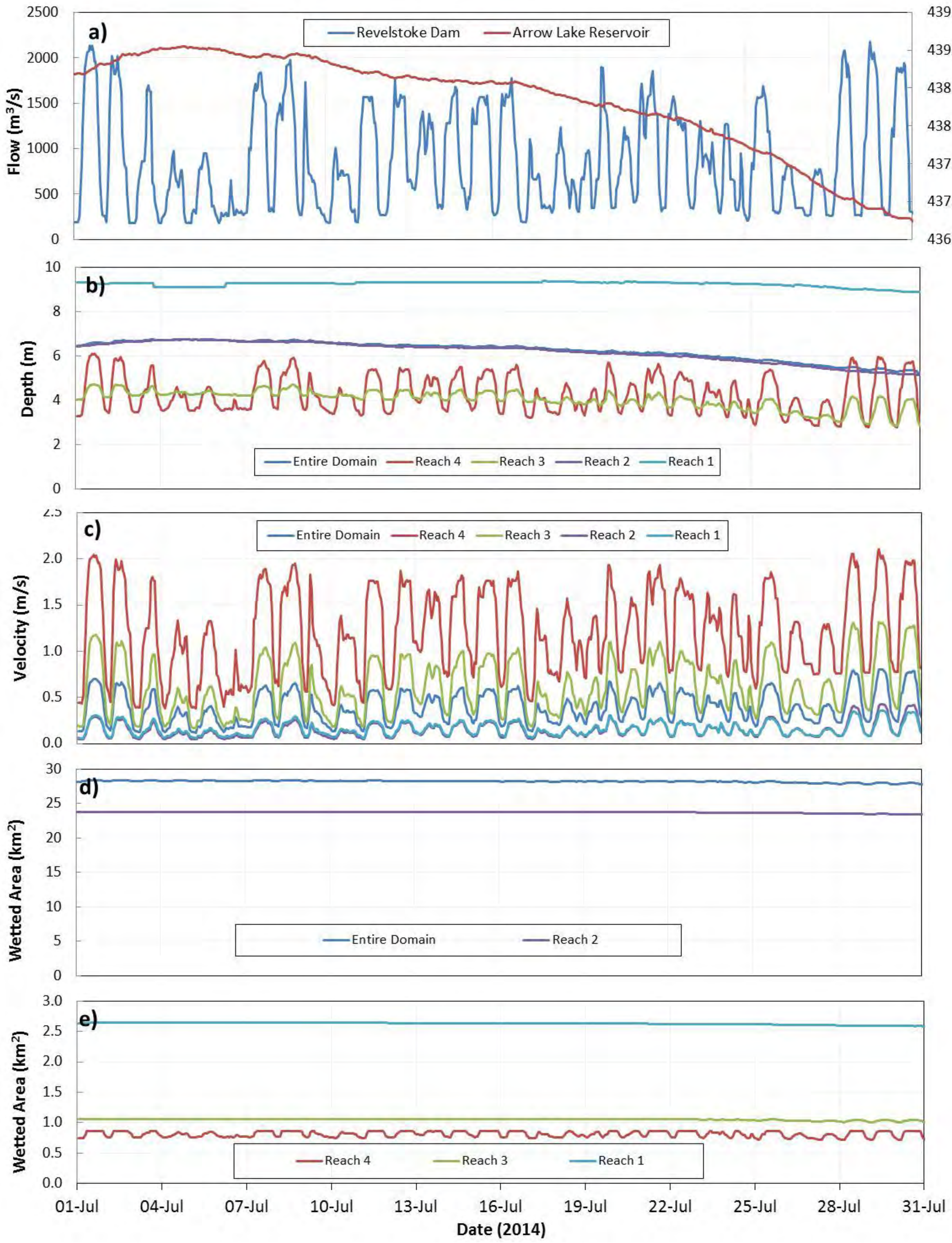


Figure 17 continued for the month of August 2014

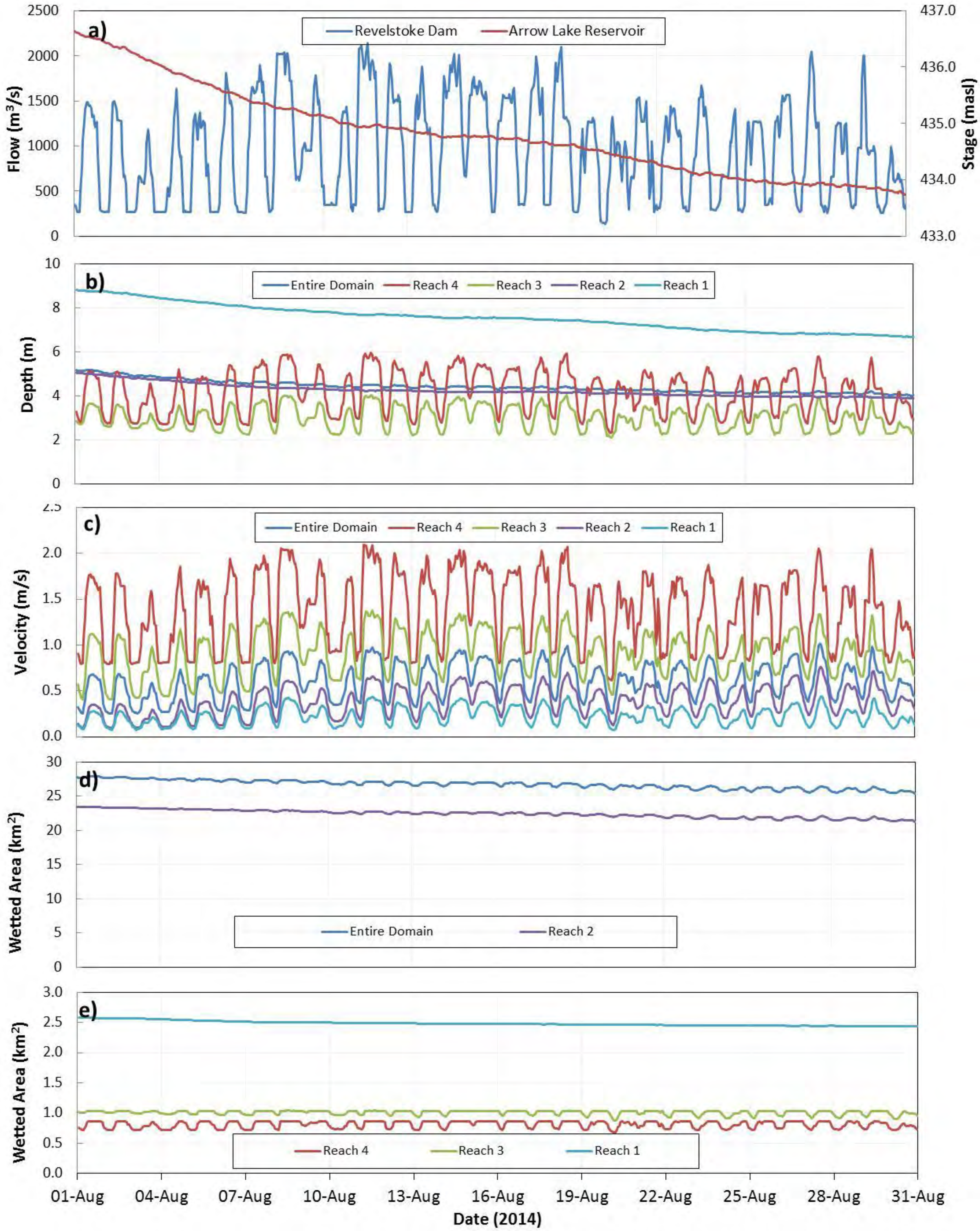


Figure 17 continued for the month of September 2014

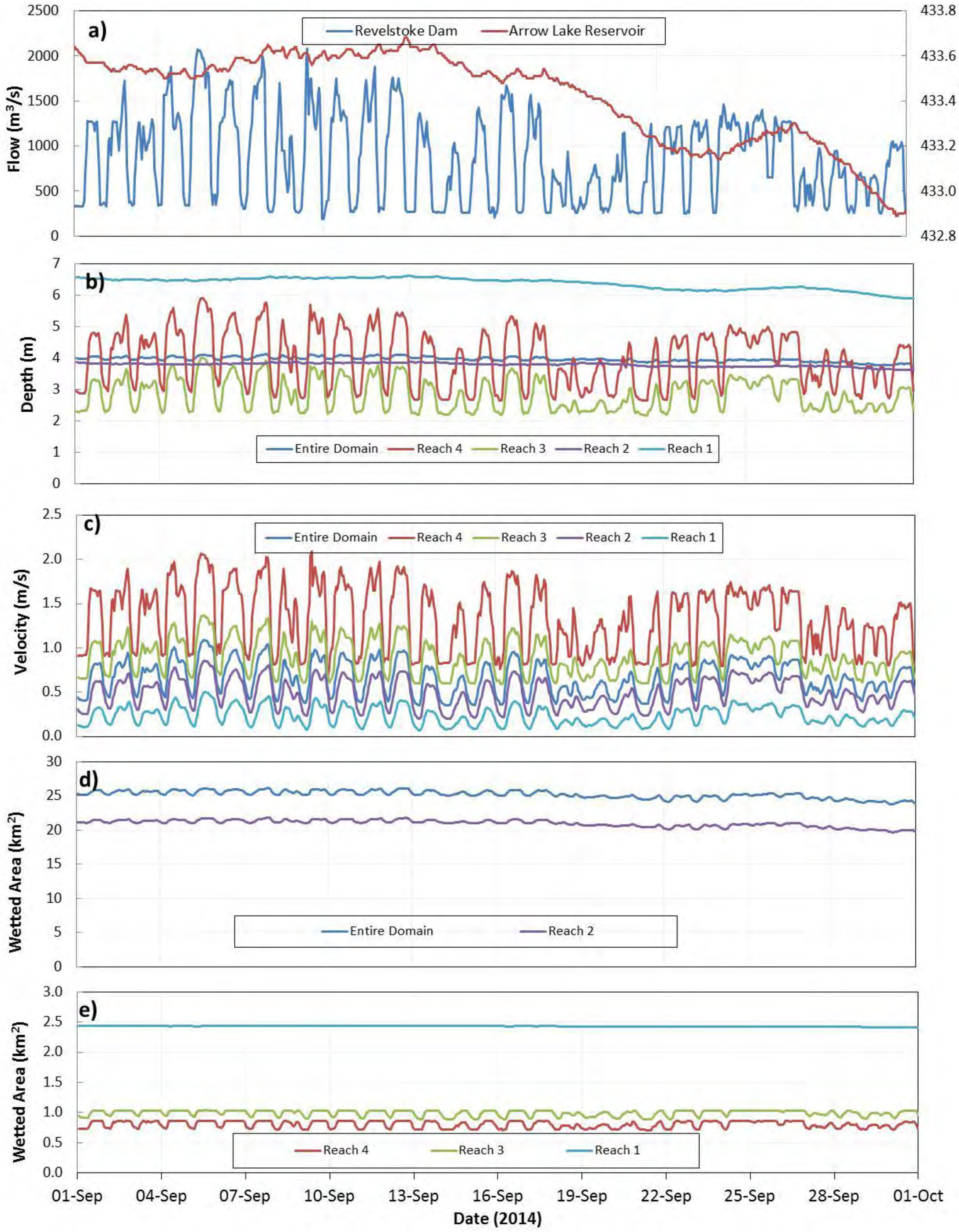
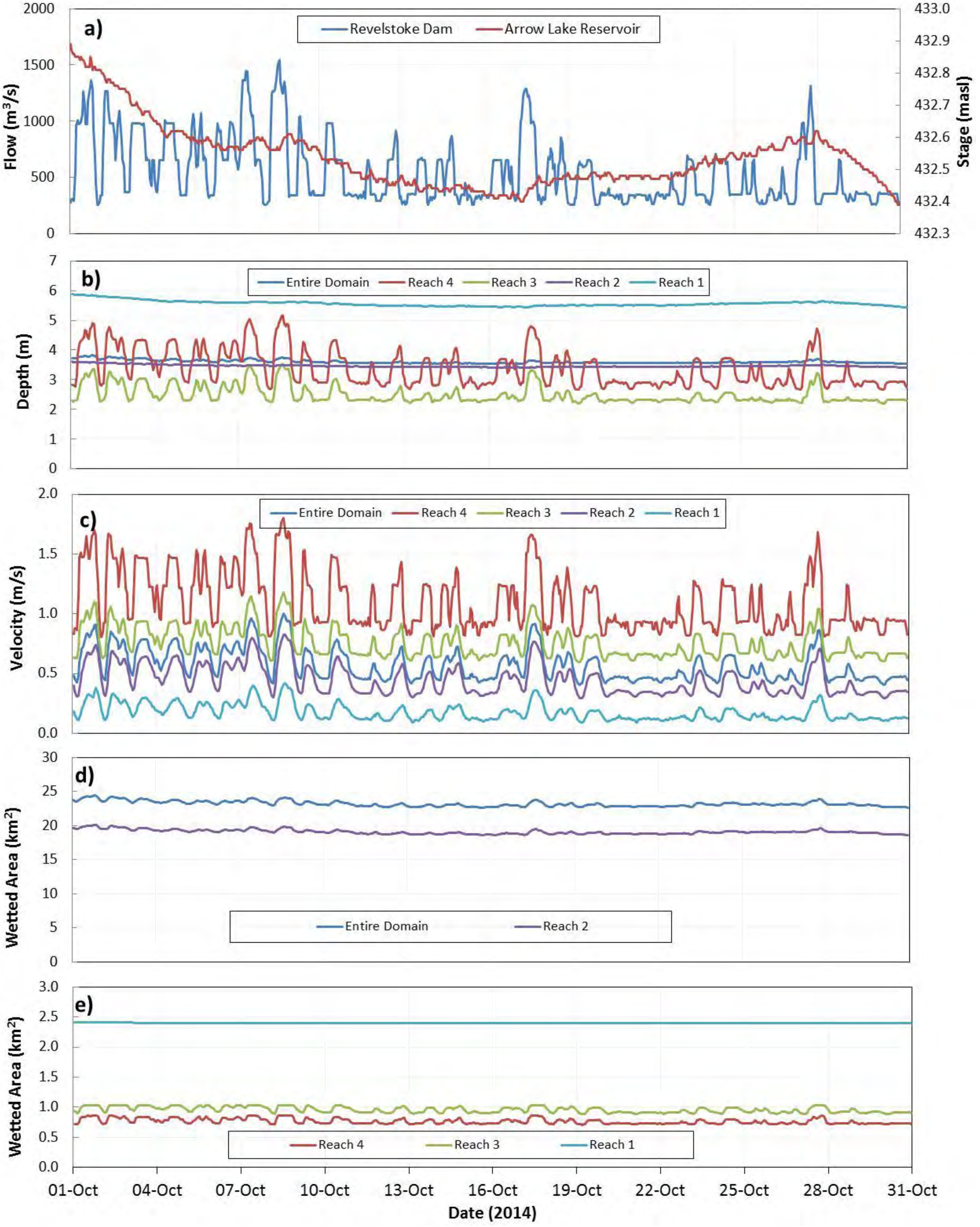


Figure 17 continued for the month of October 2014



APPENDIX F:
TABULAR REPRESENTATION OF THE 2013-2014 WETTED BED AREA, AVERAGE FLOW DEPTH, AND AVERAGE FLOW VELOCITY FOR THE REACHES OF THE MIDDLE COLUMBIA RIVER BY MONTH

Table 12 Wetted bed area, average flow depth, and average flow velocity for the reaches of the Middle Columbia River for November 06 to 30, 2013.

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	19.3	17.6	21.3	2.9	2.7	3.2	0.76	0.46	1.29
Reach 4	0.8	0.7	0.9	3.9	2.6	5.8	1.19	0.86	2.04
Reach 3	1.0	0.9	1.0	2.8	2.1	3.9	0.80	0.57	1.32
Reach 2	15.3	13.7	17.1	2.7	2.5	2.9	0.70	0.37	1.21
Reach 1	2.3	2.3	2.3	3.9	3.7	4.3	0.30	0.10	0.74

[1]For November 2013, the average, minimum, and maximum discharges of Revelstoke Dam were 805, 281, and 2109 m^3/s, respectively.

[2]The average, minimum, and maximum water levels in Arrow Lakes Reservoir were 431, 430.4, and 431.1 m, respectively.

Table 13 Wetted bed area, average flow depth, and average flow velocity for the reaches of the Middle Columbia River for December, 2013.

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	17.4	12.6	20.3	2.8	2.4	3.1	1.07	0.55	1.36
Reach 4	0.8	0.7	0.9	4.4	2.7	6.0	1.59	0.87	2.10
Reach 3	1.0	0.9	1.0	3.1	2.2	4.0	1.04	0.64	1.35
Reach 2	13.6	9.5	16.2	2.5	2.3	2.8	1.00	0.48	1.26
Reach 1	2.0	1.4	2.3	3.7	3.4	4.1	0.55	0.16	0.82

[1]For December 2013, the average, minimum, and maximum discharges of Revelstoke Dam were 1082, 187, and 2182 m^3/s, respectively.

[2]The average, minimum, and maximum water levels in Arrow Lakes Reservoir were 430, 428.8, and 430.9 m, respectively.

Table 14 Wetted bed area, average flow depth, and average flow velocity for the reaches of the Middle Columbia River for January, 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	13.3	9.9	17.6	2.6	2.1	3.0	1.16	0.62	1.53
Reach 4	0.8	0.7	0.9	4.2	2.6	5.9	1.50	0.81	2.11
Reach 3	1.0	0.9	1.0	3.0	2.2	4.0	0.99	0.59	1.37
Reach 2	10.2	7.2	14.2	2.3	1.9	2.6	1.15	0.61	1.46
Reach 1	1.3	1.1	1.5	3.6	3.1	3.9	0.79	0.23	1.27

[1]For January 2014, the average, minimum, and maximum discharges of Revelstoke Dam were 999, 256, and 2163 m^3/s, respectively.

[2]The average, minimum, and maximum water levels in Arrow Lakes Reservoir were 428, 427.1, and 428.9 m, respectively.

Table 15 Wetted bed area, average flow depth, and average flow velocity for the reaches of the Middle Columbia River for February, 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	14.2	10.5	18.0	2.7	2.2	3.1	1.38	0.82	1.64
Reach 4	0.8	0.7	0.9	4.5	2.7	6.0	1.64	0.80	2.10
Reach 3	1.0	0.9	1.0	3.1	2.2	4.1	1.09	0.62	1.40
Reach 2	11.0	7.6	14.4	2.4	2.0	2.7	1.38	0.86	1.59
Reach 1	1.3	1.1	1.7	3.6	3.1	3.9	1.25	0.45	1.73

[1] For February 2014, the average, minimum, and maximum discharges of Revelstoke Dam were 1140, 254, and 2164 m^3/s, respectively.

[2] The average, minimum, and maximum water levels in Arrow Lakes Reservoir were 428, 427.1, and 429.3 m, respectively.

Table 16 Wetted bed area, average flow depth, and average flow velocity for the reaches of the Middle Columbia River for March, 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	13.9	11.0	19.3	2.5	2.3	3.0	0.92	0.59	1.47
Reach 4	0.8	0.7	0.9	3.5	2.6	5.9	1.25	0.80	2.10
Reach 3	1.0	0.9	1.0	2.6	2.2	4.0	0.86	0.60	1.38
Reach 2	10.7	8.2	15.4	2.3	2.1	2.6	0.91	0.58	1.38
Reach 1	1.6	1.3	2.1	3.7	3.4	3.9	0.51	0.20	1.09

[1] For March 2014, the average, minimum, and maximum discharges of Revelstoke Dam were 656, 254, and 2155 m^3/s, respectively.

[2] The average, minimum, and maximum water levels in Arrow Lakes Reservoir were 429, 428.3, and 429.8 m, respectively.

Table 17 Wetted bed area, average flow depth, and average flow velocity for the reaches of the Middle Columbia River for April, 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	12.9	11.1	15.1	2.5	2.3	2.8	0.84	0.60	1.32
Reach 4	0.7	0.7	0.9	3.1	2.5	5.0	1.08	0.80	1.84
Reach 3	0.9	0.9	1.0	2.4	2.2	3.4	0.74	0.59	1.12
Reach 2	9.7	8.3	11.7	2.3	2.1	2.5	0.86	0.60	1.31
Reach 1	1.5	1.3	1.7	3.8	3.6	3.9	0.43	0.22	0.97

[1] For April 2014, the average, minimum, and maximum discharges of Revelstoke Dam were 455, 183, and 1,577 m^3/s, respectively.

[2] The average, minimum, and maximum water levels in Arrow Lakes Reservoir were 429, 428.3, and 429.3 m, respectively.

Table 18 Wetted bed area, average flow depth, and average flow velocity for the reaches of the Middle Columbia River for May, 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	19.9	13.7	26.1	3.1	2.4	4.1	0.71	0.51	1.14
Reach 4	0.8	0.7	0.9	3.6	2.4	5.9	1.00	0.65	1.77
Reach 3	1.0	0.9	1.0	2.6	2.1	4.0	0.70	0.53	1.13
Reach 2	15.9	10.4	21.8	2.9	2.2	3.9	0.69	0.49	1.10
Reach 1	2.2	1.7	2.4	4.5	3.4	6.7	0.28	0.16	0.62

[1] For May 2014, the average, minimum, and maximum discharges of Revelstoke Dam were 642, 134, and 2,044 m^3/s, respectively.

[2] The average, minimum, and maximum water levels in Arrow Lakes Reservoir were 431, 429.3, and 433.8 m, respectively.

Table 19 Wetted bed area, average flow depth, and average flow velocity for the reaches of the Middle Columbia River for June, 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	27.4	25.4	28.3	5.2	4.0	6.5	0.53	0.22	0.93
Reach 4	0.8	0.7	0.9	3.8	2.4	5.8	1.18	0.53	1.97
Reach 3	1.0	0.9	1.1	3.2	2.2	4.5	0.81	0.38	1.27
Reach 2	23.1	21.3	23.7	5.0	3.9	6.4	0.34	0.10	0.71
Reach 1	2.6	2.4	2.6	8.4	6.7	9.4	0.20	0.06	0.42

[1] For June 2014, the average, minimum, and maximum discharges of Revelstoke Dam were 690, 106, and 1,919 m^3/s, respectively.

[2] The average, minimum, and maximum water levels in Arrow Lakes Reservoir were 436, 433.8, and 438.7 m, respectively.

Table 20 Wetted bed area, average flow depth, and average flow velocity for the reaches of the Middle Columbia River for July, 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	28.2	27.7	28.3	6.2	5.2	6.8	0.36	0.12	0.70
Reach 4	0.8	0.7	0.9	4.3	2.8	6.1	1.13	0.39	2.04
Reach 3	1.0	1.0	1.1	4.0	2.8	4.7	0.55	0.17	1.18
Reach 2	23.7	23.4	23.8	6.1	5.1	6.7	0.13	0.05	0.29
Reach 1	2.6	2.6	2.7	9.2	8.8	9.4	0.15	0.05	0.31

[1] For July 2014, the average, minimum, and maximum discharges of Revelstoke Dam were 879, 177, and 2,173 m^3/s, respectively.

[2] The average, minimum, and maximum water levels in Arrow Lakes Reservoir were 438, 436.6 and 439.1 m respectively.

Table 21 Wetted bed area, average flow depth, and average flow velocity for the reaches of the Middle Columbia River for August, 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	26.7	25.2	27.8	4.4	4.0	5.2	0.56	0.25	0.97
Reach 4	0.8	0.7	0.9	4.1	2.3	6.0	1.37	0.79	2.10
Reach 3	1.0	0.9	1.0	3.0	2.1	4.0	0.88	0.41	1.38
Reach 2	22.4	21.1	23.4	4.2	3.9	5.1	0.32	0.09	0.66
Reach 1	2.5	2.4	2.6	7.5	6.6	8.8	0.22	0.08	0.43

[1] For August 2014, the average, minimum, and maximum discharges of Revelstoke Dam were 944, 141, and 2,140 m^3/s, respectively.

[2] The average, minimum, and maximum water levels in Arrow Lakes Reservoir were 435, 433.6, and 436.6 m, respectively.

Table 22 Wetted bed area, average flow depth, and average flow velocity for the reaches of the Middle Columbia River for September, 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	25.2	23.7	26.1	4.0	3.8	4.1	0.71	0.35	1.09
Reach 4	0.8	0.7	0.9	4.0	2.6	5.9	1.44	0.70	2.09
Reach 3	1.0	0.9	1.0	2.8	2.2	4.0	0.96	0.60	1.36
Reach 2	21.0	19.7	21.8	3.8	3.6	3.9	0.53	0.20	0.85
Reach 1	2.4	2.4	2.4	6.4	5.9	6.6	0.26	0.07	0.50

[1] For September 2014, the average, minimum, and maximum discharges of Revelstoke Dam were 863, 191, and 2,078 m^3/s, respectively.

[2] The average, minimum, and maximum water levels in Arrow Lakes Reservoir were 433, 432.9, and 433.7 m, respectively.

Table 23 Wetted bed area, average flow depth, and average flow velocity for the reaches of the Middle Columbia River for October, 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	23.2	22.6	24.4	3.6	3.5	3.8	0.64	0.42	1.00
Reach 4	0.8	0.7	0.9	3.4	2.7	5.2	1.22	0.81	1.80
Reach 3	1.0	0.9	1.0	2.5	2.2	3.5	0.82	0.61	1.18
Reach 2	19.1	18.5	20.1	3.0	2.2	3.6	0.50	0.30	0.83
Reach 1	2.4	2.4	2.4	5.6	5.4	5.9	0.21	0.09	0.42

[1] For October 2014, the average, minimum, and maximum discharges of Revelstoke Dam were 564, 254, and 1,544 m^3/s, respectively.

[2] The average, minimum, and maximum water levels in Arrow Lakes Reservoir were 433, 432.4, and 432.9 m, respectively.

Table 24 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 25 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