Columbia River Project Water Use Plan

LOWER COLUMBIA RIVER FISH

Reference: CLBMON-44

Lower Columbia River Physical Habitat and Ecological Productivity Monitoring – Modelling Updates

Study Period: 2019 - 2020

Ecoscape Environmental Consultants Ltd.
#102-450 Neave Court
Kelowna, BC V1V 2M2

December 2020

Lower Columbia River Fish

Monitoring Program No. CLBMON-44

Lower Columbia River Physical Habitat and Ecological Productivity – Modelling Updates

2019 - 2020 Summary Report

Prepared for

BC Hydro Generation
Water Licence Requirements

6911 Southpoint Drive
Burnaby, BC

BC Hydro Reference # C0007721800005

Prepared by

Ecoscape Environmental Consultants Ltd.

Technical Contact: Mary Ann Olson-Russello, M.Sc., R.P.Bio.
mao@ecoscapeltd.com, 250-491-7337 x205

December 10, 2020

Suggested Citation:

Plewes, R., R. Wagner and M.A. Olson-Russello. CLBMON-44 Lower Columbia River Physical Habitat and Ecological Productivity Monitoring – Modelling Updates (Study Period 2019 - 2020). Unpublished report by Ecoscape Environmental Consultants Ltd. for BC Hydro Generations, Water License Requirements, Burnaby, B.C. 27 pp + Appendix 1.

Cover photos:

From left to right: 2017 Genelle; 2016 winter deployment (S7); 2019 bathymetry survey; 2018 spring deployment (S2)

EXECUTIVE SUMMARY

Discharges from the Hugh L. Keenleyside (HLK) Dam during winter and spring have the potential to affect salmonid spawning and rearing habitats. To minimize impacts, BC Hydro altered operations of HLK Dam to include: 1) rainbow trout protection flows which stabilize or increase HLK discharges from April 1 through June 30, to reduce redd dewatering and subsequent egg loss of rainbow trout, and 2) mountain whitefish flows which limit maximum discharges during peak spawning in January and later stabilizes discharges to reduce egg dewatering until mountain whitefish emerge in late March (BC Hydro 2007). The objective of CLBMON-44 was to examine the influence of the managed flow periods (Mountain Whitefish (MWF) Jan 1 - Mar 31; and Rainbow Trout (RBT) Apr 1 - Jun 30; and a control fall fluctuating flow (FFF) Sep 1 - Oct 31) on select physical habitat components and ecological productivity measures.

Despite the implementation of RBT protection flows, it was unclear as to how these flows have affected the local RBT population abundance (BC Hydro 2018). To reduce uncertainty, an experimental approach where RBT protection flows would be turned ON and OFF in alternating years was initiated in 2019 (e.g. no RBT protection flows in 2019, but protection flows in 2020) for a maximum duration of five years, until 2023. The objective of this two-year study was to assess how the RBT protection flows (ON) or lack there of (OFF), may affect the ecological productivity of Norns Creek fan, an important spawning and rearing habitat for RBT.

Water elevation, water temperature, light intensity, turbidity and bathymetric data were collected in 2019 and 2020. The level logger and bathymetric data allowed for the creation and calibration of a hydraulic model using Telemac-2D software. Light intensity and turbidity data were collected to determine if light was a limiting factor for periphyton productivity in the Norns Creek fan. The hydraulic model required hourly WQIS3 elevations and HLK discharge. An incomplete WQIS3 level logger dataset was available from 2008-2020. As a result, hourly Birchbank flows were used to predict WQIS3 elevations for missing data.

Invertebrate dry biomass and chl-a were predicted with productivity models that used the hourly depths from the TELEMAC-2D model and growth/colonization and death curves for invertebrates and periphyton that were derived during previous Columbia Power Corporation productivity studies. The total invertebrate and periphyton production of the Norns Creek fan on June 30th were compared for six OFF years (1988-1991, 2019-2020) and seven ON years (1999, 2003-2005, 2010, 2014, 2016). Due to low statistical power from a small sample size (i.e. limited years) a significance level of 0.1 was used.

Typical RBT flow management resulted in more stable flows throughout May and June which maintained a larger wetted habitat area in the Norns Creek fan. A larger wetted habitat area resulted in a greater area available for invertebrate colonization and periphyton growth. Less substrate dewatering also reduced the mortality of invertebrates and periphyton. RBT flow management had a slightly larger benefit on invertebrate productivity compared to periphyton, likely because invertebrates are more sensitive to substrate dewatering and have slower spring recovery rates than periphyton. During ON RBT flow years invertebrate biomass was significantly higher (25%) than the invertebrate biomass during OFF years (2-sample *t*-

test; t = 2.24, *P*-value = 0.02). The ON RBT flow years also had chl-a values that were significantly higher (17%) than OFF RBT years (2-sample *t*-test; t = 1.87, *P*-value = 0.04), assuming a significance level of 0.1. We suspect that the inclusion of more ON and OFF RBT years would likely result in a statistical difference at 0.05.

Before the management of RBT flows, flows were highly variable and as a result more OFF years should be included in the productivity model. Highly variable flows resulted in a wider range of invertebrate and periphyton production. The addition of more OFF years will result in a more accurate estimate of production during OFF years. Due to data limitations, it was not possible to model productivity for 1984-1987. However, assuming flow management will continue with alternating ON and OFF years, additional OFF years will occur in 2021 and 2023. After spring of 2023, the productivity models could be updated with these additional years, and ON and OFF RBT year comparisons reanalyzed. In 2023, it would also be prudent to model productivity for more ON years to increase statistical power.

ACKNOWLEDGEMENTS

Ecoscape would like to express our appreciation of Phil Bradshaw, Teri Neighbour and Dr. Guy Martel, of BC Hydro, who have provided administrative guidance and scientific oversight.

Report Authorship
Rachel Plewes, M.Sc., (Ecoscape)
Mary Ann Olson-Russello, M.Sc., R.P.Bio. (Ecoscape)

Project Management / Review:
Mary Ann Olson-Russello, R.P.Bio. (Ecoscape)

Field Team:
Kyle Hawes, R.P.Bio. (Ecoscape)
Robert Wagner, B.Sc. (Ecoscape)

GIS and Data Analysis:
Rachel Plewes, M.Sc., (Ecoscape)
Robert Wagner, B.Sc. (Ecoscape)
Luke Crevier, B.Sc. (Ecoscape)
Dr. Joe Thorley (Poisson Consulting Ltd.)

TABLE OF CONTENTS

LIST OF FIGURES AND TABLES

LIST OF APPENDIX TABLES

1.0 INTRODUCTION

A twelve-year study of the physical habitat and ecological productivity on the Lower Columbia River (LCR) (CLBMON-44), between the outflow of the Hugh L. Keenleyside (HLK) Dam and the Birchbank gauging station (BBK) near the southern British Columbia border was finalized in 2019. A final summary report of hydrological and benthic productivity data collected between 2008 and 2019 was issued to BC Hydro and Power Authority (BC Hydro) in August 2019 (Olson-Russello et al. 2019).

Discharges from the HLK Dam during winter and spring have the potential to affect salmonid spawning and rearing habitats. To minimize impacts, BC Hydro altered operations of HLK Dam to include: 1) rainbow trout protection flows which stabilize or increase HLK discharges from April 1 through June 30, to reduce redd dewatering and subsequent egg loss of rainbow trout, and 2) mountain whitefish flows which limit maximum discharges during peak spawning in January and later stabilizes discharges to reduce egg dewatering until mountain whitefish emerge in late March (BC Hydro 2007).

The objective of CLBMON-44 was to examine the influence of the managed flow periods (Mountain Whitefish (MWF) Jan 1 - Mar 31; and Rainbow Trout (RBT) Apr 1 - Jun 30; and a control fall fluctuating flow (FFF) Sep 1 - Oct 31) period on select physical habitat components and ecological productivity measures. Benthic productivity, inclusive of periphyton and benthic invertebrates, are a primary food source for fish. Physical habitat components are important variables that influence the benthic productivity of a river.

The Physical Habitat component involved monitoring water temperature, stage, electrochemistry and nutrient levels in LCR to allow tracking of potential changes in physical habitat and ecological health due to flow conditions. The Ecological Productivity component involved monitoring periphyton and benthic invertebrates to assess potential changes in trophic productivity and overall ecological health of LCR resulting from the continued implementation of MWF, RBT and FFF (BC Hydro, 2005a,b).

Despite the implementation of RBT protection flows, it is unclear as to how these flows have affected the local RBT population abundance (BC Hydro 2018). To reduce uncertainty, an experimental approach where RBT protection flows would be stopped and re-implemented in alternating years was initiated in 2019 (e.g. ON and OFF RBT protection flows) for a maximum duration of five years, until 2023.

The objective of this 2-year extension contract is to assess how the RBT protection flows (ON) or lack thereof (OFF), may affect the ecological productivity of Norns Creek fan, an important spawning and rearing habitat for RBT. Because the lack of RBT protection flows are likely to generate increased variability in water levels, there is a potential for altered primary production. To address this question, the following work plan was developed:

- Continue the maintenance and collection of water level stage data for all pre-established sampling locations in 2019 and 2020;
- Undertake a bathymetric survey of LCR between water level loggers S2 and S3 (inclusive of Norns Creek fan);
- Develop a hydraulic model for the area using Telemac-2D software;

- Utilize the historic water elevation data at S2 and S3 to calibrate the hydraulic model; and
- Produce a productivity model to quantify total productivity estimates of invertebrate biomass and chlorophyll-a of the Norn's Creek fan when RBT protection flows were ON and OFF.

2.0 STUDY AREA

The study area is on LCR downstream of HLK Dam near Castlegar, BC at the confluence with Norns Creek (Figure 2-1). Water quality index station 2 (WQIS2) is located approximately 1 km upstream of Norns Creek, and WQIS3 is about 800 m downstream of Norns Creek. The hydraulic model extent is inclusive of the whole river between WQIS2 and 3. The productivity model extent only includes the Norns Creek fan where Rainbow Trout redds have been documented (Figure 2-1).

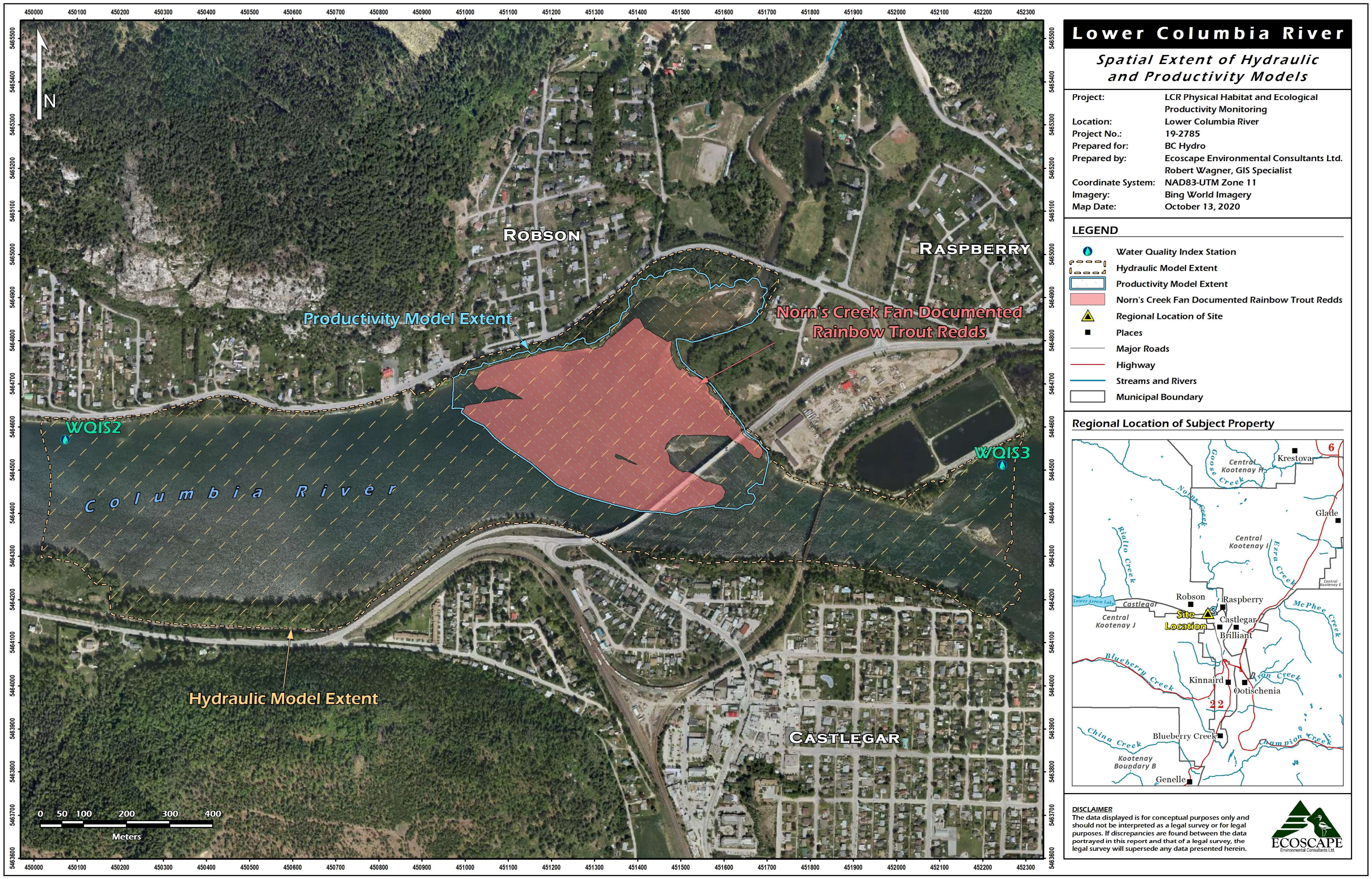

Figure 2-1: **Map of the Lower Columbia River study area.**

3.0 METHODS

3.1 Water Level Logger Data Download and Maintenance

Level loggers that were installed as part of the CLBMON-44 program (Olson-Russello et al. 2019), were left in place and data was downloaded three times in 2019 and in April and July in 2020. There are five LCR water quality index stations (WQIS1-5) on LCR and a single station on Kootenay River (WQC2) (Table 3-1). Physical parameters collected included water temperature and water elevation or stage data.

Table 3-1: Monitoring Stations, Sample Types and UTM Coordinates (UTM 11).

Station Name & General Location	Station Characteristics	Sample Type	UTM Coordinates	
			Northing	Easting
WQIS1 (across from Zellstoff Celgar Ltd.)	Upstream of Celgar outfall	Water temperature/water elevation	5,465,742	445,693
WQIS2 (upstream of boat launch)	Downstream of Celgar outfall	Water temperature /water elevation	5,464,573	450,072
WQIS3 (downstream of railway bridge)	Within back channel area	Water temperature /water elevation	5,464,517	452,244
WQIS4 (~7 km downstream of Kootenay River confluence)	Left bank off of bedrock face	Water temperature /water elevation	5,455,332	452,653
WQIS5 (~ 2.2 km upstream of Birchbank)	Right bank off of bedrock face	Water temperature /water elevation	5,450,221	448,514
WQ C2 (Kootenay River)	Right bank, off of bedrock face	Water temperature /water elevation	5,462,911	454,114

3.2 Bathymetric Survey

Ecoscape completed a bathymetric survey of LCR between WQIS2 and WQIS3 on June 6-7, 2019. A multibeam sonar and real time kinemetric (RTK) GPS base station was used to scan the bottom of the riverbed and relate it to the real-world location. Ecoscape used a multibeam system that collects point data in a swath as a function of depth. The sounder was set at an 8:1 ratio which allowed an 8-meter-wide swath for every 1 metre of water depth with at least a 50% overlap of coverage. This setup facilitated the collection of an extremely dense point cloud in a time efficient manner. Unfortunately, the day before the survey, water levels dropped by approximately 1 metre, which limited our ability to collect data in shallow water.

Our intention was to use LIDAR to infill the shallow water and land portion of the survey; however, when trying to get access to LIDAR data, the Province indicated that it would not be available in the short-term. Because it was anticipated that the model creation and simulation time would be a time constraint, it was decided to complete a second survey to fill in the bathymetric data gaps and the topographic component. The second survey was conducted on July 30-31, 2019. This survey was completed using a single beam sonar to record riverbed elevations and a RTK base station to integrate it to the first survey. The single beam sonar was chosen, as there was no benefit to the more expensive multibeam setup when surveying in very shallow water (1-2 metres). During this survey the water depth was much higher and coverage of the entire Norn's Creek fan and many of the gravel bars were surveyed with the bathymetric setup. The remaining topographic data was collected on foot using a RTK Rover connected to the common GPS base station.

3.3 PAR and Turbidity Profiles

On October 10, 2019 and July 16, 2020, photosynthetic active radiation (PAR) or light intensity, was measured at WQIS2, WQIS3, Robson boat launch and at shallow and deep sites in the Norns Creek fan. Measurements were taken at the surface and at 50 cm intervals throughout the water column using a PAR metre. *In situ* turbidity was simultaneously measured at each interval to determine the continuous light attenuation coefficient based on turbidity. The profiles extended to depths that ranged of 2- 9.5 m at the five sites.

3.3.1 Light Analysis

The light intensity, PAR and turbidity data for the five sites was used to model light attenutation and estimate the depth of the photic zone for the Norns Creek Fan study area. To model light availability, model parameters were estimated using Bayesian estimates that were produced using STAN (Carpenter et al. 2017). Refer to McElreath (2016) for additional information on Bayesian estimation. Unless otherwise indicated, the Bayesian analyses used normal and uniform prior distributions that were vague in the sense that they did not constrain the posteriors (Kery and Schaub 2011, 36). The posterior distributions were estimated from 1500 Markov Chain Monte Carlo (MCMC) samples thinned from the second halves of 3 chains (Kery and Schaub 2011, 38–40). Model convergence was confirmed by ensuring that the potential scale reduction factor $\hat{R} \leq 1.05$ (Kery and Schaub 2011, 40) and the effective sample size (Brooks et al. 2011) $\mathrm{ESS} \geq 150$ for each of the monitored parameters (Kery and Schaub 2011, 61).

The parameters are summarized in terms of the point estimate, standard deviation (sd), the z-score, lower and upper 95% confidence/credible limits (CLs) and the p-value (Kery and Schaub 2011, 37, 42). The estimate is the median (50th percentile) of the MCMC samples, the z-score is $\mathrm{mean}/\mathrm{sd}$ and the 95% CLs are the 2.5th and 97.5th percentiles. A p-value of 0.05 indicates that the lower or upper 95% CL is 0.

Model adequacy was confirmed by examination of residual plots for the full model(s).

The results were plotted with the modeled relationships between variables and the response(s) with the remaining variables held constant. In general, continuous and discrete fixed variables were held constant at their mean and first level values, respectively, while random variables were held constant at their typical values (expected values of the underlying hyperdistributions) (Kery and Schaub 2011, 77–82). When informative, the influence of variables was expressed in terms of the effect size (i.e. percent change in the response variable) with 95% confidence/credible intervals (CIs, Bradford, Korman, and Higgins 2005).

The analyses were implemented using R version 4.0.2 (R Core Team 2020) and the mbr family of packages.

The attenuation of light with water depth has been well-studied (Julian et al. 2008). The following equation captures the relationship between the irradiance at the surface (E_s) and the irradiance at depth (E_d)

$$E_d = E_0 \cdot \exp(-K_d \cdot y)$$

where E_0 is the initial irradiance, E_d is the irradiance at distance y and K_d is the diffuse attenuation coefficient (Julian, Doyle, and Stanley 2008).

The light attenuation model was used to calculate the euphotic zone depth ($z_{1\%}$) which is defined as the depth at which photosynthetic available radiation (PAR) is 1% of its surface value.

It is given by the equation

$$y = \frac{\log(100) - \log(1)}{K_d}$$

which simplifies to

$$y = \frac{4.6}{K_d}$$

3.4 Hydraulic Model Development

TELEMAC-2D is a hydraulic modelling software that provides water depth and velocity for each discrete model cell. Saint-Venant equations are used with the finite-element method and a computation mesh to model depth and velocity based on discharge (NHC 2016). The computation mesh is usually generated from bathymetric data. The implementation of a TELEMAC-2D model requires a mesh, model parameters, discharge and elevation data for the area of interest.

The mesh for the TELEMAC-2D model was generated by processing the bathymetric survey data in ArcGIS and BlueKenue. ArcGIS was used to clean the points collected from the survey and generate a raster with a 0.5 metre resolution. A 0.5 metre point cloud of the bathymetric and topographic elevations was generated from the raster to be imported into Blue Kenue. Blue Kenue was developed by the National Research Council of Canada and is used for model data preparation, simulation results analysis, visualization and animation. The resulting mesh with 7,183 nodes and 13,709 elements was used in TELEMAC-2D for the model simulation.

The TELMAC-2D model requires hourly discharge data and elevation from the downstream limits of the model. Model simulations were run on individual months and required hourly discharge data from HLK Dam and hourly elevations from the WQIS3 level logger. When WQIS3 logger data was un-available, a discharge and elevation relationship from existing data was used to predict hourly elevations at WQIS3.

Default model parameters were used for the TELEMAC-2D, except for Manning's n. Manning's n values represent the roughness of the channel which corresponds to channel bottom friction applied to flow. Model calibration was run to determine the most suitable Manning's n during the RBT flow period (Apr 1 – Jun 30). Calibration of the TELEMAC-2D model required the selection of years that had a typical range of discharges during the RBT flow period. To calibrate the model, April 2010 and 2012, and June 2015 and 2017 were run with four different Manning's n values: 0.046, 0.048, 0.050, and 0.052. Only April and June were selected for calibration because these months contained the minimum and maximum flows of the RBT period. The TELEMAC-2D predicted elevations, at WQIS2 and WQIS3, were compared to the logged elevations using each model simulation with a different Manning's n. A Manning's n of 0.048 was determined to be the most suitable, as the simulated water levels aligned most closely to logged levels at WQIS2 and WQIS3.

3.4.1 Predicting WQIS3 Elevation

The elevation at the WQIS3 was a required input for the hydraulic model and this data was only available for some ON RBT years (2008-2018) and two OFF RBT years (2019-2020). The hourly discharge at Birchbank, a real-time hydrometric station (08NE049) on the Columbia River downstream of the Kootenay River confluence, was required to accurately predict WQIS3 elevations because backwatering from the Kootenay River influenced the elevation of the WQIS3 logger in May and June. Unfortunately, Birchbank hourly discharge data was only available from May 1987 onwards. As a result, only six OFF RBT years had elevation at the WQIS3 measured or predicted (1988-1991 and 2019-2020).

The following ON RBT years were included: 1999, 2003, 2004, 2005, 2010, 2014, 2016. These seven years were selected because they were representative of a range of ON RBT HLK operations, but excluded extreme flow years greater than 1,500 m^3/s. If recorded WQIS3 elevations were available for the ON RBT years, they were used. However, for most of the ON RBT selected years, complete WQIS3 elevations were not available, so the elevations were predicted using Birchbank hourly discharge data.

Due to limits in WQIS3 elevation data availability from 1988-2008, flow measurements from Birchbank were obtained from the Environment and Climate Change Canada Real-time Hydrometric Data web site [https://wateroffice.ec.gc.ca/mainmenu/real_time_data_index_e.html] on May 5, 2020) and a linear regression model was used to predict elevation values for the time period of interest.

To fit the model, we used training data from April, May, and June from 2009, 2010, 2012, 2014, 2015, 2017, 2018, and 2019. We omitted June 2015 from the training dataset since abnormal mean discharge values from the HLK dam indicated an outlier year that could bias the model output. Flows at Birchbank significantly predicted WQIS3 elevation according to the formula: 0.011 × Birchbank + 416 Adjusted $R^2 = 0.966$, $p < 0.001$ (Figure 3-1).

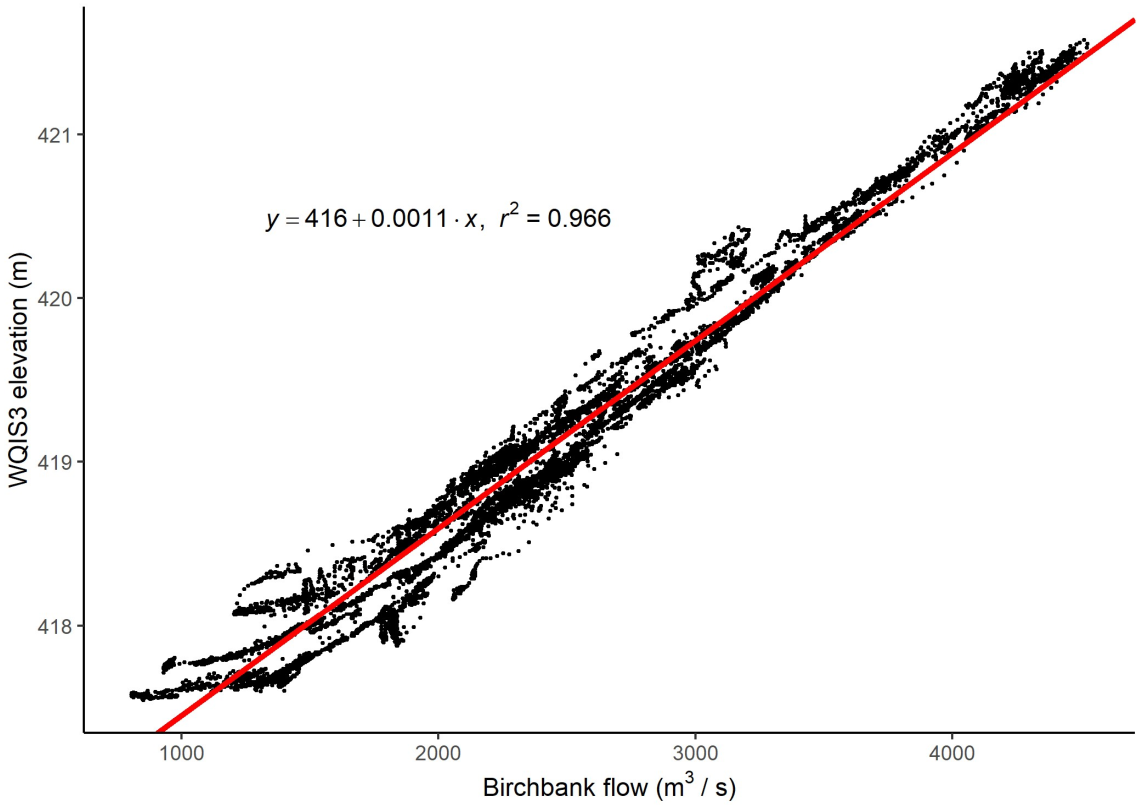

Figure 3-1: Scatter plot of elevation at WQIS3 by flow (m^3/s) at Birchbank for model training date/time intervals of interest. Solid red line indicates fitted linear regression. Data from April, May, and June from 2009, 2010, 2012, 2014, 2015, 2017, 2018, and 2019.

3.4.2 Flow Metrics

To better understand the variance in RBT operations, flow metrics were calculated for the RBT flow period on mean daily discharge from HLK and hydrographs were created. Coefficient of variation, maximum, minimum, median and mean daily flows for each RBT flow period from 1984-2020 were calculated. Hydrographs on mean HLK daily flows from April 1st to June 30th were created for the six OFF-RBT years and the seven ON-RBT years used in the model. Additionally, the hydrographs of all ON and OFF-RBT years were created to better understand the range of operations.

3.5 Productivity Model Development

Chlorophyll-a (chl-a) and invertebrate dry weight (biomass) were selected as metrics to model periphyton and benthic invertebrate productivity because these metrics have the most accurate growth curves (Schleppe et al. 2013). Growth curves for invertebrate dry weight and periphyton chl-a were originally derived for the Columbia Power Corporation by sampling these parameters at 6, 12, 24, 48 and 64 days of incubation on the lower Columbia and Kootenay rivers (Schleppe et al. 2013).

Invertebrate dry biomass and chl-a were predicted with productivity models that used the hourly depths from the TELEMAC-2D model and growth/colonization and death curves for invertebrates and periphyton that were derived during the previous Columbia Power Corporation productivity studies (Schleppe et al. 2013; Schleppe et al. 2015).

The invertebrate and chl-a production models were run separately for each selected RBT flow period (1988-1991, 1999, 2003-2005, 2010, 2014, 2016, 2019, and 2020). The invertebrate dry biomass and periphyton chl-a started at the minimum values of 1 mg/m^2 and 0.05 µg/cm^2 on April 1st at 0:00, respectively. The total productivity estimates in kg at the end of RBT flow period were estimated by taking the total production on June 30th at 12:00.

The total productivity estimates of invertebrate dry biomass and chl-a were compared between years when RBT protection flows were ON or OFF. A boxplot was used to visually compare the ON- and OFF-RBT years. A one-sided two-sample t-test was used to determine if chl-a and invertebrate biomass were higher during OFF years compared to ON-RBT flow years. Due to the small sample size (i.e. limited number of years) a significance level of 0.1 was used to increase the statistical power of the test (n_{OFF}= 6, n_{ON}= 7). With a large effect size, the power of the t-test was 0.54, meaning there was a 54% chance of detecting a true effect. The Shapiro-Wilk test and Levene's test were performed to confirm the assumptions of normal and equal variance of sample groups.

Power analysis was conducted in G*Power 3.1.9.2 (Faul et al. 2014) for the t-test used in this study and future one-tailed two sample t-tests that would be conducted once more data is collected.

3.6 Datasets

The primary data collected or generated as part of the CLBMON-44 modelling updates is summarized in Table 3-2.

Table 3-2: Datasets used or generated as part of the CLBMON-44 Modelling Updates.

Name/Description	Source	Frequency of Collection
Physical Datasets		
LCR / Kootenay River Elevation / Water Temperature	Data collected at 5 stations (LCR) and 1 station (Kootenay River)	3-4 times annually
Hourly Discharge at Hugh L. Keenleyside (HLK) and Birchbank (BBK)	Data obtained from Poisson Consulting	Continuous
Light Intensity, turbidity and depth profiles	Field data	Collected once in 2019 and 2020
Bathymetric survey data	Bathymetric and topography survey of the study area	Multiple days in summer of 2019
Hourly depths for 1 m cells	TELEMAC-2D model	April- June 1988-1991, 1999, 2003-2005, 2010, 2014, 2016, 2019, 2020
Daily chl-a and invertebrate dry weight estimates by 1 m cell	Productivity model	April- June 1988-1991, 1999, 2003-2005, 2010, 2014, 2016, 2019, 2020
June 30th total chl-a and invertebrate dry weight estimates	Productivity model	June 30th 1988-1991, 1999, 2003-2005, 2010, 2014, 2016, 2019, 2020

4.0 RESULTS AND DISCUSSION

4.1 Mean Daily Water Levels

This report includes water level elevation data collected between Jan - Jul 2020. The logger at WQ1S1 malfunctioned and unfortunately the data for 2019 and 2020 was not accurate, and therefore has not been included (Figure 4-1). The level loggers in use have been deployed since 2008 and several of them have needed replacement batteries and have exhibited issues with accurate data collection. As concerns arose, the loggers were sent back to the manufacturer for repair and/or battery replacement. We are now observing that recently repaired loggers are beginning to fail for a second time, likely indicating that their life span is limited.

The other level loggers collected accurate data in 2019 and 2020, and Figure 4-1 illustrates the variability at each site compared to the mean daily water levels during previous years.
In June 2020, mean water levels at all LCR level loggers had a large drop from June 1st to June 15th, followed by a substantial increase in water levels from mid-June to early July (Figure 4-1). The decreasing and increasing water levels in June, resulted in 2020 being managed as an OFF RBT year, despite the initial intention for 2020 to be an ON RBT year.

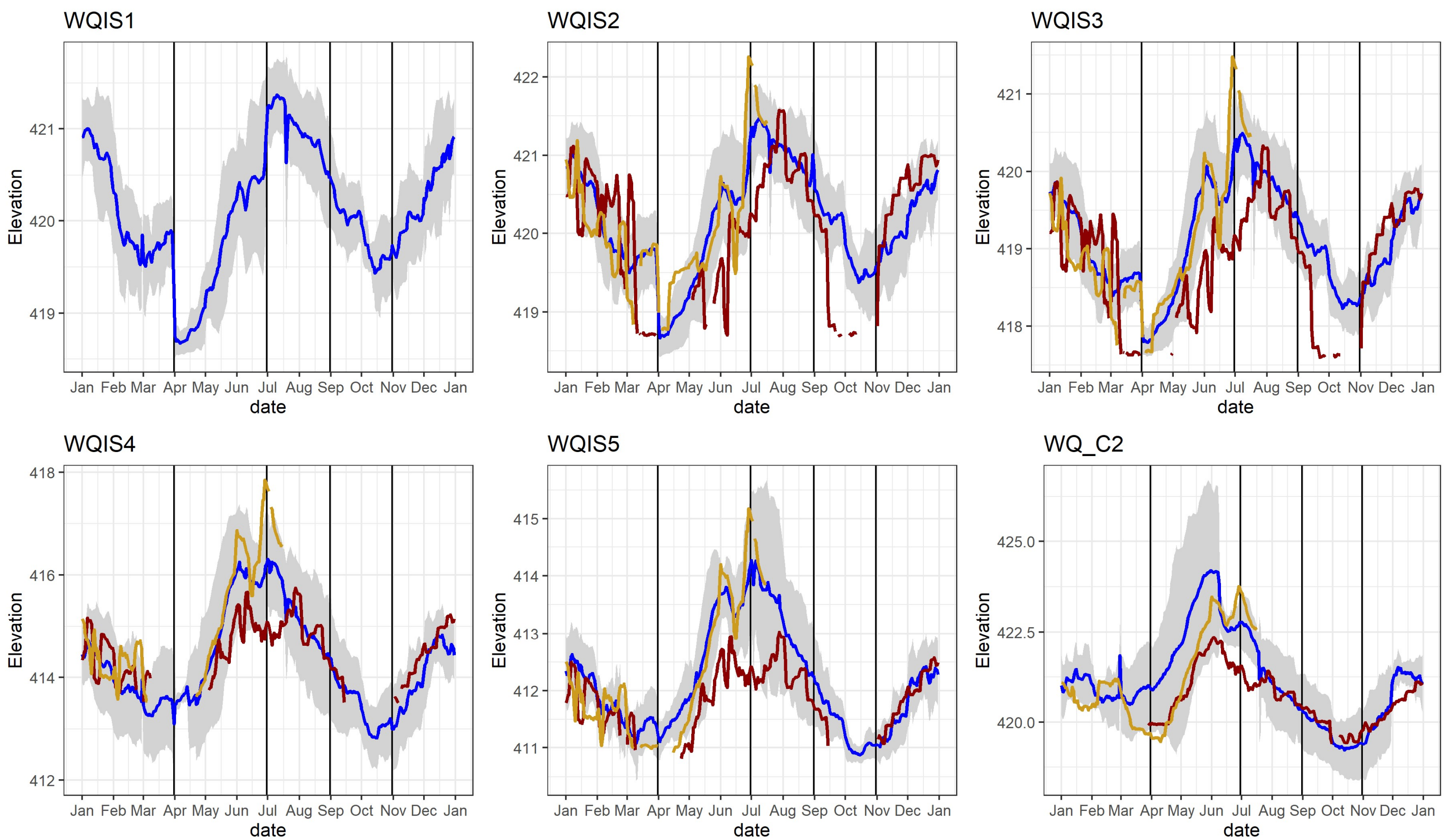

Figure 4-1: Mean daily water levels recorded at WQIS1 – 5 on LCR and at WQ C2 on Kootenay River. The red line depicts the mean daily water level recorded at each site in 2019 and the golden line depicts mean water levels in 2020. The blue line is the mean daily water level throughout the duration of the study for LCR sites (2008-2020 ± SD (gray shaded area)) and for an nine-year duration at the Kootenay River site (2011 –2020 ± SD (gray shaded area)). The SD is shown to highlight the variation in the data over multiple years, but it could not be determined for all months due to gaps in the data.

4.2 Mean Daily Water Temperature

The 2020 mean daily water temperatures were lower than the 2019 daily water temperatures at all LCR level loggers (Figure 4-2). WQIS2 and WQSI3 had lower water temperature in May 2020 relative to the average water temperature for ON-RBT years. May and June 2020 also had lower water temperatures at WQIS4 and WQIS5 compared to typical water temperatures for ON-RBT years. The low June 2020 water temperatures were likely influenced by the low June water temperatures in the Kootenay River (Figure 4-2).

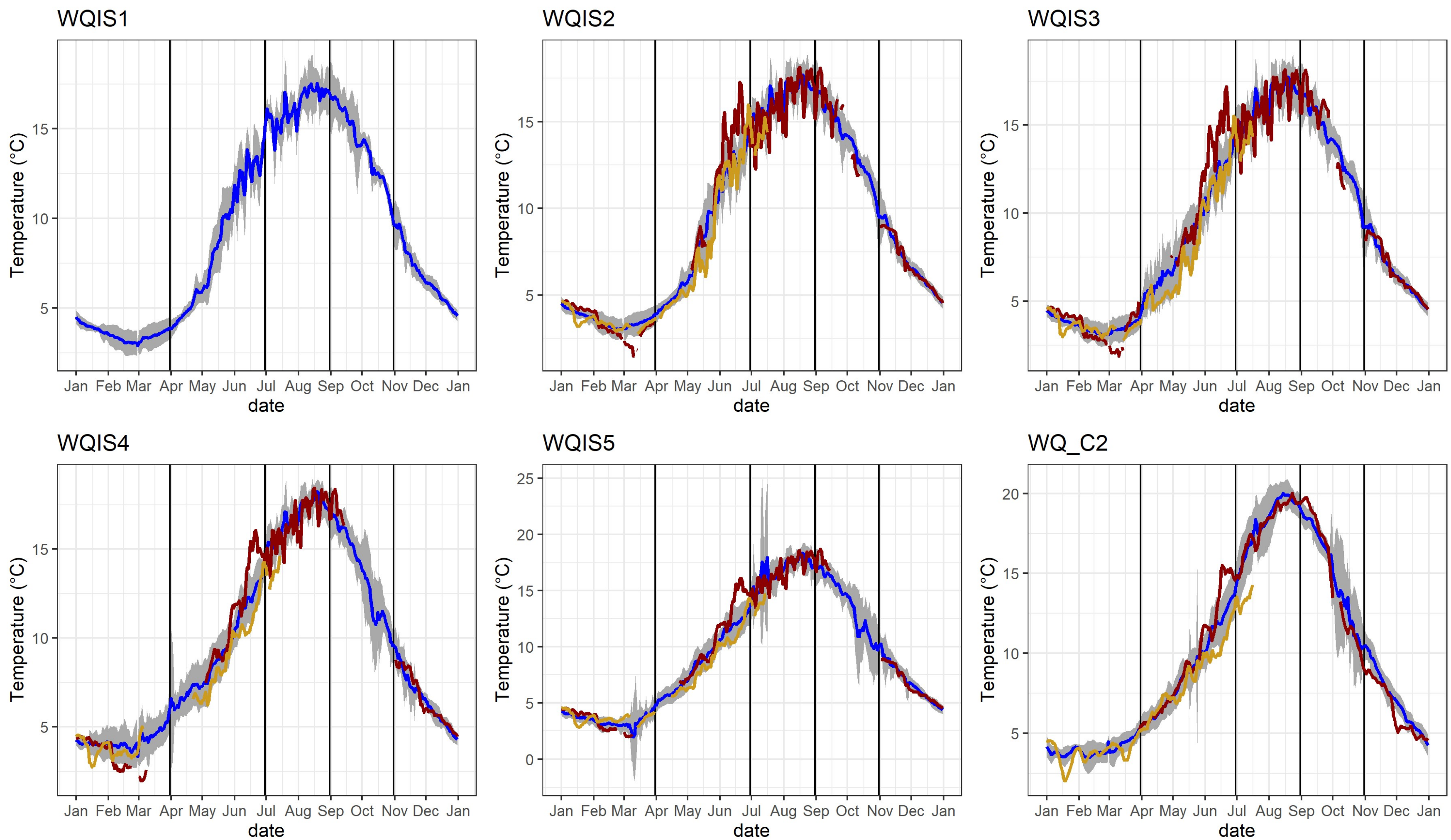

Figure 4-2: **Mean daily water temperatures recorded at WQIS1 – 5 on LCR and at WQ C2 on Kootenay River.** The red line depicts the mean daily water temperature recorded at each site in 2019 and the golden line depicts mean daily temperature in 2020. The blue line is the mean daily water temperature throughout the duration of the study (2008-2020 ± SD (gray shaded area)).

4.3 Light Attenuation

The euphotic depth is defined as the depth at which light in the photosynthetic active range (PAR) is attenuated to 1% of its surface value (Lee et al. 2007). The modelled euphotic zone depth was 10.9 m -95% CI 8.6-14.9 (Figure 4-3).The Norns Creek fan is within the photic zone and receivies adedquate light to support primary productivity because the maximum depth during the RBT flow period in the 12 years included in the productivity model was 5.5 m on June 29, 1990.

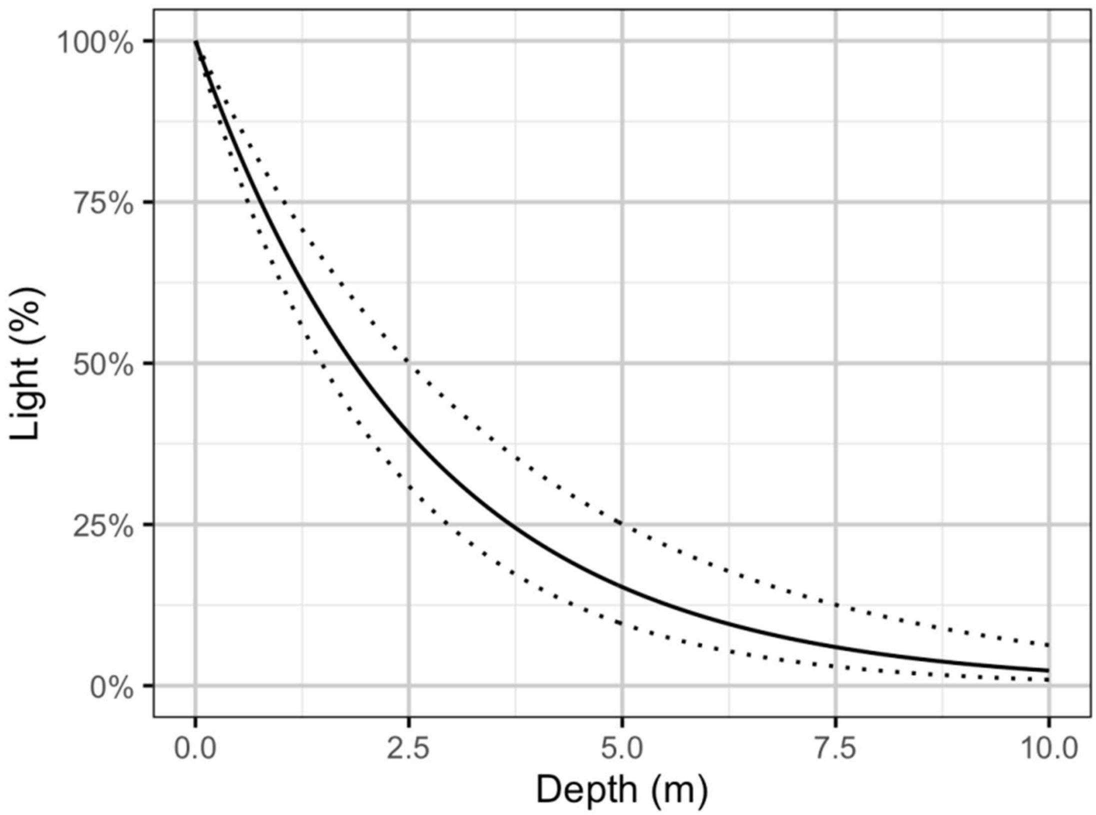

Figure 4-3: Modelled light attenuation by depth based on PAR profiles.

4.4 RBT Flows

During the RBT flow period (Apr 1 – Jun 30), HLK daily mean flows were more variable without RBT managed flows (OFF years) compared to years when there was RBT flow management (ON years). The coefficient of variation for daily flows was 0.59 ± 0.22 for OFF years compared to 0.33 ± 0.15 for ON years (Figure 4-4). Typically, OFF years had higher daily maximum flows and lower daily minimum flows compared to ON years. The highest daily maximum flows of the OFF years were 2,544.1 m^3/s in 1987, 2,009.5 m^3/s in 2020 and 1981.9 m^3/s in 1988 (Table 4-1). The first ON year, 1992, had the highest daily maximum flow of 3367.1 m^3/s. Daily minimum flows ranged from 138.6 - 294 m^3/s during OFF years and 140.7 - 838.5 m^3/s during ON years.

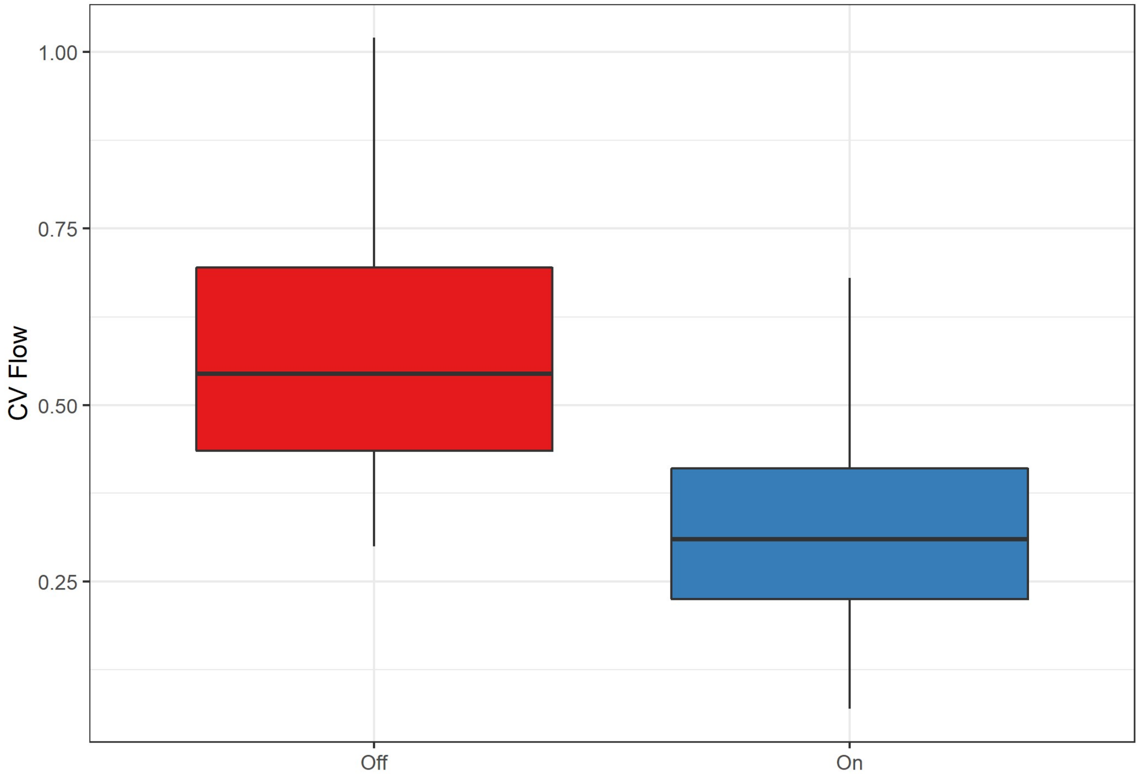

Figure 4-4: **Coefficient of Variation (CV) for HLK discharge during OFF years (1984-1991, 2019 - 2020) and ON years (1992-2018).**

Table 4-1: **Flow metrics for daily mean HLK discharge during OFF and ON RBT (Apr 1 – Jun 30) flow years.**

Year	Flow Period	Minimum	Median	Mean	Maximum	CV
1984	OFF	138.60	148.70	480.86	1,480.90	1.02
1985	OFF	140.70	469.50	512.64	1,277.50	0.65
1986	OFF	222.90	683.20	666.30	1,429.70	0.48
1987	OFF	138.70	760.30	874.21	2,544.10	0.81
1988	OFF	140.50	714.00	721.63	1,981.90	0.61
1989	OFF	227.70	569.00	588.66	1,094.60	0.43
1990	OFF	219.80	508.10	626.71	1,673.50	0.71
1991	OFF	280.60	1,116.70	1,065.84	1,710.90	0.30
1992	ON	410.70	1,093.00	1,446.03	3,367.10	0.68
1993	ON	221.40	421.40	377.73	663.90	0.26
1994	ON	141.90	566.80	817.72	1,981.40	0.58

Year	Flow Period	Minimum	Median	Mean	Maximum	CV
1995	ON	140.70	421.20	348.10	910.10	0.55
1996	ON	533.60	987.90	1,010.85	1,947.20	0.40
1997	ON	424.20	567.70	753.17	1,335.60	0.42
1998	ON	339.30	481.70	503.37	1,043.60	0.22
1999	ON	419.30	571.40	616.30	850.00	0.18
2000	ON	337.10	567.30	675.95	1,472.00	0.39
2001	ON	838.50	979.60	923.77	1,003.50	0.07
2002	ON	143.50	345.10	371.24	1,137.80	0.48
2003	ON	345.30	424.80	480.95	835.70	0.23
2004	ON	315.80	566.40	685.92	1,192.50	0.40
2005	ON	305.70	832.70	759.05	1,102.50	0.36
2006	ON	413.90	566.90	559.07	1,011.10	0.22
2007	ON	413.70	926.30	845.75	1,287.80	0.32
2008	ON	398.30	702.00	685.95	1,102.70	0.24
2009	ON	348.10	508.50	548.86	870.40	0.17
2010	ON	340.60	567.30	564.53	712.40	0.20
2011	ON	270.20	764.50	776.48	1,277.00	0.26
2012	ON	457.30	653.00	674.68	1,284.20	0.31
2013	ON	547.70	682.00	730.63	1,291.40	0.12
2014	ON	334.20	623.50	595.16	969.80	0.28
2015	ON	276.00	785.10	824.58	1,841.50	0.49
2016	ON	224.60	426.70	642.29	1,292.20	0.51
2017	ON	358.00	693.00	686.23	1,091.00	0.29
2018	ON	226.40	705.10	697.67	1,103.60	0.33
2019	OFF	294.00	426.20	575.89	1,021.10	0.43
2020	OFF	245.1	705.9	745.4	2,009.5	0.45

The mean daily discharge from HLK for the OFF-years used in the productivity models are displayed in Figure 4-5. Spring 1991 was not a typical OFF-year with high daily flows throughout April and May and a low coefficient of variation (Figure 4-5; Table 4-1). Daily flows increased from June 15 to 30th in 1988 and 1990, whereas flows decreased at the end of June in 1989, 1991, 2019 and 2020. The maximum daily flows during the RBT flow period were especially low in 1989 and 2019, at 1,095 m^3/s and 1,021 m^3/s, respectively.

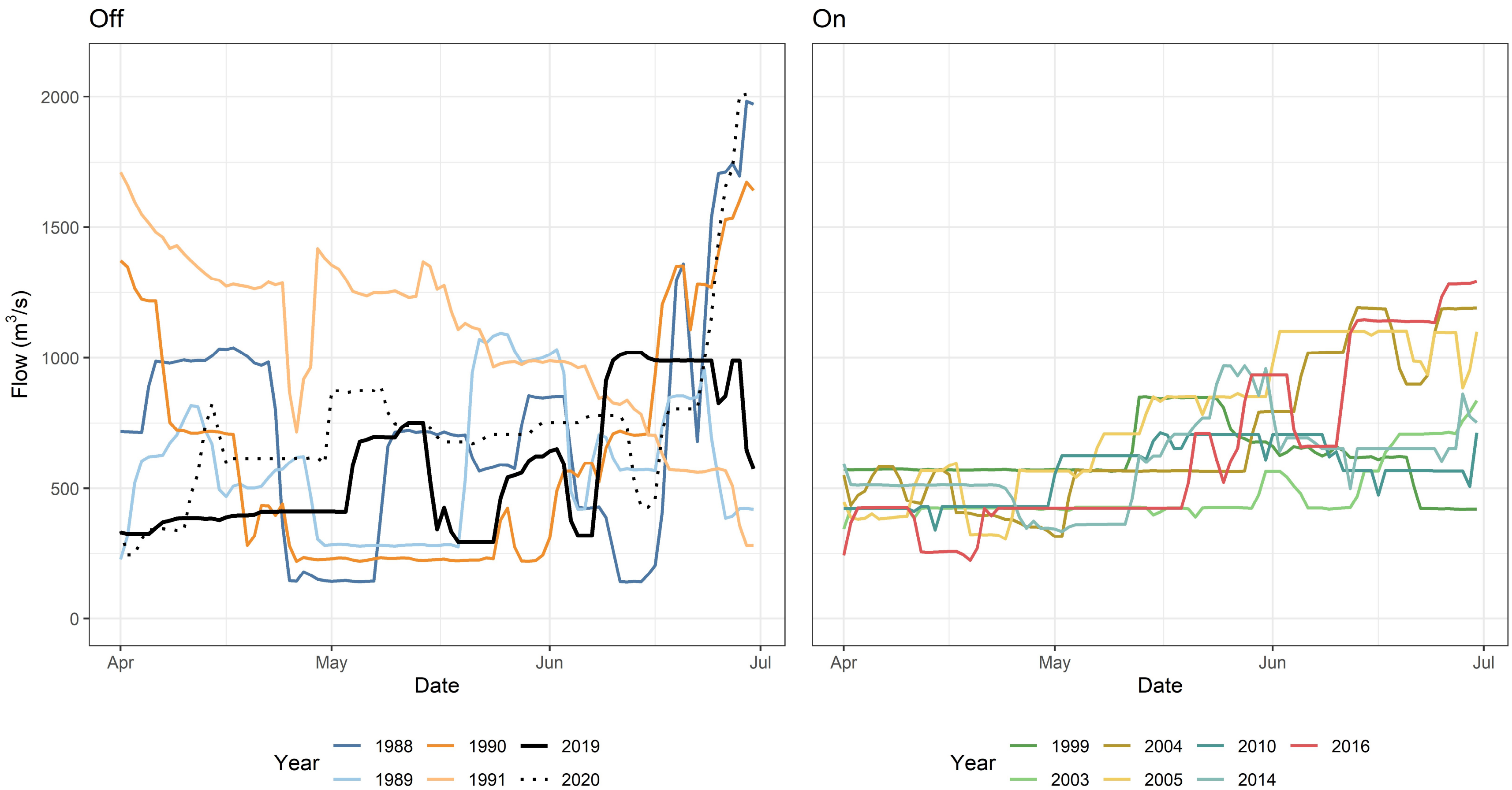

Figure 4-5: **Mean daily discharge from HLK for OFF and ON flow years included in the productivity models. Note: Experimental years, 2019 and 2020, were both OFF years and are displayed in black.**

A representative range of operating conditions during ON RBT years were selected for productivity models. High flows years were not included because WQIS3 logger elevation could not be accurately predicted for these years. High flow years had maximum flows that exceeded 1,500 m^3/s during the RBT flow period. There were four ON years (1992, 1994, 1996, 2015) that had HLK flows that exceeded 1,500 m^3/s (Table 4-1). The mean daily flow for the years selected in the productivity models are displayed in Figure 4-5. Spring 1999, 2003 and 2010 had low maximum flows that were less than 900 m^3/s, whereas spring 2004, 2005 and 2016 had higher maximum flows ~1,200 m^3/s. Typically, during managed RBT flow period, April has the lowest daily flows. However, in April 1999 the daily minimum flows were higher than 400 m^3/s (Figure 4-5).

4.5 Production ON- and OFF-RBT Years

4.5.1 Chlorophyll-a (chl-a)

The mean chl-a in the Norns Creek fan on June 30 for OFF flow years was 15.0 ± 2.4 kg and mean chl-a for ON years was 17.6 ± 2.6 kg (Figure 4-6). The mass of chl-a during ON years in Norns Creek fan was 17% higher than the mass of chl-a during OFF years (2-sample *t*-test; t = 1.87, *P*-value = 0.04; 90% confidence limits for the true difference in mean chl-a mass (kg): 0.1, ∞). The mean chl-a of the highest OFF-year (2020) was comparable to the mean chl-a for ON years (Figure 4-6). This is likely because 2020 was largely operated as an ON year, until flow constraints required that it be changed to an OFF year. If more years of data were available for OFF-years, the difference between chl-a in ON and OFF years would likely be significant using a 95% confidence limit.

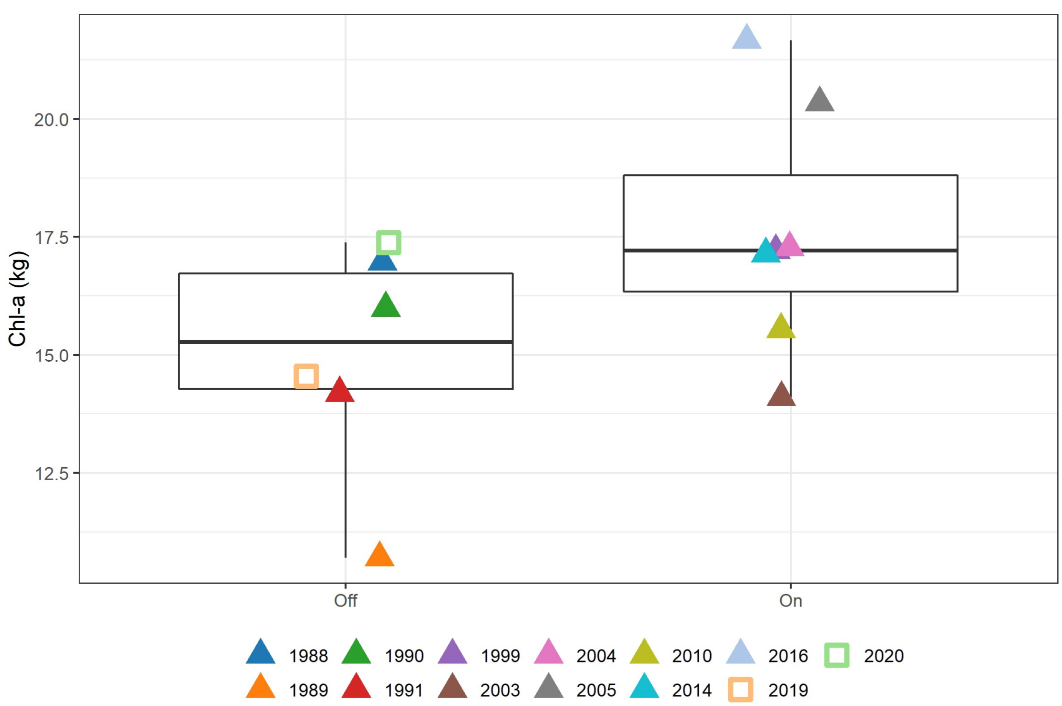

Figure 4-6: **Boxplots of chl-a of Norns Creek fan on June 30 for years when RBT flows were either ON or OFF. Note: Experimental years, 2019 and 2020 (both OFF years), are displayed with an open square.**

The most productive OFF-RBT years were 2020, 1988 and 1990; whereas, the least productive OFF-RBT year was 1989 (Figure 4-6). 2020 was planned as an ON year and flows were managed similar to ON years, except for a short drop during the second week of June. Following the drop, flows steadily increased through the end of June (Figure 4-5). In 1988 and 1990, flows also peaked at the end of June; whereas, in 1989, 1991, and 2019 maximum flows occurred before June 30th (Figure 4-5). The higher flows at the end of June resulted in more productive habitat area. The chl-a production was highest in 1998 and 2020 because daily flows were greater than 1,500 m^3/s during the latter part of June. The least productive OFF-RBT year was 1989 because of low daily flows in May and daily flows less than 500 m^3/s at the end of June. Low daily flows at the end of June substantially reduce chl-a production because 24 hours of consecutive exposure result in ~50% loss of chl-a.

The most productive ON-RBT years were 2005 and 2016, whereas the least productive were 2003 and 2010. Chl-a in 2003 and 2010 were comparable to OFF-RBT chl-a values (Figure 4-6). The low maximum daily flows of 712 m^3/s in 2010 and 835.7 m^3/s in 2003, resulted in less productive habitat area for periphyton throughout the RBT flow period. The chl-a production was lowest in 2003 because mean daily flows were below 500 m^3/s until June (Figure 4-5) The chl-a was the highest in 2005 and 2016 with total chl-a estimates of 20.3 kg and 21.7 kg, respectively. In 2005 and 2016, daily flows were above 1000 m^3/s for most of June. The higher chl-a production in 2016 was a result of higher daily flows at the end of June. Overall, higher daily flows throughout the month of June result in a larger wetted habitat area that increased total chl-a production.

4.5.2 Invertebrate Biomass

The mean invertebrate biomass in the Norns Creek fan area on June 30th was 25% higher during ON-RBT years compared to OFF-RBT years (2-sample *t*-test; $t = 2.24$, *P*-value = 0.02; 90% confidence limits for the true difference in mean invertebrate biomass (kg): 9.08, ∞). The mean biomass of OFF-RBT was 185 ± 32.5 kg and the ON-RBT biomass was 231 ± 40.2 kg (Figure 4-7). The increased biomass production in ON-RBT years was a result of the preservation of a larger wetted habitat area throughout the RBT flow period. The larger wetted habitat area increased the rate of invertebrate colonization and reduced invertebrate death through dewatering of substrates. The goal of RBT flow management was to reduce the amount of flows less than 600 m^3/s and steadily increase the hydrograph throughout the RBT flow period to limit dewatering of shallow areas (Olson-Russello et al. 2019).

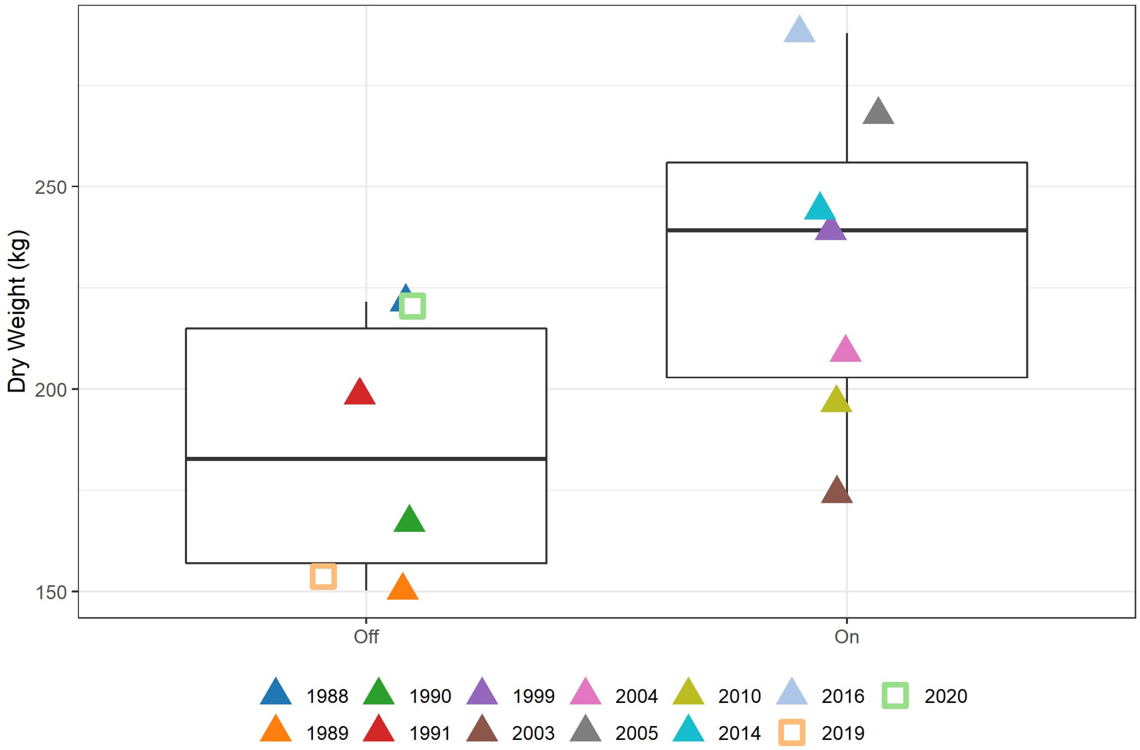

Figure 4-7: **Boxplots of total invertebrate biomass of Norns Fan on June 30th for ON and OFF RBT flow years. Note: Experimental years, 2019 and 2020 (both OFF years), are displayed with an open square.**

When RBT flows are OFF, the invertebrate biomass on June 30th ranged from 150 kg in 1989 to 222 kg in 1988 (Figure 4-7). The OFF years with the lowest invertebrate biomass were 1989 and 2019, with 150 kg and 154 kg, respectively. Coincidentally, the least productive years of 1989 and 2019 also had the lowest maximum flows of any OFF years (Table 4-1). The most productive OFF years were 2020 and 1988; they had the highest and second highest maximum flow (2,010 and 1,982 m^3/s, respectively) of all OFF years included in the productivity models. The third highest invertebrate biomass for OFF years was 1991 at 199 kg on June 30th. April 1991 had high daily flows that were above 1,000 m^3/s (Figure 4-5). These high flows resulted in an increased area available for invertebrate colonization.

During ON years the invertebrate biomass on June 30th ranged from 174 kg in 2003 to 288 kg in 2016 (Figure 4-5). Similar to chl-a, invertebrate production was the lowest in 2003 because low mean daily flows in April and May reduced the area available for invertebrate colonization (Figure 4-5). The invertebrate biomass was the second lowest in 2010 because of the low daily flows at the end of June. The highest biomasses were observed in 2005 and 2016 with total biomass estimates of 268 kg and 288 kg, respectively. In 2005 and 2016, there was a larger area available for invertebrate colonization because daily flows were above 1,000 m^3/s for most of June (Figure 4-5). The ON flow years had a wider range of June flows that resulted in larger productivity differences.

4.5.3 Production Discussion

Although hourly Birchbank flow data was not available for the entire RBT flow period from 1984-1987, the benthic production of these years can be estimated based on the RBT hydrograph and modelled productivity estimates of other OFF years. In June 1984, the mean daily flow was below 300 m^3/s for the whole month (Figure 4-8). Low flows throughout June would have caused substantial reductions in both periphyton and invertebrate productivity. We estimate that 1984 had the lowest production of all OFF years. The moderate daily flows throughout May and June of 1985 and 1986, likely resulted in moderate periphyton and invertebrate productivity comparable to the productivity estimates of 1991 and 2019. The high flows at the beginning of June and the sharp increase of daily flows at the end of June in 1987 likely benefitted periphyton and invertebrate production (Figure 4-8). June 1987 likely had comparable periphyton and invertebrate production to 1988 and 1991.

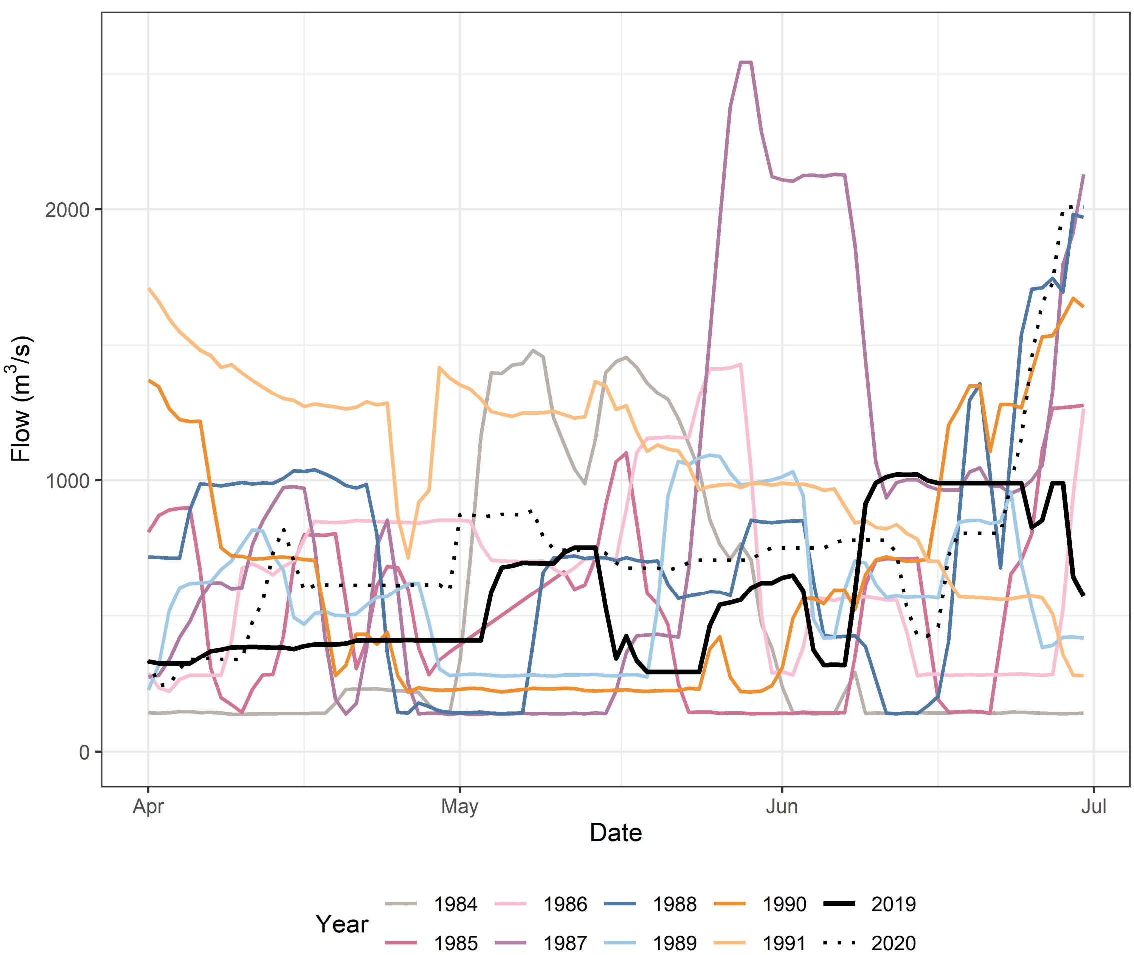

Figure 4-8: Mean daily discharge from HLK Dam for OFF years during the RBT flow period.

Based on estimates of productivity in 1984-1987, the mean chl-a and invertebrate biomass calculated from 1988-1991 and 2019-2020 was likely representative of all OFF years. However, we acknowledge the inclusion of modelled productivity estimates for 1984-1987 would increase the statistical power of ON and OFF RBT year comparisons. However, even with the inclusion of all ten OFF RBT years the statistical power of the test is still limited.

The accuracy of elevation predictions at the WQIS3 were reduced when flows exceeded 1500 m^3/s at HLK. As a result, the productivity estimate in June 1988 has a higher uncertainty compared to other years. To reduce inaccuracies of ON RBT productivity estimates, only ON RBT years with maximum flows less than 1500 m^3/s were included in the productivity models. Inclusion of these ON RBT years with high maximum flows would have increased the mean of ON RBT productivity estimates. However, inclusion of these years would have introduced a larger error to the mean ON RBT productivity estimates.

The invertebrate and periphyton production models provided simplified estimates of production in the Norns Creek fan based on hourly flows. Similarly, in the varial zone of the Middle Columbia River (MCR), the duration of substrate submergence was the most important determinant of invertebrate and periphyton production (Plewes et al. 2019). However, the LCR and MCR models did not account for annual differences in water temperature, air temperature, or precipitation. Environmental conditions can cause differences in growth and death rates. The models assumed growth and death rates were the same throughout the RBT flow period. Differences in air temperature, humidity, and precipitation can alter death rates for invertebrates and periphyton (Plewes et al. 2019); whereas, water temperature is an important factor in determining chl-a growth rates (Plewes et al. 2019). However, in LCR, variations in spring water temperatures were minimal.

Annual differences in HLK operations resulted in differences in invertebrate and periphyton production during ON and OFF RBT managed flow years. However, in most ON RBT years invertebrate and periphyton production on June 30th was higher than OFF RBT production. The invertebrate biomass and periphyton chl-a in 2003 and 2010 were comparable to OFF RBT production. The RBT flow period of 2003 and 2010 had the second and third lowest maximum flows of all ON RBT years (Table 4-1). Therefore, 2003 and 2010 were not characteristic of typical RBT flow management. Typical RBT flow management resulted in more stable flows throughout May and June which maintained a larger wetted habitat area in the Norns Creek fan. A larger wetted habitat area resulted in a larger area available for invertebrate colonization and periphyton growth. Less substrate dewatering also resulted in reduced mortality of invertebrates and periphyton.

5.0 CONCLUSIONS

Typical RBT flow management benefitted both invertebrate and periphyton production in the Norns Creek fan. Assuming a significance level of 0.1, in ON RBT years, chl-a and invertebrate biomass were significantly higher than OFF RBT years. RBT flow management had a slightly larger benefit on invertebrate productivity (p=0.02), likely because invertebrates are more sensitive to substrate dewatering and have slower spring recovery rates than periphyton (Schleppe et al. 2015). During ON RBT flow years, chl-a was significantly higher than OFF RBT flow years (p=0.04), and we suspect that the inclusion of more ON and OFF RBT years would likely result in a statistical difference at a 95% confidence level.

Before the management of RBT flows, flows were highly variable and as a result more OFF RBT years should be included in the productivity model. Highly variable flows resulted in a wider range of invertebrate and periphyton production. The addition of more OFF RBT years will result in a more accurate estimate of production during OFF RBT years. Due to data limitations, it was not possible to model productivity for 1984-1987. However, assuming flow management will continue with alternating years of ON and OFF RBT flows, additional OFF years may occur in 2021 and 2023. After spring of 2023, the productivity models for 2021 and 2023 could be run and ON and OFF RBT comparisons reanalyzed. In 2023, it would also be prudent to model productivity for more ON RBT years. Only seven ON RBT years were selected since the addition of more ON RBT years resulted in longer computer run times and the statistical power was limited by the lower number of OFF RBT years. Suitable ON RBT years for productivity modelling include 2000, 2012 and 2018. The inclusion of two additional ON RBT years and two additional OFF RBT years will result in a statistical power of 62% with a large effect size and a significance level of 0.1. The analysis conducted in this report had a statistical power of 54%. Therefore, the inclusion of additional years will result in a 8% improvement in statistical power (n_{OFF}=8, n_{ON}=9).

6.0 REFERENCES

BC Hydro. (2005a). Consultative Committee report: Columbia River Water Use Plan, Volumes 1 and 2. Report prepared for the Columbia River Water Use Plan Consultative Committee by BC Hydro, Burnaby, B.C. Available at: https://www.bchydro.com/toolbar/about/sustainability/conservation/water_use_planning/southern_interior/columbia_river/lower-columbia-fish.html

BC Hydro. (2005b). Columbia River Project, Draft Water Use Plan. 38 pp. + appendices BC Hydro. 2006. Columbia River Water Use Plan – Revelstoke Flow Management Plan. DRAFT - Monitoring Program Terms of Reference. Available at: https://www.bchydro.com/toolbar/about/sustainability/conservation/water_use_planning/southern_interior/columbia_river/lower-columbia-fish.html

BC Hydro. (2007). Columbia River project water use plan. Monitoring program terms of reference. Appendix 6 CLBMON-44 Lower Columbia River physical habitat and ecological productivity monitoring. 31p. https://www.bchydro.com/toolbar/about/sustainability/conservation/water_use_planning/southern_interior/columbia_river/lower-columbia-fish.html

BC Hydro (2019). Scope of Services: CLBMON-44: Lower Columbia Physical Habitat and Ecological Productivity – Modelling Updates.

Bradford, M. J., Korman, J., & Higgins, P. S. (2005). Using confidence intervals to estimate the response of salmon populations (Oncorhynchus spp.) to experimental habitat alterations. Canadian Journal of Fisheries and Aquatic Sciences, 62(12), 2716-2726.

Brooks, G. P., & Johanson, G. A. (2011). Sample size considerations for multiple comparison procedures in ANOVA. Journal of Modern Applied Statistical Methods, 10(1), 10.

Carpenter, Bob, Andrew Gelman, Matthew D. Hoffman, Daniel Lee, Ben Goodrich, Michael Betancourt, Marcus Brubaker, Jiqiang Guo, Peter Li, and Allen Riddell. 2017. “Stan: A Probabilistic Programming Language.” Journal of Statistical Software 76 (1). https://doi.org/10.18637/jss.v076.i01.

Faul, F., Erdfelder, E., Buchner, A., & Lang, A. G. (2014). G* Power (Version 3.1. 9.2). Germany: University of Kiel.

Kery, M., and M. Schaub. 2011. Bayesian Population Analysis Using WinBUGS : A Hierarchical Perspective. Boston: Academic Press. http://www.vogelwarte.ch/bpa.html.

Lee, Z., Weidemann, A., Kindle, J., Arnone, R., Carder, K. L., & Davis, C. (2007). Euphotic zone depth: Its derivation and implication to ocean-color remote sensing. Journal of Geophysical Research: Oceans, 112(C3).

McElreath, Richard. 2016. Statistical Rethinking: A Bayesian Course with Examples in R and Stan. Chapman & Hall/CRC Texts in Statistical Science Series 122. Boca Raton: CRC Press/Taylor & Francis Group.

NHC. (2016). Revelstoke Unit 6 Environmental Assessment TELEMAC Model Development and Hydraulic Assessment Report. Prepared for SNC-Lavalin Inc. Prepared by Northwest Hydraulic Consultants Ltd. North Vancouver, BC NHC 3000346. January 12, 2016.

Olson-Russello, M.A., H. Larratt, R. Plewes. (2019). CLBMON-44 Lower Columbia River Physical Habitat and Ecological Productivity Monitoring Final Report – 2008 - 2019. Unpublished report by Ecoscape Environmental Consultants Ltd. and Larratt Aquatic Consulting Ltd., BC for BC Hydro Generations, Water License Requirements, Burnaby, B.C. 28 pp + Appendices 1-8.

R. Plewes, H. Larratt, J. Schleppe, A. Duncan. 2019. CLBMON-15b Middle Columbia River Ecological Productivity Monitoring, Annual Report 2018. Okanagan Nation Alliance with Ecoscape Environmental Consultants Ltd. & Larratt Aquatic Consulting Ltd. 81 pp.

R Core Team (2020). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria.
URL https://www.R-project.org/.

Schleppe, J., Wagner, R., Robertson, C., Plewes, R., & Olson-Russello, M.A. (2015). Spatial Model of Benthic Productivity for the Brilliant Expansion Project. Prepared for Columbia Power Corporation (CPC), Castlegar, British Columbia. Prepared by Ecoscape Environmental Consultants Ltd. Pg. 42.

J. Schleppe, H. Larratt, and N. Swain. 2013. Benthic Productivity Monitoring for the Brilliant Expansion Project Report. Prepared for Columbia Power Corporation (CPC), Castlegar, British Columbia. Report Prepared by: Ecoscape Environmental Consultants Ltd.

7.0 APPENDIX 1. Timeline and Milestones of CLBMON-44 (Modelling Updates)

Table A1. Timeline and Milestones of CLBMON-44.

Year	Milestones
2019	Collection of water temperature / water elevation data, river bathymetry, development of a Telemac-2D model, status report
2020	Collection of water temperature / water elevation data, field data collection of light intensity, turbidity, and depth, productivity model development, final reporting