Columbia River Project Water Use Plan

LOWER COLUMBIA RIVER FISH

Reference: CLBMON-44

Lower Columbia River Physical Habitat and Ecological Productivity Monitoring – 2022-2023

Study Period: 2022

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April 2023

Lower Columbia River Fish

Monitoring Program No. CLBMON-44

Lower Columbia River Physical Habitat and Ecological Productivity – 2022-2023

2022 Interim Report

Prepared for

BC Hydro Generation
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BC Hydro Reference # 4500040484

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From left to right: 2017 Genelle; 2016 winter deployment (S7); 2019 bathymetry survey; 2022 spring data collection.

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EXECUTIVE SUMMARY

Discharges from the Hugh L. Keenleyside (HLK) Dam during winter and spring have the potential to affect salmonid spawning and rearing habitats in the Lower Columbia River (LCR). To minimize impacts, BC Hydro and Power Authority (BC Hydro) altered operations of HLK Dam to include Rainbow Trout (RBT) protection flows which stabilize or increase HLK discharges from April 1 through June 30, to reduce RBT redd dewatering and subsequent egg loss.

Despite the implementation of RBT protection flows, it was unclear how these flows affect the local RBT population abundance. To reduce uncertainty, an experimental approach of alternating RBT protection flows with standard flow operations was initiated in 2019 for five years, until 2023.

One of the objectives of CLBMON-44 was to assess how the RBT protection flows (ON) or lack thereof (OFF) may affect the ecological productivity of Norns Creek fan, an important spawning habitat for RBT. Benthic productivity, inclusive of periphyton and benthic macroinvertebrates, are key factors in a river system, because they are a primary food source for fish. Benthic productivity in the Norns Creek fan was measured in 2022 with the use of artificial samplers. Water stage (elevation), water temperature, light intensity, turbidity, substrate size, and velocity were also measured.

Periphyton and benthic invertebrate productivity and community metrics were measured at three sites throughout the Norns Creek fan and one control site (R2-S1), located along the opposite bank of the river from Norns Creek fan. In spring 2022, Norns Creek fan had a Didymo bloom, which resulted in higher abundance, biovolume, and chl-a production than are typical for the LCR. Relatively stable flows and lack of strong floods which scour surfaces and remove periphyton filaments may have contributed to the large Didymo bloom.

The benthic invertebrate community varied by site in the spring of 2022, with the largest differences in community between the Norns Creek fan sites and the control site R2-S1. Norns Creek sites differed from R2-S1 and previously surveyed sites in their functional feeding groups, distributions of dominant taxa, and taxa richness. These differences were likely driven by habitat types, particularly by substrate size. Norns creek sites have small substrates with less interstitial space, and R2-S1 substrates are larger cobble and boulder. Despite differences between sites, the invertebrate community in the LCR is typical of large, regulated river systems. Norns Creek fan was dominated by taxa that are well adapted to varial zone habitats and can resist desiccation when flows drop. These taxa include Chironomidae and Naididae, and Ephemeroptera, Plecoptera, and Trichoptera (EPT taxa).

Norns Creek fan sites had a lower fish food index and lower benthic invertebrate biomass than other LCR sites. These values indicate that the productivity of Norns Creek fan may not be as important to RBT populations as the production of other habitats in the LCR. The smaller substrate, limited interstitial habitat, and low instream cover of Norns Creek fan are not ideal conditions for RBT rearing. Juvenile RBT likely leave the fan and move to better foraging habitat after emerging from the substrates.

Productivity models were used to estimate invertebrate dry biomass and chlorophyll-a (chl-a) accrual in Norns Creek fan. The productivity models used hourly depths from a hydraulic TELEMAC-2D model and growth/colonization and death curves for invertebrates and periphyton. The mortality curve used in the invertebrate productivity model was built from data collected in the LCR and Kootenay rivers from two of the most abundant LCR invertebrate taxa, Simuliidae and Hydropsychidae. The total invertebrate and periphyton production of the Norns Creek fan between April 1st and June 30th were compared between ON and OFF years. This report focuses on productivity modelling results and observed productivity for 2022, which was managed as an OFF year, and provides an additional year of data to compare with previous modelled ON (n=7) and OFF (n=6) years.

The addition of discharge data from 2022 and a review and adjustment of discharge data from previous study years have changed model results. Modelled accrual of benthic invertebrate biomass during ON RBT flow years was higher than the accrual of benthic invertebrate biomass during OFF years (effect size = 0.88). The difference in the modelled accrual of chl-a for ON RBT flow years compared to OFF RBT years is no longer statistically significant when considering 2022 and the revised flow data for 2002 through 2020 (effect size = 0.56).

Gradually increased water elevations under RBT protection flows resulted in less variability of wetted areas and more total varial habitat in the Norns Creek fan, and thus less stress for benthic communities. Less substrate dewatering, less flow variation, and higher flows also resulted in a higher total wetted area, which increased estimated invertebrate biomass accrual in ON years. Highly variable flows among years of the same management type made the effect of ON and OFF flow management on chl-a accrual difficult to determine, and ON flows did not change the productivity of chl-a accrual in comparison to OFF years. Estimated biomass results for both invertebrates and chl-a are conservative because models are initialized with minimal amounts of biomass. The LCR productivity model does not account for variation in water temperature, air temperature, or precipitation, and assumes growth and death rates are constant throughout the RBT flow period.

The Scope of Services for this contract also requested the productivity model be updated with taxa-specific mortality curves of invertebrates consumed by juvenile RBT. A literature review was conducted with the intent to find mortality curves to improve model precision for benthic invertebrates of importance to juvenile RBT.

The invertebrate community assemblage of the LCR is driven by regulated flows, and this community assemblage determines the diets of Rainbow Trout because they forage as generalists. While mortality rates from other river systems and related species could be employed from the literature, it is unlikely that they would outperform the current curve created with the species and conditions specific to the LCR.

While substrate submergence is the most important determinant of benthic productivity, model precision may be improved with the inclusion of other flow factors that influence total wetted area. Parameters such as variability of daily flows, number of high flow events, duration of high flow events, fall rate of decreasing flows, and maximum annual flow may give a more accurate and nuanced depiction of total available habitat and the flow variability that influences benthic production. This may be particularly helpful given the high variation in flows among flow managements of the same type.

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1 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 create Rainbow Trout (*Oncorhynchus mykiss*) protection flows which stabilize or increase HLK discharges from April 1 through June 30, to reduce redd dewatering and subsequent Rainbow Trout egg loss (BC Hydro 2007).

One objective of CLBMON-44 was to examine the influence of the Rainbow Trout (RBT) managed flow periods from April 1st through June 30th on physical habitat components and benthic productivity measures. Periphyton and benthic invertebrates are primary food sources for fish. Physical habitat components, including flow dynamics, are important variables that influence the benthic productivity of a river.

Despite the implementation of RBT protection flows, it was unclear how these flows affected the local RBT population abundance (BC Hydro 2018). To reduce uncertainty, an experimental approach of alternating RBT protection flows with standard operating flows in alternating years (e.g., ON and OFF RBT protection flows) was initiated in 2019 for a maximum duration of five years, until 2023.

To understand how the RBT protection flows (ON) or lack thereof (OFF), affect the ecological productivity of the Norns Creek fan, an important spawning habitat for RBT, a series of models were developed. A hydraulic model was created using Telemac-2D software (Open Telemac Mascaret Consortium, 2020), and subsequent productivity models were then implemented to estimate total invertebrate biomass and chlorophyll-a within the Norns Creek fan (Plewes et al., 2020).

The objective of this 2-year extension contract is to build on the productivity modelling undertaken in 2019 and 2020. The following work plan was developed:

- Update the existing model of ecological productivity for 2022 and 2023, with a focus on benthic invertebrate species that are most likely to be consumed by juvenile Rainbow Trout;
- Monitor periphyton and benthic invertebrate communities within the Norns Creek fan with the use of artificial benthic samplers deployed during the RBT flow period;
- Continue the maintenance and collection of water level stage data for all pre-established sampling locations in 2022 and 2023; and
- Continue monitoring photosynthetic active radiation (PAR) and turbidity.

2 STUDY AREA

The CLBMON-44 study area is in southeast British Columbia on LCR between HLK Dam and the BBK gauging station. Kootenay River is a major tributary to LCR, and there are several smaller tributaries including Norns, Blueberry, China and Champion Creeks. The study area is divided into three reaches: 1) from HLK Dam to Norns Creek; 2) from Norns Creek confluence to the Kootenay River, and 3) from the Kootenay River confluence to BBK gauging station. The five Water Quality Index Stations (WQIR2-S1-5) on LCR are located between the HLK Dam and BBK gauging station (Figure ***2-1***).

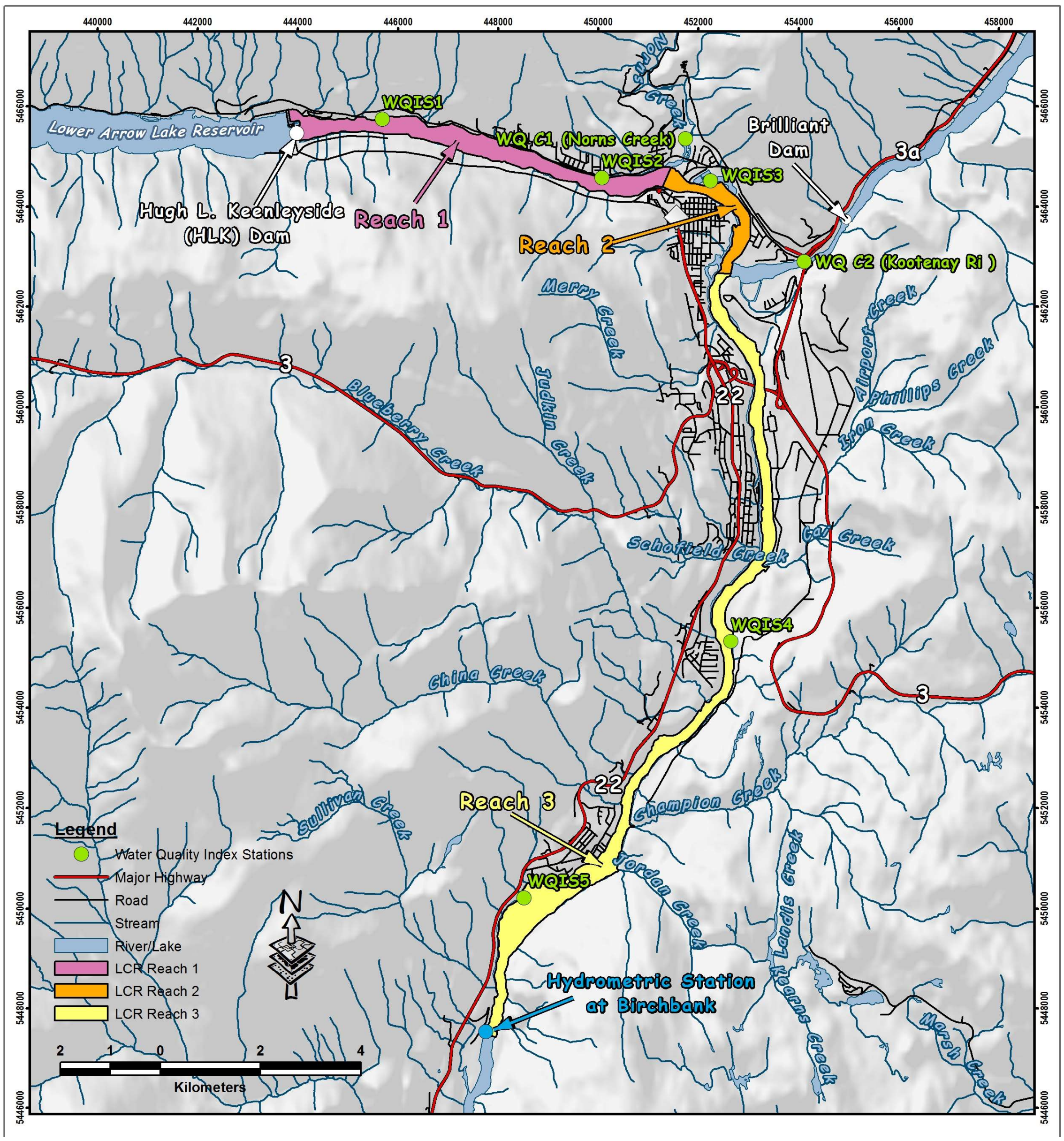

Figure 2-1: The Lower Columbia River (LCR) study area.

The focus of this two-year study is the Norns Creek confluence at the downstream end of Reach 1 (Figure 2-2). Water quality index station 2 (WQIS2) is located approximately 1 km upstream of the Norns Creek confluence, and WQIS3 is about 800 m downstream of the confluence. The hydraulic model extent includes the whole river between WQIS2 and 3. The productivity model extent only includes the Norns Creek fan where Rainbow Trout redds have been documented. Productivity sampling in 2022 included three sites (NC-1 through 3) (15 samplers) in the Norns Creek fan and one control site (R2-S1) (5 samplers) on LCR, in the channel along the opposite bank from Norns Creek fan (Figure 2-2). R2-S1 is a fitting control because it is the closest to the Norns Creek Fan. It is approximately the same distance from the HLK, so it experiences the same flow fluctuations as Norns Creek fan, without flow effects being dampened as they travel downstream. It is also not RBT spawning habitat.

Figure 2-2: The Norns Creek fan focal study area.

3 METHODS

3.1 Water Level Logger Data Download and Maintenance

On March 30 2022, level loggers were reinstalled at LCR water quality index stations (WQIS1-5) and at a single station on the Kootenay River (WQC2) (Table 3-1) (Figure 2-2). Level loggers recorded water elevation and water temperature at an hourly interval. Two new level loggers were purchased to replace aging loggers from the original CLBMON-44 program (Olson-Russello et al. 2019). The new loggers were installed at WQIS2 and WQIS3, as these stations are located at the upstream and downstream end of the hydraulic model extent. Elevation data from WQIS3 was used in the calibration of the hydraulic model. Water level data was downloaded on June 29 and October 13, 2022. Level loggers were left in place and data will be downloaded again in March 2023. Water elevation is determined using reference barometric data with two stations placed in proximity to the level loggers.

Table 3-1: Water level monitoring station locations.

Station Name	Location Description	Station Characteristics	UTM Coordinates	
			Northing	Easting
WQIS1	across from Zellstoff Celgar Ltd.	Upstream of Celgar outfall	5,465,742	445,693
WQIS2	upstream of boat launch	Downstream of Celgar outfall	5,464,573	450,072
WQIS3	downstream of railway bridge	Within back channel area	5,464,517	452,244
WQIS4	~7 km downstream of Kootenay River confluence	Left bank on bedrock face	5,455,332	452,653
WQIS5	~ 2.2 km upstream of Birchbank	Right bank on bedrock face	5,450,221	448,514
WQ C2	Kootenay River, just above confluence with LCR	Right bank, on bedrock face	5,462,911	454,114

3.2 PAR and Turbidity Profiles

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 on March 29 and October 13, 2022, to capture the spring and fall flow periods. 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 from 2 - 10 m at the five sites.

3.2.1 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. Details of the analysis are provided in Appendix A and a brief methodology overview is presented here.

To model light availability, model parameters were estimated using Bayesian methods that were produced using JAGS (Plummer 2003). Refer to McElreath (2020) for additional information on

Bayesian estimation. Unless otherwise indicated, the Bayesian analyses used weakly informative normal and half-normal distributions (Gelman et al., 2017). 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 $\widehat{R} \leq 1.05$ (Kery and Schaub 2011) and the effective sample size (Brooks et al. 2011) $\mathrm{ESS} \geq 150$ for each of the monitored parameters (Kery and Schaub 2011).

The parameters are summarised in terms of the point estimate, lower and upper 95% compatibility limits (Rafi and Greenland, 2020) and the surprisal s-value (Greenland 2019). The estimate is the median (50th percentile) of the MCMC samples while the 95% CLs are the 2.5th and 97.5th percentiles. The s-value indicates how surprising it would be to discover that the true value of the parameter is in the opposite direction to the estimate (Greenland 2019). An s-value of > 4.3 bits, which is equivalent to a significant p-value < 0.05 (Kery and Schaub 2011; Greenland and Poole 2013), indicates that the surprise would be equivalent to throwing at least 4.3 heads in a row.

The condition that parameters describing the effects of secondary (nuisance) explanatory variable(s) have significant p-values was used as a model selection heuristic (Kery and Schaub 2011). Based on a similar argument, the condition that random effects have a standard deviation with a lower 95% compatibility interval (CL) $>$ 5% of the estimate was used as an additional model selection heuristic. Model adequacy was assessed via posterior predictive checks (Kery and Schaub 2011).

The results are displayed graphically by plotting the modeled relationships between individual variables and the response with the remaining variables held constant. In general, continuous and discrete fixed variables are held constant at their mean and first level values, respectively, while random variables are held constant at their average values (expected values of the underlying hyperdistributions) (Kery and Schaub 2011, 77–82).

The analyses were implemented using R version 4.2.2 (R Core Team 2022) and the mbr family of packages.

3.3 Hydraulic Model

The TELEMAC-2D hydraulic model created in 2019 was used for the analysis of 2022 flow effects on benthic biomass productivity estimates (Plewes et al. 2020). Model simulations used hourly discharge data from HLK Dam (including Spill, HLK, and Generating Station, HLK-ALH) and hourly elevations from the WQIS3 level logger for the period of interest (April 1st – June 30th). The reader should refer to Plewes et al. (2020) for a detailed methodology of the hydraulic model development and analysis of previous years data. Additional flow sources such as Norns Creek or backwater from downstream of the fan, are not included.

3.3.1 Flow Metrics

To better understand the variation in HLK flows in 2021 and 2022, flow metrics including coefficient of variation, maximum, minimum, median and mean daily flows were calculated. Hydrographs of the mean HLK daily flows from April 1st to June 30th (RBT flow period) were also generated for 2021 and 2022 and were graphically displayed with previously modelled ON and OFF years.

3.4 Productivity Model

The biomass productivity models use asymptotic growth curves with dewatering mortality and carrying capacity components for periphyton and benthic invertebrates derived from previous desiccation survival experiments and Columbia Power Corporation productivity studies (Schleppe et al. 2013; 2015). The invertebrate mortality curve was based on data from desiccation of Chironomidae, Simuliidae (blackflies), and Hydropsychidae (net-spinning caddisfly), three of the most abundant taxa in the LCR (Schleppe et al. 2013, Olson-Russello et al. 2019). Invertebrate dry biomass and chl-a in 2022 were predicted using hourly depth results from the hydraulic model to estimate submerged/exposed times. Submerged time increased productivity of a given area, while exposed time increased periphyton and invertebrate mortality. The invertebrate dry biomass and periphyton chl-a started on April 1st, 2022, at 0:00 at the minimum values of 1 mg/m^2 and 0.05 $\mu g/cm^2$, respectively. Total chl-a and invertebrate biomass accrual in kg were estimated at the end of RBT flow period on June 30th at 12:00.

Modelled 2022 invertebrate and chl-a productivity were then compared between years when RBT protection flows were ON or OFF. A one-sided two-sample t-test with a 90% C.I. was used to determine if chl-a and invertebrate biomass accruals were higher during ON years compared to OFF flow years. A power analysis was also conducted to determine the statistical power of the t-test using the *pwr* package in R (Champely et al. 2020). 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}= 7, n_{ON}= 7). The Shapiro-Wilk test and Levene's test were performed to confirm the assumptions of normal and equal variance of sample groups.

3.5 Benthic Productivity

This was the first year that the CLBMON-44 program collected benthic productivity data directly within the Norns Creek fan. Previously all productivity data was collected in the mainstem of the LCR, mostly within Reach 2. This was also the first year that productivity samplers were deployed to entirely overlap the RBT Flow period (Apr 1 – Jun 30). Historically, summer samplers were deployed ~June 1 and were retrieved in mid-August. Although the focus of this study was the Norns Creek fan, a previously sampled site in reach 2 (R2-S1), was established as a control site. It was important to include a control site because of the inherent seasonal and annual variability of periphyton and invertebrate data.

The objective of the Norns Creek fan productivity sampling was to understand how the benthic community may or may not differ from other previously sampled sites on LCR. This was deemed important, because the productivity model that was used to estimate the effects of ON or OFF RBT flows on the Norns fan productivity, used a growth and death curve derived from periphyton and invertebrate data from other LCR sites. Benthic productivity is largely driven by physical factors such as substrate size, velocity, light and water depth. Norns Creek fan differs from most of the other LCR sites sampled previously in that it has a low gradient, smaller substrates (i.e., gravels), less velocity, and a more laminar flow. Therefore, it was unknown if the Norns Creek fan sites would have a similar species composition or to what degree they may vary.

3.5.1 Data Collection

As with previous sampling, the benthic productivity of the Norns Creek fan was investigated using artificial Styrofoam samplers for periphyton and rock baskets for benthic invertebrates. Sampler placement was determined based on flows and velocities and where RBT spawning was visually identified in the field. Sampler placement avoided exposed portions of the fan and areas where water velocities were very low to standing/backwatered and thus not conducive to RBT spawning.

Three sets of five samplers were deployed in the Norns Creek fan, and one set of five samplers were deployed at site R2-S1 on March 29, 2022 (Figure 2-2). Samplers were placed at increasing wetted depths from approximately 0.4 – 4.5 m (Table 3-2). The samplers were left in place for 13 weeks to capture the entire RBT flow period prior to their retrieval on June 29, 2022. Depths at retrieval ranged from 2.2 – 7.1 m (Table 3-2).

Table 3-2: Naming convention of sampling depths and corresponding depth strata.

Depth Label	Depth Name	Depth at Deployment (m)	Depth at Retrieval (m)
D	Deep	2.0 – 4.5	4.4 – 7.1
MD	Moderately deep	1.6 – 2.2	3.8 – 4.8
M	Mid	1.5 – 1.8	3.3 – 4.8
MS	Moderately shallow	1.1 – 1.5	2.7 – 3.1
S	Shallow	0.4 – 0.8	2.2 – 3.1

A typical design of the periphyton and macroinvertebrate sampling apparatus is illustrated in Figure 3-1. The three Norns fan sites differed from the typical design in that a single anchor and buoy were used for all five samplers. At the time of sampler deployment and retrieval, velocity and depth at each sampler were also recorded.

At the end of the deployment session, periphyton Styrofoam punches were randomly collected from each sampler to assess 1) chlorophyll-a; and 2) taxonomy and biovolume. Benthic invertebrate baskets were also retrieved following standard protocols. Individual rocks from each basket were scrubbed to release clinging invertebrates. The contents from each basket were captured on a sieve and fixed with an ethanol solution, prior to transport to a laboratory for taxonomic identification and determination of biomass and associated metrics (Olson-Russello et al., 2019).

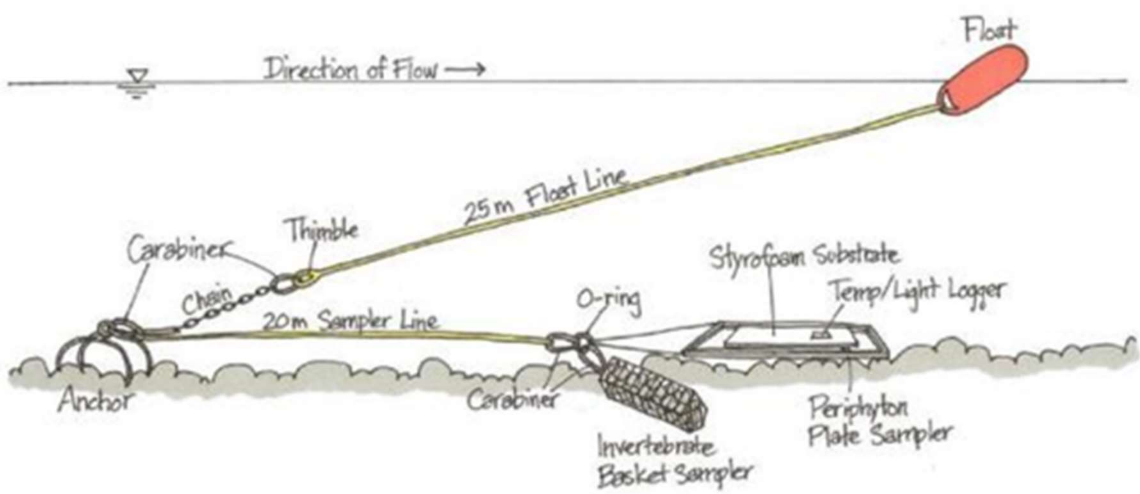

Figure 3-1: Typical benthic productivity sampler.

Table 3-3: Artificial sampler deployment and recovery rates in 2022.

Season	Reach	Site	Periphyton Samplers		Invertebrate Basket Samplers	
			# Deployed	# Retrieved (% Recovery)	# Deployed	# Retrieved (% Recovery)
RBT Flow Period (Mar 29-Jun 29) 13 weeks	1 & 2	Site 1 (R2-S1)	5	5 (100)	5	5 (100)
		Site 2 (NC-1)	5	5 (100)	5	5 (100)
		Site 3 (NC-2)	5	5 (100)	5	5 (100)
		Site 4 (NC-3)	5	5 (100)	5	5 (100)
Totals			**20**	**20 (100)**	**20**	**20 (100)**

NOTE: Although all samples were successfully retrieved, 1 chlorophyll-a sample was lost due to a laboratory accident at Caro Analytical.

3.5.2 Post Processing

Of the three Styrofoam punches obtained from each artificial substrate, one was frozen and transported to Caro Laboratories in Kelowna, BC for the processing of low-detection limit fluorometric chl-a analysis. The remaining two punches were used for taxonomic identification. Fresh, chilled punches were examined within 48-hours for protozoa and other microflora that cannot be reliably identified from preserved samples. One of the two punches was frozen and stored until taxonomic identification and biovolume measurements could be undertaken. Species cell density and total biovolume were recorded for each sample. A photographic archive was compiled from LCR samples. Detailed protocols on periphyton laboratory processing are available from Larratt Aquatic. The 2022 periphyton dataset was standardized for subsequent analyses.

Following retrieval, fixed benthic invertebrate samples were transported to Cordillera Consulting in Summerland BC. Samples were sorted and identified to the genus-species level where possible following standard procedures. Field samples had organic portions removed and rough estimates of invertebrate density were calculated to determine if sub-sampling was required. After samples were sorted, all macroinvertebrates were identified to species and all micro portions were identified following the Standard Taxonomic Effort lists compiled by the Xerces Society for Invertebrate Conservation for the Pacific Northwest. Species abundance and biomass were determined for each sample. Standard regressions from Benke (1999) for invertebrates and Smock (1980) for Oligochaetes were used to determine biomass estimates. If samples were large, subsamples were processed following similar methods. Detailed protocols on invertebrate laboratory processing are available upon request.

3.5.3 Data Analysis

Data analyses were constrained by the location, arrangement, and timing of samples during 2022. Because each site had a transect of five samplers from shallow to deep, each sample represents a pseudo-replicate. Furthermore, the four sites in Norns Creek fan were sampled in 2022 for the first time, so the resulting dataset did not have sufficient statistical power for the previous analysis method of linear mixed effects models.

To measure productivity in Norns Creek fan and at R2-S1 for 2022, the metrics in Table 3-4 were calculated. We conducted a non-metric multidimensional scale (NMDS) analysis using a Bray-Curtis dissimilarity to evaluate variations in periphyton and invertebrate community compositions. This analysis allows the visualization and interpretation of data from multiple dimensions (e.g., multiple species abundances), in fewer dimensions using rank orders. The NMDS was performed at the family level for both benthic invertebrates and periphyton and evaluated communities in different sites sampled in 2022.

Table 3-4: Metrics for periphyton and benthic invertebrates analysed in 2022.

Variable	Description	Unit
Total Abundance	Total abundance across all species (periphyton and invertebrates)	Invertebrates: #/basket,
Total Biovolume	Total biovolume across all periphyton species	cm^3/m^2
Total Biomass	Total invertebrate biomass for taxa groups	g/basket
Effective Number of Species	A measure of community diversity that is the e^s. S= Shannon-Wiener index.	#
Species Richness	Number of unique species	#
Dominant Taxa	Dominant taxa by biovolume (periphyton), biomass (benthic invertebrates), and abundance	Taxa by cm^3/m^2, taxa by g/basket, and #/basket

3.6 Datasets

The primary datasets collected or generated are summarized in Table 3-5.

Table 3-5: Datasets used or generated as part of the CLBMON-44 2022 Program.

Name/Description	Source	Frequency of Collection	Unit
Physical Datasets			
LCR / Kootenay River Elevation / Water Temperature	Data collected at 5 stations (LCR) and 1 station (Kootenay River)	twice annually	°C
Hourly Discharge from Hugh L. Keenleyside (HLK, HLK + ALS)	Data obtained from BC Hydro	Continuous	m^3/s
Light Intensity, turbidity, and depth profiles	Field data	Collected twice in 2022	Photons m^2/sec, NTU, depth in m
Modelling Datasets			
Hourly depths for 1 m^2 cells	TELEMAC-2D model	April- June 2022	Meters above sea level
Daily chl-a and invertebrate dry weight estimates by 1 m^2 cells	Productivity model	April- June 2022	kg
June 30th total chl-a and invertebrate dry weight estimates	Productivity model	June 30th 2022	kg
Productivity Datasets			
Light / Temp	Data collected at each productivity sampler	2022 spring deployment	PAR, °C
Benthic Invertebrates	Data collected at each productivity sampler. Data includes abundance, biomass, taxonomy and metrics	2022 spring deployment	# individuals/basket, g/basket, # of taxa, dominant taxa
Periphyton	Data collected at each productivity sampler. Data includes abundance, biovolume, taxonomy and chlorophyll-a	2022 spring deployment	# cm^3, cm^3/m^2, # of taxa, dominant taxa, µg/cm^2
Velocity	Data collected at each productivity sampler twice per deployment period	2022 spring deployment	m/s
Substrates	Substrate percentage at each deployment site estimated during deployment	2022	% cover

4 RESULTS AND DISCUSSION

4.1 Mean Daily Water Levels

Level loggers were reinstalled in the same locations as the previous year on March 30, 2022, and the last data download occurred in early October. The level logger at WQIS1 malfunctioned soon after deployment and recorded erroneous data (Figure 4-1). In addition, the data from the Kootenay River site (WQC2) could not be safely downloaded in October 2022 due to low water levels and an inability to access the logger by boat or land (Figure 4-1). The other level loggers at WQIS2-5 appeared to collect accurate elevation and temperature data throughout the deployment period between March and October. Mean daily water levels during the RBT flow period (Apr 1 – Jun 30) were lower than previous years in the LCR and Kootenay rivers; likely driven by the cool spring with minimal rainfall. There was a gradual increase in LCR water elevations near the end of the RBT Flow Period, with the mean daily flows generally exceeding the standard deviation of previous years after July 1.

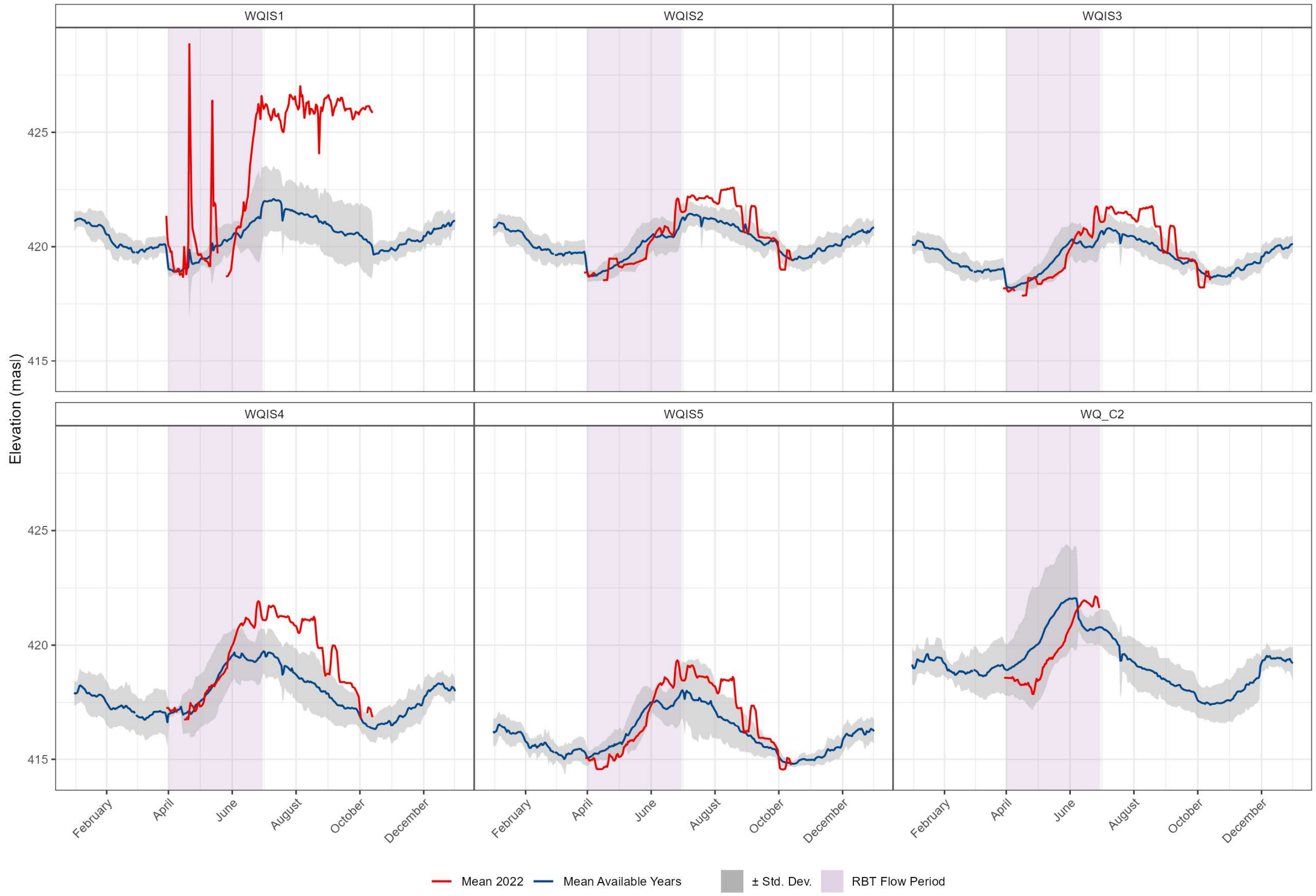

Figure 4-1: Mean daily water levels recorded at WQIS1 – 5 on LCR and at WQ C2 on Kootenay River. The red line depicts the mean daily water level recorded at each site in 2022. The blue line is the mean daily water level for 2008 – 2020 and 2022 for LCR sites and for a ten-year duration (2011-2020, 2022) at the Kootenay River site. Standard deviation is shown in gray to highlight the variation in the data over all years. Note that the S1 sensor malfunctioned shortly after deployment and that WQ_C2 could not be retrieved in October 2022 due to safety concerns.

4.2 Mean Daily Water Temperature

The temperature data at WQIS1 was more reliable in comparison to the elevation data, however there was a temperature peak in mid-April that lasted approximately two weeks and was not observed in the other level logger data (Figure 4-2). This peak also coincided with wide fluctuations in water elevation readings at the same sensor that were not recorded at other sensors. WQIS1 could have been pulled out of the water or otherwise malfunctioned. The mean daily water temperatures varied seasonally ranging from approximately 4 – 17.5°C at LCR sites between April and October. Mean daily temperatures were generally lower than previous years in the LCR and Kootenay rivers (Figure 4-2). Temperatures through April were near previous year means, but temperatures stayed lower through May and June compared to past years (Figure 4-2). In 2022, temperatures during the RBT flow period (Apr 1 – Jun 30) steadily increased from approximately 5-15°C in the LCR and from 5-12.5°C in Kootenay River.

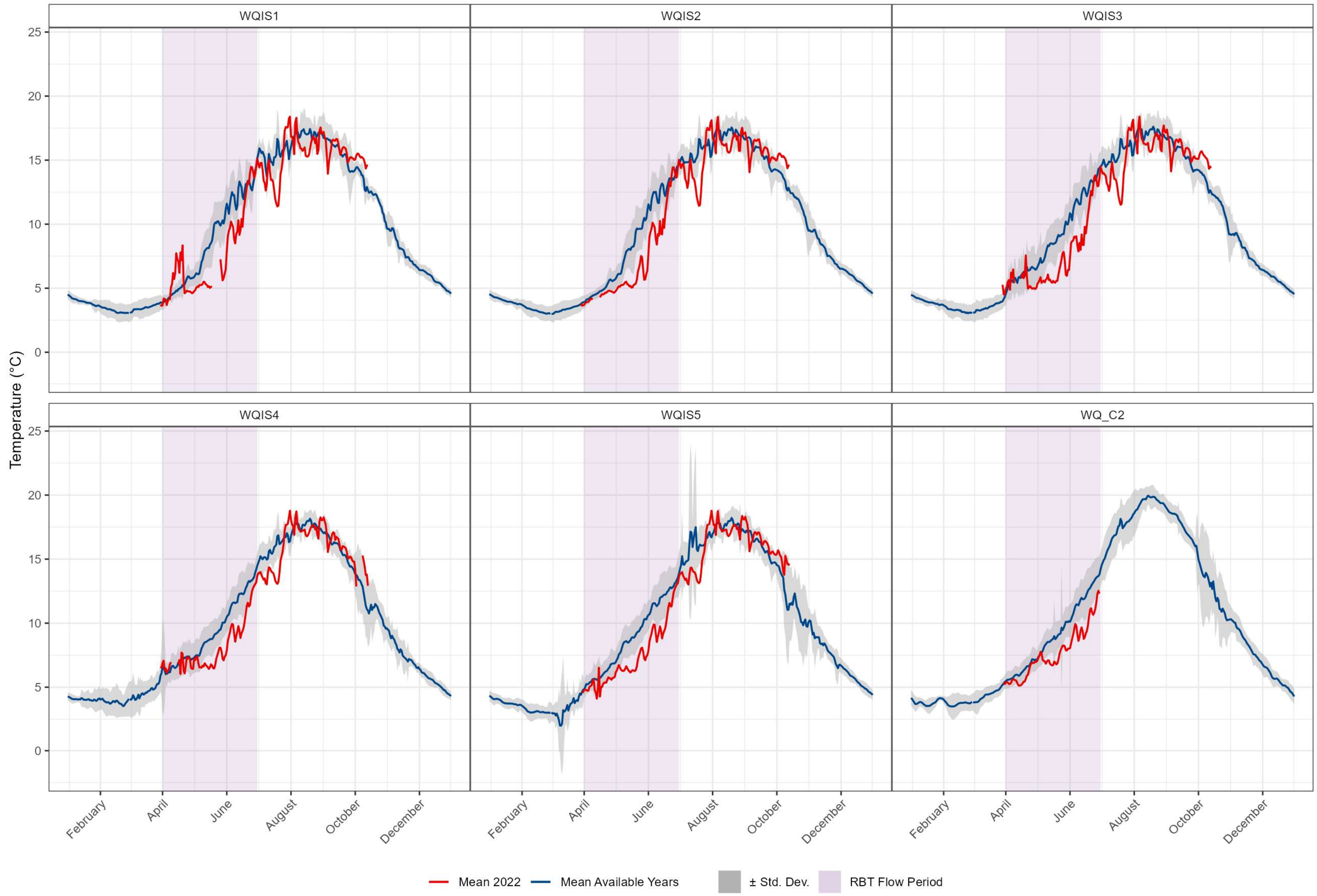

Figure 4-2: Mean daily water temperatures recorded at WQIS1 – 5 on the LCR and at WQ C2 on the Kootenay River. The red line depicts the mean daily water temperature recorded at each site in 2022. The blue line is the mean daily water temperature throughout the duration of the study and the gray area shows the standard deviation.

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 12.1 m - 95% CI 10.6-14.2 (Figure 4-3). The addition of 2022 PAR and turbidity data confirmed previous analyses and reduced model uncertainty. The Norns Creek fan and the control site R2-S1 are always within the photic zone and receive adequate light to support primary productivity. The maximum depth during the RBT flow period of the previously modelled years was 5.5 m on June 29, 1990 (Plewes et al. 2022).

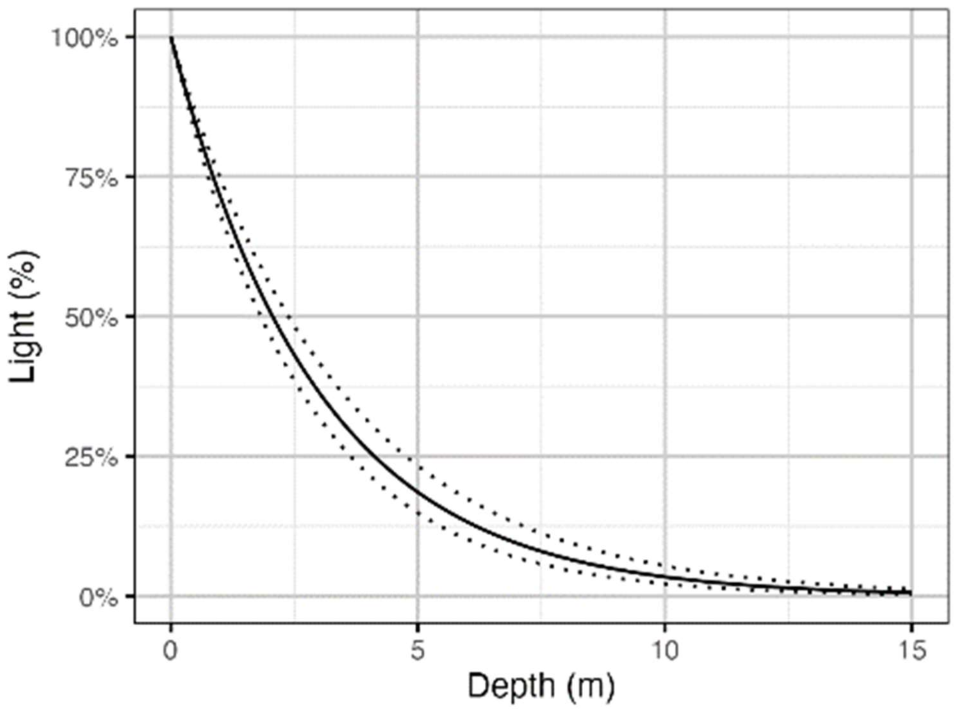

Figure 4-3: Modelled light attenuation by depth based on PAR profiles from the LCR.

4.4 Flow Variability

As expected, HLK daily mean flows were more variable without RBT managed flows (OFF years) compared to years when there was RBT flow management (ON years) during the RBT flow period from April 1 – June 30 (Figure 4-4).The mean coefficient of variation for daily flows was 0.46 ± 0.14 for OFF years and 0.32 ± 0.19 for ON years. Typically, OFF years had higher daily maximum flows and lower daily minimum flows compared to ON years. Flows in 2022 were relatively low compared to other OFF years, with a mean of 746.7 m^3/s and a maximum of 1,764.7 m^3/s. 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 1,981.9 m^3/s in 1988 (Table 4-1).

There were four ON years (1992, 1994, 1996, 2015) when HLK flows exceeded 1,500 m^3/s and were considered high flow years. The WQIS3 logger elevation could not be accurately predicted for years with flows over 1,500 m^3/s, resulting in greater uncertainty in accrual estimates for these years. Thus, high flow years were not included in the productivity modelling. There were four ON years (1992, 1994, 1996, and 2015) when flows exceeded 1,500 m^3/s during the RBT flow period (Table 4-1). The mean daily flows for years selected for the productivity model are shown in Figure 4-5.

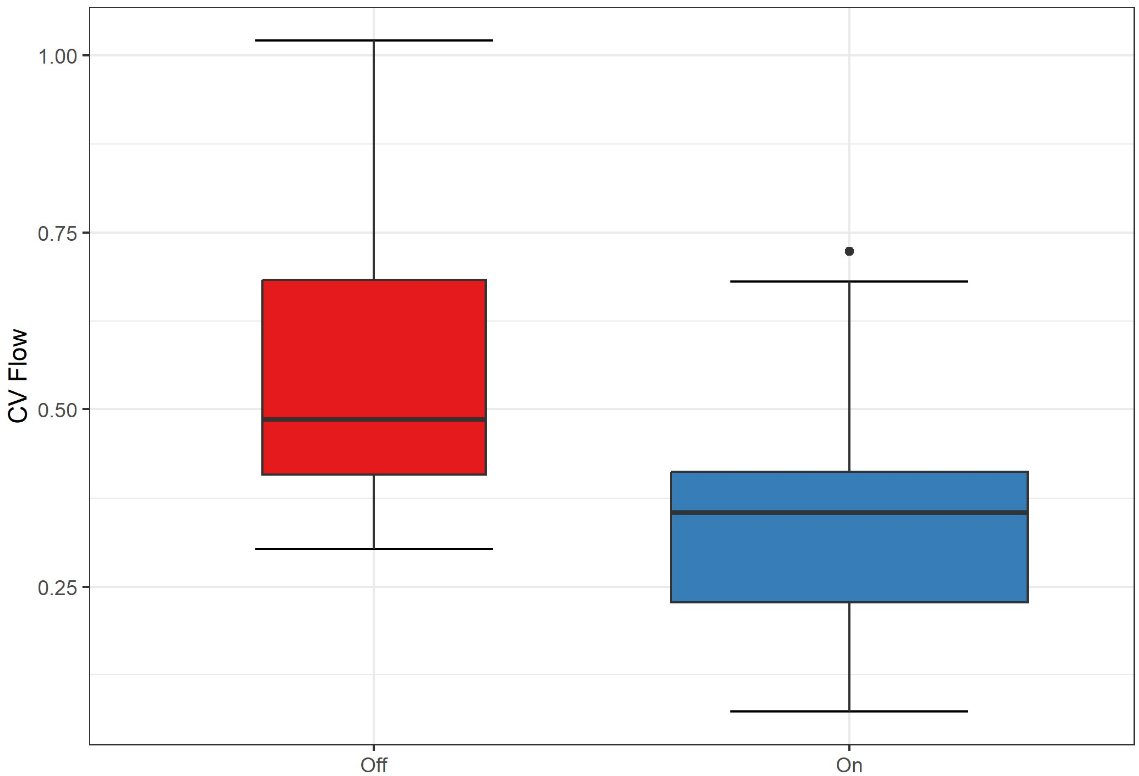

Figure 4-4: Coefficient of Variation (CV) for HLK discharge during OFF years (1984-1991, 2019, 2020, and 2022) and ON years (1992-2018, and 2020).

Table 4-1: Flow metrics for daily mean HLK discharge flows (m³/s) during OFF and ON RBT (Apr 1 – Jun 30) flow years, including standard deviation (SD) and coefficient of variation (CV).

Year	Management	Mean	SD	Median	Min	Max	CV
1984	OFF	480.9	490.7	148.7	138.6	1,480.9	1.0
1985	OFF	512.6	334.7	469.5	140.7	1,277.5	0.7
1986	OFF	665.8	323.5	683.2	185.8	1,429.7	0.5
1987	OFF	874.2	709.9	760.3	138.7	2,544.1	0.8
1988	OFF	721.6	441.3	714.0	140.5	1,981.9	0.6
1989	OFF	588.7	255.5	569.0	227.7	1,094.6	0.4
1990	OFF	623.5	444.5	508.1	219.8	1,673.5	0.7
1991	OFF	1,065.8	323.8	1,116.7	280.6	1,710.9	0.3
1992	ON	1,446.0	984.1	1,093.0	410.7	3,367.1	0.7
1993	ON	377.3	100.0	421.4	221.4	663.9	0.3
1994	ON	817.7	474.3	566.8	141.9	1,981.4	0.6
1995	ON	348.1	192.5	421.2	140.7	910.1	0.6
1996	ON	1,010.8	401.3	987.9	533.6	1,947.2	0.4
1997	ON	753.2	315.9	567.7	424.2	1,335.6	0.4
1998	ON	503.2	111.1	481.7	338.3	1,043.6	0.2
1999	ON	616.3	113.7	571.4	419.3	850.0	0.2
2000	ON	675.8	266.0	567.3	337.1	1,472.0	0.4
2001	ON	923.8	67.9	979.6	838.5	1,003.5	0.1
2002	ON	611.7	360.0	576.4	143.5	2,275.5	0.6
2003	ON	486.6	110.8	426.6	419.2	835.7	0.2
2004	ON	1,371.8	553.2	1,132.8	631.6	2,385.1	0.4
2005	ON	902.7	220.3	851.2	565.4	1,450.0	0.2
2006	ON	880.1	297.1	855.7	421.1	1,747.2	0.3
2007	ON	1,113.5	420.6	1,105.8	426.1	2,575.6	0.4
2008	ON	786.3	125.8	791.7	483.3	1,122.8	0.2
2009	ON	563.6	103.4	514.1	508.3	1,174.7	0.2
2010	ON	572.0	113.8	567.4	422.4	761.9	0.2
2011	ON	1,202.5	315.7	1,036.5	540.3	2,554.0	0.3
2012	ON	1,039.0	425.8	938.3	706.3	2,568.4	0.4
2013	ON	851.6	304.9	755.0	676.5	2,582.8	0.4
2014	ON	814.7	186.1	724.4	559.3	1,505.4	0.2
2015	ON	1,442.9	850.5	975.6	489.2	3,683.0	0.6
2016	ON	1,028.5	744.0	737.6	422.9	2,584.5	0.7
2017	ON	1,112.5	401.4	1,076.9	479.1	1,952.4	0.4
2018	ON	1,008.5	274.6	903.1	452.9	1,699.3	0.3
2019	OFF	624.7	260.2	603.7	294.0	1,147.2	0.4
2020	OFF	917.4	344.9	779.6	427.3	2,009.5	0.4
2021	ON	723.8	253.7	649.2	430.9	1,590.0	0.4
2022	OFF	746.7	298.8	680.3	284.9	1,764.7	0.4

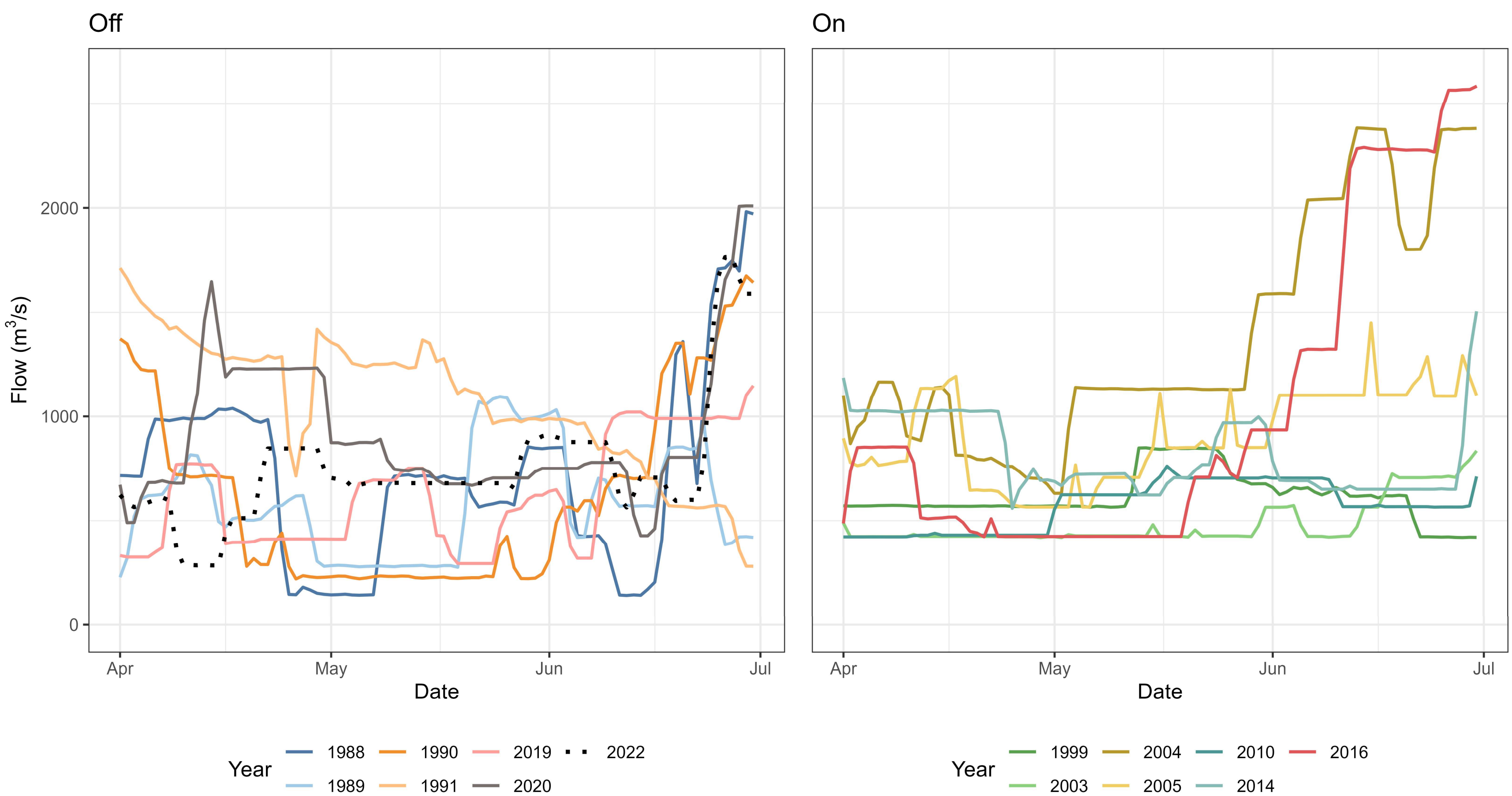

Figure 4-5: Mean daily discharge from HLK for OFF and ON flow years used in the productivity models. Experimental year 2022 (dotted line) was an OFF year.

4.5 Productivity Model 2022

4.5.1 Modelled Chlorophyll-a (chl-a)

Estimated chl-a accrual from April 1 to June 30 2022 (an OFF year) was 22 kg for Norns Creek fan, above the mean of OFF years (16.5 ± 2.6 kg). The mean estimated chl-a accrual in Norns Creek fan on June 30 for ON years was 18.5 ± 3.5 kg (Figure 4-6). The mean chl-a accruals for ON and OFF years were not significantly different (90% C.I. for the true chl-a means, 2-sample t-test, t = 1.05, p-value = 0.156). The power of the t-test was 0.3, meaning there was a 30% chance of detecting a true effect.

In general, years with higher and more stable flows maintained stable wetted areas, had lower periphyton mortality, and thus had higher estimates of chl-a productivity. However, flows and resulting accrual varied by year, even among years of the same flow management type. Years 2020 and 2022 (both OFF years) had flow variabilities similar to many ON years and thus had chl-a biomass accruals similar to most ON years (CV = 0.4). Flows were more stable in 2020 than in most OFF years because it was originally managed as an ON year before changing to OFF flow management. The least productive OFF year remains 1989 with 10.7 kg 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 caused 24 hours of consecutive exposure and resulted in an approximately 50% loss of chl-a biovolume.

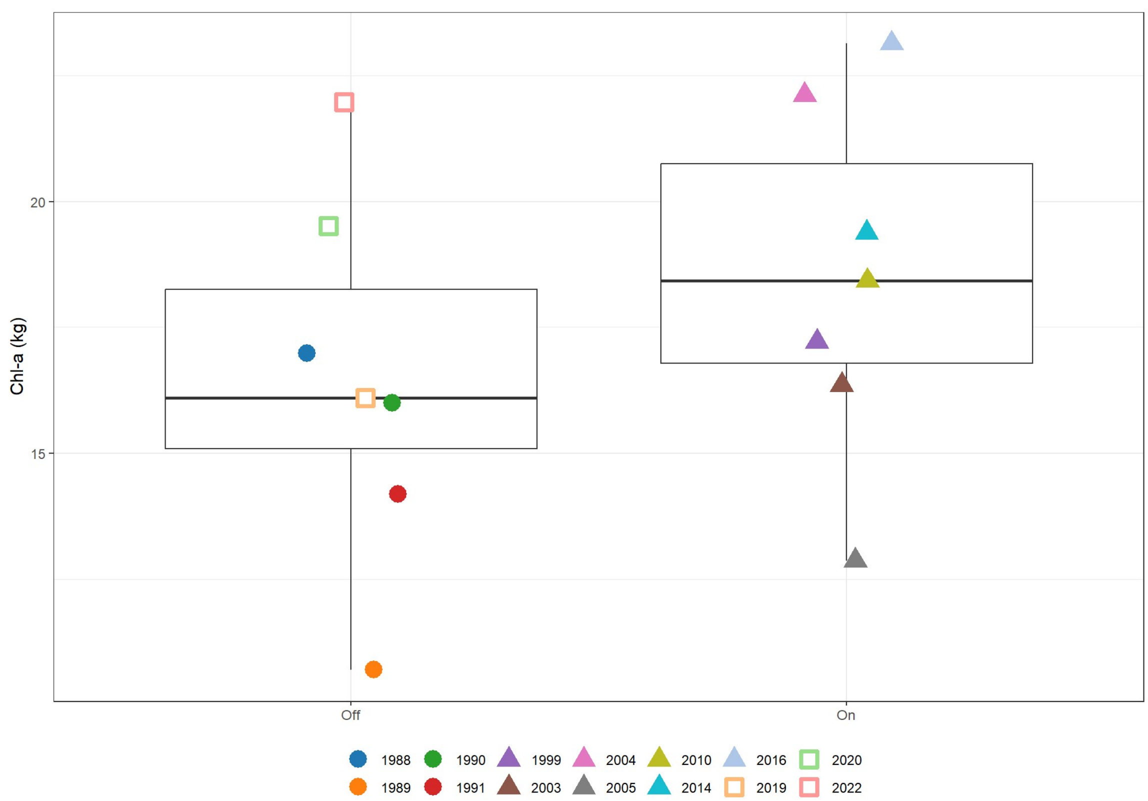

Figure 4-6: Chl-a productivity of Norns Creek fan on June 30th for all survey years when RBT flows were either ON or OFF. Experimental OFF years 2019, 2020, and 2022 are displayed as open squares.

The low maximum daily flows of 761 m^3/s in 2010 and 835.7 m^3/s in 2003 reduced productive habitat area for periphyton throughout the RBT flow period. Estimated chl-a accrual for ON years was highest during 2016 and 2004 with 23.13 kg and 22.1 kg, respectively. These two years also had relatively high mean flows, as well as the highest maximum flows of all ON years (Figure 4-5). The OFF years with the highest chl-a biomass accrual were 2022 and 2020 with 22 kg and 19.5 kg, respectively. These years had relatively high maximum flows, with a maximum of 1,764.7 m^3/s in 2022 and 2,009.5 m^3/s in 2020.

4.5.2 Modelled Invertebrate Biomass

In 2022, June 30th estimated benthic invertebrate biomass accrual was 279.3 kg for Norns Creek fan. The mean estimated benthic invertebrate biomass accrual in the Norns Creek fan between April 1st and June 30th for OFF years was 208 ± 47.5 kg and 254 ± 48.5 kg for ON years (Figure 4-7). Benthic invertebrate biomass accrual was significantly higher for ON years than OFF years (90% C.I. for the true chl-a means, 2-sample t-test, $t = 1.801$, p-value = 0.048). The power of the t-test was 0.6, meaning there was a 60% chance of detecting a true effect. The statistical significance of the difference in total biomass accrual between ON and OFF years is lower than previous reports due to a revision of discharge data from previous study years.

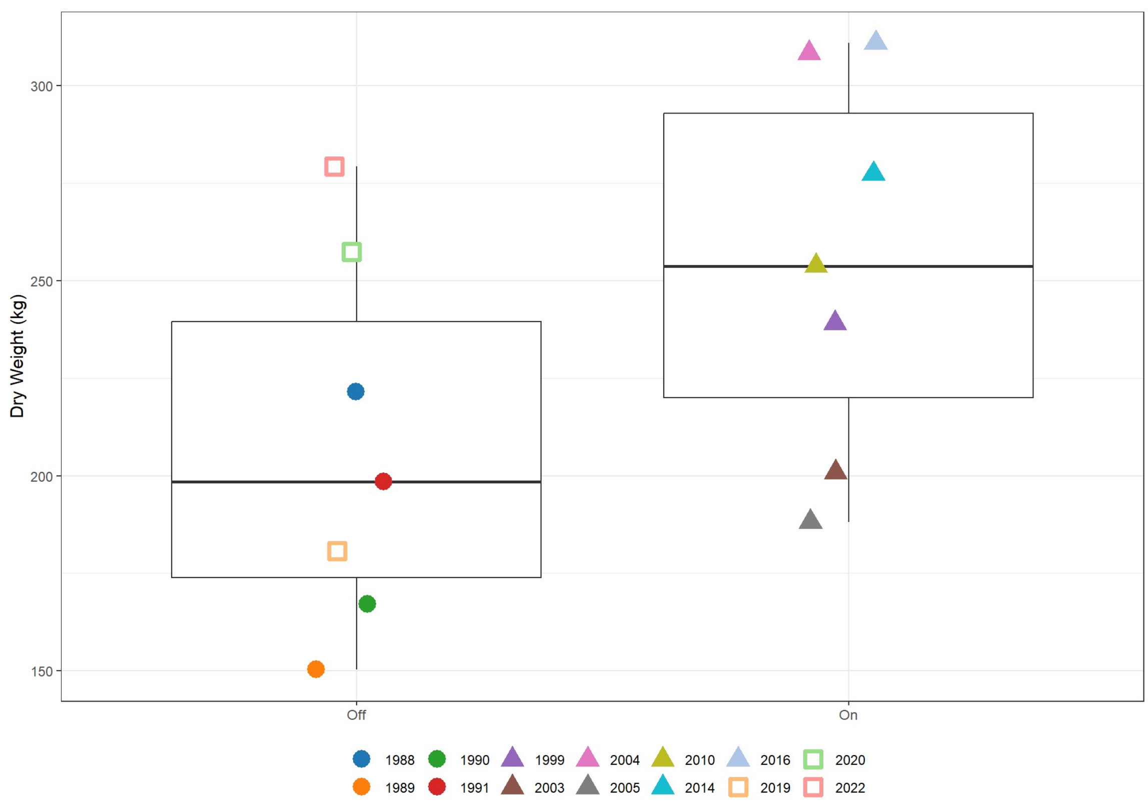

Figure 4-7: Invertebrate biomass (kg) accrual between April 1st and June 30th in all years as predicted by the productivity model. Experimental years (2019, 2020, and 2022) are depicted as open squares.

Like chl-a production, the most productive years for benthic invertebrates were years with the most stable flows. Stable flows increased the available area for invertebrate colonization and reduced mortality due to sudden dewatering, and thus increased invertebrate biomass. The invertebrate biomass accrual for ON years ranged from 188 kg in 2005 to 311 kg in 2016. During RBT OFF years, the estimated invertebrate biomass ranged from 150 kg in 1989 to 279 kg in 2022 (Figure 4-7). The most productive OFF years were 2020 and 2022, which had relatively high maximum flows of 2,010 m^3/s and 1,765 m^3/s, respectively. The most productive ON years were 2016 and 2004, which had maximum flows of 2,584.5 m^3/s and 2,385.1 m^3/s, respectively. Years with the lowest estimated biomass also had the lowest flows.

4.5.3 Productivity Model Summary

Estimated chl-a accruals did not differ significantly between ON and OFF years. Overall, estimated benthic invertebrate production was higher in ON years than OFF years. RBT flows are higher and more stable than standard operations flows and result in higher water levels, less substrate dewatering, and more productive area. Thus, ON years create more productive and more stable habitat for colonization and higher benthic invertebrate accrual. High variability among flows of the same management type makes patterns of differences in accrual between ON and OFF years difficult to detect.

4.6 Norns Creek Fan Benthic Productivity

4.6.1 Norns Creek Fan Periphyton

The spring 2022 samples were collected during an algae bloom of a diatom, *Didymosphenia geminata*(Didymo) and a filamentous green alga, *Ulothrix*. These taxa can generate filament masses that impact the periphyton community. Didymo blooms are also patchy, which increases variability. For example, the two NC-1-MS Styrofoam punches drawn from the same sampler plate had very different Didymo thicknesses, so the taxonomist combined them to help reduce sample variation. The timing of this Spring sampling effort preceded the 2022 freshet, thereby capturing the winter period which has been shown to have high productivity in LCR (Olson-Russello et al. 2019; Plewes et al. 2017).

The Didymo/Ulothrix bloom and relatively stable flows caused unusually high periphyton observations in the field and in the lab assessments (Figure 4-8). Didymo and Ulothrix are common in the LCR, but a bloom of this magnitude has not been observed during any other survey year of this project over the last decade. For example, at R2-S1, the MS depth chl-a biovolume was similar to previous years while MD and D samplers with Didymo noted in the samples were significantly more productive (Figure 4-9). Didymo filaments inflated productivity metrics because they created structure for small algae attachment, resulting in increased overall abundance where bloom masses were present. Didymo coverage was greatest at MD (1.6-2.2-4.8 m depth range) and D (2-4.5-7 m depth range) sample depths, and it tapered to low densities in shallow water on the Norns Creek fan and adjacent R2-S1.

Figure 4-8: A Periphyton sampler retrieved in June 2022 with extensive Didymo accumulation.

Abundance, biovolume and chl-a results indicated large periphyton standing crops during spring 2022 (Figure 4-9). NC-2 was productive, while NC-3 demonstrated comparatively low periphyton productivity. The chl-a results confirmed that NC-3 was a lower productivity site, while NC-1 productivity was similar to the adjacent control R2-S1 site with cobble substrate. All three productivity metrics indicated that NC-2 supported a heavy periphyton layer.

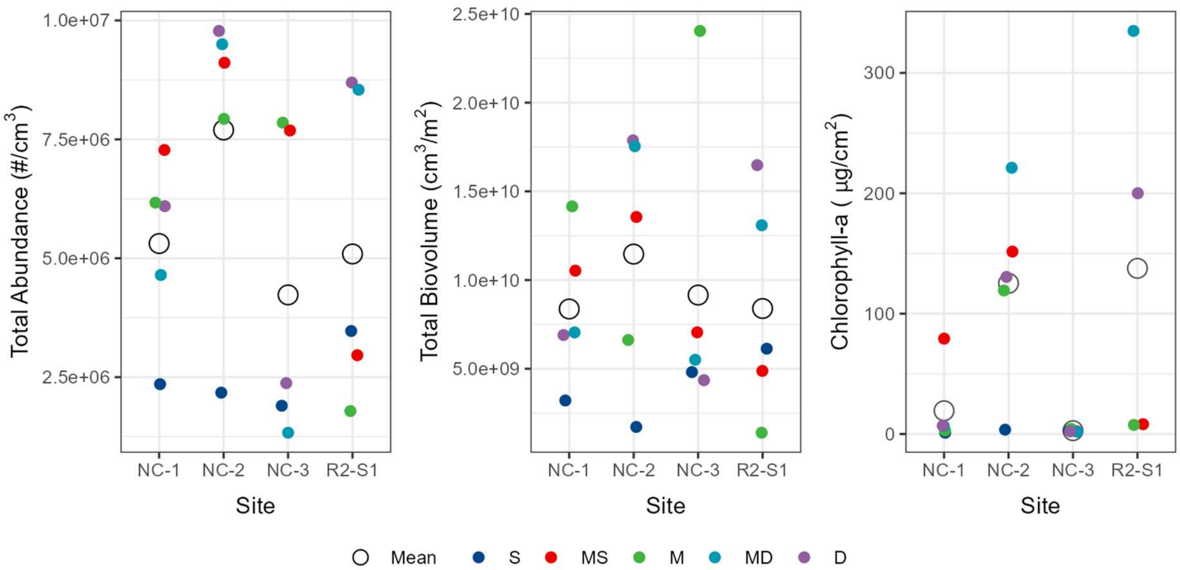

Figure 4-9: Periphyton productivity metrics of total abundance, total biovolume, and chlorophyll-a for Norns Creek fan and R2-S1 (control site) in spring 2022. Site means are indicated with a hollow circle.

The productivity metrics from Spring 2022 Norns Creek fan exceed the typical LCR values. Compared to other large rivers, these values would place the 2022 Norns Creek fan data in the eutrophic or highly productive category (Table 4-2). The Didymo/*Ulothrix* bloom likely inflated the Spring 2022 periphyton productivity results.

Table 4-2: Summary of typical LCR periphyton metrics from 2008 to 2016, and metrics from oligotrophic, typical, and eutrophic systems.

Metric	Oligo-trophic or stressed	Typical large rivers	Eutrophic or productive	LCR 2008 – 2016 (median)	Norns Creek Fan Spring 2022 (median)
Number of taxa (live & dead)	<20 – 40	25 - 60	variable	8 – 60 (31)	31-51 (42)
Chlorophyll-a (µg/cm²)	<2	2 - 5	>5 – 10 – 30+	0.01 – 55 (3.6)	1.1 – 221 (44)
Algae density (cells/cm²)	<0.2 x10⁶	1 - 4 x10⁶	>10 x10⁶	0.03–3.9 x10⁶ (0.8x10⁶)	1.3 – 9.8 x10⁶ (6.2x10⁶)
Algae biovolume (cm³/m²)	<0.5	0.5 – 5	20 - 80	0.1 – 25 (3)	17 – 240 (70)

Comparison data obtained from Biggs and Close 2006; Biggs 1996; Durr and Thomason 2009; Flinders and Hart 2009; Freese et al. 2006; Peterson and Porter 2000; Romani 2010.

Of the three-productivity metrics, chl-a varied the most between sites in the Spring 2022 data (Figure 4-9). Norns Creek fan periphyton productivity in 2022 ranged from half to 16 times the historic chl-a of R2-S1. There was also a large increase in periphyton abundance and biovolume in 2022, driven by the Didymo/Ulothrix bloom. At all LCR sites in all studied years, diatoms dominated periphyton abundance. Diatoms accounted for 90 – 97% in Norn's Creek fan samples and 88% in the control site R2-S1 samples from Spring 2022. Of these, the low profile, ubiquitous *Achnanthidium* taxa was most abundant in every sample (Table 4-3). *Achnanthidium* prevalence indicates a variable lotic environment because they are small, rapid re-colonizers.

Table 4-3: Dominant periphyton taxa in spring 2022 determined by abundance for each site.

	Reach-Site			
Dominant Taxa Rank	NC-1	NC-2	NC-3	R2-S1
1	*Achnanthidium minutissimum*	*Achnanthidium minutissimum*	*Achnanthidium minutissimum*	*Achnanthidium minutissimum*
2	*Achnanthidium linearis*	*Cyclotella atomus*	*Staurosira construens*	*Encyonema reichardtii*
3	*Staurosira construens*	*Achnanthidium linearis*	*Achnanthidium linearis*	*Encyonema minutum*
4	*picoflagellates*	*Staurosira construens*	*Encyonema reichardtii*	*Cyclotella atomus*
5	*Encyonema minutum*	*Encyonema reichardtii*	*Cyclotella atomus*	*Achnanthidium linearis*
6	*Cyclotella atomus*	*Achnanthidium gracillimum*	*Eucocconeis flexella*	*Encyonema silesiacum*
7	*Achnanthidium gracillimum*	*Encyonema minutum*	*Achnanthidium gracillimum*	*picoflagellates*
8	*Encyonema reichardtii*	*Eucocconeis flexella*	*Synechocystis cf. diplococcus*	*Staurosira construens*
9	*Eucocconeis flexella*	*Eunotia bilunaris*	*Eunotia bilunaris*	*Fragilaria capucina*
10	*Eunotia bilunaris*	*Cymbella minuta*	*Fragilariforma virescens*	*Synechocystis cf. diplococcus*

Diatoms accounted for 56% of biovolume at NC-3, compared to 82% at NC-1, 88% at NC-2 and 89% at R2-S1. Large filamentous green algae in NC-3 at the MS and M depths made up 44% of the biovolume in these samples. Green algae accounted for 10 – 17% at the other sites and was prevalent at the M, MS, and S sample depths. In all cases, cyanobacteria accounted for less than 1% of the sample periphyton biovolume and was especially low in the fine sandy substrates. Minor amounts of the other algae classes were represented in the Norns Creek fan samples.

The large filamentous Didymo and *Ulothrix* were the first and second taxa ranked by biovolume at the Norns Creek fan and R2-S1 (Table 4-4). These two algae are high profile taxa that would be sheared off by high flows, indicating that flows sufficient to shear these filaments had not yet occurred when these samplers were retrieved. Dominant taxa by biovolume also reflected the importance of large diatoms which are good forage for invertebrates. Large, motile diatoms such as *Cymbella*/*Encyonema* were prevalent in the sandy substrates of the Norns Creek fan because they can move upward as sand deposits. Epilithic diatoms such as *Staurosira* and *Eunotia* were well represented. Non-motile diatoms from upstream reservoirs were also important in these samples, notably the centric *Cyclotella, Melosira, Lindavia* families.

Table 4-4: Dominant periphyton taxa in spring 2022 determined by biovolume for each site.

	Reach-Site			
Dominant Taxa Rank	NC-1	NC-2	NC-3	R2-S1
1	Didymosphenia geminata	Didymosphenia geminata	Ulothrix zonata	Didymosphenia geminata
2	Ulothrix zonata	Ulothrix zonata	Didymosphenia geminata	Ulothrix zonata
3	Melosira varians	Discostella stelligera	Tabellaria flocculosa	Surirella undulata
4	Tabellaria flocculosa	Tabellaria flocculosa	Staurosira construens	Melosira varians
5	Cymbella cistula	Melosira varians	Cymbella cistula	Cocconeis placentula
6	Ulnaria ulna	Ulnaria ulna	Cocconeis placentula	Cymbella cistula
7	Staurosira construens	Cymbella neocristula	Tabellaria fenestrata	Discostella stelligera
8	Tabellaria fenestrata	Cyclotella atomus	Discostella stelligera	Encyonema silesiacum
9	Staurosirella leptostauron	Lindavia bodanica	Staurosirella leptostauron	Tabellaria flocculosa
10	Achnanthidium linearis	Cymbella cistula	Cymbella aspera	Cymbella aspera

Species richness is the number of novel species, regardless of their abundance. The site with the highest species richness was NC-2 had the highest species richness (41 – 54 species), and the site with the lowest species richness was NC-3 (30 – 40 species). The frequency-based Simpsons Index also showed the greatest diversity at NC-2 and the lowest at NC-3. The true diversity metric, effective number of species, again showed the greatest diversity at NC-2, and the lowest diversity at NC-3. While the other diversity measures showed the Norns Creek sites were similar to the control site R2-S1, the effective number of species indicated that NC-3 was a unique periphyton population (Figure 4-10).

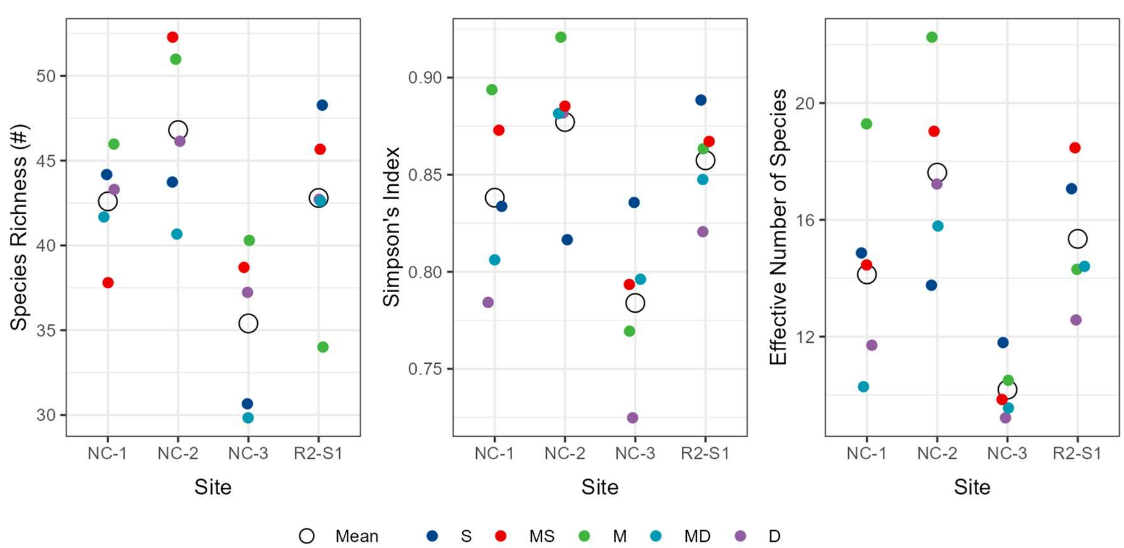

Figure 4-10: Periphyton diversity metrics species richness, Simpson's index, and effective number of species for Norns Creek fan and R2-S1 in spring 2022. Site means are indicated with a hollow circle.

An NMDS analysis conducted at the family level demonstrated substantial overlap in periphyton community structure between sites (F = 1.20, R^2 = 0.18, p = 0.30) and depths (F = 1.45, R^2 = 0.28, p = 0.21; Figure 4-11).

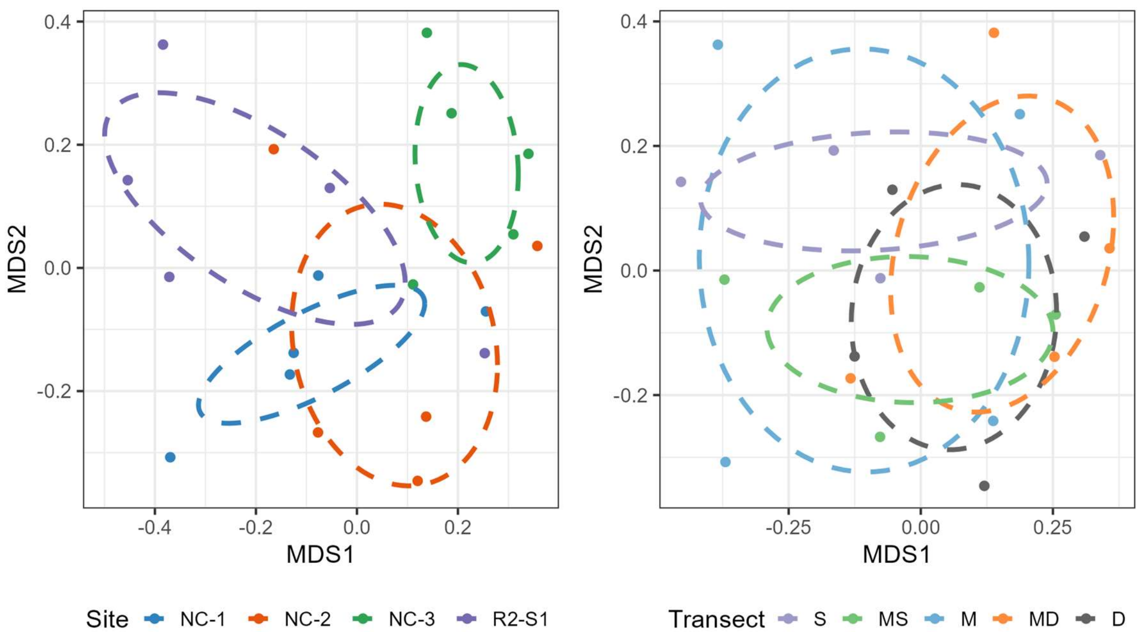

Figure 4-11: NMDS analysis of periphyton community composition by site and transect for spring 2022 periphyton.

As is often the case in the LCR and in large rivers generally, the most productive periphyton habitat occurs where ideal flow-driven velocities, light and minimal dewatering intersect. The most important factor influencing the Norns Creek fan periphyton in spring 2022 was the Didymo bloom. Together with the filamentous green algae *Ulothrix*, these filaments inflated the productivity metrics to levels not previously seen in the LCR (Table 4-1). The critical habitat features for these two taxa include full sunlight, stable substrates, and most importantly, stable flows. Didymo mats affect food web structure and ecological functioning (Cullis et al. 2013).

Didymo removal requires flood events sufficiently large to result in physical bed disturbance that scours the periphyton mats (Cullis et al. 2013). Approximate near-bed flow velocities required to remove Didymo and filamentous algae mats are greater than 0.2 m/sec (Figure 4-12). Relatively stable flows below HLK may have encouraged the Didymo/Ulothrix bloom observed in Spring 2022 samples. Regardless of flow management, the intensity of Didymo blooms varies from year to year. Over the decade of study in LCR, two winter/spring Didymo blooms were observed, while the other years had much lower Didymo abundance.

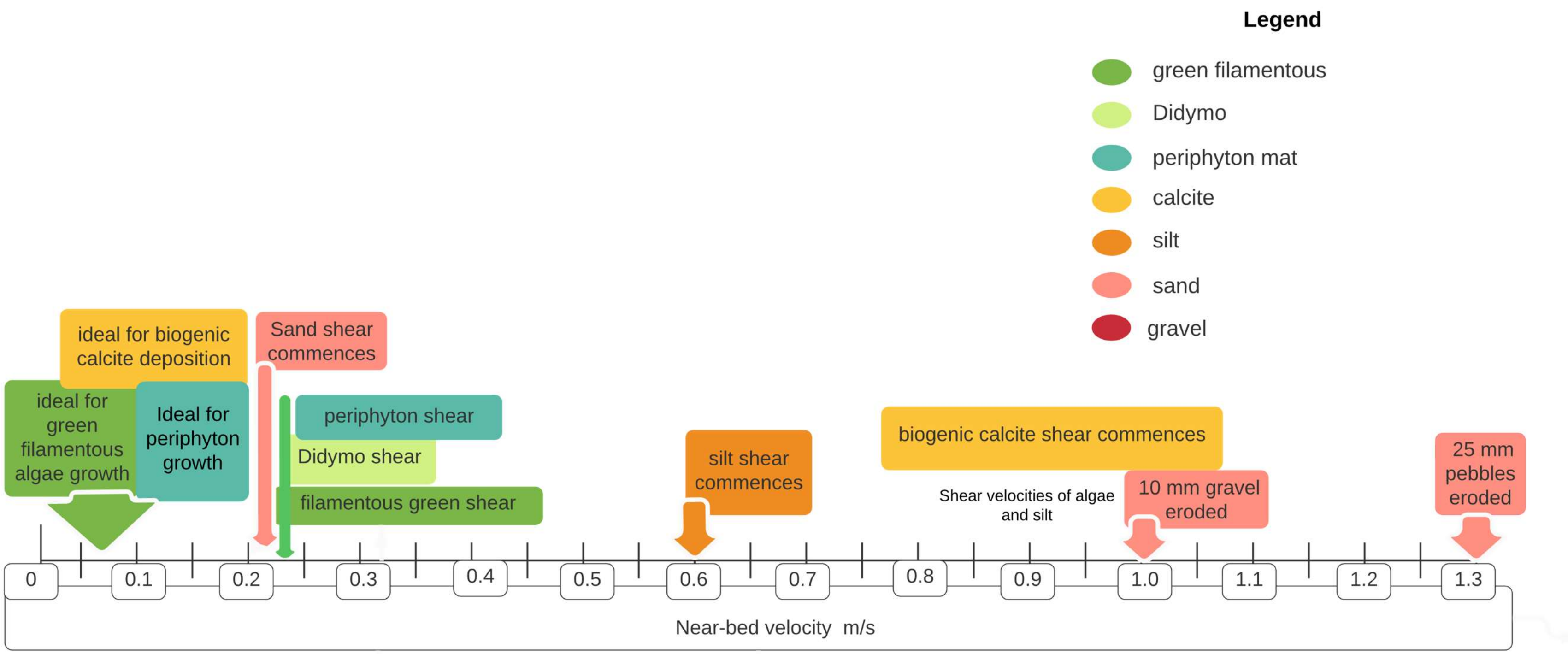

Figure 4-12: Typical shear velocities of periphyton and substrates in rivers.

4.6.2 Benthic Invertebrates

The following section presents the spring 2022 benthic invertebrate sampling results, community analysis, and interim qualitative comparison with other sites in the LCR that were sampled in previous years and seasons.

4.6.2.1 Benthic Invertebrate Community Metrics

Invertebrate community structure varied between sites. Taxa richness was highest in 2022 at NC-2 with a mean of 24.2 families and was second highest at NC-3 with a mean of 23.8 families. NC-1 had a mean of 19 families, and the R2-S1 control site had 20.8 families. The dominant taxa (family) at all 4 sites in the spring sampling were *Chironomidae* followed by the clitellate oligochaete worm *Naididae* and the mayflies *Ephemerellidae* (Figure 4-13).

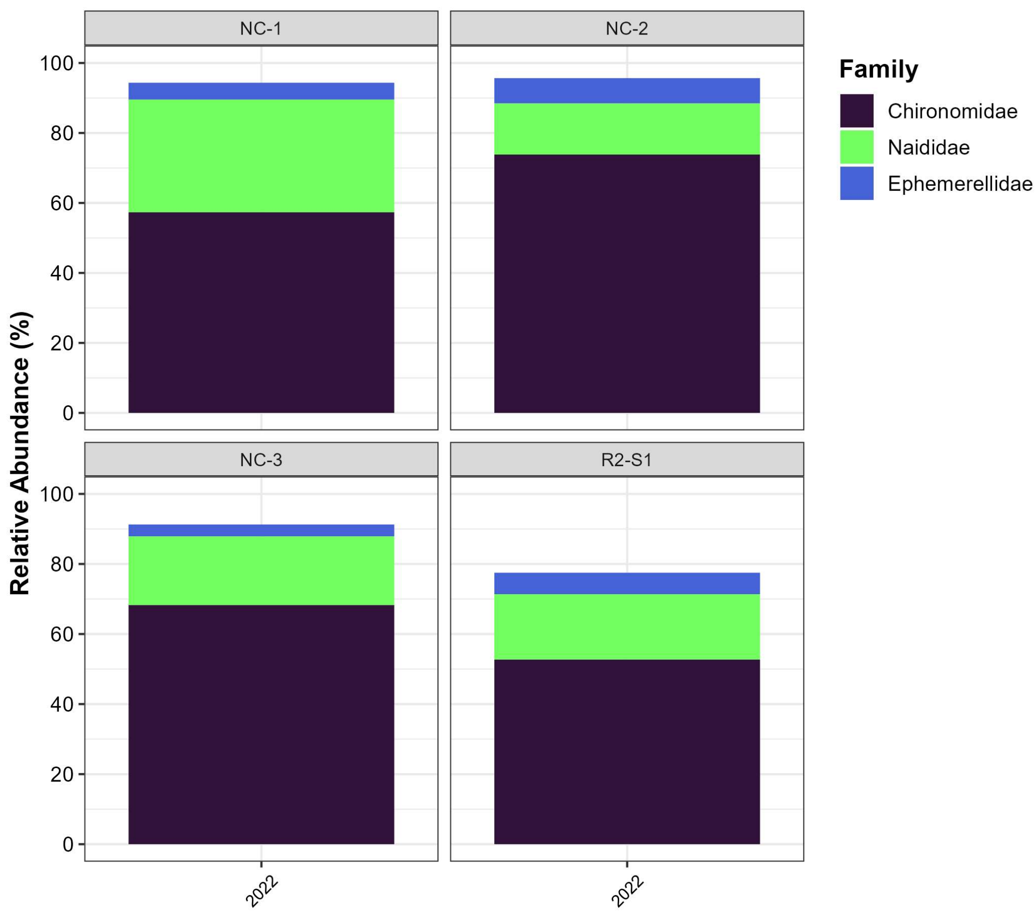

Figure 4-13: Dominant taxa by relative abundance during the spring season in 2022 for Norns Creek fan sites and R2-S1.

Despite the similarities in the dominant taxa during the spring sampling, the community assemblages were different between the Norns Creek fan sites and the R2-S1 control, as well as the other LCR sites (i.e., S2-S7) sampled previously. *Chironomidae* has been the dominant taxa in all sites expect S5 and S7 across all years and seasons sampled (Figure 4-13). While *Naididae* worms were the second dominant taxa in Norns Creek fan sites, R2-S1 and all other downstream sites in previous studies demonstrated codominance or dominance of *Trichoptera*, notably the net-spinning caddisfly (*Hydropsychidae*). Unlike the Norns sites, *Naididae* accounted for less than 5% relative abundance at the other sites downstream, which had blackflies (*Diptera*, *Simuliidae*) representing the third most dominant taxa. Norns Creek fan and R2-S1 were sampled during spring in 2022, while other benthic studies on the LCR were carried out in summer, fall and winter. This seasonal variation in sampling may explain some of the observed differences in benthic invertebrate communities.

Table 4-5: Mean percentage composition of dominant taxa across all seasons, 8 study years, and from all 5 samples in a site (i.e., S, MS, M, MD, and D). Dominant taxa are shaded and bold and second dominant taxa are shaded.

	Sites									
Dominant Taxa	**NC1**	**NC2**	**NC3**	**R2-S1**	**S2**	**S3**	**S4**	**S5**	**S6**	**S7**
Percent Chironomidae	**56.8**	**72.8**	**69.6**	**38.3**	**47.6**	**43.6**	**40.2**	25.7	**51.6**	30.5
Percent Naididae (oligochaete worm)	33.6	14.5	18.0	3.7	3.1	0.8	3.2	0.5	5.0	2.0
Percent Ephemeroptera	4.1	7.8	4.0	2.7	3.7	5.5	7.9	4.0	4.8	7.0
Percent Trichoptera	1.9	2.1	4.2	26.5	26.4	33.2	27.3	**43.3**	17.0	**35.3**
Percent Diptera	2.3	1.2	1.3	19.6	5.3	7.6	11.0	23.1	4.5	18.7
Percent Gastropoda	0.0	0.0	0.0	4.3	6.3	5.5	8.2	2.1	3.3	4.4
Percent Non-dominant Taxa	1.3	1.6	2.9	4.9	7.6	3.8	2.2	1.3	13.8	6.5

Benthic Invertebrate diversity (richness) showed a temporal pattern depending on the sampling date (e.g., season and year). Observed Family and EPT Richness were higher for samples obtained in late summer and early fall (September or October), compared to samples obtained in late winter – early spring.

The different distribution of functional feeding groups is tied to the distribution of dominant taxa (Table 4-5). The presence and relative abundance of different functional feeding groups is an indication of the physical habitat attributes that separate each of the sites (e.g., habitat structure heterogeneity, velocity, presence of coarse and fine particulate organic matter, and periphyton growth). Gatherers and collector-gatherers combined to form over 90% of the community in the Norns fan sites (Table 4-6). Invertebrates belonging to these functional feeding groups, *Chironomidae*, mayflies (*Batidae* and *Ephermerella*), *Naididae*, and casemaker caddisflies (*Brachycentridae*), collect fine particulate organic matter from the stream bottom.

In contrast to the Norns sites, R2-S1 was dominated by filterers in the spring 2022 sampling. Similarly, filterers dominated other LCR sites (e.g., S3, S4, S5, S7), sampled in previous years and seasons. Filterers collect fine particulate (drift) from the water column. In the LCR, net-spinning caddisflies (*Hydropsychidae*) and blackflies (*Simuliidae*) dominate this group.

Scrapers (grazers) were nearly absent from the Norns sites but represented over 4% of the community in R2-S1 in spring 2022. Scrapers consume periphytic algae and associated material of the biofilm. The near absence of this feeding group in the Norns sites in contrast with other sites (i.e., R2-S1) is an indication that these habitats are physically different. This group is dominated by gastropods (i.e., snails), which depend on the larger, more stable substrates. These coarser and more heterogenous habitats provide increased initial habitat and experience less saltation that combine to support improved periphyton growth.

Predators, including the bloodworm (*Chironomidae*, *Procladius*), water mite (*Sperchonidae*), and *Hydra*, as well as shredders, which consume leaf litter and coarse particulate organic matter were more prevalent in R2-S1 than in the Norns Sites. The near absence of these feeding groups from the Norns sites is another indication the habitat structure differs. In Norns Creek fan, smaller pebble and gravel substrates provide less interstitial habitat and a lower substrate roughness coefficient compared to R2-S1.

Table 4-6: Functional feeding group mean relative distribution by percentage by site with all years, seasons, and samples (i.e., S, MS, M, MD, and D).

Dominant Feeding Groups	Sites									
	NC1	NC2	NC3	R2-S1	S2	S3	S4	S5	S6	S7
Gatherer	56.4	53.4	50.2	34.0	45.6	41.2	38.1	20.7	54.8	29.4
Collector-Gatherer	38.2	41.3	40.4	9.2	6.9	6.5	11.6	8.1	7.1	9.1
Filterer	4.3	3.4	5.3	46.1	32.4	41.3	38.1	66.9	19.1	53.9
Predator	0.9	1.5	3.3	3.0	5.9	3.6	2.2	1.4	11.1	1.9
Scraper	0.0	0.1	0.1	4.5	6.7	5.6	8.5	2.2	3.8	4.6
Shredder	0.0	0.0	0.1	1.8	2.0	1.4	0.9	0.6	1.2	0.7

Despite variations in overall taxa richness, dominant taxa by abundance were consistent throughout all sites sampled in 2022. Chironomidae were the most abundant family, followed by *Naididae*, and then *Ephemerellidae* (Table 4-5). When dominant taxa were determined by biomass, *Trichoptera*, *Ephemeroptera*, and *Chironomidae* were the dominant taxa. Species can vary widely in mass, so considering both abundance and biomass is important when determining community composition from the perspective of productivity. Dominant taxa remained similar to past study years, with Chironomids dominating abundances (Olson-Russello et al. 2019). Benthic invertebrate community assemblage varies with season and year, so data from spring for 2022 alone offers a limited snapshot of benthic invertebrate communities.

Similar to EPT biomass, EPT richness was highest at R2-S1 with 8.2 mean taxa. Mean EPT richness was next highest at NC-3 with 6.6 taxa and NC-2 had a mean of 5.2 taxa. Shannon diversity was highest at R2-S1 with 2.32, followed closely by NC-3 with 2.26.

Table 4-7: Means of community metrics by site aggregated across all years, seasons, and samples at each site (i.e., S, MS, M, MD, and D). The shaded sites represent those sampled in the spring 2022.

Site	Total Abundance	Taxa Richness	Effective Species (Diversity)	Hilsenhoff Biotic Index	EPT Richness
NC1	3432.4	19.0	6.2	6.9	4.8
NC2	2078.8	24.2	9.4	5.6	5.2
NC3	1373.4	23.8	9.7	6.0	6.6
R2-S1	5812.5	19.4	7.9	5.1	5.8
S2	4113.9	23.6	8.0	5.5	5.7
S3	5796.7	19.3	6.7	4.9	5.8
S4	4721.2	22.0	8.5	4.9	7.0
S5	8934.9	17.1	5.3	4.8	5.7
S6	1616.2	29.1	11.7	5.4	6.4
S7	7099.6	20.9	7.5	4.8	6.7

4.6.2.2 Benthic Invertebrate Community Composition

NMDS analysis by invertebrate family showed invertebrate communities differed significantly between Norns Creek fan sites and the R2-S1 main-channel site (R^2 = 0.31, F = 8.03, p = 0.002). Invertebrate communities were also significantly different between sites (R^2 = 0.55, F = 6.48, p = 0.001) in 2022 (Figure 4-14). Communities within the same site did not differ by transect (R^2 = 0.12, F = 0.51, p = 0.88).

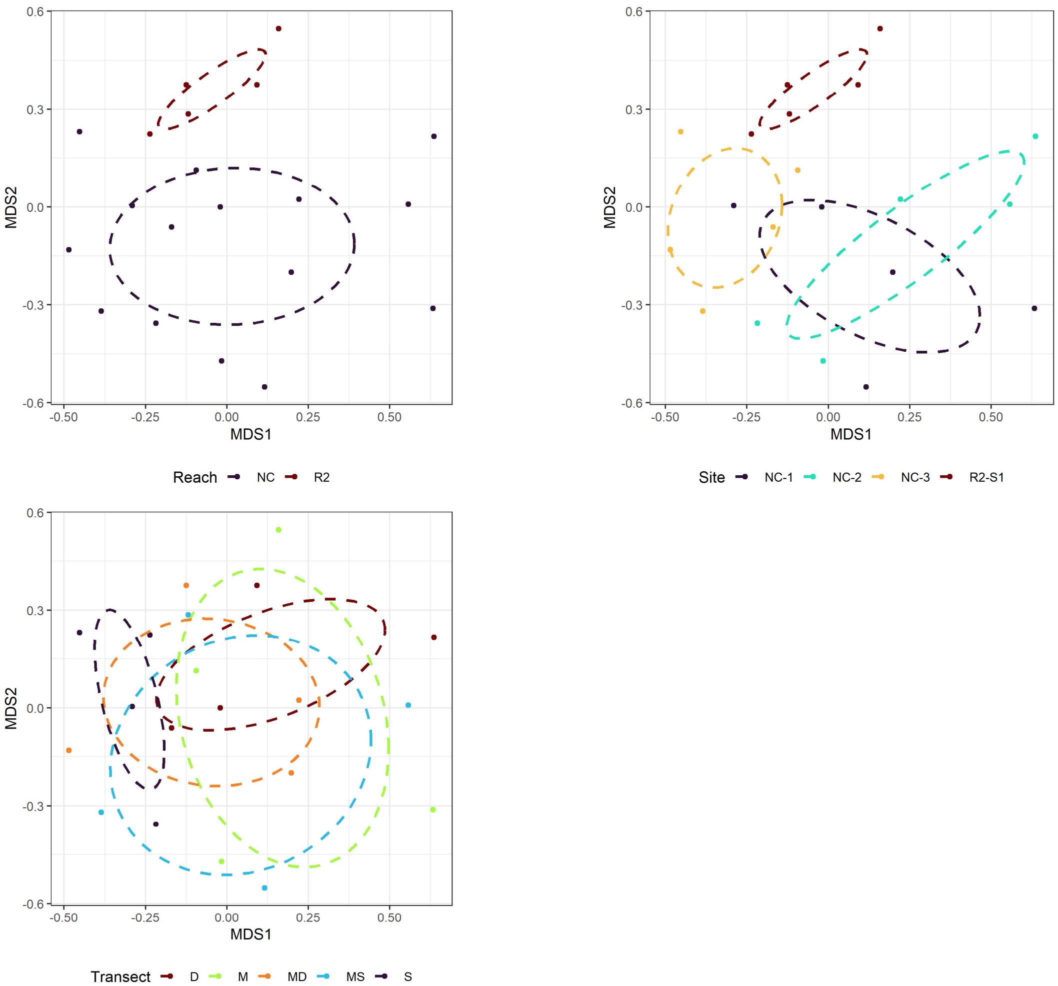

Figure 4-14: NMDS analysis of benthic invertebrate community composition by reach, site, and transect for spring 2022.

While overall biomass and EPT biomass were higher at R2-S1, taxa richness was higher in NC-2 and NC-3. Sites with faster flow velocity and larger substrates like R2-S1 tend to support more EPT taxa, while sites with more sediment and slower flows have a higher diversity of other taxa, as observed in the Norns Creek fan sites. This difference in community was reflected in the NMDS analysis, which showed a signifcant difference between Norns Creek fan sites and the R2-S1 site in the main channel. Benthic invertebrate communities within the Norns Creek fan were more similar to each other than they were to the community in R2- S1.

Overall, the benthic invertebrate community reflected an assemblage characteristic of regulated rivers. The most dominant taxa were those that can tolerate changes in flow and temperatures, and can survive and recolonize quickly following periods of dewatering, including *Naididae*, *Chironomidae*, and *Ephemeroptera* (Brittain and Saltveit 1989, Lancaster and Ledger 2015, Munn and Brusven 1991, Walters and Post 2011).

4.6.2.3 Benthic Invertebrate Productivity

The R2-S1 control had a mean benthic invertebrate biomass that was over 3.6 times higher than the mean invertebrate biomass of the Norns Creek fan. The mean invertebrate biomass in spring of 2022 in the Norns Creek fan was 0.24 g/basket and the mean biomass in the R2-S1 control area was 0.87 g/basket (Figure 4-15). Mean biomass among Norns Creek fan sites was highest at NC-1 and NC-2 with 0.25g/basket at both. NC-3 had a mean biomass of 0.22 g/basket. When only EPT taxa were considered, R2-S1 had a mean EPT biomass of 0.73 g/basket and NC-2 had the second highest EPT biomass with 0.21 g/basket. NC-1 had 0.19 g/basket and NC-3 had 0.17 g/basket for mean EPT biomass.

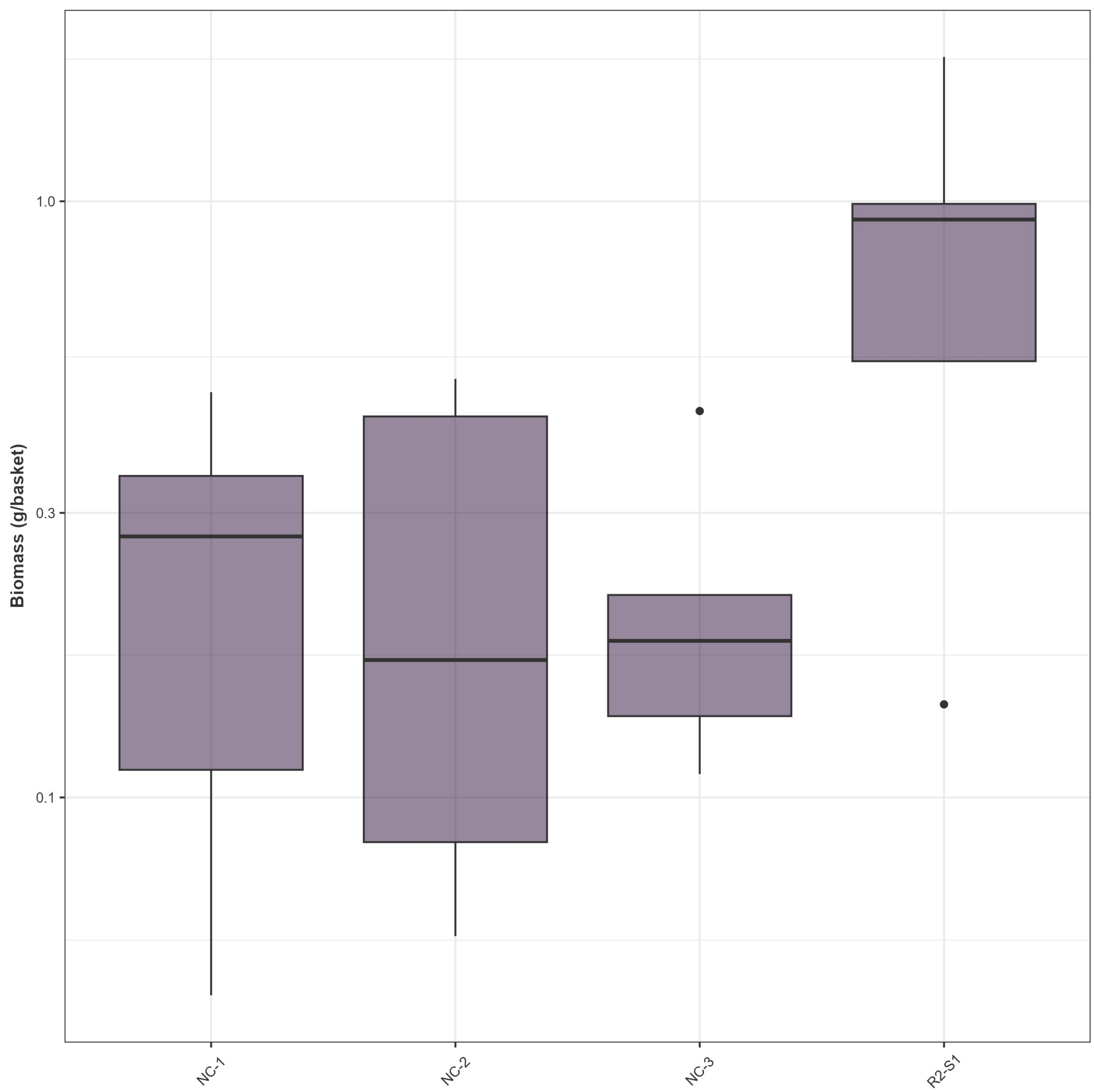

Figure 4-15: Total benthic invertebrate biomass measured in Norns Creek fan and R2-S1 in 2022. Productivity samplers were moved to Norns Creek fan for 2022 and were only deployed for the spring season.

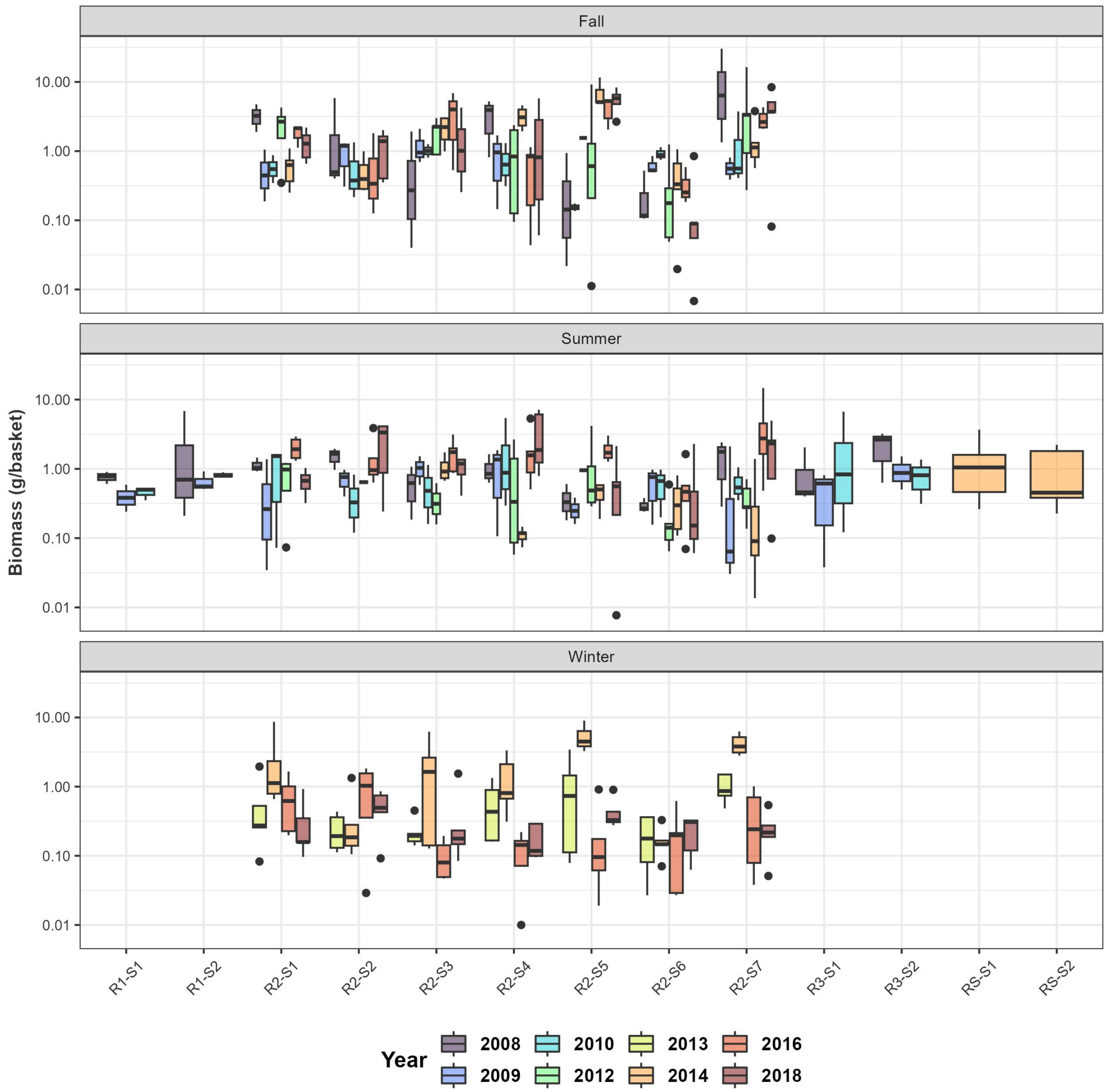

Figure 4-16: Benthic invertebrate biomass of previous years and seasons for each sample site, excluding Norns Creek Fan sites.

Despite the community dominance by *Chironomids* and *Nadidae* in the Norns Creek fan, biomass contributed by EPT taxa accounted for between 65-76% of the samples. The smaller relative biomass contributed by *Chironomidae*, combined with their lower overall fish food index rating results in a lower fish food index biomass score for the Norns sites (Table 4-8). High total abundance and presence of larger benthic fauna including gastropods at R2-S1 resulted in lower EPT relative biomass. However, increased relative abundance of taxa with higher fish food value in R2-S1 resulted in a higher fish food index biomass score. S5 had the highest total abundance and fish food index biomass of all sites sampled in the LCR. S5, unlike the Norns Creek fan, is a high velocity, high turbulence site with large stable boulder substrates, high structural heterogeneity and conditions more optimal for EPT and blackfly species habitat use.

Table 4-8: Average productivity metrics across all sampled LCR sites irrespective of year or season. The shaded sites represent those sampled in spring 2022. Values represent the average precent composition of all 5 samples in each site (i.e., S, MS, M, MD, and D).

Site	EPT Biomass (%)	Chironomid Biomass (%)	Fish Food Index Biomass Score
NC1	73.5	18.1	0.2
NC2	64.5	26.0	0.2
NC3	76.4	14.0	0.2
R2-S1	52.3	4.7	0.9
S2	33.2	6.8	0.4
S3	49.5	8.2	0.8
S4	48.8	8.1	0.8
S5	52.7	5.5	1.8
S6	27.5	9.8	0.1
S7	49.3	7.4	1.3

4.6.3 Norns Creek Fan Benthic Invertebrate Summary

The Norns Creek fan represented by the NC sites and R2-S1 are morphologically different habitats. The Norns Creek site is a large alluvial fan at the confluence with the LCR. Substrates are pebble, gravel, sand, and smaller sediment, such as silt. Conversely, the R2-S1 site is in a more confined section of the river with a steep erosional bank. Substrates are larger and dominated by cobble and boulder. The LCR is less confined at the Norns Creek fan. Hydraulic lift at the upstream end of the fan deflects more intense current to the right bank with a more smooth and laminar flow occurring as the LCR spills over the finer textured fan.

Flow velocity is controlled in streams where the bed morphology is generally complex and rough. As bed gradients steepen, flow resistance typically rises due to the increasing proportion of coarse roughness elements such as immobile boulders and bedrock and constrictions increase. The Norns Creek fan represents the natural control outlet from the Robson Reach of the LCR, which is lacustrine in character. The channel is then constricted with a slight increase in gradient downstream along the R2-S1 site as the river spills from the Robson Reach downstream.

The large Didymo bloom in 2022 may have influenced benthic invertebrate communities and productivity. Didymo can cause shifts in benthic invertebrate communities when it is prolific (Marshall 2007). However, it is difficult to conclude what impacts, if any, the 2022 Didymo bloom had on benthic invertebrates because we did not model the effect of Didymo density and invertebrate biomass or community metrics specifically. Furthermore, there are many confounding factors that influence benthic invertebrate community structure concurrently, including substrate size and flow variation. Water level fluctuations are the most important factor affecting nearshore or varial zone benthic fauna. In addition to the various anthropogenic causes of water level fluctuations, climate change is also predicted to increase the onset rate, duration, and frequency of dewatering.

There are many ways by which flow pattern alterations affect benthic invertebrate communities. For instance, benthic macroinvertebrate density and total abundance doubled in river habitats downstream of dams where operational flows were altered to reduce the amount of time that macroinvertebrates were exposed to extreme high and low flows (defined as flows less than half the average annual flow) and eliminated rapid changes in flow between extremes. In addition, these flow alterations resulted in higher quality invertebrate communities downstream (Morgan II et al., 1991).

Invertebrate communities tend to be dominated by one or two taxa with a large number of rare species in more unstable aquatic habitats such as regulated rivers (Death, 1996). The benthic invertebrate community assemblage in the LCR is characteristic of a large, regulated river. *Chironomidae* and *Naididae* dominate the Norns Creek fan of the LCR, which experiences drawdown and emersion of over 40% of the fan. These taxa are common and important in these varial zone habitats because they are relatively resistant to desiccation. *Chironomidae* and some *Naididae* are capable of surviving emersion of more than three weeks under field conditions (Poznańska et al. 2016). Some studies have shown that *Naididae* dominate emersed sediments with the highest densities immediately following re-wetting (Poznańska et al. 2016). For example, some *Naididae* species demonstrate resistance to drying by forming cysts or through behavioral adaptations of vertical migrations deeper into sediments to moisture habitats (Poznańska et al. 2016).

5 LITERATURE REVIEW PRELUDE

The Scope of Services for this contract requested that the productivity model be updated with taxa-specific mortality curves of invertebrate taxa that are consumed by juvenile RBT (BC Hydro, 2021). The objective was to use mortality curves derived from the literature to improve model precision for benthic invertebrates of importance to juvenile RBT.

The growth and mortality curves used in the productivity model were adapted from mortality and productivity models developed for the Columbia Power Corporation (CPC) (Schleppe et al., 2013). These CPC models were derived from benthic data collected in the LCR and considered other mortality curves from the literature (Schleppe et al., 2013). These models used invertebrate dry weight and chl-a concentrations for periphyton by sampling these parameters at 6, 12, 24, 48 and 64 days of incubation on the LCR and Kootenay rivers (Schleppe et al., 2013). Several curves were used to produce one growth and one mortality curve for periphyton, and one growth and one mortality curve for benthic invertebrates. The invertebrate taxa used to create these mortality curves were *Simuliidae* (blackfly) and *Hydropsychidae* (net-spinning caddisfly), two of the most abundant LCR invertebrate taxa (Schleppe et al. 2013, Schleppe et al. 2015).

The previous works by BC Hydro and the CPC have also considered preferred forage items for RBT. During the last 12 years of benthic invertebrate sampling in LCR, *Chironomidae* (nonbiting midges), *Hydropsychidae*, and *Simuliidae* together make up more than 86, 80 and 79 percent of invertebrates present in the LCR in winter, summer and fall (Olson-Russello et al. 2019). In general, *Diptera*, *Ephemeroptera* (mayflies), *Plecoptera* (stoneflies), and *Trichoptera* (caddisflies) make up the largest proportion of fish food, for all life stages.

The growth/mortality curve used in the model is specific to LCR taxa that constitute a large portion of RBT diets; *Simuliidae* and *Hydropsychidae*. Furthermore, the mortality curves were derived from data collected in the LCR, so they reflect the specific site conditions of the river system. After reviewing the literature, we concluded that the effort and associated cost of producing and integrating mortality curves for more taxa would not significantly increase model precision. The literature review and more detailed conclusions can be found in Appendix B.

6 CONCLUSION

Primary production in 2022 was influenced greatly by a large Didymo bloom. Together with green algae, these filamentous taxa inflated the productivity metrics to levels not previously seen in the LCR. Didymo mats affect food web structure and ecological functioning and can change the physical habitat structure for benthic invertebrates.

The Norns Creek fan is a morphologically different habitat than R2-S1 and other downstream habitats sampled in previous years. Substrates in Norns Creek fan are pebble, gravel, and sand. Conversely, the R2-S1 site is in a more confined section of the river with a steep erosional bank and substrates are dominated by cobble and boulder. The difference in substrates between Norns Creek fan and the control R2-S1,is important to consider when comparing benthic community metrics, as substrates and flows drive the benthic invertebrate community and productivity. Invertebrate communities measured in 2022 reflect the change in substrate and habitat type between sample sites and may also differ from previous years.

Benthic invertebrate species assemblages in the LCR are highly driven by regulated flows from the HLK dam. This influence on the community structure also affects the diets of Rainbow Trout. The benthic invertebrate communities in the Norns Creek fan differ significantly from sites with higher gradient, faster water velocities, and larger substrates, which tend to support more EPT taxa. The benthic invertebrate community biomass in these higher velocity, larger substrate habitats can be over three times higher than the mean invertebrate biomass of the Norns Creek fan.

Lower fish food index values and benthic invertebrate biomass in the Norns Creek fan indicate that the production in Norns Creek fan may not be as important as the production of other habitats in the LCR. While the Norns Creek fan is an important RBT spawning area, the smaller substrates, limited interstitial habitats, and low instream cover are not ideal conditions for RBT rearing. At fry swim up, juvenile RBT tend to move to habitats with higher structural heterogeneity and cover and likely spend less time on the fan itself, instead moving into the backwaters and downstream to more coarsely texture riffles and runs where instream cover is greater. These habitats provide cover and small aquatic insects for foraging.

6.1 Productivity Model Conclusion

Typical RBT flow management did not significantly change estimated chl-a accrual between ON and OFF years in the Norns Creek fan. RBT flow management (ON years) significantly increased invertebrate productivity above that of OFF years, likely because invertebrates are more sensitive to substrate dewatering and have slower spring recovery rates than periphyton (Schleppe et al. 2015).

The invertebrate and periphyton production models provided simplified estimates of production in the Norns Creek fan based on hourly flows. Flows of ON and OFF years are highly variable, and some OFF years, like 2022, have flow regimes similar to ON years. The variation in flows between years among a given management type can be high, depending on other requirements of flow management. Benthic production reflected this variation in flow treatments. Relatively stable flows in 2022 created higher estimates of benthic productivity than typical OFF years.

Given this flow variability, it may be advantageous to explore modeling LCR benthic productivity based on additional metrics and perspectives. While substrate submergence is the strongest predictor of productivity, increased stability of flows and increased minimum flows also increase productivity and benthic invertebrate diversity (Ellis and Jones 2013, Malmqvist and Englund 1996, Plewes et al. 2020). Recent modeling of the Columbia River's benthic productivity for the Columbia River Treaty used a suite of flow parameters as predictors, rather than water level alone (Akers et al. 2021). These predictors included variability of daily flows, number of high flow events, mean duration of high flow events, fall rate of decreasing flows, daily flow magnitude changes, and maximum annual flow (Akers et al. 2021). Data from the headwaters of the Columbia River to the international border were assessed, and showed the biological integrity of the Columbia River was low compared to reference indices, likely due to a long history of anthropogenic influences (Akers et al. 2021).

A modelling approach with similar flow parameters and the inclusion of flow thresholds, similar to the Akers model, may capture the effects of nuances in flows between and among ON and OFF years. This approach could more accurately predict the impact of flow management with finer detail, rather than just comparing between ON and OFF years exclusively. This detail will help refine the modeling estimates to the effects of changes in specific flow characteristics. For example, it could help determine if overall maximum flow, mean flow, or flow variability have more effect on inundated area, and thus chl-a and invertebrate accrual. It may also offer more insight into the specific effects of flow management decisions, which can help inform future LCR flow management. If interest and capacity to improve the productivity model remains, we suggest exploring a format similar to the Akers model.

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APPENDIX A LIGHT ATTENUATION MODELLING

Lower Columbia River Light Attenuation and Reflectance 2022

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Background

The primary goal of the analysis is to address the following question:

> How does light in the Lower Columbia River attenuate with depth?
>
> What is the light surface reflectance in the Lower Columbia River?

Methods

Data Collection

In order to estimate light attenuation, Ecoscape recorded light (PAR) and turbidity levels at different depths at various sites. Ecoscape also recorded light levels at the surface and 0.01 m below the surface in order to estimate surface reflectance.

The data were provided as Excel spreadsheets.

Data Preparation

The data were prepared for analysis using R version 4.2.2 (R Core Team 2022).

Statistical Analysis

Model parameters were estimated using Bayesian methods. The estimates were produced using JAGS (Plummer 2003). For additional information on Bayesian estimation the reader is referred to McElreath (2020).

Unless stated otherwise, the Bayesian analyses used weakly informative normal and half-normal prior distributions (Gelman, Simpson, and Betancourt 2017). 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) $\text{ESS} \geq 150$ for each of the monitored parameters (Kery and Schaub 2011, 61).

The parameters are summarised in terms of the point *estimate*, *lower* and *upper* 95% compatibility limits (Rafi and Greenland 2020) and the surprisal *s-value* (Greenland 2019). The estimate is the median (50th percentile) of the MCMC samples while the 95% CLs are the 2.5th and 97.5th percentiles. The s-value indicates how surprising it would be to discover that the true value of the parameter is in the opposite direction to the estimate (Greenland 2019). An s-value of >4.3 bits, which is equivalent to a significant p-value <0.05 (Kery and Schaub 2011; Greenland and Poole 2013), indicates that the surprise would be equivalent to throwing at least 4.3 heads in a row.

The condition that parameters describing the effects of secondary (nuisance) explanatory variable(s) have significant p-values was used as a model selection heuristic (Kery and Schaub 2011). Based on a similar argument, the condition that random effects have a standard deviation with a lower 95% compatibility interval (CL) $>5\%$ of the estimate was used as an additional model selection heuristic.

Model adequacy was assessed via posterior predictive checks (Kery and Schaub 2011). More specifically, the first four central moments (mean, variance, skewness and kurtosis) for the deviance residuals were compared to the expected values by simulating new residuals. In this context the s-value indicates how surprising each observed metric is given the estimated posterior probability distribution for the residual variation.

Where computationally practical, the sensitivity of the parameters to the choice of prior distributions was evaluated by increasing the standard deviations of all normal, half-normal and log-normal priors by an order of magnitude and then using $\hat{R}$ to evaluate whether the samples were drawn from the same posterior distribution (Thorley and Andrusak 2017).

The results are displayed graphically by plotting the modeled relationships between individual variables and the response with the remaining variables held constant. In general, continuous and discrete fixed variables are held constant at their mean and first level values, respectively, while random variables are held constant at their average values (expected values of the underlying hyperdistributions) (Kery and Schaub 2011, 77–82).

The analyses were implemented using R version 4.2.2 (R Core Team 2022) and the `mbr` family of packages.

Model Descriptions

Light Attenuation

The following equation describes how light attenuates in water

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

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).

Key assumptions of the surface reflectance model include:

- There are no measurement errors in E_0.

- The residual variation in E_d is log-normally distribution.

As all the turbidity readings were < 2 NTU, turbidity was not included in the model.

Euphotic Zone

Ignoring surface reflectance, the euphotic zone (depth at which light is 1% of the surface) is $-\log(0.01)/K_d$.

Surface Reflectance

The relationship between the irradiance at the surface (E_s) and the irradiance 0.01 m below the surface (E_0) was modelled using the relationship

$$E_0 = E_s \cdot r \cdot \exp(-K_d \cdot 0.01)$$

where r is the reflection coefficient (Julian, Doyle, and Stanley 2008) and K_d was the estimate from the attenuation model.

Key assumptions of the surface reflectance model include:

- There are no measurement errors in E_s.
- The residual variation in E_0 is log-normally distributed.

As all the turbidity readings were < 2 NTU, turbidity was not included in the model.

Euphotic Zone

Including surface reflectance, the euphotic zone (depth at which light is 1% of the surface) is $-\log(0.01/r)/K_d$.

Model Templates

Attenuation

```
.model{
  Kd ~ dnorm(-1, 2^-2)
  sLight2 ~ dnorm(0, 1^-2) T(0, )

  for (i in 1:length(Light2)) {
    eKd[i] <- exp(Kd)
    eLight2[i] <- Light[i] * exp(-eKd[i] * Distance[i])

    Light2[i] ~ dlnorm(log(eLight2[i]), sLight2^-2)
  }
```

Block 1. Model description.

Reflectance

```
.model{
  rho ~ dunif(0, 1)
  sLight2 ~ dnorm(0, 1^-2) T(0,)
```

```
  Kd ~ dnorm(-1.1, 0.07^-2) T(-1.2, -1)

  for (i in 1:length(Light2)) {
    eKd[i] <- exp(Kd)
    eLight2[i] <- Light[i] * exp(-eKd[i] * 0.01) * rho
    Light2[i] ~ dlnorm(log(eLight2[i]), sLight2^-2)
  }
```

Block 2. Model description.

Results

Tables

Attenuation

Table 1. Parameter descriptions.

Parameter	Description
`Distance`	The distance (y) in m
`eKd`	The expected diffuse attenuation coefficient in m^{-1}
`eLight2`	Expected `Light2`
`Kd`	The intercept for `log(eKd)`
`Light`	The initial irradiance (E_0) in lx
`Light2`	The irridance at distance (E_d) in lx
`sLight2`	SD of measurement error in `Light2`

Table 2. Model coefficients.

term	estimate	lower	upper	svalue
Kd	-1.0893895	-1.2337906	-0.9652501	10.55171
sLight2	0.1360966	0.1223378	0.1520452	10.55171

Table 3. Model convergence.

n	K	nchains	niters	nthin	ess	rhat	converged
158	2	3	500	20	1448	1	TRUE

Table 4. Euphotic zone depth (m) ignoring surface reflectance (with 95% CIs).

estimate	lower	upper
13.68868	15.81518	12.09062

Table 5. Model posterior predictive checks.

moment	observed	median	lower	upper	svalue

moment	observed	median	lower	upper	svalue
zeros	NA	NA	NA	NA	NA
mean	-0.0075977	-0.0043807	-0.1453396	0.1471690	0.0488765
variance	0.9903349	1.0024161	0.7928849	1.2275792	0.1098016
skewness	-0.8537086	0.0032855	-0.3773260	0.3852552	10.5517083
kurtosis	1.4197764	-0.0907401	-0.5876605	0.9413734	6.3037807

Table 6. Model sensitivity.

n	K	nchains	niters	rhat_1	rhat_2	rhat_all	converged
158	2	3	500	1.001	1.001	1	TRUE

Reflectance

Table 7. Parameter descriptions.

Parameter	Description
`Light`	The irradiance at the surface (E_s) in lx
`Light2`	The irridance just below the surface (E_0) in lx
`rho`	Reflection coefficient (r)
`sLight2`	SD of measurement error in `Light2`

Table 8. Model coefficients.

term	estimate	lower	upper	svalue
Kd	-1.0988725	-1.1907383	-1.0087445	10.55171
rho	0.5927078	0.5613640	0.6235446	10.55171
sLight2	0.1894281	0.1596365	0.2347296	10.55171

Table 9. Model convergence.

n	K	nchains	niters	nthin	ess	rhat	converged
56	3	3	500	1	806	1.004	TRUE

Table 10. Euphotic zone depth (m) including surface reflectance (with 95% CIs).

estimate	lower	upper
12.13392	14.19308	10.57472

Table 11. Model posterior predictive checks.

moment	observed	median	lower	upper	svalue
zeros	NA	NA	NA	NA	NA
mean	-0.0082173	0.0013017	-0.2604660	0.2525078	0.0709181

moment	observed	median	lower	upper	svalue
variance	0.9828269	0.9963357	0.6539335	1.3828684	0.0830842
skewness	-0.9400043	0.0032479	-0.6463506	0.6087133	8.9667458
kurtosis	0.2297131	-0.2043870	-0.8882035	1.2440925	1.0943274

Table 12. Model sensitivity.

n	K	nchains	niters	rhat_1	rhat_2	rhat_all	converged
56	3	3	500	1.004	1.003	1.002	TRUE

Figures

Attenuation

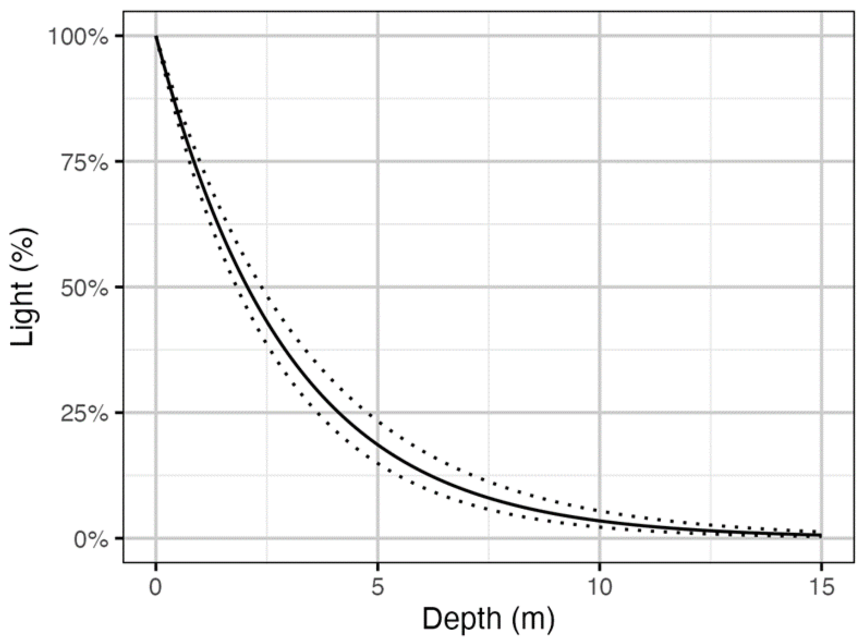

Figure 1. Light attenutation by depth.

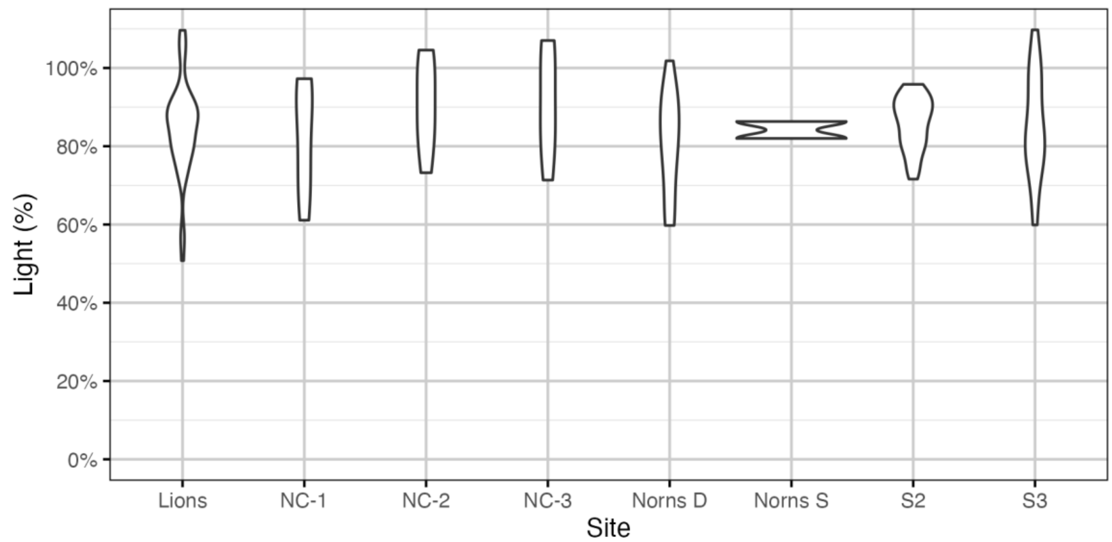

Figure 2. Light attenuation at a depth change of 0.5 m by site.

Reflectance

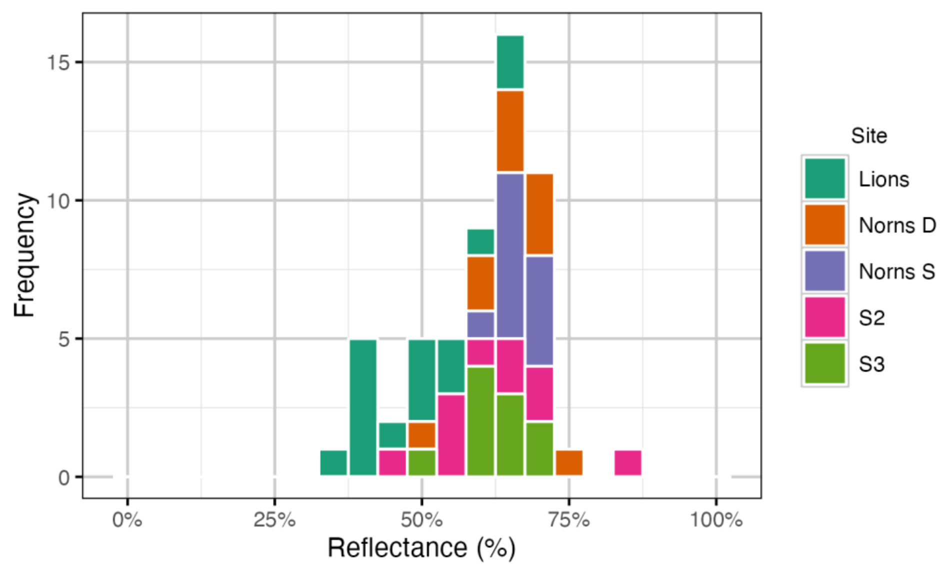

Figure 3. Surface reflectance by site.

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APPENDIX B LITERATURE REVIEW

1.1. Literature Review

Benthic invertebrate community assemblages in regulated rivers are influenced by species' abilities to tolerate rapid changes in water level and temperature. Responses to and survival of dewatering are diverse, and vary by species, life history, behaviour, and morphological traits (Jenkins and Boulton 2007, Robson et al. 2011, Thorat and Nath 2018). For example, some species with desiccation-resistant eggs can hatch and recolonize quickly after drought when their eggs are rewatered, so while mortality following a dewatering event can be high, populations recover relatively quickly (Jenkins and Boulton 2007, Miller et al. 2020, Robson et al. 2011). Behavioural responses can also change mortality rates of invertebrates. Some Chironomus larvae show grouping behaviour of bunching together to reduce water loss by evaporation (Thorat and Nath 2018). This grouping behaviour creates a density-dependent response to dewatering, where survival changes depending on how many individuals are present and grouping. Some more mobile species can also move into residual pools of standing water following dewatering to avoid desiccation (Lancaster and Ledger 2015). Some species of Ephemeroptera and Chironomidae can tolerate daily fluctuating flows and desiccation, and these taxa usually dominate the macroinvertebrate community in regulated rivers (Brittain and Saltveit 1989, Munn and Brusven 1991, Poznańska et al. 2016, Walters and Post 2011). For example, one study showed the population densities of several species of Naididae and four taxa of Chironomidae were not impacted by drying events lasting five to six days (Lancaster and Ledger 2015).

Survival of fluctuating flows and recolonization following low flows vary widely by river system and species, even within the same taxa (Brittain and Saltveit 1989). For example, Suemoto et al. (2004) found differences in desiccation tolerance between larval Chironomid species. Specifically, they found that *C. salinarius* tolerated desiccation better than *C. kiiensis* and *C. yoshimatsui*, yet Kawai et al. (2000) found that these two latter species had higher desiccation tolerances than *C. salinarius* (Kawai et al. 2000, Suemoto et al. 2004). The differences in desiccation tolerance between the two studies may be due to varying salinities and the species' varying abilities to tolerate different salinities (Suemoto et al. 2004). These studies demonstrate how physical and chemical habitat conditions will influence species' responses to dewatering and survival of desiccation.

Flow variability in regulated river systems influences community assemblages of macroinvertebrates by creating a selective pressure for species that can survive desiccation or recolonize quickly. Overall macroinvertebrate abundance can increase or decrease with river impoundment, but regulated rivers have lower macroinvertebrate diversity and taxa richness when compared to unregulated rivers or rivers that have more seasonal flow variability (De Jalon et al. 1994, Ellis and Jones 2013, Gislason 1985, Milner et al. 2019, Munn and Brusven 1991, Steel et al. 2018). For example, total abundance and species richness of Ephemeroptera was lower in regulated rivers when compared to unregulated rivers, but increased constancy in flow increased Ephemeroptera richness (Malmqvist and Englund 1996).

Annual variation in flows in regulated systems can also shift invertebrate community composition and impact different taxa and functional feeder groups in different ways. For example, aquatic taxa were more abundant during high flow years in regulated systems, and low flow years reduced aquatic insect abundance (Holt et al. 2014). Non-insect invertebrates in the same regulated system were more prevalent under low flow conditions than high flows (Holt et al. 2014). Filter-feeders and scrapers are negatively impacted by regulated flows, possibly because some net-spinning hydropsychids and other filter feeders may be easily damaged by abrasion and rapid flow changes below dams (Boon 1993, De Jalon et al. 1994). Scrapers may also decrease in relative abundance following impoundment in response to a decrease in macrophytes and periphyton biomass (De Jalon et al. 1994). These community-level assemblages are determined by species-specific adaptations and abilities to survive variable flows and temperatures.

Variable temperatures from dam releases in regulated rivers can also impact benthic invertebrates. During high reservoir periods, the water intake of the dam can occur below the thermocline and release water from much deeper depths than standard river flows, sending pulses of cold water into the river. Temperature changes like this can impact growth rates and emergence timing and duration of Ephemerellidae and Trichoptera, and the length of the time some Trichopteran species spend in late instars (Perry et al. 1985).

The dominance of Ephemeroptera and Chironomidae reported in the literature for regulated rivers is consistent with the benthic invertebrate community structure in the LCR, which is heavily influenced by regulated flows (Akers et al. 2021). Chironomidae were the dominant taxa by abundance in all sites in 2022, and Ephemerellidae were the third most common taxa. When assessed by biomass, Trichoptera, Ephemeroptera, and Chironomidae were the top three taxa in Norns Creek fan. These taxa are likely more successful and more prevalent because of their tolerance of regulated fluctuating flows and desiccation. Therefore, the mortality curve used in the productivity model is accurate for the LCR, as it is based on taxa with high desiccation tolerances.

Most studies that examine benthic invertebrate survival of dewatering measure mortality on a daily scale, or, more commonly, examine total population fluctuations over entire seasons. Lancaster and Ledger (2015) present proportional mortality curves and pre- and post-drying population densities for species of Chironomidae and Naididae from a drying experiment in artificial streams. Marchant and Hehir (1999) use population density, biomass, growth, and mortality to determine production for two Australian Trichoptera species. Another study determined survival and water loss rates for 12 Japanese species of Chironomid larvae (Suemoto et al. 2004). Poznańska et al. (2016) determined desiccation tolerances for a Chironomid species and an Oligochaete species, showing a strong difference in tolerance between the two, with the Chironomid showing far more tolerance to desiccation than the Oligochaete species. Examples of mortality curves can be found in the literature from different regions for the taxa of interest, but mortality curves determined from LCR processes and taxa are the most appropriate for the LCR productivity model.

1.1.1 Rainbow Trout Diets

Rainbow Trout diets can vary with food availability and can reflect the macroinvertebrate communities of their habitat (Fierro et al. 2016) but are often dominated by Ephemeroptera and Diptera (Meehan 1996, Whiting et al. 2014). Specifically, smaller Rainbow Trout consume smaller prey items like Ephemeroptera and Diptera in the drift and consume more large predatory benthic macroinvertebrates and smaller fish when trout grow to larger sizes above 150 mm (Whiting et al. 2014). However, diets can vary with region, stock, and season. A study of adult Rainbow Trout in the LCR showed that Diptera and Trichoptera made up greater than 50% of the benthic invertebrates in adult fish stomachs (Olson-Russello et al. 2019). The dominant taxa in RBT and Mountain Whitefish (*Prosopium williamsoni*) diets was Trichoptera, specifically net-spinning caddisflies (Hydropsychidae; Olson-Russello et al. 2019). Trichoptera and Diptera were the most abundant taxa available for fish consumption in the LCR during this study (Olson-Russello et al. 2019). While this study was a snapshot of fish diets during fall over two sampling years, it is likely that RBT foraged as generalists as their diets reflected the proportions of available taxa in the LCR at that time.

1.2. Literature Review Conclusion

Mortality from desiccation will vary by season, species, and invertebrate life stage. Recolonization following dewatering and population reduction depends on species and the life stage during which invertebrates were dewatered. Both species resilience and recolonization combined influence post-drought biomass, and these metrics vary with season and accompanying physical processes, such as temperature, light attenuation, saltation, and sand abrasion, among others. The species assemblage in the LCR is highly driven by regulated flows from the HLK dam, and in turn determines the diets of Rainbow Trout.

Physical habitat characteristics as velocity, light attenuation, temperature, and substrate size influence invertebrate community structure and productivity. The growth and mortality curves used in the model are based on peak biomass, however, abrasion from sediment and variable flows can remove periphyton and benthic invertebrates from rocks and result in biomass loss (Schleppe et al. 2013). Light attenuation is a major determinant in macrophyte and periphyton productivity, which in turn influences population densities of scraper invertebrates (de Jalon et al. 1994). The objective of the Norns Creek fan productivity model is to gain a relative understanding of the effect of flows on overall productivity. This question has a broad scope, and the model does not address physical characteristics beyond inundation. Including physical characteristics on a microsite scale may improve model precision but would require much larger and more complex datasets than are already included.

While physical site characteristics may be costly and labor intensive, additional flow metrics may be included to improve the accuracy of the hydraulic model, and the resulting benthic productivity accrual estimates. For example, recent modeling of the Columbia River's benthic productivity for the Columbia River Treaty used a suite of flow parameters as predictors, rather than water level alone (Akers et al. 2021). These predictors were variability of daily flows, number of high flow events, mean duration of high flow events, fall rate of decreasing flows, daily flow magnitude changes, and maximum annual flow (Akers et al. 2021). Including these flow parameters may help detect the specific impacts of flow variability on benthic productivity, rather than a comparison between the highly variable ON and OFF years alone.

The mortality curve used to predict invertebrate death rates in the model was adapted from previous studies conducted for the Columbia Power Corporation, and was based on Simuliidae, and Hydropsychidae, two of the most abundant LCR invertebrate taxa (Schleppe et al. 2013; Schleppe et al. 2015). RBT in the LCR can forage as generalists, and the dominant taxa in the diets of adults and some juvenile taxa was Trichoptera. Therefore, the mortality curve used in the model is specific to LCR taxa that constitute a large portion of RBT diets. Furthermore, the mortality curves were derived from data collected in the LCR, so they reflect the specific site conditions of the river system. We conclude that the effort and associated cost of producing and integrating mortality curves for more taxa would not significantly increase model precision.