Columbia River Project Water Use Plan

Kinbasket and Revelstoke Reservoirs Ecological Productivity and Kokanee Population Monitoring

Reference: CLBMON-2, CLBMON-3, and CLBMON-56

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2008-2019 (Years 1 to 12) Final Synthesis Report

K. Bray[1], T. Weir[2], R. Pieters[3], D. Brandt[4], and S. Harris[5]

[1]BC Hydro, Revelstoke, B.C.
[2]Ministry of Forests, Victoria, B.C.
[3] Earth, Ocean, and Atmospheric Sciences, University of British Columbia, Vancouver, B.C.
[4] Advanced Eco-Solutions, Newman Lake, Washington
[5] Ministry of Water, Land and Resource Stewardship, Vancouver, B.C.

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Kinbasket and Revelstoke Reservoirs
Ecological Productivity and Kokanee Population Monitoring
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2023

Cover Photo: Sullivan River flow entering Kinbasket Reservoir from the Sullivan Arm, May 2013.

Photo Credit: K. Bray

Note: While Lake Revelstoke is the gazetted name for the reservoir, this report refers to the waterbody as Revelstoke Reservoir to maintain consistency with wording in the Terms of Reference.

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Executive Summary

The Columbia River Water Use Plan (WUP), approved in 2007, was conducted by BC Hydro to achieve optimal balance among operations, environmental, and social values. On Kinbasket and Revelstoke Reservoirs, a lack of ecological data and information resulted in a recommendation to undertake a long-term program of study on reservoir limnology and the productivity of pelagic communities in conjunction with the continuation of long-term kokanee assessments. The goal of these studies was to provide the information necessary to inform future WUP Order Reviews on options and decisions for operating Kinbasket and Revelstoke Reservoirs. A 12-year program was initiated in 2008 and included regular reservoir sampling for physical and chemical parameters, and biological communities, such as phytoplankton, zooplankton, and kokanee.

This final synthesis report covers the twelve years (2008-2019) of effort on the limnological components (CLBMON-3) and kokanee population monitoring (CLBMON-2) and includes eight years (2012-2019) of continuous mooring data added to meet commitments for the Mica Project Units 5 and 6 Environmental Assessment Certificate (CLBMON 56). This work also benefits from additional years of kokanee data (2001-2007) and mooring data (2020-2021) collected outside the WUP program.

The study period encompassed both unusual activity (dam infrastructure changes) and a wide range of hydrological, meteorological, and operating conditions on Kinbasket and Revelstoke Reservoirs, challenging attempts to distinguish environmental versus operational effects on reservoir productivity and providing important contrasting conditions. The physical limnology of these reservoirs was investigated in detail and provides a critical foundation for understanding how nutrients are delivered to the photic zone and, ultimately, how reservoir operations might affect pelagic production.

Temperature, light conditions, and nutrient availability are considered to exert critical influences on pelagic production. Both reservoirs undergo an annual cycle of temperature stratification and, despite glacial inflow, there was good penetration of light (1% light to 17 m on average). Reservoir nutrient chemistry and primary production demonstrate that both reservoirs are oligotrophic to ultra-oligotrophic (very low in productivity) and limited by phosphorus. There was sufficient supply of nitrogen but exceptionally low levels of phosphorus; these low levels along with interference by glacial particles meant that biologically available phosphorus could not be resolved. No trends in tributary nutrient (nitrogen and phosphorus) inputs were evident over the study years. There was a sequence of physical processes, such as overflow in spring and interflow in summer, that, along with reservoir filling in Kinbasket, photic zone clearing and entrainment, suggested significant resupply of nutrients to the photic zone in both spring and summer. In

summer, a strong interflow formed in Revelstoke reservoir with nutrients passing below the photic zone to the outlet at Revelstoke Dam. Addition of Mica Units 5 and 6 likely had no effect on lower trophic levels in either reservoir.

Primary production was dominated by smaller phytoplankton (pico- and nano-plankton) as would be expected in a low nutrient system. Primary production increased by 13% per year over the study period predominantly from increases in smaller celled plankton. This increase was not mirrored by changes in upper trophic levels as is typically expected. Trends showed increasing phytoplankton and primary production and decreasing zooplankton and kokanee survival and biomass in the latter years of our study.

Lower trophic levels (phytoplankton and zooplankton) are influenced by an array of factors, primarily climatic and hydrological (flow). Multivariate analyses of environmental and operational factors that could influence pelagic production were conducted to assess the most important predictor variables for lower trophic levels. The major drivers in phytoplankton community structure and abundance (density) are yearly climate related factors (e.g., annual inflow variables) whereas the zooplankton community is driven more by climate related variables at a monthly or seasonal scale (e.g., photic zone temperature and monthly inflow variables). Other than Mica GS outflow, reservoir operations were not found to be significant predictors of lower trophic level productivity. There was no indication that reservoir elevation was a factor in primary or secondary productivity changes that would affect kokanee outcomes. Mica GS outflow (discharge), the main inflow to Revelstoke, was a significant predictor for some zooplankton community outcomes for Revelstoke reservoir where higher flow resulted in lower zooplankton (copepod) outcomes.

Kokanee abundance and biomass trends were broadly similar between Kinbasket and Revelstoke, higher in the first half of the time series (2001 to approximately 2010) then declining to below average afterwards. This trend was particularly evident for Revelstoke kokanee, where sustained low in-lake survival resulted in the population functioning below carrying capacity from 2012-2019. Annual weather (affecting egg to fry and in-lake survival), in conjunction with lake specific factors (high flow/entrainment in Revelstoke, the 2016 mortality event in Kinbasket) appeared to be the primary drivers of the kokanee trends. However, a short time series may have limited analyses and insight into how all operational and lower trophic interactions affected kokanee outcomes.

Comparisons of Kinbasket and Revelstoke Reservoirs with Arrow Reservoir, Kootenay Lake, and Dworshak Reservoir in the U.S., where comparable monitoring data were available, indicate an overall strong synchrony of annual trends in primary (phytoplankton), secondary (zooplankton), and tertiary (kokanee) metrics despite absolute differences in values. This synchrony across waterbodies of differing productivity, operations, and limnological characteristics is remarkable and provides another line of evidence to support climate or regional drivers as strong influences on pelagic production. Long term trend data were also used to explain individual in-lake differences where trends diverge. These results underscore the importance of climatic and regional drivers on reservoir production relative to any within year manipulation of operations or restoration activities as well as the importance of long-term monitoring.

A commitment of the Mica Unit 5 and 6 Project Environmental Assessment to investigate the potential influence of the last two turbines installed at Mica Generating Station to reservoir pelagic productivity was added to the study Terms of Reference in 2012. Results showed the predominant change in discharge (flow) was short-term (peaks with median duration of 4 hours); the season most affected was winter (November to March), with no change in spring (April to June), and intermediate change in summer/fall (July to October). There was no evidence to support any significant influence of Mica Units 5 and 6 on pelagic production or thermal properties of either reservoir. The analysis was limited by the number of years of mooring data available before 2015; however, the main drivers of pelagic production are beyond the influence of the operation of these two turbines.

Annual climatic and within year meteorological variables were shown to exert a strong influence on pelagic productivity outcomes in these reservoirs and, overall, the degree of confidence that a particular reservoir operation will consistently ensure a better pelagic productivity outcome is small. Any operation that would result in an earlier or increased outflow from Kinbasket to Revelstoke Reservoir over what would typically occur with the water year conditions is considered to contribute to poorer outcomes for kokanee in Revelstoke and, by extension, Arrow Lakes Reservoir. Setting minimum and maximum elevation targets, for example, could result in earlier or higher discharge from Kinbasket Reservoir that would have cascading negative outcomes for kokanee downstream. Operating as far as possible with the water year conditions rather than in opposition would be beneficial, especially in naturally dry years when operations could potentially change a high productivity year into a year of lower productivity, such as in 2015.

Summary of Management Questions and Hypotheses – CLBMON-2-3-56

Objective	Management Question	Management Hypothesis	Status
CLBMON-3/56			
The objective was to improve our understanding of the ecological productivity of Kinbasket and Revelstoke Reservoirs by obtaining a long-term dataset to describe trophic web mechanisms and dynamics. This information is needed to examine the sustainability of fish populations under the current operating regimes, as well as to allow better predictive capability in exploring potential operational changes.	**3-1.** What are the long-terms trends in nutrient availability and how are lower trophic levels affected by these trends? **3-3**. Is pelagic productivity, as measured by primary production, changing significantly over the course of the monitoring period?	H1: There is no change in pelagic productivity in Kinbasket and Revelstoke Reservoirs over the course of the monitoring period.	**3-1.** These reservoirs are classified as oligotrophic and are phosphorus limited systems. The supply of nitrogen is sufficient and there was no observable annual trend either in the tributaries or in the reservoir. There was a strong seasonal pattern in nitrate with increased concentrations during freshet flow. Soluble reactive phosphorus (SRP) was ephemeral, total dissolved phosphorus (TDP) was close to detection, and the presence of glacial fines interfered with the measurement of total phosphorus (TP). There were no discernable trends in phosphorus although laboratory resolution at such low levels limited the ability to detect changes. The inability to resolve biologically available phosphorus meant it was not possible to relate phosphorus levels and the lower trophic levels. **3-3.** Primary productivity increased significantly over the monitoring period ($p<0.05$) by about 13% per year in both reservoirs and reflects an increase in the abundance of smaller celled phytoplankton less than <20 um in size over the study period. H1. The hypothesis is rejected for changes as measured by primary production.

Objective	Management Question	Management Hypothesis	Status
CLBMON-3/56			
	3-2. What are the interactions between nutrient availability, productivity at lower trophic levels and reservoir operations? **3-5.** Is there a link between reservoir operation and pelagic productivity? What are the best predictive tools for forecasting reservoir productivity?	H1A: Nutrient availability is not affected by reservoir operations. H1B: Pelagic productivity is not affected by reservoir operations.	**3-2**. Winter conditions affect the onset of stratification and water temperature in spring and set the initial supply of nutrients for spring productivity. There was a complex pathway between the tributary inflows and the photic zone where additional nutrients can be utilized by lower trophic levels. This pathway included a thermal bar in early spring, periods of overflow in late spring, and interflow in summer. During plunging below the photic zone in summer, the resupply to the photic zone was set by the increasing area of the reservoir (in the case of Kinbasket), changes in water clarity which can expand or contract the photic zone, and entrainment of surface water into the plunging tributaries. Overall, indirect evidence based on the specific conductivity of the tributary inflow suggests that spring is a dynamic period and that resupply of nutrients continued in summer. The link to productivity at lower trophic levels is addressed in MQ3-5. **3-5**. Lower trophic levels (phytoplankton and zooplankton) are influenced by an array of factors, primarily climatic and hydrological (flow). The major drivers in phytoplankton community structure and abundance (density) are yearly climate related factors (e.g., annual inflow variables) whereas the zooplankton community is driven more by climate related variables at a monthly or seasonal scale (e.g., photic zone temperature and monthly inflow variables). Other than Mica GS outflow reservoir operations were not found to be significant predictors of lower trophic level productivity. There was no indication that reservoir elevation was a factor in primary or secondary productivity changes that would affect kokanee outcomes. Mica GS outflow (discharge), the main inflow to Revelstoke, was a significant predictor for some zooplankton community outcomes for Revelstoke reservoir where higher flow resulted in lower zooplankton (copepod) outcomes.

Objective	Management Question	Management Hypothesis	Status
CLBMON-3/56			
			The high degree of variability that naturally occurs in these communities requires a long-term data set to have the statistical power needed to develop a predictive model. H1A.The hypothesis is accepted. H1B.The hypothesis is partially rejected for Kinbasket Reservoir and rejected for Revelstoke Reservoir.
	3-4. If changes in pelagic productivity are detected, are the changes affecting kokanee populations?	H2: Long-term trends in pelagic productivity have no effect on kokanee populations in Kinbasket Reservoir.	**3-4**. While changes were detected at multiple trophic levels over the course of this study, we found no predictive link between primary production or lower trophic levels and kokanee populations. H2. The hypothesis is neither accepted nor rejected. Longer term data would be required to fully understand and test relationships between pelagic productivity and kokanee with sufficient statistical power.
	3-6. How do pelagic productivity trends in Kinbasket and Revelstoke reservoirs compare with similar large reservoir/lake systems (e.g., Arrow Reservoir, Kootenay Lake, Okanagan Lake, Williston Reservoir)?		**3-6**. Comparisons of Kinbasket and Revelstoke Reservoirs with Arrow Reservoir, Kootenay Lake, and Dworshak Reservoir in the U.S., where comparable monitoring data are available, indicate a strong synchrony of annual trends, particularly for zooplankton, and kokanee metrics despite absolute differences among waterbodies. Long-term trends are also used to explain individual in-lake differences where trends diverge. These results underscore the importance of climatic and regional drivers on reservoir production relative to any within year manipulation of operations or restoration activities.

Objective	Management Question	Management Hypothesis	Status
CLBMON-3/56			
	3-7. Does the addition of Mica Units 5 and 6 influence pelagic productivity?		**3-7.** There was no evidence to support any significant influence of Mica Units 5 and 6 on pelagic production or thermal properties of either reservoir. The predominant change in flow was short-term (peaks with median duration of 4 hours); the season most affected was winter (November to March), with no change in spring (April to June) and intermediate change in summer/fall (July to October). The analysis was limited by the number of years of mooring data available before 2015; however, the main drivers of pelagic production are beyond the influence of the operation of these two turbines.
	3-8. Are there operational changes that could be implemented to improve pelagic productivity in Kinbasket Reservoir?		**3-8**. Any operation that would result in an earlier or increased outflow from Kinbasket to Revelstoke Reservoir over what would typically occur with the water year conditions is considered to contribute to poorer outcomes for kokanee in Revelstoke and, by extension, Arrow Lakes Reservoir. Minimum and maximum elevation targets, for example, could result in earlier or higher discharge from Kinbasket Reservoir that would have cascading negative outcomes for kokanee downstream in Revelstoke and Arrow. Overall, the degree of confidence that a particular reservoir operation will consistently ensure a better pelagic productivity outcome is small. Operating as far as possible with the water year conditions rather than in opposition would be beneficial, especially in naturally dry years when operations could potentially change a high productivity year into a year of lower productivity, such as in 2015.

Objective	Management Question	Management Hypothesis	Status
CLBMON-2			
The objective was to collect annual time series data as a foundation for further correlation analysis. Results of this monitoring program were integrated with CLBMON-3 to enable inferences regarding the role of current operating conditions in pelagic productivity and productivity of reservoir kokanee populations.	**2-1**. What are the trends in annual distribution, abundance, and biological characteristics of kokanee populations in Kinbasket and Revelstoke reservoirs?		**2-1**. Annual distribution (relative density by transect or zone across each reservoir) remained broadly similar over the study period. Fry densities were the highest in the Main Pool and Lower Canoe zones in Kinbasket and in the Forebay and Lower zones in Revelstoke. Age 1-3 densities were relatively similar across Kinbasket Reservoir, and typically higher in the Forebay and Lower zones in Revelstoke. The impact of high flows on kokanee fry distribution was evident in 2015, when a steep density gradient was apparent with very low densities in the Middle zone that increased nearly 10-fold by the Forebay zone. Average survival from age 0-1 was 18% in Kinbasket and 12% in Revelstoke. Age 0-1 survival remained low in Revelstoke from 2011-2019. The impact of the 2016 mortality event in Kinbasket was apparent in the in-lake survival, abundance, and biomass trends. Egg to fry survival trends in Kinbasket and Revelstoke Reservoirs were remarkably similar; both averaged 14% and the trends from 2007-2018 were highly correlated. Spawner size varied with density, resulting in exceptionally large spawners in Revelstoke since 2013. Age at maturity was typically age 2 for most spawners in Kinbasket. Revelstoke spawners were a mix of age 2 and 3 although dominated most years by age 2 spawners. In general, there was a decline in kokanee abundance and biomass in both reservoirs after ~2010. Revelstoke kokanee biomass density was less than half of that of Kinbasket on average; however, the trends are remarkably similar and are correlated, particularly from 2005-2019.

Objective	Management Question	Management Hypothesis	Status
CLBMON-2			
	2-2. What role does reservoir operation play in the productivity of kokanee populations?	H1: The productivity of kokanee populations is limited by habitat impacts directly related to operation of Kinbasket Reservoir. H1A: Operation of the reservoir reduces kokanee population abundance in Kinbasket Reservoir due to entrainment from the reservoir. H1B: Operation of the reservoir reduces pelagic productivity, which affects abundance and growth of kokanee. H2: Abundance, distribution, and growth of kokanee in Revelstoke Reservoir are limited by impacts directly related to operation of Kinbasket Reservoir (through entrainment).	**2-2**. Discharge was not directly linked to Kinbasket kokanee metrics in our study, however there are lines of evidence suggesting entrainment could be of relevance to kokanee productivity in Kinbasket. For Revelstoke, there is evidence that reservoir discharge impacted kokanee productivity directly through entrainment or indirectly through zooplankton outcomes. Reservoir elevation did not have an apparent direct impact on kokanee productivity over the study period. H1: The hypothesis is accepted for impacts to the Revelstoke Reservoir kokanee population from high outflow and possible impacts to zooplankton. This hypothesis is neither accepted nor rejected for Kinbasket. H1A: This hypothesis is neither accepted nor rejected. Kokanee are known to be entrained from Kinbasket Reservoir; however, we did not directly link discharge with kokanee abundance. H1B. This hypothesis is rejected for Kinbasket with respect to primary and secondary productivity. We did not detect an effect of reservoir operations on pelagic productivity in a way that affected kokanee growth and abundance. This hypothesis is partially accepted for Revelstoke. Cumulative annual outflow was negatively associated with copepod outcomes, and Mica discharge was negatively associated with Revelstoke zooplankton outcomes mostly related to copepods, but not to *Daphnia*. H2: If only entrainment of Revelstoke kokanee is considered this hypothesis is accepted. If entrainment out of Kinbasket into Revelstoke is considered this hypothesis is neither accepted nor rejected. Some impact of entrained Kinbasket kokanee on Revelstoke kokanee outcomes is possible; however, the kokanee outcomes observed in Revelstoke were likely supported by Revelstoke recruitment alone.

Objective	Management Question	Management Hypothesis	Status
CLBMON-2			
	2-3. What are the key habitat factors that contribute to changes in productivity of the Kinbasket Reservoir kokanee population?	H1: The productivity of kokanee populations is limited by habitat impacts directly related to operation of Kinbasket Reservoir.	**2-3**. Food supply, reservoir flow, reservoir elevation (pelagic habitat), spawning habitat, and predation are all key factors discussed for both Kinbasket and Revelstoke kokanee. The most direct and evident impact was flow (discharge) resulting in entrainment for Revelstoke kokanee. Discharge from Mica GS was not associated with Kinbasket kokanee metrics. Tributary habitat (spawning) was not affected by reservoir operations. H1: The hypothesis is neither accepted nor rejected for Kinbasket Reservoir and is accepted for Revelstoke Reservoir insofar as high outflow from Mica GS can negatively influence kokanee outcomes downstream in Revelstoke and Arrow Reservoirs.
	2-4. Can modifications be made to operation of Kinbasket Reservoir to protect or enhance kokanee populations in Kinbasket or Revelstoke reservoirs?		**2-4.** Any operation that would result in an earlier or increased outflow from Kinbasket to Revelstoke Reservoir over what would typically occur with the water year conditions is considered to contribute to poorer outcomes for kokanee in Revelstoke and, by extension, Arrow Lakes Reservoir. Minimum and maximum elevation targets, for example, could result in earlier or higher discharge from Kinbasket Reservoir that would have cascading negative outcomes for kokanee downstream in Revelstoke and Arrow. Overall, the degree of confidence that a particular reservoir operation will consistently ensure a better pelagic productivity outcome is small. Operating as far as possible with the water year conditions rather than in opposition would be beneficial, especially in naturally dry years when operations could potentially change a high productivity year into a year of lower productivity, such as in 2015.

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Kootenay Lake and Arrow Lakes Reservoir phytoplankton, zooplankton, and kokanee data were collected through funding provided by the Fish and Wildlife Compensation Program, Columbia Power, the Kootenay Tribe of Idaho, and the Province of BC. Dworshak Reservoir zooplankton data were provided courtesy of Idaho Department of Fish and Game (IDFG) and the US Army Corps of Engineers (USACE). We thank these organisations for providing these data.

Acronyms and Definitions

AICc - Akaike Information Criterion, lower case “c” means corrected for small sample sizes
ALR - Arrow Lakes Reservoir
ASL – Above sea level
BPA – Bonneville Power Authority
C25 – specific conductance or conductivity adjusted to a 25°C standard
CC – Consultative Committee (of the Water Use Plan)
CI – confidence interval
CRT – Columbia River Treaty
CTD – instrument to collect profiles of Conductivity Temperature Depth through the water column
DIN - Dissolved inorganic nitrogen, which consists of nitrate, nitrite, and ammonium
DWK - Dworshak Reservoir
EA – Environmental Assessment
E-F – egg to fry
FFSBC – Freshwater Fisheries Society of BC
GIS – Gas Insulated Switchgear
GS – Generating Station
KIN – Kinbasket Reservoir
KTL – Kootenay Lake
LTA – long term average
MAF – million acre-feet
MOF – Ministry of Forests
NN – nitrite and nitrate
NTSA – Non-Treaty Storage Agreement
PAR – Photosynthetically Active Radiation
REV – Revelstoke Reservoir
TDP – Total dissolved phosphorus
TDS – Total dissolved solids
TSS – Total suspended solids
TN – Total nitrogen
TP –Total phosphorus
SRP – Soluble reactive phosphorus, also known as ortho-phosphate (PO_4)
USGRCP – U.S. Global Change Research Program (https://www.globalchange.gov/about)
WUP – Water Use Plan

Age 0 – young-of-year kokanee; interchangeable with the term ‘fry’
Age 1-3 – the combined in-lake population (or sample) of all kokanee older than age 0

Age 2+ - kokanee age 2 and older; see methods section 2.4.3

Allochthonous – material (e.g., nutrients) imported into an ecosystem

Autochthonous – material originating from within the ecosystem

Biomass - measure of the total weight of organisms. May be presented as biomass density (weight per unit: volume or area)

Biovolume – measure of the total photosynthetic volume of algal cells per volume of water

Density – measure of the total number of organisms per unit (volume or area). Expressing data in density form facilitates comparison between reservoirs.

Ensonify – to fill with sound, here using hydroacoustic equipment to produce sound waves in the water to detect fish.

Entrainment – In this report, we use entrainment in two ways: (1) [fisheries] the action by which organisms (e.g., zooplankton and fish) are transported to a downstream waterbody through dam infrastructure by water flow, and (2) [fluid mechanics] the mixing of quiescent surrounding fluid into a turbulent flow (e.g., lake surface water being mixed into a plunging river inflow)

Epilimnion - surface layer of a lake or reservoir

Fry – young-of-year kokanee; interchangeable with the term ‘age 0’

Hypolimnion – deep water layer of a lake or reservoir

Kokanee – variant of Sockeye Salmon (*Oncorhynchus nerka*) that live entirely in freshwater

Metalimnion –intermediate water between the epilimnion (surface layer) and hypolimnion (deep water)

Pelagic zone – open water area of a lake or reservoir (or ocean)

Photic zone – the near-surface region where there is enough light for phytoplankton to undergo net growth, taken to be the depth at which light declines to 1% of the surface value.

Planktivore – An organism that feeds predominantly on plankton.

Primary Production – the rate by which energy is transformed by photosynthesis to carbon biomass

Pool – water in the reservoir, in this context synonymous with reservoir

Operations (reservoir/dam) – manipulation of the storage and release of water by dams through generating stations or flow conveyance structures

Thermocline – the gradient in temperature between the warmer epilimnion (surface layer) to the cooler hypolimnion (deep water) occurring in the metalimnion

Trophic Level – a position in the hierarchy of the food chain that is comprised of organisms sharing the same function and nutritional placement with respect to energy sources. Commonly in this context: primary, secondary, and tertiary levels corresponding to phytoplankton, zooplankton, and planktivorous fish.

Water Year – the year beginning October 1st and ending September 30th. Used for reservoir operational planning to capture the period of snow accumulation and water supply for an annual cycle.

Table of Contents

List of Figures

List of Tables

1.0 INTRODUCTION

Water Use Plans (WUP) were developed for each of BC Hydro's generating facilities to achieve optimal balance among operations for power and flood control, and environmental and social values. The Columbia River Water Use Plan (BC Hydro 2007a) was accepted by the BC Comptroller of Water Rights in January 2007 following four years of public consultation (BC Hydro 2005).

A lack of basic ecological data and information on Kinbasket and Revelstoke Reservoirs impeded informed decisions for any operational changes in the upper Columbia River system. The WUP Consultative Committee (CC) acknowledged the importance of understanding reservoir limnology and the influence of current operations on ecosystem processes for planning future water management activities (BC Hydro 2005). Therefore, a monitoring program was recommended to provide long-term data on reservoir limnology, the productivity of pelagic communities, and to continue long term monitoring of kokanee populations.

Two key programs ordered by the BC Comptroller of Water Rights and scheduled for implementation over twelve years (2008-2019) were:

- CLBMON-2: Kinbasket and Revelstoke Reservoirs Kokanee Population Monitoring, and
- CLBMON-3: Kinbasket and Revelstoke Reservoirs Ecological Productivity Monitoring.

In addition, an addendum to CLBMON-3 was added for implementation over eight years (2012-2019) to meet requirements of the Mica Unit 5 and 6 Project Environmental Assessment Certificate commitments:

- CLBMON-56: Kinbasket and Revelstoke Reservoirs Ecological Productivity Monitoring, Mica Project Units 5 and 6 Addendum

This is the final synthesis report and summarises results from all years (2008-2019) of these WUP monitoring programs. The first synthesis report (Bray et al. 2013) compiled findings from the first four years of implementation (2008-2011) of CLBMON-2 and CLBMON-3, before the CLBMON-56 addendum work was initiated. A second interim synthesis report integrated the first nine years up to 2016 (Bray et al. 2018), including the first four years of CLBMON-56. Annual data reports for each monitoring study that include more details around sampling methodology and results can be found online at: Kinbasket Reservoir Fish and Wildlife Information Plan (bchydro.com).

CLBMON-3 - The objectives for the Ecological Productivity Monitoring program were to understand reservoir limnology and to determine if changes in pelagic productivity are associated with reservoir operations (BC Hydro 2007b). The sampling program built upon previous limnological studies of Kinbasket Reservoir by BC Research (1977) and three years of limnological sampling conducted by BC Hydro from 2003 to 2005 (data on file). The program was intended to monitor nutrient availability and supply, measure primary productivity, and conduct seasonal monitoring of physical, chemical, and biological (i.e., phytoplankton and zooplankton) parameters. The study was designed in three phases with each phase culminating in a synthesis of results to date: phase 1 (2008-2011), phase 2 (2012-2016), and phase 3 (2017-2019). Annual reviews of results were used to adjust the monitoring program in subsequent years. To address uncertainties around the influence of potential changes in operation of these reservoirs on pelagic productivity, the monitoring focuses on reservoir trophic web mechanisms and dynamics, obtaining measurements of aquatic productivity, and determining key indicators of change in pelagic production that would affect food availability and thus growth of kokanee

CLBMON-56 - This work was a commitment under the Mica Unit 5 and 6 Project Environmental Assessment Certificate and focuses on the incremental effect of two additional generating units at Mica Dam. The work focused on measuring temperature data in both reservoirs at a fine scale using moored arrays.

Eight Management Questions (MQs) addressed by CLBMON-3/56 were:

1. What are the long-term trends in nutrient availability and how are lower trophic levels affected by these trends?
2. What are the interactions between nutrient availability, productivity at lower trophic levels and reservoir operations?
3. Is primary production changing significantly over the monitoring period?
4. If changes in pelagic productivity are detected, are they affecting kokanee populations?
5. Is there a link between reservoir operation and pelagic productivity and what are the best predictive tools for forecasting reservoir productivity?
6. How do pelagic productivity trends in Kinbasket and Revelstoke reservoirs compare with similar large reservoir/lake systems?
7. Does the addition of Mica Units 5 and 6 influence pelagic productivity? (CLBMON-56)
8. Are there operational changes that could be implemented to improve pelagic productivity in Kinbasket Reservoir?

CLBMON-2 - The objectives for Kokanee Population Monitoring were to monitor trends in the biological characteristics, distribution, and abundance of kokanee and to provide information required to evaluate the influence of reservoir operation on kokanee (*Oncorhynchus nerka*) populations in Kinbasket and Revelstoke Reservoirs. Twelve years of kokanee monitoring under this program were used to verify and compare population trends in abundance and to interpret causes of inter-annual variation (e.g., variation in year class strength as a result of environmental or operational effects). Results of the Ecological Productivity Monitoring assist in determining whether changes in kokanee population abundance and growth over time are the result of environmental or operational effects. The kokanee monitoring takes advantage of an additional seven consecutive years of standardized kokanee time series data collected from 2001-2007 under BC Hydro's Large River Indexing Program and previously reported by Sebastian (2008a and b) and Sebastian et al. (2010). Studies specific to fish entrainment were dealt with by the Fish Entrainment Strategy for Mica and Revelstoke Generating Stations (BC Hydro 2006).

Key reservoir management uncertainties encountered during the WUP process were related to how changes in operation would affect kokanee. Interest was focused on kokanee as this species is a key component of the ecosystem, providing an important food source for other fish species and a source of nutrients to the ecosystem. The history of kokanee in these reservoirs is discussed by Sebastian et al. (2010), including stocking[1]. The most important issues to be addressed for kokanee in Kinbasket and Revelstoke Reservoirs were identified as: potential effects of physical dynamics of the reservoir (thermal stratification, water circulation patterns, and water retention time) and resulting impacts on pelagic habitat and productivity.

Four Management Questions addressed through CLBMON-2 were:

1. What are the trends in annual distribution, abundance, and biological characteristics of kokanee populations in Kinbasket and Revelstoke reservoirs?

2. What role does reservoir operation play in productivity for kokanee?

3. What are the key habitat factors that contribute to changes in productivity of the kokanee?

4. Can modifications be made to operation of dams to protect or enhance kokanee populations?

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[1] With more complete stocking records now available online, information on stocking in Sebastian et al. (2010) can be updated. It is noted that kokanee were first stocked into the upper Columbia region (Columbia Lake) in 1930 and into Windermere Lake through the early 1940s (see Province of BC Fish Stocking database).

Results of these monitoring programs are used to evaluate the role of the current operating regime on pelagic productivity and reservoir kokanee populations. In concert with similar monitoring in Arrow Reservoir and Kootenay Lake, the CLBMON-2 and CLBMON-3 time series data serve as a useful indicator of productivity in Kinbasket and Revelstoke Reservoirs and contribute to an assessment of long-term trends for the Columbia River system. These programs were intended to fill an information gap on reservoir productivity. We acknowledge the study limitations of spatial and temporal sampling coverage, that certain trophic components, such as microzooplankton or the microbial food web are not included, and that detailed examinations of compensatory mechanisms could not be explored. These may be considered for future study but were beyond the capacity of this study.

1.1 Study Area

The study area includes Kinbasket and Revelstoke Reservoirs and their associated drainage basins. Kinbasket Reservoir, situated in the Rocky Mountain Trench between Golden and Valemount B.C., is bounded by the Rocky Mountains to the east and the Selkirk and Monashee Mountains to the west. Reservoir filling was initiated in 1973 with completion of Mica Dam and subsequently flooded 431 km^2 of river and valley bottom habitat from Valemount to Donald (Figure 1). Two small lakes (<3 ha each) were inundated in the Bush Pool area as well as the larger (13 ha) Old Kinbasket Lake that is now a slightly wider and deeper section in the Columbia Reach section of the reservoir. The remaining river areas varied from the low gradient and meandering Canoe River to the steep, white water rapids of the Columbia River mainstem. Revelstoke Reservoir lies in a narrow valley between the Selkirk Mountains to the east and Monashee Mountains to the west. Completion of the Revelstoke Dam and Generating Station (GS) in 1983 led to the reservoir filling by spring 1984 and flooding of 116 km^2 of the narrow Columbia River valley.

Both reservoirs are in the Interior Cedar-Hemlock and Engelmann Spruce-Subalpine Fir biogeoclimatic zones with inflows heavily influenced by glacier and snow melt. Forestry is the predominant industrial land use. The communities of Valemount, Golden, and Revelstoke are the main settlements in the area with a small population of workers and transient tourists at Mica Creek.

Morphometrics - Characteristics of Kinbasket and Revelstoke Reservoirs are summarized in Table 1. Kinbasket Reservoir has a surface area of 431 km^3 at normal maximum and a volume of 24,800 million m^3 (Hirst 1991) at normal maximum. The mean and maximum depths are 57 m and 190 m respectively and bulk retention time is about 16 months. The reservoir is approximately 200 km in length at full pool. While the difference between allowable maximum and minimum reservoir elevation is 47 m (Table 1), the average annual drawdown from 1977-2019 was 25.5 m, with the greatest annual change in elevation to date of 39 m (2002) and the smallest of 13 m (1977). Over the study period, the average annual elevation change was 27.4 m, the maximum in 2008 (33.8 m) and the minimum in 2015 (14 m).

Revelstoke Reservoir is less than one third the size of Kinbasket with a maximum surface area of 116 km^2 and mean and maximum depths of 46 m and 120 m, respectively. The reservoir is 130 km long and averages less than 1 km in width. Pool elevation is held relatively constant at a normal maximum elevation of 573 m ASL with an annual fluctuation typically of 1.5 m in spring. Drawdowns of up to 4.5 m are allowed for operational purposes (e.g., extreme weather events) and up to 15 m for dam safety emergencies, although the latter has never been used.

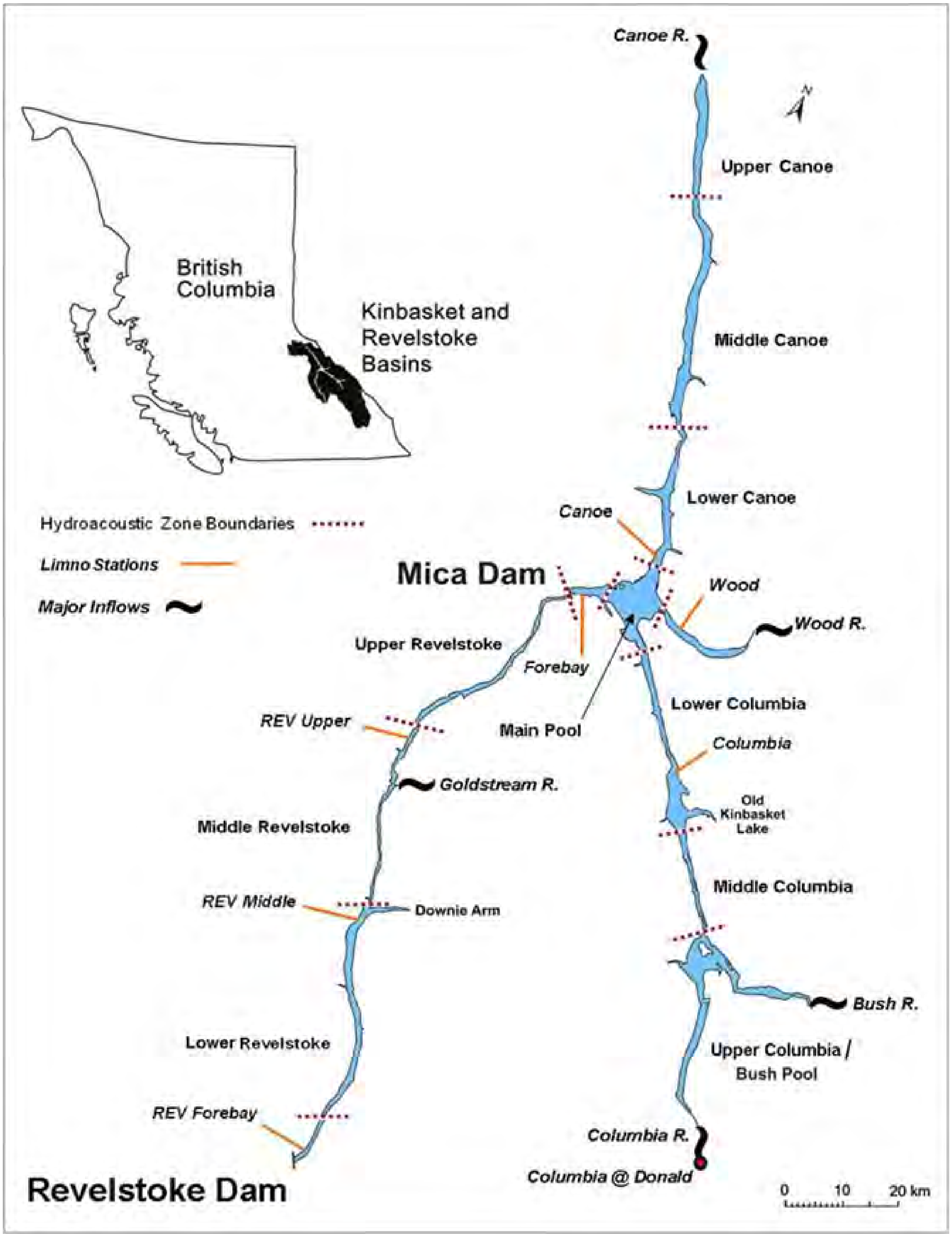

Figure 1. Map of Kinbasket and Revelstoke Reservoirs showing major inflows, location of key limnology sampling stations, and habitat zones for kokanee hydroacoustics.

Table 1. Characteristics of Kinbasket and Revelstoke Reservoirs.

	Max. Depth (m)	**Area* (km^2)**	**Mean Outflow (m^3/s)**	**Elevation of Normal Maximum (m ASL)**	**Elevation of Normal Minimum (m ASL)**	**Drawdown Area (km^2)**	**Outlet Depth** (m)**
Kinbasket **Mica Dam**	~190	431	590	754.4	707.1	220	17-65
Revelstoke **Revelstoke Dam**	~120	116	750	573.0	571.5‡	2.4	31-33

* At normal maximum as given by the BC Hydro storage elevation curves (see Pieters et al. 2022a).

‡ Normal operating minimum for Revelstoke Reservoir, water licence minimum is 554.7 m asl.

** Depth of outlet sill from water surface, from normal minimum to normal maximum reservoir elevation.

1.2 Reservoir Operations

For our purposes, operation of Kinbasket and Revelstoke Reservoirs is defined as manipulation of the storage and release of water by the Mica and Revelstoke Dams and Generating Stations. The outcome of operations is manifested in terms of reservoir elevation (level/volume) and discharge (flow), both in terms of magnitude and periodicity (timing).

Operation of dams and reservoirs in the Canadian Upper Columbia River is governed by a hierarchy of international agreements and Federal/Provincial legislation and regulations and is influenced by variations in climate (weather), flood control rules, electricity demand, facility maintenance, and unpredictable events, such as unplanned outages across the electrical system or extreme weather events.

Kinbasket Reservoir has the largest storage volume - more than twice the next largest - of all reservoirs on the Columbia River. The total active storage on Kinbasket Reservoir is 12 million acre-feet (MAF)[2] of which 7 MAF (8.61 km^3) are operated under the Canada-US Columbia River Treaty (CRT) (BC Hydro 2005). The other 5 MAF (6.17 km^3) are operated under a Columbia River Non-Treaty Storage Agreement (NTSA) between BC Hydro and Bonneville Power Administration (BPA), the US entity for CRT. Broadly, the CRT regulates Columbia River discharges at the international border primarily for flood control and secondarily for power generation benefits. Under the NTSA, BC Hydro and BPA co-ordinate the operation of storage additional to treaty storage in Kinbasket and Arrow Reservoirs with benefits to both parties, but without change to any CRT provisions. Revelstoke Dam and Reservoir was not constructed under the CRT; however,

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[2] 1 million acre feet (MAF) = 1.23 km^3. Imperial measure is used here to correspond to Columbia River Treaty values.

its operation is inherently tied to the treaty by virtue of its position between Kinbasket and Arrow Reservoirs. The CRT is currently being renegotiated by Canada and the United States.

The original NTSA was negotiated following a dispute over the filling of Revelstoke Reservoir in 1984. After some extensions, that agreement ended in 2004 with both parties fulfilling their obligations to refill their storage accounts by January 2011. This contributed to higher Kinbasket reservoir elevations throughout the first years of the study period compared to the previous decade (cf. Figure 5, Section 3.1 Hydrology). A new NTSA was signed in April 2012 with a termination date of 2024. Annual agreements were negotiated in the interim period between 2004 and 2012. Under the NTSA, both BC Hydro and BPA negotiate weekly operations for water storage or release depending on water year forecasts and both power and non-power benefits (e.g., environmental flow needs, recreation). Use of non-treaty accounts can allow for a deeper draft in Kinbasket to meet winter power demands; however, the ability to draft in Kinbasket is always constrained by elevation limits for flood control in Arrow Reservoir and CRT discharges over the international border as well as operational limits for turbine function (see https://www.bchydro.com/energy-in-bc/operations/our-facilities/columbia/ntsa.html).

Kinbasket and Revelstoke Reservoirs are operated by BC Hydro under provincial water licences that stipulate, among other things, normal minimum/maximum reservoir levels, and any provisions for specific discharges or reservoir elevations outside of operating norms. For Kinbasket Reservoir, application may be made through the Comptroller of Water Rights for additional storage (surcharge), typically up to 0.3 m above normal maximum (i.e., to 754.68 m), for economic, environmental, or other purposes to assist with managing a risk of high spill volumes at Mica Dam. Reservoir surcharge has been rarely used since the creation of Kinbasket but was implemented twice in the study period: in 2012 and 2013. In 2012, surcharge was initiated due to record high inflows throughout the Columbia basin and was needed to prevent downstream flooding. In 2013, surcharge was initiated due to operational constraints resulting from construction activities at Mica Dam.

Prior to 2015/2016 and the installation of the fifth and sixth turbines at Mica GS, the total discharge capacity of the turbines was 1,225 m^3/s. The final two units brought the total capacity to the water licence limit of approximately 1,840 m^3/s. There are no specified operational discharge requirements at Mica Dam and Generating Station.

Revelstoke Reservoir has a licensed active storage of 1.5 MAF (1.85 km^3) and an elevation range between 573.02 m and 554.66 m (18 m). The normal operating range is within 1.5 m (i.e., to 571.5 m) to maximize turbine hydraulic head and maintain a small storage buffer for operational flexibility and short-term variations in inflow. Revelstoke Reservoir elevation is kept fairly constant by regulating output at Mica and Revelstoke Dams so that the two facilities are operated in hydraulic balance. Normal surcharge can be up to 573.33 m (0.3 m), maximum up to 574.5 m; however, this can be used only for flood routing purposes and has been rarely used. During periods of unusual power demand or to maintain hydraulic balance with Mica GS the reservoir may be drafted by up to 3 m (to 569.98 m) and, in extreme emergencies (e.g., dam safety), by 15 m (to 557.8 m).

Prior to commissioning the fifth turbine at Revelstoke in December 2010, maximum discharge capacity of the turbines was approximately 1,700 m^3/s and there was no minimum discharge (therefore discharge could be zero). The Columbia Water Use Plan established a continuous minimum discharge of 142 m^3/s for the Columbia River below Revelstoke Dam that was initiated in December 2010 in conjunction with the operational start of the fifth turbine (although not related). Completion of the fifth unit brought Revelstoke GS maximum turbine discharge capacity to 2,210 m^3/s. Installation of the sixth and final generating unit has not yet been determined; however, concurrent with the Environmental Assessment Certificate application for the sixth unit was a water licence application for an additional 85 m^3/s, as the fifth and planned sixth turbines have greater generating capacity and will enable exceedance of the original water licence total of 90,000 cfs (2,548 m^3/s). A sixth unit will eventually increase the total discharge capacity at the Revelstoke Generating Station to 2,633 m^3/s.

1.2.2 Study period conditions

While each year brings its own set of weather and operating conditions related to both planned and unplanned events, it is worth noting that our study period coincided with a period of unusual activity and a wide range of conditions with respect to infrastructure changes, operations, and weather.

From their original construction up to 2010, Mica and Revelstoke Dams and Generating Stations experienced no major infrastructure changes, operating with the original four turbines installed decades before (1976 and 1984, respectively). Within the first nine years of our study period, however, three additional turbines were installed and began operation: Revelstoke Unit 5 (2011[3]), Mica Unit 5 (2015), and Mica Unit 6 (2016). In addition, there was a major upgrade to the gas insulated switchgear facility at Mica GS that affected reservoir operations in 2013. Construction at Mica GS had implications for both Kinbasket and Revelstoke Reservoir operations, particularly in 2013, and the new turbines have changed operations by virtue of

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[3] Actual in-service dates of Units at Revelstoke and Mica were in December the year prior. For this study, however, the year in parenthesis indicates the first study year affected.

providing increased capacity. Coinciding with Revelstoke Unit 5 was implementation of a continuous minimum flow (ordered at 142 m3/s) from Revelstoke GS. Initially these minimum discharges were delivered at ~163 m^3/s; however, in June 2013, minimum discharges increased to ~283 m^3/s for turbine reliability. Currently, only during small spill events is minimum discharge provided at a lower discharge (~170 m^3/s).

Climate and operational scenarios were also highly variable during the study period and included many new or previously rare events. Inflows ranged from almost record highs (2012) to almost record lows (2015). The first large spill events in over 20 years occurred at Revelstoke and Mica (2012), as well as reservoir surcharges at Kinbasket (2012, 2013), periods of lower than normal elevation (i.e., below 571.5 m) at Revelstoke (2013), and initiation of heretofore unknown spring spilling events at Revelstoke due to lack of electricity demand and to maintain the new minimum flow (2012 to 2019, except for 2013 and 2015). The third driest year in the United States and the strongest El Niño year on record (2015) triggered higher than normal and previously unseen CRT outflows from Kinbasket Reservoir with resulting high flows through Revelstoke and Arrow Reservoirs through the growing season (April to September). The smallest annual elevation change for Kinbasket Reservoir (14 m) since 1977 also occurred in 2015 and left Bush Pool inundated over the winter for only the second time. In addition to these operational and climatic anomalies, kokanee in Kinbasket Reservoir were affected by a unique and large-scale die-off in spring 2016 (likely disease related). 2017 and 2018 were two of the worst forest fire seasons on record for B.C. contributing to heavy smoke during the sampling period.

All this is to illustrate the wide range of conditions experienced over the course of our study. Useful for demonstrating variability and extremes, this variability injects both opportunity and challenges for data interpretation and confounds the ability to test operational versus environmental influences on these reservoir ecosystems. With climate change effects having an increasing and destabilizing presence on the region's ecology (USGCRP 2018) and with concomitant impacts to flood control and energy demands (operations), it is increasingly difficult to develop prescriptive operations for maintaining maximum reservoir productivity based on historical trend data as anticipated in the study TORs.

2.0 METHODS

The following is a summary of methods for sampling conducted over the course of the study. Details on station coordinates, sampling schedules, equipment, and specifications used for data collection and in post field data processing and analyses are available in annual data reports for CLBMON-2 and CLBMON-3/56 at: Kinbasket Reservoir Fish and Wildlife Information Plan (bchydro.com).

2.1 Hydrology

Flow and water level records were provided by BC Hydro and Water Survey Canada. The local flow to each reservoir was computed from a water balance as described in Pieters et al. (2022a). Daily average values are shown unless noted otherwise.

2.2 Tributary chemistry and temperature

Two types of tributary sampling were undertaken over the study period: (1) occasional surveys of many tributaries to assess variations across the drainage; and (2) frequent sampling of a set of reference tributaries to assess seasonal variations and long-term trends. Surveys were undertaken across both reservoirs on 25 June and 5 August 2008, 7-8 July 2009, and 6 May 2013 to capture a range of seasonal flows (for further detail see Pieters et al. 2016). Tributary surveys sampled approximately 2/3 of the total inflow to Kinbasket and 9/10 of the inflow to Revelstoke Reservoir.

Sampling of reference tributaries was conducted from 2009 to 2018 and reference tributaries were generally sampled monthly from March to December except twice monthly during freshet from April to June; for sampling details see Pieters et al. (2022b). The reference tributaries were: Columbia River at Donald, Kinbasket (Mica) outflow, Goldstream River, and Revelstoke outflow. Beaver River was added in 2013 to complement samples collected by Parks Canada and analysed by Environment Canada. Downie Creek was added in 2016 because of its importance to the lower Revelstoke Reservoir. From 2008 to 2012, water samples were analysed by the Cultus Lake Salmon Research Laboratory, Department of Fisheries and Oceans, Cultus Lake, British Columbia. From 2013 to 2018, samples were analysed by Maxxam Analytics Inc., Burnaby, British Columbia.

2.3 Reservoir Limnology

2.3.1 Reservoir sampling stations

Reservoir pelagic sampling was scheduled once a month from April/May to October at four stations in Kinbasket Reservoir (KIN Forebay, KIN Canoe, KIN Wood, and KIN Columbia) and three stations in Revelstoke Reservoir (REV Upper, REV Middle, and REV Forebay) from 2008-2019 (Figure 1). Sampling was conducted for physical properties (depth profiles, Secchi), water chemistry, phytoplankton, picoplankton, and zooplankton.

The study began in July 2008 with the first full seasonal reservoir sampling conducted in 2009. In 2013, April sampling was added to the regular schedule to improve data for early season conditions. Some monthly data are incomplete or missing when sampling was curtailed due to logistical (e.g., field conditions) or mechanical (e.g., equipment failure) issues. Kinbasket

Reservoir presented a greater challenge for sampling due to debris, fluctuating water levels, and more dangerous conditions; therefore, the dataset for this reservoir is less complete than for Revelstoke Reservoir.

2.3.2 CTD

Profiles of water properties were collected with a CTD (conductivity-temperature-depth) profiler at each station and at the middle of the main pool in Kinbasket. A Sea-Bird Electronics SBE 19plus V2 profiler was used, with the following additional sensors:

- Turner SCUFA II fluorometer and optical back scatter (OBS) sensor,
- Biospherical QSP-2300L (4 pi) photosynthetically active radiation (PAR) sensor,
- Sea-Bird SBE 43 dissolved oxygen sensor, and
- WETlabs C-Star transmissometer (red, with 25 cm path).

The profiler collected data at 4 Hz and, when lowered at approximately 0.3 m/s, collected data every 0.1 m. Raw *in situ* conductivity was converted to conductivity at 25 °C (C25 or specific conductivity); only C25 is shown and conductivity in the report refers to C25 throughout.

2.3.3 Moored temperature recorders

Beginning in 2012, temperature data were collected at fixed sites in Kinbasket and Revelstoke Reservoirs as part of the CLBMON-56 Addendum #1 to CLBMON-3 (BC Hydro 2007b). Data were collected from two base locations: the forebay of Revelstoke Reservoir and the forebay of Kinbasket Reservoir. Each mooring consisted of two parts: a line with instruments hung from the log boom at the dam to collect temperature near the surface, and a subsurface line approximately 1 km from the dam to collect temperature from depth. Instrument lines were also moored at other locations, such as at the middle and upper sampling stations in Revelstoke Reservoir, and at the location of the Old Kinbasket Lake on the Columbia Arm of Kinbasket Reservoir (Figure 1).

All instruments were internally recording and were recovered, uploaded, serviced, and re-installed annually. Onset Hobo U22 temperature recorders (accuracy 0.2 °C) were generally spaced every 2 m, with higher resolution Seabird SBE56 or RBR Solo-T recorders (accuracy 0.002 °C) every 20 m. Also used were autonomous vertical profilers tethered in Revelstoke Reservoir that collected a temperature, conductivity, and turbidity profile once a day.

2.3.4 Water chemistry

Five litre Niskin bottles were lowered by cable in series to collect discrete depth samples at 2, 5, 10, 15, 20, 60 and 5 m off bottom (where possible) for all years except 2019 when only 2 to 20 m depths were sampled. Intermediate depth samples between 25 to 80 m were collected in various years to determine the most appropriate metalimnion depths to sample. A plastic tube with inside diameter of 2.54 cm was used to obtain a 0-20 m integrated depth sample. Additional details can be obtained from annual reports.

Discrete depth samples were analysed for nitrite+nitrate (NO_2+NO_3 or NN), total phosphorus (TP), total dissolved phosphorus (TDP), soluble reactive phosphorus (SRP), alkalinity, conductivity, pH, and turbidity. Total nitrogen (TN) was included from 2016-2019. Integrated tube samples were analysed for soluble reactive silica. Secchi disk readings were taken without a viewing tube at each site using a standard 20 cm Secchi disk. Further details on sample preparation, analytical methods, and laboratory detection limits are available in annual data reports.

From 2008-2012, samples were analysed at the DFO Cultus Lake laboratory; however, beginning in 2013 samples were sent to Maxxam Analytics Laboratory (Burnaby) as sample analysis at the DFO lab was no longer available. In 2019, samples were sent to ALS labs. Detection limits changed between the DFO Cultus Lake and commercial laboratories, particularly for phosphorus fractions, and some analytical differences resulted in adjustments to results for phosphorus, alkalinity, and soluble reactive silica that are described in annual reports.

2.3.5 Primary production

Primary productivity, chlorophyll *a*, and alkalinity were measured once a month from June to September in Kinbasket Reservoir at the Forebay station, and in Revelstoke Reservoir at the Forebay station and Middle station. Exceptions are 2002 (Kinbasket August only), 2008 (all sites July to September only), and 2011 (Kinbasket June to August only). Data presented here from 2002 and 2008 were obtained by methods described in Stockner and Korman (2002) and TG Ecologic LLC (2009), respectively. Sampling methods and analytical procedures are described in detail in Harris and Sarchuk (2018).

2.3.6 Phytoplankton and picoplankton

Discrete samples were typically collected monthly from April through October at the four Kinbasket Reservoir and three Revelstoke Reservoir sites at depths of 2, 5, 10, 15, and 25 m, and preserved in the field in acid Lugol's iodine preservative for identification and enumeration by Advanced Eco-Solutions Inc. in Newman Lake, WA.

Two depth strata, the epilimnion and hypolimnion, were assessed by creating composites of discrete samples. The mean of the taxa densities from samples collected at 2, 5, and 10 m were used to calculate epilimnetic density and biovolume while samples from 15 and 25 m were used to calculate the hypolimnetic density and biovolume. In 2008 and 2009, samples taken at various depths were composited in the field and then identified and enumerated in the laboratory. A change in methodology in 2010 through 2019 whereby samples were not composited in the field is compatible with the previous sampling methodology. However, the taxa richness could be higher in the composited samples from 2010 to 2019 since counting multiple samples and then compositing them after identification and enumeration will result in an increase in the fraction of the sample counted compared with counting a single field composited sample.

Phytoplankton samples were gently shaken for 60 seconds and poured into 25 mL settling chambers and allowed to settle for a minimum of 3 hrs prior to quantitative enumeration using the Utermohl Method (Utermohl 1958). Counts were done using a plankton microscope. All cells within a random transect of 3.5 mm in length were counted at high power (900X magnification) that permitted a semi-quantitative enumeration of minute (<2 µ) autotrophic pico-cyanobacteria cells (1.0-2.0 µ) [Class Cyanophyceae], and of small, delicate auto-, mixo-, and hetero-trophic nano-flagellates (2.0-20.0 µ) [Classes Chrysophyceae and Cryptophyceae]. Comments on the relative density of ciliates in each sample were also noted on count sheets. Where feasible, from 250-300 cells were enumerated in each sample to assure counting consistency and statistical accuracy (Lund et al. 1958). The compendium of Canter-Lund and Lund (1995) was used as a taxonomic reference. The primary taxonomist was Nichole Manley of Advanced Eco-Solutions Inc.

2.3.7 Zooplankton

Samples were collected monthly at each of the seven reservoir sites with a vertically hauled 153 µm mesh Wisconsin net having a 0.2 m throat diameter. Each haul was to 30 m and duplicate samples were taken at each site. Collected zooplankton samples were rinsed from the dolphin bucket and preserved in 70% ethanol. Zooplankton samples were analysed for species composition, density, biomass, and fecundity by Dr. Lidija Vidmanic. Enumeration protocols for zooplankton are described in Vidmanic (2018). Zooplankton species were identified with reference to taxonomic keys (Sandercock and Scudder 1996; Pennak 1989; Wilson 1959; Brooks 1959).

2.4 Kokanee

2.4.1 Habitat

Estimates of pelagic habitat area for kokanee at maximum and minimum annual pool elevations and for summer survey periods were derived following methods in Appendix 5 of Sebastian et al. (2010). In Kinbasket Reservoir, the Main Pool is located upstream of the Forebay and represents a junction of three upstream reaches, Canoe, Wood, and Columbia (Figure 1). Habitat zones for both Kinbasket and Revelstoke are described in (Table 2). A summary of all survey dates, pool elevation, and pelagic habitat area for all previous hydroacoustic surveys of Kinbasket Reservoir is provided by Weir (2022).

Table 2. Kinbasket and Revelstoke Reservoirs kokanee hydroacoustic survey habitat zones.

Zone Name (Number)	**Description**	**Hydroacoustic Transects**	**Limno Sampling**
Kinbasket Reservoir			
Upper Canoe (1)	40 m contour to Valemount	NOT SURVEYED	
Middle Canoe (2)	Narrows to 40 m contour	1-4	
Lower Canoe (3)	Main Pool to Narrows	5-8	Yes
Main Pool (4)	East of Sprague point	12-16, 20	
Forebay (5)	Mica Dam to Main Pool outlet	9-11	Yes
Wood Arm (6)	Main Pool to Wood River	17-19	Yes
Lower Columbia (7)	Main Pool to Old Kinbasket L. inlet	21-27	Yes
Middle Columbia (8)	Old Kinbasket Lake to Bush Pool	28-30	
Upper Columbia/Bush Pool (9)	Bush Pool to Upper Columbia R	31-36a	
Revelstoke Reservoir			
Forebay (1)	Revelstoke Dam to Martha Cr	1-3	Yes
Lower (2)	Martha Cr. to Downie Narrows	4-12	Yes
Middle (3)	Downie Narrows to Nicholls Cr	13-20	Yes
Upper	Nicholls Cr to Mica Camp	NOT SURVEYED	

a) Bush Pool was surveyed for the first time in 2015 when 9 transects were completed to examine kokanee use of Bush Pool. From 2016 to 2019 six transects were completed annually.

In previous reporting we described pelagic habitat as water 20 m and deeper, however the pelagic habitat areas presented in this report are the areas at 17 m. The discrepancy exists because acoustic data are analysed in 5 m layers, and the habitat area applied to each layer density is ~the layer mid-point (upper layer bound plus 2 m). Accordingly, the 15-20 m acoustic analysis layer has the area at 17 m applied. Ultimately, the difference between the habitat at 20 m and at 17 m is relatively small for the entire reservoir (~2%), however the difference can be substantial in shallow habitat such as Bush Pool (30+%).

2.4.2. Hydroacoustic surveys

Kokanee hydroacoustic surveys were conducted at night within 6 days of the new moon from mid-July to mid-August 2008-2019. Surveys consisted of 30 transects in Kinbasket Reservoir and 20 transects in Revelstoke Reservoir following the survey design in Sebastian et al. (2010). An additional 9 transects were done in 2015 to assess kokanee use in Bush Pool as outlined in Sebastian and Weir (2016). Six of the nine new transects in Bush Pool were repeated in 2016-2019. Due to adverse sampling conditions (e.g., high winds and dense debris fields) not all transects could be accessed in all years. Detailed descriptions of equipment and specifications used in data collection and in post field data processing and analyses are found in annual CLBMON-2 data reports, and are summarized by Sebastian et al. (2010), Johner and Weir (2012), and Weir (2022).

2.4.3 Estimating age-specific abundances

Weir (2022) describes methodology for estimating kokanee age structure that relies on empirical relations between kokanee acoustic target strength and fork length (TS:FL) derived from Kinbasket acoustic, trawl, and gillnet data. The approach involved first determining where the length cut-off thresholds occurred between age 0 and age 1 as well as between age 1 and 2/3 kokanee based on evaluation of annual fish capture data (trawl and/or gillnet data). Cut-off thresholds were typically indicated by valleys between length frequency modes, however where ages were overlapping, the age data were used in conjunction with length frequency breaks to determine the best length for partitioning age groups. Extensive overlap between age 2 and age 3 fish made separation unreliable, so those fish remained in one group referred to as age 2+. The second step was to convert the cut-offs established from trawl/gillnet data to their acoustic equivalent using the TS:FL relations. The third step was to determine where the acoustic age 0/1 cut-off occurred on the acoustic size distribution for each survey. The acoustic age 0/1 cut-off was typically apparent as an inflection point in the distribution where high numbers of small age 0 (fry) intersected with lower numbers of larger sized (age 1-3) fish. The acoustic and trawl age 0/1 cut-offs were then compared for each survey and their difference (if any) was used as a correction factor that was applied to the trawl age 1/2+ cut-off to correct/align it with the acoustic size distribution. The final step was to apportion the total survey abundance (which is output in 1dB size increments) into age 0, age 1, and age 2+ groups by using the acoustic age 0/1 cut-off and the trawl age 1/2+ cut-off corrected to the acoustic scale. Where no or sparse trawl and gillnet data existed, other options were applied based on professional judgement and understanding of the historic acoustic datasets. This was primarily an issue for Revelstoke as Kinbasket had reasonable trawl data most years and gillnet data from 2013 onwards (see Weir 2022 for details).

2.4.4 Trawl sampling

Trawl sampling was conducted to verify that kokanee were the dominant species observed at night during the hydroacoustic survey and to collect biological samples for determining size at age and maturity. Trawling occurred during the nighttime hours in Kinbasket Reservoir concurrent with the acoustic surveys and typically consisted of 1-2 trawls in the Main Pool or Forebay zone and 1-3 trawls in Wood Arm as weather, debris, and other sampling logistics allowed. Acoustic data collected during the nights immediately prior to trawl sampling were evaluated to determine the vertical fish distribution and the highest density depth layers were targeted using a 7 x 3 m beam net.

Trawling was discontinued in Revelstoke Reservoir following 2012 due to poor catch efficiency at low densities and because initial gillnet surveys proved to be more successful at capturing age 1-3 kokanee.

2.4.5 Gillnet sampling

Mid-water gillnetting was conducted to complement trawl catches on Kinbasket Reservoir from 2013-2019, and as the sole method of capturing kokanee samples for Revelstoke Reservoir from 2012-2019. Gillnet sites were chosen to maximize catch by targeting locations and depths with the highest age 1-3 kokanee densities, based on evaluation of acoustic data collected prior to gillnetting and are described in annual reports. Each gillnet set consisted of three or four modified Resources Information Standards Committee standard nets (RIC 1997)[4] attached end to end for a total length of 320 or 427 m per set, respectively. Gillnets were suspended mid-water within the depth range of the nighttime fish layer, set in the evening, and pulled the following morning. Gillnet set and retrieval followed the methods outlined by Sebastian and Weir (2016).

As per Weir (2022), given the broadly similar outcomes among capture methods (trawl and gillnet) and between locations we pooled all trawl and gillnet captured kokanee, unless otherwise specified. See Weir (2022) for kokanee fork length statistics from all Kinbasket Reservoir trawl and gillnet sampling.

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[4] A modification was made to RIC standard nets (RIC, 1997) starting in 2015 when an additional panel of 32 mm stretched mesh size was added to each net (see Appendix 8 in Sebastian and Weir (2016) for RIC net modifications).

2.4.6 Biomass estimation

Biomass estimates for each survey were produced by multiplying the acoustic abundance for each age group by the mean weight for the corresponding age group derived from annual trawl and gillnet data. Since age 2 and 3 fish were combined for an estimate of age 2+ abundance, the mean weight of combined age 2 and 3 fish was applied to estimate age 2+ biomass. The total biomass for the survey was the sum of biomass estimates by age group.

In some years catch data were absent or sparse which presented challenges for age structure determination and for estimation of biomass. To generate mean weights where data were insufficient or absent for age 0 and age 1, we used the long-term mean weight at age as both those age classes did not demonstrate density dependant growth relationships. Age 2+ kokanee did demonstrate density dependant growth so age 2+ acoustic density was used to predict mean weight at age 2+ where catch data were absent or where the sample size was low (n=<10). See Weir (2022) for further details including the regression used to predict mean weights for age 2+ kokanee from age 2+ acoustic density.

2.4.7 Spawner surveys and alternatives to direct enumeration

Aerial survey methods described by Johner and Weir (2012) were subject to variability from stream to stream and year to year depending on water clarity, weather, flow stage, and peak spawn timing. As a result of difficulties in direct enumeration, an alternate method was developed to provide an index of basin wide spawner abundance for Kinbasket and Revelstoke Reservoirs. Notably, the spawner index estimates are not based on mature fish/spawners observed at, or in transit to, spawning tributaries; instead, they are derived from the summer acoustic abundance estimates in conjunction with sexual maturity information from concurrent gillnet and trawl sampling. The annual index estimates are generated by multiplying the acoustic estimate of age 2+ kokanee abundance by the percentage of age 2+ fish captured in gillnets that were maturing in the summer surveys. As gillnetting did not begin until 2013 in both reservoirs, the 2013-2019 average for percent mature for age 2+ kokanee was applied to earlier years, which was considered appropriate given the relatively consistent proportion of maturing fish observed each year from 2013-2019. The average proportion of maturing age 2 and older kokanee in the gillnet catch for Kinbasket was 81% (SD 7%, range 70-90%) and for Revelstoke was 83% (SD 8%, range 76-94%). The comparability of these acoustic/gillnet data derived index estimates relative to estimates based on standard methods of enumerating kokanee spawners (fence/bank/helicopter) is unknown. However, we assume they are reliable as an index of annual spawner abundance and are comparable across waterbodies with similar survey timing, data collection, and analysis methodology.

2.4.8 Biological sampling of spawners

Kinbasket spawners were sampled during the fall for biological data in various tributaries including Camp Creek (tributary to Canoe River), Bush River, Wood River, Luxor Creek, and the Upper Columbia River near Fairmont. Tributaries sampled and sampling frequency varied across the study period. Camp Creek was sampled the most consistently and has the longest intact time series. Standard Creek was sampled for Revelstoke spawners.

Following recommendations from the first synthesis report, effort directed at biological sampling was increased. Biological sampling of spawners by angling continued at Camp Creek. Dip-net sampling continued at Luxor and Standard Creeks and was extended to include Bush River starting in 2013 and the Upper Columbia River in 2014-2015. Both angling and dip-netting were used to capture fish on Upper Columbia in 2014 and angling was used in 2015. Following a recommendation from the phase 1 synthesis (Bray et al. 2013), an effort was made to conduct multiple sampling trips spread across the spawning period to ensure annual age structure and size at age estimates adequately represent all stages of the run. This was moderately successful but was sometimes limited by heavy rain events resulting in an inability to observe or capture fish on multiple dates some years. Sex and fork length were recorded, and otoliths collected the same day of capture. Spawner ages were determined from otolith interpretations completed at the Provincial Ageing Laboratory operated by the Freshwater Fisheries Society of BC (FFSBC) following protocols in Casselman (1990). The intent of increased biological sampling was to improve our understanding of spawner size, age at maturity, and age composition among different spawning populations around the reservoir.

2.4.9 Survival

Annual kokanee cohort survival was calculated for age 0 to age 1 and age 1 to 2+ using the age partitioned acoustic data by dividing the cohort population by its population the previous year.

Estimating survival from age 1 to age 2 may be confounded by an inability to partition age 2 and older kokanee into age specific estimates. However, age 2 kokanee would have typically made up the majority of the age 2+ population component, given that the age at maturity was dominated by age 2 in Kinbasket and Revelstoke in most years [except for Camp Creek, a tributary to Canoe River (Kinbasket) but with a small proportion of total spawners]. Accordingly, the trends in age 1 to age 2+ survival are presented and are expected to broadly represent survival trends of age 1 kokanee, although should be interpreted with some caution.

A length to fecundity relation reported by McGurk (2000) was applied to female spawner length data to estimate fecundity for each fish and provided an estimate of average fecundity for each reservoir and year. Assuming a 1:1 sex ratio, the reservoir spawner index and average fecundity were used to predict annual egg deposition. The resulting egg deposition values were divided by the following year summer acoustic fry abundance to produce an index of egg to summer fry survival. As no spawner size data exist from 2001-2006 and 2008, we estimated reservoir-specific annual average female fork lengths based on regressions between female spawner fork lengths (all sampled tributaries except Camp for Kinbasket and Standard Creek for Revelstoke) and spawner densities for 2007 and 2009-2019. The resulting equations were $y = 292.88x^{-0.088}$ (R^2 0.52) for Kinbasket and $y = 334.77x^{-0.111}$ (R^2 0.79) for Revelstoke.

2.4.10 Egg to fry survival regression analysis

Potential factors affecting egg to fry survival were assumed to be tributary flow during spawning, air temperature, egg deposition, and spawner size. Water Survey of Canada data from Columbia at Donald (08NB005) were used as a regional proxy of unregulated flow to represent conditions in spawning tributaries. Environment Canada air temperature at Revelstoke was used as a regional proxy for temperature. To better understand common regional drivers (i.e., flow and temperature) Arrow Lakes Reservoir kokanee data were also included in the analysis. Egg deposition estimates for Arrow are slightly different than described above for Kinbasket and Revelstoke because Arrow has estimates for spawners from direct enumeration and a spawning channel where annual spawner biological characteristics are measured, including sex ratio and fecundity (see Bassett et al. 2020a). For Arrow, the fry estimates were from October surveys so the egg to fry survival period is slightly longer than for Kinbasket and Revelstoke where fry estimates occur mid-summer. Specific variables and rationale are detailed in Table 2. Predictor variables were standardized to a mean of 0 and standard deviation of 1 to make the regression coefficients commensurate. The egg to fry survival data were transformed using a logit transformation (Warton and Hui, 2011). A small number of variables allowed for all possible variable combinations to be fit by regression analysis using the branch-and-bound algorithm. The models were ranked using Akaike Information Criterion corrected for small sample sizes (AICc), where all models within ~2 units of the lowest AIC were considered, and variable importance was defined as the sum of the model weights that contain the variable of interest.

Table 3. Variables and rationale for inclusion in analysis of factors affecting kokanee egg to fry survival in Kinbasket, Revelstoke, and Arrow Reservoirs. Kinbasket and Revelstoke fish variables spanned from 2001-2019 and for Arrow except for 2003 due to incomplete spawner data.

Variable	Period (abbreviation)	Rationale/Assumption
Flow	Mean; September 1 - 30 (Flow.Sept.1.30)	flow/water level affects position of redds (i.e., high flow could result in redds built in locations that later become dewatered at low flow)
Flow	Peak daily; September 1 - 30 (PeakDailyFlow.Sept.1.30)	flow/water level affects position of redds (i.e., high flow could result in redds built in locations that later become dewatered at low flow)
Air temp	Mean; September of year (AirT.Sept)	Surrogate for water temperature which could impact pre-spawn mortality and/or run timing
Air temp	Mean; December of year (AirT.Dec)	Cold temperatures result in lower water level and egg freezing/ice scour
Air temp	Mean; January of year+1 (AirT.Jan)	Cold temperatures result in lower water level and egg freezing/ice scour
Air temp	Mean; February of year+1 (AirT.Feb)	Cold temperatures result in lower water level and egg freezing/ice scour
Air temp	Mean; March of year+1 (AirT.Mar)	Cold temperatures result in lower water level and egg freezing/ice scour
Air temp	Coldest week mean; Dec-Mar year+1 (AirT.coldest)	Cold temperatures result in lower water level and egg freezing/ice scour
Egg deposition	Occurs in September (ED.s)	Survival impacts from redd superimposition at higher densities
Spawner Fork Length	Length at spawning in September (SS.s)	Spawner size related to redd position (water depth and velocity, substrate size)
Reservoir	(ReR, ReK)	Categorical variable of reservoir

2.4.11 In-lake survival regression analysis

Potential factors affecting in-lake survival for age 0-1 kokanee were assumed to be reservoir outflow, air temperature, prey availability (zooplankton metrics) minimum reservoir elevation, kokanee density, max local inflow, total kokanee biomass density, and upstream kokanee densities (Table 4). Kokanee data from Arrow Lakes Reservoir were also included in the analysis for comparison. All available data from 2001 to 2019 were included, although Kinbasket and Revelstoke zooplankton data were mostly absent prior to 2009. Large scale kokanee mortality events were observed in Arrow (2012) and Kinbasket (2016) that were linked to disease; consequently, those survival points were removed from the analysis. Environment Canada air temperature at Revelstoke was used as a regional proxy for temperature. Cumulative outflow data are the sum of daily outflow values between August 1 and July 31 the following year for Kinbasket Reservoir (Mica Dam), Revelstoke Reservoir (Revelstoke Dam) and from Oct 1 to Sept 30 for Arrow Reservoir (Hugh Keenleyside Dam); annual periods coincide with the reservoir-specific measurement interval of kokanee survival. Outflow and air temperature data were common to all reservoirs. For other variables (zooplankton, reservoir elevation, kokanee biomass), only the values for the specific reservoir were used, i.e., Arrow Reservoir used Arrow zooplankton density only. For maximum local inflow (all inflow other than Mica outflow), Arrow data were unavailable, so Revelstoke data were used as a proxy. The upstream age 0 density variable was applicable only to Revelstoke and Arrow. Due to the small population in Revelstoke relative to Arrow and Kinbasket, Kinbasket age 0 densities were also used for the upstream density variable for Arrow. Brief rationale for inclusion of each variable is provided in Table 4.

A standard normal-theory regression analysis was performed using the empirical logit transformation of the survival as recommended by Warton and Hui (2011). Two sets of model fits were performed: all reservoirs were combined for a single combined model, then a separate model was fit for each reservoir. A small number of variables allowed for all possible variable combinations to be fit by regression analysis using the branch-and-bound algorithm. The models were ranked using AICc, where all models within ~2 units of the lowest AIC were considered, and variable importance was defined as the sum of the model weights that contained the variable of interest.

For the combined model, the survival probabilities differed between reservoirs, so a reservoir effect was included. Missing zooplankton data for most years prior to 2009 resulted in those years being omitted for Kinbasket and Revelstoke. For the separate reservoir models, all variables were used except the zooplankton variables were included only for the Arrow analysis where there were sufficient data (i.e., 2001-2019 for Arrow). The inclusion of zooplankton data meant the number of variables could be larger than the number of available observations for Arrow, so the model search was restricted to models with 10 or fewer terms.

Table 4. Variables and rationale for inclusion in multiple regression analysis of factors affecting kokanee in-lake survival in Kinbasket, Revelstoke, and Arrow reservoirs. All available data were included for the 2001-2019 period.

Variable	Unit	Period (abbreviation)	Rationale/assumption
Reservoir outflow	Cumulative, millions of m^3	Annual (outflow_Ann; concurrent with survival period), January-March (Outflow_Win), April-June (Outflow_Spr)	Outflow results in entrainment of kokanee and food resources.
Air temp	Average °C	January-March (Air.T_Jan_Mar), April-June (Air.T_Apr_June)	Proxy for water temperature. Relates to thermal stratification, may influence predator prey dynamics, zooplankton productivity, kokanee growth.
Copepod density	Average #/L	October (Cope_Oct), May (Cope_May), June (Cope_Jun)	Prey availability going into and out of winter.
Total zooplankton biomass	Average µg/L	August (ZoopB_Aug), October (ZoopB_Oct), May (ZoopB_May), June (ZoopB_Jun)	Prey availability near peak of productive season and going into and out of winter.
Minimum reservoir elevation	Monthly average	Annual (Min_Elev)	Predator/prey interactions at low pool when kokanee are at increased density.
Kokanee Density	#/ha	Annual (Age 0 = Den0)	Density dependent survival (intra-cohort competition).
Maximum local inflow	m^3/s	Annual (Max_Inflow)	Relevant variable in lower trophic analysis. Represents hydroclimatic variation.
Kokanee total biomass	kg/ha	Annual (KookB)	Density dependent survival (inter-cohort competition).
Upstream age 0 density	#/ha	Annual (Den_up)	Used Kinbasket densities to test for impact of upstream densities which could result in variable entrainment affecting 'survival' estimate if entrained fish are enumerated with the downstream population.

Kootenay Lake and Arrow Reservoir data - Where applicable, data from nearby Arrow Lakes Reservoir (ALR) and Kootenay Lake (KTL) are presented for comparison to Kinbasket and Revelstoke Reservoirs and to assist with addressing the management questions. Long-term datasets exist for these two nearby waterbodies that were collected and managed by the

Province of BC through partnerships and funding from BC Hydro and the Fish and Wildlife Compensation Program, the Kootenay Tribe of Idaho, and the Columbia Power Corporation. Zooplankton and kokanee data are on file with Ministry of Forests (Nelson & Victoria, BC) and have also been reported in annual data reports, the most recent being Bassett et al. (2020a) for Arrow, and Bassett et al. (2020b) for Kootenay Lake. Hydroacoustic surveys on these systems were also conducted by the Province of BC and equipment, data collection, and analysis methods were nearly identical among all systems; however, the Kootenay and Arrow surveys occur in September and October, respectively, compared to the Kinbasket and Revelstoke surveys which occur between mid-July and mid-August. All available data for each system from 2001-19 are presented, which aligns with the extent of the continuous kokanee time series for Kinbasket and Revelstoke.

3.0 RESULTS

3.1 Hydrology

Kinbasket and Revelstoke Reservoirs are part of the Columbia River headwaters in southeast British Columbia (Figure 1). While this region comprises only 4% of the Columbia River drainage area, it contributes 11% of the flow.

Kinbasket Reservoir - Kinbasket Reservoir is composed of two main arms, the Canoe Reach to the north, and the Columbia Reach to the south (Figure 1). The Columbia River is the largest tributary to Kinbasket Reservoir, accounting for 30% of inflow (Pieters et al. 2022a). In addition, tributaries along the Upper Columbia Reach of the reservoir also contribute significantly to the total inflow (29%) and, together with the Columbia River, provide 59% of the inflow to Kinbasket Reservoir at the outlet of Bush Pool (Figure 1). The Middle and Lower Columbia Reaches together contribute a further 15%, for a total of 74% from the entire Columbia Reach. In contrast, the contribution from tributaries to the northern part of Kinbasket Reservoir – Canoe Reach – is only 15%, of which the Canoe River, entering at the north end, contributes only 3%, for a total of 18%. Wood Arm, entering the main pool from the east contributes the balance of 7%.

The water level and flows averaged over the study period are shown for both reservoirs in Figure 2. The water level in Kinbasket Reservoir is drawn down in winter for hydroelectric generation (Figure 2a). Inflow to Kinbasket Reservoir has a natural hydrograph with a large freshet peak of snowmelt in spring that tails off gradually through summer (Figure 2b). From May to July, the water level rises as freshet inflow is stored to provide flood control downstream; during this time the outflow from Kinbasket Reservoir is low (Figure 2b). Once Kinbasket Reservoir has almost filled, the tail of the freshet is released, with increasing outflow from Kinbasket Reservoir in July and August.

Revelstoke Reservoir - In contrast to Kinbasket Reservoir, Revelstoke Reservoir is operated run-of-the-river, a type of hydroelectric generation where inflow is balanced by outflow, and as a result there is little change in water level and only a small amount of water storage (Figure 2c). The outflow from Kinbasket Reservoir provides the majority (71%) of the annual inflow to Revelstoke Reservoir. However, from May to July when Kinbasket Reservoir is filling and outflow from Kinbasket is low, the inflow to Revelstoke Reservoir is dominated by local inflows (Figure 2d). The outflow from Revelstoke Reservoir, which combines both inflow from Kinbasket Reservoir and inflow from local tributaries, is relatively steady throughout the year (Figure 2d).

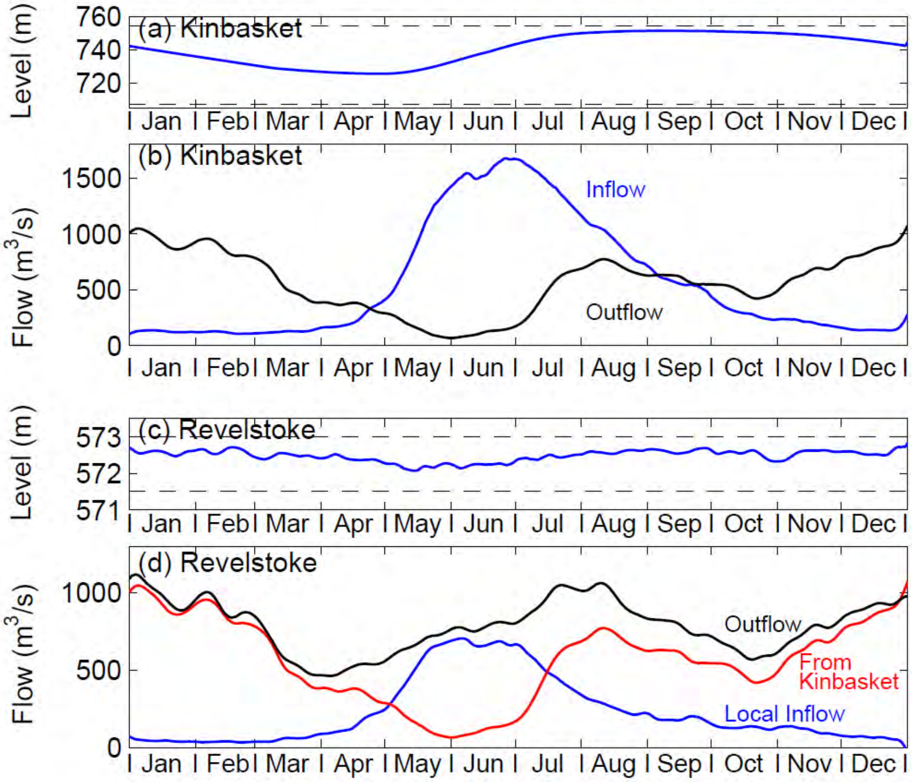

Figure 2. (a) Average water level for Kinbasket Reservoir, (b) average inflow and outflow for Kinbasket Reservoir, (c) average water level for Revelstoke Reservoir, and (d) average local inflow, inflow from Kinbasket Reservoir, and outflow for Revelstoke Reservoir. Data were averaged for 2008-2019.

Variation in tributary inflow - Year to year variation in the natural inflow during the study period is illustrated using selected years for Columbia River at Donald (Figure 3). Other gauged tributaries (Beaver and Goldstream Rivers), as well as the computed local inflow to both Kinbasket and Revelstoke Reservoirs, were similar (Pieters et al. 2022a). The natural inflow was close to average in 2014 (Figure 3a), significantly above average in late June and July 2012 due to heavy rain (Figure 3b), and below average in 2009 (Figure 3c).

To compare the overall inflow from year to year, the flow of the Columbia River at Donald is shown averaged over the productive period, April through October, in Figure 4. A wide variety of natural inflows were observed during the study period, including those that were both significantly high (2012) and low (2009, 2010).

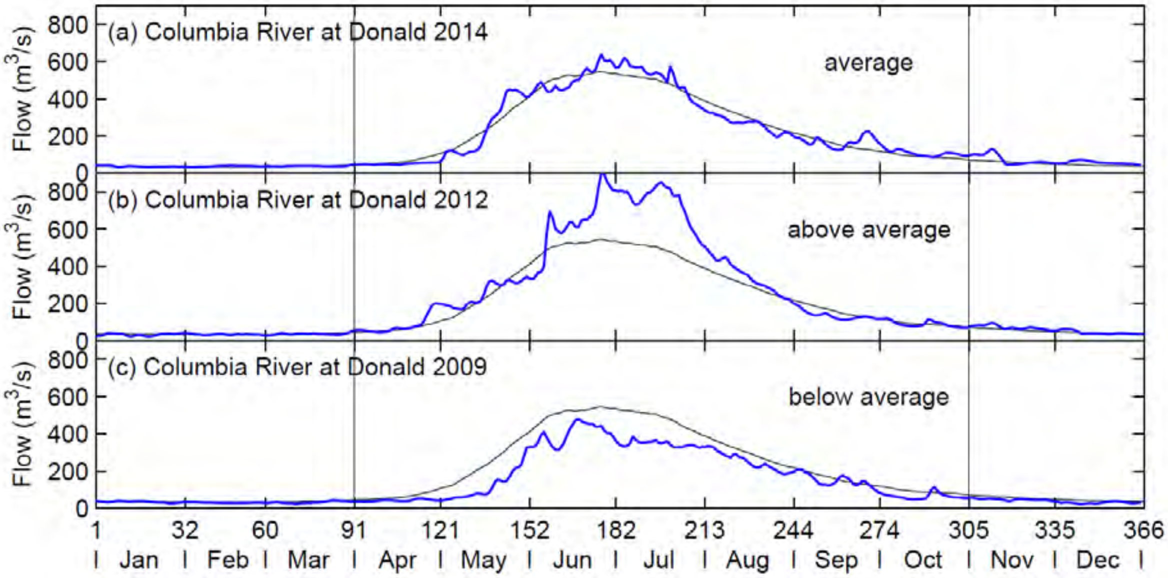

Figure 3. Columbia River at Donald, selected years. The black line is the daily average, 1945-2019. The vertical lines mark April to October.

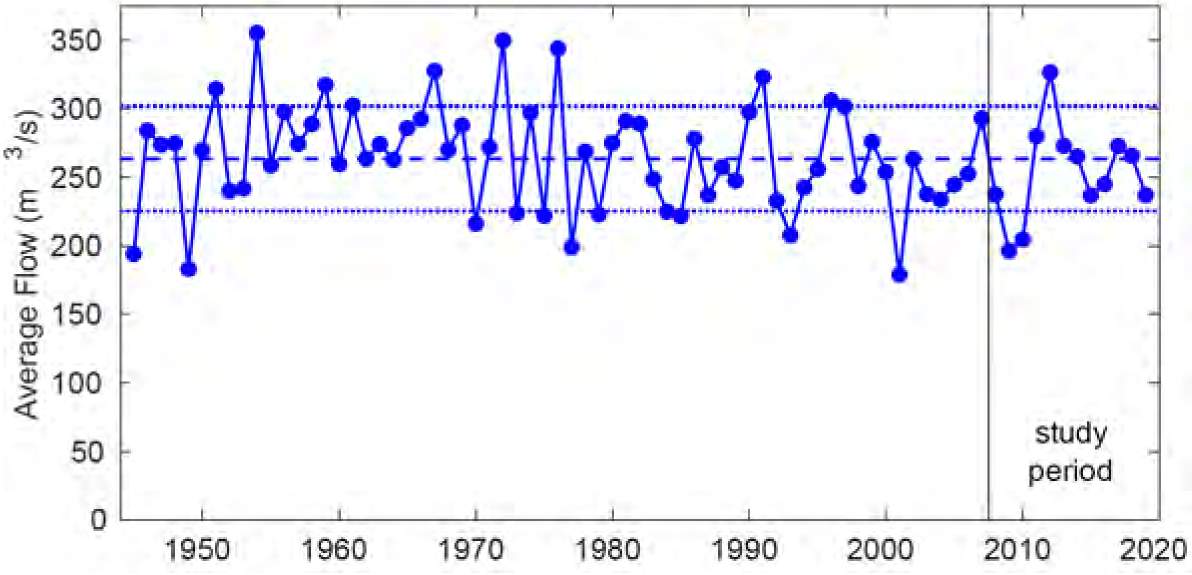

Figure 4. Average flow of the Columbia River at Donald through the productive season, April-October, 1945-2019. The dash line marks the average and the dotted lines mark ±1 standard deviation.

Variation in Kinbasket Reservoir water level - The water level in Kinbasket Reservoir for 1973-2019 is shown in Figure 5a. While the difference between the normal minimum (707.41 m ASL) and the normal maximum (754.38 m ASL) is 47 m, drawdown in any given year has averaged ~26 m. The area of the reservoir changes significantly; the area of the reservoir at minimum water level ranged from 218 to 354 km^2 (1977-2019, Figure 5a, right scale), which was 52-86% of the area at maximum water level later in the year. The average increase in area was 49%.

There were periods of time when the water level was relatively low throughout the year (e.g., 1992-1994) and other periods when the water level was relatively high (e.g., 2010-2014). The minimum and maximum water levels are shown in Figure 5b, along with the corresponding dates in Figure 5c. During the first 4 years of the study period, the minimum water level occurred significantly later than average, in early May, in contrast to 2016 when the minimum water level was reached in late March (Figure 5c).

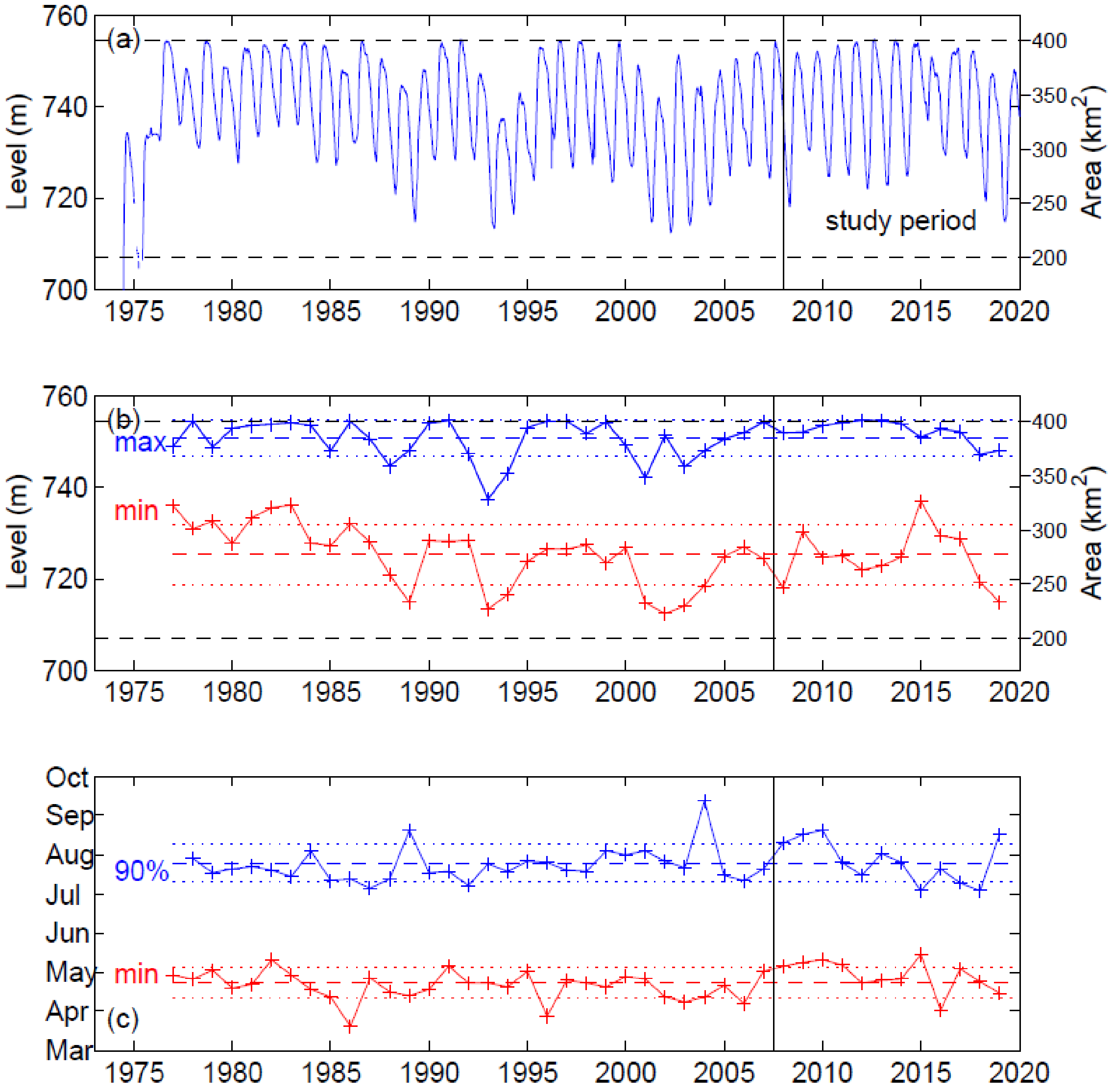

Figure 5. (a) Water level in Kinbasket Reservoir, 1973-2019. (b) Minimum (red) and maximum (blue) water level for 1977-2019. (c) Date of minimum (red), and 90% maximum (blue) water level for 1977-2019. The time to 90% of the annual maximum is shown, as the time to the maximum water level can occur later in some years. (a) Black dash lines mark normal minimum and maximum water level. (b, c) Red and blue dash lines mark the average, and dotted lines mark ±1 standard deviation.

Variation in Kinbasket Reservoir outflow - The outflow from Kinbasket Reservoir is shown for selected years in Figure 6. Of particular note is the very low outflow during late May to early July, during the time that Kinbasket Reservoir was filling. In 2014, the outflow from Kinbasket Reservoir was close to average (Figure 6a). In 2012, the outflow was far above average beginning in mid-July (Figure 6b). This flow pattern resulted from mid-June to late-July rainstorms noted earlier (Figure 3b), as well as the decision to lower water levels on Kootenay Lake to reduce flooding before releasing water from Kinbasket Reservoir. Outflow in 2015 was also high during the productive season but showing an unusual pattern with above average outflow from April to September (Figure 6c). In contrast, 2019 illustrates outflow that was generally below average through the productive period (Figure 6d).

As an illustration of unusual flow patterns, we briefly highlight conditions for 2015. As described in the Introduction (Section 1.2.2), 2015 was the strongest El Niño year on record with near record drought in the southern part of the Columbia River drainage. For Kinbasket and Revelstoke, however, local inflow was low but not below one standard deviation (Figure 4). Because of the mild winter with reduced power demand, and because the low snowpack (Table 5) indicated upcoming drought conditions, the water level in Kinbasket Reservoir was not drawn down as far as usual in the first three months of 2015 (Figure 5b). In addition, outflow from Kinbasket Reservoir was high in spring and summer when, in other years, freshet inflow was normally retained (Figure 6); this high outflow was to accommodate provisions of the Columbia River Treaty and related agreements. The net result of the higher than usual outflow in spring and summer meant that the increase in water level in the summer of 2015 was much less than usual (Figure 5a).

Short-term variation in outflow - There were significant hourly and daily variations in the outflow from both reservoirs. An example of outflow from Revelstoke Reservoir is shown in Figure 7**,** where the daily flow increased rapidly around 6 AM and then decreased rapidly around midnight. The flow can decline slightly mid-day (e.g., Tue and Wed), and, in this example, flow on the weekend is reduced from that during weekdays**.** Revelstoke Dam (along with Mica Dam) is used for peaking capacity, which means generation is used to meet hourly energy demands, and outflow can cycle rapidly to meet provincial power needs. Note the required minimum outflow of 142 m^3/s from Revelstoke Reservoir began on 20 December 2010 in conjunction with the start of the fifth turbine operation (see Section 1.2).

Climate - Characteristics of each study year are summarized in Table 5. The deviation from the seasonal mean air temperature measured at Revelstoke Airport is shown in Figure 8. For example, in 2011 and 2012, the average spring and summer air temperatures were notably below average. Air temperature data at other sites (e.g., Mica Dam, H. Keenleyside Dam, Goldstream River gauging station, and Golden Airport) are all closely correlated to that at Revelstoke Airport.

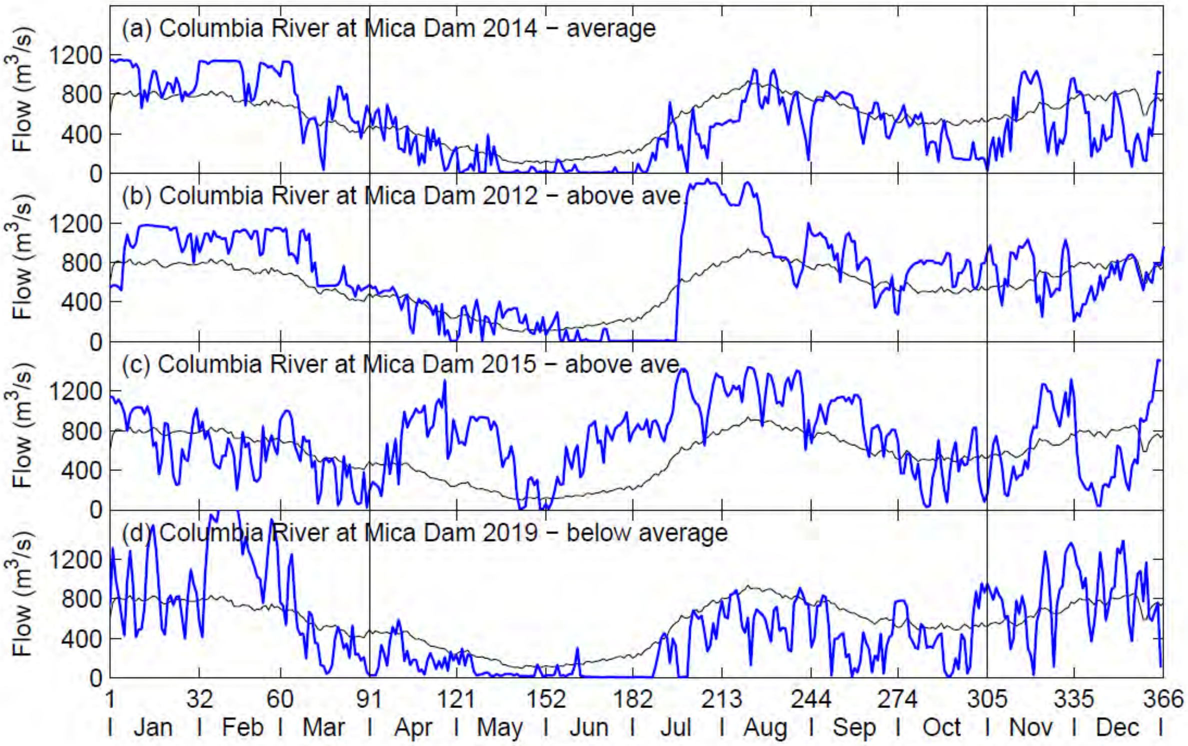

Figure 6. Daily average outflow from Kinbasket Reservoir, selected years. Black line gives average, 1976-2019. The vertical lines mark April to October.

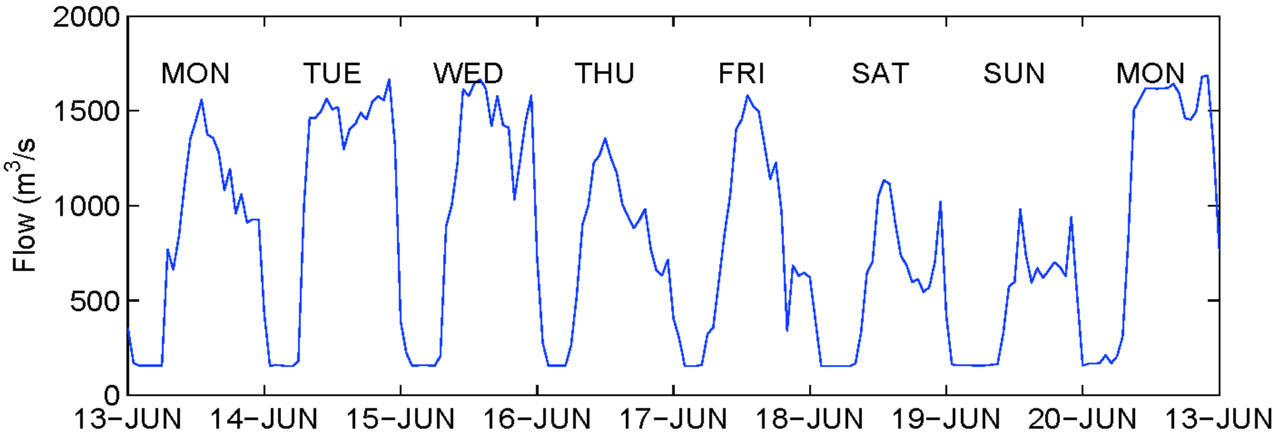

Figure 7. Hourly outflow from Revelstoke Reservoir over 8 days, 13-21 Jun 2011.

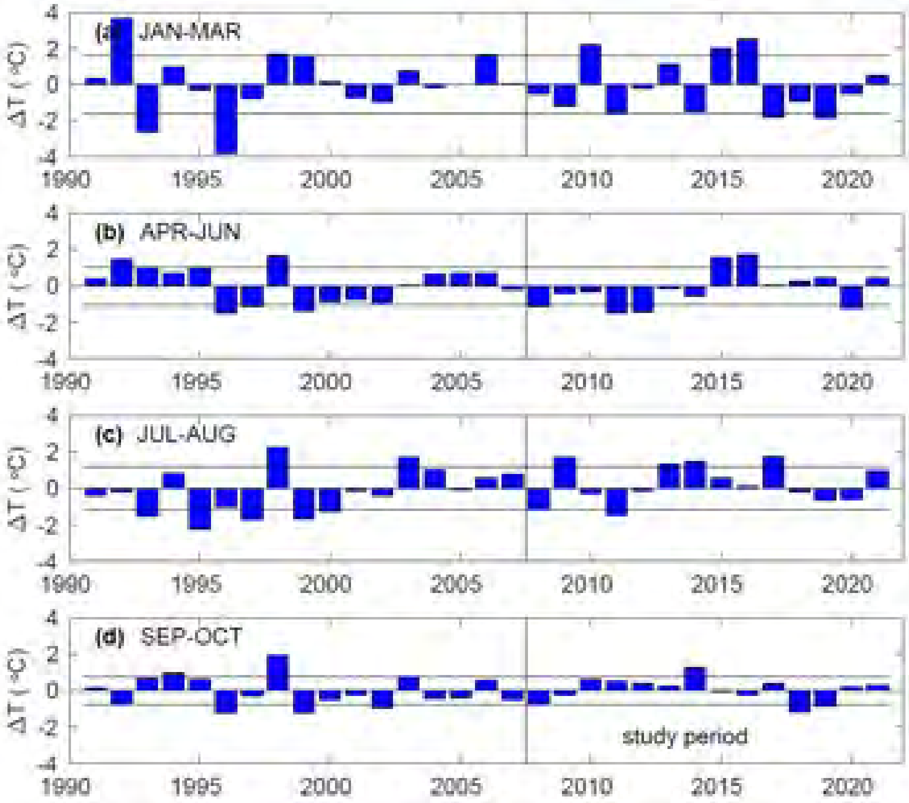

Figure 8. Deviation of the air temperature at Revelstoke Airport from the seasonal mean, 1991-2021. Horizontal black lines show the mean and the mean ±1 standard deviation.

Table 5. Summary of meteorological and hydrological conditions during study years.

2008	Columbia Region Snow Basin Index (April 1st), 104% Flow slightly below average, delayed and sharp onset of freshet in mid-May Cool mid-March to mid-May Strong La Niña (Jan-Mar 2008)
2009	Columbia Region Snow Basin Index (April 1st), 78% Flow generally below average Weak La Niña (Aug 2007 - Feb 2008)
2010	Columbia Region Snow Basin Index (April 1st), 84% Flow generally below average Strong El Niño (Jan-Mar 2010)
2011	Columbia Region Snow Basin Index (April 1st), 101% Flow average Colder than average from April to July Strong La Niña (Jul 2010 - Apr 2011)
2012	Columbia Region Snow Basin Index (April 1st), 125% Local flow above average in late June and early July Weak El Niño (Apr 2012)
2013	Columbia Region Snow Basin Index (April 1st), 103% Flow average Weak La Niña (Jun - Aug 2013)
2014	Upper Columbia Region Snow Basin Index (April 1st), 123% Flow average El Niño (Apr - Aug 2014)
2015	Upper Columbia Region Snow Basin Index (April 1st), 86% Flow below average (after early and high freshet mid-May to mid-June) High inflow event during late September High outflow from Kinbasket Reservoir, April to September (CRT obligations)
2016	Upper Columbia Region Snow Basin Index (April 1st), 99% Flow average (mid-Apr to mid-May slightly above average; mid-Jun to end Jul, slightly below average) Mica outflow average Strong El Niño (Apr 2015 - May 2016)
2017	Columbia Region Snow Basin Index (April 1st), 100% Winter of 2016-2017 cold with extensive ice cover Local inflow average, Mica outflow average
2018	Columbia Region Snow Basin Index (April 1st), 111% Local inflow average, Mica outflow average Weak La Niña (Jun 2017 – May 2018)
2019	Columbia Region Snow Basin Index (April 1st), 89% Local inflow below average, Mica outflow below average Weak El Niño (Jul 2018 – Jun 2019)

Lake ice - Depending on the year, Kinbasket Reservoir can range from having no ice cover to full ice cover, summarized in Table 6. Winter air temperature (Figure 8a) was strongly correlated with the extent of lake ice. While Revelstoke Reservoir does freeze, it does so only in patches, and there are typically open areas.

Table 6. Ice cover observed on Kinbasket Reservoir.

Year	ATA [1]	Ice cover (month ice cover observed)[2]
2008	C	all or almost all; hard to tell if coverage was complete (March)
2009	C	all or almost all; hard to tell if coverage was complete (March)
2010	WW	little to none; no sign of ice in the Columbia Reach
2011	C	mostly complete (March)
2012	N	little to none; no sign of ice in the Columbia Reach
2013	W	little, no sign of ice in the Columbia Reach
2014	C	all or almost all, hard to tell if main pool was completely covered
2015	WW	none
2016	WW	minimal to none; does not look like Columbia River froze at all
2017	CC	All
2018	C	all (March)
2019	CC	All

[1] Air temperature anomaly for January to March: CC cold < 1 SD; C cold; N neutral; W warm; WW warm > 1 SD, Figure 8a.

[2] Imagery provided by NASA Worldview (Global Imagery Browse Services (GIBS), operated by the NASA/GSFC/ESDIS, https://earthdata.nasa.gov).

3.2 Temperature Stratification

Most lakes and reservoirs at mid-latitudes undergo a cycle of annual temperature stratification (Wetzel 2001). Warming in spring gives rise to a surface layer of warmer, buoyant water that sits overtop cooler, denser water. This difference in density resists mixing and stratifies the water body vertically into separate layers. Thermal stratification of the reservoir has important biological consequences. Stratification provides both increased temperature as well as stable near surface light (photic zone) in which phytoplankton can grow. Thermal stratification also plays an important role in zooplankton and kokanee feeding and predator/prey interactions. In addition, temperature stratification controls the depth at which tributary inflows enter the reservoir, and whether these inflows resupply nutrients for phytoplankton in the photic zone.

In section 3.2.1, we first present temperature, conductivity (C25), and turbidity of the tributaries. Then we examine the stratification of Kinbasket Reservoir (Section 3.2.2) and Revelstoke

Reservoir (Section 3.2.3). We conclude this section by examining the onset of stratification (Section 3.2.4), comparing reservoir stations (Section 3.2.5), estimating tributary plunge depth (Section 3.2.6), and giving an example of internal motions within the thermocline (Section 3.2.7). Note that tributary nutrients are shown in Section 3.3, and a summary of the physical limnology is given in Section 4.1. Because temperature moorings began part way through the project, in 2012, we have included temperature data in the forebay of each reservoir for two additional years (2020 & 2021) to extend the analysis for both the onset of stratification (Section 3.2.4), and the effect of Mica Units 5 and 6 (MQ 3-7, Section 4.2).

3.2.1 Tributary temperature, conductivity, and turbidity

Tributary temperatures, along with conductivity (C25) and turbidity, are shown in Figure 9. Tributary temperature shows a seasonal cycle (Figure 9a). Of the available tributary data, the Columbia River at Donald was the warmest and the other tributaries were cooler, with the one year of data from the Sullivan River being remarkably cold.

Conductivity varied significantly between tributaries, with the Columbia River at Donald high and the Beaver and Goldstream Rivers low. The conductivity of all the natural tributaries underwent a seasonal decline during the freshet because of the large fraction of snow melt (Figure 9b). Conductivity rose again in fall and winter reflecting dominance of groundwater base flows. The exception was the conductivity of Mica outflow which remained relatively constant. This seasonal pattern in conductivity provides a convenient tracer of water masses, as used in sections below. The turbidity of the tributaries rose during freshet, was variable through summer, and declined in fall (Figure 9c). Additional tributary water chemistry data is shown in Section 3.3.

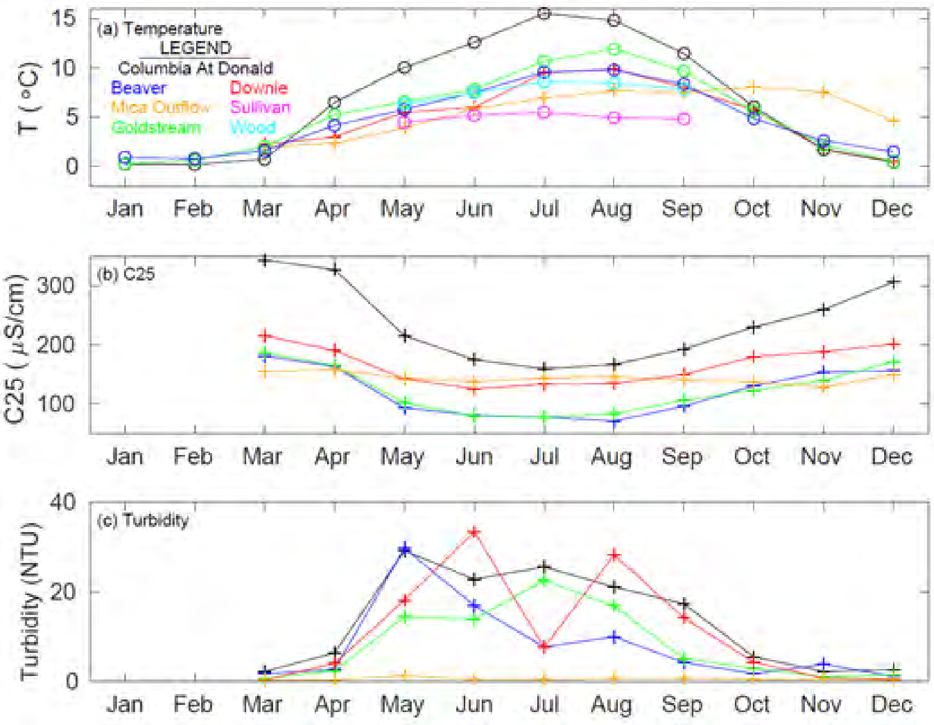

Figure 9. Monthly average (a) temperature, (b) conductivity (C25) and (c) turbidity in selected tributaries. (o) From hourly temperature records for Columbia at Donald (2016-2022), Beaver River (2017-2021), Goldstream River (2012-2022), Sullivan River (2010) and Wood River (2010). (+) From monthly reference tributary samples, 2008-2018 (except Beaver River, 2013-2018, and Downie Creek, 2017-2018); see also Section 3.3.

3.2.2 Stratification in Kinbasket Reservoir

Kinbasket Reservoir went through a cycle of temperature stratification each year (Figure 10). The near surface warmed in spring, reached a maximum temperature in summer, and then cooled in fall, while the deep part of the reservoir remained close to 4 °C.

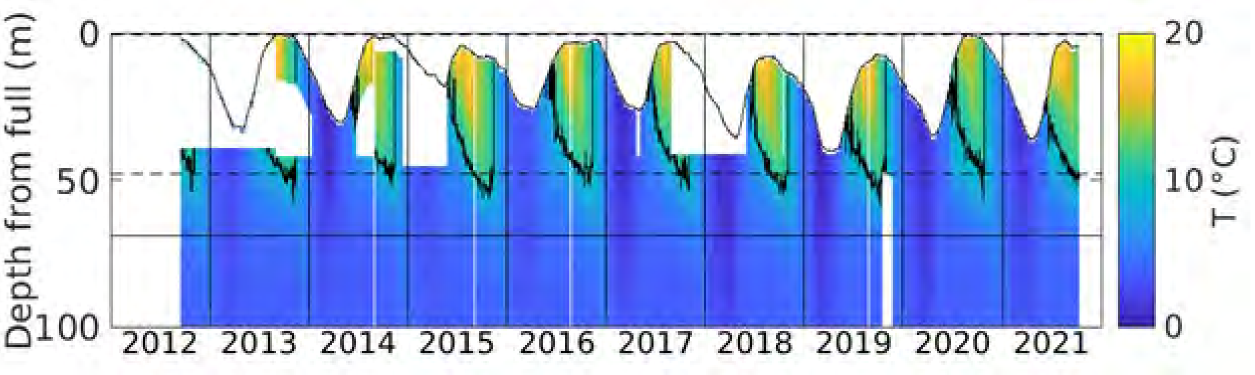

Figure 10. Contour plot of temperature, Kinbasket Reservoir Forebay, 2012-2021, top 100 m, plotted at fixed elevation. Zero depth is normal full pool. The black contour is 10 °C. The dash line marks normal minimum. The solid line at 68 m marks the sill elevation of the power intakes. White blocks are missing data; missing near surface data resulted from breakages at the dam log booms.

Many lakes have strong two-layer stratification with a distinct surface mixed layer (epilimnion) below which a sharp temperature gradient (thermocline) leads to the cooler deep water (hypolimnion). Strong two-layer stratification occurs, for example, in Nechako and Carpenter Reservoirs (Imam 2013; Robb 2021). However, Kinbasket Reservoir has a more gradual stratification during much of the summer. An example is given in Figure 11a, showing an almost linear decline in temperature from 15°C near the surface to 6°C at 50 m depth in July 2018. Similar stratification is seen in all other years. Later in the fall, as the reservoir starts to cool and deepen, a surface mixed layer does develop, as shown for October 2018 in Figure 11b. The factors influencing this atypical stratification include wind (Kalff 2002), withdrawal through a deep outlet (Casamitjana et al. 2003), and deep plunging inflows carrying heat to depth. This type of stratification has also been seen in Slocan Lake (Pieters 2002), and in the Arrow Lakes Reservoir hinted at both in low-resolution profiles before impoundment and in post-impoundment data (Figure 5.3 in Pieters et al. 2003a).

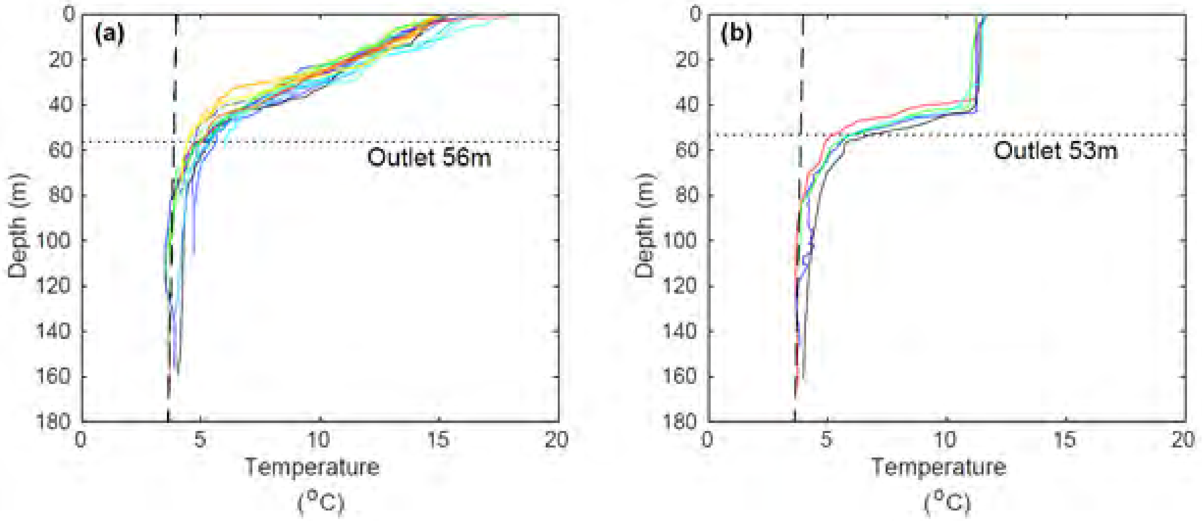

Figure 11. Temperature, Kinbasket Reservoir Forebay, (a) 11-12 July and (b) 15-16 October 2018. The black dashed line marks the temperature of maximum density. Depth plotted from the water surface. The dotted line marks the sill depth of the power intakes at Mica Dam; during the October survey the water level was 3 m lower making the outlet 3 m shallower. Profiles in (a) are also shown as a contour plot in Figure 12a.

An example of the gradients along Kinbasket Reservoir is shown for 11-12 July 2018 in Figure 12. The reservoir was thermally stratified with warmer water near the surface capping cooler, denser water at depth. At that time, the temperature stratification was relatively uniform across the reservoir although some variations due to internal motions are evident (Figure 12a). The conductivity provides a tracer that shows the generally lower conductivity freshet inflow near the surface (Figure 12b). It also shows the effect of lower conductivity in tributaries to Canoe Reach in contrast with the higher conductivity inflow to the Columbia Reach (Pieters et al. 2016). Turbidity is generally low especially near the dam, though lenses of elevated turbidity can be seen at several locations (Figure 12c). These lenses mark the depth to which turbid tributaries plunge and which are, in these instances, below the photic zone. There are also lenses of chlorophyll fluorescence just above the photic depth, both at the centre of the reservoir and in Canoe Reach (Figure 12d).

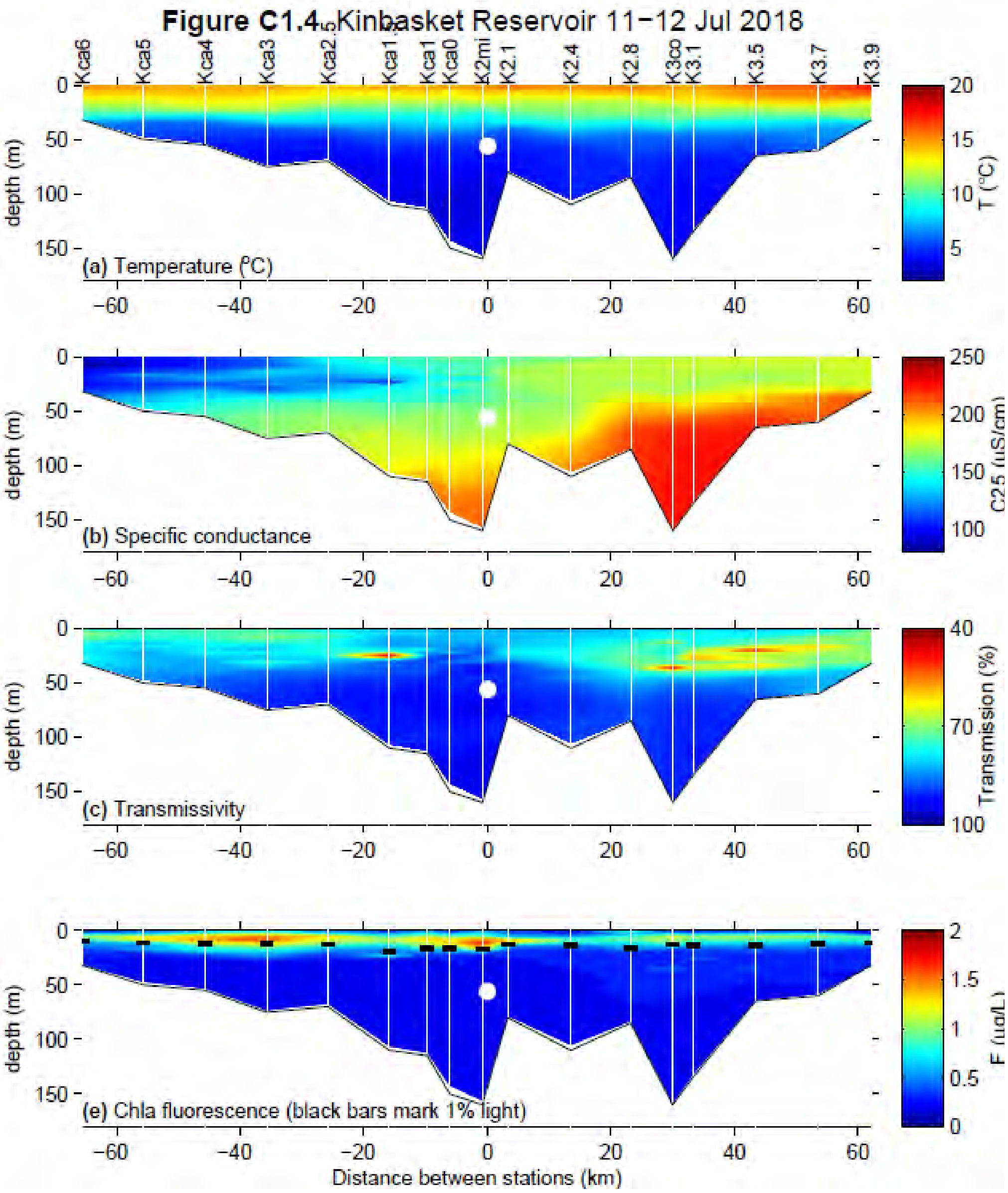

Figure 12. Contours of (a) temperature, (b) conductivity (C25), (c) turbidity and (d) fluorescence, Kinbasket Reservoir, 11-12 September 2018. The contours are taken along the length of Canoe and Columbia Reaches, where Kca1 is the Canoe sampling station, K2mi is in the main pool, K3co is the Columbia sampling station in Old Kinbasket Lake, and K3.9 is just downstream of Bush Pool (Figure 1). The outlet is marked at 56 m with a circle. White lines mark the location of the CTD casts. Black bars mark the depth of the photic zone. At the bottom of the contours, the maximum depth of each cast is simply joined by a line to the maximum depth of the adjacent cast and does not provide an accurate depiction of the bottom bathymetry. Temperature data in (a) was also shown as profiles in Figure 11a.

3.2.3 Stratification in Revelstoke Reservoir

Like Kinbasket Reservoir, Revelstoke also undergoes temperature stratification. Rather than a contour plot as shown for Kinbasket Reservoir (Figure 10), in this case we show a line plot (Figure 13), from which it is easier to see what is happening in winter, as discussed below.

In each year, Revelstoke Reservoir stratified in spring, with warmer surface water over cooler water at depth. The maximum stratification occurred in July and August and, as the reservoir cooled in fall, the surface layer mixed deeper. Because of the large volume of water in the reservoir, fall turnover (complete mixing) did not occur until December (Figure 13). The entire reservoir continued to cool through January and early February, and often cooled below 4 °C, the temperature of maximum density, T_{MD}. As water cooled *below* $T_{MD,}$ it became *less* dense and formed what is known as 'reverse' stratification. This is noticeable, for example, in January to March 2017, when colder (1 °C) and buoyant water was over warmer (2 °C) and denser water below. In March and April, the reservoir began to warm, and summer stratification began soon after the reservoir warmed above T_{MD}.

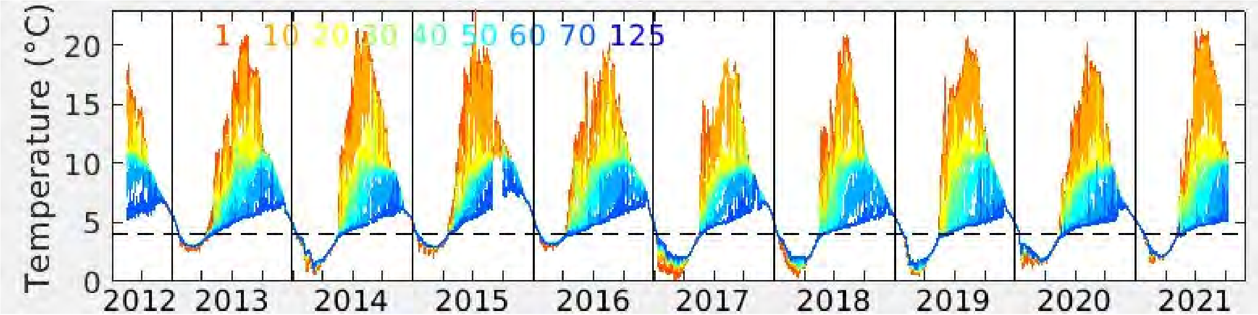

Figure 13. Temperature at selected depths, Revelstoke Forebay, 2012-2021. Depth is marked by colour. The black dash line marks the temperature of maximum density, $T_{MD} = 4$ °C. At Revelstoke there was only one gap in near surface temperature of 22 Jun-31 Aug 2017 for boom replacement.

An example of the temperature and conductivity along Revelstoke Reservoir is given for 8-9 September 2008 in Figure 14. The temperature showed three layers, a warmer surface layer, a layer of intermediate temperature (10°C) from 15 to 60 m, and a cold (5 °C) deep layer below 60 m (Figure 14a). Conductivity was lower in the top 60 m as a result of fresh tributary inflow during snowmelt, and higher below 60 m indicating this water remained from winter (Figure 14b). However, at the time of these observations there was high inflow from Kinbasket Reservoir; this inflow was cool and had a conductivity intermediate to that in Revelstoke. This Kinbasket water formed an interflow in Revelstoke Reservoir centered on the outlet depth at 28 m (110-120 µS/cm, yellow to orange). At the time of this profiler survey, the inflow from Kinbasket Reservoir short circuited below the photic zone to the Revelstoke outlet. This suggests that the nutrients in the flow from Kinbasket were not available for biological production; however, data described below hints that some of this water can occasionally be moved into the photic zone by internal waves.

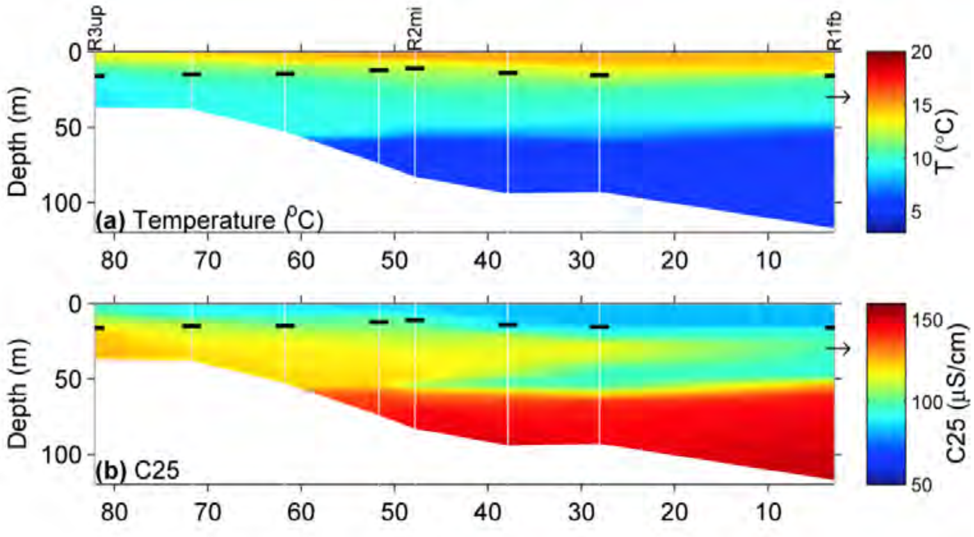

Figure 14. Contour plots of (a) temperature and (b) conductivity (C25) in Revelstoke Reservoir, 8-9 September 2008. The inflow from Kinbasket Reservoir, which has slightly elevated conductivity, forms an interflow between 15 and 60 m depth which exits through the outlet marked by an arrow at 28 m on the right. White lines mark the location of the CTD casts. Black bars mark the depth of the photic zone.

An autonomous profiler in the Revelstoke Forebay collected daily profiles of temperature and salinity (proportional to conductivity at 25 °C, Figure 15). As described earlier, upstream Kinbasket Reservoir provided little inflow from May to July, while local tributaries to Revelstoke Reservoir provided high inflow of low salinity snowmelt (Section 3.2.1). From Figure 15b we can see clearly how from May to July this low salinity inflow gave rise to a fresher surface layer that deepened to almost 60 m by the end of July. The upper part of this fresh layer stratified thermally, giving rise to a shallow epilimnion (Figure 15a).

After July, outflow of colder and more saline water from Kinbasket Reservoir increased. As described above, the Kinbasket inflow plunges and forms an interflow from the upper end of Revelstoke Reservoir to the outlet at Revelstoke Dam. The interflow can be seen in the autonomous profiler data from Revelstoke Forebay in early August (higher salinity water [red] from 20 to 40 m depth, Figure 15b). The profiler data show the significant internal motions on the interface between the interflow and the surface layer with a period of a week to ten days. From late-August to mid-October, these motions brought water from the interflow into the photic zone for periods of time. This suggests that some of the nutrients in the interflow may occasionally be available for photosynthesis in the photic zone.

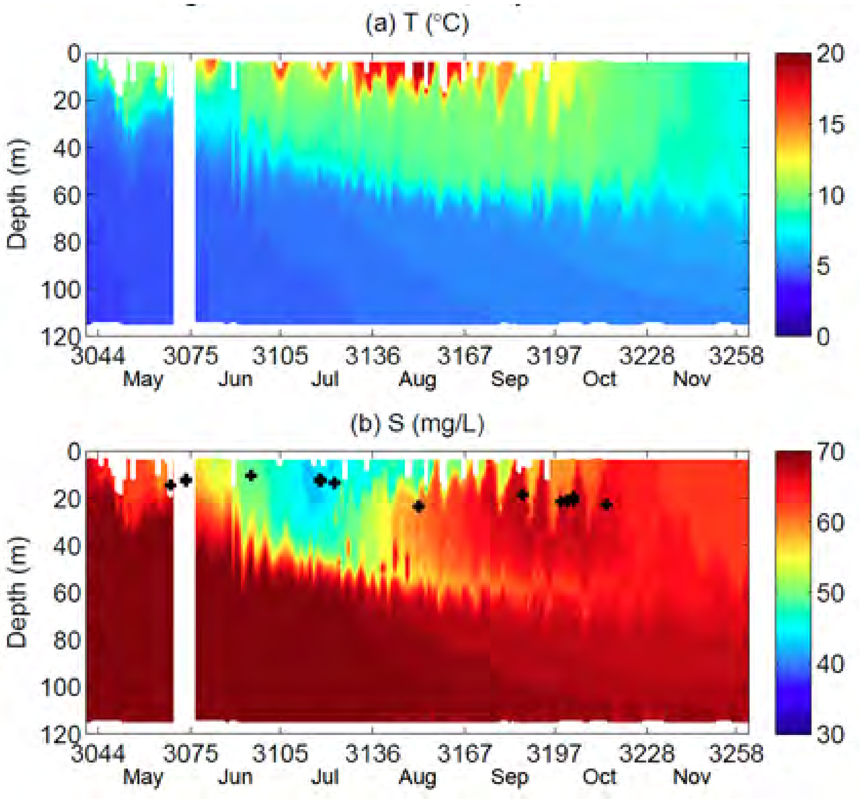

Figure 15. Contours of (a) temperature and (b) uncalibrated salinity (proportional to conductivity at 25 °C) from daily profiles collected using an autonomous profiler at Revelstoke Forebay, May to November 2016. (b) The '+' marks the 1% light level determined from Seabird profiles.

3.2.4 Onset of stratification in spring

Time of onset - The timing of stratification in spring depends on conditions in the reservoir in the previous winter. As shown for Revelstoke Reservoir in Figure 13, both milder winters were observed, during which the reservoir did not cool much below T_{MD} (e.g., 2015-2016), and colder winters were observed, when the surface cooled toward 0 °C and reverse stratification formed (e.g., 2016-2017, Figure 13). A colder winter resulted in: (1) a colder deep-water temperature, (2) later warming to 4 °C, and (3) a significant delay in the onset of stratification in spring. For example, following the mild winter of 2015-2016, stratification in Revelstoke Reservoir began on 13 April 2016, while after the cold winter of 2016-2017, stratification began over a month later, on 19 May 2017 (Table 7). In Revelstoke Reservoir, there was a strong correlation between the mean air temperature from January to March and (1) the minimum deep temperature (r = 0.85, not shown), (2) the warming to 4 °C (r > 0.9, see Figure 17), and (3) the onset of summer stratification (r = 0.91, Figure 16).

Delayed onset of stratification also resulted in colder average April to June water temperature. For example, the average April to June water temperature was 7.4 °C in 2016 but only 4.6 °C in 2017 (0-40 m, Table 7). The April to June water temperature was also correlated to the January to March air temperature (r = 0.89, not shown). Both the late onset of stratification and lower water temperature in April to June will affect spring dynamics of phytoplankton and zooplankton production. Zooplankton require both adequate phytoplankton forage and warmer water temperature for growth to reach gestation (Schalau et al. 2008).

In contrast to average spring temperature (Apr-Jun) which showed significant variation between years, the average summer (Jul-Aug) and fall (Sep-Oct) temperature was relatively uniform between years (Table 7). The temperature in Kinbasket Reservoir followed a similar pattern to that in Revelstoke Reservoir; the onset of stratification in Kinbasket forebay occurs, on average, within one day of that in Revelstoke forebay (Table 7).

Table 7. Onset of stratification in Kinbasket and Revelstoke Forebay, and seasonally average water temperature (0-40 m), Revelstoke Forebay, 2012-2021.

Year	Onset of stratification (1), Kinbasket Reservoir	Onset of Stratification (1), Revelstoke Reservoir	Apr-Jun, Ave T (°C), Revelstoke Reservoir	Jul-Aug, Ave T (°C), Revelstoke Reservoir	Sep-Oct, Ave T (°C), Revelstoke Reservoir
2012	-	-	-	12.3	10.9
2013	2 May	24 Apr	6.3	12.4	11.4
2014	9 May	19 May	4.9	12.2	11.0
2015	NA	26 Apr	7.2	12.1	NA
2016	18 Apr	15 Apr	7.4	12.2	11.1
2017	19 May	20 May	4.6	NA	10.8
2018	NA	15 May	5.0	12.0	10.7
2019	7 May	15 May	5.2	12.4	11.3
2020	12 May	16 May	4.7	10.9	10.9
2021	14 May	14 May	5.7	12.7	11.2
Average	*7 May*	*8 May*	*5.7*	*12.1*	*11.0*
Deviation	*10 days*	*13 days*	*1.1*	*0.5*	*0.2*

(1) Onset defined as date when T(1m) - T(20m) > 1 °C; the results are not sensitive to the choice of bottom depth.

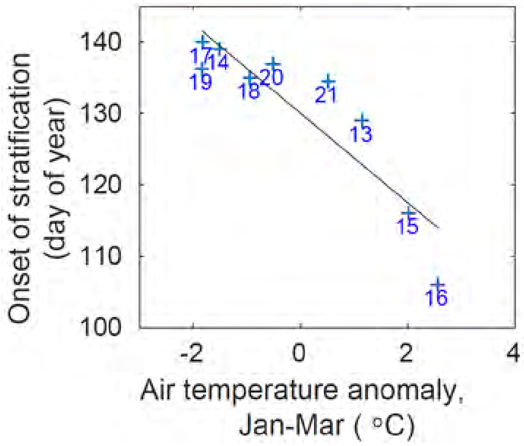

Figure 16. Onset of stratification in spring versus winter temperature, 2013-2021. Onset of stratification was defined as the date at which the temperature difference between 1 m and 20 m depth was 1 °C.

Progression of onset - Note that the warming and subsequent stratification does not occur at the same time over the whole reservoir, rather the onset gradually moves from shallower locations, which warm earlier, to deeper locations. A boundary forms between shallower water that has already warmed above 4 °C, and deeper water still below 4 °C, known as a thermal bar, which will be discussed in more detail in Section 4.1.

For Revelstoke Reservoir, the progressive warming to 4 °C at the Upper, Middle, and Forebay stations is shown in Figure 17. Note that the moorings at the Middle and Upper stations did not include near surface temperature (Pieters et al. 2022c), and here we use warming to 4 °C of temperature averaged over the depths common to all three Revelstoke moorings, 7 to 39 m. Recall that warming to 4 °C occurs before the lake can stratify and was used as a proxy for the onset of summer stratification in Lake Ontario (Rodgers 1987) and in large B.C. lakes (Carmack et al. 2014). Based on the Kinbasket and Revelstoke Forebay moorings, after reaching 4 °C, stratification with T(1m) - T(20m) > 1 °C occurred, on average, four days later. Also using data from the forebay stations, the date at which the average of 7 to 39 m reached 4 °C was compared to that for 1 to 60 m and both reached 4 °C within one day; the results are not sensitive to the depth range.

Depending on the winter, the warming to 4 °C ranged by over a month at each station; at the forebay the range was 41 days from 6 April in 2016 to 18 May in 2014. On average, the Upper, Middle, and Forebay stations reached 4 °C on 8 April, 21 April, and 4 May, respectively. After the Upper Station reached 4 °C, it was, on average, 13 days until the Middle Station reached 4 °C, and, on average, a further 11 days until the Forebay station reached 4 °C. The speed of the thermal bar depends on the volume and temperature of the riverine inflow, the atmospheric heat fluxes, and the bottom slope of the reservoir (Carmack 2012).

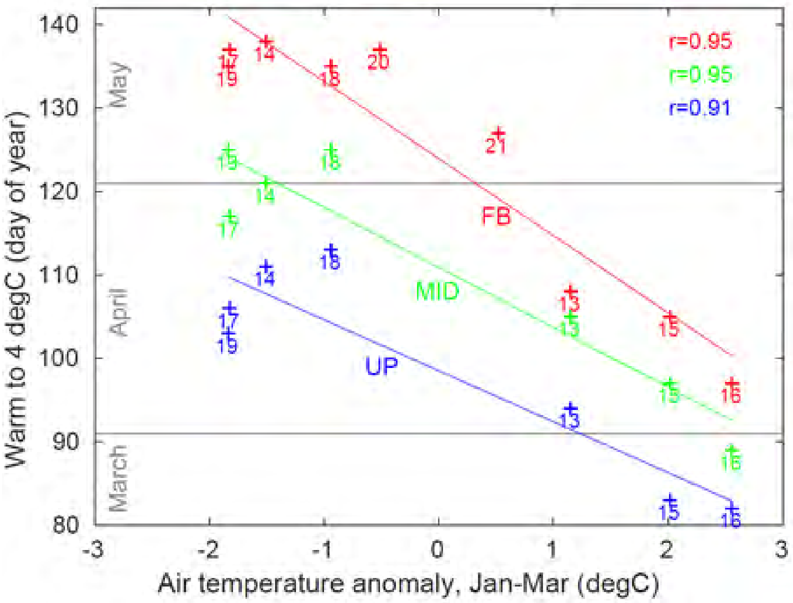

Figure 17. Date of warming to 4 °C at Revelstoke Upper (blue), Middle (green) and Forebay (red) stations (for depth averaged temperature from 7 to 39 m), versus the winter air temperature anomaly at Revelstoke Airport, 2013-2019 (with additional data for 2020 and 2021 at the forebay).

3.2.5 *Comparison of reservoir stations*

At the seven main stations in Revelstoke and Kinbasket, 664 CTD profiles were collected from 2008 to 2019. These data were averaged to produce a monthly climatology at each station and allows comparison among stations. The temperature averaged to 10 m is used to illustrate the near surface temperature and minimize the influence of the interflow in Revelstoke Reservoir (Figure 18). In April, the 0-10 m temperature at all stations was close to the temperature of maximum density (4 °C) and increases through August to an average high of 16 °C. Within the resolution of the data, the temperature both within and between the reservoirs, was very similar. The notable exception was the Revelstoke Upper station where the temperature was consistently colder from July to October likely reflecting the colder inflow from Kinbasket.

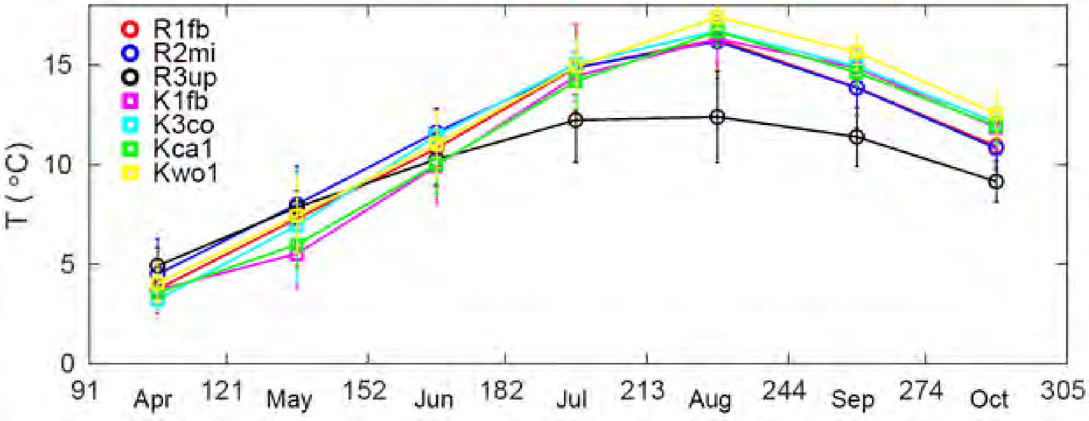

Figure 18. Monthly averages of water temperature 0 - 10 m for all CTD casts at the 7 main stations, 2008-2019.

This set of CTD casts also allows for comparison of the 1% light level between stations (Figure 19). The depth of the 1% light level defines the photic zone. In spring the photic zone was over 20 m in depth, becoming shallower in June with an average depth of 14 m in Kinbasket and 12 m in Revelstoke, and then gradually increasing in depth again through summer and fall. These deep photic zone depths are consistent with oligotrophic conditions in both reservoirs.

Observed, on average, are the following:

- both Kinbasket and Revelstoke Reservoirs are clearest in April with photic depths of 24 and 22 m, respectively,
- both are most turbid in June with photic depths of 14 and 12 m, respectively,
- averaging from April to October, the photic depths are 19 and 16 m, respectively, indicating that Revelstoke is slightly more turbid,
- the forebay stations have the highest photic depths in both reservoirs (the forebay stations receive the least amount of glacial input),
- the Wood and Columbia stations in Kinbasket, and the Upper station in Revelstoke have the lowest photic depths of 10 to 11 m in June, and
- from July to August, the photic depth increases more rapidly in Kinbasket than in Revelstoke.

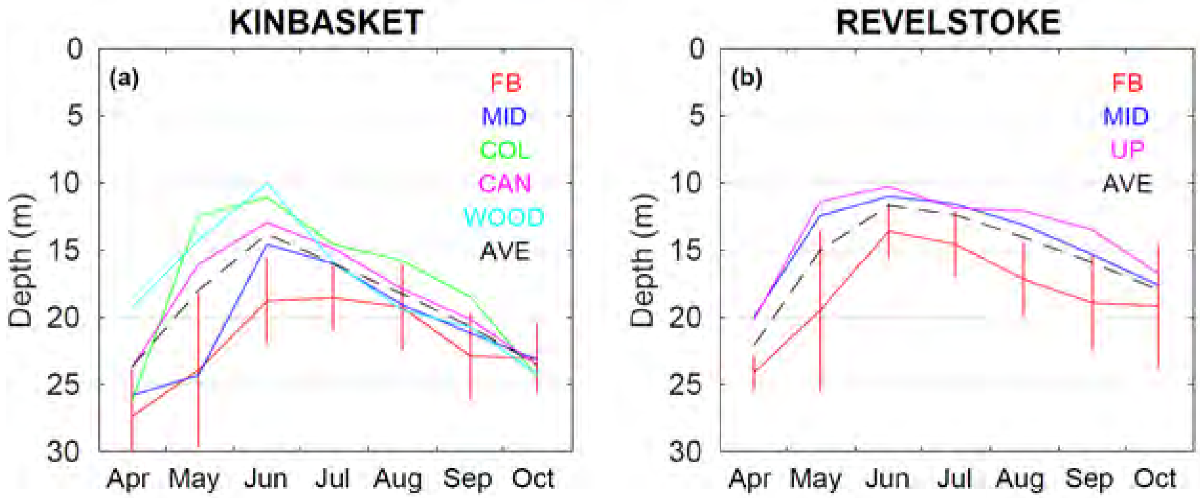

Figure 19. Monthly average depth of the 1% light level, 2008-2019, (a) 5 stations in Kinbasket Reservoir, and (b) 3 stations in Revelstoke Reservoir. The black dashed line shows the average over all stations shown; the vertical bars mark the standard deviation at the forebay that is representative of each station.

3.2.6 Tributary plunge depth

While conductivity (dissolved salts) and turbidity (suspended particles) do contribute to density, this contribution was small compared to that of temperature, and can be ignored in what follows. Here the monthly average temperature of the tributaries is compared to the temperature of the photic zone in the reservoir to assess the general trends; examples including shorter time-scale fluctuations in tributary temperature are shown in Section 4.1. The heavy red line shows the temperature near the top of the photic zone (2m) while the heavy blue line gives the temperature at the 1% light level, namely at the bottom of the photic zone. For Kinbasket, the temperature of the main inflow, Columbia River at Donald, was relatively warm and was unlikely to plunge below the photic zone until September at which time it cooled more rapidly than the reservoir (Figure 20a). In contrast, local tributary inflows were relatively cool; for example, the glacially fed Sullivan River averaged 5 °C through the summer of 2010. While not all the tributaries were as cold as this, the existing tributary data suggest that, in the absence of entrainment, many inflows plunge below the photic zone.

The outflow from Mica Dam forms the main inflow to Revelstoke Reservoir (Figure 1), and this inflow remained colder than the bottom of the photic zone from April to October (Figure 20b). Also shown are the average temperature of Downie Creek and Goldstream River which were generally cooler than the photic zone. An example of plunging inflow is shown in Figure 21.

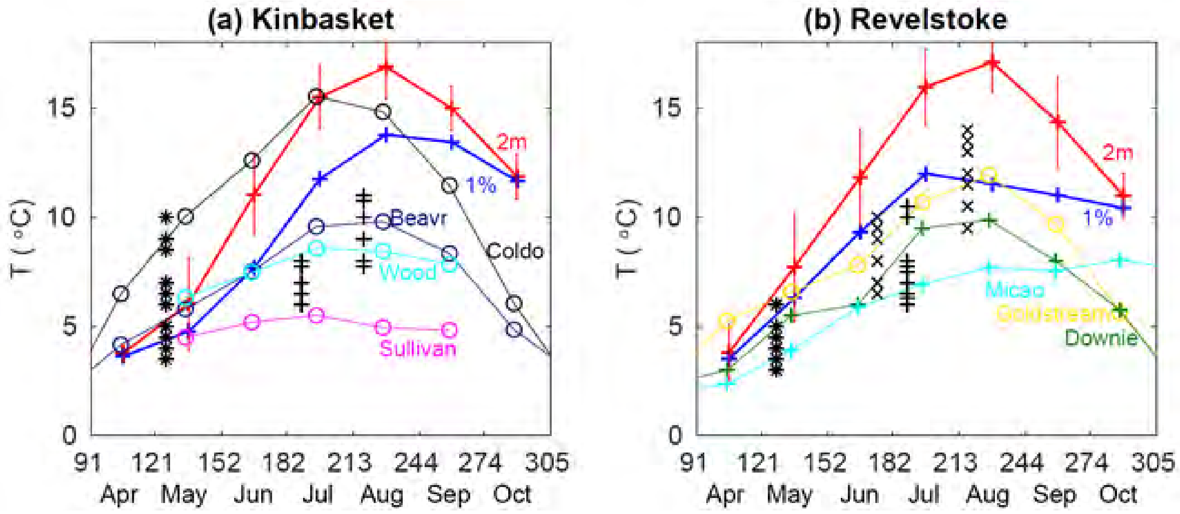

Figure 20. Temperature at 2m (red), and at the 1% light level (blue) in (a) Kinbasket Forebay, and (b) Revelstoke Forebay, from profiles averaged monthly, 2008–2019. Included are the monthly average temperatures for the (a) Columbia River at Donald (‘Coldo’, 2016-2022), Beaver River (2017-2021), Wood River (2010), and Sullivan River (2010); (b) outflow from Mica Dam (‘Micao’, 2008-2018), Goldstream River (2012-2022), and Downie Creek (2017-2018). Temperature from tributary surveys: (×) 2008, (+) 2009 and (*) 2013; see Section 3.3.1 for detail.

Figure 21. Goldstream River entering Revelstoke Reservoir, 1 October 2021. Note the plunge line between the turbid (tan) water from Goldstream River and the clearer (green) water in the reservoir. Photo K. Bray.

3.2.7 Internal motions

Rather than basin scale seiches, the most common internal motions observed in Kinbasket and Revelstoke Reservoirs are typically shorter in wavelength. This likely reflects the nature of summer storms which move along (or across) the reservoir, rather than providing many days of consistent wind along the whole length of these large water bodies. Even if such winds were to occur, basin scale, or even sub-basin scale seiches, can rapidly sharpen into shorter wavelength motions often referred to as internal bores, or solitary-like waves (Horn et al. 2001). An example of such an internal motion was captured in the survey of lower Revelstoke on 5 September 2017 (Figure 22), where the internal bore is between station R1.4 and R1.6. To the left of the bore the warm and fresh surface layer was approximately 6 m deep, and to the right it was 22 m in depth.

These internal motions can result in significant changes in temperature at one elevation. Consider the temperature at 15 m in Revelstoke Forebay, shown for May to October 2017 in Figure 23. From July to September, the temperature was generally 10 °C, however there were brief times when the temperature rose suddenly by up to 8 °C. Note, the peak of 18 °C on 5 September 2017 corresponds to the example shown in Figure 22. These internal motions interfere with the determination of summer water temperature from monthly profiles for a given year (cf. analysis for Arrow Lakes Reservoir, Chapter 4, Pieters et al. 1999).

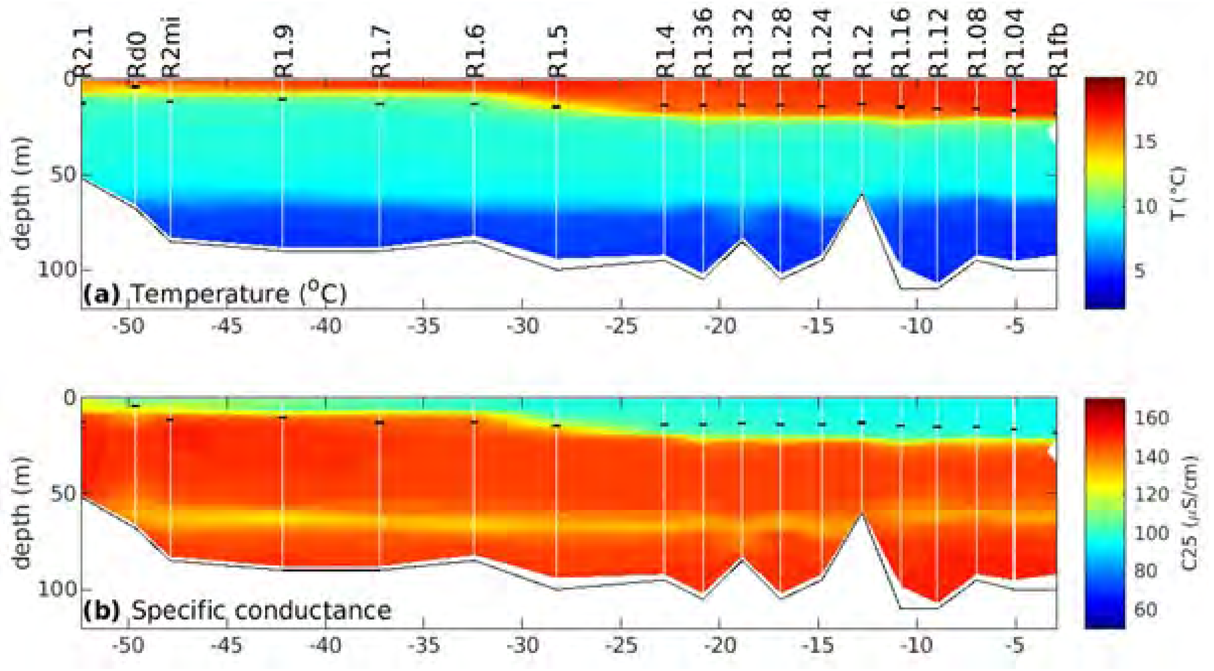

Figure 22. (a) Temperature and (b) conductivity (C25) in Revelstoke Reservoir 5 Sep 2017. The half circle marks the outlet. The black bars mark the photic depth.

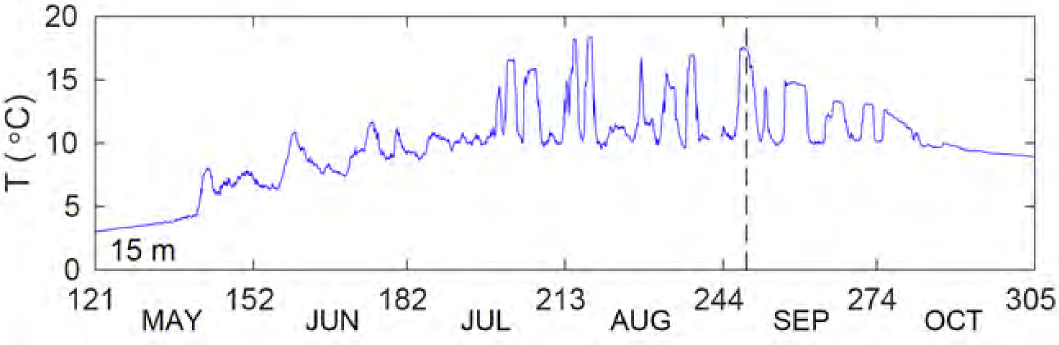

Figure 23. Temperature at 15 m, Revelstoke Reservoir Forebay, May-Oct 2017. The black dashed line marks the survey of 5 September 2017 shown in Figure 21.

3.3 Tributary nutrients

Two types of tributary sampling were undertaken over the study period: (1) occasional surveys of many tributaries to assess variations across the drainage described in Section 3.3.1, and (2) frequent sampling of a set of reference tributaries to assess seasonal variations and long-term trends described in Section 3.3.2. Here we focus on tributary nutrients and include, for reference, some additional water quality data, such as turbidity.

3.3.1 Tributary surveys

Tributary chemistry results from the three surveys are summarised in Table 8. Tributaries to both Kinbasket and Revelstoke Reservoirs were generally low in nutrients. Soluble reactive phosphorus (SRP) was very low, close to the detection limit of 0.5 or 1.0 µg/L (depending on laboratory). Total dissolved phosphorus (TDP) was also low, with a median of 2.2 and 2.4 µg/L, for the tributaries to Kinbasket and Revelstoke Reservoirs, respectively. Total phosphorus was relatively high and variable, with a median of 21 and 8.5 µg/L, in Kinbasket and Revelstoke, respectively. Total phosphorus (TP) is composed of two fractions, the dissolved fraction, TDP (which passes through a 0.45 µm filter), and the particulate fraction, particulate phosphorus (PP), which is trapped by the filter, where PP = TP - TDP. Since TDP is low, most of TP is composed of PP, reflecting the glacial origin of many of the tributaries, and PP is likely dominated by glacial fines of inorganic origin having low biological availability. In addition, since PP in both reservoirs averaged < 1 µg/L (Section 3.4), the vast majority of the PP settles once the tributaries enter the reservoir. For glacial inflows, such as those to Kinbasket and Revelstoke Reservoirs, TP overestimates the available phosphorus and TDP is used instead as a measure of available phosphorus (cf. Pieters et al. 2003a). The fraction of both TDP and PP that is biologically available is a key unknown.

Nitrate[5] is the dominant form of nitrogen in the tributaries. Nitrate values varied between tributaries with a median of 91 and 103 µg/L for tributaries to Kinbasket and Revelstoke Reservoirs, respectively. Total nitrogen (TN) was not collected during these surveys.

Table 8. Summary of tributary chemistry, surveys 2008, 2009 and 2013(1).

Station/ Parameter	*Units*	*KIN Median*	*KIN Min*	*KIN Max*	*REV Median*	*REV Min*	*REV Max*
NO_2+NO_3 (NN)	µg/L	91	18	929	103	1.6	1170
SRP	µg/L	1.8	0.6	5.4	1.8	0.7	4.9
TP	µg/L	21	2.5	1650	8.5	2.0	79
PP(2)	µg/L	19	1.5	1648	6.8	0.1	75
TDP	µg/L	2.2	0.8	5.4	2.4	1.0	9.1
NN:TDP (w/w)		50	7.2	465	43	0.8	310
Conductivity	µS/cm	81	24	296	38	10	149
Alkalinity	mg$CaCO_3$/L	37	7.5	156	17	4	64
pH	pH units	7.7	6.6	8.4	7.3	6.3	8.0
Turbidity	NTU	13	0.4	1830	2.2	0.14	68

(1) TP, TDP, PP, SRP and alkalinity for Cultus Lake Lab shown corrected, see Methods.
(2) Particulate phosphorus PP = TP – TDP.

3.3.2 Reference tributaries

Five reference tributaries were sampled monthly from April to October, for 2008 to 2018. Three of the tributaries have natural flows (Colombia River at Donald, Beaver River, Goldstream River) and two were the regulated outflow from Kinbasket and Revelstoke Reservoirs. Data from Beaver River is a combination of data collected by Environment Canada (sampling approximately half the drainage) and data collected as part of this study (sampling the entire drainage, 2013-2018), for detail see Pieters et al. 2022b. Additional data from a sixth site, Downie Creek, were also collected in the last two years (2017-2018). We first examine averages over the study period, then show the seasonal variation of phosphorus and nitrate, and finally we present flow weighted average concentrations and nutrient loads from the reference tributaries.

Soluble reactive phosphorus (SRP) was low, noisy, and close to the detection limit (Table 9). The average SRP for the natural tributaries was slightly higher (and noisier) than for the reservoir outflows. Total phosphorus (TP) was high and variable in the natural tributaries (19 to 32 µg/L), but much lower in the reservoir outflows (3 to 5 µg/L, Table 9). As discussed for the surveys, total

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[5] The laboratory method measures both nitrate, NO_3, and nitrite, NO_2, but nitrite is low in systems with high levels of dissolved oxygen such as Kinbasket and Revelstoke Reservoirs. We will use NO_3 and NN interchangeably.

phosphorus can be divided into total dissolved phosphorus and particulate phosphorus (PP = TP - TDP). In the four natural tributaries, the vast majority of the TP was in the particulate form, in contrast to the reservoir outflows where less than half was particulate. Like TP and PP, turbidity was high and variable in the four natural tributaries with mean turbidity ranging from 11 to 18 NTU. In contrast, outflows from both reservoirs had remarkably low mean turbidity of 0.6 NTU (Table 9; see also Figure 9).

Table 9. Summary of tributary chemistry, reference tributaries, 2009-2018(1)

Station/ Parameter	***Units***	***Columbia At Donald***	***Beaver River(2)***	***Goldstream River***	***Downie Creek(3)***	***Kinbasket Outflow(5)***	***Revelstoke Outflow***
NO_2+NO_3(NN)	µg/L	91 ± 54	149 ± 111	189 ± 149	217 ± 110	117 ± 20	133 ± 49
TN(6)	µg/L	213 ± 107	222 ± 134	257 ± 121	282 ± 127	218 ± 86	213 ± 63
TP	µg/L	19 ± 16	19 ± 33	22 ± 31	32 ± 35	3.2 ± 2.1	4.6 ± 7.1
PP(4)	µg/L	16 ± 15	16 ± 33	19 ± 31	29 ± 35	0.9 ± 1.0	1.8 ± 4.7
TDP	µg/L	2.9 ± 1.3	2.9 ± 1.7	2.6 ± 1.4	3.0 ± 1.8	2.2 ± 0.6	2.2 ± 0.5
SRP	µg/L	2.4 ± 2.2	2.2 ± 1.5	1.9 ± 1.4	3.2 ± 4.3	1.5 ± 1.0	1.4 ± 0.7
NN:TDP(w/w)		36 ± 27	60 ± 48	79 ± 50	88 ± 54	57 ± 24	64 ± 30
Conductivity	µS/cm	212 ± 63	108 ± 37	108 ± 36	158 ± 32	143 ± 19	123 ± 27
Alkalinity	mgCaCO$_3$/L	97 ± 22	43 ± 15	51 ± 15	71 ± 16	64 ± 4	56 ± 9
pH	pH units	8.1 ± 0.1	7.8 ± 0.2	7.8 ± 0.2	8.0 ± 0.1	7.9 ± 0.1	7.8 ± 0.2
Turbidity	NTU	18 ± 19	11 ± 23	11 ± 23	15 ± 20	0.6 ± 0.8	0.6 ± 0.4

(1) TP, TDP, SRP and alkalinity for Cultus Lake Lab shown corrected, see Methods.

(2) Beaver River averages for BCH data only (full drainage, 2013-2018).

(3) Downie Creek averages for 2017-2018.

(4) Particulate phosphorus PP = TP – TDP.

(5) Data during low outflow from Kinbasket were affected by backwater from Revelstoke Reservoir and were removed.

(6) TN measured from 2016-2018 only.

In the reference tributaries, average nitrate (NO_3) ranged from 91 to 189 µg/L. The measurement of total nitrogen, TN, was added from 2016-2018, and ranged from 213 to 282 µg/L; in general TN was approximately 1.5 times greater than nitrate. The ratio NN:TDP was generally well above 10, indicating phosphorus limitation of phytoplankton growth (Horne and Goldman 1994). The exception is the Columbia River at Donald, where NN:TDP can occasionally be less than 10 in the summer (Pieters et al. 2022b), although these cases do not account for TN and likely remain P limited.

Variation, April to October, phosphorus - Data for both SRP and TDP show no variation by month for any of the reference tributaries. In contrast, TP shows large variation in monthly average values for the natural tributaries with a peak in May, driven by a peak in PP; monthly average PP was highly correlated with monthly average turbidity (r = 0.87).

Seasonal variation, nitrogen - Data from the four reference tributaries with natural flows showed a significant change in nitrate concentration with time of year. For example, data from Beaver River for 2009-2018 are shown in Figure 24. Nitrate increased from winter levels of below 200 µg/L to over 300 µg/L during the start of freshet, and then declined rapidly to summer values of approximately 50 µg/L. Nitrate concentrations gradually increased through fall, returning to winter levels in December. A similar pattern was observed in the other reference tributaries with natural flows (Pieters et al. 2022b), in the unregulated tributaries to the Arrow Reservoir (Pieters et al. 2003a), and in other systems (e.g., Pellerin et al. 2012). In the regulated outflows from Kinbasket and Revelstoke Reservoirs, there was little variation in nitrate concentration.

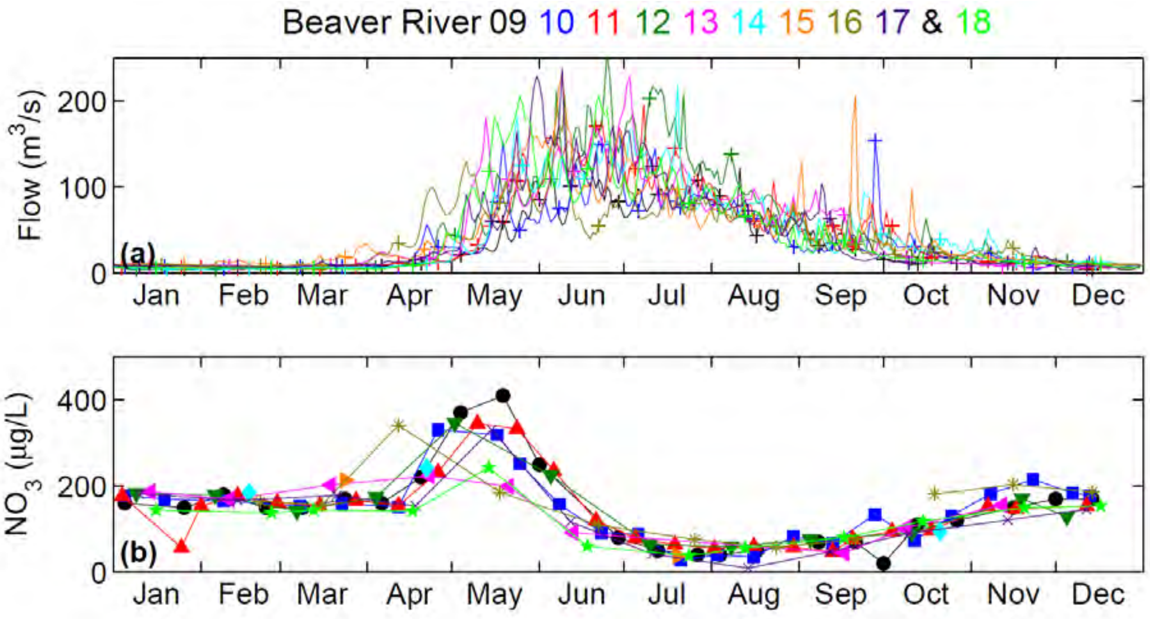


Figure 24. (a) Flow and (b) nitrate concentrations for Beaver River near East Park Gate, 2009-2018. Note the increase in nitrate at the start of freshet, followed by lower values in summer. Data courtesy of Environment Canada (station BC08NB00002).

Flow weighted averages, April-October - The flow weighted average concentration of TDP and TP for April to October are shown for the reference tributaries in Figure 25 and Figure 26, respectively. Only one sample was collected from the reference tributaries in 2008, insufficient to calculate a volume weighted average, and this year is excluded. For TDP, the Maxxam laboratory used from 2013-2018 resulted in more readings at or below the detection limit of 2 µg/L, over 40% for the natural tributaries and 80% for the reservoir outflows. The volume weighted TDP concentrations are low for all the reference tributaries (Figure 25). Total phosphorus is high and variable for the natural tributaries and low for the reservoir outflows (Figure 26).

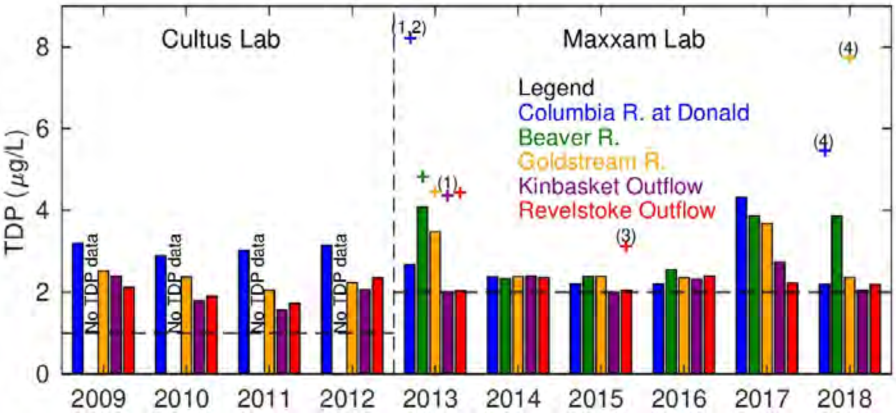


Figure 25. Estimated volume weighted concentration of TDP from reference tributaries, for April to October, 2009-2018. The vertical dashed line marks the change in laboratory at the start of 2013. The horizontal dashed line marks the detection limit. Data from the Cultus Lab shown corrected. The following nine outliers from Maxxam Lab were excluded: note (1), all samples of 6-7 August 2013 had high TDP of 7.4-15.3 µg/L; note (2), a single value of 46 µg/L on 10 September 2013; note (3), a single value of 29 µg/L on 8 April 2015; and note (4), two values of 28 and 23 µg/L on 26 and 27 June 2018 respectively. The '+' marks the height of the bars *including* the outliers.

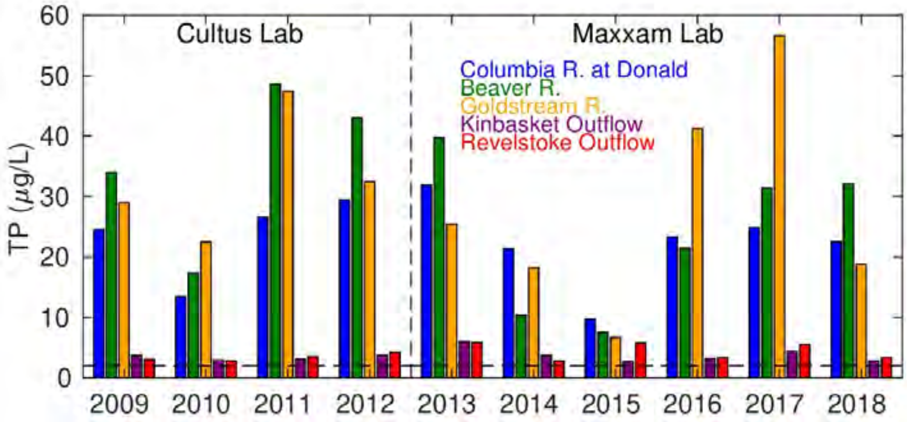


Figure 26. Estimated volume weighted concentration of TP from reference tributaries, for April to October, 2009-2018. The vertical dashed line marks the change in laboratory. The horizontal dashed line marks the detection limit.

The flow weighted average concentration of nitrate (NO_3) is shown for the reference tributaries in Figure 27. The nitrate data are consistent between the laboratories and there were no significant trends across time. Of the natural flow, the average nitrate concentration in the Columbia River at Donald is lowest and that in the Goldstream River is highest.

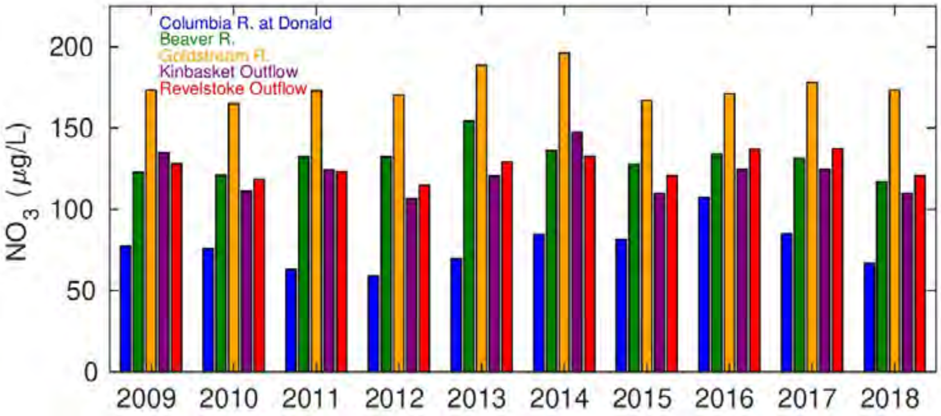


Figure 27. Estimated volume weighted concentration of NO_3 from reference tributaries, for April to October, 2009-2018.

Load, April to October - The nutrient concentrations were interpolated to daily values and multiplied by the flow to give the load of TDP, TP, and NO_3 for April to October in the reference tributaries, shown in Figures 27 to 29, respectively. The largest loads are observed in the reference tributaries with the largest flow, of which the top three are Revelstoke outflow, Kinbasket outflow, and Columbia River at Donald. For example, in the Columbia at Donald, the load of TDP for April to October was higher for 2012 (Figure 28), because, even though the TDP concentration was close to average (Figure 25), the flow was high for April to October 2012 (Figure 4). In contrast, the load of TDP was low for 2015 (Figure 28), because the TDP concentration was the lowest during the study period (Figure 25), and the flow was average for April to October 2015 (Figure 4).

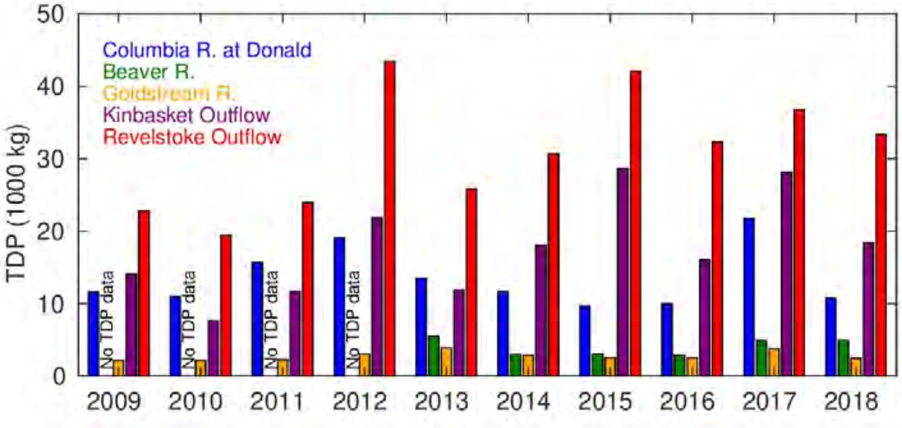


Figure 28. Load of TDP from reference tributaries, for April to October, 2009-2018. Data from the Cultus Lab (2009-2012) shown corrected and nine outliers from Maxxam Lab excluded.

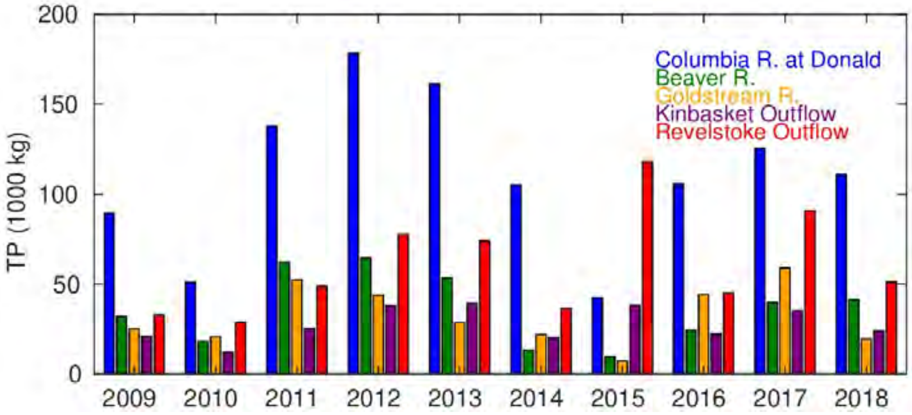


Figure 29. Load of TP from reference tributaries, for April to October, 2009-2018. Data from the Cultus Lake (2009-2012) shown corrected.

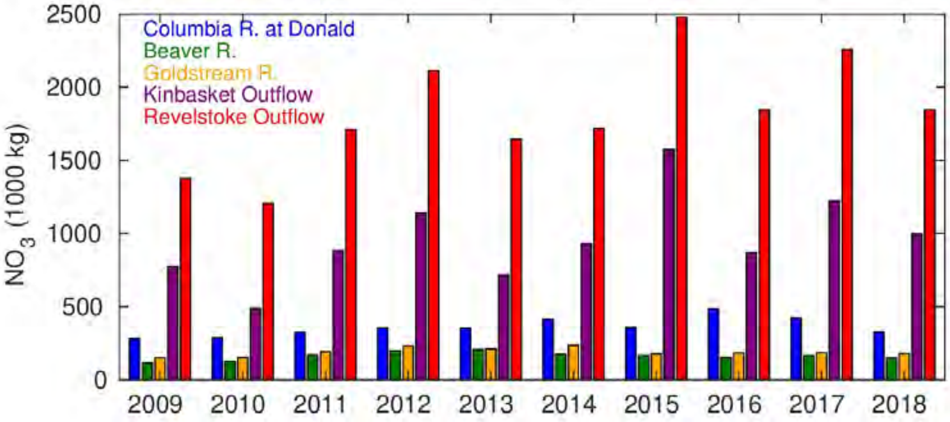


Figure 30. Load of NO_3 from reference tributaries, for April to October, 2009-2018.

Seasonal load - The seasonal pattern for the load of TDP, TP, and NO_3 is compared with that for the flow, using the fraction of the total load for April to October averaged over all years (Figure 31). The Columbia at Donald was representative of the natural inflows, and the fraction of flow peaked with freshet in June (Figure 31a). Recall that TDP had little seasonal variation and as a result the fraction of TDP load followed the flow closely. TP increased with turbidity during freshet and shows slightly higher fraction of load than the flow in May and June. Nitrate, which had strong seasonal variation (Figure 24), gave both a higher fraction during May and a lower fraction in July (Figure 31a).

For Kinbasket Reservoir (Figure 31b) and Revelstoke Reservoir (Figure 31c), the load of all quantities follows the flow closely. For the outflow from Kinbasket Reservoir the fraction of flow was low in May and June and rose to a peak in August (Figure 31b). In contrast, the outflow from Revelstoke Reservoir showed less variation from April to October (Figure 31c).

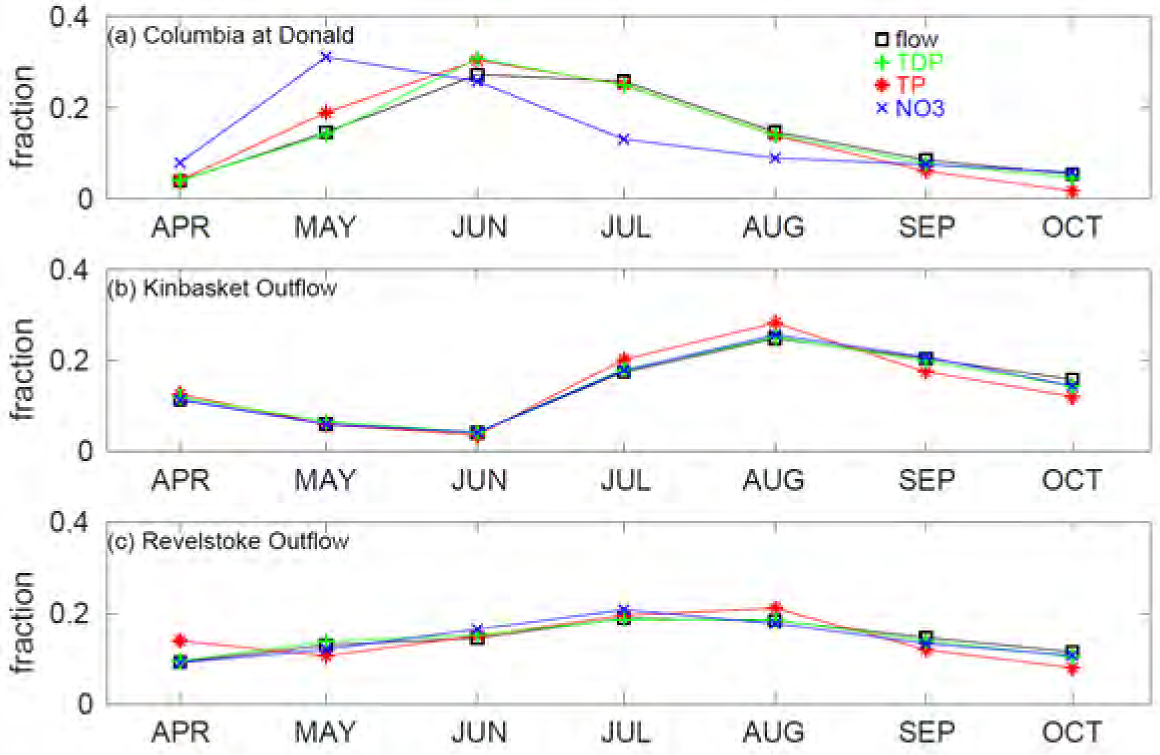


Figure 31. Fraction of the flow, TDP load, TP load, and NO_3 load for (a) Columbia at Donald, (b) Kinbasket outflow and (c) Revelstoke outflow, monthly, April to October, averaged for 2009-2018.

3.4 Reservoir Water Chemistry

Mean values for reservoir station water chemistry, 2 to 20 m depths averaged, are summarised in Table 10. Total phosphorus (TP) includes both dissolved and particulate phosphorus while total dissolved phosphorus (TDP) is a measure of inorganic and organic phosphorus in solution, i.e., not attached to particles. Total phosphorus (TP, $\bar{x}$ = 3.08 ± 1.85 µg/L both reservoirs) can be variable given the glacial inputs to both reservoirs and is, however, generally lower in pelagic reservoir samples than in tributaries samples where there can be a much higher component of glacial fines. Total dissolved phosphorus (TDP, $\bar{x}$ = 2.24 ± 1.10 µg/L both reservoirs) was often at or below the detection limit of 2 µg/L and sometimes higher than total phosphorus. Lab results can be highly variable due to a combination of extremely low levels of phosphorus that are difficult to accurately measure and samples that can easily be compromised by contamination, aliquot variability, or lab error. Soluble reactive phosphorus (SRP) is a form of dissolved inorganic phosphorus that is readily available to, and cycles rapidly through, biota (SRP, $\bar{x}$ = 1.4 ± 0.81 µg/L both reservoirs. There was no significant long-term annual trend in phosphorus or nitrogen fractions in either reservoir over the monitoring period (Figure 32).

Table 10. Summary of Kinbasket and Revelstoke Reservoir water chemistry, 2 to 20 m averaged, 2008-2019.

Station/ Parameter	Units	KIN Forebay	KIN Canoe	KIN Wood	KIN Columbia	REV Forebay	REV Middle	REV Upper	KIN Mean	REV Mean
NO_2+NO_3	µg/L	107	109	105	111	122	122	128	108	124
TN	µg/L	175	181	179	191	182	191	189	182	187
TP	µg/L	2.93	3.07	3.49	3.34	2.72	3.24	2.87	3.19	2.95
TDP	µg/L	2.29	2.27	2.28	2.38	2.15	2.17	2.10	2.30	2.15
SRP	µg/L	1.19	1.26	1.35	1.45	1.23	1.29	1.32	1.31	1.27
NN:TDP		39.6	40.5	38.2	38.6	45.9	46.2	51.2	39.2	47.7
Conductivity	µS/cm	146	138	140	170	116	114	111	149	114
Alkalinity	mg $CaCO_3$/L	66.9	62.9	65.5	80.1	53.5	52.3	50.0	68.9	52.2
Silica (SiO_2)	mg/L	2.81	2.82	2.75	2.83	3.22	3.25	3.51	2.80	3.32
Turbidity	NTU	0.46	0.49	1.39	0.90	0.57	0.94	1.04	0.77	0.82
pH		8.0	7.9	8.0	8.0	7.8	7.8	7.8	8.0	7.8

N.B. Mean values are based on available months, stations, and depths sampled. Not all months and stations were sampled each year. Total nitrogen data from 2016-2019 only.

Both reservoirs fall under the classification of ultra-oligotrophic as defined by epilimnetic phosphorus (Wetzel 2001) and are limited by phosphorus rather than by nitrogen. NN:TDP ratios in the upper layer (average 2 to 20 m) of Kinbasket Reservoir ($\bar{x}$ = 39.2 ± 19.0) and Revelstoke Reservoir ($\bar{x}$ = 47.7 ± 20.3) are likely underestimating the true ratio as so many TDP results were below detection (63%, 2013-2019). Where lab results were returned below the 2 µg/L detection limit (MAXXAM/ALS), the detection limit was substituted. Although some discrete depth samples were occasionally below 10, averaged NN:TDP in the upper layer was below 10 only once, in September 2019, at Kinbasket Columbia station.

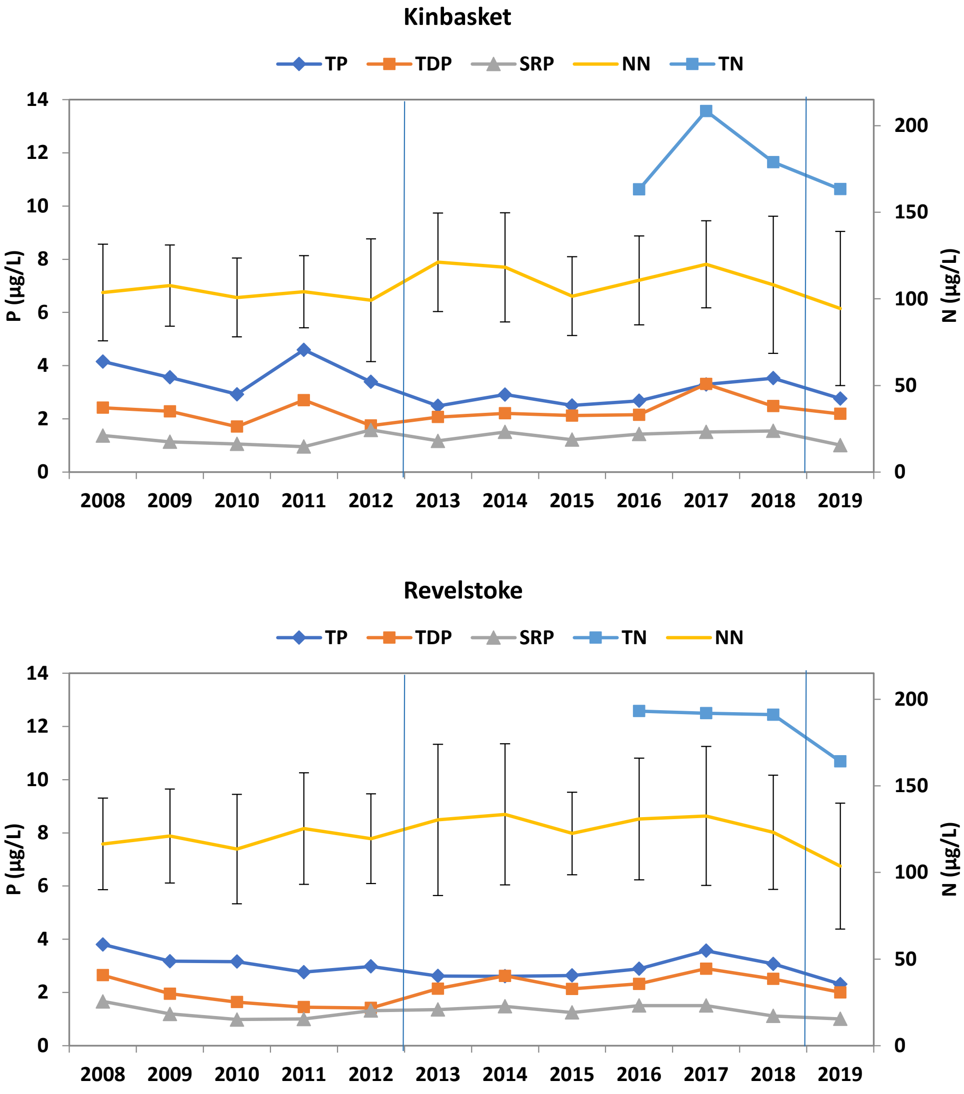


Figure 32. Annual averaged 2 to 20 m TN, NN, TP, TDP, and SRP in Kinbasket and Revelstoke Reservoirs, 2008-2019. Error bars are ±1 standard deviation and are not included for all parameters (to keep the graph readable). Vertical blue line indicates when laboratory changes occurred in 2013 and 2019. *Note that the 2008 average is based on a partial year.

Unavoidable changes in analytical labs contributes to uncertainty, especially with phosphorus values. Very low-level phosphorus detection is uncommon for most commercial laboratories and requires ultra clean methodologies. A lab comparison conducted in 2018 (Bray 2022) demonstrated that results can vary widely by lab and that if accurate measurement of TDP and SRP is required then lower detection limits are necessary and maintaining laboratory consistency is important.

Both Kinbasket and Revelstoke Reservoirs are slightly alkaline with pH varying little with season or depth. Silica, an important element for diatoms, was consistently above 0.5 mg/L (Table 10) which is the level considered limiting for growth (Wetzel 2001).

3.5 Primary Production

In this section we discuss the availability of light for photosynthesis in the water column (Section 3.5.1), the chlorophyll *a* concentration observed in both reservoirs (Section 3.5.2), and the measured rates of primary productivity (Section 3.5.3).

3.5.1 Light in the water column

The optical properties of lakes and reservoirs are important regulatory parameters in the physiology and behavior of aquatic organisms (Wetzel 2001). From June to September, the months during which primary production was measured, the photic zone was typically between 0 and 20 m and on rare occasion the 1% light level dropped below 20 m (cf. Figure 19) and maximum 1% light depths were typically reached at the end of the measurement period in September. CTD casts show forebay stations have the deepest photic depths given they receive the least amount of glacial input. Annual average photic zone depth measured during primary production sampling (June-Sept) from 2009-2019 was 18.1 m at Kinbasket, 15.4 m at Revelstoke Forebay, and 12.6 m at Revelstoke Middle. These values are lower than reported earlier in Section 3.2.5 since these values represent photic depths for a subset of the months reported in Section 3.2.5, however, the general trends are similar.

The attenuation coefficient is a measure of water transparency and depends largely on the concentration and composition of suspended and dissolved matter. A high attenuation coefficient is indicative of low transparency caused by high concentration of colloidal matter and a low attenuation coefficient indicates high transparency caused by low turbidity. In Kinbasket and Revelstoke, the attenuation coefficient has generally shown consistent seasonal variation (2002, 2008 to 2019) where water transparency is generally lower early in the growing season in June and July, then increases in August, and again in September (Figure 33). Typical attenuation coefficients for Kinbasket in June and July are 0.31 cm^{-1}, or 69% transmission m^{-1}, dropping to 0.28 cm^{-1}, or 72% transmission m^{-1}, in August, and dropping again in September to 0.24 cm^{-1}, or 76% transmission m^{-1}. Attenuation coefficients are typically higher and transparency lower for Revelstoke Middle, where in June and July attenuation coefficients of 0.42 cm^{-1}, or 58%

transmission m^{-1}, are measured, dropping to 0.35 cm^{-1}, or 65% transmission m^{-1}, in August and dropping again in September to 0.33 cm^{-1}, or 67% transmission m^{-1}. At Revelstoke Forebay, water transparency followed the same seasonal trend as measured at Kinbasket Forebay and Revelstoke Middle, but the attenuation coefficients generally fall between those measured at Kinbasket and Revelstoke Middle. In June and July, the attenuation coefficient at Revelstoke Forebay was on average 0.35 cm^{-1}, or 65% transmission m^{-1}, 0.31 cm^{-1}, or 65% transmission m^{-1}, in August and 0.29 cm^{-1}, or 65% transmission m^{-1} in September. On one sampling trip (July 2012) a particularly high attenuation coefficient was measured at both Revelstoke Middle and Revelstoke Forebay where values were 0.6 cm^{-1}, or 40% transmission m^{-1} (Figure 33), indicating high turbidity during these two sampling events. On average, water transparency has been higher in Kinbasket followed by Revelstoke Forebay, while transparency has generally been the lowest at Revelstoke Middle. On average, between 2002 to 2019 the attenuation coefficient in Kinbasket was 0.29 cm^{-1} and at Revelstoke Forebay and Revelstoke Middle, 0.37 cm^{-1} and 0.33 cm^{-1}, respectively.

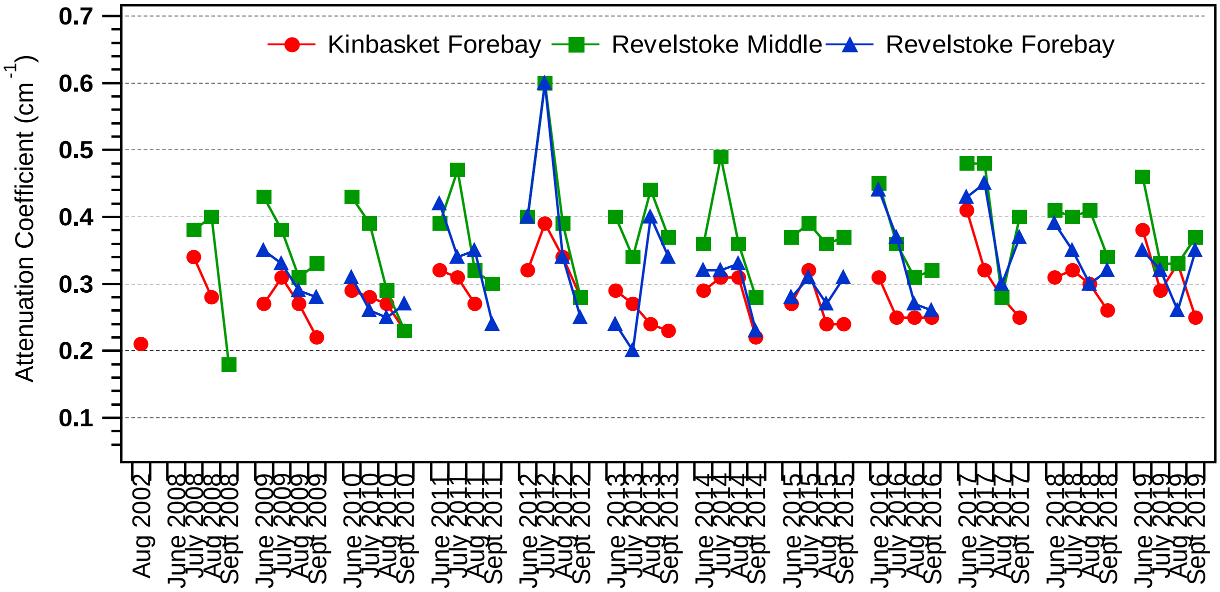


Figure 33. Attenuation coefficient (cm^{-1}) in Kinbasket, Revelstoke Middle and Revelstoke Forebay from 2002-2019. Attenuation coefficients were calculated from Secchi disk depths in 2002 and 2008 and from the vertical profiles of photosynthetically available radiation in 2009-2019.

3.5.2 Chlorophyll

Chlorophyll *a* concentration in Kinbasket and Revelstoke Reservoirs was generally low; in Kinbasket the vast majority of the measurements of chlorophyll ranged between 1.0 to 2.0 µg/L while in Revelstoke biomass was even lower with most chlorophyll values ranging from 0.5 to 1.5 µg/L (Figure 34). Concentrations less than 0.5 µg/L were not measured at Kinbasket Forebay whereas concentrations below 0.5 µg/L were measured in most years in Revelstoke, except for 2013 at both stations in Revelstoke Reservoir and in 2015 and 2017 at Revelstoke Middle. The highest concentration of 3.38 µg/L was measured in Kinbasket in August 2013 and the lowest concentrations of 0.05 µg/L was measured in Revelstoke Forebay in September 2010. Chlorophyll concentrations rarely exceeded 3.0 µg/L except for a small number of samples in 2011, 2013, and 2018. On average, the 2009-2016 chlorophyll concentrations are higher in Kinbasket at 1.44 µg/L compared to 1.02 µg/L and 0.99 µg/L at Revelstoke Forebay and Revelstoke Middle, respectively. These low chlorophyll values are indicative of oligotrophic conditions (Wetzel 2001).

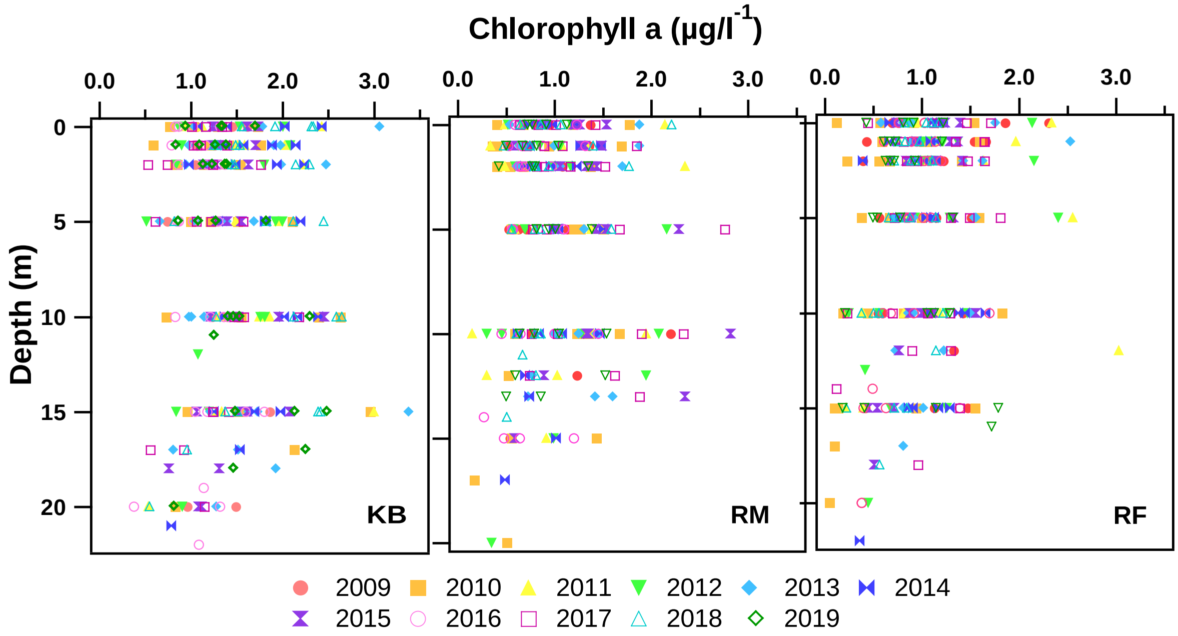


Figure 34. Vertical profiles of chlorophyll *a* (µg/L) for 0.2µm filter in Kinbasket, Revelstoke Middle and Revelstoke Forebay in 2009-2019. Data are not available for 2002 and 2008.

Depth integrated chlorophyll concentrations were consistently low, rarely exceeding 20 mg Chl *a*/m^2 in Revelstoke Reservoir and rarely exceeding 35 mg Chl *a*/m^2 in Kinbasket (Figure 35). On average, similar seasonal variability was observed in both Kinbasket and Revelstoke during the study period (Figure 35). For Kinbasket Forebay, higher variability was measured in 2010, 2012, 2014, and 2019, whereas lower variability was measured in 2009, 2011, 2013, 2015, 2017, and

2018 than in the other study years. For Revelstoke Forebay, seasonal variability was high from 2009 to 2012, then from 2013-2019 the biomass became more stable and there was very little seasonal or interannual variability, except for moderate variability in 2017 (Figure 35). During all study years the annual average chlorophyll *a* biomass was highest at Kinbasket Forebay where concentrations were greater than 20 mg/m^2 in all years while at Revelstoke Middle and Revelstoke Forebay the biomass was between 10-20 mg/m^2 (Figure 36). No consistent trend was observed with respect to the two stations in Revelstoke Reservoir; in 7 out of 10 years biomass was lower in Revelstoke Middle than at Revelstoke Forebay and in three years biomass was slightly higher at Revelstoke Middle than at Revelstoke Forebay (Figure 36). Despite no consistent trend it should be noted that chlorophyll concentrations at the two stations in Revelstoke were more similar to each other than to concentrations observed at Kinbasket. The 2009-2019 depth integrated averages were 25.1, 14.5, and 15.8 mg/m^2 for Kinbasket, Revelstoke Middle, and Revelstoke Forebay, respectively.

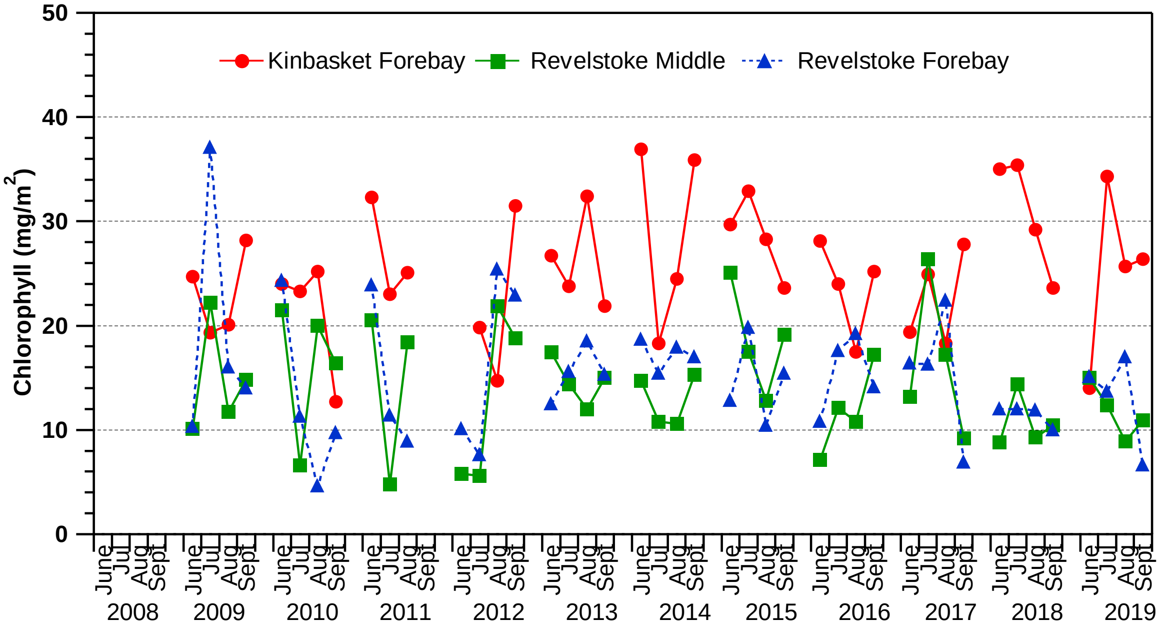


Figure 35. Monthly depth integrated (1-100% surface PAR) chlorophyll (mg Chl a/m^2) concentrations in Kinbasket, Revelstoke Middle, and Revelstoke Forebay, 2009-2019. Data were not collected in 2002 and 2008.

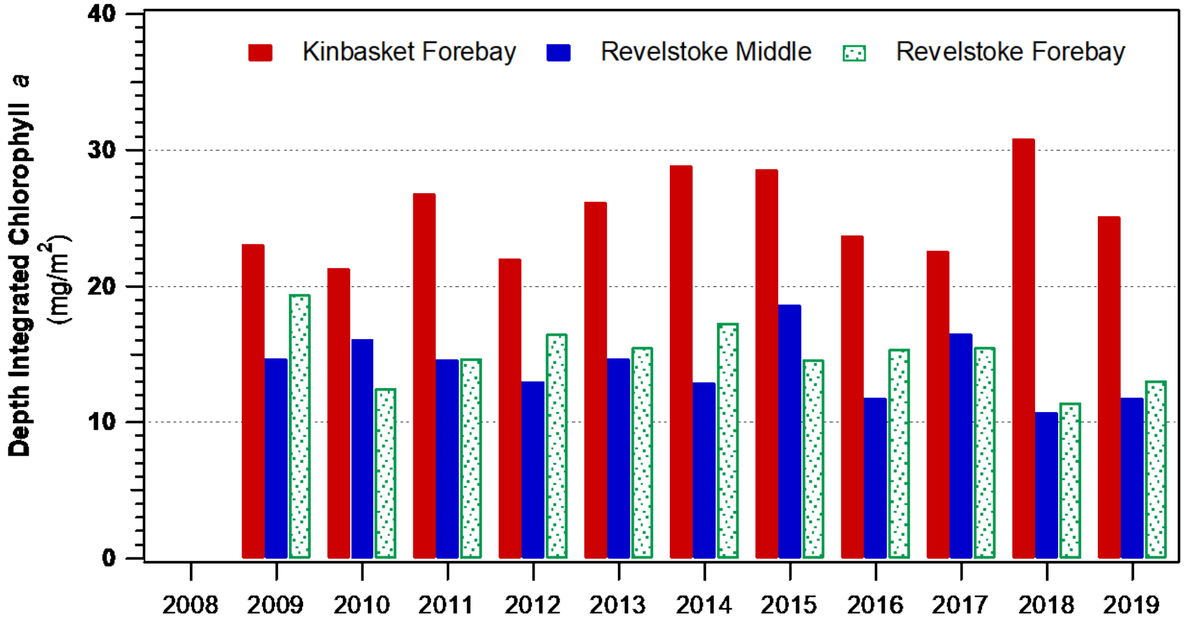


Figure 36. Annual average depth integrated chlorophyll *a* (mg/m^2) in Kinbasket, Revelstoke Middle, and Revelstoke Forebay, 2009-2019. Data were not collected in 2002 and 2008.

On average, the small sized phytoplankton, cells <20.0 µm, accounted for 87% of the total biomass while larger sized phytoplankton, >20 µm in size, accounted for just 13% of the total biomass (Figure 37). In Kinbasket Reservoir, the relative importance of picoplankton and nanoplankton varied interannually where in 2009, 2010, 2016, 2017, and 2018 picoplankton were the dominant size class while in 2011, 2012, 2013, 2014, 2015, and 2019 nanoplankton were the dominant size class. Despite this variability in the dominant size class, the difference between the relative percentages accounted for by the two size classes was extremely small; on average picoplankton accounted for 43.6% of the chlorophyll biomass and nanoplankton accounted for 43.9%. Microplankton were the least abundant size class at Kinbasket Forebay in all years, accounting for an average 12% of the chlorophyll biomass. In Revelstoke Middle and Forebay, chlorophyll biomass was dominated by picoplankton (mean 50%) in all years (2009-2019), with one exception in 2015 at Revelstoke Forebay where nanoplankton were the dominant size fraction. Despite picoplankton dominating the biomass, a high relative contribution of nanoplankton was also measured in 2015 where 39% of the chlorophyll biomass was composed of nanoplankton sized cells, followed by microplankton that accounted for ~11% of the chlorophyll biomass. The size fractionation results show Revelstoke has more stable size structure than was measured in Kinbasket Reservoir. This size distribution of a relative high contribution of small sized cells is typically found in oligotrophic lakes and reservoirs (Wetzel 2001).

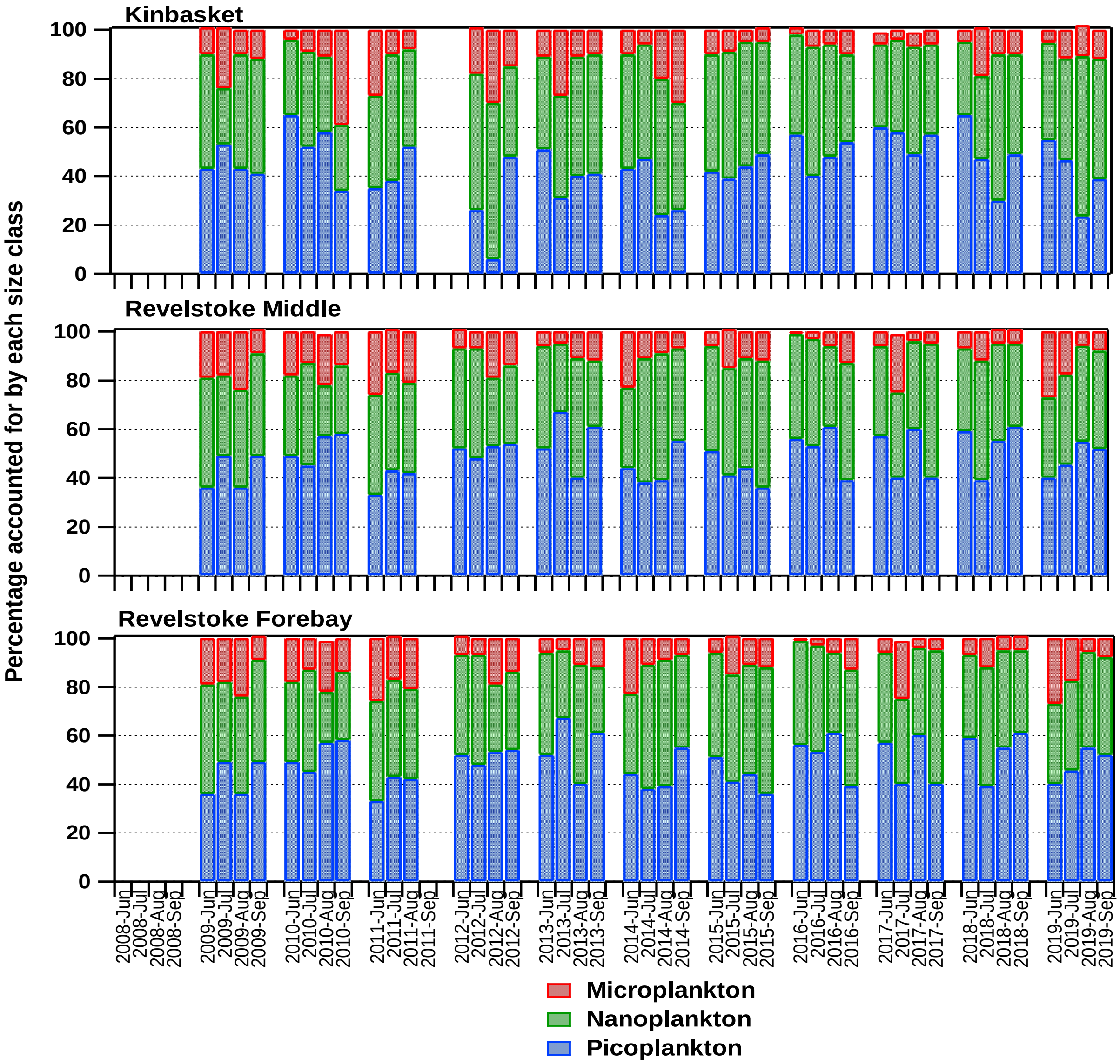


Figure 37. Monthly relative contribution of picoplankton (0.2-2 µm), nanoplankton (2.0-20 µm) and microplankton (>20 µm) to depth integrated chlorophyll in Kinbasket, Revelstoke Middle, and Revelstoke Forebay in 2009-2019.

3.5.3 Primary productivity

Productivity rates in Kinbasket Reservoir were typically under 100 mg C/m^2/d from 2008-2012 and above 100 mg C/m^2/d from 2013-2019 (Figure 38). Production was highest in Kinbasket Reservoir for this site at 361.7 mg C/m^2/d in July 2019, which is an order of magnitude higher than the lowest production measured on 2 June 2009 at 21.6 mg C/m^2/d. A similar pattern was observed in production at Revelstoke Forebay whereas at Revelstoke Middle production was typically below 100 mg C/m^2/d for the entire time series. From a production perspective, the time series suggests Kinbasket Forebay and Revelstoke Forebay are more similar to each other than to Revelstoke Middle. The similarity between forebay stations was also shown in Section 3.2.5 where the forebay stations had the highest photic depths as they receive the least amount of glacial input. Seasonal variability of production is greater at Kinbasket Reservoir and Revelstoke Forebay while at Revelstoke Middle the productivity is much more stable over the study period. In general, mean primary productivity was higher in Kinbasket (112.9 mg C/m^2/d) than in Revelstoke (69 mg C/m^2/d). The 2008-2019 annual primary productivity averages were 112.9, 66.3, and 87.1 mg C/m^2/d for Kinbasket, Revelstoke Middle, and Revelstoke Forebay, respectively.

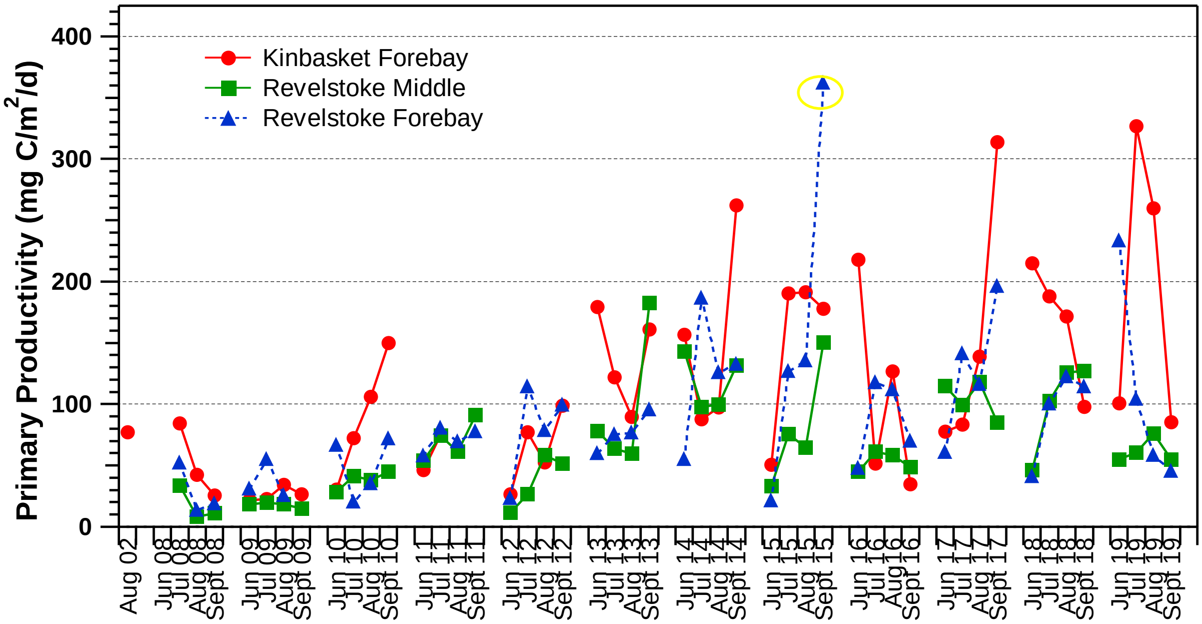


Figure 38. Monthly depth integrated primary productivity (mg C/m^2/d) in Kinbasket and Revelstoke Middle, and Revelstoke Forebay, 2002-2019. Note: yellow circled point in Sep 2015 is uncharacteristically high, analysis was re-run to verify results.

A general increase in primary productivity was observed at all stations from 2008 to 2019 (Figure 39). A small reduction in production was measured at all stations in 2016, that was also measured in phytoplankton densities (cf. Figure 43), however the rates measured in 2016 were still well above the production rates measured early in the time series (2008-2012). Primary productivity is often used for determination of the trophic classification based on the assumption that littoral and allochthonous sources are often small relative to pelagic sources (Wetzel 2001). These low primary productivity rates measured in Kinbasket and Revelstoke Reservoirs are further indications of oligotrophic conditions.

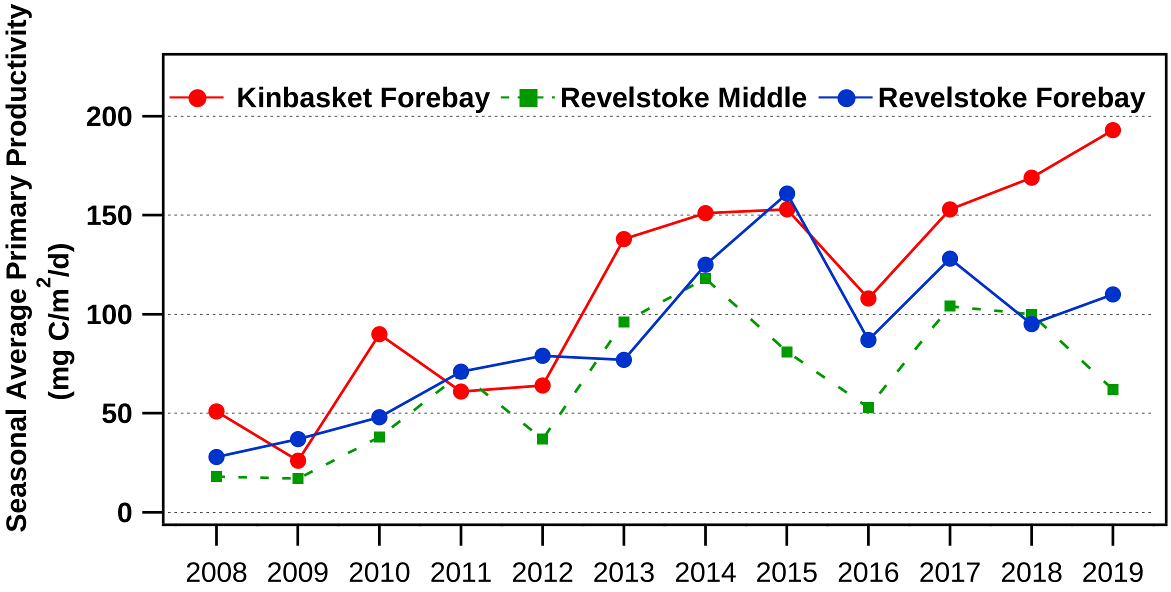


Figure 39. Annual average depth integrated primary productivity (mg C/m^2/d) in Kinbasket, Revelstoke Middle and Revelstoke Forebay in 2008-2019.

Throughout the time series, picoplankton (0.2-2.0 µm) and nanoplankton (2.0-20.0 µm) consistently accounted for the greatest percentage of primary productivity in Kinbasket and Revelstoke Reservoirs. Phytoplankton <20 um in size accounted for between 60-97% of productivity while microplankton (2.0-20.0 µm) were the least productive, generally accounting for 3-40% of productivity (Figure 40). In general, nanoplankton, the preferred size class consumed by *Daphnia* sp., are the most productive size class at all three stations accounting for 42% of the production; however, the differences between nanoplankton and picoplankton productivity was minor, generally less than 4% difference for all three stations. In fact, in Revelstoke Forebay the difference between nanoplankton and picoplankton was less than 1%. Microplankton were the least productive fraction accounting for less than 20% of the total production (Figure 40).

Over the course of the study, the measurement of the size structure of the primary productivity revealed some changes where the relative contribution of picoplankton and nanoplankton has generally increased at all three stations while microplankton productivity has decreased (Figure 40). At the beginning of the time series in 2009, picoplankton and nanoplankton accounted for around 70% of the total productivity, while from 2010-2019 picoplankton and nanoplankton productivity accounted for 83% of total production, showing the relative importance of increases to small-celled plankton during the study. In Kinbasket Reservoir, the relative importance of picoplankton increased from 2009-2012. Nanoplankton, however, were generally the most productive fraction, except for 2018 when picoplankton productivity accounted for the greatest percentage of production. At Revelstoke Middle, the number of years where picoplankton accounted for the greatest percentage of production was approximately equal to the number of years where nanoplankton were the most productive fraction. Finally, there were two distinct periods in the time series at Revelstoke Middle: 2010-2015 when picoplankton production was greater and 2016-2019 when nanoplankton were the more productive fraction. At Revelstoke Forebay, the number of years where picoplankton accounted for the greatest percentage of production was equal to the number of years where nanoplankton were the most productive fraction; however, the relative importance of the two size fractions was more dynamic than at Revelstoke Middle. For instance, nanoplankton were the most productive fraction in 2009 and 2010, followed by more productive picoplankton in 2011 and 2012, equal contribution of both fractions in 2013 and then in general, the relative importance of the two fractions alternating from 2014-2019.

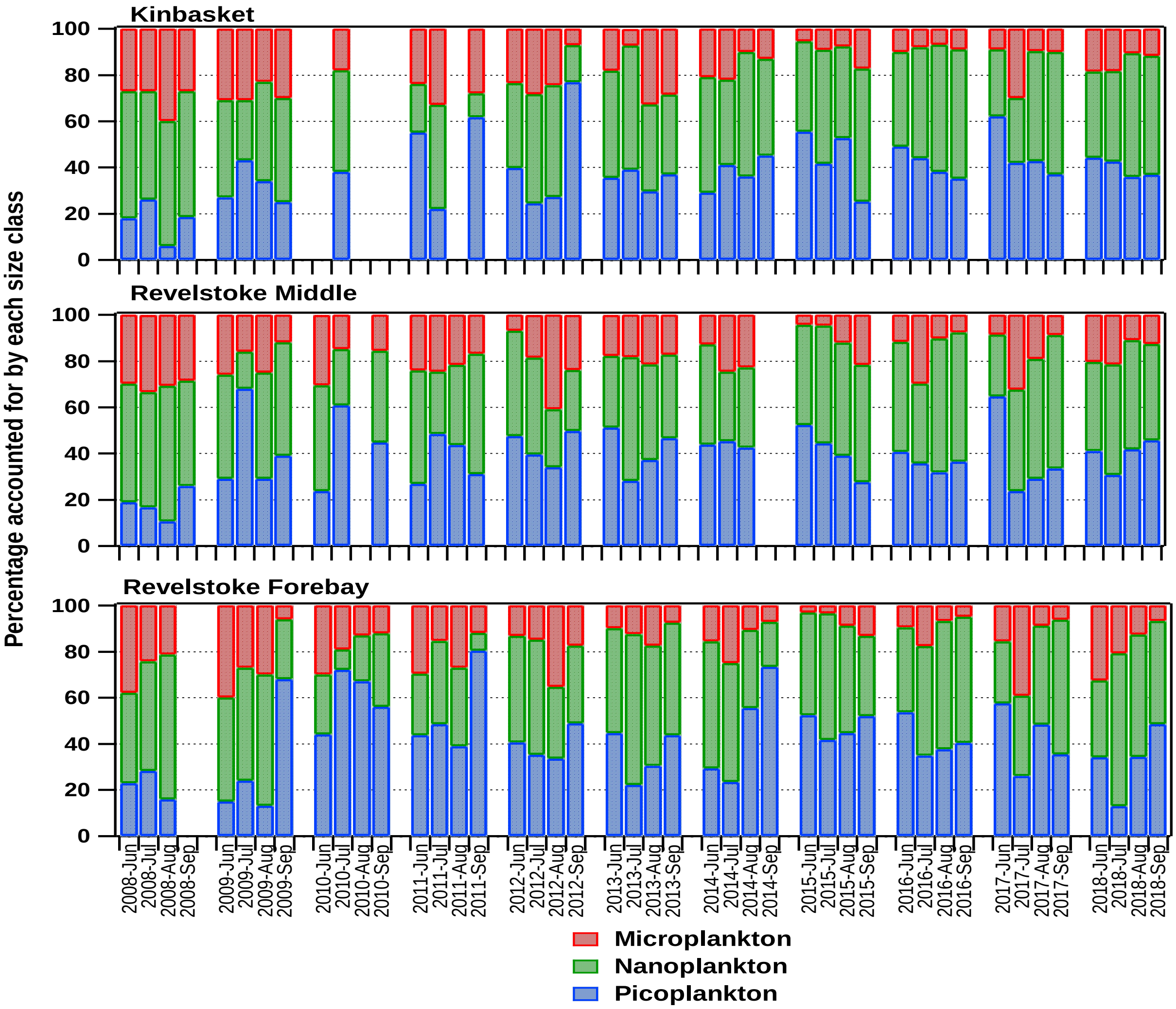


Figure 40. Monthly relative contribution of picoplankton (0.2-2 µm), nanoplankton (2.0-20 µm) and microplankton (>20 µm) to primary productivity in Kinbasket, Revelstoke Middle and Revelstoke Forebay in 2009-2019. Fractionation was not completed in 2002 and fractions were not comparable in 2008.

3.6 Phytoplankton

3.6.1. Taxa composition

From 2008 to 2019, 168 unique phytoplankton taxa were identified in Kinbasket Reservoir and 164 taxa were identified in Revelstoke Reservoir. Most of these taxa are grouped into the major taxonomic groups of greens and flagellates, with the remaining taxa consisting of diatoms, blue-greens, and dinoflagellates. The most common taxa was *Synechococcus* sp. and over 30 taxa were observed only once in 1,969 distinct phytoplankton samples over twelve years.

3.6.2 Density and biovolume

From 2008-2019, seasonal average epilimnetic (0-10 m) phytoplankton density was 1,542 cells/mL in Kinbasket Reservoir and 1,472 cells/mL in Revelstoke Reservoir. Both reservoirs show a clear seasonal pattern of low densities in the spring and late fall with higher densities in the late spring and summer (Figure 41 and Figure 42). A statistical analysis indicated that average density and biomass was significantly different between months (Kruskal-Wallis Test) in Kinbasket ($p<0.001$) and marginally significant in Revelstoke ($p=0.054$). In both reservoirs phytoplankton density and biovolume was significantly different in May when compared to the other months. September and October were also found to be significantly different from the June through August samples.

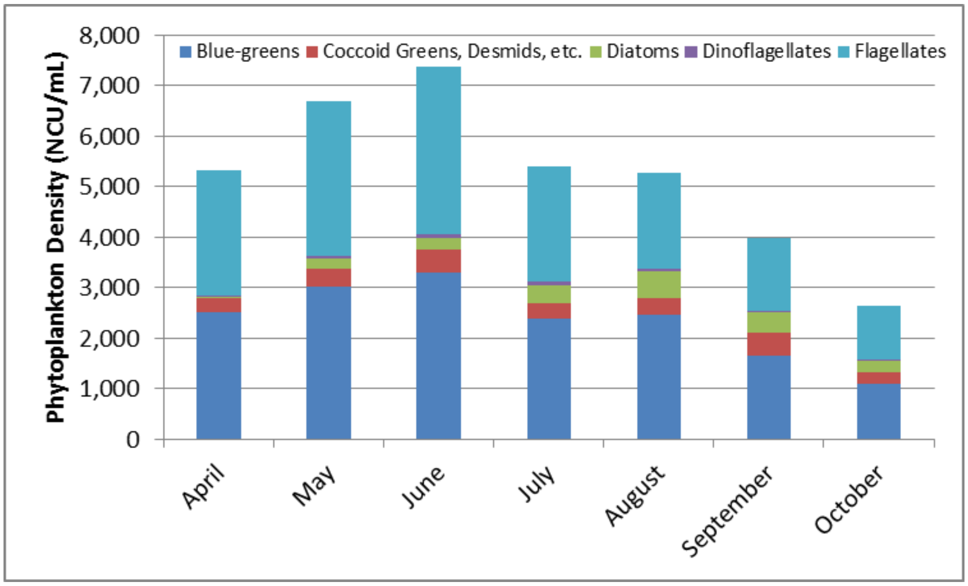


Figure 41. Monthly average phytoplankton density for Kinbasket over the study period, 2008-2019.

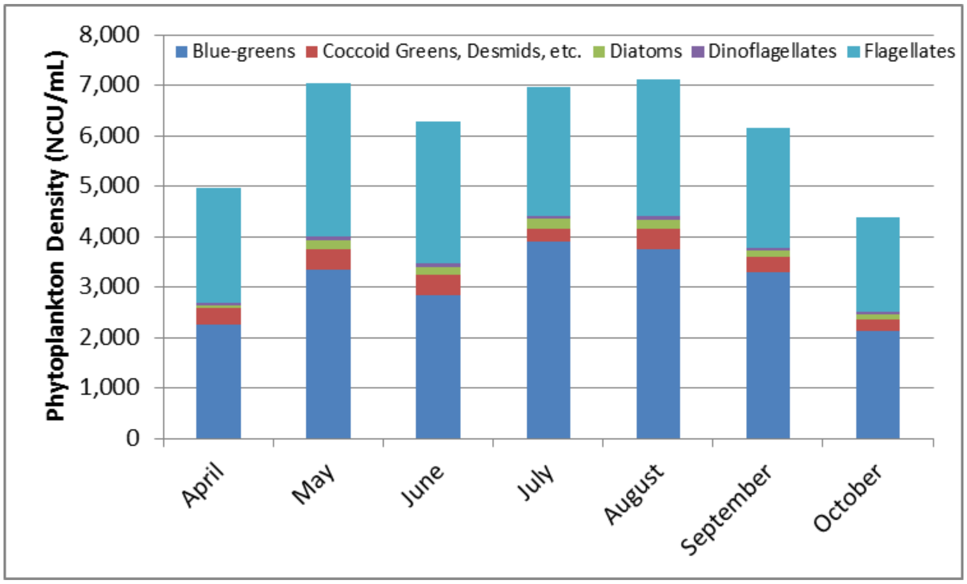


Figure 42. Monthly average phytoplankton density for Revelstoke over the study period, 2008-2019.

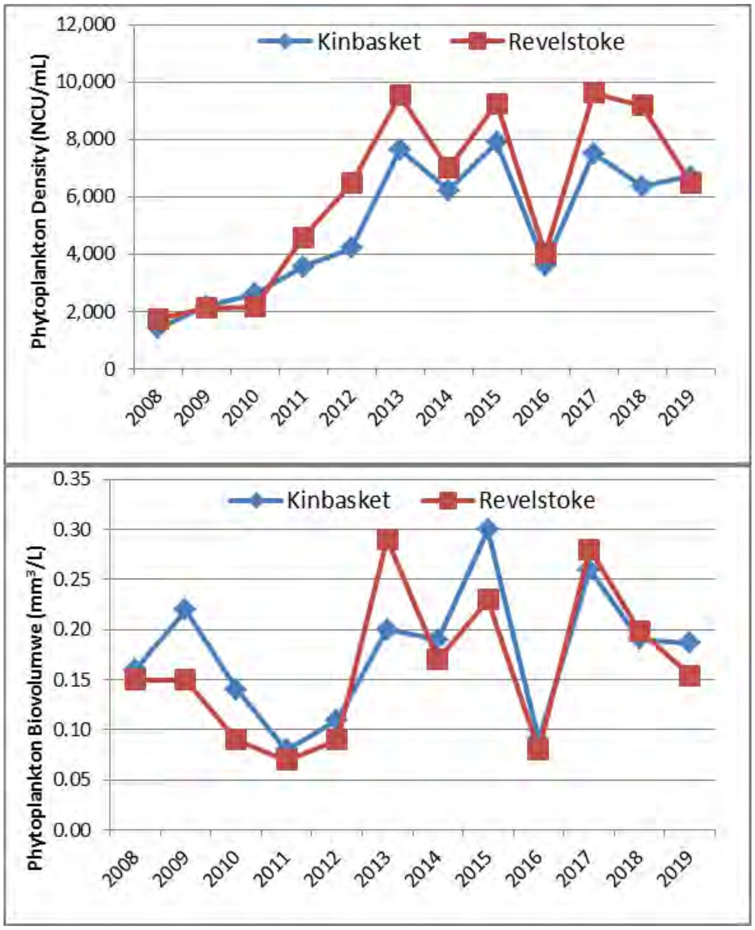


Figure 43. Yearly average total phytoplankton density (top) and biovolume (bottom) in Kinbasket Reservoir and Revelstoke Reservoir, 2008-2019.

Yearly average phytoplankton density and biovolume varied considerably between years (Figure 43). There was a significant difference in density and biovolume between years in both Kinbasket and Revelstoke Reservoirs (Kruskal-Wallis Test, $p<0.001$). There is also a clear trend with increasing density from 2008 through 2015, but this trend was not observed in the average phytoplankton biovolumes in the systems. This difference is due to the density increase in the smaller sized phytoplankton groups such as blue-greens and flagellates. This is further supported in primary production estimates presented previously. Primary production estimates are indicative of the rate at which carbon is assimilated into the phytoplankton community. The smaller phytoplankton taxa have a large respiration rate that will result in an increase in carbon uptake in a given unit of time when compared to slower growing larger taxa.

In Kinbasket, average phytoplankton density falls into three groups that are not significantly different from the others within the group, but are significantly different from those outside the group. The statistical grouping results are: (1) 2008, 2011, 2012; (2) 2009 and 2010; and (3) 2013 to 2019. Membership to a particular group does not mean they are similar, just not significantly different. One of the driving factors in determining group membership is monthly variability. The annual mean between years may be quite different but they can be in the same statistical group due to greater similarity in the variation pattern. In Revelstoke Reservoir, phytoplankton density and biovolume from 2008 was significantly different from all other years except for 2012 and 2014. The other years in the study were not significantly different from any other year.

Kinbasket and Revelstoke phytoplankton density and biovolume are tightly correlated when we look at yearly average values (Figure 44 and Figure 45). This could indicate that they are responding to similar environmental and trophic level interactions.

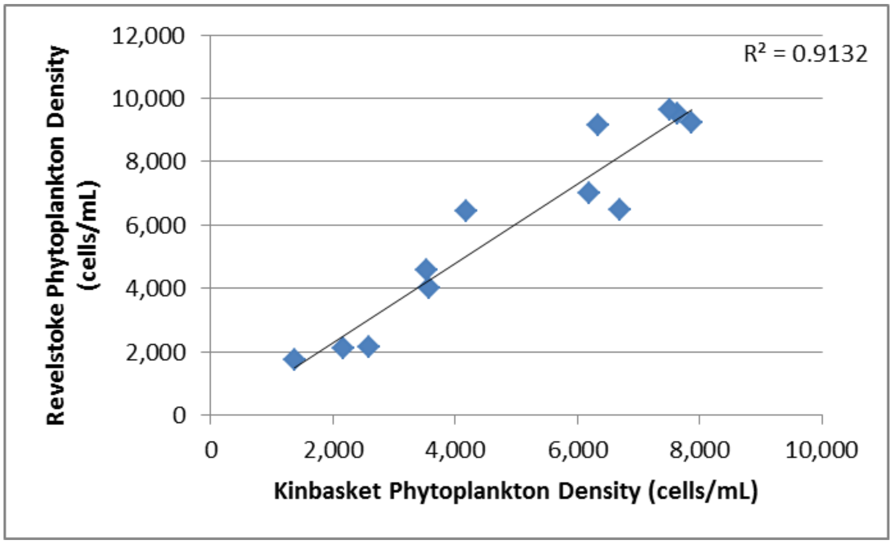


Figure 44. Correlation between Kinbasket and Revelstoke Reservoir yearly average phytoplankton density for 2008-2019.

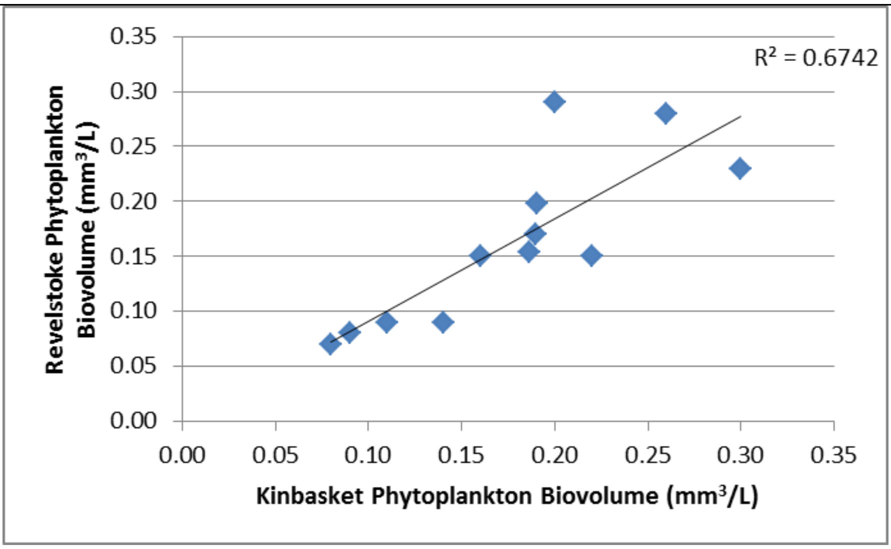


Figure 45. Correlation between Kinbasket and Revelstoke Reservoir yearly average phytoplankton biovolume for 2008-2019.

The phytoplankton community variation was not consistent between locations within the reservoirs over the course of the study. In Kinbasket Reservoir, the Canoe and Columbia sampling locations had greater between year variability than the Forebay and Wood locations (Figure 46). In Revelstoke Reservoir, the Upper station had considerably lower inter-annual variability than the Middle or Forebay stations (Figure 47).

Another noticeable change during the study has been the community composition by year. The increase in total phytoplankton density observed in 2012-2015 can be accounted for by an increase in two major taxonomic groups (blue-greens and greens) in both reservoirs.

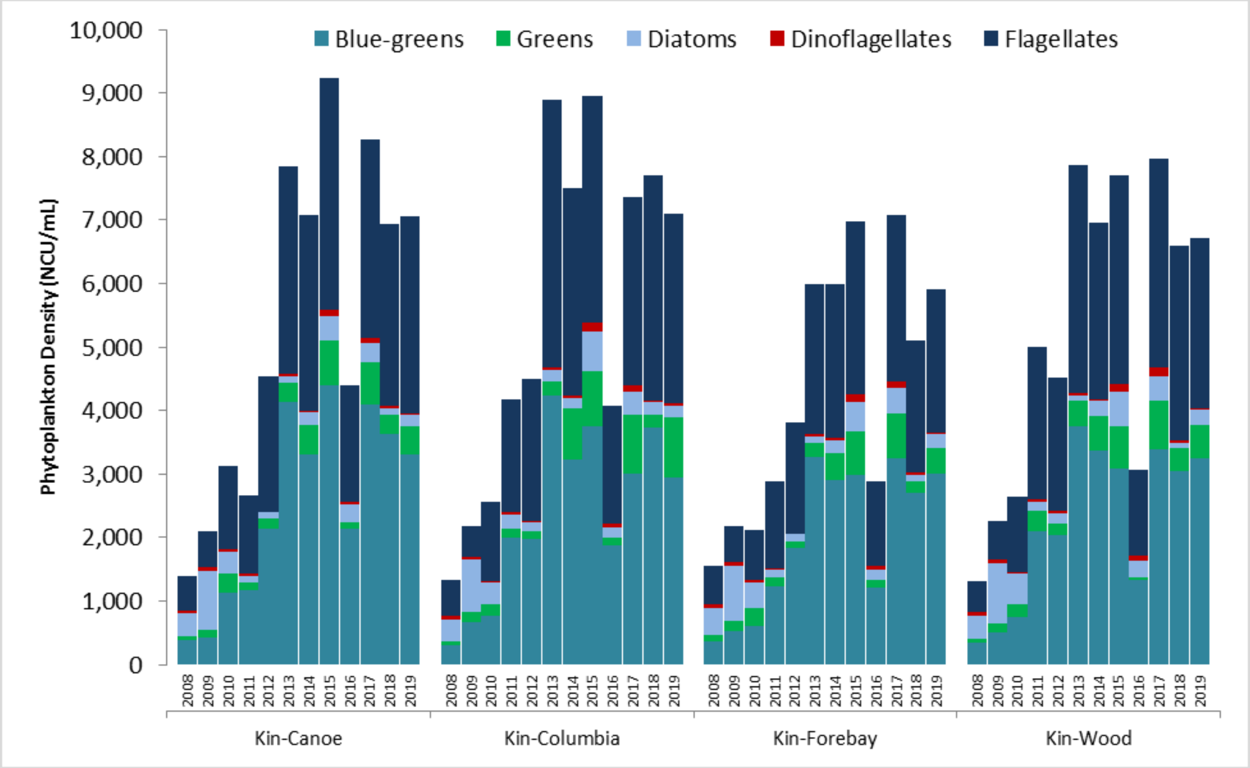


Figure 46. Seasonal average phytoplankton density by group and station in Kinbasket Reservoir over the study period, 2008-2019.

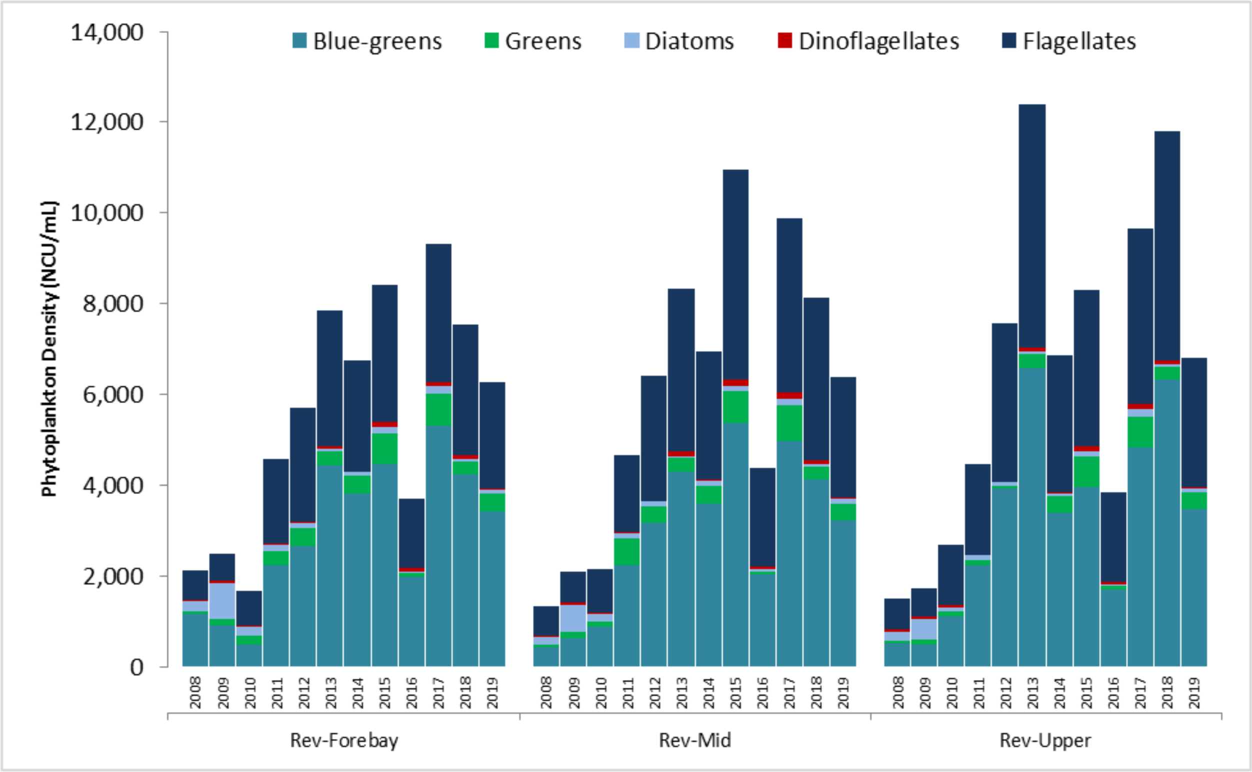


Figure 47. Seasonal average phytoplankton density by group and station in Revelstoke Reservoir over the study period, 2008-2019.

3.7 Zooplankton

3.7.1. Species composition

From 2008 to 2019, eleven species of Cladocera were recorded in Kinbasket Reservoir and sixteen species in Revelstoke Reservoir. Of these, six cladocerans were found in each reservoir every year, only four of which were common to both reservoirs: *Daphnia galeata mendotae* (Birge), *Daphnia rosea* (Sars), *Bosmina longirostris* (O.F.M.), and *Leptodora kindtii* (Focke). In Kinbasket Reservoir, *Daphnia schodleri* (Sars) and *Scapholeberis rammneri* (O.F.M.) were also found in each year while in Revelstoke Reservoir *Daphnia pulex* (Leydig) and *Holopedium gibberum* (Zaddach) were found in each year. Other species were observed sporadically. *Daphnia schodleri* occurred only in Kinbasket and *Daphnia pulex* occurred only in Revelstoke*,* while *H. gibberum*, common in Revelstoke Reservoir, was detected only sporadically in Kinbasket Reservoir. *Daphnia* were not identified to species for density counts.

Copepod density and biomass in both reservoirs was always almost exclusively composed of the cyclopoid copepod, *Diacyclops bicuspidatus thomasi* (Forbes). Two calanoid copepod species common to both reservoirs were consistently present but in very low numbers throughout the sampling period: *Epischura nevadensis* (Lillj.) and *Leptodiaptomus sicilis* (Forbes), while *Leptodiaptomus ashlandi* (Marsh) was infrequent and *Aglaodiaptomus leptopus* (Forbes) identified only rarely in Kinbasket Reservoir.

In both reservoirs, density was dominated by copepods throughout the season, tending to peak in in July. Early season biomass was also dominated by copepods until about July/August when the larger bodied cladocerans, especially *Daphnia*, became dominant (Figure 48). *Bosmina* was at times more abundant than *Daphnia*, but its smaller size meant it contributed much less to biomass.

While Kinbasket Reservoir had greater total zooplankton density and biomass (Kruskal-Wallis Test, p<0.001), the proportion of seasonal zooplankton composition was usually similar between reservoirs. Copepods made up 57-89% of the total zooplankton density in Kinbasket Reservoir and 66-80% in Revelstoke Reservoir, while *Daphnia* densities contributed 1-24% in Kinbasket and 4-15% in Revelstoke Reservoir (Figure 48). Even though monthly densities of *Daphnia* and other cladocerans were similar between reservoirs, the proportion of biomass contributed by cladocerans tended to be higher in Revelstoke Reservoir, particularly early in the season: 40% at the lowest compared to a low of 20% in Kinbasket Reservoir. There was a larger proportion of other cladocerans, mostly *Bosmina longirostris* and some *Leptodora kindtii*, from April to July in Revelstoke Reservoir compared to Kinbasket. By August and through to October, *Daphnia* contributed up to 70-80% of the zooplankton biomass in both reservoirs (Figure 48). The presence of the large-bodied *Daphnia pulex* in Revelstoke could contribute to overall biomass being higher relative to density when compared with Kinbasket where *D. pulex* was not found.

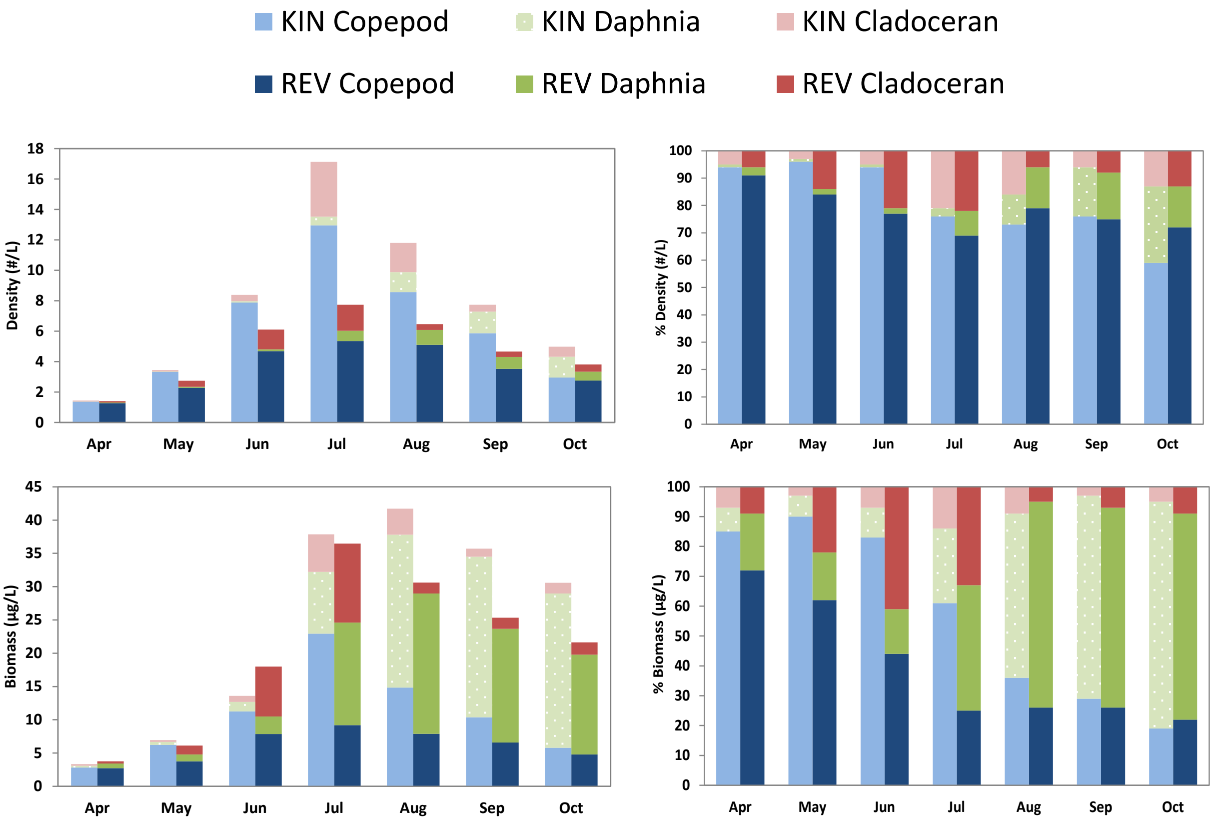


Figure 48. Monthly average zooplankton density and biomass (left) and monthly zooplankton density and biomass percent frequency composition (right) over the study period, 2008-2019. Kinbasket Reservoir data are left side bars and Revelstoke Reservoir data are right side bars.

3.7.2 Density and biomass

Seasonal average May to October zooplankton density over the study period was 9.41 #/L in Kinbasket Reservoir and 5.31 #/L in Revelstoke Reservoir, and seasonal average zooplankton biomass was 28.82 µg/L and 23.50 µg/L, respectively (Table 11). As April sampling was introduced in 2013, those monthly data are not included in the long-term average (Figure 49). Not all months and stations were possible to sample each year; however, only two years are missing two consecutive months for the entire reservoir, one in spring and one in fall which would likely have the effect of lowering the long-term average slightly if those data existed, particularly for the missing spring months as fall months can still have high abundance and biomass. in 2008, sampling began in July therefore the spring months are missing from the long-term average calculation and, in 2013, the two fall months (Sep-Oct) are missing from the Kinbasket dataset.

Since 2011, and except for 2013, average seasonal densities have been at or below the long-term average. The same general trend occurs for biomass although biomass also increased above the long-term average in 2012 in Kinbasket only and in 2016 in both reservoirs (Figure 49).

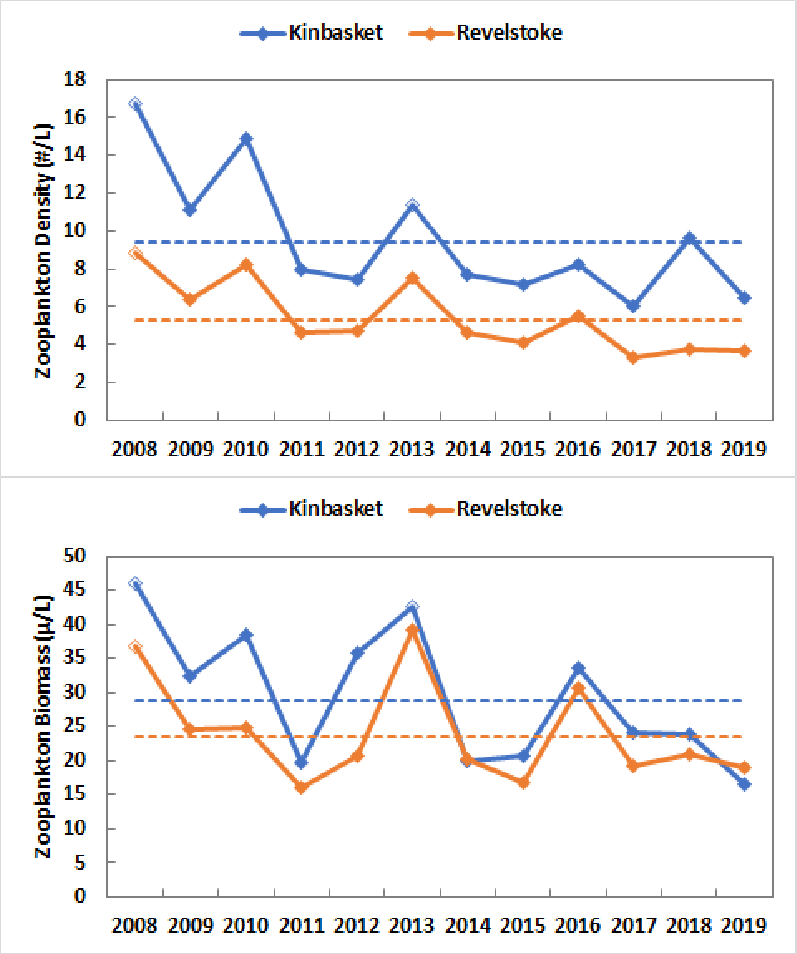


Figure 49. Long term seasonal average (May-Oct) total zooplankton density and biomass. Dashed lines are mean values over all years sampled. Open points indicate two months are missing from the data set which results in a higher value than would occur with full seasonal data.

Density and biomass of zooplankton can be variable as zooplankton are not uniformly distributed in waterbodies although outliers were only occasionally observed in the individual station data. Overall, average May to October total zooplankton density and biomass was greater in Kinbasket Reservoir than in Revelstoke (Kruskal-Wallis Test, p<0.001). *Daphnia* biomass, however, was not significantly different (Kruskal-Wallis Test, p=0.275) between reservoirs and could be reflective of the larger bodied *D. pulex* in Revelstoke contributing more to biomass per individual. There were no significant differences in the zooplankton community between years 2008-2019 except for copepod density in 2010 and 2008. The 2010 copepod density was significantly higher than

2012, 2015 and 2017-2019 and copepod biomass was significantly higher in 2010 than 2012 or 2017 but not significantly different from the other years of the study. In 2008, the difference may be attributable to the lack of spring samples, but there was also an unusually high abundance of *Diacyclops* in the July sample that year that was an outlier especially for biomass. In both 2008 and 2010, some samples had very large counts of *Diacyclops* not seen in other years contributing to the peaks in annual averages (Figure 49), especially so in 2008.

Within Kinbasket Reservoir, there was no significant difference in the average total zooplankton density or biomass among all stations (Kruskal-Wallis, p>0.10), nor any difference in average density or biomass of copepods, *Daphnia*, or other cladocera, (Kruskal-Wallis, p>0.10) suggesting a relatively even distribution of a forage base (Table 11). The morphometry of Revelstoke Reservoir creates a longitudinal gradient from north to south that would influence habitat conditions as the reservoir transitions from a shallow riverine environment highly influenced by Mica GS outflow (REV Upper) to a deeper, more pelagic habitat towards REV Middle and REV Forebay. REV Middle station is subject to a greater influence from the nearby Downie Arm and is typically more turbid. Within Revelstoke Reservoir, REV Upper station density and biomass was lowest (Table 11) and was significantly different than the Middle and Forebay stations in terms of density and biomass (Dwass-Steel-Chritchlow-Fligner Test, p<0.05).

Table 11. Summary of zooplankton metrics by reservoir and station, May to October, 2008-2019.

Station/ Parameter	**Units**	**KIN Forebay**	**KIN Canoe**	**KIN Wood**	**KIN Columbia**	**REV Forebay**	**REV Middle**	**REV Upper**	**KIN Mean**	**REV Mean**
Total Zooplankton										
Density	#/L	10.31	8.94	9.54	8.85	6.03	6.80	3.03	9.41	5.31
Biomass	µg/L	31.07	28.88	28.55	26.77	25.25	31.87	13.03	28.82	23.50
Copepods										
Density	#/L	8.08	7.08	7.76	6.21	4.64	5.08	2.19	7.28	3.99
Biomass	µg/L	14.22	11.72	12.47	11.62	7.57	8.29	4.28	12.51	6.74
Daphnia										
Density	#/L	0.89	0.83	0.77	0.77	0.50	0.81	0.34	0.81	0.55
Biomass	µg/L	13.95	15.00	13.85	12.52	12.39	17.94	6.79	13.83	12.43
Other Cladocera										
Density	#/L	1.34	1.03	1.02	1.87	0.89	0.91	0.51	1.31	0.77
Biomass	µg/L	2.90	2.16	2.23	2.59	5.30	5.64	1.96	2.47	4.33

The availability of *Daphnia* as prey is important for kokanee growth and survival. Kokanee are known to select for large prey items and will preferentially choose *Daphnia* whenever they are available, even when in low abundance (Thompson 1999), although they will not eschew other prey when *Daphnia* are scarce. Scheuerell et al. (2005) found that juvenile Sockeye Salmon (*O. nerka)* in Lake Washington switched to exclusive consumption of *Daphnia* at a density of 0.4 #/L. In Kinbasket Reservoir, this threshold *Daphnia* density was first reached in July for five of the twelve years (2009, 2010, 2013, 2016, 2017), in August for six years (2011, 2012, 2014, 2015, 2018, 2019), and once as late as September (2008). In Revelstoke Reservoir, *Daphnia* first surpassed the 0.4 #/L threshold in July in seven of twelve years (2008, 2012, 2013, 2014, 2015, 2018, 2019), August in three years (2009, 2010,2017), once in September (2011), and once as early as June (2016) (Figure 50). Of note is this early high density of *Daphnia* (and other cladocerans) in May/June 2016 in Revelstoke Reservoir when spring air temperatures were unusually warm (Figure 8) and onset of stratification was particularly early (Table 7). In June 2016, *Daphnia* density in Kinbasket was also higher than average and close to the threshold (0.34 #/L). Daphnia can overwinter either as diapausing ephippia (eggs) on the sediment or as asexual clones in the water column. These overwintering clones can respond more quickly to temperature cues and would be able to quickly take early advantage of a warm spring, benefiting from and early phytoplankton bloom after the relative food scarcity of winter (Rellstab and Spaak 2009).

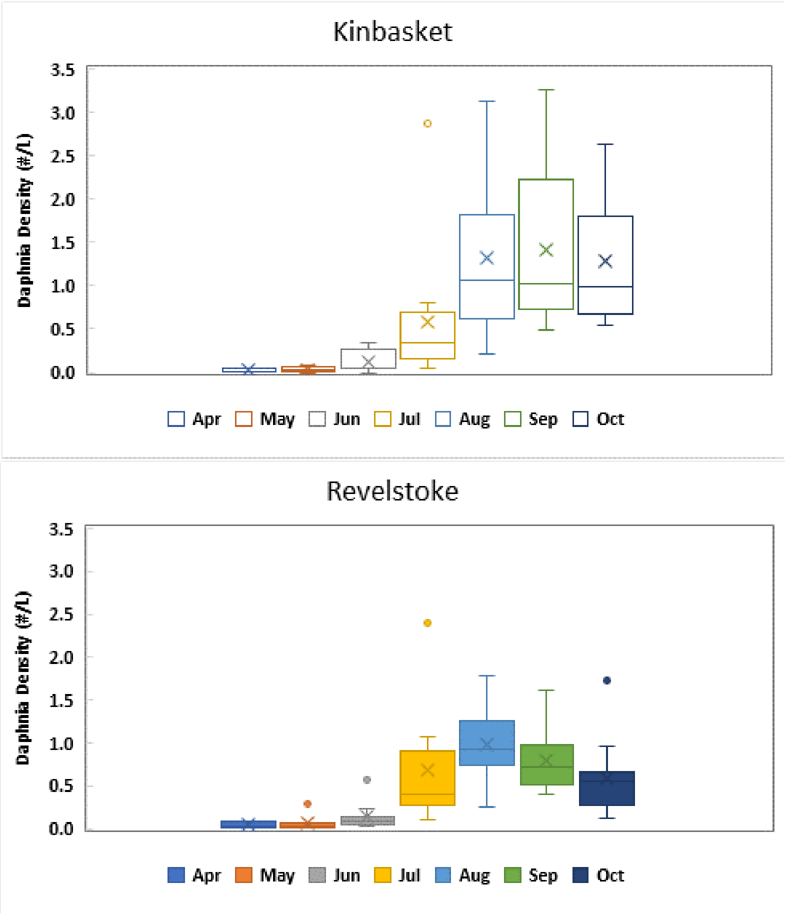
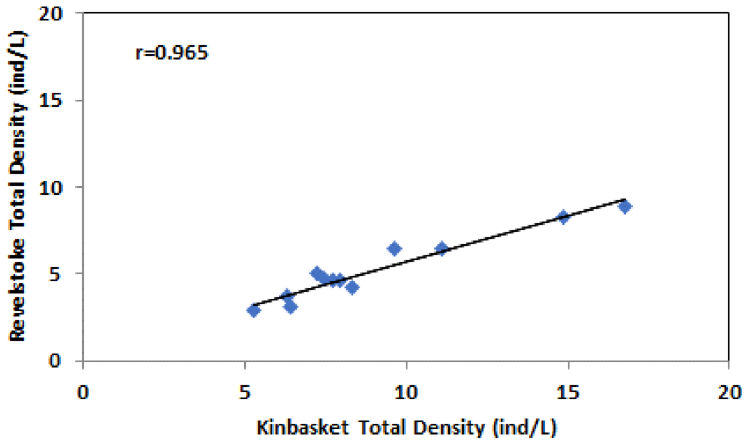


Figure 50. Seasonal *Daphnia* spp. density box plots for Kinbasket and Revelstoke Reservoirs, 2008-2019.

Zooplankton densities across all seasons and summer (Jul-Aug) biomass are most strongly correlated between reservoirs, likely a result of copepods driving density all year and *Daphnia* heavily influencing biomass starting in the summer (Figure 51). As with phytoplankton, this could indicate a similarity of environmental conditions or that Kinbasket is a significant source of Revelstoke zooplankton. That *D. schodleri* is found only in Kinbasket Reservoir and was not once detected in Revelstoke Reservoir could be an indication that Kinbasket is not a significant contributor to the Revelstoke zooplankton community, or that a specific life history characteristic of the species minimises either its entrainment or downstream survival. As *D. schodleri* is regularly found in Arrow Lakes Reservoir the latter may have more to do with its absence from Revelstoke, but the reason is unknown.



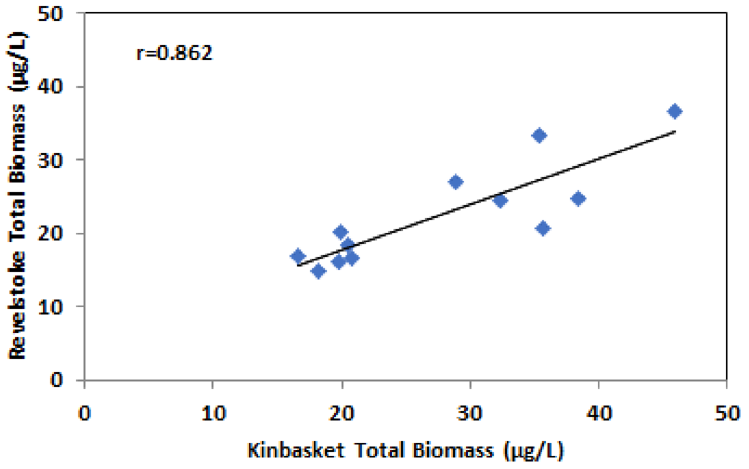


Figure 51. Correlations of seasonal total zooplankton density (#/L) (top) and biomass (µg/L) (bottom) between Kinbasket and Revelstoke Reservoirs, 2008-2019.

3.8 Kokanee

3.8.1 Kokanee habitat

Kokanee prefer pelagic or deep-water habitat commonly defined as areas at least 20 m deep. Pelagic habitat in Kinbasket Reservoir changed substantially with annual and seasonal changes in reservoir level. As the reservoir filled from spring through late summer the pelagic area increased by an average of 13,273 ha (72%)[6]. A substantial portion of the increase, 6,860 ha, was the low gradient habitat at either end of the main reservoir that became filled to a depth of 17 m or greater (zones 1 & 9). These additional habitats described as Upper Canoe and Upper Columbia (Bush Pool) zones have previously been considered marginal for kokanee production since they had to be re-colonized with age 1-3 kokanee every summer as they re-filled and were not originally included in the acoustic surveys. Relatively high pool levels enabled hydroacoustic and gillnet surveys to be undertaken in Bush Pool in 2015; kokanee were observed utilizing the habitat, so Bush Pool was included in annual surveys in subsequent years through to 2019.

In most years, summer hydroacoustic surveys were conducted close to the maximum reservoir elevation for that year. Estimates of pelagic habitat area available to kokanee at annual minimum and maximum pool elevations in Kinbasket Reservoir from 2001-2019 are presented in Appendix 7.1, and a summary of all survey dates, pool elevation and pelagic habitat area for all previous hydroacoustic surveys of Kinbasket Reservoir is provided by Weir (2022).

Revelstoke Reservoir pool elevations remained relatively constant, and the surface area and pelagic habitat area surveyed (zones 1-3) were consistent across years at 9,200 and 7,250 ha, respectively. Zone 4 of Revelstoke has never been included in annual abundance surveys since it is shallow, riverine, and has very little pelagic habitat suitable for kokanee rearing.

3.8.2 Kokanee distribution

For the primary survey area (zones 2-8), the Main Pool and Lower Canoe zones generally supported the highest densities of age 0 kokanee in Kinbasket Reservoir, with the remaining zones supporting lower, but generally similar, densities across the study period (Figure 52a). By phase 3[7] (2017-2019) densities were lower in most zones, in particular at the Forebay, Middle

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[6] Note there is a discrepancy between this estimate and that provided in the Hydrology section 3.1. In the Hydrology section the focus is on surface area as opposed to the area at 17 m depth presented here.

[7] In this section, data are presented in groups of years called phases that correspond with the synthesis reporting intervals over the study period in order to evaluate whether changes in distribution were occurring over time.

Canoe, and Wood Arm zones. Bush Pool fry densities were the lowest (although similar to the Middle Canoe and Wood Arm in phase 3), however, as Bush Pool was surveyed only from 2015-2019, all five years were pooled together but are less comparable to earlier phases due to a general decline in densities across the study period.

Revelstoke age 0 densities were the highest at the Forebay and Lower zones in 2001-2007 and were in a range similar to most Kinbasket zones (Figure 52a). By phase 1, the Forebay zone mean density had declined to less than half the 2001-2007 period, and the Lower and Middle zones had declined as well, although to a lesser degree. Mean densities by zone were very similar between phases 2 and 3 and were substantially lower than phase 1 and the 2001-2007 period for the Lower and Middle zones. The upstream Middle zone had by far the lowest mean densities during each phase.

During the 2001-2007 and phase 1 periods, age 1-3 mean densities were relatively similar in Kinbasket Reservoir across zones (Figure 52b). A declining density trend across all zones was apparent in phase 2 and again in phase 3. Wood Arm maintained generally higher densities in each phase, as did the Middle Columbia in phases 1 and 3. Bush Pool mean densities (2015-2019) were among the lowest but were similar to many zones in phase 3.

Revelstoke age 1-3 densities were substantially lower than Kinbasket (Figure 52b). In the 2001-2007 period, the age 1-3 distribution was very similar to fry distribution with highest densities at the Forebay, slightly less in the Lower zone, and substantially less in the Middle zone. By phase 1, the distribution had shifted, the Middle zone had higher densities than the Forebay zone, and the Lower zone had the greatest densities. In phase 2 and 3 the Lower zone continued to support the highest densities, followed by the Forebay and then the Middle zone.

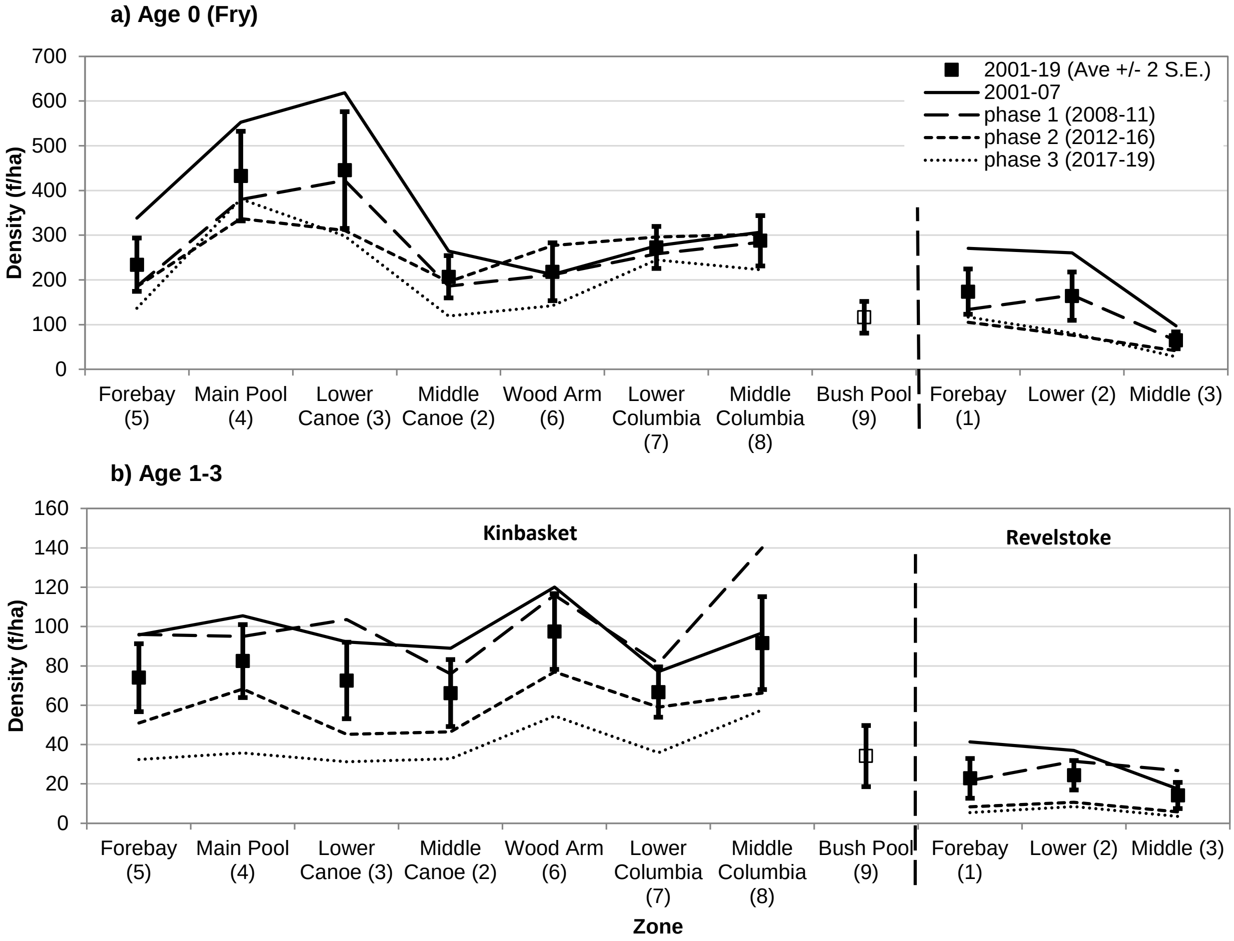

Figure 52. Mean kokanee density (fish/ha) of a) age 0 (fry) and b) age 1-3 kokanee by zone in Kinbasket and Revelstoke Reservoir from 2001-2019 summer acoustic surveys. The Bush Pool means only include 2015-2019 data.

3.8.2. Trends in kokanee abundance

Kinbasket Reservoir age 0 (fry) abundance ranged from 4 to 14 million and averaged 6.6 million for all years in zones 2-8 (Figure 53a). Fry abundances were highest in 2007 and were higher on average prior to 2009. After 2009, fry abundances did not exceed ~8 million. Bush Pool (zone 9) fry abundances ranged from a high of 350,000 in 2015 to a low of 65,000 in 2019.

The age 1-3 fish abundance ranged from 0.6-3.3 million and averaged 1.7 million (Figure 53b). The highest abundance of age 1-3 fish occurred in 2008 following the highest fry abundance on record in 2007. The age 1-3 population declined after 2008 and reached the lowest on record in

2016 at 0.6 million. From 2016 to 2019, age 1-3 abundances remained well below average, although appeared to be trending upwards by 2019.

A large-scale kokanee die-off (likely attributable to disease) was reported in Kinbasket Reservoir in late May 2016 prior to the summer sampling and likely contributed to the dramatic decline in age 1-3 kokanee abundance that year (Sebastian and Weir 2017). This also would have impacted the 2017 age 1-3 population abundance.

Revelstoke Reservoir fry abundance estimates ranged from 0.3 to 2.0 million and averaged 0.9 million (Figure 54a). Fry abundance was highest in 2003 then remained above 1 million though to 2008, another high abundance year with 1.7 million fry. Fry abundance then declined dramatically in 2009, after which they failed to move beyond 1 million through to 2019, and in 2012, 2014, 2016, 2018, and 2019 failed to surpass 0.5 million. There appear to be two distinct eras in the Revelstoke fry abundance time series, where fry abundances averaged 2.5X higher from 2001-2008 compared to 2009-2019.

Revelstoke age 1-3 kokanee abundance ranged from 0.04 to 0.39 million and averaged 0.15 million (Figure 54b). The highest abundance of age 1-3 occurred in 2003, then declined remarkably by nearly four-fold by 2004. The lowest abundance of age 1-3 occurred in 2013, although 2015, 2017, and 2019 were all similarly low. The age 1-3 abundance time series shares similarities with the fry time series where there appear to be two distinct eras: age 1-3 averaged nearly four times higher from 2001-2011 compared to 2012-2019.

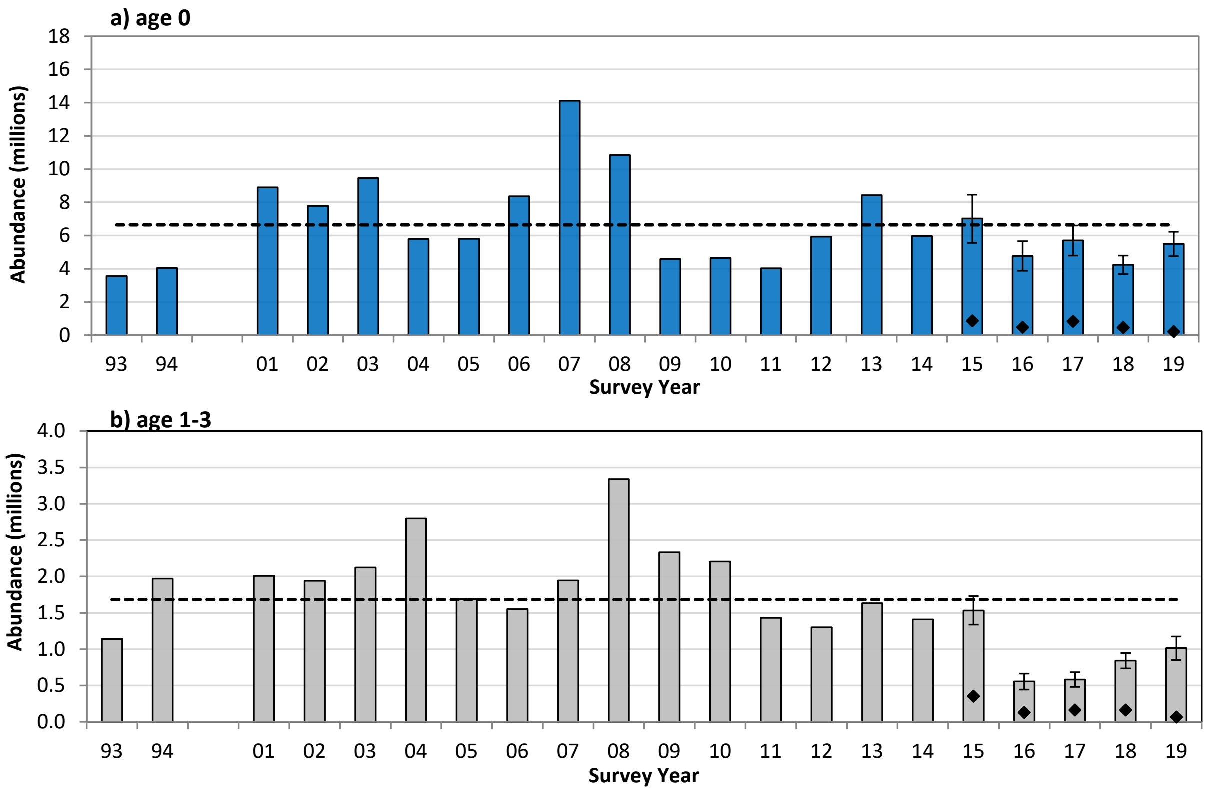

Figure 53. Kinbasket Reservoir kokanee abundance trends for a) age 0 and b) age 1-3 fish based on July/August hydroacoustic surveys. Bars identify abundances for zones 2-8 and error bars denote 95% confidence limits on maximum likelihood estimates[8]. The diamond points identify abundances for zone 9 (Bush Pool). The dashed lines identify the long-term averages (1993-94, 2001-19) for zones 2-8.

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[8] Confidence limits were only calculated back to 2015 following a timeseries review in 2018 related to the process of developing methodology for estimating age specific abundances (Weir 2022).

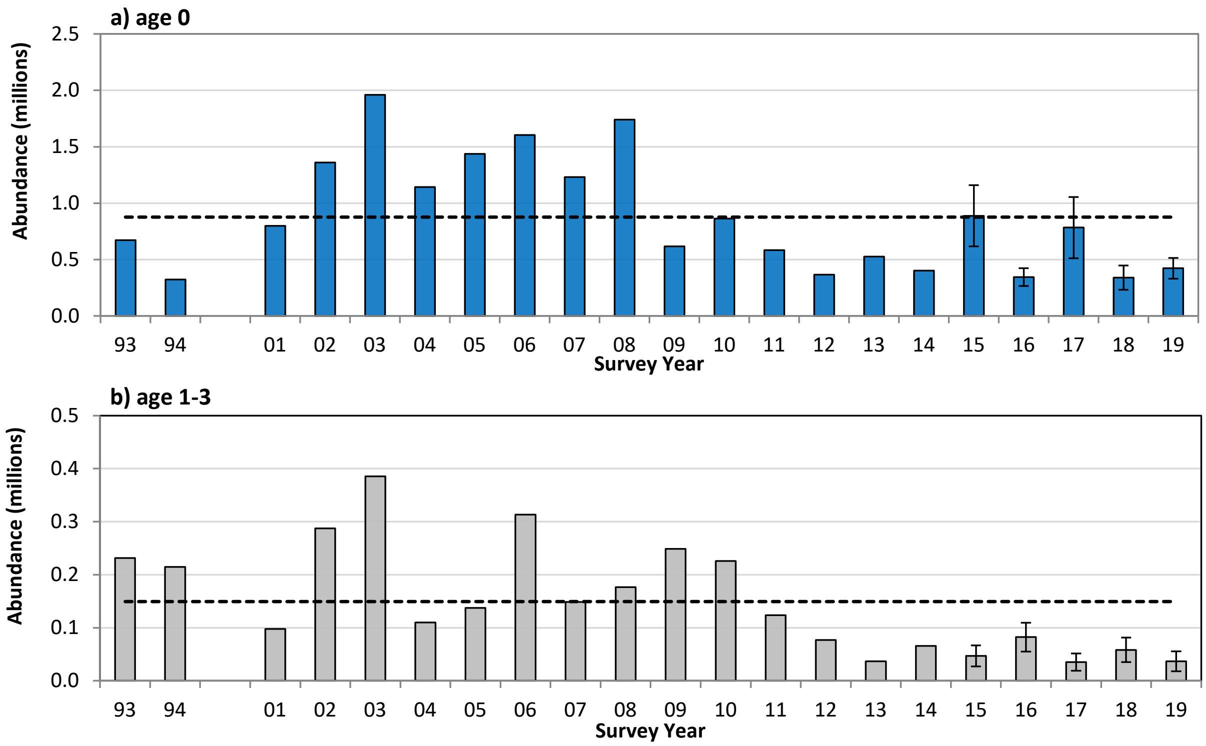

Figure 54. Revelstoke Reservoir kokanee abundance trends for a) age 0 and b) age 1-3 fish based on July/August hydroacoustic surveys. The dashed lines identify the long-term averages (1993-94, 2001-19). Error bars for survey years denote 95% confidence limits on maximum likelihood estimates[8]. Estimates presented include zones 1-3 for all years.

3.8.3 Trawl and gillnet sampling

The historic catch record for all trawl and gillnet sampling that occurred concurrent with hydroacoustic surveys for both Kinbasket and Revelstoke demonstrates that the vast majority of fish present in the pelagic habitat were kokanee (Table 12). After the addition of gillnet sampling (2012 in Revelstoke, 2013 in Kinbasket), a greater variety and proportion of other species were captured, although they remained low relative to kokanee. Bull Trout were the second most common species captured; however, they are expected to be more susceptible to capture by gillnet than kokanee due to their larger size, different body form, and behavioural differences (for example, several Bull Trout were captured in gillnets while attempting to consume kokanee already entangled). Given that kokanee consistently dominated the trawl and gillnet catches, we assumed they represented close to 100% of the fish ensonified at night at depth in pelagic habitat and did not attempt to partition the hydroacoustic data by species.

With very few exceptions, all age 1 kokanee captured were immature in both reservoirs. Of the age 2+ component (age 2 and 3 combined), the average proportion from 2013-2019 maturing to spawn the coming fall for Kinbasket was 81% (SD 7%, range 70-90%) and for Revelstoke was 83% (SD 8%, range 76-94%). The percent mature estimate may over-represent the true proportion given that the maturing fish are generally the oldest and largest and are most vulnerable to the gillnets. Similarly, regardless of maturity, the oldest age classes are assumed to be over-represented given their larger size. This is particularly evident in Revelstoke where age 2 and older fish are exceptionally large relative to age 1 fish, resulting in a cumulative age structure where age 2 fish greatly outnumber age 1 fish (Table 12).

Table 12. Number of fish captured for Kinbasket and Revelstoke Reservoirs from trawl (TR) and mid-water gillnet (GN) sampling. KO=kokanee, BT=Bull Trout, CC=Sculpin, PW=Pygmy Whitefish, RB=Rainbow Trout, SU=Sucker, CBC=Chub, MW=Mountain Whitefish.

	Method	**KO**					**BT**	**CC**	**PW**	**RB**	**SU**	**CBC**	**MW**	**% KO**
		Age 0	**Age 1**	**Age 2**	**Age 3**	**Age 4**								
Kinbasket														
1993	TR	175	25	61	11									100%
2001	TR	114	8	7	1									100%
2002	TR	138		4										100%
2003	TR	470	7	7										100%
2004	TR	2	1	1										100%
2005	TR	63	3	8										100%
2006	TR	173	5	8	4									100%
2008	TR	366	10	10										100%
2009	TR	192	3	6				1						100%
2010	TR	58	9	16	6			1						99%
2011	TR	222	1	4				1						100%
2012	TR	202	3	1										100%
2013	TR, GN	52	40	41	5		2	2						97%
2014	TR, GN	84	54	45	14	1								100%
2015	TR, GN	35	131	65	2		11	1		4	1	1		93%
2016	TR, GN	45	35	24	9		5	3	1					93%
2017	TR, GN	108	76	10			20		1					90%
2018	TR, GN	150	95	70			8			1		1		97%
2019	TR, GN	255	22	63			5			1		1		98%
Revelstoke														
1992	TR	99	2		1									
2004	TR	54												100%
2005	TR	146	1		1		1	1						100%
2006	TR	125		1				1						99%
2007	TR	25	1											99%
2008	TR	154						1						100%
2009	TR	156	3											99%
2010	TR	95	2	1										100%
2011	TR	96												100%
2012	TR, GN	26	4	6	11		3	2						100%
2013	GN		1	47	25	2	4			1	1			90%
2014	GN		9	36	13	5	3							93%
2015	GN		31	21	5		3						3	95%
2016	GN		17	79	16		1						3	90%
2017	GN		12	26	12		5			1			3	97%
2018	GN		24	27	9		7			1			1	85%
2019	GN			22	3		5							87%

3.8.4 Kokanee length at age

Weir (2022) presented mean length at age for all trawl and gillnet caught kokanee for ages 1-3 for both Kinbasket and Revelstoke. For Kinbasket, there were no clear trends in length at age for in-lake kokanee, except for what appeared to be two distinct eras for age 1 which were generally larger on average up to 2012 then remained generally smaller than average from 2013-2019. However, it is difficult to determine if that reflected a real change as sample sizes for age 1 were small most years prior to 2012 (Table 12) and spatial coverage increased in 2013 with the addition of gillnet sampling. For Revelstoke, age 1-3 size data were sparse prior to 2012 and provide minimal insight into long term trends. From 2013 through 2019, age 2 were large and fork length was relatively stable, which is consistent with the relatively constant low densities over that period.

Spawner length at age provides a longer time series for both reservoirs and typically better sample sizes, although collecting spawners in Revelstoke was difficult some years due to low numbers resulting in some limited sample sizes. The complete summary statistics for length by age and tributary are presented in Appendix 7.4 and the annual mean fork length trends are illustrated in Figure 55. Camp Creek provides the longest time series and demonstrates several peaks and valleys of mean length since 2000. For example, lengths consistently peaked just under 280 mm and typically declined to as low as 240 mm, except for 2009 and 2010 when the mean length declined to less than 230 mm. Camp Creek spawners typically return at a larger size than other Kinbasket tributaries, which was previously attributed an older average age at maturity; however, multiple years of data have demonstrated that Camp Creek spawners are also typically larger at a given age than other tributaries (Weir 2022). Camp Creek is unique relative to the other spawning tributaries that are monitored as it is located at the north end of the reservoir compared to the others which flow into the Columbia Reach far to the south.

Spawner sampling has been intermittent for the other Kinbasket tributaries; however, the age structure and size is generally similar among all other tributaries relative to Camp Creek (Appendix 17 in Weir 2022) so they have been pooled in Figure 55. The trend for other tributaries follows the same pattern as Camp Creek and the two datasets are highly correlated ($r=0.9$, $p<0.01$) indicating that where longer time series trend data are of value, Camp Creek data can be used as an index for the entire reservoir. However, where average or annual spawner size data are required to represent the reservoir as a whole, data from any other tributary or the pooled data are better suited than Camp Creek because those spawners make up a very small proportion of Kinbasket spawners [based on relative numbers observed during this study among tributaries, and relative to counts in other tributaries by Oliver (1995)].

Revelstoke spawners were sampled from Standard Creek in 2007 and 2009-2019, a period sufficient to demonstrate substantial variability in mean size (Figure 55). In 2009-2011, Revelstoke spawners averaged less than 270 mm annually, which was larger than most years for Kinbasket spawners but much smaller than the Revelstoke spawners from 2013-2019, which averaged between 310-360 mm annually.

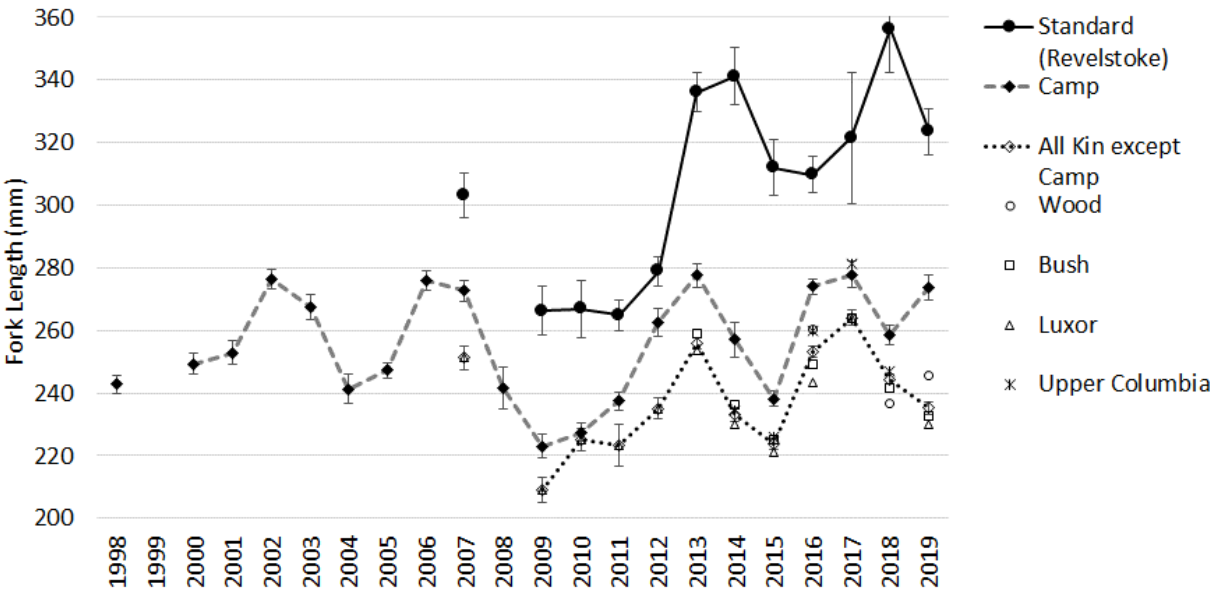

Figure 55. Trends in mean spawner fork length ± 2 S.E. for Kinbasket Reservoir tributaries (Bush, Luxor, Camp, and the Upper Columbia River near Fairmont), and for Revelstoke Reservoir (Standard Creek).

The spawner size trends provide an opportunity to evaluate the effect of spawner density on spawner size. For both Kinbasket and Revelstoke, the expected density dependant growth relationship is apparent (Figure 56). The best fit lines can also be informative in demonstrating relative kokanee productivity between the reservoirs. For example, Figure 55 suggests that Revelstoke may be more productive than Kinbasket (larger spawners at a given density), however, the disparity in density between the two systems, and indication that Revelstoke was functioning below productive carrying capacity (See MQ 2-3), confounds this interpretation.

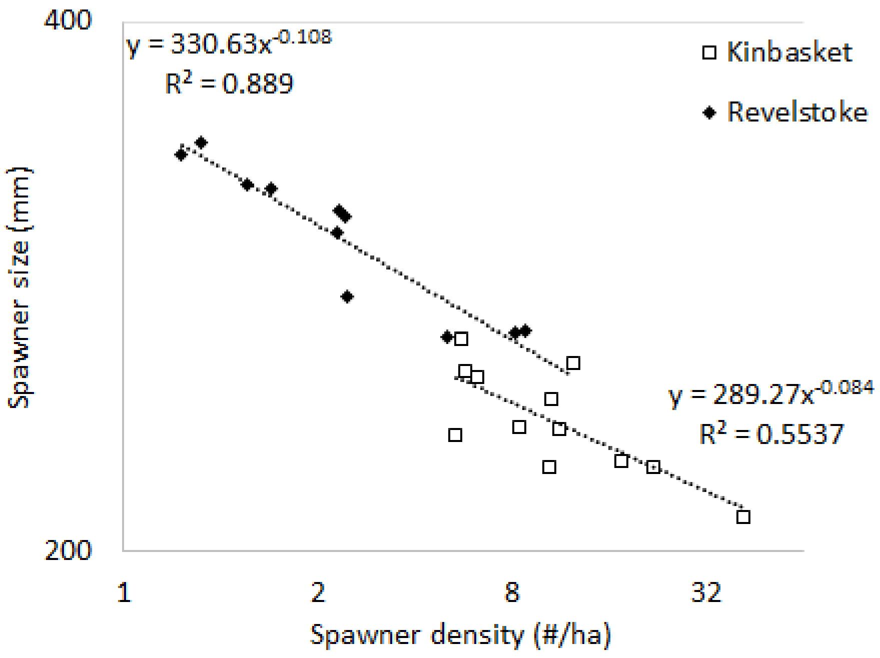

Figure 56. Mean spawner size vs density for Revelstoke (Standard Creek) and Kinbasket (Bush, Wood and Columbia Rivers and Luxor Creek). Spawner density estimates are for the entire reservoir and are derived from the summer hydroacoustic, trawl and gillnet data. The 2018 spawner data for Revelstoke was removed due to small sample size for spawner length (n=9). The spawner data for Kinbasket are the annual average of all data except for Camp Creek.

3.8.5 Trends in kokanee biomass

Kokanee biomass density in Kinbasket Reservoir, based on summer surveys, has ranged from 1.8 to 7.0 kg/ha, and averaged 4.4 kg/ha across all survey years (1993-1994, 2001-2019; Figure 57). Kokanee biomass in Revelstoke Reservoir has ranged from 0.7 to 4.5 kg/ha, and averaged 2.1 kg/ha (1993-1994, 2001-2019; Figure 57), approximately half the biomass measured in Kinbasket Reservoir. Biomass estimates by age groups are presented by Weir (2022).

While Kinbasket Reservoir kokanee biomass density was ~ double that of Revelstoke, the trends exhibited broadly similar patterns over time and the trends from 2001 to 2019 were significantly correlated. A primary feature in both reservoirs was the decline to below average biomass in the latter part of the time series, after ~2012/2013 in Revelstoke and 2014 in Kinbasket.

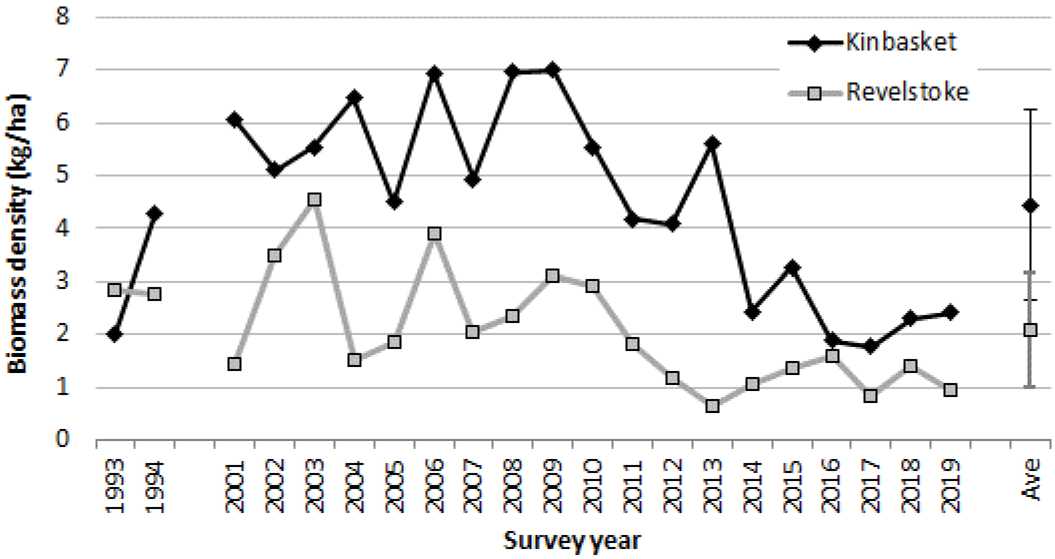

Figure 57. Trends in biomass density (kg/ha) for Kinbasket and Revelstoke reservoirs based on summer hydroacoustic surveys. Error bars on the long-term average represent ± 1 standard deviation.

3.8.6 Spawner abundance and egg deposition

The reservoir-wide spawner abundance estimates for Kinbasket has ranged from 128,000 to 982,000 and averaged 359,000 across all survey years (1993-1994, 2001-2019; Figure 58, Appendix 7.2). Revelstoke spawner abundance estimates ranged from 6,000 to 89,000 and averaged 28,000 (Figure 58, Appendix 7.3). Spawner abundances were higher on average for both reservoirs up to ~2011, after which they remained lower and below the long-term average, particularly for Revelstoke.

Basin-wide egg deposition averaged 57 million and ranged from 22 to 123 million from 2001-2019 in Kinbasket (Appendix 7.2). In Revelstoke, egg deposition averaged 8 million and ranged from 3 to 19 million (Appendix 7.3).

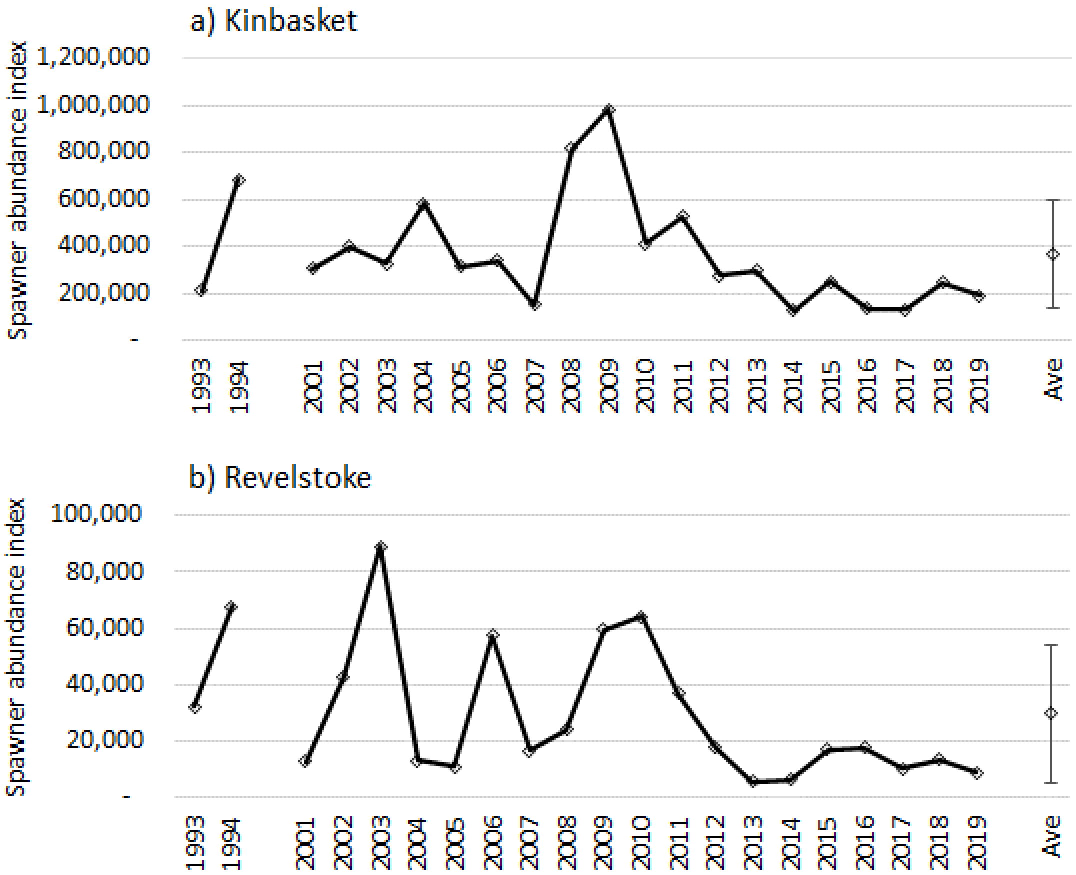

Figure 58. Kokanee spawner index trends for Kinbasket and Revelstoke Reservoirs. Estimates are derived from summer acoustic and gillnet data.

3.8.7 Kokanee survival

Egg to fry survival trends in Kinbasket and Revelstoke Reservoirs were remarkably similar, both averaged 14% and the range from 2001-2019 was 4 to 34% and 4 to 36%, respectively. From 2001-2006, the trends did not correlate but from 2007-2018 they were highly correlated (not shown; r=0.89) (Figure 59).

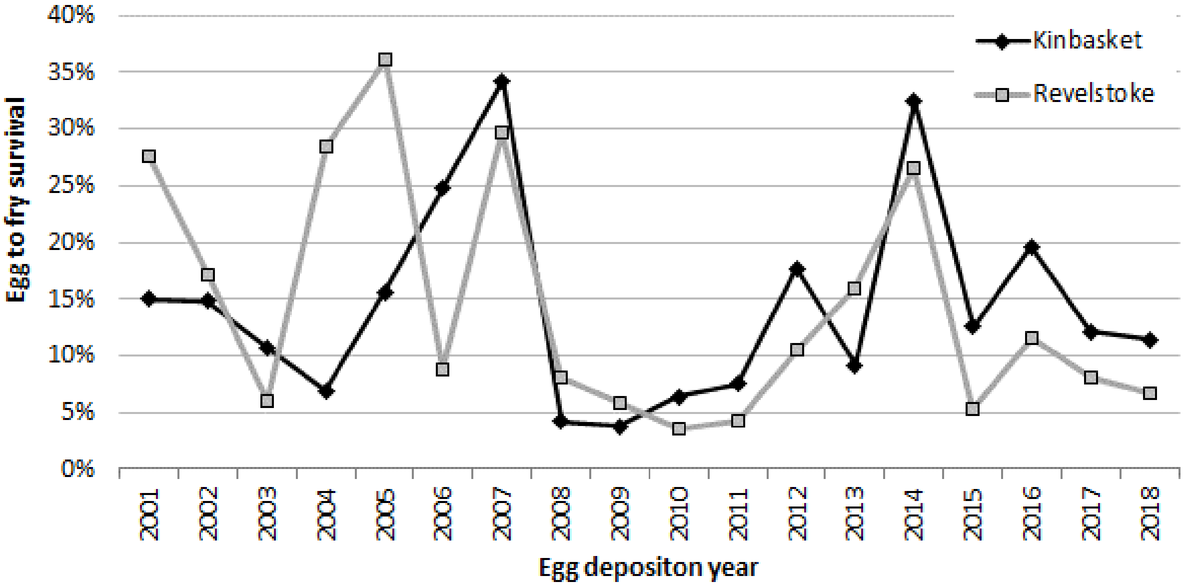

Figure 59. Trends in egg to fry survival indices for Kinbasket and Revelstoke reservoirs. Survival period spans from egg deposition to the following summer.

All possible subset multiple regression analysis was conducted to evaluate factors affecting egg to fry survival for Kinbasket and Revelstoke. Arrow Reservoir kokanee data were also included to strengthen insight into regional drivers (i.e., air temp/flow). See Table 3 for a description of variables and rationale for inclusion. The top model included indicator variables for the individual reservoirs, Sept 1-30 mean flow (Columbia R. at Donald), mean February air temperature, and spawner size and egg deposition (i.e., density). There were, however, additional models that were a close fit (Table 13).

Table 13. Top models for egg to fry survival for Kinbasket, Revelstoke, and Arrow Reservoirs (delta AIC <3) from model selection. Abbreviations are described in Table 3.

AICc	Delta AICc	Weight	Terms
-70.9	0.0	0.142	Flow.Sept.1.30 + AirT.Feb + SS.s + ED.s + ReK + ReR
-69.1	1.8	0.059	Flow.Sept.1.30 + AirT.Feb + AirT.Mar + SS.s + ED.s + ReK + ReR
-68.5	2.4	0.044	Flow.Sept.1.30 + AirT.Sept + AirT.Feb + SS.s + ED.s + ReK + ReR
-68.2	2.7	0.037	Flow.Sept.1.30 + AirT.Feb + AirT.coldest + SS.s + ED.s + ReK + ReR
-68.1	2.7	0.036	Flow.Sept.1.30 + PeakDailyFlow.Sept.1.30 + AirT.Feb + SS.s + ED.s + ReK + ReR
-68.0	2.9	0.034	Flow.Sept.1.30 + AirT.Jan + AirT.Feb + SS.s + ED.s + ReK + ReR
-68.0	2.9	0.034	Flow.Sept.1.30 + AirT.Dec + AirT.Feb + SS.s + ED.s + ReK + ReR

The model weights were diffuse, so the variable importance was considered. Using a variable importance threshold of 0.8, egg deposition, February air temperature, and spawner size were all important (Figure 60). These variables were fit with a regression model, demonstrating a good fit (R^2=0.62, p=<0.01; Figure 61).

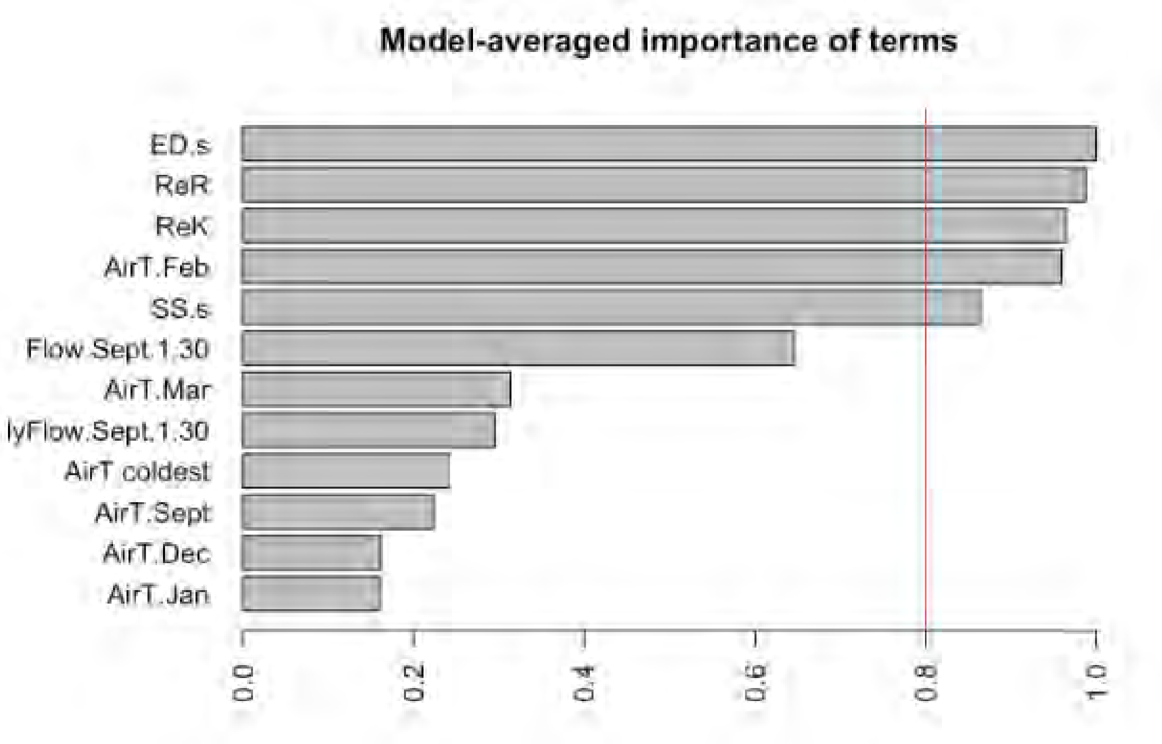

Figure 60. Model-averaged importance of terms affecting egg to fry survival in Kinbasket, Revelstoke, and Arrow Reservoirs. Abbreviations are described in Table 3.

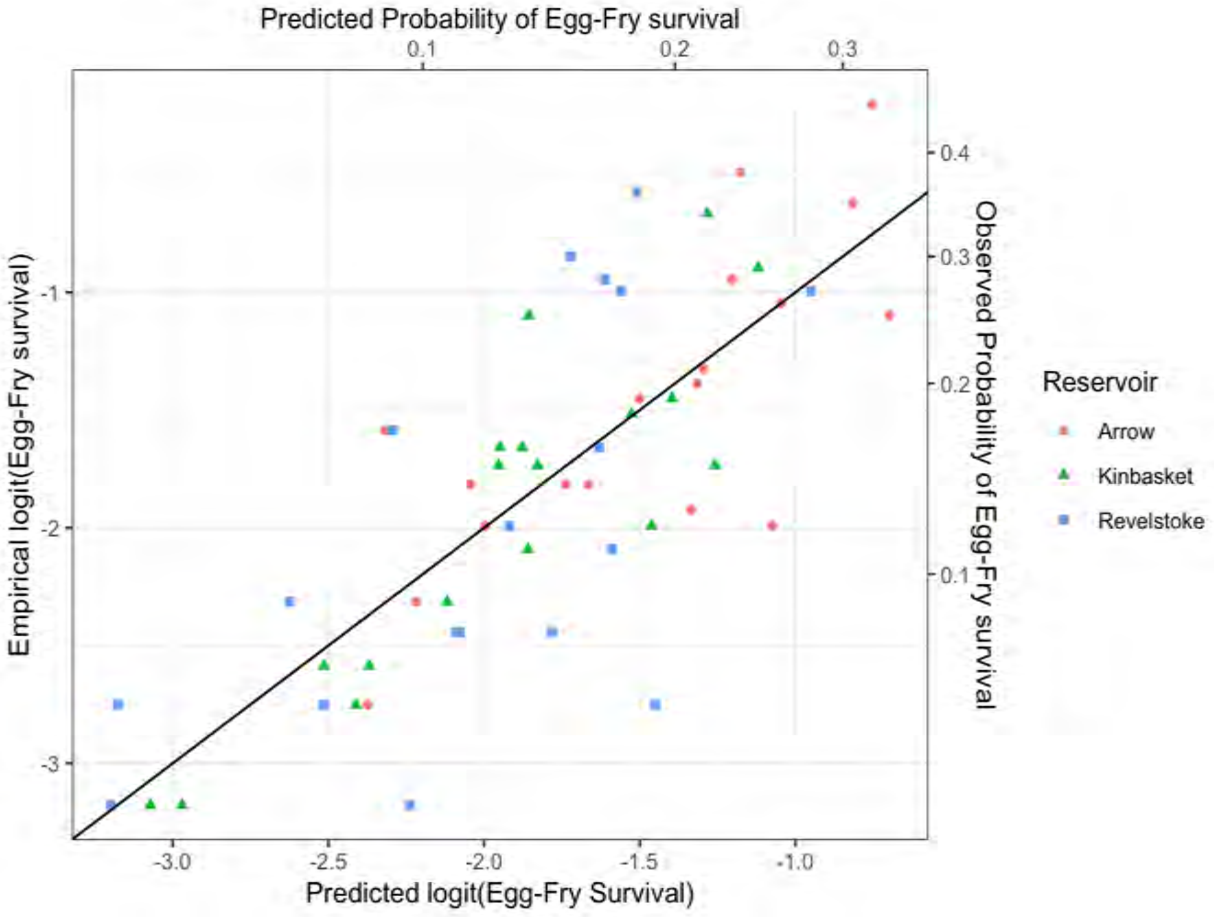

Figure 61. Plot of actual vs predicted kokanee egg to fry survival for Kinbasket, Revelstoke, and Arrow Reservoirs.

Age 0-1 kokanee in-lake survival from 2001-2019 averaged 18% for Kinbasket compared to only 12% for Revelstoke (Figure 62). In only 2 of 18 years was age 0-1 survival lower in Kinbasket than Revelstoke, 2002 and 2016. In 2016, the cause of the exceptionally low survival in Kinbasket was thought to be related to the large-scale mortality event observed over a protracted period in May of that year (Sebastian and Weir, 2017). Age 0-1 survival trends between reservoirs showed some correlation (r=0.43, p=0.08), however the 2010 data point leveraged the relationship substantially.

In comparison to age 0-1 survival, cohort survival from age 1 to age 2+[9] was on average more similar between Kinbasket and Revelstoke at 35% and 33%, respectively. Variability was substantial for both reservoirs, with no clear trends over time.

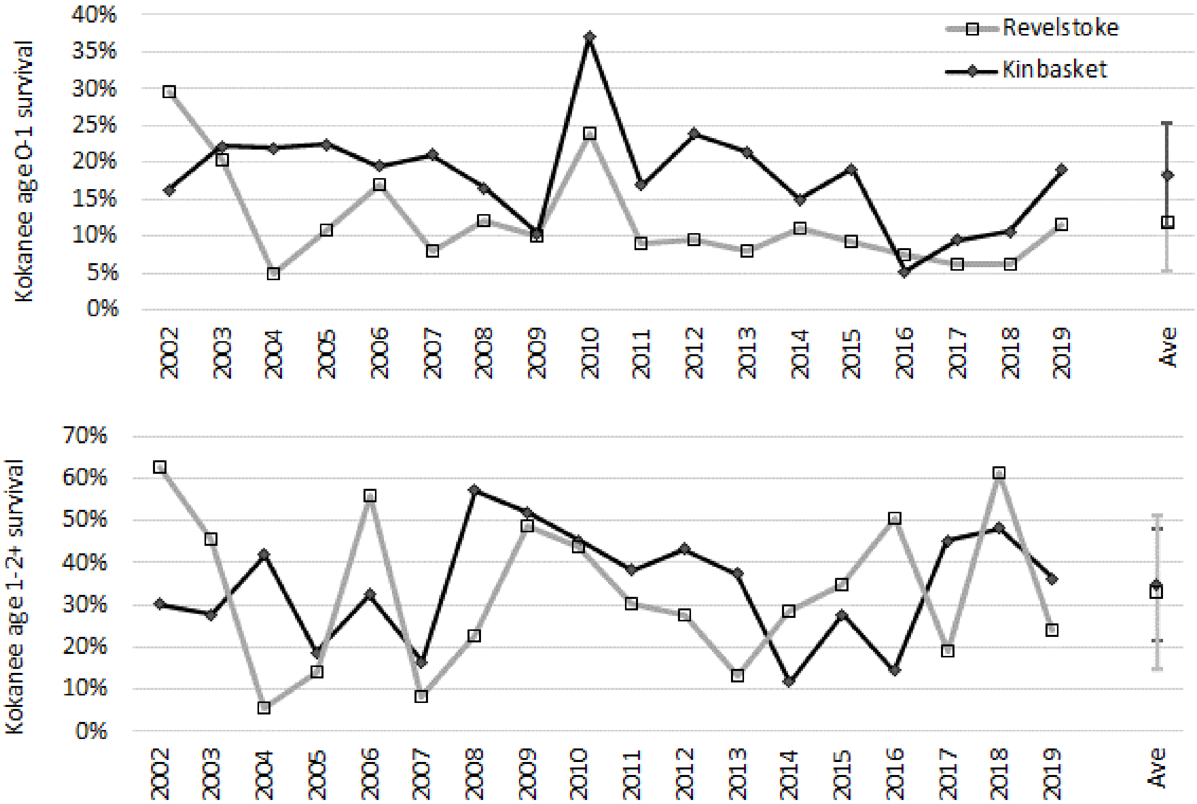

Figure 62. Trends in kokanee cohort survival between mid-summer acoustic surveys for Kinbasket Reservoir and Revelstoke Reservoirs from age 0 to age 1 and age 1 to 2+. The values are labelled by the latter year as each value includes data from two consecutive years. The age 2+ group includes age 2 and older fish[9].

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[9] Estimating survival from age 1 to age 2 may be confounded by an inability to partition age 2 and older kokanee into age specific estimates. They are still expected to broadly represent the trends in age 1 survival, though should be interpreted with some caution (see Methods section 2.4.9 – Survival).

All possible subset multiple regression analysis was conducted to evaluate factors affecting in-lake survival for age 0-1 in Kinbasket, Revelstoke, and Arrow Reservoirs. See Table 4 for a description of variables and rationale for inclusion. Two sets of model fits were performed: (1) all reservoirs were combined for a single combined reservoir model (34 observations: Arrow=16, Kinbasket=8, Revelstoke=10) and then (2) a separate model was fit for each reservoir (17 observations for Kinbasket and Arrow, 18 for Revelstoke).

3.8.8 Combined reservoir analysis

The top model included indicator variables for the individual reservoirs, January to March air temperature, and annual outflow, however, there were additional models that were a close fit. The top models are provided in Table 14.

Table 14. Top six models for Kinbasket, Revelstoke and Arrow reservoirs age 0-1 survival (delta AIC <3) from model selection. Abbreviations are described in Table 4.

AICc	**Delta AICc**	**Weight**	**Terms**
37.3	0	0.020	Air.T_Jan_Mar + Outflow_Ann + Reservoir
38.1	0.8	0.013	Air.T_Jan_Mar + Outflow_Ann + Air.T_Apr_June + Reservoir
38.4	1.1	0.011	Air.T_Jan_Mar + Outflow_Ann + Outflow_Win + Reservoir
38.9	1.6	0.009	Air.T_Jan_Mar + Outflow_Ann + Den0 + Reservoir
39.0	1.7	0.009	Air.T_Jan_Mar + Outflow_Ann + ZooB_Jun + Reservoir
39.0	1.7	0.009	Air.T_Jan_Mar + Outflow_Ann + Cope_May + Den0 + ZooB_May

The model weights were diffuse, so the variable importance was considered. Using a variable importance threshold of 0.8, Jan-March air temperature, annual outflow, and reservoir effect were all important (Figure 63). Finally, these variables were fit with a regression model, demonstrating a good fit (R^2=0.70 p=<0.01; Figure 64).

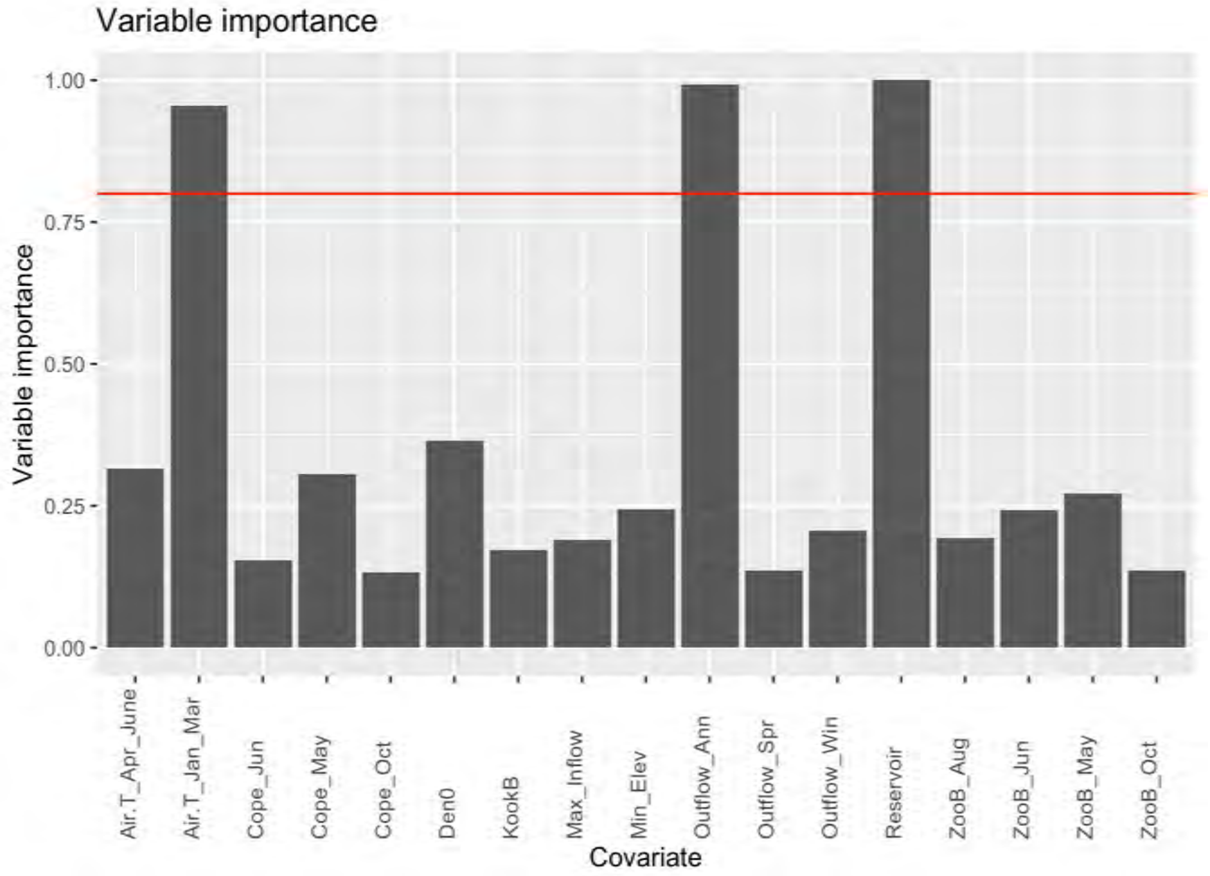

Figure 63. Model-averaged importance of terms affecting age 0-1 kokanee survival in the combined model for Kinbasket, Revelstoke, and Arrow Reservoirs. See Table 4 for description of abbreviations.

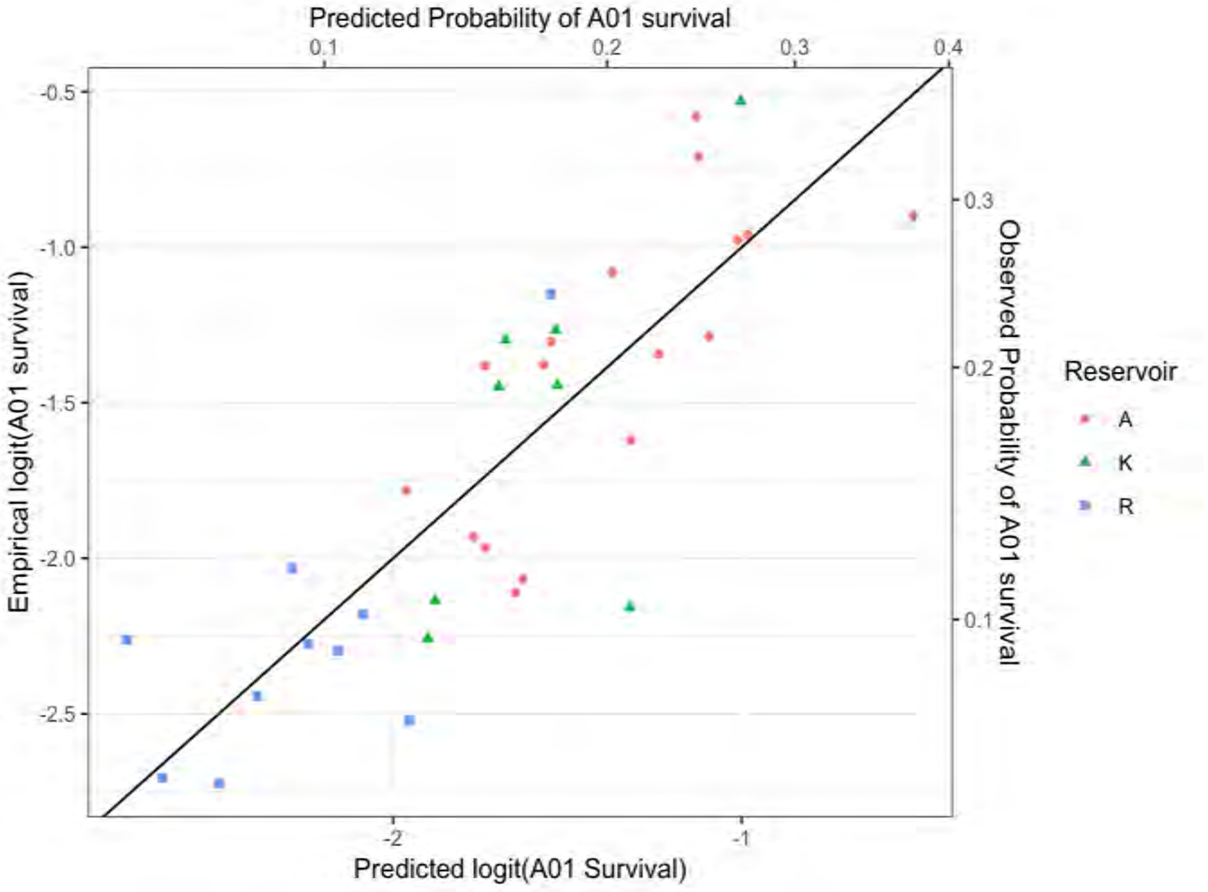

Figure 64. Plot of actual vs predicted kokanee age 0-1 survival for the combined reservoir analysis including Kinbasket (K), Revelstoke (R) and Arrow (A) Reservoirs.

3.8.9 Separate reservoir analyses

The top model for Kinbasket included indicator variables for January-March air temperature, age 0 density, kokanee total biomass, and minimum reservoir elevation; however, there were additional models that were a close fit (Table 15).

Table 15. Top models for Kinbasket Reservoir age 0-1 kokanee survival (delta AIC <3) from model selection. Abbreviations are described in Table 4.

AICc	Delta AICc	Weight	Terms
12.3	0	0.1556	Air.T_Jan_Mar + Den0 + KookB + Min_Elev
13.4	1.1	0.0896	Air.T_Jan_Mar + Outflow_Ann + Outflow_Win
14.1	1.8	0.0633	Air.T_Jan_Mar + Min_Elev
15.1	2.8	0.0377	Air.T_Jan_Mar + Den0 + KookB + Min_Elev + Outflow_Spr
15.2	2.9	0.0369	Air.T_Jan_Mar + KookB + Min_Elev
15.2	2.9	0.0364	Air.T_Jan_Mar

The model weights were diffuse, so the variable importance was considered. Using a variable importance threshold of 0.8, only Jan-March air temperature was deemed important, with minimum elevation a distant second at just over 0.5 (Figure 65).

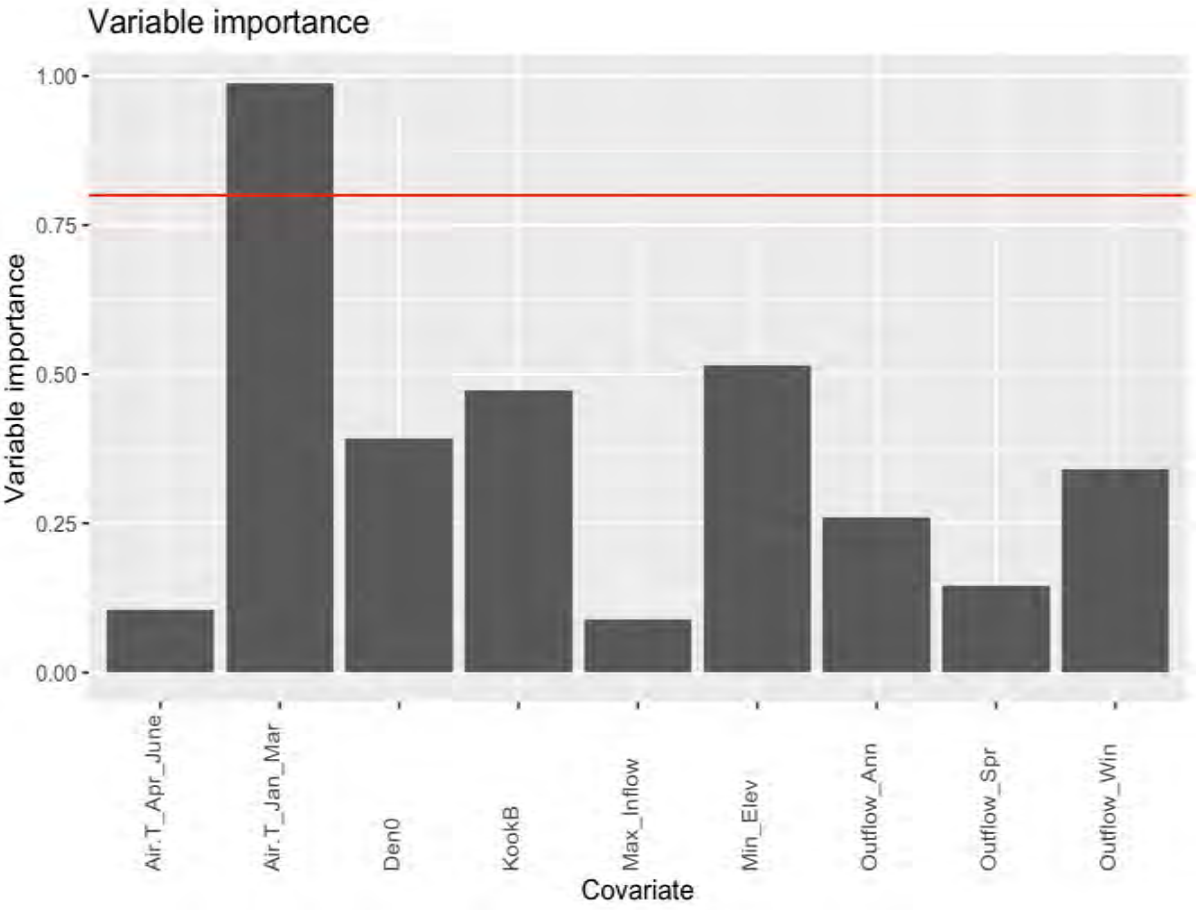

Figure 65. Model-averaged importance of terms affecting age 0-1 kokanee survival in Kinbasket Reservoir. See Table 4 for description of abbreviations.

The top model for Revelstoke included indicator variables for April-June air temperature and winter outflow; however, there were additional models that were a close fit (Table 16).

Table 16. Top models for Revelstoke Reservoir age 0-1 kokanee survival (delta AIC <3) from model selection. Abbreviations are described in Table 4.

AICc	Delta AICc	Weight	Terms
28.7	0.00	0.0889	Air.T_Apr_June + Outflow_Win
30.3	1.6	0.0406	Air.T_Apr_June + Air.T_Jan_Mar + Outflow_Win
30.5	1.8	0.0355	Air.T_Apr_June + Air.T_Jan_Mar + Outflow_Ann
30.6	1.9	0.0342	Air.T_Apr_June + Outflow_Spr + Outflow_Win
30.7	2.0	0.0321	Air.T_Apr_June + Air.T_Jan_Mar + KookB + Outflow_Win
31.1	2.4	0.0270	Outflow_Ann
31.2	2.5	0.0255	Air.T_Apr_June + Den0 + Outflow_Win
31.6	2.9	0.0207	Air.T_Apr_June + Outflow_Ann + Outflow_Win
31.7	3.0	0.0203	Air.T_Apr_June + Air.T_Jan_Mar + Outflow_Spr + Outflow_Win

The model weights were diffuse, so the variable importance was considered. Using a variable importance threshold of 0.8, none of the variables were deemed important. April-June air temperature was close to the threshold at just over 0.7, followed by Jan-March outflow at 0.6 (Figure 66).

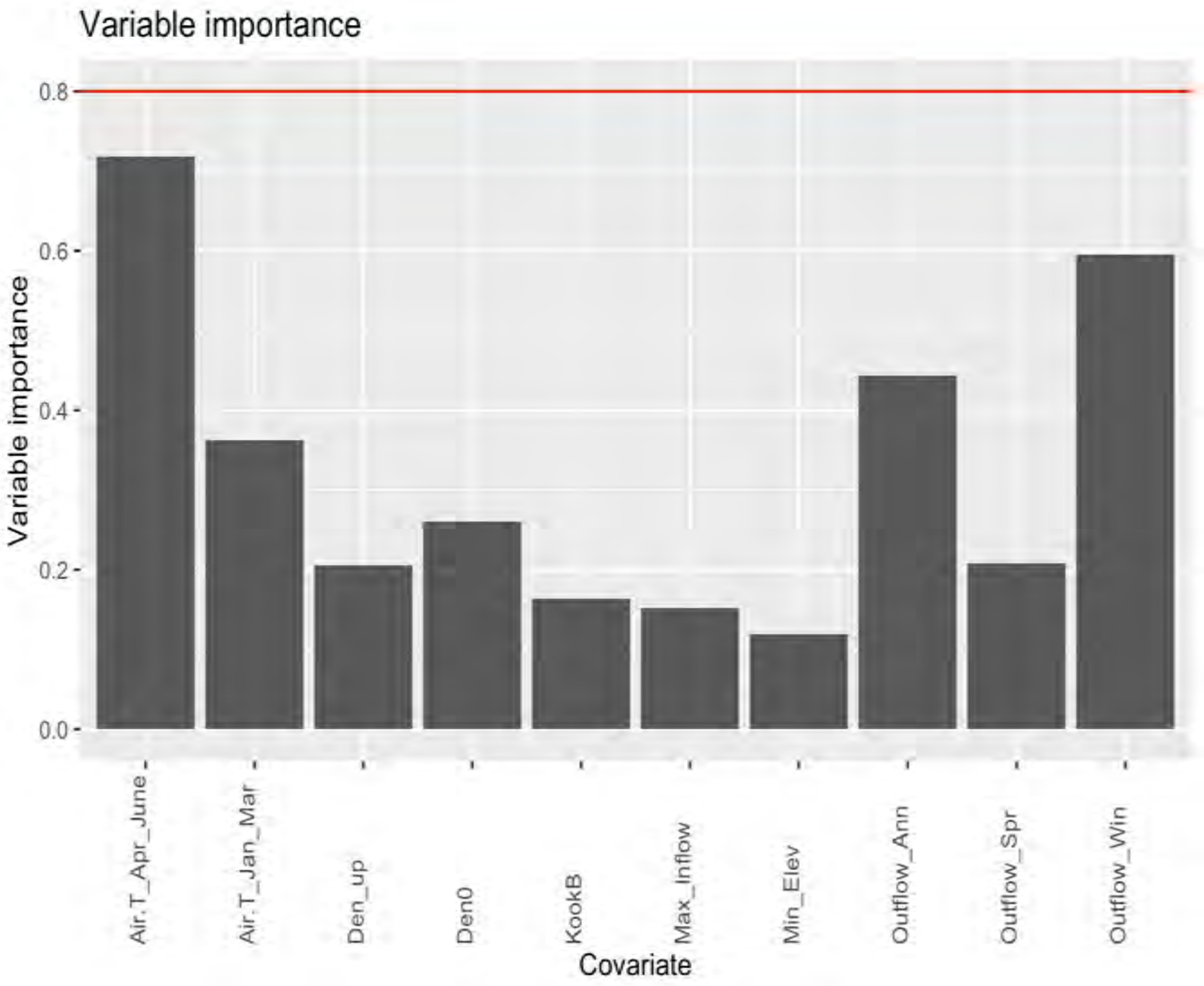

Figure 66. Model-averaged importance of terms affecting age 0-1 kokanee survival in Revelstoke Reservoir. See Table 4 for description of abbreviations.

The top model for Arrow included indicator variables for April-June air temperature, maximum inflow, outflow (Annual & Winter), and October total zooplankton biomass; however, there were additional models that were a close fit (Table 17).

Table 17. Top models for Arrow Reservoir age 0-1 kokanee survival (delta AIC <3) from model selection. Abbreviations are described in Table 4.

AICc	**Delta AICc**	**Weight**	**Terms**
11.4	0	0.1089	Air.T_Apr_June + Max_Inflow + Outflow_Ann + Outflow_Win + ZooB_Oct
12.2	0.8	0.0717	Max_Inflow + Outflow_Ann
13.2	1.8	0.0433	Max_Inflow + Outflow_Ann + Outflow_Win
13.3	1.9	0.0421	Max_Inflow + Outflow_Ann + Outflow_Win + ZooB_Oct
14.2	2.9	0.0261	Cope_Oct + Max_Inflow + Outflow_Ann

The model weights were diffuse, so the variable importance was considered. Using a variable importance threshold of 0.8, annual outflow and maximum inflow were deemed important (Figure 67). Arrow was the only reservoir where zooplankton variables were included, however none were deemed important.

These variables of importance were fit with a regression model for each reservoir demonstrating a reasonable fit for Kinbasket (R^2=0.46, p=<0.01) and Arrow (R^2=0.71, p=<0.01) (Figure 68). The Revelstoke model failed to identify any variables of importance that passed the threshold of 0.8 so no regression was fitted.

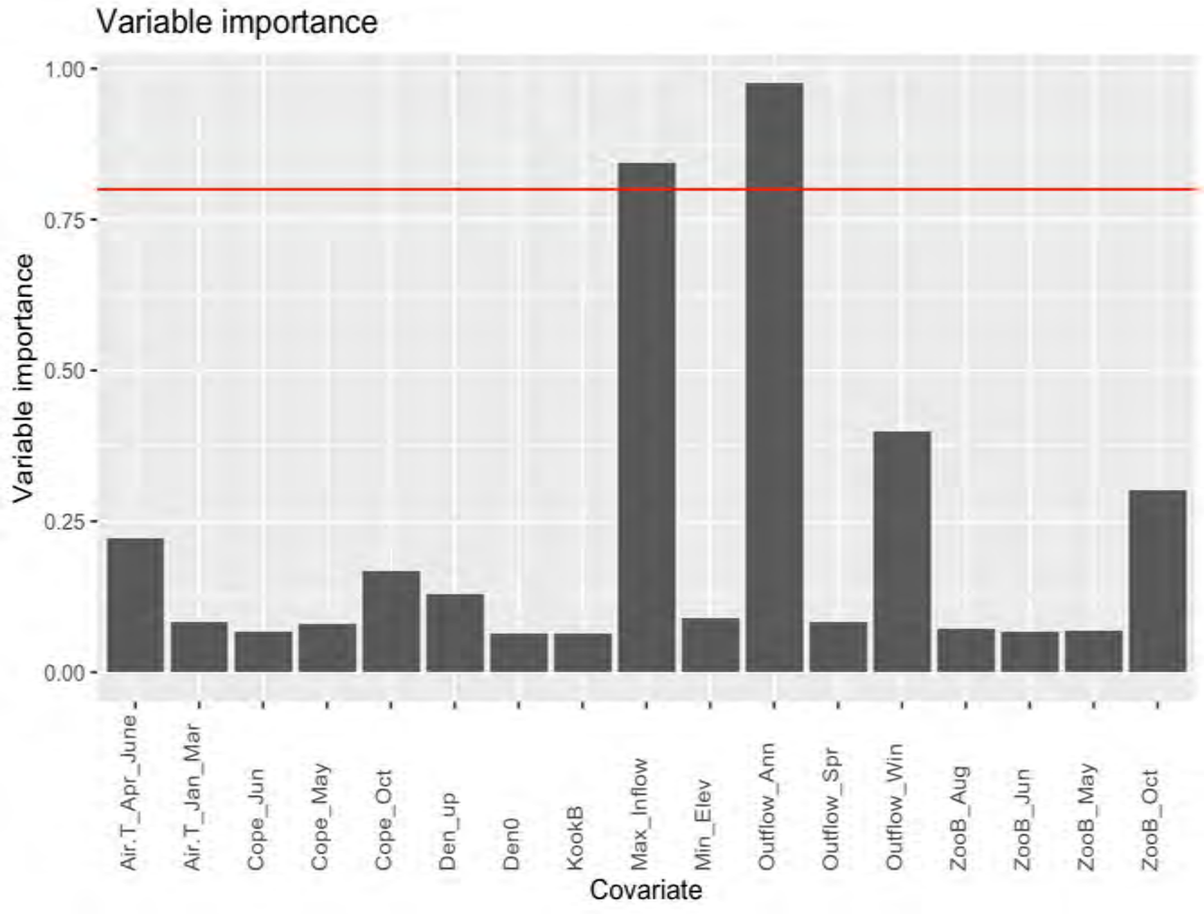

Figure 67. Model-averaged importance of terms affecting age 0-1 kokanee survival in Arrow Reservoir. See Table 4 for description of abbreviations.

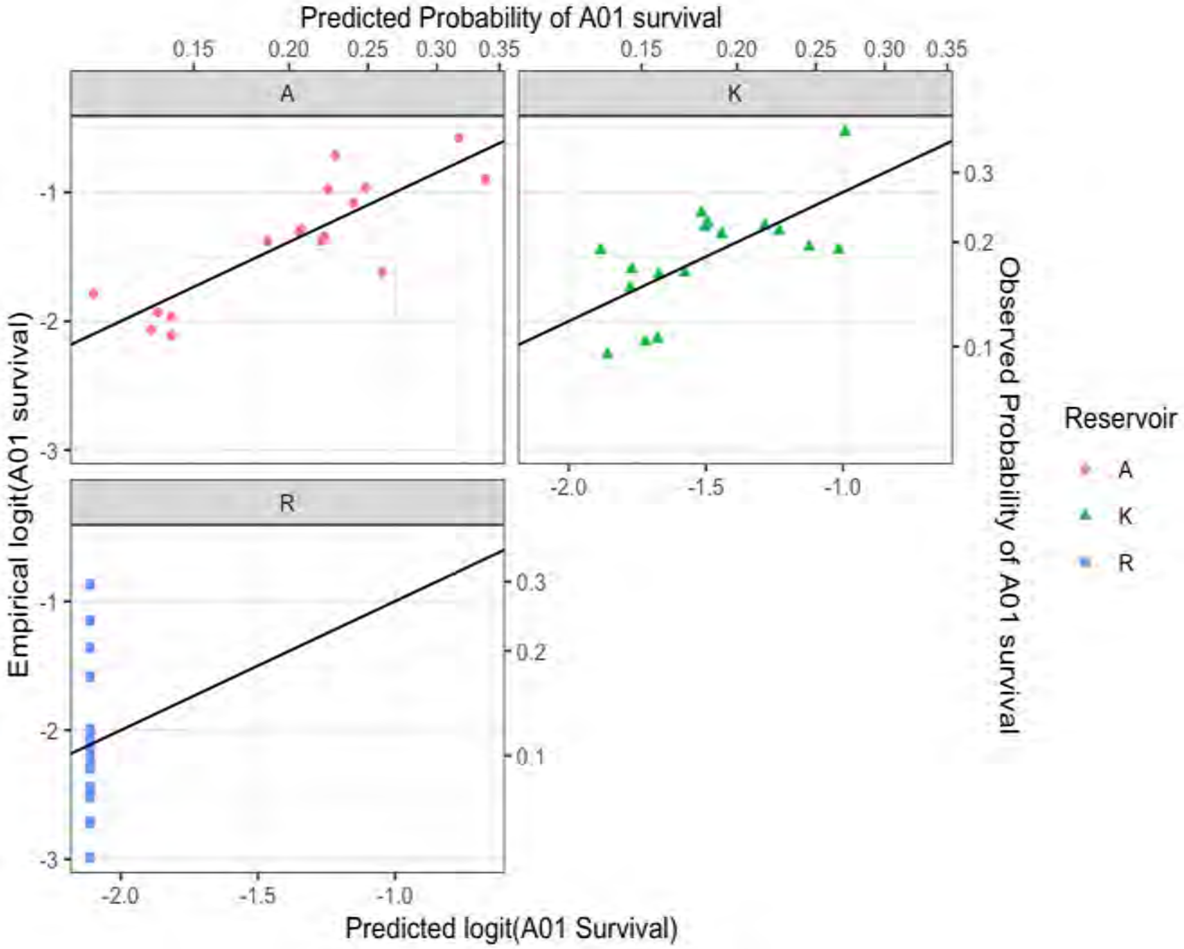

Figure 68. Plot of actual vs predicted kokanee age 0-1 survival for Kinbasket (K), Revelstoke (R) and Arrow (A) Reservoirs.

4.0 Discussion

This section is focused on addressing the management questions (MQ) presented in an order best suited to the overall discussion and not sequentially as per the TOR. We begin by presenting an introductory synthesis of physical limnology findings for Kinbasket and Revelstoke Reservoirs, followed by MQs related to identifying or describing trends and interactions among trophic levels, then those MQs involving analyses of productivity metrics with environmental variables, including reservoir operation, and concluding with an evaluation of potential reservoir operational changes and implications to pelagic production. For a summary of the MQs and related hypotheses from the Terms of Reference see the table in the Executive Summary.

This monitoring program represents the longest and most comprehensive time series available to date for Kinbasket and Revelstoke Reservoirs and is a significant contribution to the scientific information available for pelagic productivity of these waterbodies. The long-term study of Kinbasket and Revelstoke Reservoirs also adds significantly to the data available for understanding other British Columbia lakes and reservoirs, especially Arrow Lakes Reservoir. Despite this long-term data set, the time series still represents a snapshot in time in the context of the four-year life cycle of kokanee salmon as well the wide range of infrastructure and operational changes and the extremely variable meteorological and hydrological conditions observed during our study years.

4.1 Physical Limnology of Kinbasket and Revelstoke Reservoirs

Circulation patterns during the productive season

Summer temperature stratification provides the favoured conditions for algal productivity of warmth, light, and nutrients. The warming of the near surface water allows algae (and zooplankton) to grow more rapidly. Light is required for photosynthesis; light is gradually extinguished with depth until photosynthesis declines below the respiratory needs of the cells, around the 1% light level. This depth defines the bottom of the photic zone, below which net growth does not occur.

There is a store of nutrients in the near surface water in spring which provides the initial resources for growth. Some of these nutrients are sequestered by biological activity, while some are recycled within the near surface waters. However, continued growth requires an ongoing supply of additional nutrients. Kinbasket and Revelstoke Reservoir are large flow-through systems, and the focus of this section is to discuss how these high inflows might replenish nutrients in the atypical stratification (Section 3.2.2) observed in these systems.

As discussed later, we were not able to resolve the low levels of the key nutrient phosphorus (see MQ 3-1). We were not able to determine, for example, whether one tributary provides more or less biologically available phosphorus than another. In this discussion we assumed that all tributaries provide, however small, the same relative supply of biologically available phosphorus.

We begin by summarizing the main process in spring, summer, and fall, then examine how these processes play out in Kinbasket Reservoir and Revelstoke Reservoirs, followed by a summary.

Spring, summer, and fall processes

In spring, the tributaries warm rapidly and the temperature of the tributaries rise above the temperature of maximum density, 4 °C, earlier than that in the reservoirs. When the inflow (> 4 °C) mixes with water in the reservoir (< 4 °C), the mixture formed has a temperature closer to 4 °C, and as a result the mixture is denser and sinks (Figure 69a). The boundary of sinking water creates a front with convergence near the surface and is known as a riverine thermal bar (Carmack 2012). The water will sink until it is arrested by a halocline (salinity gradient) as illustrated in Figure 69a (as occurs in the deepest parts of Kinbasket Reservoir) or until it reaches the bottom (as occurs in Revelstoke Reservoir). The sinking plume transports heat to depth, contributing to deep lake warming. As inflow continues, the thermal bar moves away from the shore, and the center of lakes and reservoirs are typically the last areas to reach 4 °C. The beginning of thermal stratification occurs on the shore side of the thermal bar; both the thermal stratification and warmer temperature promotes plankton growth (Holland and Kay 2003). The progress of the thermal bar along Revelstoke Reservoir is shown in Figure 17.

Once the reservoir is above 4 °C, there is a period when the tributaries remain warmer than the reservoir, and the warmer, more buoyant inflow forms an overflow (Figure 69b). Namely, the tributary inflow spreads over the surface of the reservoir, and wind will begin to mix it with the water below. This is the start of permanent summer stratification where phytoplankton can enjoy warming temperature, along with light and nutrients.

The reservoir temperature soon rises to be greater than the temperature of the tributaries. In this case the tributary inflow is denser than the surface of the reservoir, yet less dense than the deep water, and, as a result, inflows plunge to form interflows, typically in the thermocline (Figure 69c). Note that the inflow can entrain water from the lake as it plunges; this warms the inflow, reducing its density, and reduces the depth to which the inflow plunges. The inflow temperature, the degree of entrainment, as well as the temperature structure in the reservoir, together control the depth to which the tributary will plunge. The inflows form an interflow through most of the summer and early fall, giving rise to a long period of stable thermal stratification for phytoplankton growth. For Kinbasket, these deep plunging inflows provide the volume to lift the near surface water which then spreads into additional area as the reservoir fills (for further detail see discussion in MQ 3-2).

Finally, in fall, heat loss from the surface of the reservoir results in significant cooling and this, along with wind, results in deepening of the surface mixed layer (Figure 69d). Because density differences decline, internal motions can become larger (and slower) as illustrated (Figure 69d). Deepening replenishes nutrients in the surface layer, even as the water gets cooler, and incident light declines as the days get shorter. During this time the photic zone is also typically shallower than the thermocline depth and phytoplankton experience periods of both light and dark as they are convected in and out of the photic zone.

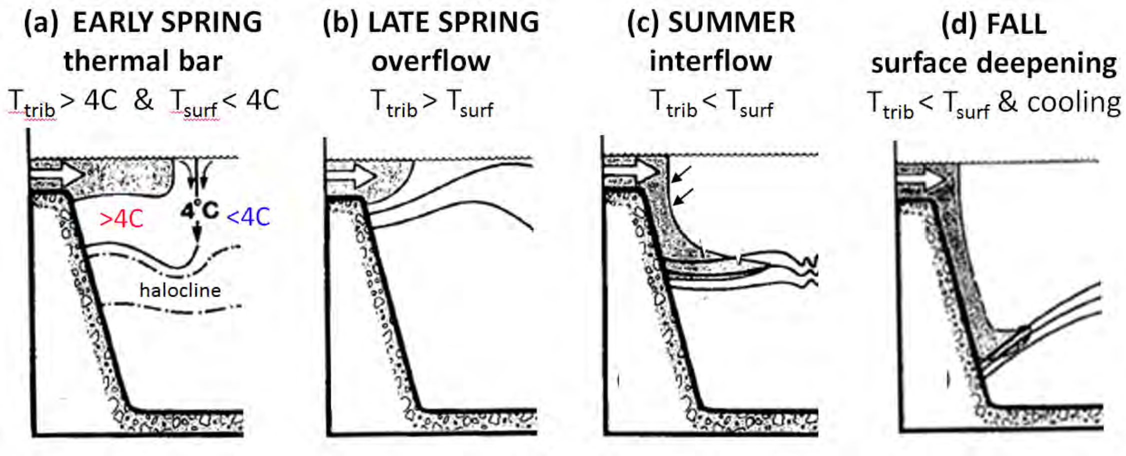

Figure 69. Schematic of processes: (a) thermal bar in early spring, (b) overflow in late spring, (c) interflow in summer, and (d) surface mixed layer deepening in fall. The large white arrow marks tributary inflow. Adapted from Daley et al. (1981).

Kinbasket Reservoir

Here we illustrate the above processes for Kinbasket Reservoir using data from 2018 when additional Seabird profiles were available (Figure 70 and Figure 71). In 2018, the winter air temperature was cool (Figure 8), the onset of stratification was delayed, freshet was early, inflow was above average for May, and inflow was then below average for July onward (Figure 70b). Note, the time periods for inflow processes marked on Figure 70 and Figure 71 will vary by tributary and location in the reservoir. The temperature stratification in the forebay is shown in Figure 70a; while temperature at depth was available year-round, the near surface temperature was only available from 31 May 2018 onward; the previous data were lost when the log boom broke.

The freshet began in late April 2018 (vertical dashed blue line, Figure 70b). The temperature of the Columbia River at Donald (coldo) rose above 4 °C on 8 April 2018 (day 98, Figure 70c); while the temperature for Beaver River (beavr) reached 4 °C earlier, on 28 March 2018 (day 87), it fluctuated around 4 °C until 19 May 2018 (day 139, Figure 70c). The CTD survey conducted on 30 April 2018 (not shown) indicated that all the reservoir was between 2.5 and 3.5 °C, while the survey two weeks later on 14-15 May 2018 (not shown) had temperature above 4 °C in all the arms (including the forebay) except for the middle of the reservoir which remained less than 4 °C, typical of the progression of the thermal bar.

Of the tributaries, the Columbia River at Donald was warmer than the others (Figure 9) and remained warmer than the reservoir until mid-July (Figure 70c). During this time the Columbia River inflow would have formed an overflow on the surface of the Columbia Reach, consistent with the CTD survey of 11-12 June 2018 (not shown). As discussed for MQ 3-1, we don't know how the biologically available phosphorus concentration in the Columbia River at Donald compares to that in the reservoir in spring; if more, this would benefit phytoplankton during the extended period of overflow. On the other hand, the Beaver River was warmer than the reservoir only until mid-June, as marked, and periods of overflow would have been brief.

The reservoir temperature rose above that of Beaver River by mid-June (Figure 70c), and tributary temperatures remained cooler than the surface of the reservoir through October. The fall surface mixed layer cooled to 10 °C and reached 33 m in late October and cooled to 6 °C and deepened to the level of the Mica penstock intakes in early December. Kinbasket Reservoir cools slowly compared to smaller lakes because of its great depth.

Figure 71a shows again the contours of temperature from Figure 70a, along with contours for conductivity at 25 °C (C25), turbidity and fluorescence. Recall that tributary conductivity declined significantly during freshet (Figure 9b) and this provides a convenient way to trace freshet inflows. At Kinbasket forebay, the conductivity of the near surface water declined progressively, beginning during the period of thermal bar formation, continuing with the period of overflow and into the period of summer stratification (Figure 71b). There was a period in summer when there was some C25 stratification, as fresher tributary inflow plunged to 10 or 20 m depth and left higher C25 water near the surface (top 5 m, mid-June to mid-July, Figure 71b). However, this did not persist, and, instead, C25 continued to decline, possibly due to entrainment driven mixing through the gradual thermal structure (Figure 11). In effect, the top 50 m of the reservoir was primarily filled with freshet inflow.

The turbidity in Kinbasket Reservoir remained generally less than 1 NTU in the forebay (Figure 71c), though turbidity was much higher at other locations such as Wood Arm. At the forebay, there was a lens of turbidity > 1 NTU possibly the influence of inflow from Wood Arm (Figure 1). Fluorescence suggests chlorophyll levels were also generally low, with an algal bloom in mid-June (Figure 71d).

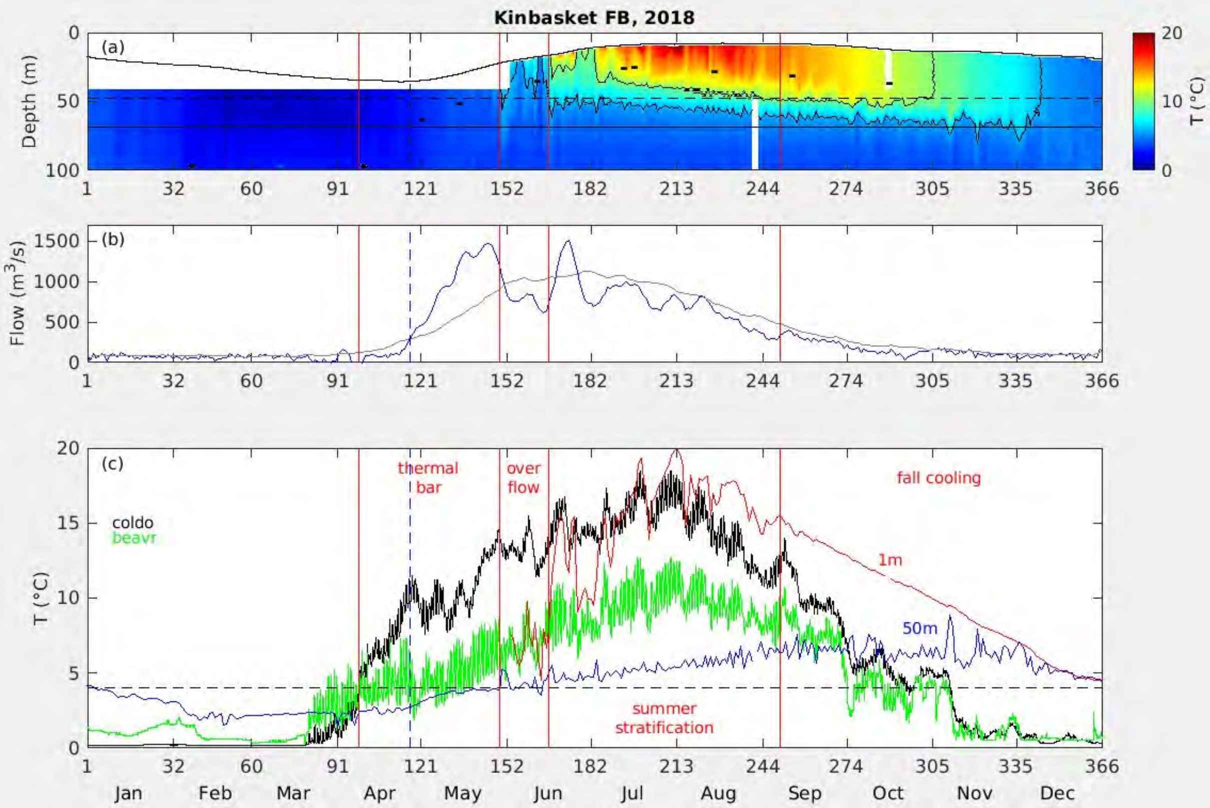

Figure 70. (a) Contours of temperature; (b) local inflow; and (c) tributary and reservoir temperature, Kinbasket Reservoir, Forebay, 2018. (a) Contours of temperature were plotted as depth from full pool; the black line at the surface marks the water level; black contours mark 6 and 10 °C; the black dashes mark the depth of the photic zone; the dash line marks normal minimum; the solid line marks the sill depth of the power intakes; and white blocks mark missing data. (b) The grey line marks the average flow. (c) The black dash line marks T_{MD}. The blue dash line marks the start of freshet. Time periods shown are approximate and will vary by location in the reservoir.

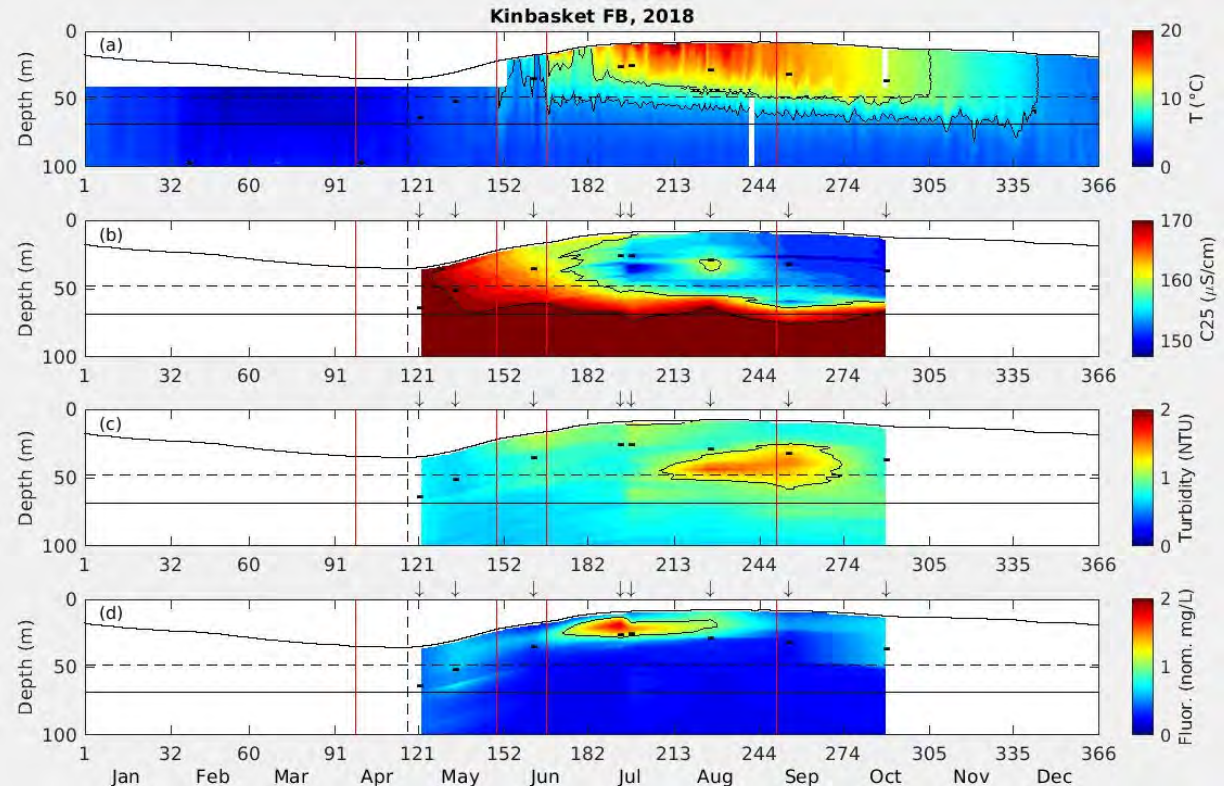

Figure 71. Contours of (a) temperature, (b) conductivity at 25 ° (C25), (c) turbidity and (d) fluorescence, Kinbasket Reservoir, Forebay, 2018. Temperature data from the mooring; C25, turbidity and fluorescence data are from CTD profiles marked by arrows. Contours were plotted as depth from full pool; the black line at the surface marks the water level; the black dashes mark the depth of the photic zone; the dash line marks normal minimum; the solid line marks the sill depth of the power intakes; and white blocks mark missing data. Black contours mark (a) 6 and 10 °C, (b) 160 and 170 µS/cm, (c) 1 NTU and (d) 1 mg/L.

Revelstoke Reservoir

Now we turn to look at Revelstoke Reservoir, where we will highlight differences from Kinbasket. The largest difference is that the primary inflow to Revelstoke Reservoir is outflow from Kinbasket Reservoir (Figure 72b). In 2018, outflow from Kinbasket Reservoir followed the usual pattern (Figure 2) and was shut off just at the time that freshet began (26 April 2018, day 116), and was kept low until early July.

Goldstream River warmed to 4 °C on 28 March 2018 (day 87) marking the start of the thermal bar period (Figure 72c). From the limited data available it appears that Downie Creek was a little cooler than Goldstream River (Figure 9); for the discussion here Goldstream will be considered representative of local inflows. The temperature of water released from Mica Dam in spring can be approximated by the temperature in Mica forebay at the elevation of the intakes (Figure 72c). The Mica outflow remained colder than either Goldstream or Downie and warmed to 4 °C at about the same time as Revelstoke Reservoir around mid-May.

The temperature in the Revelstoke Reservoir forebay reached 4 °C on 15 May 2018 (day 135), and this marked the end of the thermal bar period. After reaching 4 °C, the temperature at the surface of Revelstoke Reservoir rose very quickly and exceeded that of Goldstream River four days later on 19 May 2018 (day 139), giving a very short period of overflow (Figure 72c). Summer stratification continued through August; the point at which fall cooling began is somewhat arbitrary and is shown here as 1 September 2018 (Day 244), though it could just as well have been chosen to be 8 August 2018 (day 220) when the temperature at the surface reached a maximum.

Contours of conductivity (C25), turbidity and fluorescence are shown for Revelstoke Reservoir in Figure 73, based on the eight Seabird profiles (marked by arrows). The C25 of the surface water in Revelstoke Reservoir declined rapidly after the onset of freshet, reaching a minimum at the cast on 24 July 2018 (day 205). Note this decline occurred while outflow from Kinbasket was turned off and was driven solely by *local* inflow to Revelstoke Reservoir which had low conductivity. After inflow from Kinbasket resumed in early July (Figure 72b), it took time for the interflow of higher conductivity water from Kinbasket to make its way through Revelstoke Reservoir; higher conductivity at 30 m depth was observed in the cast on 21 August 2018 (day 233). There was a lens of turbidity > 1 NTU at 20 m depth in August (Figure 73c). There was also a slight lens of fluorescence from mid-May to mid-July at 15 m depth just above the photic depth suggesting a small spring bloom (Figure 73d).

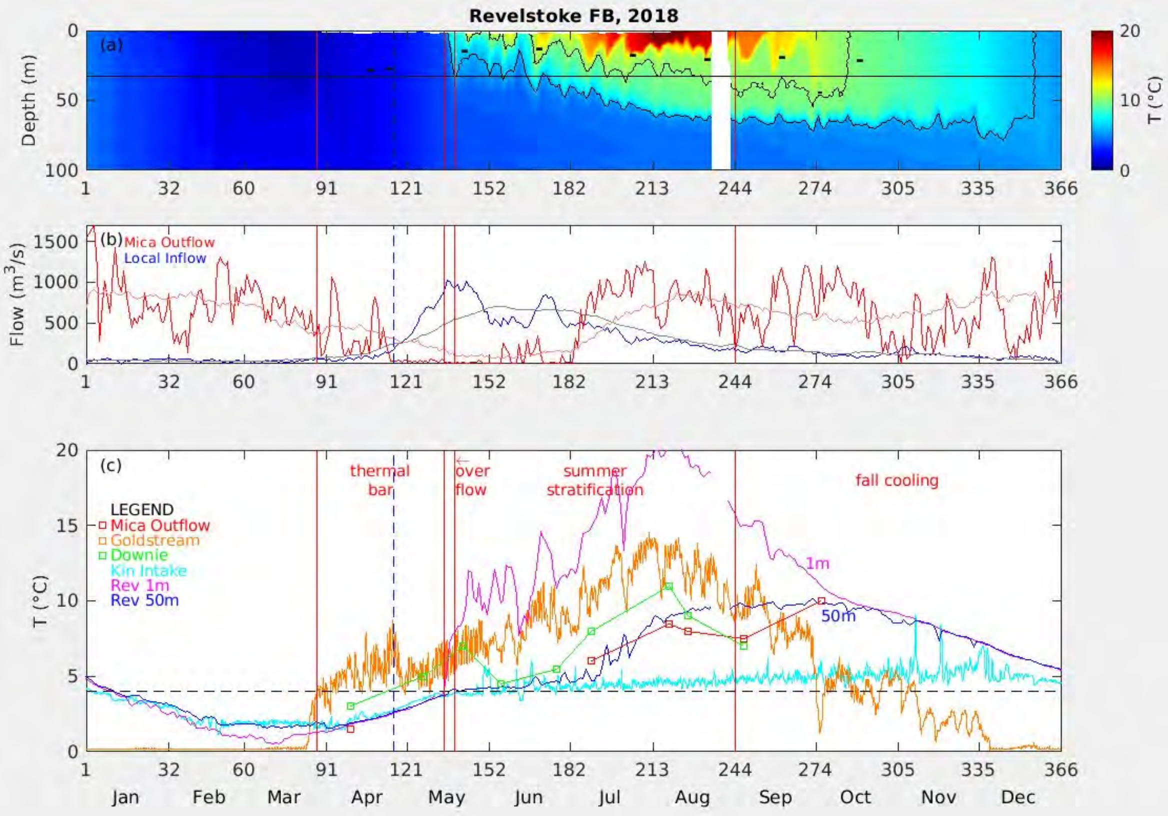

Figure 72. (a) Contours of temperature; (b) local inflow and Mica outflow; and (c) tributary and reservoir temperature, Revelstoke Reservoir, Forebay, 2018. (a) Contours of temperature were plotted as depth from full pool; black contours mark 6 and 10 °C; the solid line marks the sill depth of the power intakes; and white blocks mark missing data. (b) The grey (pink) lines marks the average inflow (Mica outflow). (c) The black dash line marks T_{MD}. The blue dash line marks the start of freshet. Time periods shown are approximate and will vary by location in the reservoir.

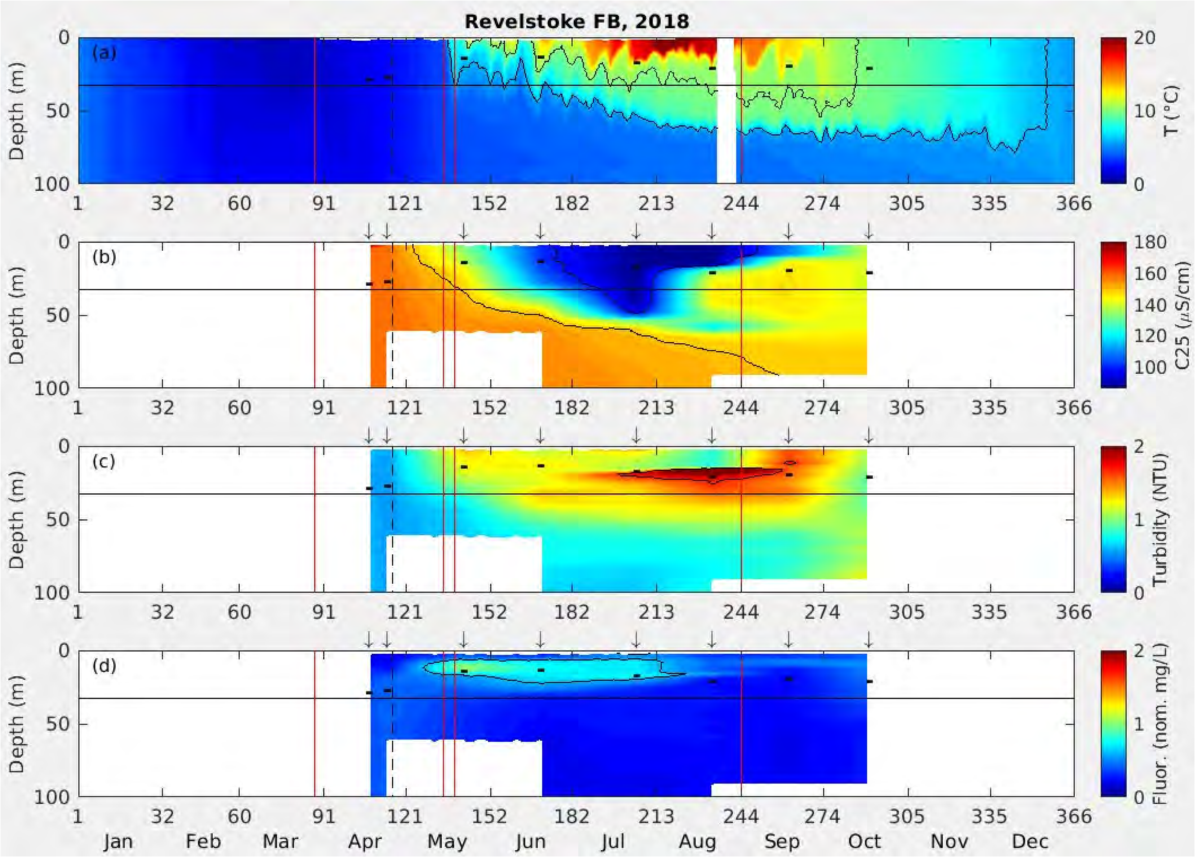

Figure 73. Contours of (a) temperature, (b) conductivity at 25 °C (C25), (c) turbidity and (d) fluorescence, Revelstoke Reservoir, Forebay, 2018. Temperature data from the mooring; C25, turbidity and fluorescence data are from CTD profiles marked by arrows. Contours were plotted as depth from full pool; the black dashes mark the depth of the photic zone; the solid line marks the sill depth of the power intakes; and white blocks mark missing data. Black contours mark (a) 6 and 10 °C, (b) 100 and 150 μS/cm, (c) 1 NTU and (d) 1 mg/L.

Summary

In summary, spring is a dynamic period of time in both Kinbasket and Revelstoke Reservoirs. The decline in conductivity provides a convenient tracer of freshet inflow; the conductivity declines markedly throughout the top 60 m of both Kinbasket (Figure 71) and Revelstoke (Figure 73) Reservoirs. In Kinbasket, with low outflow during much of the spring (Figure 2), freshet water is stored in the reservoir (Figure 74a). This is enhanced by the increasing area of Kinbasket Reservoir, which increases the volume (and nutrients) in the photic zone (for further discussion, see MQ 3-2). In Revelstoke Reservoir that is operated run-of-the-river, the withdrawal of water from 32.7 m results in replacement of winter water with that from freshet inflow (Figure 74c). While these two reservoirs operate in a very different manner, the net result is similar: spring is a dynamic period when new freshet inflow has the opportunity to continually replenish nutrients in the photic zone.

We hypothesize that the summer is different than the spring for both reservoirs. Once Kinbasket begins to reach maximum water level for the year, the tail of freshet inflow is discharged from the deep outlets (Figure 2). Since tributary inflow remains cool compared to the surface of the reservoir, inflow tends to plunge deep (below the photic zone, Figure 20), from where it is *downwelled* to the outlet (Figure 74b). The degree of isolation of the photic zone in summer depends on the amount of entrainment into the plunging inflows.

Summer in Revelstoke Reservoir is characterized by the interflow of cool water from Kinbasket Reservoir (Figure 14 and Figure 15). In Revelstoke, local tributaries form a much smaller fraction of the inflow and so their influence on the surface layer would decline correspondingly in summer, especially in the lower half of the reservoir which has a relatively small drainage area (Pieters et al. 2022a). The boundary between the photic zone and interflow has a strong degree of thermal stratification. While water from the interflow can occasionally be moved into the photic zone by internal motions, this is unlikely to contribute significantly to the overall productivity. Note that the conductivity of the surface water does increase slightly over the course of the summer, suggesting some ongoing exchange with the higher conductivity interflow from below.

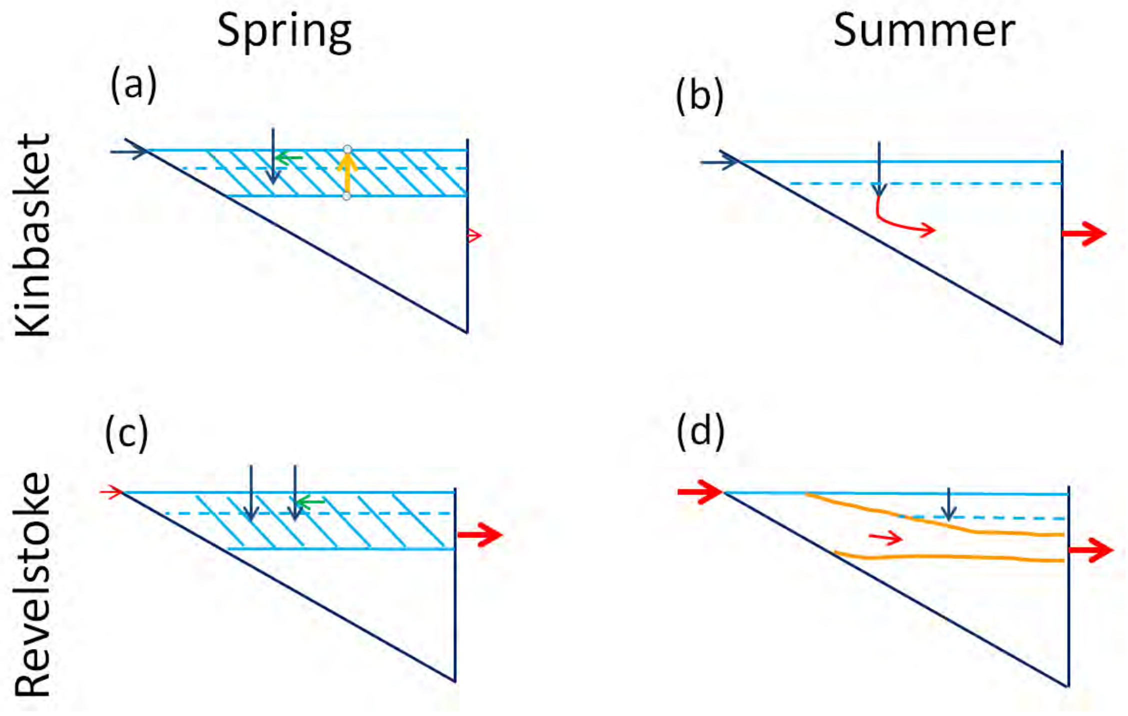

Figure 74. Schematic for (a, b) Kinbasket and (c, d) Revelstoke Reservoirs for (left) spring and (right) summer. The dash line marks the photic zone. Blue arrows mark tributary inflow, the green arrows mark entrainment of water from the photic zone by tributary inflow. Red arrows mark major inflows and outflows. In (a) the orange arrow marks the increase in water level over the spring. In (a) and (c) the hash lines mark the region influenced by freshet inflows. In (d) the orange lines outline the interflow of Kinbasket outflow through Revelstoke Reservoir.

4.2 CLBMON-2-3-56 Management Questions

MQ 3-1. What are the long-terms trends in nutrient availability and how are lower trophic levels affected by these trends?

In this section, we will address the first part of the question regarding long-term trends in nutrient availability. The second part of the question will be addressed in subsequent sections MQ 3-2 and MQ 3-5.

There are two sources of nutrients for pelagic productivity: allochthonous nutrients that originate from outside the reservoir and are transported into the reservoir by tributary inflow, and autochthonous nutrients that originate within the reservoir, for example, from decomposition of organic matter at the bottom. New reservoirs often undergo a ‘boom and bust’ cycle, where, shortly after impoundment, nutrient availability is high due to flooding of soils and decomposition of organic matter (Stockner et al. 2000). As a result, pelagic productivity is initially high, but then decreases as this source of nutrients declines. To assess the long-term trends in nutrient availability we examine both nutrients transported by inflows and nutrient concentrations in the reservoir. In the following, we will first describe tributary and reservoir nutrients and the conclusions to be drawn from them, and then we will return and discuss the problem of phosphorus measurement in greater detail.

Tributary nutrients - Data were collected from five reference tributaries to address the question of long-term trends in nutrient input. For the first nutrient, phosphorus, concentrations were low, with soluble reactive phosphorus (SRP) and total dissolved phosphorus (TDP, Figure 25) close to the detection limit, similar to results in other ultra-oligotrophic systems. Total phosphorus ranged from a mean of 19 to 32 µg/L (Table 9) and was dominated by particulate phosphorus much of which settled within the reservoir. The results were affected by a change in laboratory in 2013, which will be discussed below.

The second nutrient, nitrogen, is found primarily as nitrate (NO_3) and the average ranged from 91 to 217 µg/L N (Table 9). Total nitrogen (TN) was measured from 2016 onward and ranged from 213 to 282 µg/L N. In general, TN was roughly 1.5 times greater than nitrate. Nitrogen concentrations were not affected by the change in laboratory.

For the reference tributaries, neither the flow weighted average concentrations (TDP, Figure 25; TP, Figure 26; NO_3, Figure 27) nor the load (TDP, Figure 28; TP, Figure 29; NO_3, Figure 30) showed trends.

Reservoir nutrients - Data have also been collected from four stations in Kinbasket Reservoir and three stations in Revelstoke Reservoir (Figure 1). These data also show low SRP and TDP concentrations that were close to the detection limit. In the reservoirs, TP averaged 3.2 and 3.0 µg/L in Kinbasket and Revelstoke, respectively (Table 10). In contrast, nitrate remained high, averaging 108 µg/L N in Kinbasket Reservoir and 224 µg/L N in Revelstoke Reservoir (Table 10). Total nitrogen (TN) measured from 2016 onward, averaged 182 and 187 µg/L N in Kinbasket and Revelstoke Reservoirs, respectively. There were no long-term trends in the reservoir nutrients (0-20m average, Section 3.4).

From both the tributary and reservoir data over the study period (2008-2019), we conclude the following about Kinbasket and Revelstoke Reservoirs:

- they are oligotrophic systems,
- concentrations of dissolved inorganic nitrogen are well above 20 µg/L, the threshold considered limiting to phytoplankton growth (Wetzel 2001),
- they are phosphorus limited (N:P > 10 by weight),
- given the proximity of phosphorus concentrations to the detection limit, and given the limitations of the laboratory measurements (discussed below), there were no trends observable over the study period in the mean annual phosphorus concentrations, and
- there were no evident trends over the study period in the mean annual nitrogen concentrations.

The seasonal trends in nutrients were also examined:

- there were no seasonal variations in SRP and TDP from the reference tributaries,
- particulate phosphorus (PP) and total phosphorus (TP) in the tributaries were strongly correlated with turbidity, which increased during spring freshet,
- nitrate (NO_3) showed a strong seasonal cycle (Figure 24 and Figure 31a) but did not become limiting and total nitrogen (TN) shows a similar pattern,
- this seasonal trend in nitrate (NO_3) is reflected in the 0-20 m concentrations in the reservoirs.

The study period (2008-2019) began 35 years after completion of Kinbasket Reservoir (1973) and 24 years after completion of Revelstoke Reservoir (1984). Within the resolution of the data available, there was no sign of a declining trend in nutrients suggesting that both reservoirs have reached a post-dam steady state. The results described above have clearly shown that phytoplankton productivity is not limited by the availability of dissolved nitrogen over the study period, and suggest that phosphorus is the key limiting nutrient, and the measurement of phosphorus will be discussed in more detail in the next section.

Measurement of phosphorus

The ultimate goal is to be able to measure biologically available phosphorus (BAP) and to trace phosphorus inputs from the tributary sources to the photic zone of the reservoir. In this section we briefly discuss the measurement of phosphorus in these glacially dominated systems.

Soluble reactive phosphorus (SRP) - In oligotrophic lakes SRP concentrations are considered mostly ephemeral (J. Stockner, pers. communication). For example, in a set of oligotrophic lakes, significant concentrations of SRP were measured only in the fertilized zone within 24 hours of fertilizer application by an aircraft (Stockner et al. 1980). SRP is generally ‘snapped up’ by the algae which sequester phosphorus for future use (luxury consumption). If SRP is above detection, this can result from a short-term imbalance at the sampling depth, this could reflect transformations in the sample between collection and analysis, and/or this could result from even small residuals from prior samples in the analysis system itself. While we deem there is little meaning in the minor fluctuations in the SRP concentrations, we continued with the analysis for this parameter for this survey study to confirm the low concentrations.

Total phosphorus (TP) - Dodson (2005) writes “In many cases, total phosphorus is the preferred indicator of a lake’s nutrient status.” Total phosphorus (TP) is obtained after digestion of an unfiltered sample and includes all the phosphorus available in various pools, such as soluble reactive phosphorus (SRP) that can be taken up directly by algae, as well phosphorus in organic colloids, in detritus, and in the cells of the living algae themselves.

Particulate phosphorus (PP) - As described in the results, TP is divided into two functional components, the first is total dissolved phosphorus (TDP), which passes through a 0.45 µm filter, and the second is particulate phosphorus (PP), which is the balance. In the tributary surveys, the median PP ranged from 6.8 to 19 µg/L (Table 8); in the reference tributaries with natural flows, the average PP ranged from 16 to 29 µg/L (Table 9). In contrast, the reservoir PP ranged from 0.8 to 0.9 µg/L (Table 10), suggesting that a large fraction of incoming PP settles.

Biologically available phosphorus (BAP) - Glacier-fed tributaries are dominated by glacial fines of inorganic origin having low biological availability. The question is what fraction of TDP and PP are biologically available. In addition, the vast majority of PP settles after inflows enter the reservoir, leaving on order of 1 µg/L PP in the water column (Table 10); the question is then what fraction of the PP that remains in suspension is biologically available. Regardless, as a result of settling, the tributary TP load is a significant overestimate. Instead, TDP was used to calculate N:P ratios for the tributaries. Using TDP may be a slight underestimate depending on the degree to which the remaining PP in the water column is biological available (maximum order 1 µg/L). Of course, as mentioned, the TDP itself may not necessarily be all biologically available, potentially making TDP an overestimate. Note that glacial fines may also adsorb and desorb phosphorus (e.g., Muller et al. 2006). Finally, microbial activity adds a question about the time scale over which phosphorus can become biologically available.

Change in laboratory - As mentioned, the change in laboratory caused noticeable shifts in the results. The phosphorus data from the Cultus Lake Laboratory (2008-2012) was adjusted (Bray 2022). Data from Maxxam (2013-2018) and ALS (2019) had a large number of TDP samples at or below detection. The Maxxam laboratory also had some groups of unusually high values (cf. Figure 25). An inter-comparison, with phosphorus samples sent to four laboratories, was conducted in September 2018, and showed significant variability in measurements at low phosphorus levels (Bray 2022). Any change in laboratory or analytical methods should include an overlap period of several months with samples sent to both laboratories to provide suitable data for cross-calibration.

Sample digestion - Paul Harrison (UBC, personal communication) found that the amount of phosphorus in samples of Fraser River water increased with the length of digestion. Note that, for example, Standard Methods (APHA 1992) and the BC Environmental Laboratory Manual (Austin 2020), provide a wide variety of digestion protocols, and that digestion time is not specified. We wonder if the differences in TDP and TP data between laboratories, and perhaps also within a given laboratory, could, in part, represent varying periods of digestion.

To summarize, the factors that affect determination of phosphorus include:

- low phosphorus levels,
- the presence of glacial fines which are of low biological availability,
- adsorption/desorption of phosphorus to glacial particles,
- inability of standard techniques (SRP, TDP, TP) to ascertain BAP in these systems,
- variations in laboratory methods (e.g., sample digestion)
- laboratory detection limits, and
- change in laboratory.

Nutrient budget - In the results we have shown the volume weighted average concentration (µg/L) and load (tonnes) for phosphorus in the reference tributaries to Kinbasket and Revelstoke Reservoirs (Section 3.2.2). However, it should be noted that we have not conducted a full nutrient budget for two reasons: first because the fraction of the inflow sampled by the reference tributaries was relatively small (especially for Kinbasket Reservoir), and second, and more notably, because such a budget has limited value due to the uncertainties in the phosphorus measurements.

A full nutrient budget was completed for Arrow Reservoir for seven years 1997-2003 (e.g., Pieters et al. 2003a). This budget included samples from a significant fraction of the inflows, the reservoir basins, and outflows from which detailed nutrient loads and estimates of retention were calculated for SRP, TDP, PP, and TP. Analysis of the error indicated that for shorter times and smaller scales, the uncertainty in the estimates increased significantly, as would be expected. Using, for example, a simple fraction of TP as bioavailable is not, in our opinion, sufficient to justify the significant logistical, laboratory, and reporting costs for further nutrient budgets.

It would be of great benefit to have a measure of the biologically available phosphorus load to assist in assessing the biological response. We are not aware of a straightforward way of measuring biologically available phosphorus; however, we would suggest making small exploratory efforts at understanding nutrients in these large oligotrophic and glacially dominated systems. One place to start might be contacting a focused set of researchers to canvas how this might be approached, including the suggestions made in Hecky and Guildford (2022). Based on feedback, we would then suggest developing modest and focused research projects to explore the most promising avenues. Note there are other sources of phosphorus such as deposition from the atmosphere and runoff from the drawdown zone, and these would be worth investigating to identify if their contributions could be significant both locally and regionally.

We have understood intuitively that there is something different about these glacial systems. The number and size of these systems - Kootenay, Duncan, Slocan, Upper Arrow, Lower Arrow, Revelstoke, and Kinbasket - and the importance they play in the region, make the attempt to characterize this difference valuable.

In summary, there were no discernable trends in nutrient availability over the duration of the study period. The system is phosphorus limited; soluble reactive phosphorus (SRP) was ephemeral, total dissolved phosphorus (TDP) was close to detection, and the presence of glacial fines interfered with the measurement of total phosphorus (TP). There were no discernable trends in the three types of phosphorus. The supply of nitrogen was sufficient, and there was no observable trend over time either in the tributaries or in the reservoir. The second part of the question asks how lower trophic levels are affected by nutrient trends of which there were none. The effect of nutrients in general will be addressed in subsequent sections MQ 3-2 and MQ 3-5.

MQ 3-2. What are the interactions between nutrient availability, productivity at lower trophic levels and reservoir operations?

We address the first part of this question regarding nutrient availability here and defer the second part of the question regarding productivity at lower trophic levels to the closely related MQ 3-5 below.

Phytoplankton productivity is largely controlled by light, temperature, and nutrients. Production in freshwater ecosystems is primarily controlled by the availability of phosphorus and in some cases nitrogen. In the stereotypical lake, the primary source of phosphorus is the initial concentration in the water column at the start of stratification in spring. Once the lake stratifies, this typically results in a spring bloom of phytoplankton. Ongoing growth can result from recycling of phosphorus within the epilimnion especially through the microbial loop; phosphorus can also be lost from the epilimnion by settling of organic material.

The potential to resupply phosphorus to the photic zone over the course of the summer is, in the stereotypical lake, limited by transport across a strong thermocline. There is the potential, for example, for the surface mixed layer (epilimnion) to deepen slightly over the course of the summer introducing new phosphorus from the top of the thermocline into the epilimnion. Alternatively, if light is able to penetrate to the top of the thermocline, there may be growth of phytoplankton at the boundary of diminishing light from above and increasing phosphorus with depth. In early autumn, cooling and deepening of the surface mixed layer will introduce new phosphorus into the epilimnion, and can, under certain circumstances, result in a fall bloom.

Against this backdrop, we discuss Kinbasket and Revelstoke Reservoirs, and, in particular, focus on the resupply of nutrients to the photic zone. One feature of reservoirs that make them different from lakes is the presence of deep outlets which can introduce flow patterns not observed in lakes (e.g., Robb et al. 2021). A sequence of reservoirs can also introduce novel patterns, driven, for example, by the cold outflow from an upstream reservoir. Reservoirs are also subject to large through-flows, which can make them riverine in character. In addition, the timing of the flows can differ in reservoirs from that in natural lakes; for example, peak flows can occur at other times of year than freshet (e.g., Figure 2b).

Fraction of inflow entering the photic zone - As described in previous sections, Kinbasket and Revelstoke Reservoirs are phosphorus limited. The existing laboratory measurements of phosphorus, while indicating that phosphorus levels are very low, are unable to discriminate between low levels of phosphorus. We do not know, for example, whether the Columbia River at Donald contributes more or less biologically available phosphorus to Kinbasket Reservoir than Beaver River. Also, we are not able to track changes in the biologically available phosphorus concentrations within the reservoirs over the course of the summer and cannot compare phosphorus levels between reservoirs.

Given these limitations, we make the assumption that all inflows to Kinbasket and Revelstoke Reservoirs have the same (low) concentration of biologically available phosphorus (BAP), and here we examine the degree to which new water enters the photic zone during summer stratification (Section 4.1).

In particular, we examine the case of cold inflows that plunge deep into the non-traditional stratification, a schematic of which is shown in Figure 75. Inflow Q_o plunges below the photic zone, and, as it plunges, entrains water from the photic zone Q_e, which results in a flow of $Q_o + Q_e$ inserted beneath the photic zone (Figure 75). In the case we consider here there is no surface outflow, $Q_s = 0$, only outflow from a deep outlet, Q_d.

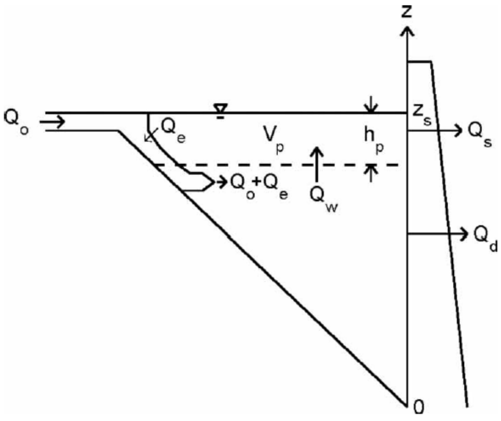

Figure 75. Schematic of cold plunging inflow where the dashed line marks the bottom of the photic zone at depth h_p from the surface level z_s; Q_o is the inflow; Q_e is the water entrained as the inflow passes through the photic zone; Q_s and Q_d are shallow and deep outlets; Q_w is the flow of water into the photic zone from below; and V_p is the volume of the photic zone. Adapted from Pieters and Lawrence (2012).

The fraction of inflow phosphorus that enters the photic zone can be approximated as,

$$f = \frac{\left(1 - \frac{A_p}{A_s}\right)\left(1 - \frac{Q_d}{Q_o}\right) + \left(\frac{A_p}{Q_o}\right)\frac{dh_p}{dt} + E_p}{1 + E_p},$$

where, A_s is the surface area of the reservoir, and A_p is the area of the reservoir at the photic depth and $E_p = Q_e/Q_o$ is the entrainment factor. For further detail, including model assumptions, see Pieters and Lawrence (2012).

In the numerator are three terms. The first term is the bathymetric effect: as the reservoir fills and widens the amount of water in the photic zone increases. If the reservoir had vertical walls, then $A_s = A_p$, and this term would be zero. The second term is the effect of water clarity: as the water clears, the photic depth, h_p, increases, and the volume of the photic zone increases. The third term is the entrainment factor, E_p: the higher the entrainment, the more water is removed from the photic zone by the inflow (namely $Q_e = E_p Q_o$ in Figure 75), and the more water must be brought up into the photic zone from below (Q_w) to maintain the photic zone volume. Unfortunately, we do not have good estimates for E_p, which depends on a variety of factors not the least of which is the bathymetry of the plunge zone, and predicting E_p is an area of active research (Rueda et al. 2007; Hogg et al. 2013; Cortés et al. 2014). Here we will consider three values of E_p = 0, 0.5 and 1.

Consider the average data for 2008-2019 for both Kinbasket and Revelstoke Reservoirs in Figure 76. In Kinbasket Reservoir the total inflow reached a peak during freshet in late June of 1,700 m^3/s, during which time the outflow from the reservoir was low (Figure 76a). In contrast, total inflow and outflow match closely in Revelstoke Reservoir (Figure 76b), as it is operated with little change in water level (Figure 76c). The turbidity in both reservoirs increased from April to June, during which time the photic depth became shallower (Figure 76c, d). From July onward, turbidity declined, and the average photic depth gradually increased through to October. The mean monthly photic depth in Revelstoke Reservoir was, on average, 3.5 m shallower, than in Kinbasket Reservoir; also, Revelstoke cleared more slowly than Kinbasket through summer and fall (Figure 76c, d).

Kinbasket Reservoir had a large increase in surface area, A_s, from May to July, with a corresponding increase in the area at the photic depth, A_p (Figure 76e). In contrast, the surface area, A_s, in Revelstoke Reservoir was effectively constant, and the area at the photic depth, A_p, simply reflected the change in photic depth (Figure 76f).

The two first terms in the numerator for f are compared in Figure 76 g, h; both terms are dimensionless. The first term for the bathymetric effect in Kinbasket Reservoir was largest in May and June as the reservoir filled rapidly (blue, Figure 76g). As expected, the bathymetric effect was zero in Revelstoke (blue, Figure 76h).

Note that we are using monthly average data for the photic depth (Figure 76c, d) and, as a result, the derivative of the photic depth, dh_p/dt, had steps when the slope changed at mid-month; the steps themselves are not significant and simply reflect the coarseness of monthly sampling. In Kinbasket from April to May, term 2 was large and negative as the photic depth became shallower (red, Figure 76g). Between May and June, term 2, resulting from declining photic depth, almost perfectly balanced term1, resulting from the bathymetric effect (blue, Figure 76g). That is, the bathymetric dividend of increased photic volume through filling of the reservoir was cancelled by the increasing turbidity and decreased light penetration in the water column.

Beginning in mid-July, term 1 for the bathymetric effect was declining (blue, Figure 76g) as Kinbasket Reservoir approached full pool, while now term 2 was both positive and gradually increasing through to October (red, Figure 76g).

In Revelstoke Reservoir, as already mentioned, there is no bathymetric effect, and term 1 is zero (blue, Figure 76h). Term 2 for the photic depth followed a similar pattern to that in Kinbasket Reservoir, only diminished due to lower surface area, A_s, and higher inflow, Q_o.

The addition of entrainment, E_p = 0.5 and 1, increased the fraction of inflow entering the photic zone in both Kinbasket and Revelstoke Reservoirs (Figure 76i, j). At higher E_p, the entrainment dominated the other two terms. That some entrainment occurred can be inferred from the conductivity (C25) data as described in Section 4.1.

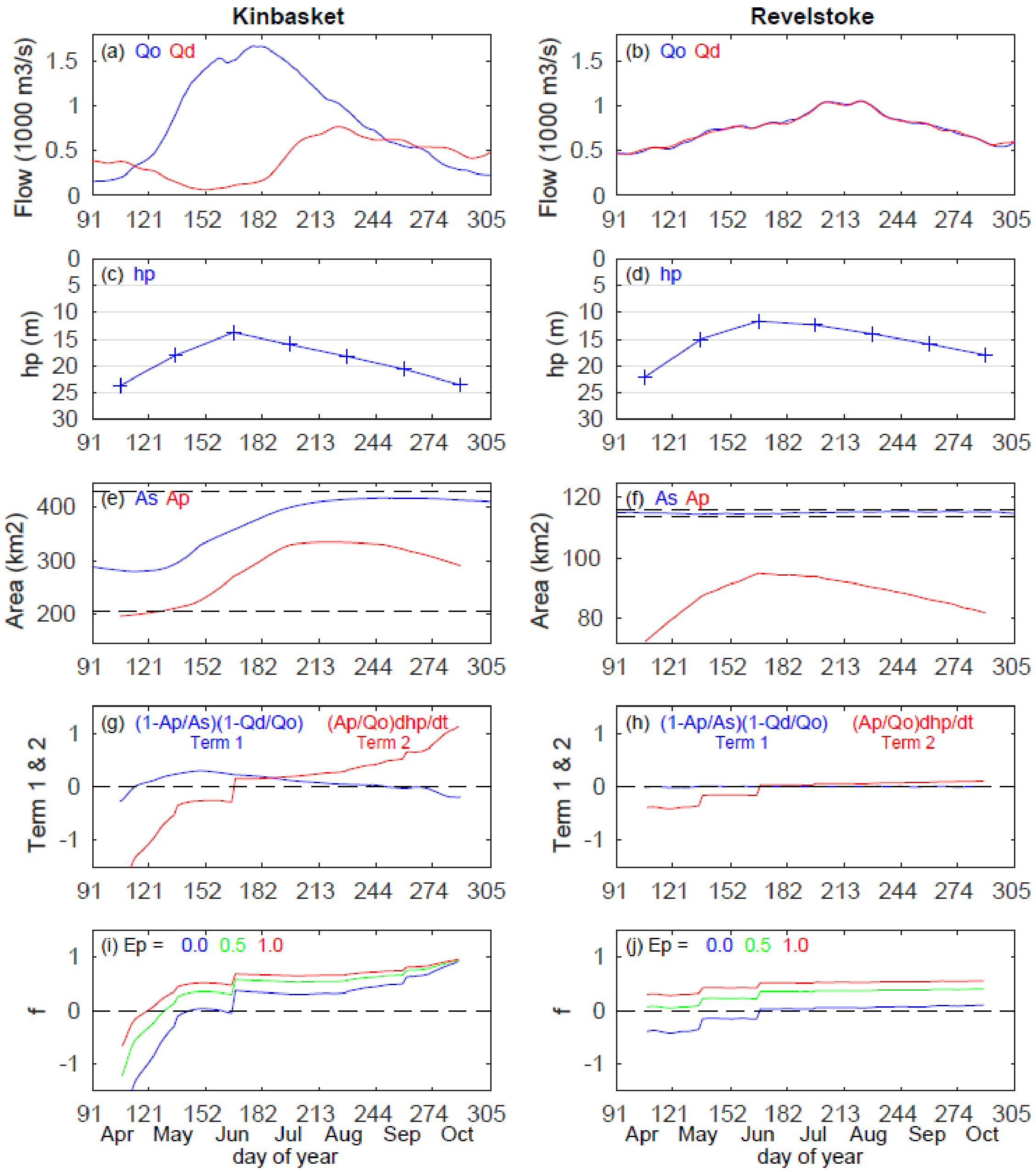

Figure 76. (a, b) Total inflow, Q_o, and outflow, Q_d. (c, d) Photic depth, h_p. (e, f) Surface area, A_S, and area at the photic depth, A_p. (g, h) Numerator term 1 and 2. (i, j) Estimated fraction of inflow nutrients entering the photic zone, f, for E_p = 0, 0.5 and 1. The left column is for Kinbasket Reservoir and the right for Revelstoke Reservoir; average data for 2008-2019.

In summary, while the concentration of phosphorus was low, the factor considered here was the importance of loading rates and the physical dynamics of these allochthonous nutrients in the water column. The principal drivers of nutrients to primary production are whether these nutrients enter the photic zone, the time of year they enter the photic zone, as well as the amount of time these nutrients spend in the photic zone.

One key observation from our study was recording numerous examples of interflow of Kinbasket outflow in Revelstoke Reservoir (e.g., Figure 14 and Figure 15). Water discharged from Kinbasket Reservoir was transported directly to the outlet of Revelstoke Reservoir, bypassing the photic zone. In effect, water from Kinbasket Reservoir was short circuited below the photic zone through much of the summer. Information from the autonomous profilers has detailed, for example, the possibility that the interflow can extend briefly into the photic zone, but whether this is biologically significant is not known (Figure 15).

The interflow dissipated in the fall due to water cooling which allowed Kinbasket water to enter the photic zone of Revelstoke, and thereby allowing biological uptake of potential nutrients in the Kinbasket source water by the phytoplankton community. The availability of these nutrients in October when biological productivity is winding down, however, is much less valuable than they would have been in June or July, when strong phytoplankton growth occurs. This short circuiting of the nutrients from Kinbasket during the warmer months could result in a cascade of reduced productivity in all trophic levels of Revelstoke Reservoir.

The timing of the inflows from the watershed was highly variable during the time frame of our study. For example, in 2012, the flow from Kinbasket was at or below average through mid-July, when the flow rose to very high levels to the end of August (Figure 6b). Changes in inflow characteristics can have a profound impact on the productivity of these systems given that the phytoplankton community can rapidly respond to pulse sources of nutrients due to extremely high uptake rates. These uptake dynamics allow the phytoplankton community to respond positively to a changing environment. Phytoplankton are also able to assimilate phosphorus in excess of their actual needs and store phosphorus for future use when external concentrations of phosphorus are low (luxury consumption); this allows the phytoplankton community to maximize growth in environments where phosphorus is dynamic.

In summary, winter conditions affect the onset of stratification and water temperature in spring and set the initial supply of nutrients for spring productivity. There was a complex pathway between the tributary inflows and the photic zone where additional nutrients can be utilized by lower trophic levels. This pathway included a thermal bar in early spring, periods of overflow in late spring, and interflow in summer. During plunging below the photic zone in summer, the resupply to the photic zone was set by the increasing area of the reservoir (in the case of Kinbasket), changes in water clarity which can expand or contract the photic zone, and entrainment of surface water into the plunging tributaries. Overall, indirect evidence based on the specific conductivity of the tributary inflow suggests that spring is a dynamic period and that resupply continued in summer. The link to productivity at lower trophic levels is addressed in MQ3-5.

MQ 3-3 Is pelagic productivity, as measured by primary production, changing significantly over the course of the monitoring period?

This is the first study to obtain long term measurements of primary productivity on Kinbasket and Revelstoke Reservoirs which permits us to evaluate whether primary productivity is changing over time. Previous studies of primary productivity were limited to one measurement in a single year (Stockner and Korman 2002). This is also the first long term study in the history of these two reservoirs to include comprehensive monitoring of physical, chemical, and biological parameters which will allow us to increase our understanding of reservoir and food web dynamics. While this study is unique in its collection of data over a 12-year period, it represents only a snapshot in time of the ecosystem response over an array of climatological conditions.

Regardless of these caveats, over the course of the monitoring period from 2008 to 2019, while variation in productivity was observed from year to year, there is an increasing trend in primary productivity in both Kinbasket and Revelstoke Reservoirs at all stations. There is strong evidence of a linear trend (all p-values <0.05) for all three stations and a linear regression model fitted to the log (primary productivity) to estimate the proportional change over time found primary productivity in Kinbasket was increasing by 14% per year followed by an increase by 13% per year at Revelstoke Middle and 12% per year at Revelstoke Middle (Figure 77). While the annual proportional changes are all slightly different, 14% vs 13% vs 12% per year, they are remarkably similar implying a common external factor is driving productivity at all three stations. While a strong linear trend was found for all stations, there was weak evidence of a quadratic trend for Revelstoke Forebay and Revelstoke Middle providing some evidence in a downturn in the later years of the study at the two Revelstoke stations.

The consequence of these annual increases is that rates of primary productivity have increased approximately 3 to 4-fold from the beginning of this study in 2008 to the end in 2019 (Figure 10). In Kinbasket, primary productivity rates were less than 50 mg C/m^2/d, increasing to ~200 mg C/m^2/d in 2019. In Revelstoke Reservoir a similar increase was noted however rates are generally lower in Revelstoke compared to Kinbasket Reservoir increasing from ~30 mg C/m^2/d in 2008 to ~110 mg C/m^2/d in 2019, while in Revelstoke Middle rates of primary productivity increased 3-fold from ~20 mg C/m^2/d in 2008 to ~60 mg C/m^2/d until in 2019. This linear trend is surprising given variation observed from year to year and the high degree of variability in meteorological and hydrological condition noted over the study period including strong El Niño, strong La Niña, weak El Niño and weak La Niña (Table 5).

In general, rates of primary productivity at Kinbasket Forebay and Revelstoke Forebay were typically under 100 mg C/m^2/d in the first five years of the study; however, for the last five years of the study primary productivity rates over 100 mg C/m^2/d were typically measured (Figure 78).

For Revelstoke Middle, rates over 100 mg C/m^2/d were rarely measured (Figure 78) implying an additional external factor influenced primary production at this site.

Over the course of the monitoring period, primary productivity measurements were consistently low in these reservoirs compared to other systems (see Section 3.6) with a mean rate of 112.9 mg C/m^2/d in Kinbasket followed by 87.1 mg C/m^2/d in Revelstoke Forebay and 66.3 mg C/m^2/d at Revelstoke Middle. Production has been consistently higher at Kinbasket Reservoir than at Revelstoke Reservoir over the entire monitoring period and production was consistently higher at Revelstoke Forebay than Revelstoke Middle. Primary productivity is often used as a factor for determining trophic state and despite these changes over the course of the monitoring period, our results clearly point to the oligotrophic status of the two reservoirs (Wetzel 2001).

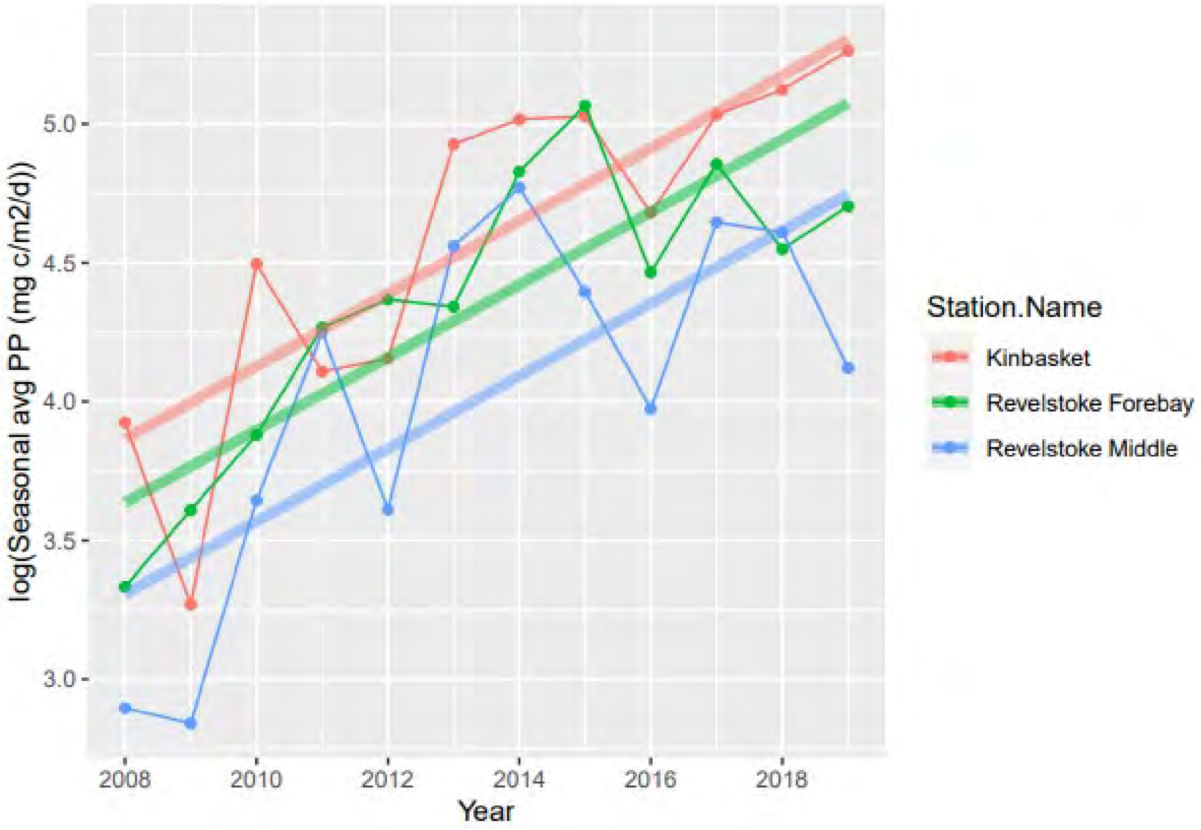

Figure 77. Log (seasonal avg PP (mg C/m2/d) in Kinbasket and Revelstoke Reservoirs.

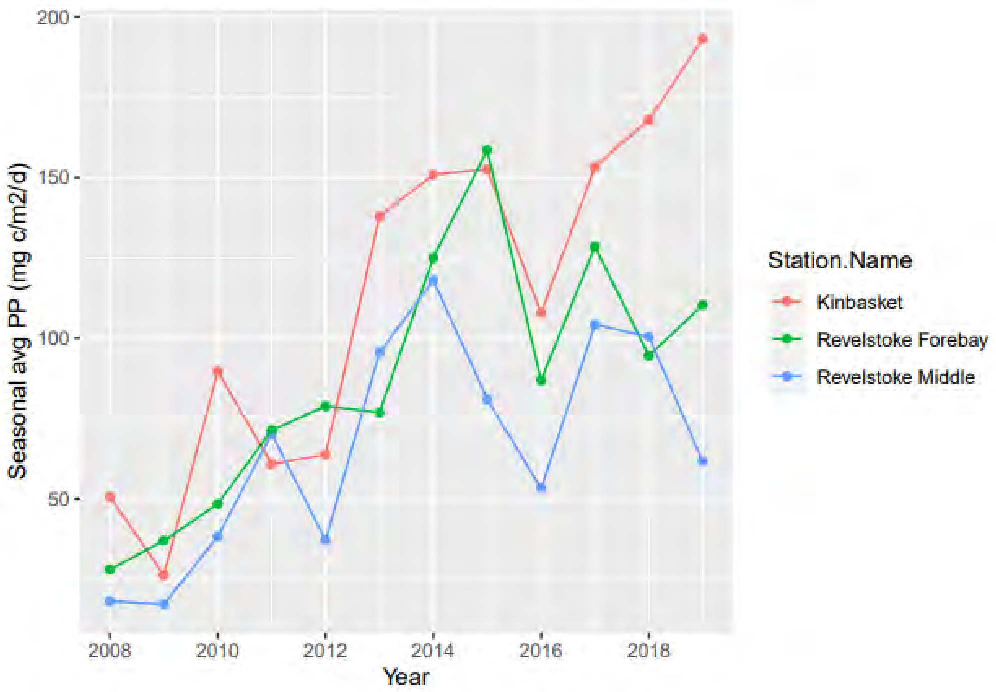

Figure 78. Seasonal average primary productivity (mg C/m^2/d) in Kinbasket, Revelstoke Middle and Revelstoke Forebay in 2008-2019.

The first four years of data show an increasing trend in picoplankton, the smallest size class measured, and a declining trend in nanoplankton, the middle size class measured. Nanoplankton are the fraction readily consumed by *Daphnia* spp. the preferred food source of kokanee, and a community dominated by picoplankton can lead to less efficient transfer of carbon up the food chain. However, starting in 2012, picoplankton production levelled off and nanoplankton production increased each successive year in Kinbasket where nanoplankton became the most productive fraction of the phytoplankton community (Figure 79). Microplankton production, the largest size fraction in our study, declined steadily over the study period from 33% in 2008 to 10% in 2016. There was a small uptick in production in the last two years of the study to ~16% of total production (Figure 79).

Our study showed that picoplankton and nanoplankton were the most productive fractions in Kinbasket and Revelstoke Reservoirs where they accounted for ~81% of the total productivity while microplankton were the least productive fraction accounting for between ~20% of total productivity. This provides further evidence of the importance of nutrient availability as small sized cells are generally favoured in nutrient poor conditions due to high surface area to cell volume ratios. Large-sized phytoplankton have large storage vacuoles allowing them to assimilate phosphorus rapidly in nutrient rich systems, and therefore, tending to dominate the phytoplankton community only where nutrients are abundant.

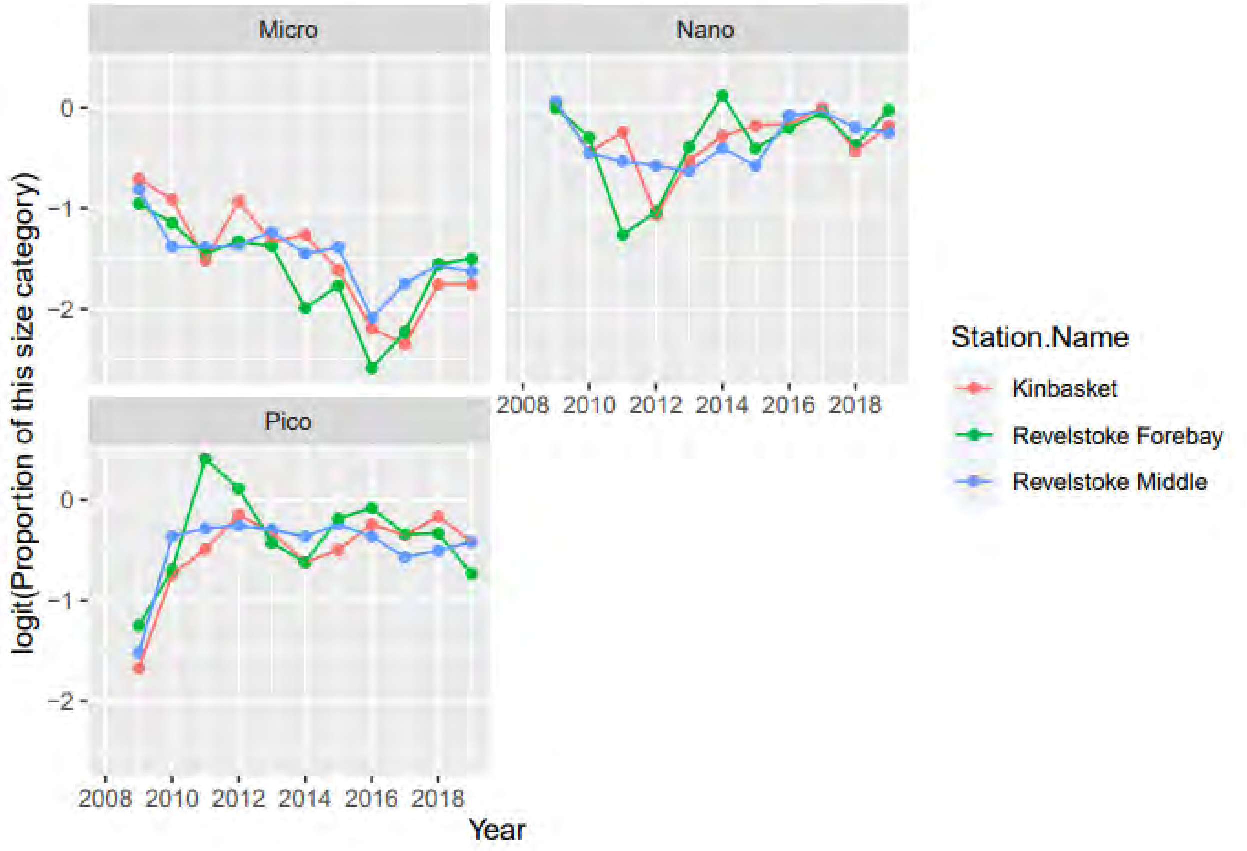

Figure 79. Logit (Proportion of this size category) in Kinbasket Forebay, Revelstoke Forebay and Revelstoke Middle.

In summary, a statistically significant increasing trend of primary productivity rates was measured over the study period in Kinbasket and Revelstoke Reservoirs. The size structure of phytoplankton production also changed over time with a reduction in microplankton production, a shift to the prevalence of nanoplankton production starting in approximately 2012, and finally a levelling off in picoplankton production after an increase from 2009 to 2011.

MQ 2-1 What are the trends in annual distribution, abundance, and biological characteristics of kokanee populations in Kinbasket and Revelstoke Reservoirs?

Annual distribution

In Kinbasket Reservoir, age 0 kokanee were found at highest densities in the Main Pool and Lower Canoe zones with all other zones supporting lower and relatively similar densities. One exception is in mean zone densities across the 2008-2019 study period phases relative to 2001-07, which declined in the forebay, Main Pool, Lower and Middle Canoe zones relative to the remaining zones (Figure 1). This may have been related to changes in the relative contribution of fry from spawning tributaries over time; however, the lack of reliable annual system-wide tributary spawner estimates precludes further insight. As suggested by Bray et al. (2013), passive drift of fry in reservoir currents may be the primary mechanism affecting fry distribution, given a lack of supporting evidence for other possible influences, including proximity to spawning sites or local productivity.

The distribution trend for age 1-3 did not demonstrate the same pattern as age 0. Mean densities were relatively similar across zones, with only moderately higher densities in Wood Arm and the Middle Columbia on average (Figure 53). It is expected that food availability is a primary driver of the distribution of age 1-3 kokanee, and while zooplankton data are not available at the scale required to link to kokanee distribution across the entire reservoir, the available data suggests relatively uniform feeding conditions for kokanee (Table 11).

Most years, Bush Pool was functionally dry in terms of kokanee rearing habitat in the spring, requiring re-colonization by age 1-3 kokanee from the downstream zone(s) as the reservoir filled (see Appendix 7.1). Fry would have colonized Bush Pool from upstream tributaries each year, however depending on timing of annual fry emigration as well as Bush Pool re-fill. In some years the majority may have transited through prior to re-filling. The timing at which Bush Pool refilled relative to the annual acoustic survey would have been relevant to the Bush Pool densities observed, but also in the adjacent Middle Columbia Zone, where the displaced age 1-3 kokanee would move to and from. An example was 2019, when Bush Pool did not fill to a level suitable (defined as 10 m in spring; Weir 2022) for kokanee rearing until late June, which likely played a role in the proportionally lower densities of fry and age 1-3 kokanee observed in the summer hydroacoustic survey compared to other years. Conversely, in 2016 the reservoir refilled earlier than most years, and achieved a 10 m depth in Bush Pool by May 1, allowing substantially more time for re-colonization of Bush Pool; correspondingly, the age 1-3 densities were proportionally low in the Middle Columbia and higher in Bush Pool in 2016.

In Revelstoke Reservoir, age 0 kokanee were found at highest densities in the Forebay and Lower Zones, with lower densities in the narrow and riverine-like Middle Zone. This distribution was expected given that Downie Creek is the main fry recruitment area and enters the Lower zone, and fry are vulnerable to transport downstream into the Forebay Zone with reservoir current. The impact of water flow on kokanee fry was particularly evident in 2015, when a steep density gradient was apparent with very low densities in the Middle zone that increased nearly 5-fold by the Lower zone and nearly 10-fold by the Forebay zone. The unusual fry distribution in 2015 corresponded with exceptionally high flow throughout the productive season (Figure 6), that likely caused increased advective drift of fry in reservoir currents towards the forebay. This density distribution was not apparent in 2015 for the age 1-3 kokanee, which are expected to be less directly affected by advective drift in reservoir current. Bassett et al. (2018a) reported an unusual proportion of large kokanee fry in the October trawl sampling in Upper Arrow Reservoir in 2015 and speculated they may have originated from Revelstoke Reservoir based on an assumption of increased entrainment related to the exceptionally high flows throughout the 2015 growing season and supported by the density gradient observed in our summer acoustic survey of Revelstoke that year. With future developments in genetic analysis tools the archived 2015 (or other years) Arrow Reservoir trawl caught fry samples could be analyzed for assignment of proportions to each reservoir and will add to our understanding of entrainment of fry out of Revelstoke.

The age 1-3 kokanee distribution in Revelstoke was similar to the fry distribution with higher densities in the Forebay and Lower zones compared to the Middle zone. On average, the kokanee density distribution by zone corresponded with mean zooplankton density and biomass estimates, which were both higher at the Forebay and Middle limnology stations compared to the Upper limnology station (Table 11). This suggests the age 1-3 kokanee distribution was associated with food availability in Revelstoke, although the habitat in the Middle and Forebay zones is also deeper so presumably more preferred habitat for kokanee.

Similar to Kinbasket, a generally declining trend in densities over time for both age 0 and age 1-3 was found in Revelstoke although the longitudinal trend remained broadly similar.

Abundance

Kinbasket Reservoir age 0 kokanee abundance was relatively stable from 2001-2006 ranging from 6 to 9.5 million, before reaching a time series peak abundance of 14 million in 2007 followed by another high abundance year in 2008. However, in 2009 age 0 abundance declined to 4.5 million, then averaged only 5.5 million and did not exceed ~8 million through to 2019. Bush Pool (zone 9) fry abundances ranged from a high of 350,000 in 2015 to a low of 65,000 in 2019 (see Annual distribution section above related to the interaction of pool level with Bush Pool densities). A key driver of annual fry abundance is egg to fry survival, which is discussed below and in MQ 2-3.

The Kinbasket age 1-3 abundance trend was similar to the fry trend; average abundances were higher earlier in the time series and lower in the latter half. Age 1-3 abundance peaked in 2008 at 3.3 million, the year following peak fry abundance. Age 1-3 abundance stayed relatively high through 2010, then in 2011 declined to close to 1.5 million where it remained through 2015. This period of reduced age 1-3 abundance aligned with three relatively weak fry cohorts from 2009-2011. A primary feature of the age 1-3 abundance trend is the dramatic decline in abundance to a record low of 0.6 million in 2016, after which the population recovered slightly yet remained below 1 million through 2019. A large-scale kokanee die-off was reported in Kinbasket Reservoir in late May 2016 prior to the summer hydroacoustic survey that was linked to the dramatic decline in age 1-3 kokanee abundance that year (Sebastian and Weir 2017). The mortality event would have had an impact on the 2017 age 1-3 population abundance as well, although in-lake survival remained low in 2017 and 2018 which would have dramatically impacted the 2017-2019 age 1-3 abundances.

The Kinbasket spawner trend demonstrated a peak in 2008 and 2009 that corresponded with strong cohorts observed in the fry and age 1-3 trends in prior years. Subsequently, the spawner trend declined though to 2012 then remained relatively low through 2019, particularly in 2014, 2016, and 2017 when the spawner index was less than 140,000. The low abundance in 2016 and 2017 was associated with the May 2016 mortality event. The low spawner abundance in 2014 was a result of very low survival from age 1-2+ between 2013 and 2014, the reason for which is not readily apparent.

A fence[10] was installed at the Columbia River near Fairmont where spawners were collected for egg takes from 2016 to 2018, although in 2018 the spawner return was low and only 144 spawners were collected for biological characteristics. Approximately 1.7 million and 1.3 million eggs were removed in 2016 and 2017, respectively, which was ~ 5% of the total estimated egg deposition for Kinbasket Reservoir each year. For further context, the 2016 and 2017 egg takes harvested only ~25-30% of the eggs that would otherwise have been spawned at or above the fence location, as most spawners were passed above the fence in order to reduce the impact to the local population (and spawning occurs below the fence site in the Columbia as well). Given the low proportion of

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[10] The fence was operated by the Freshwater Fisheries Society of BC (FFSBC) on behalf of the Province of BC as part of an egg collection program for Kootenay Lake kokanee recovery efforts. The FFSBC provided biological sampling data to this project from 2016-2018.

eggs removed relative to the total, we consider the egg takes as minor influences on the 2017-2019 kokanee estimates and inconsequential to the outcomes of our study period.

Revelstoke fry abundance ranged from 0.8 to 2 million from 2001-2008, with peak abundances in 2003 and 2008 at 2.0 and 1.7 million respectively. The key feature of the Revelstoke fry abundance trend was the dramatic decline to only 0.6 million in 2009, then sustained low abundances through to 2019. The Revelstoke age 1-3 abundance trend was broadly similar but demonstrated a greater variability early in the time series, and the dramatic decline to a new low abundance era was not apparent until 2011/2012 for the age 1-3 population. Revelstoke spawner abundance followed a similar pattern as age 1-3 although the variability in the first half of the time series was more severe. The variability in age 1-3 and spawner abundances are a function of erratic swings in survival from age 0-1 and 1-2+. Survival was generally high in the 2008-10 period for either age 0-1 or age 1-2+ or both, leading to a peak in spawner abundance during that period that matches that of Kinbasket. Similarly, both spawner numbers in both reservoirs then trended downwards and remained low through to 2019.

Drivers of abundance trends are discussed further in subsequent sections and in MQ 2-3, including egg to fry and in-lake survival impacts and the 2016 mortality event in Kinbasket. There were no mortality events documented at Revelstoke of similar nature to that observed in Kinbasket in 2016.

Kokanee biomass

Biomass in Kinbasket remained relatively stable between 2001 and 2010, fluctuating between 4.5 and 7 kg/ha. After 2010, biomass declined and surpassed 5 kg/ha only in 2013. Revelstoke kokanee biomass density was less than half of that of Kinbasket on average. The trends are remarkably similar and are correlated, particularly from 2005-2019. After 2005, there were only two years where biomass moved in substantially opposite directions between the two reservoirs: in 2013 when biomass declined to very low levels in Revelstoke but increased in Kinbasket, and in 2016 when the opposite occurred. In 2016, the Kinbasket kokanee population was impacted dramatically by the early season mortality event, that was not observed in Revelstoke. The cause of the diverging biomass trends in 2013 is less apparent, however, it may have been a result of the exceptional high flow observed in Revelstoke in 2012, that would have increased entrainment and led to a reduced population of age 1-3 in 2013. The high 2012 flows are not likely to have had a similar impact on Kinbasket kokanee entrainment given that for the majority of the spring and early summer Kinbasket Reservoir was filling and Mica GS not discharging at a high rate similar to Revelstoke GS (Figure 6). Further, zooplankton monitoring identified that 2012 was an above average year for *Daphnia* in Kinbasket, and below average year in Revelstoke (Figure 49) and feeding conditions in 2012 would have been relevant to the size and biomass of older age class kokanee in 2013.

Common environmental drivers that could have affected both trends include weather-mediated egg to fry and in-lake survival impacts (see MQ 2-3). An important driver of variability in kokanee size and survival is *Daphnia* availability, which is linked to annual temperature (Schalau et al. 2008; Paragamian and Bowles 1995; Reiman and Bowler 1980), indicating that a common driver of the trends could be air temperature (see MQ 2-3 and 3-6). Our analysis of factors affecting in-lake survival for age 0-1 (a key driver of abundance) did not find links to zooplankton variables where included (combined reservoir analysis and for Arrow reservoir); however, it is likely that the spatial/temporal intensity of the zooplankton sampling was insufficient, and the data were too sparse for inclusion in the Kinbasket and Revelstoke analysis.

Egg to fry survival

Egg to fry survival trends in Kinbasket and Revelstoke Reservoirs were remarkably similar, both averaged 14% and the range from 2001-2019 was 4%-34% and 4%-36%, respectively. The nearly identical outcomes suggest generally similar spawning/incubation habitat quality between the two reservoirs. However, a key consideration is that Revelstoke spawners were much larger than those in Kinbasket. Spawner size was an important driver of egg to fry survival in our analysis (Figure 60), where larger spawners tended to result in better egg to fry survival, and vice versa. Accordingly, with smaller spawners (i.e., equivalent to those of Kinbasket) the Revelstoke egg to fry survival would have presumably been lower on average than Kinbasket. Therefore, we can assume that Revelstoke spawning/incubation habitat may have been limited and/or of lower quality than Kinbasket. In contrast, Arrow Reservoir egg to fry survival averaged 20% (range 6-45%) over the same period, indicating superior spawning habitat, particularly given that Arrow spawners are relatively small on average (similar to Kinbasket). Notably, a large component of Arrow habitat is Hill Creek Spawning Channel, where survival is higher due to management of habitat and flow which presumably accounts for the higher average egg to fry survival.

In addition to similar long term average egg to fry survival, the annual trends from 2007-2018 were highly correlated between Kinbasket and Revelstoke (r=0.89). Key drivers of egg to fry survival were egg deposition (i.e., density), spawner size, and February air temperature (Figure 60; Table 3 for assumptions on variable impact). The correlation between trends can be explained by broadly similar spawner abundance trends, leading to similar size trends, and resulting in similar trends in egg deposition. For example, during the 2008-2011 period there were generally high spawner numbers in both reservoirs which, accordingly, were relatively small and which produced large numbers of eggs. As a result, egg to fry survival was very low in both reservoirs over this period leading to generally weak age 0 cohorts beginning in 2009 in both reservoirs (as described above). Further, the impact of winter air temperature (specifically the month of February) on egg survival would have been similar between the two reservoirs.

Although reservoir operations play a role in egg to fry survival by impacting abundance and size through in-lake survival and productivity (discussed subsequently), we are not aware of any direct impacts of reservoir operations on egg to fry survival (e.g., annual variability in inundation of incubation habitat, impacts to tributary access by changing reservoir levels).

While egg to fry survival has played a role in driving abundance trends in both reservoirs, in-lake survival greatly affects abundance as well (and subsequently egg to fry survival as a key compensation mechanism).

In-lake survival

Kinbasket age 0-1 survival was relatively stable from 2001/02 through 2014/15, except for a period of fluctuation from low survival in 2008/09 to a time series high in 2010/11. Age 0-1 survival declined to a low of 5% in 2015/16 because of the mortality event in May 2016, then remained low for two years before returning to near average in 2018/19. Revelstoke age 0-1 survival was variable from 2001/02 through 2007/08 then also exhibited excellent survival in 2009/10 suggesting that a common environmental driver played a role that year, particularly given that nearby Arrow and Kootenay Lake kokanee populations also had high 0-1 survival (see MQ 3-6). The Revelstoke age 0-1 survival trend remained very low from 2010/11 onwards, rarely surpassing 10% through to 2019. This period of sustained low survival was not as apparent for Kinbasket but was similar to both Arrow and Kootenay Lake although for different reasons. Kootenay Lake age 0-1 survival has been extremely low since 2012, owing to extremely high predation resulting from a predator/prey imbalance (Warnock et al. 2021). There was no evidence suggesting that Revelstoke (or Arrow) kokanee are under similar predation pressure. Arrow and Revelstoke kokanee, however, both share sensitivity to high flow via increased entrainment, and both reservoirs sustained higher flow on average since 2012, including two extremely high flow years in 2012 and 2015 (see MQ 2-3 for further discussion of in-lake survival).

Survival from age 0-1 averaged 18% (SD 7%, range 5-37%) in Kinbasket from 2001-2019 versus only 12% (SD 7%, range 5-30%) in Revelstoke. The disparity is presumably related to Kinbasket kokanee being less vulnerable to high flow/entrainment due to the different nature of each reservoir (storage vs run of river, depth of intakes). However, Kinbasket kokanee may still be impacted meaningfully by entrainment given the results of the Revelstoke entrainment study (discussed below under *Relevance of Kinbasket entrainment on Revelstoke kokanee outcomes* section) and because Kinbasket survival was low in comparison with Arrow (2001-19 average 23%, SD 9%, range 11%-45%) and Kootenay (pre-collapse 2001-11 average 27%, SD 13%, range 17%-53%). Kinbasket Reservoir is also much lower in productivity, with long term average zooplankton densities almost half of those in Arrow and a third to a quarter of Kootenay Lake (see MQ 3-6).

In contrast to age 0-1 survival, age 1 to age 2+ survival was similar on average between Kinbasket and Revelstoke at 35% (SD 13%, range 12-57%) and 33% (SD 18%, range 6-63%), respectively. Average survival at the age 1-2+ stage may be similar because entrainment is less relevant to older, larger kokanee. Variability was substantial for age 1-2+ survival for both reservoirs with no clear trends over time, with the exception of the 2005-13 period where the trends appear weakly correlated, though not significantly (r^2=0.21, p = 0.22). However, viewed in relation to Kootenay and Arrow age 1-2+ survival trends, there does appear to be a degree of synchrony in age 1-2+ survival over time among all populations (see MQ 3-6). Drivers of age 1-2+ survival are not clear, although synchronous trends across reservoirs suggests annual weather may play a role, possibly influencing predator/prey interactions. It is important to note that estimating survival from age 1 to age 2 is confounded by an inability to partition age 2 and older kokanee into age specific estimates. The trends in age 1 to age 2+ survival are expected to broadly represent survival trends of age 1 kokanee, although these should be interpreted with some caution.

Kokanee harvest is another possible factor impacting 1-2+ survival rates. Kokanee harvest is likely proportionally higher in Revelstoke reservoir given the established kokanee fishery (Bray and Campbell 2000), proximity to Revelstoke and large sized kokanee, whereas harvest would have been very low in Kinbasket relative to population size due to the remote location and relatively small sized kokanee. Bray and Campbell (2000) estimated the total kokanee catch in Revelstoke from May to September of 2000 at ~7,000 ± 3,500. There was no acoustic survey in 2000 to compare the estimate against, however it was equivalent to 13% (±6%) of the average age 2+ population[11] from 2001-2012 (the period prior to the recent low abundance period, likely most comparable to 2000). Bray and Campbell (2000) also noted that the kokanee harvest estimate was also likely negatively biased. Annual creel data would be required to decipher the role of harvest in the Revelstoke kokanee survival and abundance trends. Further, the catch rate in the recent low abundance period is unknown and may have changed substantially due

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[11] Calculated as the harvest estimate / pre-harvest abundance which was the average acoustic age 2+ population + harvest estimate.

to low kokanee abundance and possibly changing effort, regulations, and angler dynamics with time.

Age at maturity

Camp Creek spawners generally matured as a mix of age 2 and age 3 with a mean age at maturity of 48% age 3 over 21 years of sampling. At Luxor Creek, a tributary to the upper Columbia River near Brisco, spawners returned primarily at age 2, averaging only 7% age 3 over nine years of sampling, and in no year was the % age 3 higher than 18%. The other Kinbasket tributaries sampled were Bush, Wood and the Upper Columbia River, all of which were also dominated by age 2 spawners, although with slightly higher proportions of age 3 than Luxor. Revelstoke spawners, sampled in Standard Creek, were a mix of age 2 and 3 though dominated most years by age 2 spawners and with an average age of maturity of 29% age 3 over 12 years of sampling. Complete spawner sampling length and age statistics by year are provided in Appendix 7.4.

Size

Size data for age 1-3 kokanee are sparse early in the study period (Table 12), however spawner length at age provides a longer time series for both reservoirs and typically better sample sizes (collecting sufficient spawners in Revelstoke was difficult some years due to low numbers resulting in some limited sample sizes).

For Kinbasket, Camp Creek spawner data provides the longest time series. Camp Creek spawners typically return at a larger size than in other Kinbasket tributaries, which may be partly attributed to an older average age at maturity. Camp Creek spawners are also typically larger at a given age than those in other tributaries, the reason for which is not readily apparent. Camp Creek supports very few spawners compared to the other tributaries and is also uniquely located at the far north end of the reservoir. One possibility is that Camp Creek origin kokanee rear for at least part of their lifecycle within Canoe Arm, largely isolated from the remainder of the population, where they grow faster than the majority of the kokanee residing in the remainder of the reservoir. While there were no limnology sampling stations in the middle or upper Canoe Reach to evaluate lower trophic metrics, there is no reason to expect elevated productivity in Canoe Reach compared to the remainder of the reservoir. Rather, it is possible that the larger size of Camp Creek kokanee is a function of different lake entry timing or lower densities at some point while rearing in the reservoir (Canoe densities are among the lowest but similar to other zones; Figure 52). The long-term trend for Camp Creek closely matches the trend for the remaining tributaries (Figure 55) indicating they are not entirely isolated in Canoe Reach and their growth is still impacted by the densities in the remainder of the reservoir.

The Kinbasket spawner size trend demonstrates several peaks and valleys of mean length since 2000, with a range in mean size between ~220-280 mm. In Revelstoke, the trend from 2007-2019 also demonstrates peaks and valleys, but the spawners were much larger than in Kinbasket, ranging in mean length from ~260-360 mm. The Revelstoke spawner size trend shifted to substantially larger fish from 2013 to 2019. For both Kinbasket and Revelstoke, the expected density dependent growth relationship is apparent (Figure 56) and is the primary driver behind the variation in the mean size at maturity trend, as well as the step-change to very large Revelstoke spawners beginning in 2013.

Relevance of Kinbasket entrainment on Revelstoke kokanee outcomes

A long-standing assumption is that Kinbasket supplies a significant proportion of the kokanee population in Revelstoke through entrainment, apparent in the interpretation of entrainment estimates out of Revelstoke and associated population modelling (Biosonics 2013; Parkinson 2011). Biosonics (2013) estimated annual entrainment out of Revelstoke from July 1, 2010, to June 30, 2011, at approximately 2 million age 0 and 0.25 million age 1 kokanee. These estimates are 2.4 and 1.7 times greater than in-lake acoustic estimates from early August 2010 surveys of 0.9 million age 0 and 0.15 million age 1 kokanee, respectively, which suggests that the vast majority of the kokanee estimated as entrained out of Revelstoke would have been of Kinbasket origin. Notably, the Kinbasket acoustic estimates in 2010 were 4.6 million and 1.7 million age 0 and age 1 kokanee, respectively. If we assume 100% of Revelstoke kokanee lost for each of the age 0 and age 1 cohorts between 2010 and 2011 were all entrained (i.e., no predation or other mortality) out of Revelstoke, the remainder must have originated from Kinbasket. Assuming (arbitrarily) 50% survival of entrained Kinbasket kokanee through Mica GS and then through to Revelstoke GS, and that no Kinbasket kokanee remain to rear in Revelstoke, this would have accounted for 56% and 18% of the age 0 and age 1 Kinbasket populations estimated by our 2010 survey. The proportions appear exceptionally high given the assumptions, which casts doubt on the comparability of the in-lake and entrainment estimates. Regardless, we expect that the number entrained was indeed large proportional to Revelstoke, possibly for Kinbasket as well.

Independent of the entrainment estimates, our data suggest that the kokanee outcomes we observed in Revelstoke over time could have been, or in most years likely were, supported by Revelstoke recruitment alone. For example, our estimates of spawners based on the number of maturing kokanee from summer acoustic and gillnet surveys allows for estimation of egg deposition and egg to fry survival reported herein. As discussed above, egg to fry survival trends were very similar in form, on average, and in range between Kinbasket and Revelstoke; therefore, unrealistically high egg survival or atypical variability was not required to achieve the following year fry estimates in Revelstoke. This outcome supports our assumption that both our age 0 and older age class estimates were kokanee of predominantly Revelstoke origin.

We also explored the possible relevance of Kinbasket entrainment with respect to our Revelstoke dataset by including upstream densities in our in-lake survival analysis; however, there was no evidence that Kinbasket entrainment was a factor in Revelstoke in-lake ‘survival’ (see MQ 2-3). In another approach, we found that Kinbasket densities weakly correlate with following year Revelstoke densities (not shown, R^2 0.17 and 0.14 for 0-1 and 1-2+, respectively), a possible indication of an entrainment effect. However, same year cohort densities correlate similarly or better (not shown, R^2 0.39, 0.16, and 0.22 for age 0, 1 and 2+, respectively) which would not be a function of entrainment given survey timing, but rather related to the common habitat and environmental factors causing synchrony in trends discussed throughout this report.

In summary, we expect that entrainment out of Kinbasket could influence our estimates of Revelstoke kokanee metrics and even small proportions of the larger Kinbasket population rearing in Revelstoke could be significant to the Revelstoke population. This may be a factor in any analysis attempting to determine the habitat and operational factors affecting the Revelstoke kokanee population. However, the weight of evidence indicates it is reasonable to assume that the Revelstoke kokanee population does not *require* annual supplementation through Kinbasket entrainment to achieve the magnitude of observed outcomes, and that the outcomes we observed were likely driven by Revelstoke recruitment as opposed to Kinbasket entrainment.

MQ 2-3 What are the key habitat factors that contribute to changes in productivity of the kokanee?

Habitat factors considered as potentially contributing to changes in productivity for kokanee are food supply, reservoir flow, reservoir elevation, spawning habitat, and predation. The way in which these factors affect kokanee growth, survival, and reproductive success culminate in the productivity of the population. We conducted multiple regression analysis on factors that affect egg to fry (E-F) and in-lake survival including variables representing the expected habitat factors of relevance to survival and reproductive success. Kokanee growth/size was a variable in the analysis for E-F survival, but we did not conduct specific analyses on factors affecting kokanee size, primarily due to a paucity of in-lake size at age data. Further, density dependent growth was the key driver of the majority of the variability in size at maturity (Figure 56), so a focus on impacts to density (i.e., survival) is relevant to size outcomes. Links between kokanee food supply and growth have also been well established in the literature and it is widely understood that *Daphnia,* in particular, are key to kokanee growth and size (discussed further below).

Egg to fry survival analysis

Potential factors affecting E-F survival were assumed to be tributary flow during spawning, air temperature, egg deposition, and spawner size (Table 3). Kokanee data from Arrow Lakes Reservoir were also included in the analysis for comparison. Food supply may also be relevant to survival after lake entry; however, zooplankton data were sparse so were not included. Our analysis indicated variables for egg deposition (i.e., density), February air temperature, and spawner size were all important once reservoir effect was accounted for (Table 13; Figure 60), and together explained 62% of the variability in E-F survival across the three reservoirs.

Egg density impacts survival due to redd superimposition when spawners are at higher densities, a factor known to affect the reproductive success of salmonids (Fukushima et al. 1998). Spawner size is also deemed important although it correlates with egg density, where higher numbers of spawners deposit higher numbers of eggs but are also smaller than spawners at low density. Regardless, spawner size may have a relatively independent influence on egg survival due to larger spawners utilizing higher quality habitat to build redds. Larger spawners can utilize larger substrate in deeper, more stable stream habitat with better flow, improving embryo survival by reducing risk of redd scouring or impacts of sedimentation (Thorne and Ames 1987; Montgomery et al. 1996; Newcombe and Jensen 1996; DeVries 1997). Further, low flows combined with cold temperatures can cause inter-gravel freezing and embryo mortality (Cope and Macdonald 1998), which would impact redds in shallower edge habitat used by smaller spawners. This impact pathway also aligns with our finding that February air temperature was an important variable, where colder average February temperatures result in reduced E-F survival. We were not able to acquire reliable flow data to represent spawning tributary water levels for the winter period, however we suspect that flow/water level may also have been relevant in combination with cold temperatures.

Egg to fry survival rates were a key factor driving cohort abundance, and accordingly our understanding of kokanee productivity for these reservoirs. Common environmental factors that contribute to changes in E-F survival outcomes played a significant role in our observation of synchrony in trends of kokanee metrics as described in MQ 2-1. The role of various habitat factors that may culminate in changes to kokanee size and density, and accordingly E-F survival, are discussed below.

In-lake survival analysis

Potential factors affecting in-lake survival were assumed to be reservoir outflow, air temperature, prey availability (zooplankton metrics), minimum reservoir elevation (depth and pelagic area), kokanee density, maximum local inflow, total kokanee biomass, and upstream kokanee densities (Table 4). Kokanee data from Arrow Lakes Reservoir were also included in the analysis for comparison. The age 0-1 survival period was the focus of analysis and is discussed below. A similar analysis approach was attempted for age 1-2+ survival but did not result in meaningful outcomes, possibly due in part to the inability to partition age 2 and age 3 fish affecting the integrity of the estimates (see methods section 2.4.9 – Survival).

Two sets of model fits were performed: first all reservoirs were included for a single combined reservoir model, and second a separate model was fit for each reservoir. The combined reservoir analysis benefitted from a larger number of observations and resulted in a regression model including cumulative annual outflow and January to March average air temperature that predicted 70% of the variability in survival for the pooled data (accounting for reservoir effect). Outflow was an expected variable of importance given observations in simple linear regressions for Arrow and to a lesser degree Revelstoke (see reservoir flow section below), and because flow has been linked to entrainment and reduced survival in other studies, including the Revelstoke entrainment study (Baldwin and Polacek 2002; Biosonics 2013). January to March air temperature (late winter) was not anticipated to be a primary driver of survival outcomes, although the relevance of the season has become increasingly evident throughout our study. Late winter air temperatures are highly correlated to timing of reservoir thermal stratification (Figure 16), which has important implications for zooplankton productivity (Paragamian and Bowles 1995). Schalau et al. (2008) found that temperature was the dominant factor driving interannual variability of *Daphnia* population dynamics during spring. This may have been the primary pathway linking kokanee survival to air temperature, given that zooplankton resources have been linked to kokanee survival (Reiman and Bowler 1980; Paragamian and Bowles 1995). Although zooplankton metrics included in the analysis did not appear relevant, it is possible that the spatial/temporal intensity of the zooplankton sampling was insufficient for statistical power. Stratification timing would also be relevant to predator/prey interaction dynamics (zooplankton/kokanee/piscivores), and accordingly predation rates on kokanee, although the way these interactions could unfold would be complex and are unknown.

Winter air temperature also affects the extent and duration of ice cover (Table 6), particularly on Kinbasket Reservoir that can freeze completely in cold years as early as February. Revelstoke Reservoir will also freeze, but ice cover is typically not complete, even in very cold years. Ice and snow cover limits light penetration, and therefore, production of plankton. Steinhart and Wurtsbaugh (2003) found that ice cover limited food production reducing kokanee forage supply and their ability to consume enough food. Reduced food supply can affect kokanee behaviour as they forage less to minimise predation risk (Steinhart and Wurtsbaugh 2003). Ice cover in Kinbasket could force more fish into the Main Pool area as it is the last to freeze and could increase predation in winter.

While informative, the combined reservoir analysis may suffer from "ecological fallacy” (https://en.wikipedia.org/wiki/Ecological_fallacy) where the analysis on combined data does not translate into the same results when applied to individual groups. Accordingly, the results from the separate reservoirs did not align entirely with the combined reservoir analysis. While the separate reservoir analysis was the preferred route to meet the objective of improved understanding of in-lake survival drivers, the number of observations per reservoir was a limiting factor (n=17 for Arrow and Kinbasket and n=18 for Revelstoke). Further, zooplankton data were omitted from the Kinbasket and Revelstoke models because of the limited time series.

Similar to the combined reservoir model, outflow remained the primary predictor variable for Arrow (annual outflow) and was the second (winter) and third (annual) most important variable for Revelstoke; although, for Revelstoke, outflow did not meet a commonly applied threshold to determine variables of importance. Outflow did not appear as a variable of importance for Kinbasket. These outcomes align with our expectations and understanding of these reservoirs. While outflow was not anticipated to be highly important for Kinbasket due to the nature of the reservoir (storage), it is notable that outflow did not appear highly important for Revelstoke, given Revelstoke is a run-of-river type reservoir where kokanee are entrained at high rates and where increasing flow rate increases entrainment rate (Biosonics 2013). Winter outflow was ranked of slightly higher importance than annual outflow for Revelstoke, although the two are correlated, and we were not able to include a summer season flow variable due to the Revelstoke survival interval being based on mid-summer surveys. Accordingly, based on this analysis, we do not attempt to infer that winter outflow is of particular relevance to Revelstoke kokanee survival relative to other periods of the year.

Similar to the combined reservoir analysis, air temperature was a variable of importance in the individual reservoir analyses though was also not consistent among reservoirs. Late winter air temperature came through as the lone variable of importance for Kinbasket, while spring (April-June) air temperature was the highest ranked variable for Revelstoke (though still did not meet the threshold defining terms of importance). Neither air temperature metric appeared important for Arrow. Possible late winter air temperature interactions with kokanee survival are discussed above, although it is not clear why this variable would be relevant only to Kinbasket, or, similarly, why spring air temperature would be most relevant to Revelstoke. However, spring air temperature would also be relevant to the rate at which the thermocline strengthens and deepens and the epilimnetic water warms, affecting zooplankton prey dynamics (Schalau et al. 2008). Regardless, it appears that early season weather, including well in advance of the productive season, plays a role in kokanee survival.

Maximum local inflow was included in the analysis since it was a relevant variable in lower trophic analysis and represented climatic variation through the magnitude of the freshet peak. While not deemed important to outcomes in the combined reservoir analysis or for Kinbasket or Revelstoke survival, it was important for Arrow. Maximum local inflow correlates only weakly with annual reservoir outflow for Arrow (R^2= 0.2), which was considered as a factor. Other ways in which annual maximum local inflow could affect kokanee survival are unclear; regardless, it appeared to be relevant only to Arrow reservoir kokanee.

There was no evidence for density dependent survival for the age 0-1 stage in our analysis (neither intra- nor inter-cohort), nor was there evidence that upstream densities in Kinbasket were relevant to outcomes for Revelstoke. Our assumption for including the upstream densities variable was that entrainment rate out of Kinbasket would be positively correlated with density, and higher entrainment of age 0 out of Kinbasket could result in higher apparent 'survival' of kokanee if entrained Kinbasket fish were counted as Revelstoke fish at age 1. There has been a historic perspective that kokanee recruitment in Revelstoke may be limited to the degree that the observed population level would require annual supplementation from entrained Kinbasket kokanee. While these findings do not refute that perspective, neither do they support it. See MQ 2-1 - *Relevance of Kinbasket entrainment on Revelstoke kokanee outcomes* for further discussion.

Unfortunately, no data were available for predators/predation rates for inclusion in the analysis. Indirectly, we attempted to capture an element of predator/prey interactions related to reservoir operations by including minimum reservoir elevation as a variable, as water level fluctuations may affect predator-prey interactions (e.g., Klobucar and Budy 2015). Predation pressure is likely to increase due to increased prey vulnerability at low reservoir levels when prey densities are highest (McMahon and Bennett 1996) and visual foraging efficiency is greatest when not limited by light or turbidity (Beauchamp et al. 1999). Thus, predation risk could be amplified at low reservoir elevations in late winter/early spring when kokanee are at higher densities due to the reduced habitat area and are more visible due to the relatively high water transparency prior to freshet. This variable did not show relevance for Revelstoke, which was anticipated due to the very small annual fluctuation in pool level. Minimum elevation did not meet the threshold as a variable of importance for Arrow or Kinbasket either, although it was the second most important variable for Kinbasket, hinting at the possibility there may be some influence of pool level on survival. However, this outcome is opaque, particularly considering the relationship was negative where higher minimum pool levels corresponded with lower survival.

Overall, we conclude that the regression analysis confirmed our previous interpretation of factors affecting age 0-1 kokanee survival in these reservoirs, although did uncover the unexpected driver of winter and spring air temperatures. Unfortunately, there were no predator/predation rate data available to include in the analysis. Regardless, we did find a reasonable amount of the variation in survival from age 0-1 could be accounted for without those data in Arrow (71%) and to a lesser degree Kinbasket (46%). For Revelstoke, the primary age 0-1 survival drivers were not revealed, which could be a function of lacking predator data, although we have no reason to believe predation pressure is substantially different in Revelstoke than the other reservoirs (and may in fact be less relevant as Revelstoke is not known as a piscivore fishery compared to Arrow and Kinbasket). Rather, it could be that there is more measurement error in the Revelstoke data owing to the exceptionally low densities, that zooplankton data were not included in the individual reservoir analysis, or that Kinbasket entrainment affects Revelstoke outcomes in an undetermined way (See MQ 2-1 - *Relevance of Kinbasket entrainment on Revelstoke kokanee outcomes* for further discussion). Finally, it is likely that the small number of observations was a limiting factor in our analysis for all reservoirs.

Food Supply

Daphnia are the preferred food source for kokanee, affecting growth and survival (Scheuerell et al. 2005; Reiman and Bowler 1980; Paragamian and Bowles 1995). Kokanee size is a key factor driving productivity by culminating in changes in fecundity and egg to fry survival (see above). We did not study kokanee diet intensively but did evaluate a very small sub-sample of stomachs from kokanee captured in gillnets (set in July/August) that confirmed *Daphnia* were a key prey source for both juvenile and adults, representing 98% to 100% of the stomach contents despite lower proportions in the pelagic samples. There were also rare cases of kokanee with stomachs full of terrestrial insects noted from the gillnet samples. Kokanee are known to consume a variety of prey items, but they still preferentially select *Daphnia* when they can, even when at low abundance.

In Bray et al. (2018), we presented simple linear relationships between *Daphnia* and kokanee size and biomass and found generally weak or no relationships for kokanee biomass and moderate to strong positive correlations between *Daphnia* and spawner fork length. However, we noted these relationships would be affected by variable and unquantified grazing impacts, and the key insight was the similarity observed between Revelstoke and post-2012 Kootenay Lake (i.e., post-kokanee collapse; Warnock et al. 2021), providing evidence for Revelstoke Reservoir functioning below carrying capacity for kokanee. The inclusion of data to 2019 results in similar relationships between kokanee and *Daphnia* (not shown) and our interpretation remains the same; i.e., there is evidence for Revelstoke kokanee functioning below carrying capacity since ~2013, and *Daphnia* play a key role in kokanee productivity. Accordingly, factors that affect *Daphnia* productivity will contribute to changes in productivity of kokanee (see MQ 3-5 for lower trophic analysis).

Copepods are available as a food source for kokanee throughout the year and usually peak in abundance earlier in the productive season than *Daphnia* (Figure 48). Copepods (and other prey items) are known to be consumed when the preferred *Daphnia* are not available (Clarke et al. 2004), and they can sustain kokanee growth and survival, particularly for kokanee fry (Klein et al. 2020; Clarke and Bennett 2002).

Correlations between copepod seasonal average density and kokanee biomass density and age 0-1 survival for Kinbasket, Revelstoke, and Arrow Reservoirs with data to 2016 were examined by Bray et al. (2018) and generally moderate positive correlations were found. Including data to 2019, we found similar outcomes (not shown), suggesting that kokanee biomass and survival may be influenced by copepod productivity and/or kokanee and copepod metrics may co-vary due to other factors such flow (see below). Copepod density variables were also included in our analysis of factors affecting age 0-1 survival, although only for the combined analysis and the Arrow analysis due to limited data for Kinbasket and Revelstoke. These did not appear relevant; however, it is possible that the spatial/temporal intensity of the zooplankton sampling was insufficient. While a cause-and-effect relationship between kokanee metrics and copepod density was not demonstrated in our data, observations in other studies of kokanee reliance on copepods for fry or when *Daphnia* are scarce, suggests that copepods could be important to kokanee productivity. Accordingly, factors that influence copepod productivity are also likely to affect kokanee (see Reservoir flow and elevation sections below, as well as MQ 3-5 for lower trophic analysis).

Reservoir flow

Figure 80 illustrates the annual cumulative outflow values for each of Kinbasket, Revelstoke, and Arrow Reservoirs, representing an annual time period that aligns with the kokanee survey timing and corresponding survival period interval (July/August for Kinbasket and Revelstoke, and October for Arrow). The three highest outflow points occurred in 2011/12, 2012/13, and 2014/15, which generally corresponded with years of below average kokanee abundance, biomass, and survival, particularly for Revelstoke and Arrow. Conversely, cumulative outflow was below average from 2008-09 to 2010-11, a time frame that corresponded with generally average or better outcomes for kokanee metrics. Annual outflow was below average only one year (2018-2019) after 2009-2010. As a result, there appear to be two relatively distinct eras for outflow: 1) lower flows on average prior to 2010 and 2) higher flows after 2010 (13% higher for Kinbasket and 11% higher for Revelstoke and Arrow). The two-year moving average is also shown in Figure 80 in acknowledgment that ecosystem processes that occur in any given year are often linked to the adjacent years.

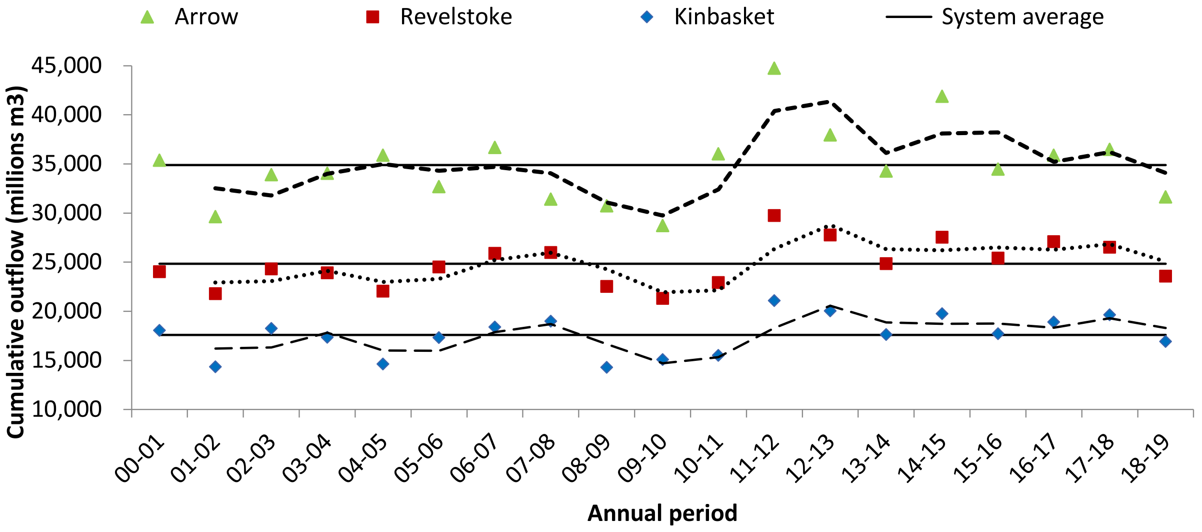


Figure 80. Cumulative outflow from August 1st to July 31st the following year for Kinbasket Reservoir (Mica Dam), Revelstoke Reservoir (Revelstoke Dam), and from Oct 1st to Sept 30th the following year for Arrow Reservoir (Hugh Keenleyside Dam) in millions of cubic metres per second. The hatched lines are 2 period moving averages.

Figure 81 illustrates the relationships between cumulative annual outflow and kokanee survival and copepod seasonal average density. For kokanee survival (Figure 81a) there was no apparent relationship for Kinbasket and negative correlations for Revelstoke and Arrow, which aligns with the in-lake survival analysis results discussed above. A secondary outcome demonstrating the relevance of flow to Revelstoke kokanee was the apparent impact of extremely high flows on age 0 distribution in 2015, which, in conjunction with evidence from the Arrow acoustic survey that fall suggested substantial entrainment occurred (see MQ 2-1 – annual distribution). Cumulative annual outflow was also correlated with kokanee total biomass in Revelstoke (R^2 0.25, $p < 0.05$), although not for Kinbasket or Arrow (not shown).

For copepod densities, there were very similar negative relationships among all three reservoirs with R^2 values around 0.2 (Figure 81). The relationships were not significant for Kinbasket and Revelstoke (p=0.20 and 0.17, respectively) but was nearly significant for Arrow (p=0.051), possibly due to a larger sample size in Arrow (n=19 in Arrow vs n=7 in Kinbasket and Revelstoke). While these relationships are relatively weak, they do suggest that outflow could be relevant to copepod outcomes. Conversely, outflow was not found to be of relevance to copepod outcomes in the lower trophic analysis (MQ 3-5) for Kinbasket. This discrepancy is likely due to a difference in the form of these metrics in each case. Here we show seasonal average copepod density and cumulative annual outflow, whereas the lower trophic analysis used all station and monthly copepod data and total and maximum monthly outflow. Notably however, Mica GS outflow was included in the Revelstoke analysis (labeled Main Inflow) and was a significant predictor for several zooplankton community outcomes for Revelstoke Reservoir (other cladoceran and total zooplankton density, and copepod and total zooplankton biomass). Coincidentally, Campbell et al. (1998) found that in Newfoundland reservoir copepods were more susceptible to outflow entrainment than *Daphnia*.

There was no relationship apparent between cumulative annual outflow and *Daphnia* density for any of the three reservoirs (not shown), although we expect that cumulative outflow may not be the most appropriate variant of the flow metric to evaluate against *Daphnia* metrics. *Daphnia* are present in pelagic sampling in very low numbers up until mid-summer and are expected to be influenced primarily by factors that occur within, or in closer proximity to, the productive season, such as temperature (Schalau et al. 2008).

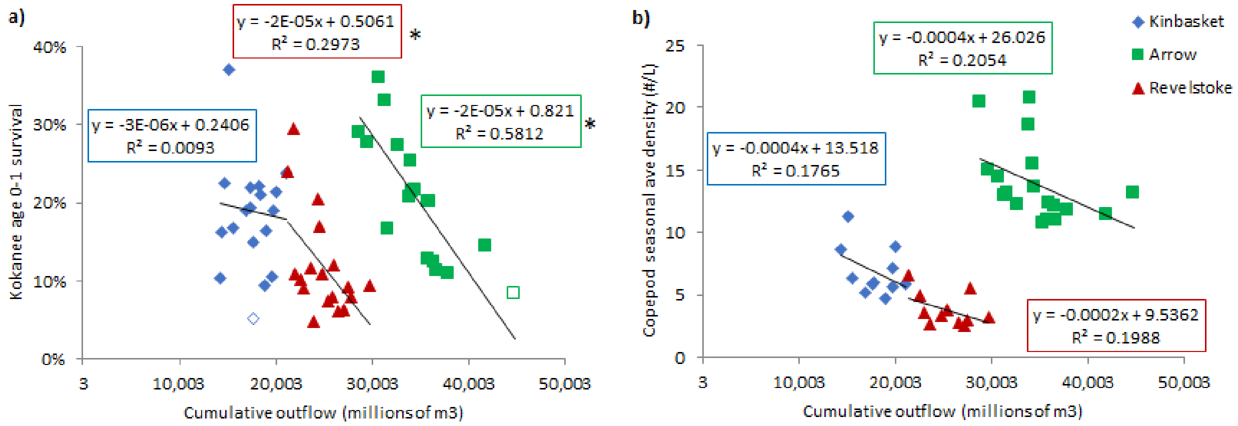


Figure 81. Relationships between annual cumulative outflow (millions of m^3) and a) kokanee a) kokanee age 0-1 survival and b) copepod seasonal average density (#/L)). Cumulative outflow is the sum of daily outflow values between August 1st to July 31st the following year for Kinbasket Reservoir (Mica Dam), Revelstoke Reservoir (Revelstoke Dam) and from Oct 1 to Sept 30 for Arrow Reservoir (Hugh Keenleyside Dam). All available data from 2001 to 2019 are presented. Kokanee data for Kinbasket in 2016 and Arrow 2012 were omitted due to large-scale spring mortality events and are presented as hollow points in panel a. *Denotes statistical significance at $p<0.05$.

The similarity of outcomes between Arrow kokanee and Revelstoke kokanee survival in relation to cumulative annual outflow lends strength to the relevance of cumulative annual outflow as the broad driver of outcomes as opposed to finer scale operational factors, such as short-term peaking. The potential for the minimum flow (implemented late 2010) at Revelstoke GS to influence pelagic production or kokanee entrainment is unknown. A detailed evaluation similar to the entrainment study by Biosonics (2013) would be required to understand any of these finer scale impacts to kokanee entrainment.

Reservoir elevation (pelagic habitat)

Reservoir elevation was included in the in-lake survival analyses in the form of minimum reservoir elevation under the assumption that predator/prey interactions may be affected by changes in habitat (water depth, volume) and accordingly density at low pool and is discussed in detail above. Ultimately, the analyses did not provide any conclusive evidence that minimum pool elevation is a key driver of kokanee survival.

In our previous synthesis reports, (Bray et al. 2013, 2018) we discussed relationships between summer pool elevation and age 1-3 kokanee abundance, which showed weak negative linear relationships (R^2=0.2). These relationships disintegrated with the inclusion of data through to 2019. Summer pool elevation (at time of the acoustic survey, generally near the 90% max pool level or greater) was also plotted against age 0-1 survival in Kinbasket, but no relationship was apparent (not shown). For insight into whether pool elevation dynamics in Kinbasket over the course of the year had an influence on kokanee productivity through impacts to lower trophic productivity/prey supply, we refer to the outcomes of the lower trophic analysis (discussed in detail subsequently in MQ 3-5). Reservoir elevation, in the form of monthly reservoir water elevation, was found to be a variable of importance for lower trophic primary productivity as well as for copepod density and biomass (and total zooplankton density which is largely driven by copepods). Higher monthly pool levels were negatively associated with both phytoplankton and copepod outcomes, which is counter-intuitive given the assumption that higher pool levels should result in more pelagic productivity potential. However, the associations were likely spurious rather than causal and are discussed further in MQ 3-5. There is no indication that reservoir elevations were a factor in secondary productivity changes that would affect kokanee outcomes. Further, there was no evidence that reservoir elevation affected *Daphnia*, which are critical to kokanee growth and productivity. Given the lack of convincing outcomes from the lower trophic analysis that reservoir elevation during the productive season was influential in secondary productivity, we do not expect that reservoir elevation was a key driver of kokanee productivity based on our period of study and available data.

Reservoir elevation was also considered as a factor potentially impacting access to spawning habitat and/or inundation of kokanee redds for Kinbasket, although was not considered of consequence (see spawning habitat section below).

A factor affecting kokanee distribution in Bush Pool and the adjacent Middle Columbia zone is reservoir elevation (variation and timing – see MQ 2-1, Annual distribution), although if there were significant impacts on kokanee productivity from kokanee having to move out then re-colonize Bush Pool (or other low gradient dewatered habitat) after re-fill, they were not apparent.

In summary, the weight of evidence suggests that reservoir elevation was not a key driver of kokanee outcomes based on our period of study and available data.

Spawning habitat

In general, populations with small spawner sizes signal that spawning habitat is not limited. Although Kinbasket spawners have varied in length, they were relatively small on average, similar to other nearby populations, like Kootenay and Arrow where spawning habitat is not considered limiting. Further, our observation of abundant viable spawning habitat availability during spawner surveys also indicates spawning habitat is not limiting.

Conversely, Revelstoke does have atypically large kokanee from a regional perspective, suggesting limiting factors that may include spawning habitat. In-lake survival impacts exert substantial influence on Revelstoke spawner abundance (and accordingly size) in Revelstoke and are the primary driver of the significant increase in size post 2012. However, spawning habitat limitation cannot be entirely ruled out as a contributing factor in the lower density/larger size of kokanee, at minimum prior to the recent period of low spawners/larger sizes. Observations during spawner sampling flights were that spawning habitat in Revelstoke is limited to primarily Downie Creek (although other creeks do support smaller numbers), and extensive stable side channels are lacking, meaning fish are more reliant on using mainstem channels with larger substrates and higher flow. Accordingly, there may be limited suitable habitat for smaller kokanee, and potentially for larger kokanee, although we do not have quantitative data on total available spawning habitat. Notably, E-F survival in Revelstoke was very similar to Kinbasket on average, suggesting similar quality habitat. However, once spawner size was considered it was apparent that the habitat was unlikely equivalent (see egg to fry survival analysis section above and in MQ 2-1).

Reservoir elevation was also considered as a factor potentially impacting access to spawning habitat and/or inundation of redds for Kinbasket. Our observations during spawner sampling flights indicated that reservoir elevation had no impact because the majority of spawning takes place well above the reservoir full pool elevation, and no barriers were present for the spawning tributaries regardless of pool elevation. When pool elevations were lower a very small number of redds were observed in side channels exposed in the upper drawdown zone at the Bush River, however the total contribution would be insignificant to the total spawning habitat and number of spawners in Bush River and the total population of Kinbasket Reservoir.

Predation

Predation can have a significant impact on kokanee populations, including driving kokanee populations to extremely low abundance (Warnock et al. 2021, Martinez et al. 2009). In Kinbasket and Revelstoke, we expect the dominant pelagic piscivore species to be Bull Trout, which were consistently encountered in our pelagic gillnet sets targeting kokanee (Table 12). Large-bodied piscivorous Rainbow Trout may also be present in Kinbasket, although likely in relatively low numbers based on regionally low catch rates in a short duration tagging study by Caley and Warnock (2016). Large bodied piscivorous Rainbow Trout were not documented in a creel survey of Revelstoke in 2000 (Bray and Campbell 2000), however we have seen evidence of this ecotype caught on rare occasions. Burbot and Northern Pikeminnow are also present in both reservoirs. None of these other piscivores were captured in our gillnetting on either reservoir, although neither are expected to be encountered in the pelagic habitat at depths gillnetted in our study.

Burbot may be moderately abundant based on CPUE comparison to other BC lakes (Kang et al. 2016) and there is no information on Northern Pikeminnow abundance.

Predation is expected to be a significant factor affecting kokanee outcomes; however, no data exist on predator trends for either Kinbasket or Revelstoke. See above for further discussion related to the in-lake survival analysis.

MQ 3-4 If changes in pelagic productivity are detected, are the changes affecting kokanee populations?

Changes were detected in multiple trophic levels over the course of this study. Our monitoring of the first trophic level found an increasing trend in primary productivity and in phytoplankton densities in both Kinbasket and Revelstoke Reservoirs from 2008 to 2019 (Figure 82). At the secondary trophic level, we observed the opposite trend for zooplankton (Figure 82) where a decreasing trend was found for zooplankton density and biomass. Although this trend was not statistically significant, the data clearly show that, except for 2013 and 2016, densities have been at or below the long-term average since 2011. Finally, at the uppermost trophic level monitored in this study, we measured generally decreasing population estimates in kokanee fry and age 1-3 as well declining kokanee biomass (Figure 82) and spawner abundance during the latter half of the study. In summary, increasing productivity of the primary trophic level contrasts with zooplankton and kokanee trends in that higher productivity measured at the phytoplankton trophic level did not correlate with zooplankton (Figure 82), nor did it translate into higher kokanee metrics.

Our current understanding of trophic dynamics includes many widely accepted paradigms, including Lindeman’s Law of 10%. Lindeman (1942) conceptualized a simplistic understanding of ecosystem structure and energy flow where the efficiency of energy transfer in a food chain from one trophic level to the next is approximately 10%. This implies that increases in energy at the first trophic level should transfer up the food chain resulting in increases in the secondary trophic level. Lindeman’s Law of 10% also suggests that primary producers, the foundation of all food webs, set the productivity thresholds for upper trophic levels. If this simplistic understanding was applied to Kinbasket and Revelstoke Reservoirs where we measured increasing primary productivity and phytoplankton densities, zooplankton densities should have been stimulated which in turn should provide better food availability for kokanee salmon. In fact, our study measured the opposite response in the zooplankton community where it appears that the energy from the primary producers may not have transferred up the food chain to zooplankton as reflected in the declining trend in the zooplankton data. This is not surprising since organisms in aquatic communities exist in complex food webs where feeding strategies are often mixed (omnivores) confounding a simple linear food chain. Our data do not support Lindeman’s Law which agrees with recent studies suggesting that Lindeman’s Law of 10% may vary greatly and is dependent on many more factors than trophic position in a food chain.

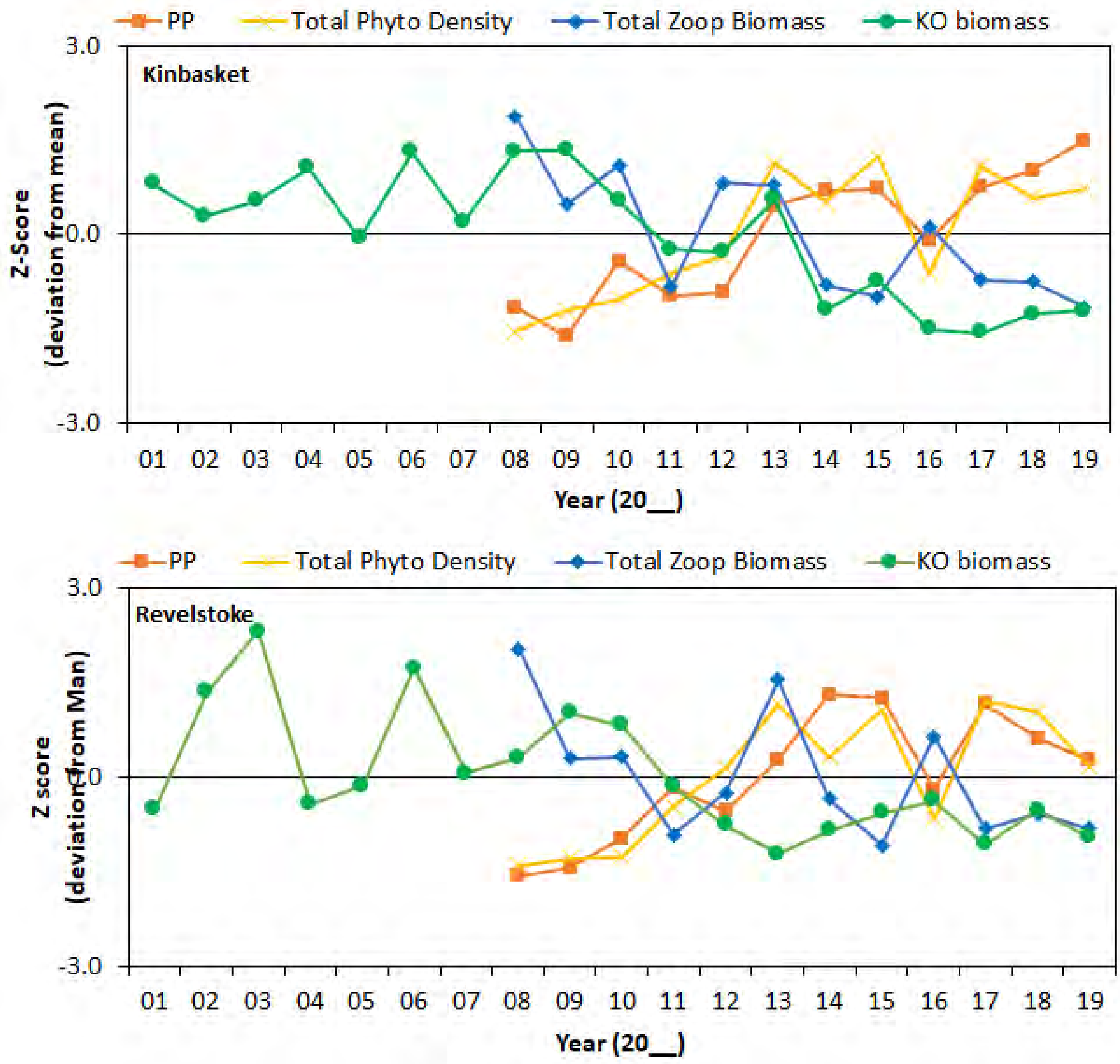


Figure 82. Standardised trends for primary production, total phytoplankton density, total zooplankton biomass, and kokanee biomass for Kinbasket and Revelstoke Reservoirs.

We explored other hypotheses to explain the trends in our data. One commonly cited hypothesis widely used in limnological literature is that of the trophic cascade in which changes at upper trophic levels are predicted to cascade down to the lowest level of the food chain (phytoplankton). Lazzaro (1987) and Northcote (1988) provided support for the cascading effects of planktivorous fish on the zooplankton community, therefore, if the trophic cascade hypothesis applies to Kinbasket and Revelstoke Reservoir, declining planktivore populations (kokanee) over the course of the study should relieve grazing pressure on zooplankton, increase zooplankton abundance which would then depress phytoplankton through increased grazing. However, our study results did not find this response; we found a declining trend in the zooplankton community suggesting little regulation of zooplankton by planktivorous kokanee. It is important to note that the trophic cascade hypothesis as proposed by Carpenter et al. (1985) presented no data to support their hypothesis. Unfortunately, since this time the trophic cascade hypothesis has evolved into a widely accepted paradigm even though many studies have failed to provide empirical support. Wetzel (2001) criticized the cascading trophic interactions hypothesis as highly simplistic and one that often fails to operate in natural pelagic ecosystems because of the multitude of compensatory mechanisms that arise. Reynolds (1994) examined 33 whole-lake experiments, finding only 11 out of 33 experiments supported the trophic cascade hypothesis and concluding the trophic cascade theory cannot be regarded as generally valid. Drenner and Hambright (2002) reviewed the available literature testing the trophic cascade hypothesis and found the majority of the studies (10 out of 17) failed to provide supporting evidence. They, and Benndorf et al. (2002), also suggest that in oligotrophic systems there is little chance of detecting trophic cascade effects. As Kinbasket and Revelstoke Reservoirs are classified as oligotrophic it is possible that the effects of changing grazing pressure by planktivorous kokanee are not detectable. Regardless, the zooplankton trend data in Kinbasket and Revelstoke Reservoirs clearly does not provide any evidence of trophic cascade or top-down control by planktivorous kokanee.

Our data show that zooplankton trended downward, and, since 2011 (with exception of 2013 and 2016), zooplankton were below the long-term average for the majority of the study years despite seemingly favorable conditions of the primary trophic levels (Figure 82). The phytoplankton community was dominated by smaller size classes (<20 µm, picoplankton and nanoplankton) which is commonly observed in oligotrophic ecosystems. The prevalence of picoplankton productivity increased from 2009-2012 then leveled off at an elevated state for the remainder of the study (Figure 79). This was in contrast to nanoplankton productivity, the size class readily consumed by *Daphnia* sp., where the relative importance decreased from 2009-2012 and then levelled off at a similar level as picoplankton. From 2012-2019, picoplankton and nanoplankton productivity were nearly equal with only up to 4% difference between the two size classes. The difference between the two reached 4% at the forebay stations and only 1% at Revelstoke Middle. The increase in total phytoplankton density observed in both reservoirs from 2012-2015 can be accounted for by an increase in two major taxonomic groups of small-celled organisms: blue-greens and greens. It is plausible that the elevated productivity did not readily transfer to secondary productivity due to the large contribution of these small-sized cells that are metabolically active with high respiration rates, and that are generally consumed by small ciliates and rotifers.

Results presented in the next section for MQ 3-5 show that the primary (phytoplankton) and secondary (zooplankton) trophic levels are driven by different variables operating at different time scales. The major drivers at the primary trophic level are yearly climate related variables such as winter precipitation, spring runoff, and air temperature. These variables change on a yearly basis rather than on a monthly or seasonal basis. In contrast, the secondary trophic level is driven more by climate related variables that do change on a monthly or seasonal scale such as photic zone temperature, inflow, and nutrient load. The multivariate analysis clearly shows that phytoplankton and zooplankton are driven by different variables, so it is not surprising they are not correlated.

We explored links between zooplankton (namely, copepods and *Daphnia*) and kokanee survival, biomass, and size, however, a cause-and-effect outcome identifying zooplankton as the key driver of kokanee trends was not uncovered. Rather, we found that common annual weather factors (affecting egg to fry and in-lake survival), in conjunction with lake specific factors independent of zooplankton (high flow/entrainment in Revelstoke, the 2016 mortality event in Kinbasket) were the primary drivers of the decline in kokanee trends in the latter half of our study period. We expect that zooplankton outcomes may have contributed to, but did not direct, the kokanee trends over our study period. For example, egg to fry survival may be affected by zooplankton directly (though we did not test that due to data limitations), or indirectly by contributing to kokanee spawner size, but in both cases the contribution would be less than other factors (density primarily drives kokanee size trends, and our egg to fry survival analysis indicated most of the variability was explained without zooplankton variables). Accordingly, regardless of what the trends in primary or secondary productivity were, independent factors of a higher order were responsible for sustaining the depressed state of kokanee after ~2010.

In summary, changes were detected in multiple trophic levels over the course of this study, and we did not detect a direct link between primary trophic levels and kokanee populations. It appears that the increases in phytoplankton productivity did not stimulate macrozooplankton productivity, and that zooplankton outcomes may have contributed to the observed kokanee trends but did not direct the kokanee trends. Our data also provide evidence that generalized hypotheses, such as Lindeman's Law of 10% and the trophic cascade hypothesis, do not apply to Kinbasket and Revelstoke Reservoirs over our study period. A longer time series and sampling at a higher resolution, including the microbial food web, may be required to understand the ways in which changes in primary productivity between discrete time periods would culminate in changes at higher trophic levels.

MQ 3-6 How do pelagic productivity trends in Kinbasket and Revelstoke Reservoirs compare with similar large reservoir/lake systems (e.g., Arrow Reservoir, Kootenay Lake, Okanagan Lake, Williston Reservoir)?

This study benefits from the collection of limnological and kokanee data on Kinbasket and Revelstoke Reservoirs in a consistent manner that allows for a comprehensive comparison of the two reservoirs. The monitoring protocols were established so that our data will be comparable with datasets for Kootenay Lake and particularly Arrow Reservoir, reservoirs with multi-year monitoring programs of multiple trophic levels intended to assess the effects of large-scale multi-year nutrient restoration programs.

Unfortunately, similar studies over the same time frame are limited for many lakes and reservoirs in British Columbia due to the high cost of monitoring programs, competing priorities, and/or limited personnel. Williston Reservoir, located in the northeast of BC in the Peace River system, would be a logical waterbody to include given its potential similarities to Kinbasket; however, the last comprehensive monitoring program on Williston Reservoir was completed over 20 years ago and spanned only 2 years (1999-2000), and thus prevents a comparison of pelagic production trends with Kinbasket and Revelstoke Reservoirs.

Some large hydroelectric reservoirs in the US have similar longer-term monitoring at multiple trophic levels, in particular Koocanusa Reservoir (Libby Dam) (e.g., Dunnigan, et al. 2021; Sylvester et al. 2019; Yassein and Ward 2018) and Dworshak Reservoir (e.g., Wilson and Corsi 2016) intended to evaluate operational impacts or restoration initiatives on the pelagic ecosystem or downstream riverine reaches.

We focus on comparing Kinbasket and Revelstoke Reservoir trends with Arrow Lakes Reservoir (ALR) and Kootenay Lake (KTL) given their proximity and similar datasets. For some zooplankton trends we also use data from Dworshak Reservoir (DWK) in the United States. A summary of characteristics that relate to pelagic production in these five waterbodies is presented in Table 18 to illustrate both similarities and key contrasting characteristics.

While both ALR and KTL are influenced by dams raising their water level, they were original lakes with pelagic ecosystems functioning for thousands of years compared to the new pelagic habitat in Kinbasket, Revelstoke, and Dworshak Reservoirs that are measured in decades. All these systems support kokanee populations and only ALR and KTL have *Mysis relicta* from introductions beginning in the 1960s and 1940s, respectively (Pieters et al. 2003b; Ashley et al. 1997)

Arrow Lakes Reservoir is formed from the impoundment of two large lakes (Upper and Lower Arrow Lakes) by the Hugh L. Keenleyside Dam (HLK) completed in 1969. It was the first of the

Columbia River mainstem dams to be constructed under the Columbia River Treaty and, although a generating station was added in 2003 by Columbia Power Corporation, its primary purpose is flood control. The ALR is long (240 km), fed by many glacial tributaries, particularly in the north (Upper) basin, and dominated by Columbia River regulated inflow (i.e., outflow from Revelstoke Dam). The reservoir has a potential elevation range of 20 m (average ~14 m) and at full pool reaches to the base of Revelstoke Dam.

Three other large dams on the Columbia River have had a major impact to nutrient supply to the Arrow Lakes: Grand Coulee Dam in the US (1938) that blocked anadromous salmon, and Mica (1973) and Revelstoke (1984) Dams that halted much of the river's suspended load carrying phosphorus that would otherwise have reached the Arrow Lakes. The repercussion of these impoundments to nutrient supply and fishery decline led to restoration actions, notably a continuing program to add seasonal nutrients otherwise lost to upstream reservoirs beginning in 1999 (Bassett et al. 2020a; Pieters et al. 2003a, b).

Kootenay Lake is a large lake not directly connected hydrologically to the other three waterbodies. The lake has two major regulated inflows: Kootenay River at the south (Libby Dam) and Duncan River to the north (Duncan Dam) and was impounded in the 1930s by the Corra Linn Dam on the Kootenay River. The outflow is mid lake through the West Arm to a short stretch of Kootenay River that joins the mainstem Columbia River downstream of ALR. A natural falls on this section of Kootenay River long blocked anadromous salmon to KTL although kokanee remain from post-glacial colonisation. The history of nutrient supply issues to KTL is more complicated than ALR, see Ashley et al. (1997), as well as Bassett et al. (2020b) for more details and current status of Kootenay Lake nutrient restoration activities, and Schindler et al. (2020) for long term changes to lower trophic levels. Recent changes in the trophic dynamics in Kootenay Lake, specifically the collapse of the kokanee population (Warnock et al. 2021) and the large response of the zooplankton community (particularly *Daphnia*) due to relaxation of grazing pressure, provide for an interesting comparison among reservoirs and some illumination on the effects of kokanee grazing pressure on the zooplankton community.

Dworshak Reservoir was formed by impounding the North Fork and Little North Fork of the Clearwater River and, like Kinbasket, is a headwater reservoir with no upstream impoundment (Yearsley 2003). Unlike the other waterbodies in Canada, DWK does not receive much glacial inflow and is situated farther south in a drier part of the Columbia River Basin. The reservoir is small in comparison to the others, but deep, and the dam is equipped with the ability to selectively withdraw water from different depths. A nutrient supplementation project was implemented in 2007 and has continued through 2022.

Table 18. Characteristics of Kinbasket, Revelstoke, Arrow Lakes, Kootenay Lake, and Dworshak Reservoirs.

Reservoir	Kinbasket (KIN)	Revelstoke (REV)	Arrow Lakes (ALR)	Kootenay Lake (KTL)	Dworshak (DWK)
Operator/Entity	BC Hydro	BC Hydro	BC Hydro	IJC (IKLBC)[1]	USACE[1]
Year Filled	1976	1984	1969	1931[2]	1973
Downstream Reservoir	Revelstoke	Arrow	Lake Roosevelt	Lake Roosevelt	Lower Granite Lake
Origin and River Basin	Large river (Columbia)	Large river (Columbia)	Two large lakes (Columbia)	Large lake (Kootenay to Columbia)	Large river (North Fork Clearwater to Snake/Columbia
Latitude at Midpoint (°N)	52	51	50	49	46
Reservoir Max Elevation (m ASL)	754.38	573	440.1	532	487.7
Reservoir Area at Full (km^2)	430	115	464	400	69
Reservoir Volume at Full (km^3)	24.8	n/a	38.6	37	4.4
Max Drawdown (m)	47	1.5 (typical)	20	3	47
Max Depth (m)	190	120	290	154	194
Glacial?	Yes	Yes	Yes	Yes	No
Nutrient Additions? (Start Year)	No	No	Yes (1999)	Yes (1992)	Yes (2007)
Dam (impounding)	Mica	Revelstoke	Hugh Keenleyside	Corra Linn[2]	Dworshak
Dam Height (m)	244	175	52	n/a	218.5
Generation Capacity (MW)	2,781	2,480	185	n/a	400
Outflow Depth at Full Pool (m)	68	32	Variable[3]	Variable	62 (variable, selective withdrawal)

N.B. Sources various

[1] IJC=International Joint Commission. IKLBC=International Kootenay Lake Board of Control. USACE=US Army Corps of Engineers

[2] Corra Linn was finished n 1931 but did not start impounding Kootenay Lake until a few years later. Two upstream dams, Duncan (1967) and Libby (1972), had major implications for limiting nutrient supply to Kootenay Lake.

[3] Outflow can originate from Arrow Lakes Hydro, or from HLK low level outlet gates or spillway gates, or through the navigation lock.

Using total zooplankton density for comparison, in absolute measures Kootenay Lake and Dworshak are the most productive of the four systems, followed by Arrow Lakes Reservoir (Lower then Upper), Kinbasket Reservoir, and Revelstoke Reservoir. For example, total annual average zooplankton densities 2009-2019 (May to October) were 18 #/L in Arrow, 9 #/L in Kinbasket, and 5 #/L in Revelstoke. For the same time period in Kootenay Lake total zooplankton density was 36 #/L although this includes both pre and post collapse years. Average zooplankton density pre-collapse (1992-2012) in Kootenay Lake was 28 #/L which is the same as Dworshak from 2009-2019.

To compare trends, available annual data were standardised against the long term mean for: annual primary production rates (Figure 83), annual phytoplankton density (Figure 84), copepod density and *Daphnia* biomass (Figure 85), and kokanee biomass and survival (Figure 86). While absolute measures of pelagic production differ among these reservoirs, the standardised trends show a remarkable synchrony across trophic levels despite the many individual differences among waterbodies (Table 18) and even through the period of significant changes in Kootenay Lake kokanee and *Daphnia* post collapse. This adds further evidence to our analyses and results that broader scale climate and meteorological forces are significant drivers of pelagic productivity trends regardless of in-reservoir operations or other manipulations. For example, while nutrient additions are successful for increasing zooplankton and kokanee biomass in individual systems (Hecky and Guildford 2022), annual variation of relative productivity appear to be more often independent of these within system changes (Figure 85 and Figure 86).

Synchronicity of ecological responses to large scale climate forcing has been documented in both the western North Pacific (Black et al. 2018) and eastern North Atlantic (Straile 2002) and is an increasing focus for climate change studies. Among central European lakes hundreds of kilometres apart and with distinct limnological characteristics, Straile (2002) found synchronous timing of stratification onset that was influenced by the North Atlantic Oscillation (NAO), a climate pattern that is the dominant influence for winter conditions in Europe. The study links the NAO to local weather that influences spring water temperature and thus, by inference, *Daphnia* population dynamics and cascading food web interactions. George (2000) describes the link between winter abundance of copepods and summer *Daphnia* abundance with regional climate patterns driven by the NAO across a series of English lakes. The NAO influences both winter air temperature and winds that in turn affect winter water temperatures and summer stratification depths due to wind mixing creating favourable conditions in years of a strong NAO (George and Hewitt 2006). In the western hemisphere, the Pacific Decadal Oscillation (PDO) has been implicated in changes to lakes in western North America by advancing and extending stratification (Winder and Schindler 2004) and the El Niño-Southern Oscillation (ENSO) has also been found to exert synchronies in limnological variables (Gerten and Adrian 2002).

These findings were possible where researchers had long term datasets that often spanned multiple decades; however, synchronous trends can be affected by the length or specific set of years covered by the dataset and Gerten and Adrian (2002) caution that these large-scale climate patterns are not always the main drivers across lake systems and that more local meteorological factors can be a primary driver. Our trend analyses benefit from the longer time series available for other waterbodies, such as Arrow Lakes Reservoir and Kootenay Lake, that could be used as barometers for regional conditions.

The synchrony observed demonstrates that broad scale climate and meteorological forces are significant drivers of variability in pelagic productivity trends. The role of annual weather as the primary driver of outcomes is particularly evident in certain years or groups of years. For example, air temperature appears to be the key driver of *Daphnia* outcomes, e.g., 2011 (very cold) and 2013 and 2016 (very warm). However, certain years where trends diverge substantially are also informative of where lake specific factors are driving outcomes. For example, *Daphnia* outcomes in 2012 diverge widely among systems, Arrow and Revelstoke were well below average and Kinbasket and Dworshak were well above average. Extreme rainfall occurred in the spring and early summer of 2012 followed by a warm August and September and reservoir flow (discharge) was very high for Revelstoke and Arrow from mid-July onward, but not for Kinbasket or Dworshak. This indicates that while flow may not be a primary driver of the trends most years, it may be the key driver in some circumstances. This type of observation is important and may not be apparent when conducting other types of analysis.

The kokanee trends provide another opportunity to unravel regional weather/climatic drivers versus lake specific factors. All populations experienced one or more years of abnormally high survival in the 08-10 period, presumably related to one or more common, though undetermined, environmental drivers which contributed to above average biomass during that period. From 2009-2012, we observed low egg to fry survival as well (Kinbasket and Revelstoke in particular, Arrow from 2010-2012 to a lesser degree; Kootenay Lake data were unavailable), which is another variable that can be influenced by annual weather. Subsequently, a very cold year and lower survival (and low zooplankton prey resources) in 2011 culminated in a steep decline to below average biomass in all systems by 2012. From 2012-2019, however, each lake experienced a variety of unique factors not clearly linked to regional weather/climatic drivers. Kootenay Lake kokanee became entrenched in a predator pit, Arrow and Kinbasket underwent large scale die offs (likely disease related and 4 years apart), and Revelstoke and Arrow shared the common impact of higher reservoir discharge from 2012-2018. Accordingly, while strong climatic drivers may have initiated a period of high then rapidly declining kokanee biomass, other factors then drove outcomes in a common direction for multiple years.

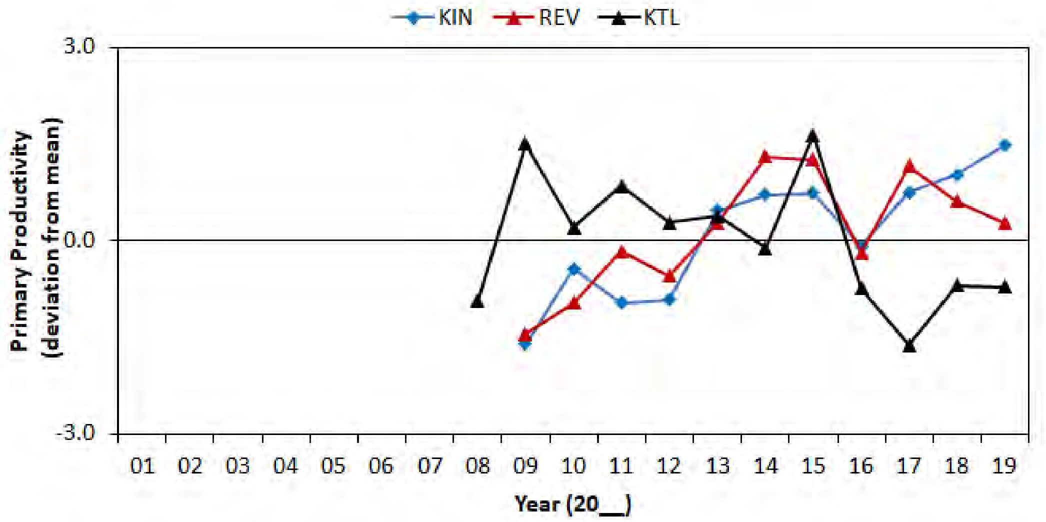


Figure 83. Long term trends of standardized primary production rates in Kinbasket, Revelstoke, and Kootenay.

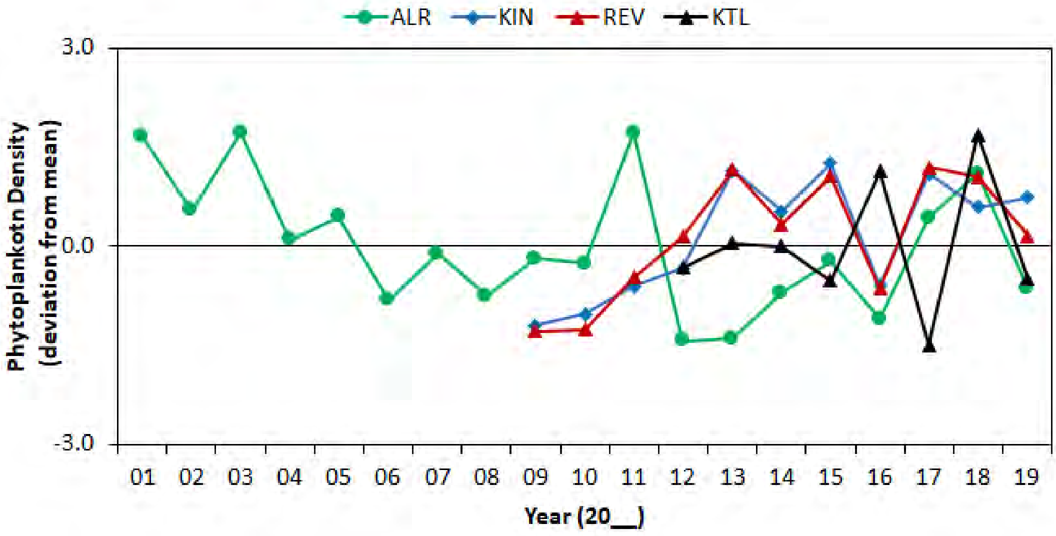


Figure 84. Long term trends of standardized phytoplankton density in Kinbasket, Revelstoke, Arrow, and Kootenay.

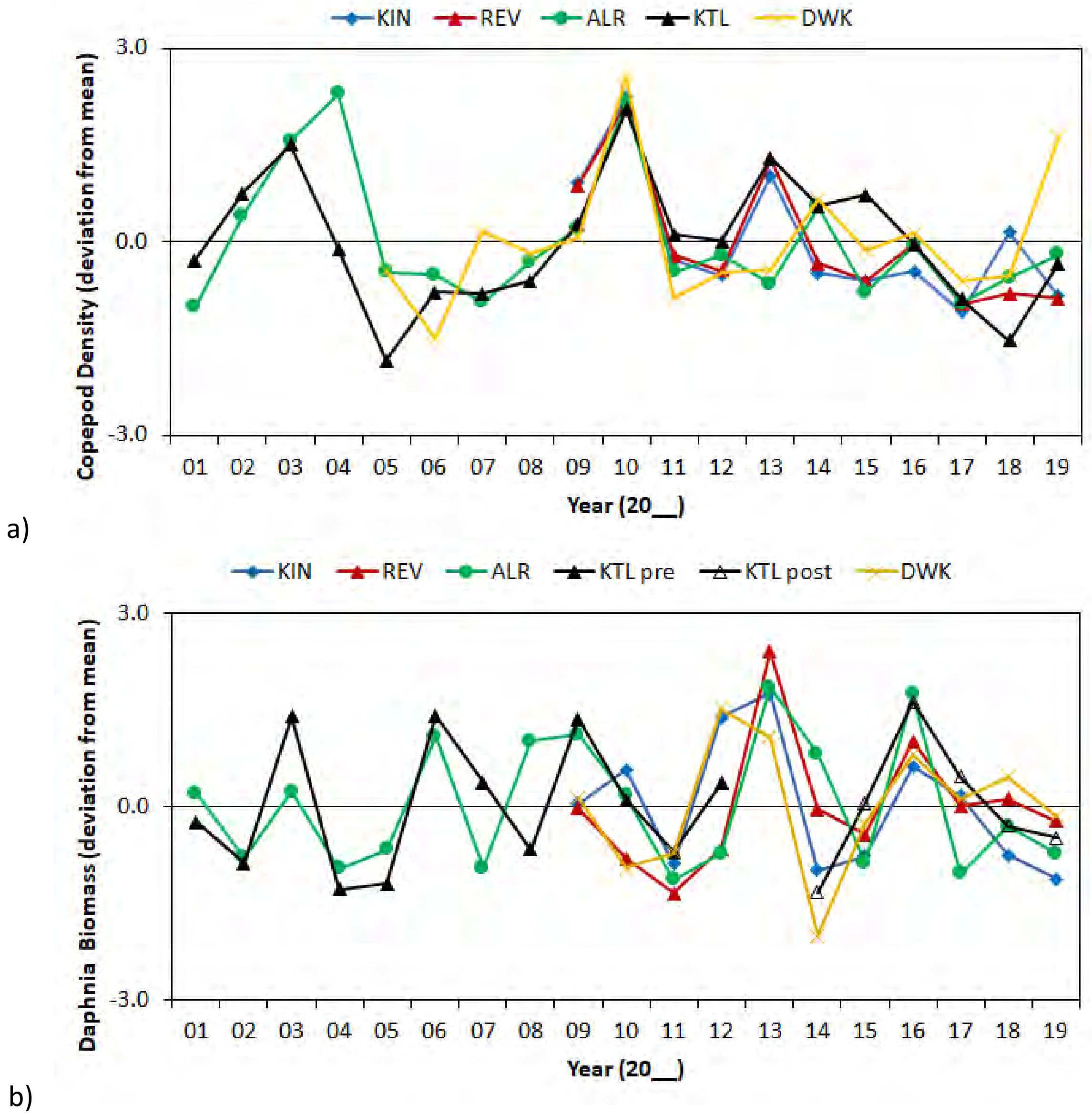


Figure 85. Long term trends of standardized zooplankton metrics a) copepod density and b) *Daphnia* biomass in Kinbasket, Revelstoke, Arrow, Kootenay, and Dworshak. Kootenay Lake data in panel b have been standardized separately by pre and post kokanee collapse periods due to the dramatic change in grazing pressure on *Daphnia*, and 2013 data were removed as that is considered a transition year between pre and post collapse periods.

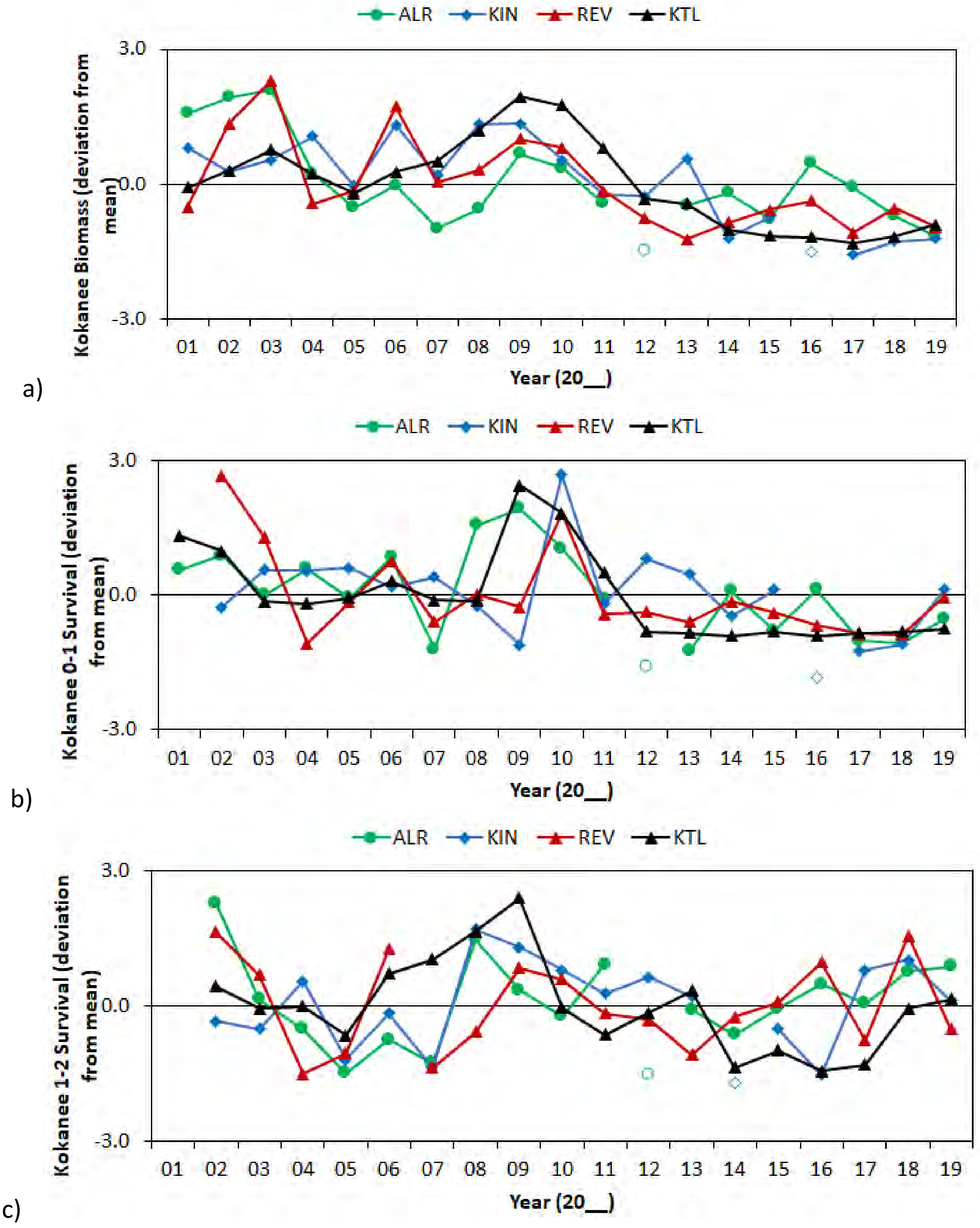


Figure 86. Long term trends of standardized kokanee metrics a) biomass, b) age 0-1 survival and c) age 1-2+ survival in Kinbasket, Revelstoke, Arrow, and Kootenay. Hollow points denote the large-scale mortality events in Arrow (2012) and Kinbasket (2016), affecting survival and biomass estimates.

MQ 3-5 Is there a link between reservoir operation and pelagic productivity? What are the best predictive tools for forecasting reservoir productivity?

Pelagic productivity can be influenced by a number of macro and micro-scaled factors at both spatial and temporal scales. These include climate, landscape, and operational factors on the macro-scale, and nutrients, water currents, and other habitat conditions on the micro-scale. Sampling for this project was intended to gain a better understanding of the pelagic community and how reservoir operations might be linked to changes. It is not practical or feasible to attempt to measure all potential factors that can affect pelagic productivity therefore the study was designed to collect data on many of the more commonly sampled variables known to impact pelagic production and that could be used to compare with other waterbodies and values in the literature.

Environmental factors may be driving the biological community in different directions, thereby confounding one's ability to identify which factors are causing changes in biological communities using classical statistical methods such as ANOVA, regression, and correlation analyses. Due to these complicated ecological systems, an alternative statistical method to determine factors influencing biological populations must be employed. Multivariate statistical methods can be a very effective tool in these situations. Two of the most common methods that can be employed are Redundancy Analysis (RDA) and Canonical Correspondence Analysis (CCA). It was determined through consultation with Carl Schwarz, Ph.D., that these two statistical techniques were appropriate for our dataset.

The biological data were compiled into a database along with 75 predictor variables (Table 19). The predictor variables were discrete data collected in the field or they were calculated data based on a sub-set of the discrete data. The data were parsed into various time components in the development of a statistical model to address different temporal scales of influence. For example, the impact of a change in water temperature may take hours, days, or weeks to be observed in the biological community, therefore temperature data were included in several different ways including air temperature for the 30 days prior to the biological data collection, average of January-September air temperature for each year, average water temperature of the photic zone on the sample date, and average temperature of the upper half of the photic zone on the sample date. Composite variables were developed based on previous data analysis and professional judgement. Some variables were excluded early in the analysis due to data gaps that affected the discriminatory power of the statistical tests. This included primary productivity data as this sampling was limited to four months each year. Output from the statistical analytical is on file with BC Hydro.

Table 19. Predictor variables used in both RDA and CCA analyses.

Variable	Unit	Definition
Photic Zone Characteristics (calculated for each reservoir)		
Photic zone volume	km^3	Photic zone volume is h_p*A, where h_p is the photic depth from the PAR sensor on the Seabird profile measured on the sample date, and A is the reservoir surface area averaged from the previous sampling event or 30 days whichever is less. All other parameters measured monthly at sample event station from the Seabird profile. The photic depth, h_p, is the depth at which light declines to 1%; with exponential decay of light, half the photic depth, $h_p/2$, corresponds to the 10% light level. Half photic depth values are representative of near surface conditions.
Photic zone (1% light) depth	m	
Photic zone (1% light) mean water temp	°C	
Photic zone (1% light) mean conductivity (C25)	μS/cm	
Photic zone (1% light) mean turbidity	NTU	
Photic zone (1% light) mean fluorescence	mg/L	
Half photic zone (10% light) depth	m	
Half photic zone (10% light) mean water temp	°C	
Half photic zone (10% light) mean conductivity (C25)	μS/cm^2	
Half photic zone (10% light) mean turbidity	NTU	
Half photic zone (10% light) mean fluorescence	mg/L	
Average Brunt-Väisälä frequency squared in photic zone	s^{-2}	
Flow (for each reservoir unless noted)		
Main inflow	m^3/s	Average from previous sampling event or 30 days whichever is less. Water Survey of Canada stations and BC Hydro data.
Local inflow	m^3/s	
Total outflow	m^3/s	
Maximum outflow	m^3/s	
Mean reservoir water elevation	m	
Snow Water Equivalent - April 1st % Normal	m	Upper Columbia snowpack in April (representative of max snowpack)
Maximum daily inflow by year from main source	m^3/s	April-Oct
Maximum daily inflow by year from local sources	m^3/s	April-Oct
Maximum daily inflow by year from total sources	m^3/s	April-Oct
Day of maximum inflow from main source	Julian Day	April-Oct
Day of maximum inflow from local sources	Julian Day	April-Oct
Day of maximum total inflow from all sources	Julian Day	April-Oct
Climate		
Air temperature, Revelstoke Airport Air temperature, Mica Townsite	°C	Average from previous sampling event or 30 days whichever is less. Data from Atmospheric Environment Service (AES); missing data interpolated for Mica Townsite.
Mean air temperature for Jan to Sep at Revelstoke	°C	Revelstoke AES data (representative of regional air temperature)
Precipitation at Revelstoke	mm/day	Average from previous sampling event or 30 days whichever is less. Revelstoke AES data (representative of regional precipitation)
Incident solar radiation at Revelstoke Dam	W/m^2	Average from previous sampling event or 30 days whichever is less (representative of regional solar radiation)
Calendar month average air temp and monthly deviation from long-term seasonal mean (1970-2021)	°C	Revelstoke AES data (representative of regional temperature)
Calendar month average daily precipitation and monthly deviation from long-term seasonal mean (1970-2021)	mm/day	Revelstoke AES data (representative of regional precipitation). Apr-Oct data

Variable	Unit	Definition
Onset of stratification by year, T(1m) - T(20m) > 1 °C	Julian day	Observations for 2013-2019 (Table 7); estimated for 2008-2012 using winter air temp.
Reference Tributary Chemistry and Nutrient Loading		
Columbia River at Donald nitrate	µg/L	monthly data from reference tributaries 2008-2018
Columbia River at Donald conductivity	µS/cm^2	
Columbia River at Donald turbidity	NTU	
Beaver River nitrate	µg/L	
Beaver River conductivity	µS/cm^2	
Beaver River turbidity	NTU	
Mica Outflow nitrate	µg/L	
Mica Outflow conductivity	µS/cm^2	
Mica Outflow turbidity	NTU	
Goldstream River nitrate	µg/L	
Goldstream River conductivity	µS/cm^2	
Goldstream River turbidity	NTU	
Columbia R. at Donald nitrate, TDS, and TSS load	kg/day	monthly data from reference tributaries were interpolated to daily values; load is daily concentration*flow averaged over the month, 2008-2018. TDS was estimated from conductivity at 25 °C, and TSS from turbidity.
Beaver River nitrate, TDS, and TSS load	kg/day	
Mica Outflow nitrate, TDS, and TSS load	kg/day	
Goldstream River nitrate, TDS, and TSS load	kg/day	
Primary Production		
Integrated Primary Production	mgC/m^2/day	Kinbasket: 1 station, Revelstoke: 2 stations, Sampled monthly Jun to Sep, 2008-2019
Integrated Chlorophyll a (Chl a)	mg/m^2	
Vertically integrated Chl a on 0.2µm filter	µg /L	
Vertically integrated Chl a, 0.2µm to 2.0µm	µg /L	
Vertically integrated Chl a, 0.2µm to 2.0µm (% of total)	%	
Vertically integrated Chl a, 2µm to 20µm	µg /L	
Vertically integrated Chl a, 2µm to 20µm (% of total)	%	
Vertically integrated Chl a > 20µm	µg /L	
Vertically integrated Chl a >20µm (% of total)	%	
Reservoir Water Chemistry		
Total Nitrogen (TN)	µg /L	Kinbasket: 4 stations, Revelstoke: 3 stations 2,5,10,15,20m depths averaged Sampled monthly Apr/May to Oct, 2008-2019 Adjusted values for 2008-2012 samples of phosphorus fractions to account for laboratory change.
Nitrite + Nitrate (NN)	µg /L	
Total Phosphorus (TP) and TP adjusted	µg /L	
Total Dissolved Phosphorus (TDP) and TDP adjusted	µg /L	
Soluble Reactive Phosphorus (SRP) and SRP adjusted	µg /L	
Alkalinity	mgCaCO$_3$/L	
Turbidity	NTU	
pH		
Conductivity	µS/cm^2	
Soluble Reactive Silica (as SiO$_2$)	mg/L	

Due to the differences between the reservoirs and differences in community characteristics between zooplankton and phytoplankton, it was determined that the data analysis and interpretation would be done separately for Kinbasket and Revelstoke and for zooplankton and phytoplankton communities in each reservoir.

Note that RDA includes both density (#/L) and biovolume (mm^3/L) for phytoplankton and density (#/L) and biomass (mg/L) zooplankton. However, CCA requires the response variables to be commensurate, hence CCA cannot be performed on the combined set of response variables that include both density and biomass. As a result, a separate CCA was conducted for each set of the response variables of density and biovolume.

It should be noted that the key to a successful RDA/CCA analysis is contrast in the environmental variables. It is not possible to delineate the impact of a variable that does not change over the course of a study. In an observational study, this is often a key limitation because you cannot "force" a variable to change and can use only the values that occur naturally. This is a particular problem for variables that can be measured only at a large scale, such as those available only a yearly scale. External climate variables can have oscillations scaled beyond the relatively small number of years in this study that could preclude obtaining sufficient contrast in these variables.

In the following section we discuss:

- the RDA and CCA analysis for phytoplankton and zooplankton for each reservoir, (RDA density and biomass, CCA for density and CCA for biomass),
- the predictor variables with the highest relative correlations from the RDA and CCA, and
- the multiple linear regression analysis based on these predictor variables.

Phytoplankton RDA and CCA Results

The RDA and CCA analysis starts by portioning the variance of the taxonomic groups. For this analysis the phytoplankton community was divided into five large functional groups: blue-greens, diatoms, flagellates, greens, and dinoflagellates. The groups were plotted on the RDA1 and RDA2 axes (Figure 87) as well as the CCA1 and CCA2 axes (Figure 88 and Figure 89). These two axes are composed of the predictor variables that minimized residuals from a linear least squares analysis in the case of RDA, and for the CCA that minimized the least square errors as determined using the predictor variables. The response variables on RDA1 are divided into a measure of the overall phytoplankton community. The first axis groups all of the taxonomic groups on the same side of the axis with the exception of diatoms. The second component shows additional distinction between diatoms and the other taxonomic groups. In the CCA analysis, CCA1 separates the diatom densities from the other taxonomic groups. The same occurs for diatom biovolume, but to a lesser extent.

The associated eigenvalues identified important components. The relative correlation values were used to determine the predictive power of the variable on the phytoplankton community structure. Many of the predictor variables have very low correlation to the phytoplankton community structure. After examining the relative vector length data, which is scaled between 0 and 1, with 1 indicating 100% correlation to the eigenvalue of one or more axis, it was determined to concentrate our analysis on predictor variables with relative correlations >0.5 for both RDA and CCA for phytoplankton.

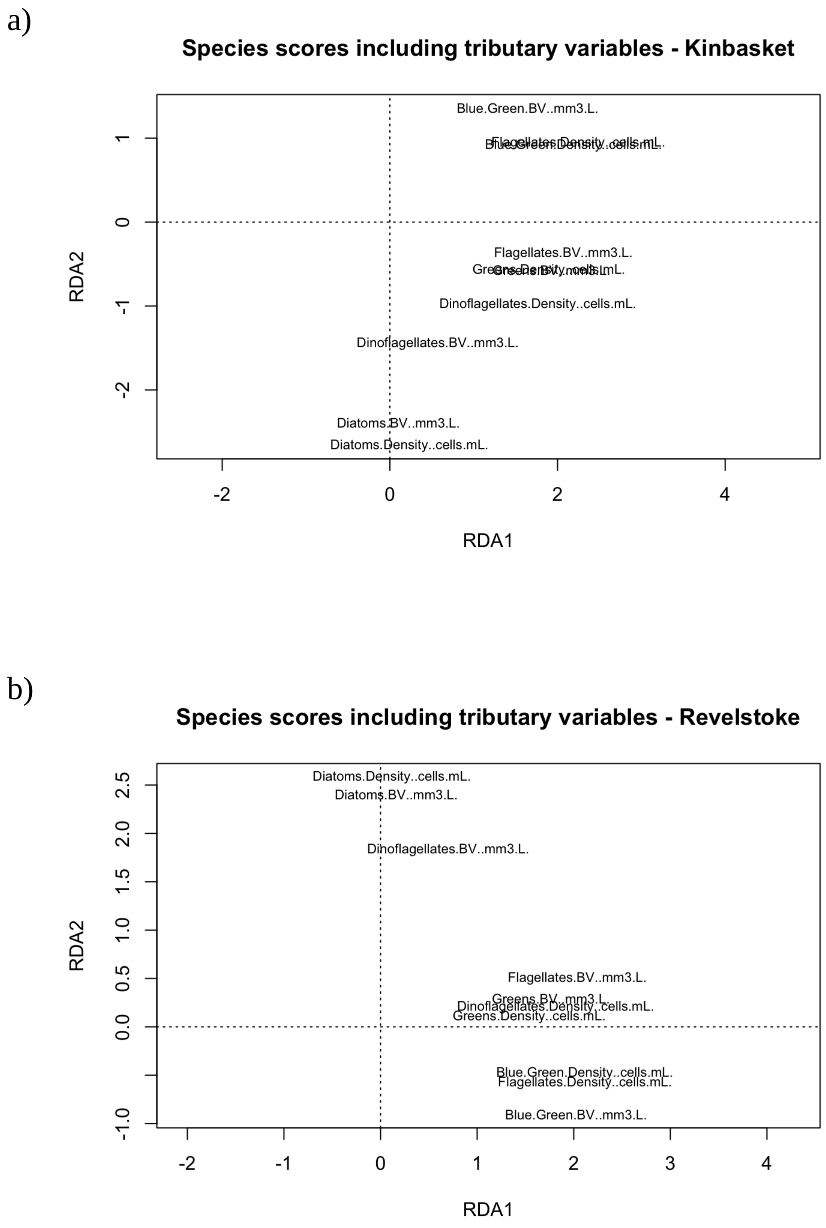
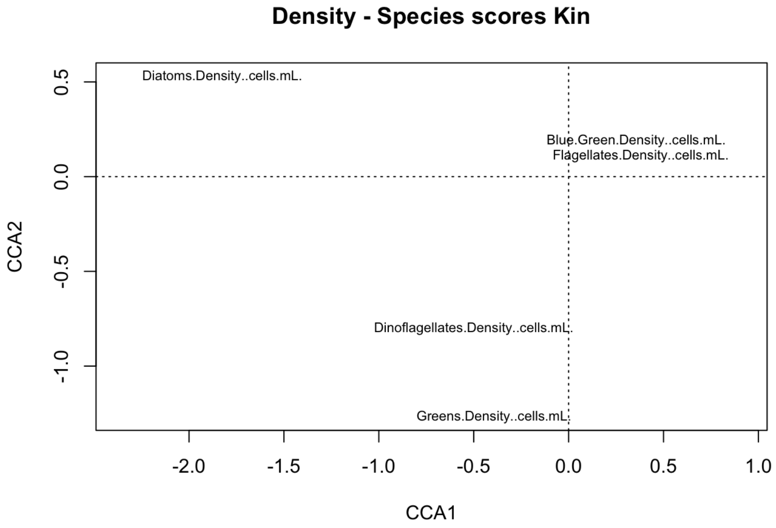


Figure 87. Taxonomic RDA grouping of phytoplankton community by reservoir using the predictor variables.

a)



b)

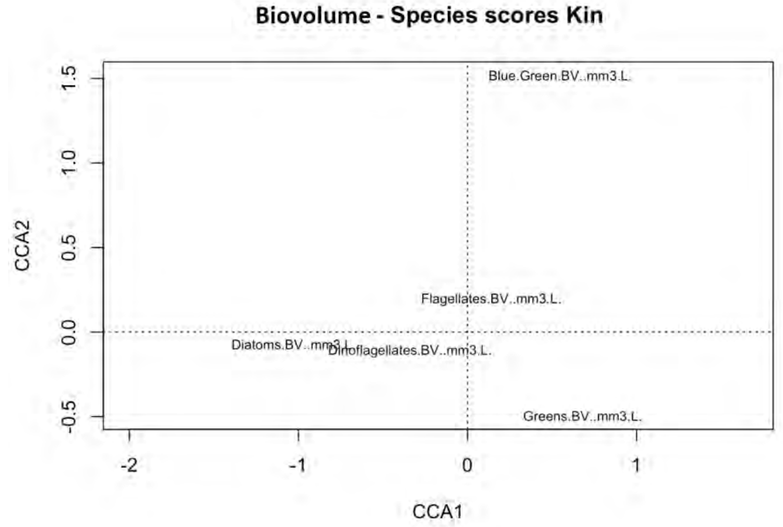
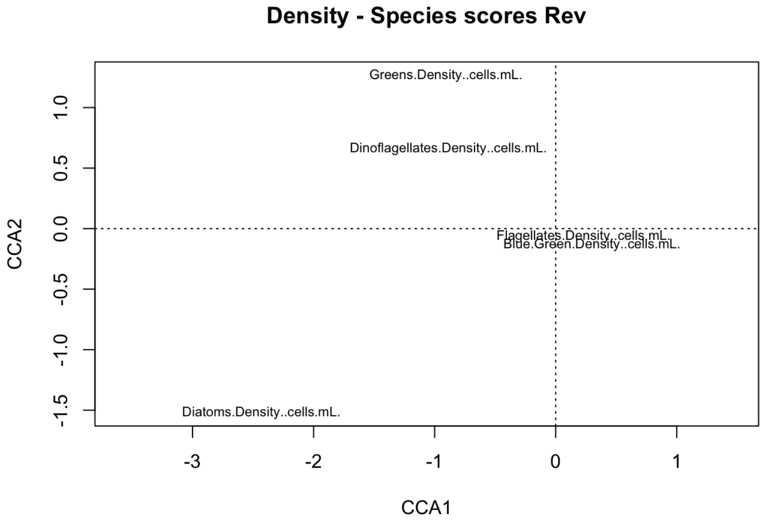


Figure 88. Taxonomic CCA grouping of phytoplankton community in Kinbasket using the predictor variables.

a)



b)

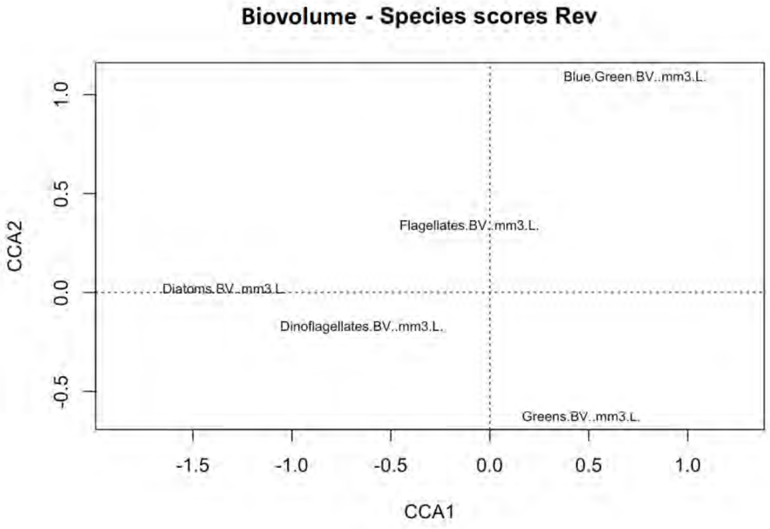


Figure 89. Taxonomic CCA grouping of phytoplankton community in Revelstoke Reservoir using predictor variables

Phytoplankton Density - Kinbasket

The phytoplankton density in Kinbasket had five variables above the 0.5 threshold in the RDA analysis and six variables in the CCA analysis (Table 20). There is considerable overlap in the important predictor variables between RDA and CCA, with maximum daily inflow, April snow water equivalent and average air temp Jan-Sept, being the top three in both analyses. The predictor variables that have the longest length and therefore greatest correlation to the RDA1 and RDA2 as well as the CCA1 and CCA2 axes are predominantly yearly climate related variables. That is, they are all variables that differ between years rather than between seasons or months. These are best categorized as winter precipitation, spring runoff, and air or water temperature variables.

Table 20. Kinbasket RDA and CCA relative correlations for major phytoplankton groups.

RDA		**CCA**	
Maximum Daily Inflow of Columbia (m^3/sec)	*0.586*	*Maximum Daily Inflow of Columbia (m^3/sec)*	*0.672*
April Snow Water Equivalent	*0.585*	*Average Air Temp Jan-September*	*0.607*
Air Temp Jan-Sept (°C)	*0.545*	*April Snow Water Equivalent*	*0.591*
Columbia River at Donald Conductivity	0.537	Day of Onset of Stratification	0.59
Average Temperature of top half or Photic Zone	0.514	Day of Maximum Inflow of Columbia	0.574
		Day of Maximum Total Inflow	0.573

Italics indicates predictor values common to both statistical models.

Phytoplankton Density - Revelstoke

The phytoplankton density in Revelstoke had three variables with relative correlations above the 0.5 threshold in the RDA analysis and six variables in the CCA analysis (Table 21). Two of the predictors in the RDA analysis are also observed in the CCA analysis. The predictor variables with the longest relative correlation to the CCA1 and CCA2 axes are also yearly climate variables. They are best categorized as winter precipitation, spring runoff, and water temperature. The greatest relative correlations for RDA1 and RDA2 are a combination of seasonal and yearly climate related variables.

Table 21. Revelstoke RDA and CCA relative correlations with predictor variables for major phytoplankton groups.

RDA		**CCA**	
Local Inflow by month (m^3/sec)	*0.797*	*Local Maximum Inflow (m^3/sec)*	*0.791*
April Snow Water Equivalent	*0.598*	Day of Local Maximum Inflow	0.664
Goldstream River Monthly Turbidity	0.539	Maximum Inflow of Main (m^3/sec)	0.637
		Total Inflow Maximum (m^3/sec)	0.570
		Day of Onset of Stratification	0.544
		April Snow Water Equivalent	*0.537*

Italics indicates predictor values common to both statistical models.

Zooplankton RDA and CCA Results

As previously stated, the RDA and CCA analysis begins by portioning the variance of the taxonomic groups. For this analysis the zooplankton community was divided into eight large functional groups: copepod density and biomass, *Daphnia* density and biomass, other cladoceran density and biomass, and total zooplankton density and biomass.

The groups were plotted on the RDA1 and RDA2 axes (Figure 90) as well as the CCA1 and CCA2 axes (Figure 91 and Figure 92). The response variables are divided into a measure of overall zooplankton (first component has all coefficients with the same sign, left side of the x-axis) and a second component contrasting *Daphnia* vs other zooplankton (y-axis). Results are similar for the two reservoirs as shown in the biplots.

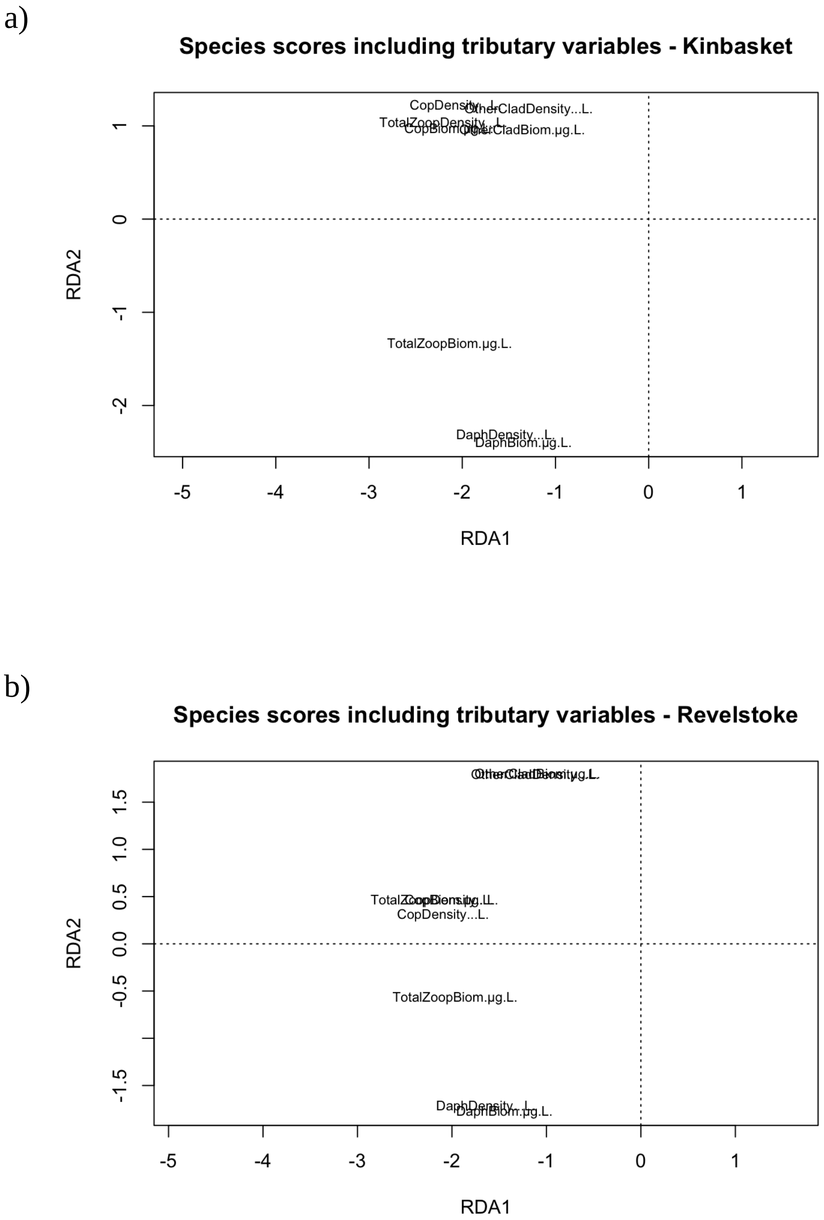


Figure 90. Taxonomic RDA grouping of zooplankton community density and biomass.

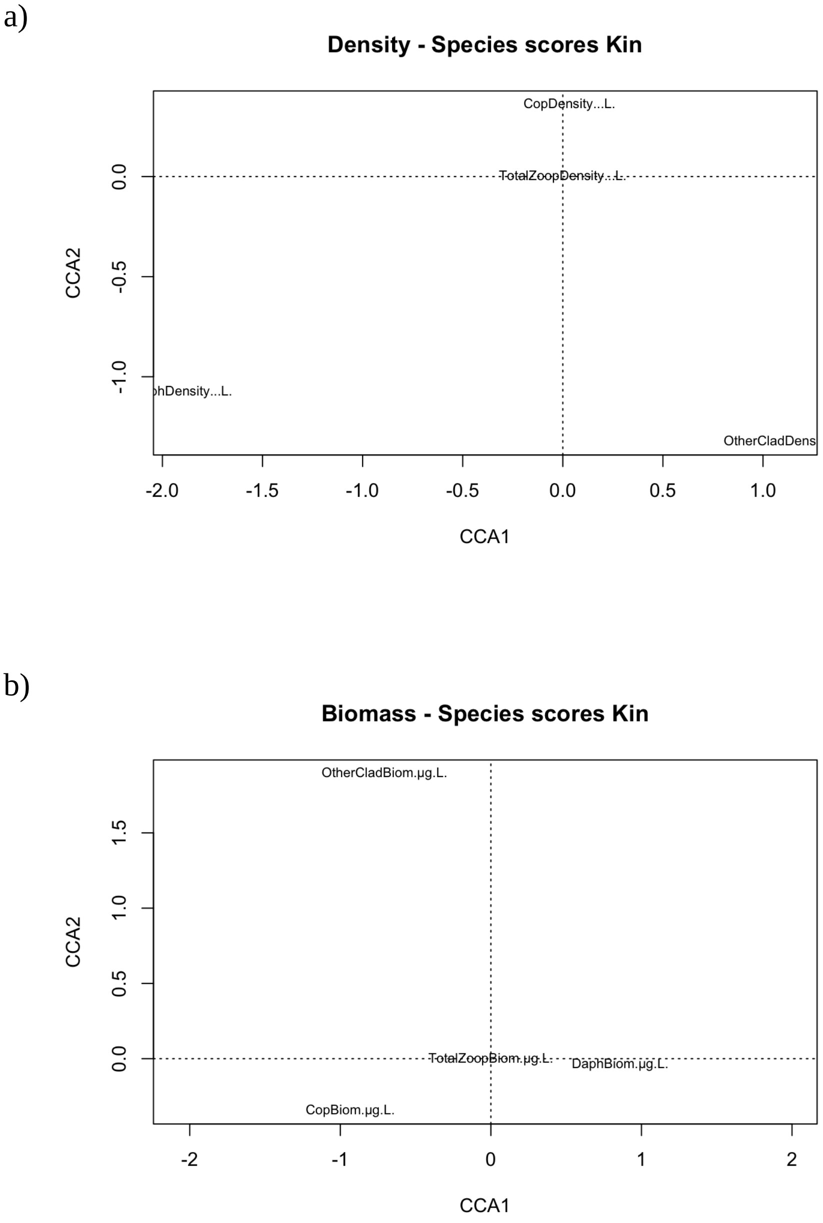


Figure 91. Taxonomic CCA grouping of the zooplankton community of Kinbasket Reservoir.

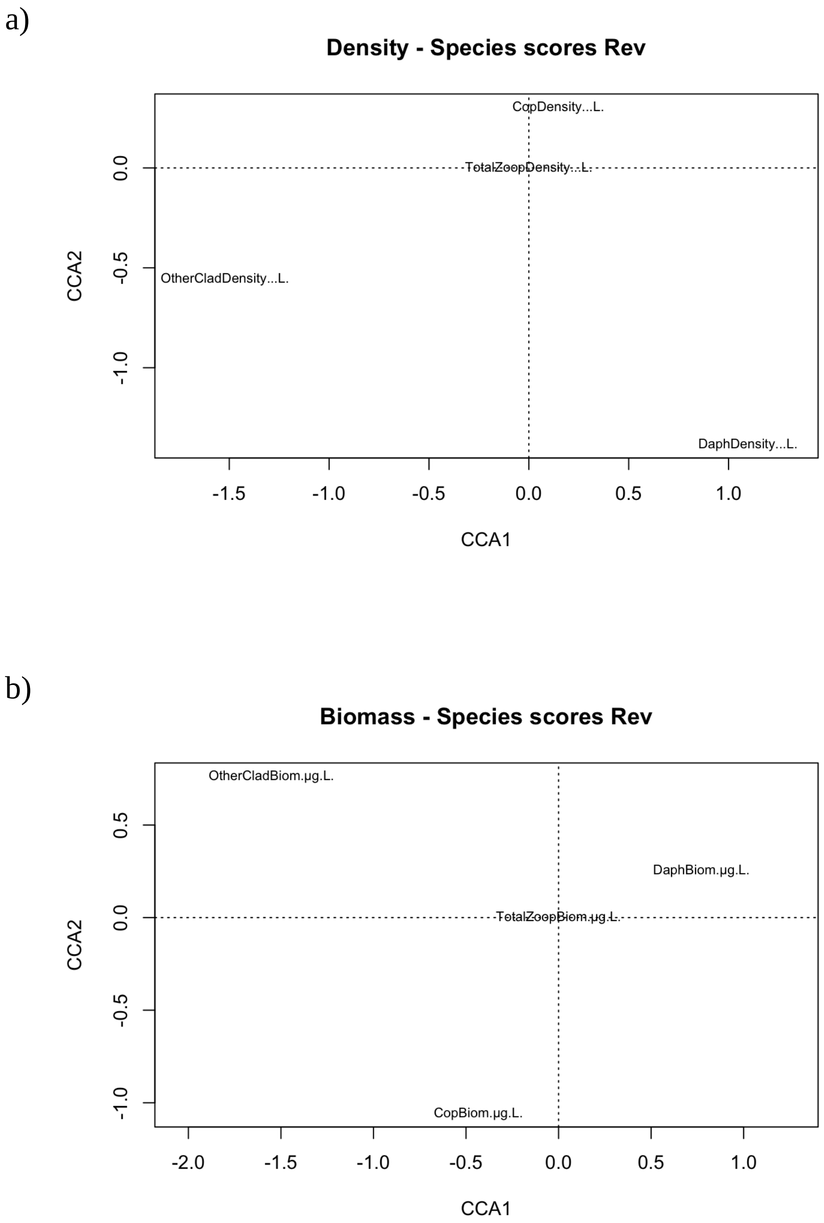


Figure 92. Taxonomic CCA grouping of the zooplankton community of Revelstoke Reservoir.

Zooplankton Density and Biomass - Kinbasket

The relative correlation cut off chosen for the zooplankton community was >0.6. This is due to the number of variables with higher relative correlations in the predictor variable data set when compared to the phytoplankton community. The zooplankton density in Kinbasket had six variables above the 0.6 relative correlation threshold in the RDA analysis and six variables in the CCA analysis (Table 22). Two of the predictors in the RDA analysis are also observed in the CCA analysis, reservoir level and Beaver River nitrogen load. The predictor variables with the longest length, and therefore greatest correlation to the RDA1 and RDA2 as well as the CCA1 and CCA2 axes, are predominantly seasonal climate variables.

Table 22. Zooplankton relative correlations for zooplankton community in Kinbasket Reservoir.

RDA		**CCA**	
Previous Month Photic Zone Temp	0.723	*Previous Month Mean Reservoir Water Elevation*	0.744
Previous Month Photic Zone Temp (top ½)	0.708	Beaver River Nitrate Load (Monthly)	0.688
Previous Month Mean Reservoir Elevation	0.708	Beaver River TDS Load (Monthly)	0.678
Previous Month Air Temperature	0.662	Columbia at Donald Nitrate Load (Monthly)	0.657
Beaver River Nitrate Load (Monthly)	0.64	Solar (W/m^2) from prior 30 days	0.64
Previous Month Local Inflow	0.606	Photic Volume (km^3) from prior 30 days	0.62

Italics indicates predictor values common to both statistical models.

Zooplankton Density and Biomass - Revelstoke

For Revelstoke Reservoir zooplankton density there were four variables above the 0.6 relative correlation threshold in the RDA analysis and seven variables in the CCA analysis (Table 23). The predictor variables with the greatest relative correlation with the RDA1 and RDA2 as well as the CCA1 and CCA2 axes are predominantly seasonal climate variables. Most of the variables with the greatest importance are related to temperature, inflow, and nutrient concentration or load.

Table 23. Zooplankton relative correlations for zooplankton in Revelstoke Reservoir.

RDA		**CCA**	
Previous Month Photic Zone Temp	0.717	*Previous Month Local Inflow*	*0.688*
Previous Month Photic Zone Temp (top ½)	0.695	Reservoir Nitrate Concentration (Monthly)	0.672
Previous Month Local Inflow	*0.666*	Previous Month Main Inflow	0.658
Mica Outflow Conductivity (Monthly)	0.602	Goldstream Nitrate Load (Monthly)	0.648
		Goldstream Conductivity Load (Monthly)	0.643
		Mica Outflow TDS Load (Monthly)	0.637
		Mica Outflow Nitrate Load (Monthly)	0.626

Italics indicates predictor values common to both statistical models.

Phytoplankton Multiple Linear Regression

To explore these correlations further, the predictor variables with high relative correlations were used next to develop a multiple linear regression model. Final inclusion in the model was based on whether the variable increased the significance value of the overall model. For the next series of tables, the first column under a predictor variable indicates significance level as p. The second column indicates the slope direction. Greyed out cells indicate variables that do not contribute to explaining a significant amount of the variability.

The multiple regression models for Kinbasket resulted in seven primary predictor variables (Table 24). A model was developed for each taxonomic group as well as a total phytoplankton. Green algae did not have any predictor variables that were significant in predicting their abundance. The effect (positive or negative correlation) of these predictor variables was typically consistent between groups except for diatom density and the date of onset of stratification and monthly reservoir elevation.

The regression models for Revelstoke resulted in eight primary predictor variables but one of the variables was significant in only one model (Table 25). A model was developed for each taxonomic group as well as a total phytoplankton. The variables common to most models were the April snow water equivalent (SWE), onset of stratification (OSS), Jan-Sept mean epilimnetic water temperature, and a measurement of either water inflow.

Zooplankton Multiple Linear Regression

Regression models for the Kinbasket zooplankton community resulted in eight primary predictor variables (Table 26). A model was developed for each taxonomic group (density and biomass) as well as a total zooplankton density and biomass. Variables correlated with changes in the zooplankton community were primarily related to monthly changes in nutrient loading, flow, and temperature. It should be noted that only a few tributaries were selected for monitoring during the study to serve as references for the whole reservoir. Significant tributary predictors, i.e., Beaver River conductivity, is being interpreted as a surrogate for unmonitored tributaries to the system rather than to indicate that biological community response being due to that singular tributary. The effect of these predictor variables was typically consistent between groups except for *Daphnia* density and biomass with respect to Beaver River conductivity.

The regression models for Revelstoke's zooplankton community resulted in nine primary predictor variables (Table 27). As with Kinbasket Reservoir, a model was developed for each zooplankton taxonomic group (density and biomass) as well as for total zooplankton density and biomass. Variables that were correlated with changes in the zooplankton community were primarily related to monthly changes in nutrient loading, flow, and temperature. The effect of these predictor variables was typically consistent between groups with a few minor exceptions.

The zooplankton community is influenced by predictors that are based on monthly data rather than yearly. This indicates that the zooplankton community is primarily responding to seasonal changes rather than longer term climate related variables such as over winter precipitation or spring hydrological variables.

Table 24. Multiple linear regression phytoplankton results for Kinbasket Reservoir.

Kinbasket Annual	**OSS**		**Jan-Sept Temp**		**Main Inflow Max**		**Day of Max Main Inflow**		**Day of Maximum inflow all sources**		**Monthly Reservoir Water Elevation**		**Average Monthly Outflow**		**Total model p-value**
Blue Greens	0.01	+	0.032	+							0.02	-	0.046	+	0.005
Greens															
Diatoms	0.03	-	0.032	+	0.01	-	0.035	+	0.035	+	0.02	+			0.056
Flagellates					0.022	-			0.004	+	0.115	-	0.01	+	0.027
Total Phyto Density	0.02	+	0.027	+	0.049	-			0.074	+			0.05	+	0.095

Table 25. Multiple linear regression phytoplankton results for Revelstoke Reservoir.

Revelstoke Annual	**April SWE**		**OSS**		**Jan-Sept Temp**		**Main Inflow Max**		**Trib Inflow Max**		**Day of Maximum Trib inflow**		**Maximum Inflow all sources**		**Day of Maximum inflow all sources**		**Total model p-value**
Blue Greens	0.021	-	0.001	+	0.024	+	<0.001	+			0.002	-	0.001	-	0.028	-	0.002
Greens	0.123	-	0.02	+	0.131	+	0.022	+									0.053
Diatoms	0.016	-					0.007	-	0.025	-			0.012	+			0.012
Flagellates	0.005	-	<0.001	+	0.047	+	<0.001	+			<0.001	-	<0.001	-	0.014	-	0.001
Total Phyto Density	0.012	-	0.001	+	0.029	+	<0.001	+			0.002	-	0.001	-	0.026	-	0.002

Table 26. Multiple linear regression zooplankton results for Kinbasket Reservoir.

Kinbasket	**Monthly Average Beaver River TDS Load**		**Monthly Average Local Inflow**		**Monthly Average Photic Temp**		**Monthly Average Beaver River Nitrate Load**		**Monthly Reservoir Water Elevation**		**Monthly Average Solar Watts**		**Monthly Average Columbia at Donald Nitrate Load**		**Monthly Average Air Temp**		**Total Model p-value**
Daphnia Density	0.02	+	0.099	+	0.045	+											<0.001
Copepod Density	0.013	+					0.001	-	0.28	-	0.02	+	0.11	+			<0.001
Other Clad Density							0.058	-			0.007	+	0.058	+			0.006
Total Zoop Density			0.25	+	0.15	+	0.047	-	0.051	-	0.582	+	0.119	+			<0.001
Daphnia Biomass	0.003	-	0.032	+	0.011	+									0.166	-	<0.001
Copepod Biomass			0.021	+	0.281	+	0.012	-	0.024	-			0.058	+			<0.001
Other Clad Biomass							0.006	-			0.004	+	0.049	+			<0.001
Total Zoop Biomass	0.011	-	0.014	+	<0.001	+					0.283	+			0.033	-	<0.001

Table 27. Multiple linear regression zooplankton results for Revelstoke Reservoir.

Revelstoke	**Reservoir Nitrate**		**Mica Outflow Nitrate Load**		**Mica Outflow TDS Load**		**Photic Temp**		**Mica Outflow Cond**		**Goldstream TDS Load**		**Main inflow**		**Local Inflow**		**Goldstream Nitrate Load**		**Total Model p-value**
Daphnia Density	0.018	-	0.001	+	0.170	+	0.002	+											<0.001
Copepod Density	0.017	-			0.006	+	0.063	+	0.031	+									0.001
Other Clad Density	0.001	-									0.049	+	0.001	-	0.001	-			<0.001
Total Zoop Density	0.149	-					0.424	+			0.451	-	0.08	-					<0.001
Daphnia Biomass	0.105	-			0.041	-	0.060	+	0.026	+									0.001
Copepod Biomass	0.010	-	0.177	-			0.025	+			0.073	+	0.001	-	0.001	-	0.074	-	<0.001
Other Clad Biomass			0.033	-			0.050	+			0.052	+			0.035	-	0.092	-	0.007
Total Zoop Biomass	0.031	-					0.085	+	0.159	+	0.290	+	0.004	-	0.006	-			0.001

One of the difficulties in answering whether there is link between reservoir operation and pelagic productivity is in distinguishing a reservoir operation apart from climate related and hydrology factors. Many operational decisions and/or changes are dictated by a combination of Columbia River Treaty obligations and other agreements, flood control rules, electricity demand, and system constraints, that are themselves also influenced by climate related hydrological variables affecting the water year. Any attempt to determine the effect of reservoir operations must consider these interdependencies.

The multivariate analyses performed on the primary and secondary production data collected for this study indicate that the major drivers in phytoplankton community structure and abundance (density) are yearly climate related variables whereas the zooplankton community is driven more by climate related variables at a monthly or seasonal scale.

Some of the predictor variables that are climate related (yearly and seasonal) are independent of reservoir operations, such as local tributary inflow, tributary nutrient loading, and solar watts, and no reservoir operational change could result in changes to pelagic productivity.

For other predictor variables the effect on reservoir productivity is likely a combination of these climatologically related variables and the impact these same variables would have on reservoir operations. For instance, monthly average reservoir water elevation has been determined to be an important predictor variable for changes in primary productivity. However, reservoir water elevation can be impacted by several climate related variables as well as decisions for reservoir operations.

Prior to any discussion regarding the statistical results of the effect of reservoir operations on pelagic production, one must understand that the statistical models developed are applicable only for the ranges of experiences used in the statistical analysis. If significant changes in reservoir operations are made that fall outside of the range of conditions observed between 2008 and 2019 the reliability of our analyses will decrease, and the validity will decrease with increasing variance from the existing data set. Fortuitously, and as noted in Section 1.2.2, the study period coincided with a period of great range in conditions. With these caveats an assessment of reservoir operations on reservoir productivity can occur.

Phytoplankton Productivity

For Kinbasket Reservoir, under conditions observed during the period of study, the only predictor variable that is statistically significant and may be influenced by reservoir operations is reservoir level, where phytoplankton productivity decreases with increased reservoir water elevation. This may be a spurious correlation rather than a causative one. The phytoplankton community may be responding to another variable such as winter runoff that is also correlated with reservoir elevation. The phytoplankton community can have a large increase in density in the spring as nutrients are being supplied to the reservoir from the winter runoff but as the nutrient supply decreases the phytoplankton density also declines. This would be occurring at the same time as the reservoir elevation was increasing resulting in the correlation observed between reservoir elevation and phytoplankton density. At this point it is unclear if the phytoplankton response is driven by changes in reservoir operations or due to some other concomitant factor. Furthermore, as previously discussed, this is only valid in the range of data observed in 2008 through 2019. Reservoir levels considerably lower than those observed may not continue to correlate with increased productivity.

Revelstoke Reservoir experiences similar climatological conditions as Kinbasket Reservoir, but due to its position downstream the potential exists for a greater impact to Revelstoke from operational changes made for Kinbasket. Water inflow (quantity and timing), nutrient loading from releases at Mica GS, as well as photic zone temperatures are all significant predictor variables for primary production in Revelstoke Reservoir. Each of these significant predictor variables can be altered to some degree by reservoir operations and are also heavily influenced by climate related factors in the year. Changes in Mica GS operations impact the downstream system of Revelstoke (and Arrow); i.e., main inflow/outflow, in addition to conditions within Kinbasket Reservoir, i.e., storage (elevation).

Zooplankton Productivity

For both Kinbasket and Revelstoke Reservoirs, zooplankton productivity is more responsive to seasonal changes rather than between year differences. Variables related to photic zone temperature and inflow characteristics (nutrient loading) were significant predictors for zooplankton. Of the significant predictor variables, only monthly reservoir water elevation can be linked to an operational factor where increasing reservoir elevation was negatively associated with copepod density and biomass. This may also be a spurious correlation. Changes in reservoir elevation may not be the cause of changes seen in the copepod community but may be occurring on the same temporal scale as other factors. For instance, as in many lakes and reservoirs, copepod density here typically undergoes a rapid increase in mid to late spring followed by a decline throughout the summer (Figure 48). During the time that the copepod community is in decline, Kinbasket Reservoir elevation is nearing its maximum for the year due to operations and hydrologic conditions. This may have resulted in a spurious correlation that reservoir elevation is causing the decrease in copepod density when it is actually a copepod life history pattern driving the zooplankton density. Whether this is what is occurring in Kinbasket Reservoir is unknown, but it is an important consideration for evaluating operational effects and the potential these changes may or may not have on copepod densities in Kinbasket Reservoir. The fact that these seasonal changes in the copepod community are also occurring in Revelstoke Reservoir where water level remains relatively stable adds credence to the argument that the correlation is not causative.

Photic zone temperature, nutrient loading, and inflow variables were significant predictors in zooplankton community density and biomass for Revelstoke Reservoir. Only the outflow from Mica GS (labelled Main Inflow) is influenced by operations, all other predictor variables are either climate, hydrology, or tributary conditions that would not be affected by reservoir operations. The inclusion of nutrient parameters in the zooplankton model but not the phytoplankton model is also likely due to observed seasonal changes in nutrient concentrations and loads rather than a causative factor of zooplankton production. The significance of photic temperature to *Daphnia* in both reservoirs is in line with many other studies on *Daphnia* life history requirements cited throughout this report.

Due to the number of factors that can affect primary and secondary producers it is difficult to clearly delineate variables that can predict pelagic productivity. Furthermore, the high degree of variability that naturally occurs in these communities requires a long-term dataset to have the statistical power needed to develop a predictive model. From these data it appears as these systems are primarily responding to climate, or upstream hydrologic (flow) variables at an annual scale for phytoplankton and a seasonal scale for zooplankton.

MQ 2-2 What role does reservoir operation play in productivity for kokanee?

The summary below constitutes our conclusions based a weight of evidence approach after evaluating 12 years of observational data collected under CLBMON 2 and 3, as well as an additional 7 years of kokanee data dating back to 2001.

Reservoir Discharge

Reservoir discharge (i.e., outflow) was discussed in detail as a possible factor affecting kokanee productivity in MQ 2-3. Discharge did not have an apparent direct impact on kokanee productivity in Kinbasket over the study period based on three possible impact pathways: 1) cumulative annual outflow from Mica GS was not a variable of importance for the in-lake survival analysis, 2) reservoir discharge was not an apparent driver of secondary productivity in the lower trophic analysis, and 3) cumulative annual outflow did not correlate with kokanee biomass or age 0-1 survival in simple linear regressions.

However, there are two lines of evidence that entrainment (associated with discharge) may be of relevance to the Kinbasket population: 1) estimates of entrainment over the course of one year out of Revelstoke (Biosonics 2013) suggest that significant proportions of the Kinbasket age 0 and 1 populations would have to have been entrained, and 2) average age 0-1 survival of Kinbasket kokanee were well below estimates for Arrow and Kootenay Lake.

In summary, although we did not directly link Kinbasket discharge to kokanee metrics in our study, there are lines of evidence suggesting entrainment could be of relevance to kokanee survival and accordingly age 1-3 abundance in Kinbasket. Density dependent growth would have likely compensated for entrainment impacts however, and there was no evidence the population was functioning below productive capacity over time.

For Revelstoke, there is evidence that reservoir discharge impacts kokanee productivity and is explored in MQ 2-3. The lines of evidence in support include: 1) the correlations between cumulative annual reservoir outflow and kokanee survival and biomass, 2) discharge variables occurred in all of the top models for Revelstoke Reservoir age 0-1 kokanee survival in multiple regression analysis and 3) Mica GS discharge, the main inflow to Revelstoke, was a significant predictor for several zooplankton community outcomes for Revelstoke reservoir where higher inflow resulted in lower zooplankton outcomes. As a run-of-river type reservoir, Revelstoke inflow is roughly the same as its outflow.

Other factors that culminate in a weight of evidence conclusion that reservoir discharge impacts kokanee productivity in Revelstoke are that: 1) entrainment was studied directly at Revelstoke GS and kokanee were entrained at high rates that increased with flow (Biosonics 2013), 2) Revelstoke kokanee have been functioning below productive capacity since ~ 2012, which corresponds with the era of consistent higher discharges and low survival and biomass (Figure 93), and 3) there was a weak correlation between cumulative annual reservoir discharge and copepod seasonal average density. The sample size was small, and the correlation was only marginally statistically significant for Arrow, however the similarity of the relationships between all three systems lends weight to the assumption of possible biological significance.

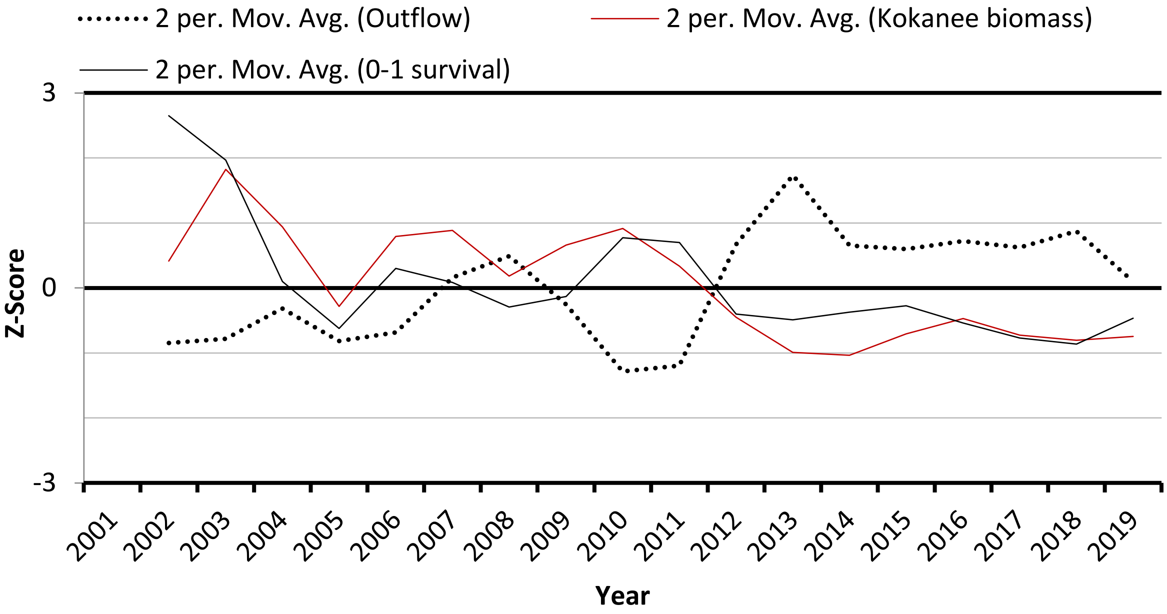


Figure 93. Standardised trends for Revelstoke kokanee age 0-1 survival and biomass and discharge from Revelstoke GS represented by 2 period moving averages over the study period. The year represents the latter year for discharge and kokanee survival, both of which span 2 calendar years.

Reservoir Elevation

Reservoir elevation was discussed in detail as a possible factor affecting kokanee productivity in MQ 2-3. Reservoir elevation did not have an apparent direct impact on kokanee productivity in Kinbasket over the study period based on four possible impact pathways: 1) spawner access issues or impacts to available spawning area were not apparent, 2) annual low pool levels were not a variable of importance for in-lake survival, 3) summer pool elevation was not correlated with kokanee age 1-3 abundance or survival, and 4) the lower trophic analysis detailed in MQ 3-

5 did not indicate that reservoir elevation outcomes were resulting in secondary productivity changes that would affect kokanee outcomes.

Revelstoke Reservoir, by design, has insignificant elevation changes and reservoir level is not considered a factor in Revelstoke kokanee productivity. However, the way in which Kinbasket is operated results in impacts to Revelstoke productivity via changes in water flow through Revelstoke and, by extension, Arrow.

MQ 3-7 Does the addition of Mica Units 5 and 6 influence pelagic productivity?

This management question stems from CLBMON-56, the addendum to CLBMON-3 resulting from the Mica Units 5/6 Project Environmental Assessment (EA) (BC Hydro 2009). To address this question, we first provide a brief introduction to the addition of Mica Units 5 and 6, and then examine how the flow from the Mica Generating Station changed after the installation of these two units. Next, we briefly look at the temperature in Kinbasket and Revelstoke Reservoirs, and, finally, provide a brief summary. Data are summarized in Figure 94; two additional years (2020 & 2021) of flow and mooring data were added to the analysis.

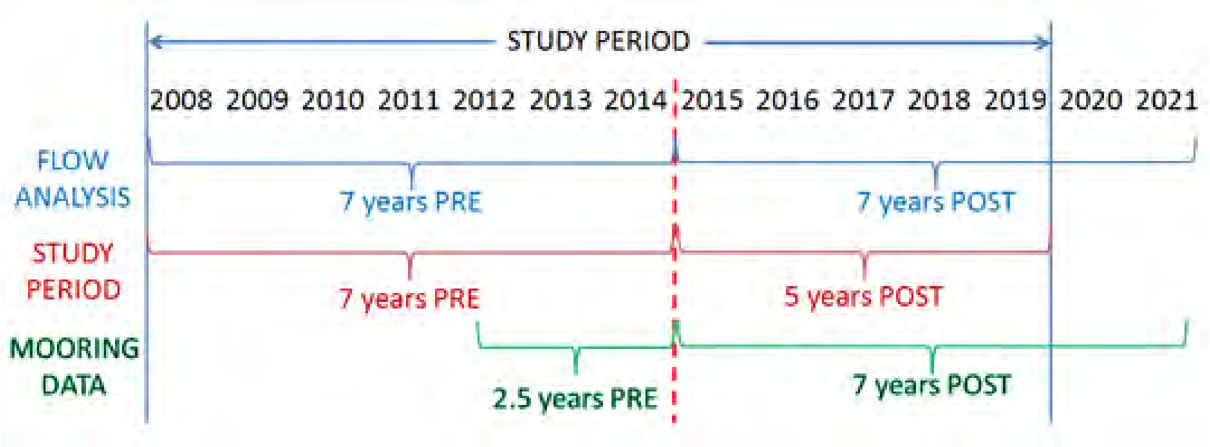


Figure 94. Summary of flow data, study period and moorings in relation to the addition of Units 5 and 6. The red dashed line marks the installation of Unit 5.

The final two turbines at Mica Generating Station (GS), Units 5 and 6, were constructed in tandem starting in 2012 and concluding with in service dates of mid-December 2014 for Unit 5 and mid-December 2015 for Unit 6. In conjunction with the installation of these two turbines, the Gas Insulated Switchgear (GIS) facility at Mica GS was upgraded in 2013, work that resulted in unusual operating conditions for both Kinbasket and Revelstoke Reservoirs. For example, a two-week shutdown of Mica GS in August 2013 was required for construction safety during installation of GIS components. This contributed to a surcharge operation (raising water level above the normal maximum) for Kinbasket Reservoir and a low drawdown (lowering water level below the normal minimum) in Revelstoke Reservoir, unusual both in terms of magnitude and seasonal timing.

The Mica Unit 5/6 Project EA (BC Hydro 2009) predicted that changes in operations due to the installation of Units 5 and 6 would be:

- Increased maximum discharge capacity at Mica GS of ~335 m^3/s per unit bringing the total maximum capacity to 1840 m^3/s.
- No net changes to discharge as water supply remains the same, but a greater time spent at higher flows and less time at lower flows within the year.

Small potential changes to Kinbasket and Revelstoke Reservoir elevations were modelled by the Mica 5/6 EA for representative wet, normal, and dry years; however, these were not suggested as important to reservoir thermal properties, or therefore to pelagic production, as they represented a small fraction of the typical variability of the reservoirs.

The predicted operations of Mica Units 5 and 6 were not anticipated to result in measurable changes to pelagic production in Revelstoke Reservoir, but it was speculated that increasing the maximum flow at the intakes could change thermal properties in the Kinbasket Forebay. This study was included to ongoing work under CLBMON-3 to address these uncertainties. Work on this component began in 2012 with the testing and deployment of moored temperature arrays and profilers and continued to fall 2019 when most instruments were removed, except for instruments in the forebays which were continued for an additional two years, to fall 2021.

As there is only one year in between the two new turbine in-service dates, we do not believe it possible or valuable to distinguish an operational effect of Units 1 to 5 versus Units 1 to 6. As such, we combine seven years 2008-2014 (Units 1-4) as “pre” and seven years 2015-2021 (Units 1-5 and 1-6) as “post.”

The Water Licence for Mica Generating Station authorises a maximum discharge of 1,840 m^3/s. Prior to 2014, when the facility had only 4 units, the maximum discharge capacity was 1,225 m^3/s. Units 1 to 4 have a smaller capacity than Units 5 and 6 and are of a significantly different vintage having been installed in the original powerhouse in 1976. The recently installed turbines benefit from improvements in technology such that their capacity is roughly 16% greater than the original turbines.

The installation of Units 5 and 6 made no change to the facility structure as all intakes, penstocks, draft tubes, and tailraces were constructed during the original build in the 1970s and are identical. Power intakes for all six units are the same size and at the same elevation in the reservoir arranged in ascending order from east to west (i.e., Unit 6 is closest to shore). In the tailrace, the discharge from Units 1 to 3 is combined and exits via the tailrace tunnel closest to the dam and the discharge from Units 4 to 6 is combined and flows through the adjacent tunnel to the downstream side. None of these configurations are expected to change the physical properties of the water (i.e., temperature or chemical composition) flowing through a unit compared to any other. Therefore, the influence of Units 5 and 6 is assessed in terms of changes to discharge magnitude and duration.

The elevation of Kinbasket Reservoir is regulated by Columbia River Treaty obligations, including limits for flood control, and Non-Treaty Storage Agreements. Discharge from Mica GS will vary depending on Kinbasket Reservoir level (gross head), electricity demand, system constraints, and availability of units. The addition of two units does not change the total quantity of water available in any given year, only the capacity to pass flows at any one time. That is, as maximum discharge capacity has increased, the duration of flow at any given discharge will change, but total outflow should balance out within the year or two.

Maximum generation typically occurs in winter when electricity demand peaks in the province. In recent years, summer load has been increasing to record high levels as the demand for air conditioning has soared during more frequent heat waves of greater intensity (BC Hydro 2021). Mica and Revelstoke Generating Stations contribute to meeting peak provincial electricity demands, both seasonally and for hourly peaking.

Change in outflow – The total outflow from the six units of Mica Generating Station is shown for 2008-2021 in Figure 2a. The change in maximum outflow is evident following the commissioning of Mica Unit 5 in December 2014 and Mica Unit 6 in December 2015. The highest flows occurred during the winter, with the second highest in summer (Figure 95a). In the pre period (2008-2014), the highest total outflow from Mica Units 1 to 4 was 1,221 m^3/s, effectively the same as the licensed maximum of 1,225 m^3/s. In the post period (2015-2021), the highest total outflow from Mica Units 1 to 6 was 1,822 m^3/s, close to the licensed maximum of 1,840 m^3/s.

An example of winter flow is shown in Figure 95b. In general, the outflow shows a strong daily cycle with peaks during the day and declining to a minimum just after midnight (cf. Figure 7 for Revelstoke outflow). Particularly notable was the long block of high flow from 4 - 17 Feb 2019 during a severe cold snap. This consisted of two blocks > 1,221 m^3/s, namely 3.0 days from 4 to 7 Feb 2019, a brief drop below 1,221 m^3s, and an additional 8.4 days from 7 to 16 Feb 2019, for a total of 11.4 days. Long periods above 1,221 m^3/s were unusual, as described below.

An example of summer flows is given in Figure 95c, where a daily cycle was also dominant. Summer flows did not consistently reach values as high as in winter. The highest summer flow in this record occurred on 28 August 2017 peaking at 1,720 m^3/s; the duration of the peak above 1,221 m^3/s was 9 hours.

Finally, the flow for July and August 2015 contain seven blocks of flow above 1,221 m^3/s, with a duration ranging from 1.5 to 4.8 days, as shown in Figure 95d. Only one of the additional turbines, Unit 5, was in service at this time, as indicated by the intermediate height of the peaks. Peaks with a duration of greater than 1 day did not occur in July or August in any of the subsequent six years (2016-2021), making these flows in the summer of 2015 unusual. Recall that 2015 was a drought year in the southern part of the Columbia River drainage and there was unusually large summer outflow from Kinbasket to meet various agreements and obligations, see Sections 1.2 and 3.1 for further detail.

The change in discharge related to Mica Units 5 and 6 was not only higher discharge, but also discharge distributed across a greater range, as well as a smaller proportion of discharge at low flow (Figure 96a, b) as predicted in the EA (BC Hydro 2009). The percent change is largest in winter, small in spring, and moderate in summer (Figure 97).

As the averaging period increased, the percentage of time during which the flow in the post period exceeded the maximum in the pre period declined (Table 28), suggesting that the changes due to the addition of Mica Units 5 and 6 were primarily short term. Note, this particular analysis is sensitive to the maximum average that occurred in the pre period.

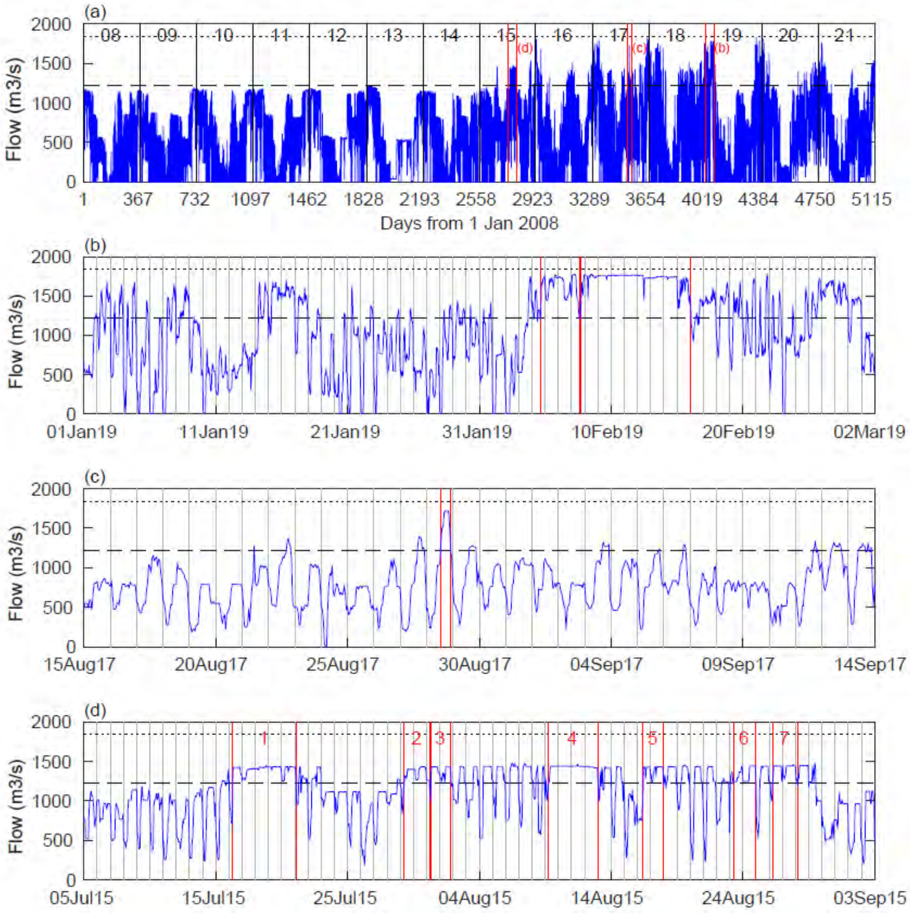


Figure 95. (a) Total hourly outflow from the six units of Mica Generating Station, 2008-2021. (b) Total hourly outflow for 1 Jan to 2 Mar 2019. (c) Total hourly outflow for 15 Aug to 14 Sep 2017. (d) Total hourly outflow for 5 Jul to 3 Sep 2015. The dotted line marks 1,840 m^3/s. The dashed line marks 1,221 m^3/s, the maximum outflow for 2008-2014. (a) Vertical red lines mark the time of panels (b), (c) and (d). (b, c, d) Vertical red lines mark peaks discussed in the text.

Table 28. Percentage of time the flow in the POST period was greater than the maximum in the PRE period for a given averaging period.

Averaging Period	**PRE MAX (m3/s)**	**Time POST flow > PRE MAX (%)**
Hour	1,221	11.3%
Day	1,213	8.7%
Month	1,149	3.6%

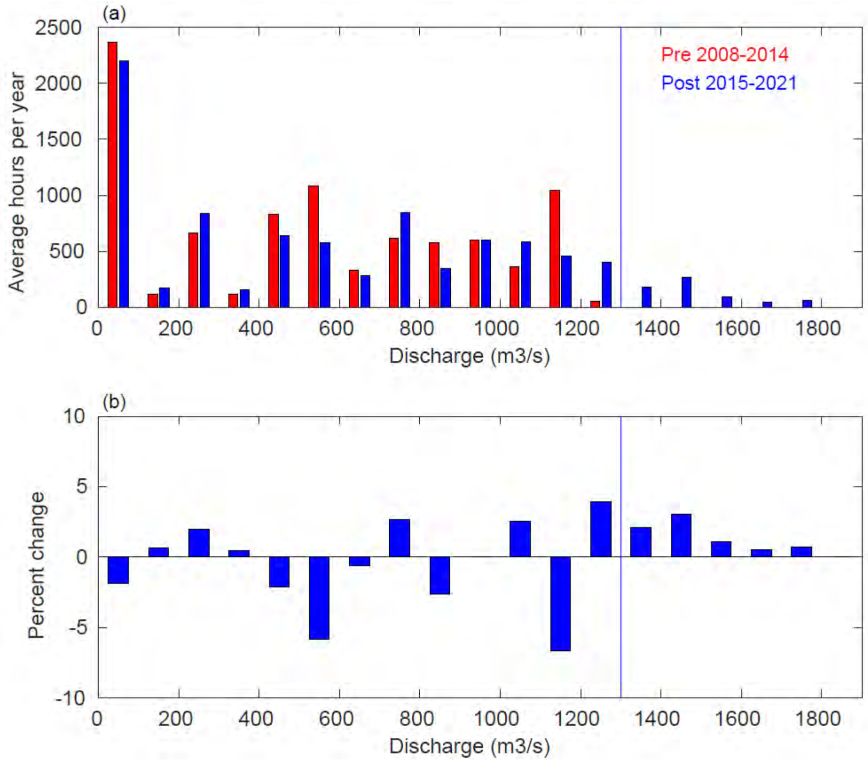


Figure 96. (a) Frequency distribution of hourly discharge at Mica Generating Station for pre (2008-2014) with Units 1-4 (max. 1,221 m^3/s), and post (2015-2021) with Units 1-6 (max. 1,822 m^3/s). (b) Percent change in time spent at discharge from pre to post Units 5 and 6. Vertical blue line indicates the maximum generation capacity of Units 1-4.

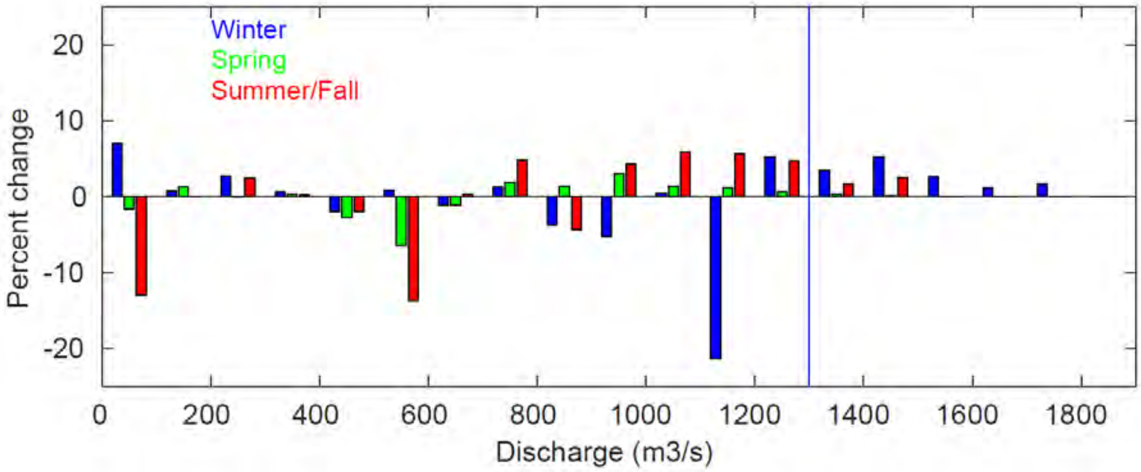


Figure 97. Percent change in seasonal distribution of hourly discharge from pre (2008-2014) to post (2015-2021) Units 5 and 6. Winter is November to March, Spring is April to June, Summer/Fall is July to October. Vertical blue line indicates the maximum generation capacity of Units 1-4.

From 2015 to 2021, there were a total of 840 peaks above 1,221 m^3/s, giving an average of one peak every 3 days. For each peak, the duration was determined as the time when the flow exceeded 1,221 m^3/s to the time it declined below 1,221 m^3/s. For peaks above 1,221 m^3/s, the duration was low with a median of 4 hours, namely, half of the peaks had a duration of 4 hours or less (Figure 98a). Of the peaks, 96% had a duration of less than one day (Figure 98a). There were a sparse set of 36 peaks with a duration greater than one day, shown on expanded scale in Figure 98b), and these include the periods of greater than one day discussed above (Figure 95b, d).

For peaks > 1,221 m^3/s, the maximum duration was largest in winter (Figure 98c). As discussed above, the maximum duration in summer was only greater than one day in 2015, and subsequent years it remained less than one day (Figure 98c). The median duration does not show much variation over the year, ranging from 1 to 6 hours, with the lowest median duration in spring (Figure 98d). The number of peaks was greatest in winter (more than 20 per month), there were no peaks in June, and the number of peaks increased again in July and August (8 to 12 peaks per month, Figure 98e). The total days with discharge > 1,221 m^3/s was also greatest in winter (up to 10 days/month), with a second peak in summer (3 to 5 days/month); note the number of days > 1,221 m^3/s from March to June was very low (Figure 98f). Demand for electricity peaks in winter during a cold snap and in summer during hot spells. In contrast, in spring there is a combination of both reduced demand for electricity along with abundant freshet electricity production in the region.

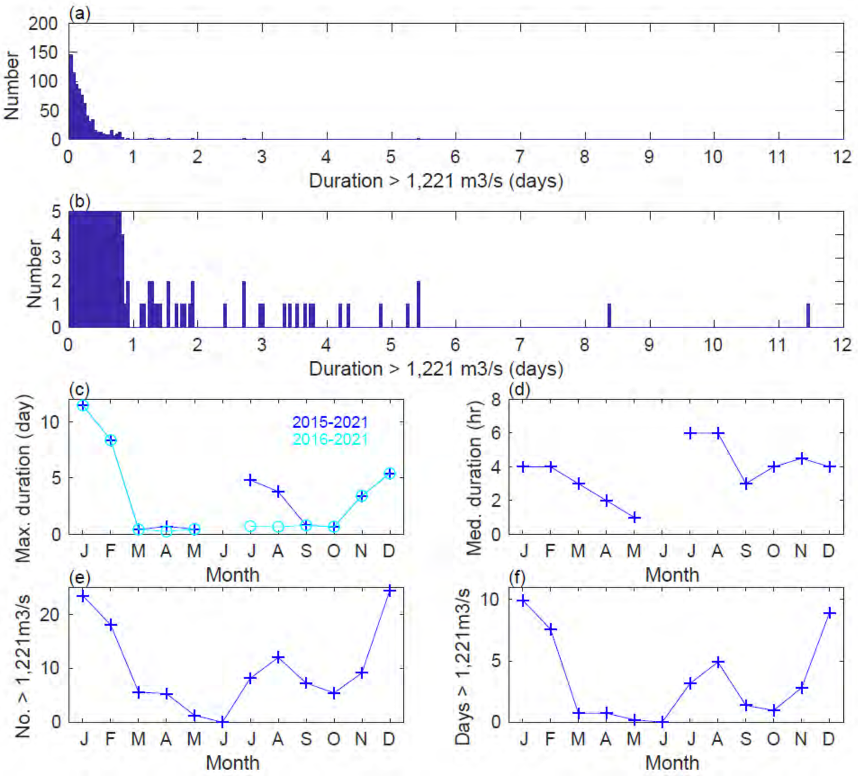


Figure 98. (a) Histogram of the duration for peaks > 1,221 m^3/s in Mica Units 1-6 total outflow, 2015-2021. (b) The same as (a) with expanded y axis. (c) Maximum duration of peaks > 1,221 m^3/s by month; note there were no peaks in June. (d) Median duration of peaks > 1,221 m^3/s by month. (e) Annual average number of peaks > 1,221 m^3/s by month. (f) Annual average total days > 1,221 m^3/s by month.

Temperature in Kinbasket Reservoir Forebay – Seasonally averaged temperature in the forebay of Kinbasket Reservoir is shown in Figure 99. Problems with the log booms at Mica Dam resulted in significant gaps in the data, and, as a result, there was only one year of data before installation of Mica Units 5 and 6. This one year of data was generally consistent with the data in the post period.

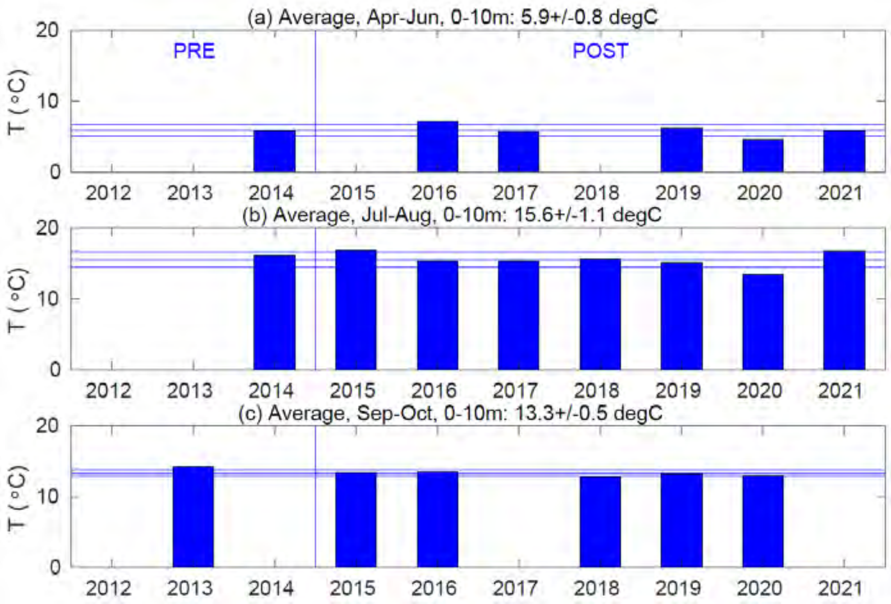


Figure 99. Average water temperature, Kinbasket Reservoir, (a) Apr-Jun, (b) Jul-Aug and (c) Sep-Oct, 0-10m, 2012-2021. The blue lines mark the average and the average ± one standard deviation.

Temperature in Revelstoke Reservoir – For Revelstoke Reservoir there were two to three years of data in the pre period, which compared favourably with that in the post period (Figure 100).

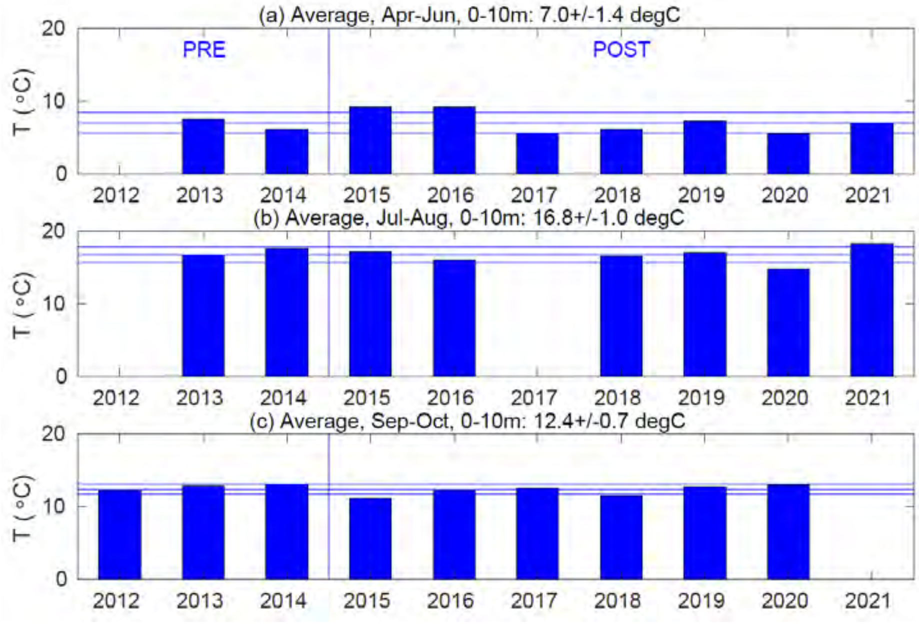


Figure 100. Average water temperature, Revelstoke Reservoir, (a) Apr-Jun, (b) Jul-Aug and (c) Sep-Oct, 0-10m, 2012-2021. The blue lines mark the average and the average ± one standard deviation.

Summary - The influence of changes from the addition of Mica Units 5 and 6 on pelagic production in Kinbasket is likely undetectable. In spring, when Kinbasket Reservoir was filling, outflow from Kinbasket Reservoir was low (Figure 2b) and no significant outflows above 1,221 m^3/s occurred during the post period of 2015-2021 examined here. In summer, when short periods of higher outflow were observed in the 2015-2021 period, the outlets are deep, and we expect that these high outflows will have little effect on processes in and around the photic zone (cf. Figure 74). In Revelstoke, during summer, the inflow from Kinbasket Reservoir forms an interflow below the photic zone and thermocline. Relatively brief periods of additional inflow to the interflow will also have little effect on the photic zone. However, sustained high outflow from Kinbasket, as occurred in 2012 and 2015, appears to have a negative effect on productivity in Revelstoke (and Upper Arrow), see MQ 2-3 and 3-5 for further discussion.

We have examined a wide range of data, including that from the moorings, from the autonomous profilers, and from CTD profiler surveys. Despite significant inter-annual variations in snowpack, water level, flows, air temperature and other factors, both reservoirs have continued to function in a similar fashion in both the pre and post Mica Unit 5 and 6 periods. The CTD profiles, for example, show consistent summer stratification in the Kinbasket Forebay from 2008 to 2019. The autonomous profilers, deployed in Revelstoke, have documented the arrival and evolution of the interflow of water from Kinbasket Reservoir; when water is released early from Kinbasket Reservoir the interflow arrives earlier at Revelstoke forebay and vice versa, but the overall structure of the stratification remained similar over the years.

There is no evidence to support any significant influence from the addition of Mica Units 5 and 6 on pelagic production in either reservoir. The analysis is limited by a number of factors including limited mooring data before the addition of the units and significant inter-annual variability during the study period; however, the main drivers of pelagic production are beyond the influence of the operation of these two turbines.

MQ 3-8 Are there operational changes that could be implemented to improve pelagic productivity in Kinbasket Reservoir?

MQ 2-4 Can modifications be made to operation of dams to protect or enhance kokanee populations?

These similar management questions from CLBMON-2 and 3 are addressed together with reference to pelagic production including both lower trophic levels (primary and secondary) and kokanee. Operations at Mica and Revelstoke Generating Stations are fundamentally about the release of water through the dam infrastructure, the timing and magnitude of which determine Kinbasket Reservoir elevation and flow through Revelstoke Reservoir. Both reservoirs are the result of impoundment of riverine habitat and their pelagic communities have developed, and continue to develop, as result of operating conditions over the past four to five decades.

The WUP Consultative Committee (CC) was interested in a minimum (i.e., higher in spring) reservoir elevation for Kinbasket Reservoir and considered a target of 730 m (BC Hydro 2005). This target was presumed to increase the probability of refilling the reservoir, a desired state for both navigation and recreation interests. The WUP CC also made a connection to benefits for pelagic production in that a higher reservoir would translate to a greater pelagic area, and therefore, more productivity. Due to insufficient data and the high costs associated with this constraint, the WUP CC agreed to drop operating constraints for Kinbasket Reservoir at the time and recommended this study to provide information for a future review. Other interests may find a lower maximum reservoir elevation (i.e., lower than full pool in the year) to be desirable, for example, for terrestrial habitat values.

Answering these Management Questions on improving or enhancing pelagic production or kokanee populations requires establishing the state against which changes can be evaluated, problematic for a system undergoing continuous ecological cycles and change. Instead, we provide an evaluation of reservoir operations and likely ecological productivity outcomes. Kokanee play an important role in these aquatic ecosystems and, like many salmon species, are also vital food for wildlife, transferring nutrients from pelagic to riverine and terrestrial environments, and contributing to geomorphic processes in tributaries (Fremier et al. 2018). Actions that have the potential to negatively impact kokanee, therefore, would have far-reaching ecological consequences.

While reservoir operations are to a large degree dependent on climate and conditions of the water year, operational decisions are made that influence reservoir elevation and discharge (Section 1.2). Our analyses presented in the previous Management Questions have attempted to unravel complex pelagic interactions in these reservoirs and together the results inform the answer to these two questions, summarised in Table 29.

The degree of confidence that a particular reservoir operation can be assured to consistently ensure a better pelagic productivity outcome is small. Kinbasket Reservoir is large enough that operational decisions of storage and discharge in one year have cascading implications for the next two or three years. As some potential operating constraints, for example a targeted minimum reservoir elevation in Kinbasket, would be implemented in advance of the productive season and regardless of water year conditions, there is also a risk of inadvertently worsening pelagic productivity conditions. Decisions made for Kinbasket Reservoir ultimately have the greatest effect on pelagic productivity of Revelstoke and, perhaps even more so, for Arrow Lakes Reservoirs by strongly influencing flow through the system. While storage at or discharge from Kinbasket has little effect on pelagic production in that reservoir, years with higher cumulative outflow from Mica GS were shown to negatively affect zooplankton and kokanee metrics downstream in both Revelstoke and Arrow. As a reduction to Kinbasket elevation range reduces storage volume and could result in an earlier or higher outflow, minimum and maximum elevation targets are not seen as beneficial to pelagic production across the system. Filling Kinbasket Reservoir and delaying outflow in the spring could be advantageous to Kinbasket, Revelstoke, and Arrow Reservoirs.

Ecological communities depend on natural variability and are able to withstand and compensate for environmental shifts, including extremes and cycles of good and poor conditions. Kokanee populations have resilient compensatory mechanisms but driving populations too far for too long in one direction can limit that resiliency, for example in Revelstoke Reservoir (post-2011) and Kootenay Lake (post-2012) (Warnock et al. 2021). Operational decisions that might transform what would naturally be a ‘good’ year into a ‘poor’ year could have greater negative consequences, particularly if it extended a longer cycle of poor year conditions.

Based on our observations and results, we present three years to illustrate how contrasting environmental conditions and operations could occur. We compare 2012, a year with high reservoir and high outflow matching climate induced factors and considered a poor year except for Kinbasket, with two operations induced climate mismatch years: 2013 with high reservoir and low outflow, a good year, and 2015, with very high outflow, and poor biological outcomes.

Extremely high inflows were experienced throughout the basin in 2012 (Figure 3) and the spring was colder and wetter than normal, especially June (Figure 8). Kinbasket Reservoir was filled and surcharged to mitigate downstream flooding impacts and discharge from Mica GS was curtailed until July when high outflows began (Figure 6). The remainder of the summer and fall were close to average temperatures (Figure 8). Zooplankton abundance and biomass were low until July in both Kinbasket and Revelstoke Reservoirs. By August, however, values were well above average in Kinbasket, but in Revelstoke (and Arrow) where flows remained high, zooplankton metrics remained below average (Figure 49). Kokanee survival in 2012 was also above average in Kinbasket and below average in Revelstoke and Arrow (Figure 86). The operation of Kinbasket in 2012 was a result of climate induced conditions from a cold, wet spring and extremely high inflows throughout the basin.

In comparison, 2013 was an average spring and the summer was warm as in 2012 (Figure 8); inflows were close to average (Figure 4). Kinbasket Reservoir also filled and surcharged that year, but the surcharge operation was a result of constraints at Mica GS from construction of the gas insulated switchgear equipment and the facility could not be operated for two weeks in August to ensure safety (see also Section 1.2.2). This meant that at the peak of summer production Revelstoke inflows were limited to local inflows. In 2013, zooplankton biomass, especially *Daphnia*, were well above average in Kinbasket, Revelstoke, and Arrow Reservoirs (Figure 85b).

Consider next 2015, the third driest year in the United States and the strongest El Niño year on record that triggered operations for an earlier season and higher than average prolonged outflows from Kinbasket Reservoir throughout the growing season (April to September) (Figure 6) with no typical spring shutdown. This operation of earlier, higher, and more prolonged outflow through Revelstoke and Arrow Reservoirs contrasted with what might otherwise have been season of good growing conditions with very warm spring and average summer temperatures (Figure 8) and low flow-through. Zooplankton metrics in all three reservoirs were below average in 2015 (Figure 85) and kokanee age 0-1 survival was also below average (Figure 86b).

In summary, any operation of Kinbasket Reservoir that results in an earlier or higher outflow than would occur otherwise within the water year will contribute to poorer outcomes for kokanee survival and growth in Revelstoke, and by extension, Arrow. Setting minimum and maximum elevation targets, for example, could result in earlier or higher discharge from Kinbasket Reservoir that would have cascading negative outcomes for kokanee downstream. Operating as far as possible with the water year conditions rather than in opposition would be beneficial, especially in naturally dry years when operations could potentially change a high productivity year into a year of lower productivity, such as in 2015.

Table 29. Summary of main operations and the potential influence on pelagic production of Kinbasket and Revelstoke Reservoirs.

Operation	Description	Potential Influence on Pelagic Productivity
KIN minimum elevation	Targeting a higher elevation in spring by reducing the reservoir draft. Setting a minimum elevation for reservoir draft is thought to be beneficial for pelagic production in that it increases the chance of the reservoir refilling to full which would maximise pelagic area and is therefore thought to increase pelagic productivity. WUP Consultative Committee considered a 730 m minimum elevation for Kinbasket Reservoir early on, but ultimately rejected any operating constraints. Increasing the chance for reservoir refill benefits other interests, such as navigation and recreation.	Likely no benefit, potentially adverse outcome. A reduction to the reservoir elevation range reduces storage volume. If limiting the draft results in earlier releases at Mica GS to manage full pool, then there is no overall benefit and a potentially negative outcome downstream in Revelstoke and Arrow Lakes Reservoir. Refilling the reservoir could be good for pelagic production, but less so to achieve a specific elevation target than to retain water for as long as possible. Climate and flow variables were found to be a greater influence on pelagic production in any year over reservoir elevation.
KIN maximum elevation	Targeting a lower maximum elevation by reducing the reservoir fill. Reducing the reservoir elevation of full pool could be a desired value for terrestrial habitat values. However, maximising reservoir elevation was thought to be desirable for kokanee by maximising pelagic habitat area.	Potentially adverse outcome, minimal short-term benefit. A reduction to the reservoir elevation range reduces storage volume. If limiting the maximum reservoir elevation results in earlier or increased releases at Mica GS to achieve the target, then there is no overall benefit and a potentially negative outcome downstream in Revelstoke and Arrow Lakes Reservoir. Filling the reservoir to maximum could be good for pelagic production, but potentially less so to achieve a specific maximum elevation target than to retain water for as long as possible. A few years of lower reservoir could produce a bump in production the year that it fills by flooding areas that had time to vegetate and capture atmospheric deposition of nitrogen, and re-animate zooplankton ephippia in sediments. Climate and flow variables are a greater influence on pelagic production in any year over reservoir elevation.

Operation	Description	Potential Influence on Pelagic Productivity
KIN Surcharge	An infrequent operation (8 of 46 years to date) requiring permission from the Comptroller of Water Rights. Up to and additional 0.3 m from full pool can occur (i.e., to 754.68m max). Usually in later season Aug-Sep but possible late July to Oct. Typically to manage spill or basin flooding risks in high water years.	Undetectable. The elevation change from full pool is very small and of short duration. Potentially a small benefit as inundation of a small portion of terrestrial habitat could release nutrients.
Mica spring shutdown and KIN refill	Typical current operation to curtail discharge at Mica GS to store freshet inflows for flood control and at a period of low electricity demand. Revelstoke Reservoir operates on local inflow during this time.	Major, beneficial influence for Revelstoke, potential benefits for Kinbasket. Reducing outflow in spring allows for benefits downstream at Revelstoke and Arrow by reducing outflow.
Outflow at Mica	With respect to cumulative annual outflow at Mica GS, not at the hourly or daily scale.	Major influence for Revelstoke and Arrow in that higher cumulative annual outflow or earlier season outflow negatively impacts Revelstoke and Arrow kokanee.
Addition of Mica Units 5 and 6	Two units added at Mica GS increased the maximum discharge capacity. The increase in time spent at higher discharges is balanced by increased time at lower discharges. Overall water balance remains the same in the year. Higher outflows were thought to potentially affect thermal properties of the Kinbasket Forebay and Revelstoke Reservoir leading to impacts on pelagic production.	Undetectable. There is no evidence to support any significant influence from the addition of Mica Units 5 and 6 on pelagic production or thermal properties in either reservoir. The changes to flow are mainly short term (median duration of peaks 4 hrs) and the greatest change occurs during winter. The analysis is limited by several factors, including limited mooring data before the addition of the units and significant inter-annual variability during the study period; however, the main drivers of pelagic production are beyond the influence of the operation of these two turbines.

5.0 Summary

1. Kinbasket and Revelstoke Reservoirs are oligotrophic to ultra-oligotrophic and are phosphorus limited.

2. There was no detectable trend in nutrient availability (nitrogen or phosphorus) over the study period either in tributary delivery or availability in the reservoir.

3. Laboratory detection limits and the presence of glacial particles constrain the assessment of very low levels of biologically available phosphorus in these reservoirs. Total phosphorus (TP) includes a large component of biologically unavailable phosphorus complicating the use of this traditional measure in these glacially impacted systems.

4. Both reservoirs undergo an annual cycle of temperature stratification. The data suggest that a variety of physical processes provide nutrient resupply to the photic zone over the course of spring and summer. Winter conditions affect the onset of stratification and water temperature in spring and set the initial supply of nutrients for spring productivity. There was a complex pathway between the tributary inflows and the photic zone where additional nutrients can be utilized by lower trophic levels. In summer, a strong interflow formed in Revelstoke reservoir with nutrients short circuiting below the photic zone to the outlet at Revelstoke Dam.

5. Despite glacial inflow, there was reasonable penetration of light into the water column (1% light to 17 m on average, both reservoirs).

6. While primary production increased by ~13% per year over the course of the study period, production was low in both reservoirs, typical of oligotrophic systems. Small sized picoplankton and nanoplankton were the most productive fractions in Kinbasket and Revelstoke Reservoirs while large sized microplankton were the least productive fraction.

7. Zooplankton density was dominated by the copepod *Diacyclops* sp. all year and *Daphnia* spp. typically dominated biomass from July/August into the fall. The timing of *Daphnia* availability is strongly associated with temperature and the month when their abundance reached a threshold for kokanee to actively choose *Daphnia* to the exclusion of other prey items could be as early as June or as late as September.

8. Lower trophic levels (phytoplankton and zooplankton) are influenced by an array of factors, primarily climatic and hydrological (flow). The major drivers in phytoplankton community structure and abundance (density) are yearly climate related variables (e.g., annual inflow

variables) whereas the zooplankton community is driven more by climate related variables at a monthly or seasonal scale (e.g., photic zone temperature and monthly inflow variables).

9. Other than Mica GS outflow reservoir operations were not found to be significant predictors of lower trophic level productivity. There was no indication that reservoir elevation was a factor in primary or secondary productivity changes that would affect kokanee outcomes. Mica GS outflow (discharge), the main inflow to Revelstoke, was a significant predictor for several zooplankton community outcomes for Revelstoke reservoir where higher flow resulted in lower outcomes for copepods, but not *Daphnia*.

10. Changes were detected in multiple trophic levels over the course of this study, and we did not find a predictive link between primary production (phytoplankton) and kokanee (planktivore).

11. Kokanee abundance and biomass trends were broadly similar between Kinbasket and Revelstoke, higher in the first half of the time series (2001 to approximately 2010) then declining to below average afterwards. Revelstoke kokanee sustained low in-lake survival from 2011 onwards resulting in the population functioning below carrying capacity from 2012-2019.

12. Annual weather (affecting egg to fry and in-lake survival), in conjunction with lake specific factors (high flow/entrainment in Revelstoke, the 2016 mortality event in Kinbasket), appeared to be the primary drivers of the decline in kokanee trends.

13. Of reservoir operational factors, discharge at Mica GS was found to have the greatest impacts to kokanee productivity, particularly in Revelstoke Reservoir due to entrainment. While discharge did not have an apparent direct impact on kokanee productivity in Kinbasket over the study period, there were signals that entrainment (associated with discharge) may be of relevance to the Kinbasket population. Reservoir elevation did not have an apparent direct impact on kokanee productivity in Kinbasket or Revelstoke.

14. Strong synchrony of annual trends in phytoplankton, zooplankton, and kokanee across Kinbasket, Revelstoke, Arrow Lakes, Kootenay Lake, and Dworshak Reservoirs demonstrate the substantial influence of both large-scale climate factors and regional weather in shaping annual outcomes and provide the opportunity to understand lake specific drivers.

15. The addition of Mica Units 5 and 6 had no detectable effect on pelagic production or thermal properties of Kinbasket and Revelstoke Reservoirs.

16. Negative effects on pelagic production, especially in Revelstoke and Arrow, can be expected where operations of Kinbasket Reservoir lead to an earlier or increased annual cumulative outflow.

17. Minimum and maximum elevation targets for Kinbasket Reservoir could result in earlier or higher discharge from Mica GS that would have cascading negative outcomes for kokanee downstream. Operating as far as possible with the water year conditions rather than in opposition would be beneficial, especially in naturally dry years when operations could potentially change a high productivity year into a year of lower productivity, such as in 2015.

18. Annual climatic and within year meteorological variables exert a strong influence on pelagic productivity outcomes in these reservoirs and, overall, the degree of confidence that a particular reservoir operation will consistently ensure a better pelagic productivity outcome is small.

19. Long-term monitoring is necessary to understand the dynamics of large, complex ecosystems where multiple trophic levels are involved and where statistical power is limited by small datasets, particularly with respect to annual variables. Consistency is an important factor for success, in design, methods, and personnel who are involved in project management, field work, sample and data analyses, and reporting.

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7.0 APPENDICES

Appendix 7.1 Estimates of hectares of pelagic habitat area (area > 17 m) available to kokanee at annual minimum and maximum pool elevations in Kinbasket Reservoir, 2001-2019. Relative elev. refers to elevation in meters from the full pool elevation of 754.38 m.

	Minimum pool elevation and habitat area for kokanee					Maximum pool elevation and habitat area for kokanee					Change	
Year	Low pool elevation (m)	Relative elev.	Zones 2-8 pelagic area	Zones 1, 9 pelagic area	Total pelagic area	High pool elevation (m)	Relative elev.	Zones 2-8 pelagic area	Zones 1, 9 pelagic area	Total pelagic area	Total Increased pelagic area	% increase from low pool
2001	715	-40	16,696	-	16,696	742	-12	22,368	3,962	26,330	9,634	58%
2002	712	-42	15,574	-	15,574	751	-3	23,735	8,285	32,020	16,446	106%
2003	714	-40	16,322	-	16,322	745	-10	22,767	5,423	28,190	11,868	73%
2004	719	-36	17,811	-	17,811	748	-6	23,234	6,860	30,094	12,283	69%
2005	725	-29	19,293	-	19,293	751	-4	23,735	8,285	32,020	12,727	66%
2006	727	-27	19,743	-	19,743	752	-2	23,902	8,760	32,662	12,919	65%
2007	724	-30	19,046	-	19,046	754	0	24,236	9,710	33,946	14,900	78%
2008	718	-36	17,564	-	17,564	752	-2	23,902	8,760	32,662	15,098	86%
2009	730	-24	20,352	-	20,352	752	-2	23,902	8,760	32,662	12,310	60%
2010	725	-30	19,293	-	19,293	754	-1	24,236	9,710	33,946	14,653	76%
2011	725	-29	19,293	-	19,293	754	0	24,236	9,710	33,946	14,653	76%
2012	722	-32	18,552	-	18,552	754.7	0	24,236	9,710	33,946	15,394	83%
2013	723	-32	18,799	-	18,799	754.6	0	24,236	9,710	33,946	15,147	81%
2014	725	-30	19,293	-	19,293	754	0	24,236	9,710	33,946	14,653	76%
2015	737	-17	21,703	1,527	23,230	751	-3	23,735	8,285	32,020	8,790	38%
2016	729	-25	20,149	-	20,149	753	-2	24,069	9,235	33,304	13,155	65%
2017	729	-26	20,149	-	20,149	752	-2	23,902	8,760	32,662	12,513	62%
2018	719	-35	17,811	-	17,811	747	-7	23,067	6,385	29,452	11,641	65%
2019	715	-39	16,696	-	16,696	748	-6	23,234	6,860	30,094	13,398	80%
Average	***723***	***-32***	**18,639**	**80**	**18,719**	***751***	***-3***	**23,735**	**8,257**	**31,992**	**13,273**	***72%***

Appendix 7.2 Kokanee egg to fry survival estimates and relevant spawner and hydroacoustic data inputs for Kinbasket Reservoir. Fecundity estimates are predicted based on McGurk (2000). Data shaded grey for female fork length are predicted from spawner density (y = 292.88x-0.088; R^2 0.52). Following year fry estimates are from summer hydroacoustic surveys.

	Spawner index	Female FL (mm)	Fecundity	Egg deposition (millions)	Following Yr. Fry (millions)	E-F survival
2001	306,833	233	337	51.7	7.8	15%
2002	399,138	228	320	63.9	9.5	15%
2003	326,324	231	332	54.2	5.8	11%
2004	583,334	220	287	83.8	5.8	7%
2005	315,722	233	339	53.5	8.4	16%
2006	341,488	232	333	56.9	14.1	25%
2007	151,618	251	417	31.6	10.8	34%
2008	816,174	214	267	109.1	4.6	4%
2009	981,549	209	251	123.2	4.6	4%
2010	412,015	225	308	63.3	4.0	6%
2011	526,865	223	301	79.4	5.9	7%
2012	274,233	235	347	47.6	8.4	18%
2013	296,947	256	438	65.1	6.0	9%
2014	127,594	233	339	21.6	7.0	32%
2015	250,573	224	302	37.8	4.8	13%
2016	136,914	253	425	29.1	5.7	20%
2017	132,443	274	528	35.0	4.2	12%
2018	245,085	246	392	48.0	5.5	11%
2019	190,256	232	333	31.7		
Ave	358,690	234	347	57.2	6.8	14%

Appendix 7.3 Kokanee egg to fry survival estimates and relevant spawner and hydroacoustic data inputs for Revelstoke Reservoir. Fecundity estimates are predicted based on McGurk (2000). Data shaded grey for female fork length are predicted from spawner density (y = 334.77x-0.111; R^2 0.79). Following year fry estimates are from summer hydroacoustic surveys.

	Spawner index	Female FL (mm)	Fecundity	Egg deposition (millions)	Following Yr. Fry (millions)	E-F survival
2001	12,664	315	779	4.9	1.4	28%
2002	42,992	275	535	11.5	2.0	17%
2003	88,973	253	427	19.0	1.1	6%
2004	13,121	313	771	5.1	1.4	28%
2005	10,914	320	816	4.5	1.6	36%
2006	57,411	266	489	14.0	1.2	9%
2007	16,760	303	701	5.9	1.7	30%
2008	23,903	293	641	7.7	0.6	8%
2009	59,443	268	501	14.9	0.9	6%
2010	64,057	270	508	16.3	0.6	4%
2011	36,950	262	468	8.6	0.4	4%
2012	17,858	279	558	5.0	0.5	11%
2013	5,523	334	920	2.5	0.4	16%
2014	6,369	350	1048	3.3	0.9	27%
2015	16,929	315	782	6.6	0.3	5%
2016	17,782	312	759	6.7	0.8	12%
2017	10,384	320	817	4.2	0.3	8%
2018	13,336	338	950	6.3	0.4	7%
2019	8,758	322	828	3.6		
Ave	27,586	300	700	7.9	0.9	14%

Appendix 7.4 Kinbasket Reservoir kokanee spawner fork length (mm) and age statistics from sampling at Camp Creek, Wood River, Bush River, Luxor Creek, and the Upper Columbia River (U. Col.).

Tributary	Year	Sample Date(s)	Age 2 spawners			Age 3 spawners			All spawners combined			% Age 3
			Mean	S.D.	n	Mean	S.D.	n	Mean	S.D.	n	
Camp Cr	1998	Sep 28-Oct 17	238	9.0	62	264	7.9	15	243	13.6	77	*19*
	2000	Sep 24-28	244	9.5	47	267	9.7	13	249	13.1	60	*22*
	2001	Sep 23-25	242	8.4	30	264	10.9	30	253	14.8	60	*50*
	2002	Sep 28-Oct 17	265	12.3	7	278	11.2	53	276	11.9	60	*88*
	2003	Sep 28-Oct 17	250	6.0	21	277	9.0	39	267	15.1	60	*65*
	2004	Sep 25	235	14.5	43	257	15.9	17	241	17.8	60	*28*
	2005*	Oct 4	242	6.6	32	253	8.2	27	247	9.4	60	*46*
	2006	Sep 25	226		1	277	10.7	59	276	12.5	60	*98*
	2007	Sep 29				273	13.6	60	273	13.6	60	*100*
	2008	Sep 28, Oct 4	223	15.6	11	253	8.7	19	242	18.5	30	*63*
	2009	Sep 29	223	10.3	30				223	10.3	30	*0*
	2010	Sep 30	228	10.6	60				228	10.6	60	*0*
	2011	Sep 23	237	7.8	28	244	1.4	2	237	7.8	30	*7*
	2012	Sep 29	247	9.4	4	265	10.7	26	263	12.2	30	*87*
	2013	Sep 13,19 & 26	264	6.3	15	283	10.3	34	278	12.7	49	*69*
	2014	Sep 22, 29, Oct 6	238	13.0	19	266	18.0	41	257	21.2	60	*68*
	2015	Sep 15, 21 & 28	237	9.3	40	241	10.8	17	238	9.6	60	*30*
	2016*	Sep 15, 22 & 28	271	14.3	10	275	8.0	27	274	9.9	60	*73*
	2017*	Sep 18, 22 & 28	273	15.1	47	297	10.6	10	278	17.2	60	*18*
	2018	Sep 24, Oct 1 & 4	258	11.9	60				258	11.9	60	*0*
	2019	Sep 13, 18 & 24	249	6.8	9	278	12.1	51	274	15.4	60	*85*
	Mean		**245**			**267**			**256**			**48**
Wood R	2016	Sep 21	259	6.9	9	264	8.5	3	260	7.4	12	*25*
	2018	Oct 5	237	9.3	30				237	9.3	30	*0*
	2019	Sep 1	241	7.5	24	261	7.0	8	246	11.4	32	*25*
	Mean		**246**			**263**			**248**			***17***
Bush R	2013	Sep 20 & 26	259	8.3	34				259	8.3	34	*0*
	2014	Sep 15 & 25	234	14.1	16	244	18.8	6	236	15.5	22	*27*
	2015	Sep 17	224	7.8	19	233	16.5	3	225	9.2	23	*14*
	2016	Sep 15 & 28	248	11.5	51	255	13.2	5	249	11.2	89	*9*
	2017	Sep 12*, 21 & 29	258	20.8	48	290	7.0	10	264	22.4	60	*17*
	2018	Sep 19 & 29	242	7.5	57				242	7.5	57	*0*
	2019	Sep 24 & 30	231	7.5	57	258	14.5	3	233	9.7	60	*5*
	Mean		**242**			**256**			**244**			***10***
Luxor Cr	2007		249	8.4	27	268	3.2	4	251	10.2	31	*13*
	2009		209	11.0	30				209	11.0	30	*0*
	2010		224	9.2	29	244		1	225	9.7	30	*3*
	2011		223	10.3	10				223	10.3	10	*0*
	2012	Sep 25	233	8.3	24	247	5.3	5	235	9.5	29	*17*
	2013	Sep 13,20 &26	252	6.7	41	264	10.3	6	253	8.1	47	*13*
	2014*	Sep 15 & 25	231	10.0	36	256		1	230	12.2	39	*3*
	2015	Sep 17	221	6.4	33				221	6.3	34	*0*
	2016	Sep 15 & 21	243	11.9	46	255	4.0	3	243	12.5	54	*6*
	2017	Sep 12 & 21	261	10.1	36	278	8.5	8	264	11.7	45	*18*
	2019	Sep 24	230	8.0	33				230	8.0	33	*0*
	Mean		**234**			**259**			**235**			**7**
U. Col.	2014	Sep 29	234	10.1	45			0	234	10.0	45	*0*
	2015	Sep 29	226	6.1	14	225	1.2	2	226	7.5	23	*13*
	2016	Sep 13, 27, Oct 4	261	10.5	39			0	260	11.2	119	*0*
	2017								281	16.1	129	
	2018	Sep 18-29	247	13.1	144				247	13.1	144	*0*
	Mean		**242**			**225**			**250**			**13**

*** Notes:**
One age 4 spawner at 260mm in Camp Creek in 2005 excluded from this table.
Two very small males in Luxor in 2014 were potentially age 1 excluded from this table.
One age 4 spawner at 271mm in Camp Creek in 2016 excluded from this table.
Ages were not available for 2017 Upper Columbia River (U. Col.).

Appendix 7.4 (cont'd) Revelstoke Reservoir kokanee spawner fork length (mm) and age statistics from sampling at Standard Creek.

Tributary	Year	Sample Date	Age 2 spawners			Age 3 spawners			All spawners combined			% Age 3
			Mean	S.D.	n	Mean	S.D.	n	Mean	S.D.	n	
Standard Cr	2007		292	10.6	22	329	11.9	10	303	20.5	32	31
	2009		263	10.7	14	306		1	266	15.1	15	7
	2010		264	11.8	9	293		1	267	14.4	10	10
	2011		260	7.5	14	277	5.5	6	265	10.7	20	30
	2012	Sep 27	265		1	280	8.4	14	279	9.0	15	93
	2013	Oct 4	332	11.9	5	340	5.7	5	336	9.7	10	50
	2014	Oct 2	330	8.3	16	375	5.3	5	341	21.0	21	24
	2015*	Oct 2	303	18.8	18	333	23.6	9	312	23.9	30	33
	2016	Sep 28	307	8.3	14	342		1	310	11.7	16	7
	2017	Sep 29	303	38.4	8	361	6.4	4	321	38.9	14	33
	2018	Oct 5	350	19.0	7	379	5.7	2	356	21.0	9	22
	2019	Oct 1	318	15.5	31	364	24.1	4	323	22.0	35	11
	Mean		**299**			**332**			**307**			**29**

*** Note:**
A single abnormally small age 3 spawner (236 mm) was measured in 2015 which contributed to high S.D. and lowered the mean length for age 3 spawners. It is possible this fish was entrained from Kinbasket Reservoir.