Arrow Lakes Reservoir Nutrient Restoration Program

(COL-F24-F-3793-DCA)

2023-24 (F24) Activity Report

1 April 2023 to 31 March 2024

Taite Creek 2023 Kokanee Spawners; M. Bassett

Prepared for: Fish & Wildlife Compensation Program (FWCP)

Prepared by: Ministry of Water, Land and Resource Stewardship (WLRS), Resource Management (FWCP – Section) and Aquatic Ecosystems

Prepared by: Marley Bassett and Tyler Weir (WLRS)

Prepared with financial support from the Fish & Wildlife Compensation Program, on behalf of its program partners BC Hydro, the Province of B.C., Fisheries and Oceans Canada, First Nations and Public Stakeholders.

Acknowledgements

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Executive Summary

Nutrient additions, in the form of liquid agricultural grade fertilizer occurred in Upper Arrow Lakes Reservoir in 2023 following the same methods as recent years. In total, 42.9 MT of phosphorus and 204.9 MT of nitrogen were added to the Reservoir between late April and early September. The annual loading of phosphorus from fertilizer additions has been around 40 MT since 2016 (2023 was the 8th year of holding similar loading rates). The 2023 April-October daily mean outflow for Arrow was 1065 m^3/s which was below the 1997-2023 mean of 1122 m^3/s. Mean reservoir outflow in July and August (warm growing season) was near the 2011-2023 mean. Water clarity, measured as a Secchi depth, was below average for both basins in 2023. Phosphorus and nitrogen values were similar to previous years and in the range of an oligotrophic system. Phytoplankton density was above average in both basins. For zooplankton, Daphnia was slightly above average in Upper Arrow and average in Lower Arrow. Copepods were near average in Upper Arrow, and lower in Lower Arrow in 2023. The timing of *Daphnia* detection was the same as 2021 and 2022, early compared to 2017-2020. Mysid densities in 2023 were average in both basins.

Approximately 320,000 kokanee spawners were enumerated in the index tributaries and Hill Creek Spawning Channel in 2023, which was near the post-nutrient restoration program average of 345,000. The 2023 age 0 (fry) and age 1-3 kokanee populations for the combined basins were 6.33 million and 1.55 million respectively, both below the post-nutrient restoration program average. Annual kokanee cohort survival was near average for both age 0 to 1 and age 1-2+. Kokanee biomass density (combined in-lake and spawners) was 224 tonnes in 2023, which was 20% higher than the post-nutrient restoration program average.

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Introduction

Arrow Lakes Reservoir has been influenced by the construction of 3 dams – Hugh Keenleyside (1968), Mica (1973) and Revelstoke (1984). Hugh Keenleyside raised maximum water levels inundating the former Upper and Lower Arrow Lakes to form Arrow Lakes Reservoir. The increased water levels impacted high quality spawning and rearing habitat in tributaries. Revelstoke Dam blocked access to spawning and rearing habitat in tributaries upstream of the reservoir, and both Mica and Revelstoke Dams caused long-term changes in light penetration and nutrients in the lentic habitat of Arrow Lakes Reservoir. As a result of decreased upstream nutrient inputs, kokanee stocks in Arrow Lakes declined substantially by the mid-1990s. To address the nutrient losses in Arrow Lakes Reservoir, a bottom-up approach was taken with the addition of nutrients (nitrogen and phosphorus in the form of liquid fertilizer) to increase phytoplankton populations that are suitable to produce *Daphnia*, the main food source for Kokanee. Through the Nutrient Restoration Program (NRP), nutrients have been added to Upper Arrow since 1999 and are dispensed from Waterbridge ferries from approximately April to September. Columbia Power Corporation contributes 25% of the costs to this project to compensate for fish entrainment through the Arrow Lakes Generating Station as per DFO Authorization No. 5300-10-002.

Nutrient addition has been a successful technique used for the enhancement and conservation of sockeye salmon populations and for kokanee populations in lakes and reservoirs altered by hydroelectric construction. To ensure the Arrow Lakes NRP has been effective and efficient at meeting its objectives an external review occurred from 2020-2022. The review concluded the NRP is achieving the objective of restoring productivity to the reservoir through nutrient additions (Hecky & Guilford, 2022).

Linkage to Fish and Wildlife Compensation Program Action Plans

The NRP is a priority one habitat-based action (Figure 1) described in the Columbia Region Reservoirs and Large Lakes Action Plan (FWCP, 2019).

Action Tables

Reservoir & Large Lake Ecosystem Actions

RESERVOIRS AND LARGE LAKES ACTION TABLE - ECOSYSTEMS (AQUATIC PRODUCTIVITY)							Version:AUG2019	
Action #	**Action Type**	**Priority Action Short Description**	**Priority**	**Priority Area**	**Target Species**	**Priority Action**	**Intended Outcome**	**Delivery Approach**
8	Habitat-based	**COLRLL.ECO.HB.08.01 Implementation of Kootenay Lake and Arrow Lakes Nutrient Restoration Programs-P1**	**1**	Kootenay Lake Arrow Lakes	Fish	Implement and adaptively manage nutrient restoration programs in Kootenay Lake and Arrow Lakes Reservoir to sustain in-lake productivity at levels sufficient to support secondary productivity (forage for Kokanee).	Successfully demonstrate improved health and productivity of reservoirs.	Directed
9	Habitat-based	**COLRLL.ECO.HB.09.01 Operation of Meadow Creek and Hill Creek spawning channels-P1**	**1**	Kootenay Lake Arrow Lakes	Fish	Support the maintenance and operation of the Meadow Creek and Hill Creek spawning channels to ensure sufficient kokanee production in Kootenay Lake and Arrow Lakes Reservoir.	Improved Kokanee productivity to support a healthy and resilient reservoir ecosystem.	Directed
10	Monitoring and Evaluation	**COLRLL.ECO.ME.10.01 In-season Monitoring of Kootenay Lake and Arrow Lakes Nutrient Restoration Programs-P1**	**1**	Kootenay Lake Arrow Lakes	Fish	Implement in-season monitoring and evaluation of indicators and trends in ecosystem components (e.g. water chemistry, plankton, Kokanee) related to the Kootenay Lake and Arrow Lakes Reservoir nutrient restoration programs.	Improved understanding of indicators and annual trends of in lake productivity.	Directed

- **Habitat-based Actions** – These actions will conserve, restore, and enhance reservoir and large lake habitats. Examples include habitat creation, restoration, and enhancement; enhancing habitat connectivity; nutrient restoration; and invasive species prevention.
- **Monitoring and Evaluation** – These actions will monitor and evaluate reservoir and large lake projects supported by the FWCP to understand the effectiveness of habitat- or species-based actions.

Figure 1. Nutrient Restoration Program components of the Reservoirs and Large Lakes Action Table – Ecosystems (Aquatic Productivity) in the Columbia Region Reservoirs and Large Lakes Action Plan (FWCP, 2019).

Methods

The nutrient addition zone on Arrow Lakes Reservoir is the pelagic area between Shelter Bay and Galena Bay (Figure 2). The trophic levels monitored as components of the program are physical limnology, phytoplankton, zooplankton, mysids, in-lake kokanee (hydroacoustics and trawling), and kokanee spawners. A summary of data types collected for 2023 is in Appendix 2. Methods for nutrient additions and the sampling of various trophic levels for the nutrient restoration programs were generally the same as in the previous years, and are described in detail by (Bassett, Weir, & Fox, 2020).

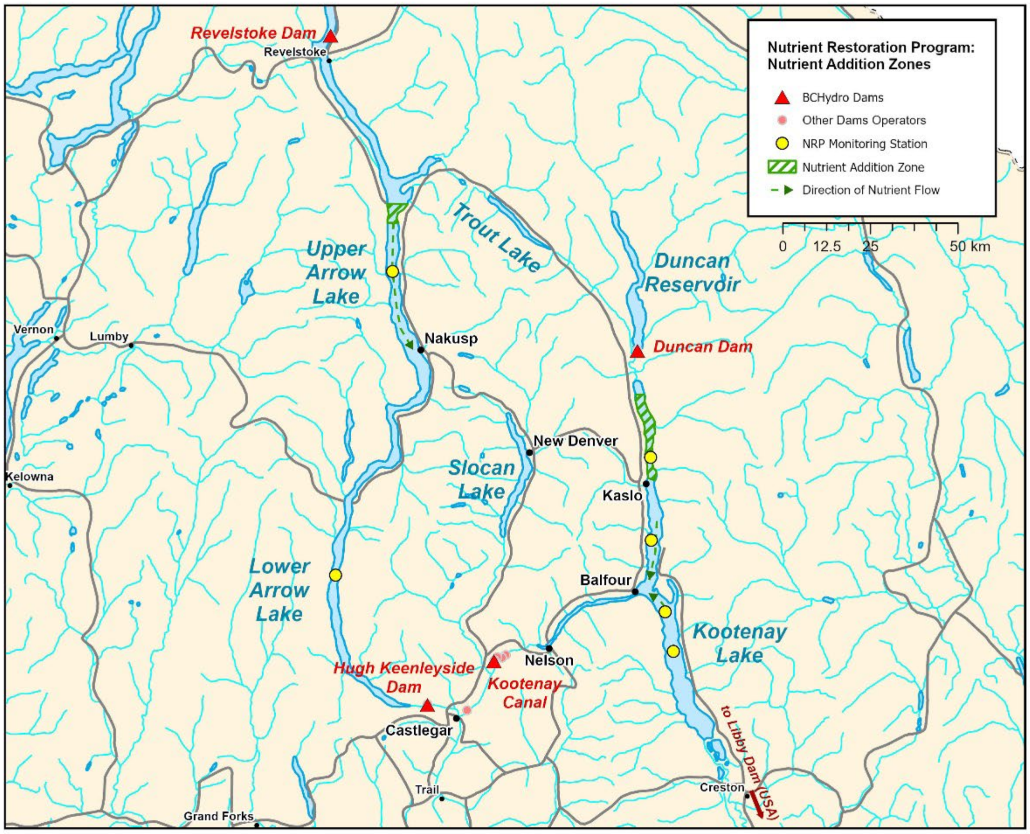

Figure 2. Arrow Lakes Reservoir nutrient addition zone and monitoring stations.

Results

Nutrient Loading

In total, 42.9 MT of phosphorus and 204.9 MT of nitrogen were added to Upper Arrow Reservoir in the form of liquid agricultural grade fertilizers, 10-34-0 and 28-0-0. The annual loading of phosphorus from fertilizer has been approximately 40 MT since 2016.

Flow

The 2023 mean outflow (April 1 to Oct 31) for Arrow was 1065 (m^3/s), which was near the 1997-2010 mean and below the more recent era (2011-2023) mean (Figure 3). The outflow regime fluctuated throughout the year and was generally higher in late July and August and lower in the fall compared to average (Figure 4). Specific to the warm summer months (July and August), the mean outflow was average in 2023 for the recent era (2011-2023) and above the long-term mean (1997-2023) (Figure 5). There was a significant difference ($p<0.05$) between the two eras, 1997-2010 and 2011-2023, for both the April-October season (Figure 3), and the July-

August season (Figure 5). Figure 6 shows the April to October outflows for the current year (2023) and the two years with the highest July and August outflows, 2012 and 2022.

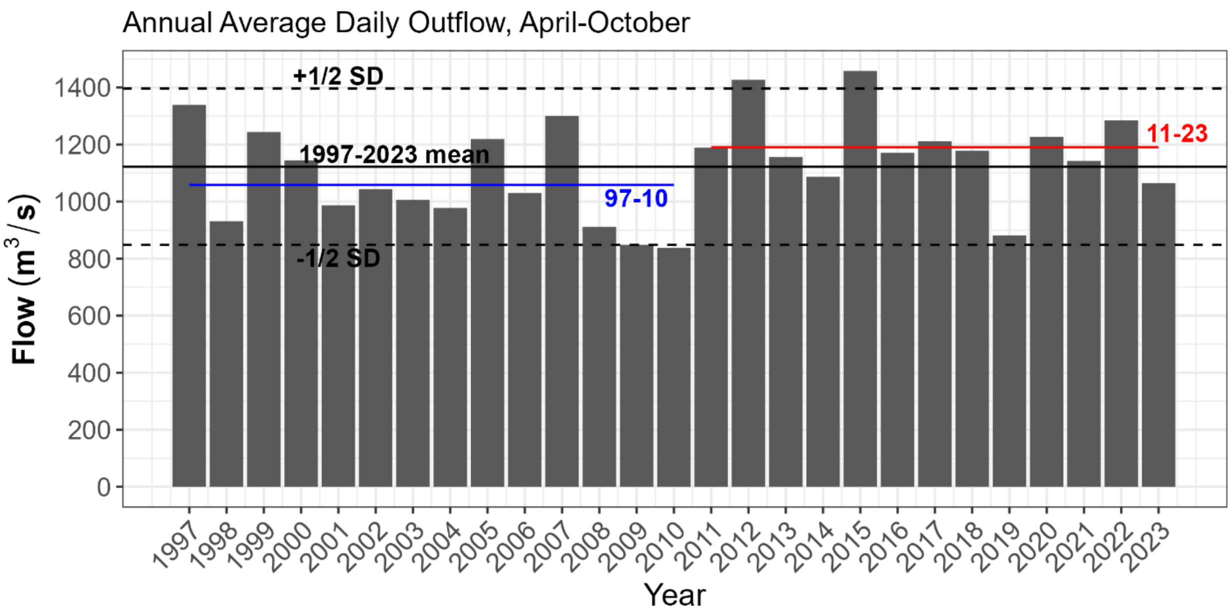

Figure 3. Annual mean of daily outflow (m^3/s) between April and October in Arrow Lakes Reservoir 1997-2023. Solid blue line is 1997-2010 outflow mean and solid red line is 2011-2023 outflow mean. Solid black horizonal line is 1997-2023 mean and dashed black horizonal lines are ±1/2 SD.

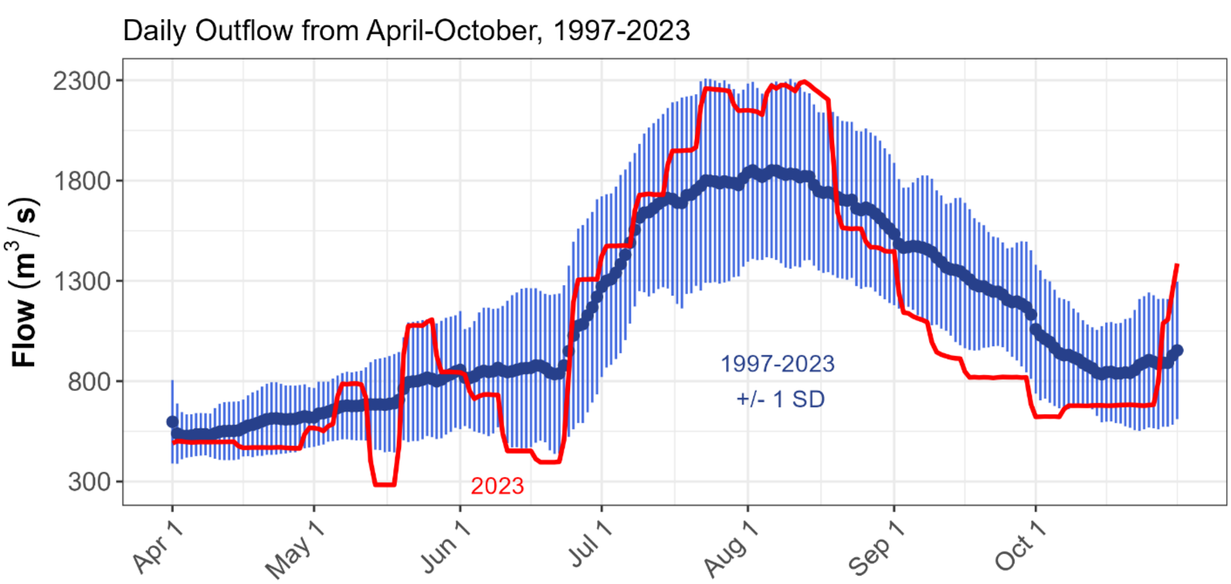

Figure 4. Arrow Lakes Reservoir daily outflow, April-October 1997-2023. Blue circles are 1997–2023 daily average, blue vertical lines ± 1 standard deviation. Red line is 2023 daily outflow.

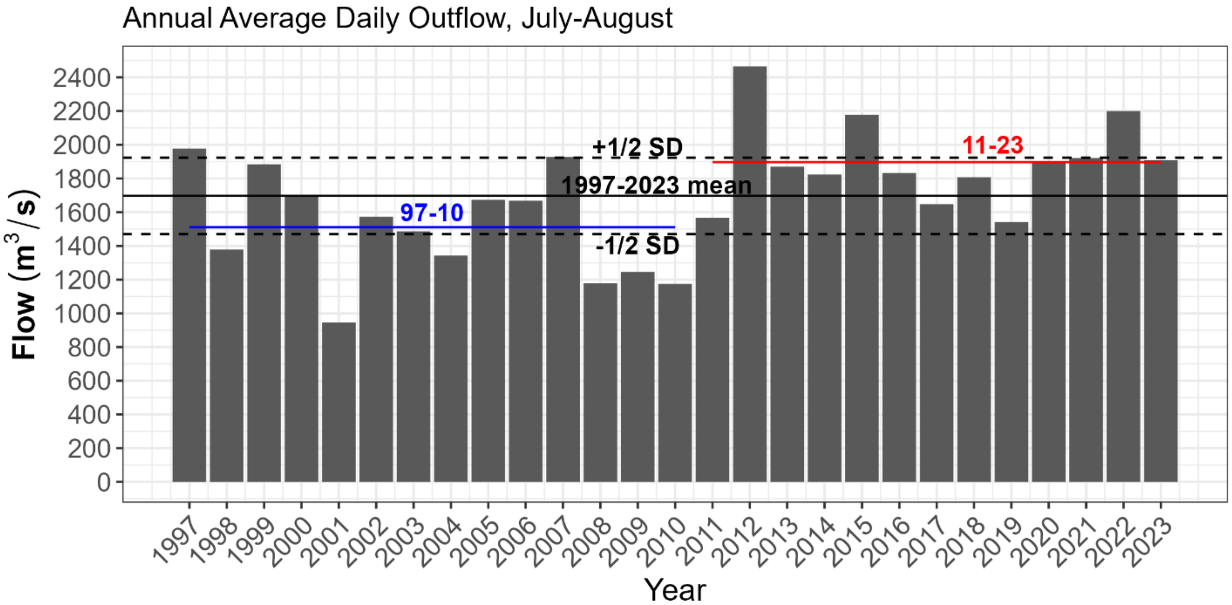

Figure 5. Annual mean of daily outflow (m³/s) between July and August in Arrow Lakes Reservoir 1997-2023. Solid blue line is 1997-2010 outflow mean and solid red line is 2011-2023 outflow mean. Solid black horizonal line is 1997-2023 mean and dashed black horizonal lines are ±1/2 SD.

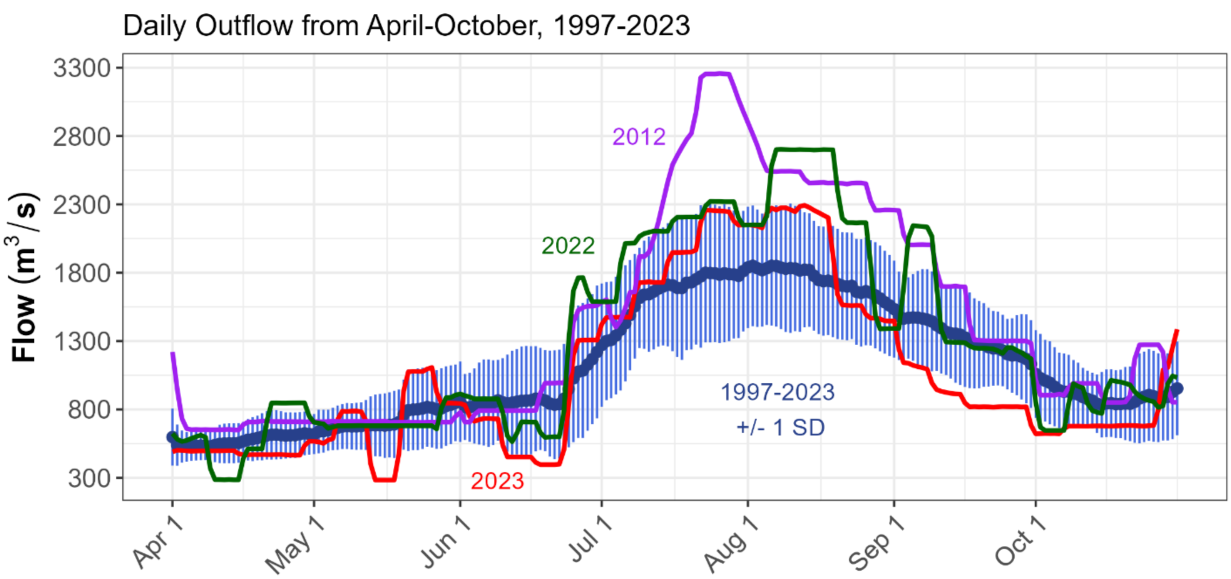

Figure 6. Arrow Lakes Reservoir daily outflow, April-October 1997-2023. Blue circles are 1997–2023 daily average, blue vertical lines ± 1 standard deviation. Purple line is 2012 daily outflow. Green line is 2022 daily outflow. Red line is 2023 daily outflow.

Physical Limnology

Secchi depth is a measure of water clarity, where the higher the number, the clearer the water. In 2023, the mean Secchi depth in Upper Arrow was 4.2 m while the 1997-2023 average was 6.2 m (Figure 7). The mean Secchi depth in Lower Arrow a was 5.5 m while the 1997-2023 mean was 6.7 m (Figure 7). The seasonal trend in 2023 was similar to the pattern across months in the averaged 1997-2022 data, though the April and May Secchi depth was slightly higher in Upper Arrow and in May in Lower Arrow (Figure 8).

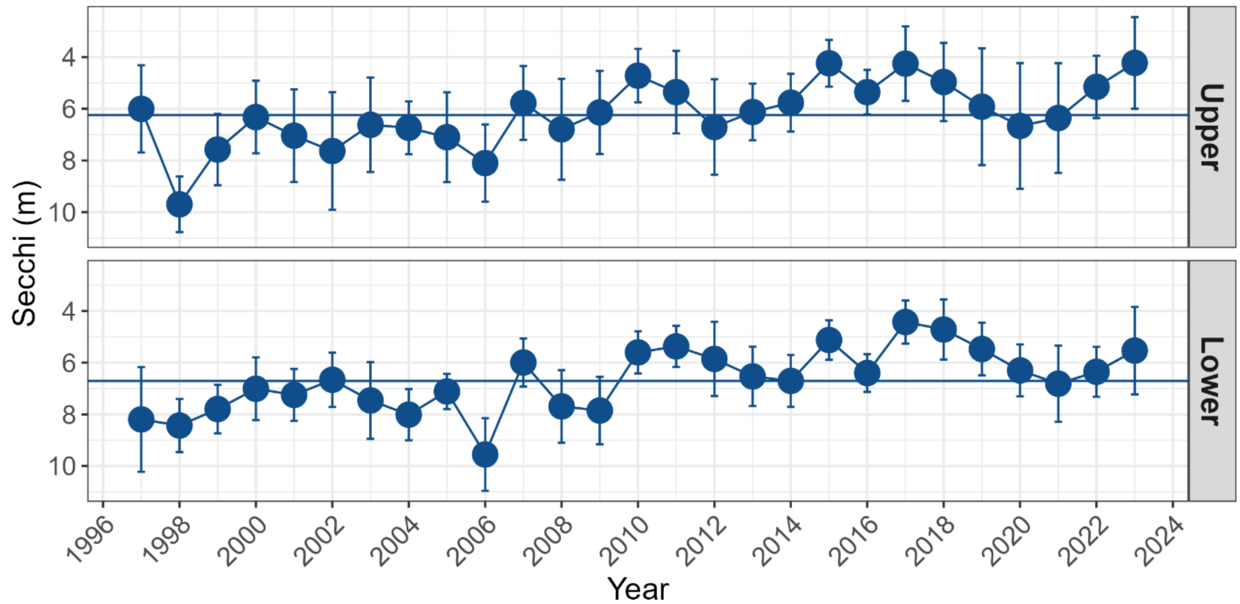

Figure 7. Arrow Secchi (m) annual mean (April – October), by basin. Horizontal lines are long term basin averages. Means ± 2SE.

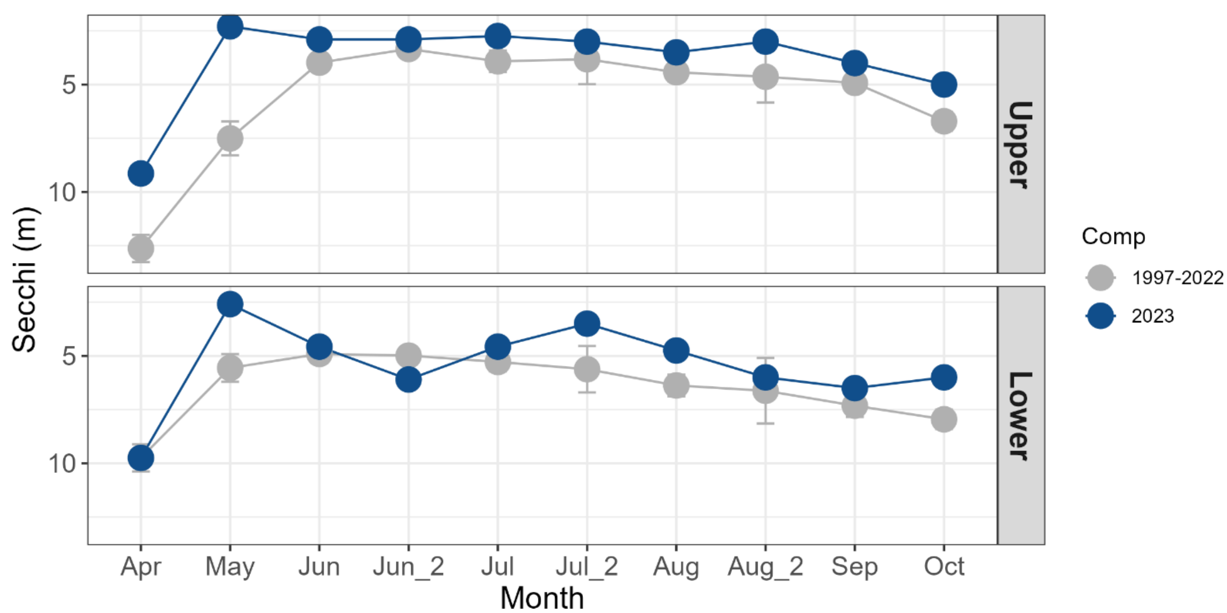

Figure 8. Arrow Secchi (m) monthly mean by basin (Upper and Lower) 2022 (blue) and 1998–2021 (grey). Jul_2 and Aug_2 sampling began in 2012. Means ±SE.

Water Chemistry: Nutrients

Parameters of particular interest to the program are the nutrients nitrogen and phosphorus. The form of phosphorus most readily available for biological uptake is total dissolved phosphorus (TDP). In 2023, the mean TDP for both basins were 2.0 µg/L which was below both Upper and Lower Arrow long-term means (Figure 9). Minimal seasonal variability occurred in the TDP values in 2023 (Figure 10). The TDP values are often reported at or under the detection limit of 2 µg/L, as was again the case in 2023, where 75% of the values in the integrated samples were reported under the detection limit. Total phosphorus (TP) in 2023 was on the long-term average for both basins (Figure 11). Minimal seasonal variability was noted in the monthly means, although a high TP result was reported in July in Lower Arrow (Figure 12). The phosphorus values observed in Arrow continue to categorize the reservoir as ultra-oligotrophic (Wetzel, 2001). The dissolved components of nitrogen (dissolved inorganic nitrogen; DIN) concentrations in both Upper and Lower Arrow in 2023 were at the 2004-2023 means (Figure 13). Note that in 2004, the sampling depth was modified from 0-30m to 0-20m. The 0-30m samples had higher concentrations because 30m is below the thermocline where higher concentrations of nitrate occur (Schindler, et al., 2007). Comparing 2023 to the 2004-2022 seasonal trends (Figure 14), the monthly means in both basins were similar to previous years, though higher in May and lower in June-July for Upper Arrow, and for Lower Arrow lower in 2023 in early August. Total nitrogen was below average in 2023, though similar to the previous eight years (Figure 15). Below average total nitrogen was apparent for Upper Arrow for most months and notably lower in April and August in Lower Arrow (Figure 16). The nitrogen-phosphorus ratios, dissolved (Figure 17 and Figure 18) and total (Figure 19 and Figure 20), were all above ratios of concern for non-preferred phytoplankton growth.

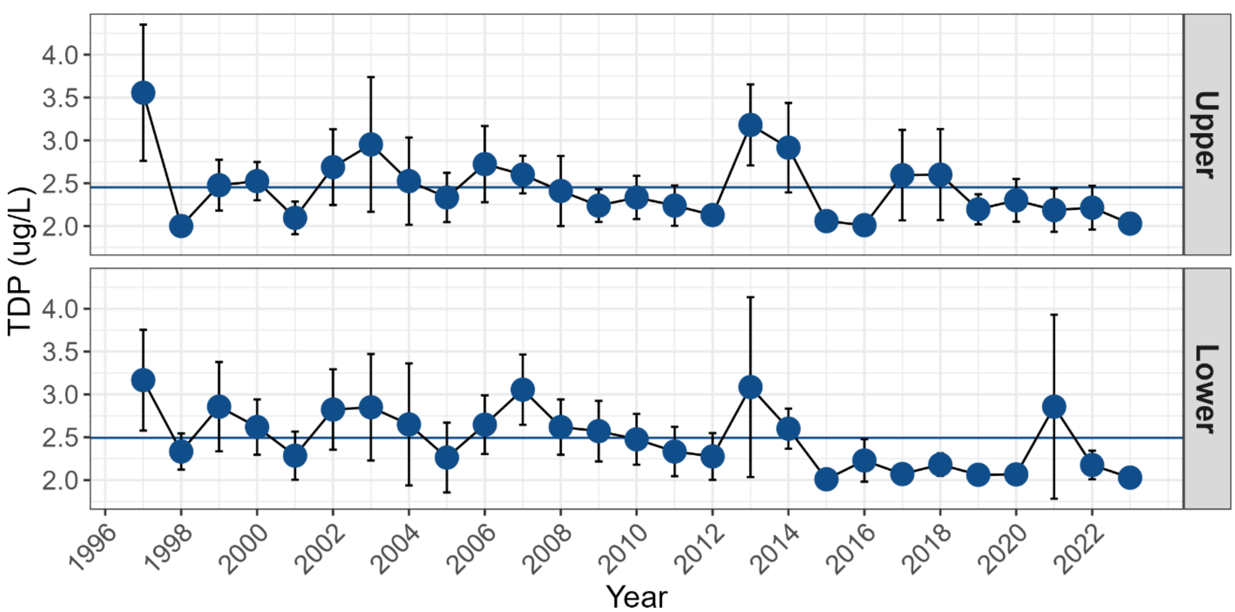

Figure 9. Arrow total dissolved phosphorus (TDP) annual mean (April – October), by basin. Horizontal lines are long term basin averages. Means ± 2SE.

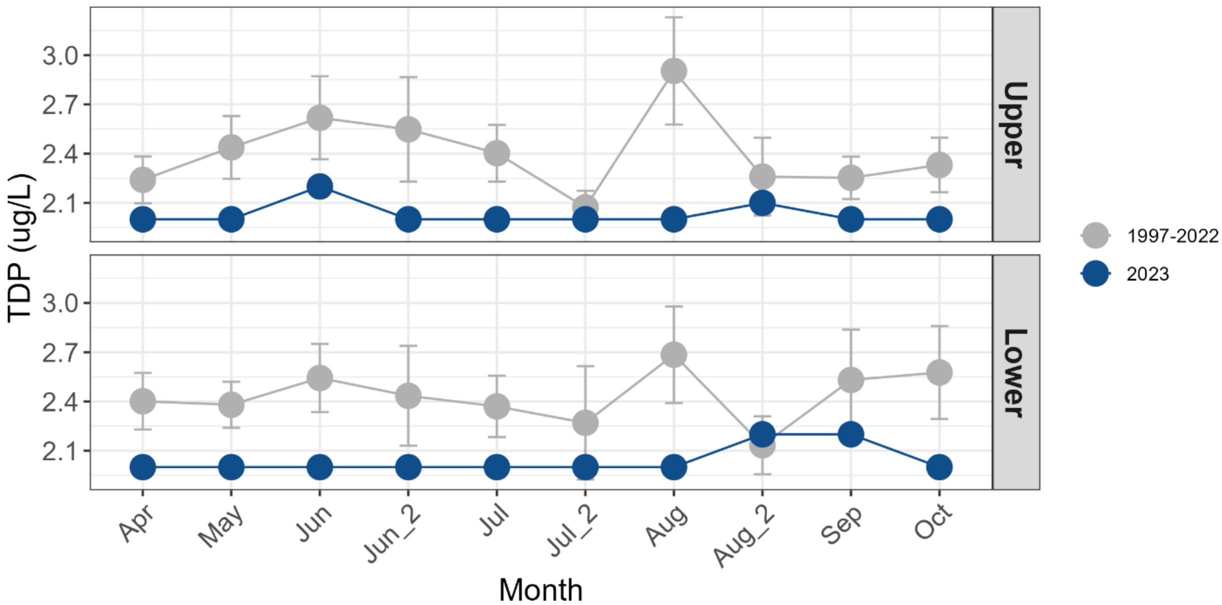

Figure 10. Arrow total dissolved phosphorus (TDP - µg/L) monthly mean by basin (Upper and Lower) 2023 (blue) and 1998–2022 (grey). Jul_2 and Aug_2 sampling began in 2012. Means ±SE.

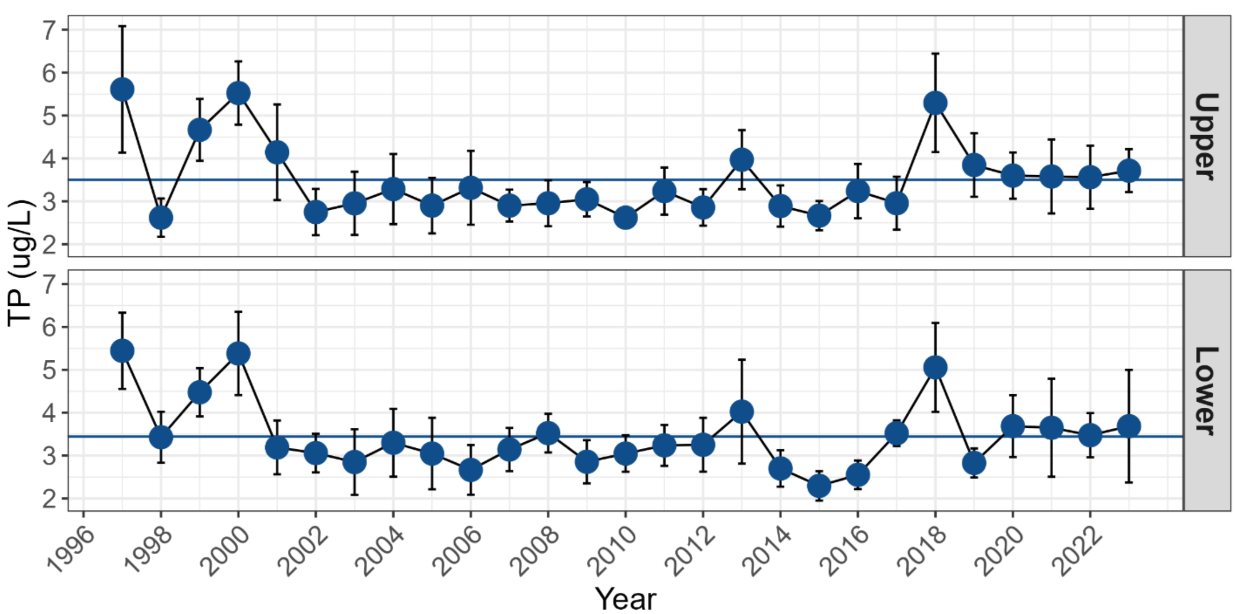

Figure 11. Arrow total phosphorus (TP - µg/L) annual mean (April – October), by basin. Horizontal lines are long term basin averages. Means ± 2SE.

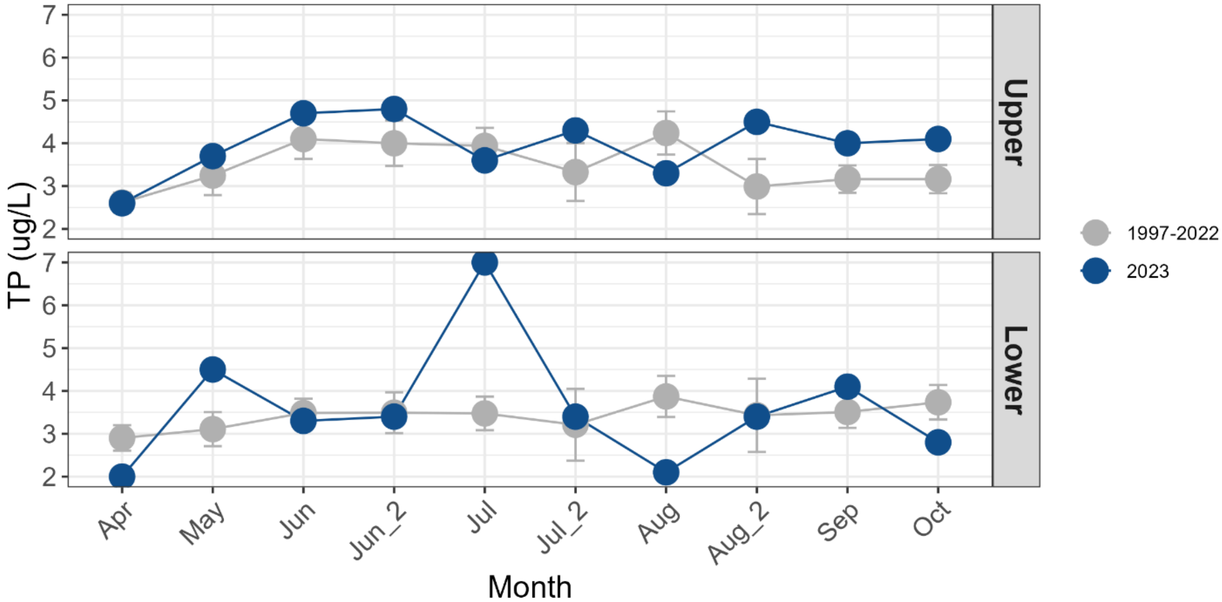

Figure 12. Arrow total dissolved phosphorus (TP - µg/L) monthly mean by basin (Upper and Lower) 2023 (blue) and 1998–2022 (grey). Jul_2 and Aug_2 sampling began in 2012. Means ±SE.

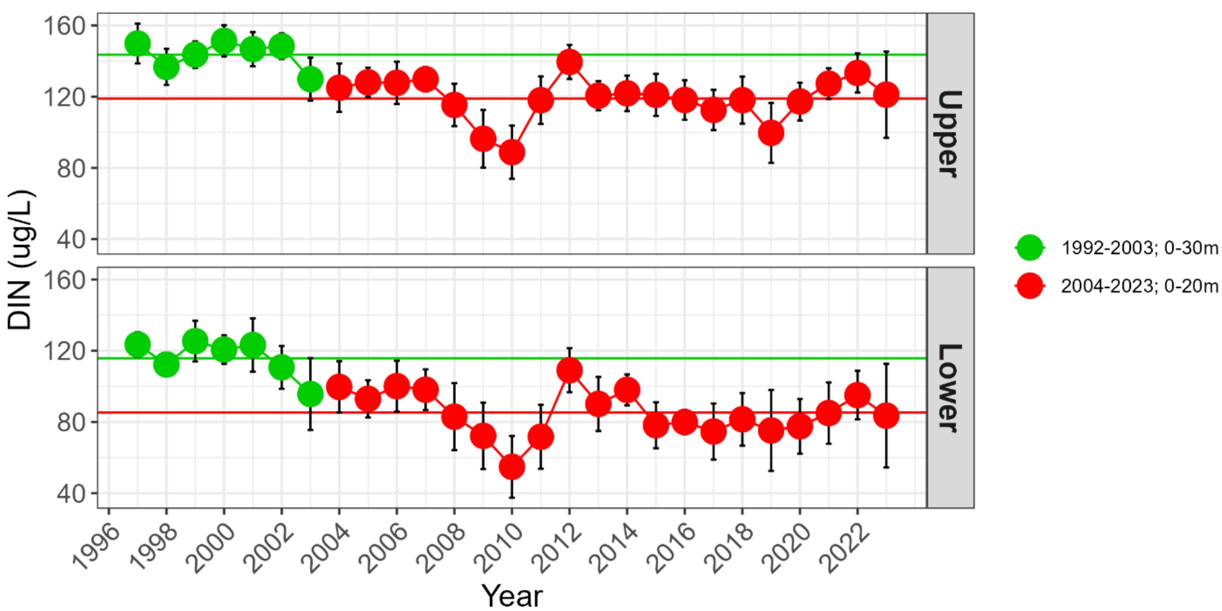

Figure 13. Arrow dissolved inorganic nitrogen (DIN - µg/L) annual mean (April – October), by basin. Sampling depth 0-30 m (green) and 0-20 m and 2023 (red). Horizontal lines are long term basin averages (by sampling depth). Means ± 2SE.

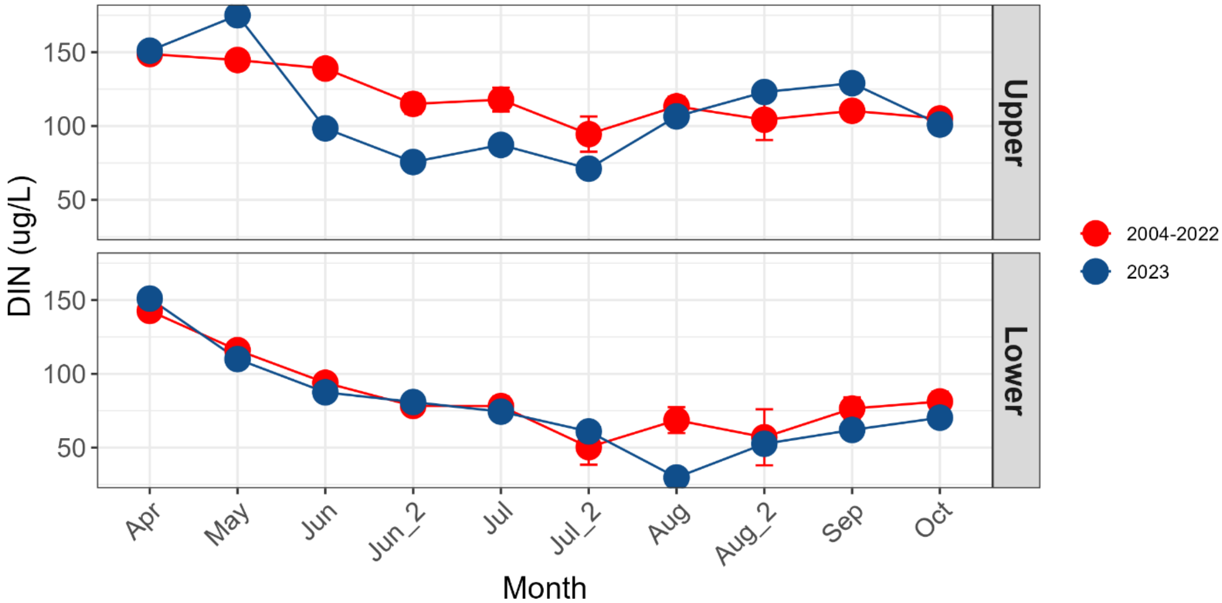

Figure 14. Arrow dissolved inorganic nitrogen (DIN - µg/L) monthly mean by basin (Upper and Lower) 2023 (blue) and 2004–2022 (red). Jul_2 and Aug_2 sampling began in 2012. Means ±SE.

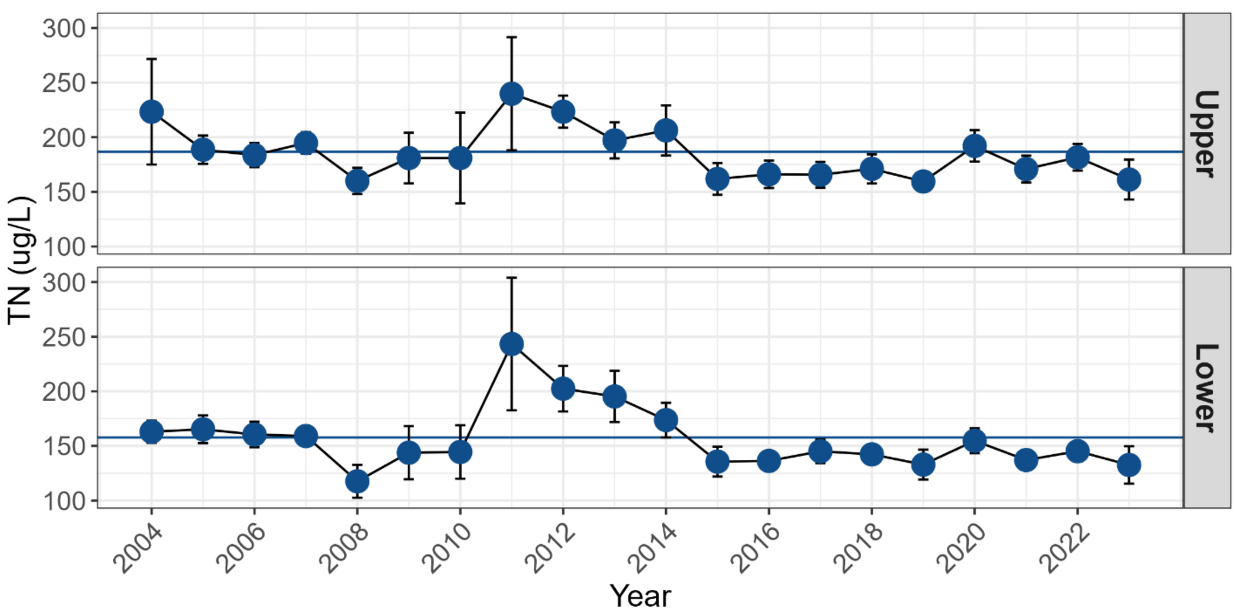

Figure 15. Arrow total nitrogen (TN - µg/L) annual mean (April – October), by basin. Comparative (0-20 m) sampling began in 2004. Means ± 2SE.

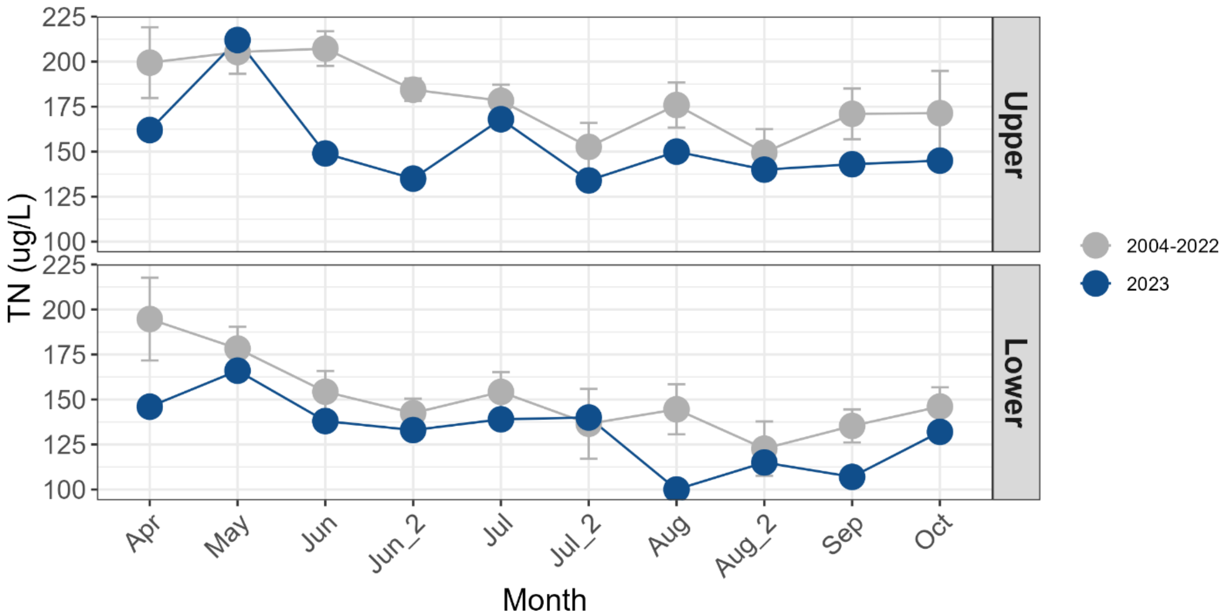

Figure 16. Arrow total nitrogen (TN - µg/L) monthly mean by basin (Upper and Lower) 2023 (blue) and 2004–2022 (grey). Jul_2 and Aug_2 sampling began in 2012. Means ±SE.

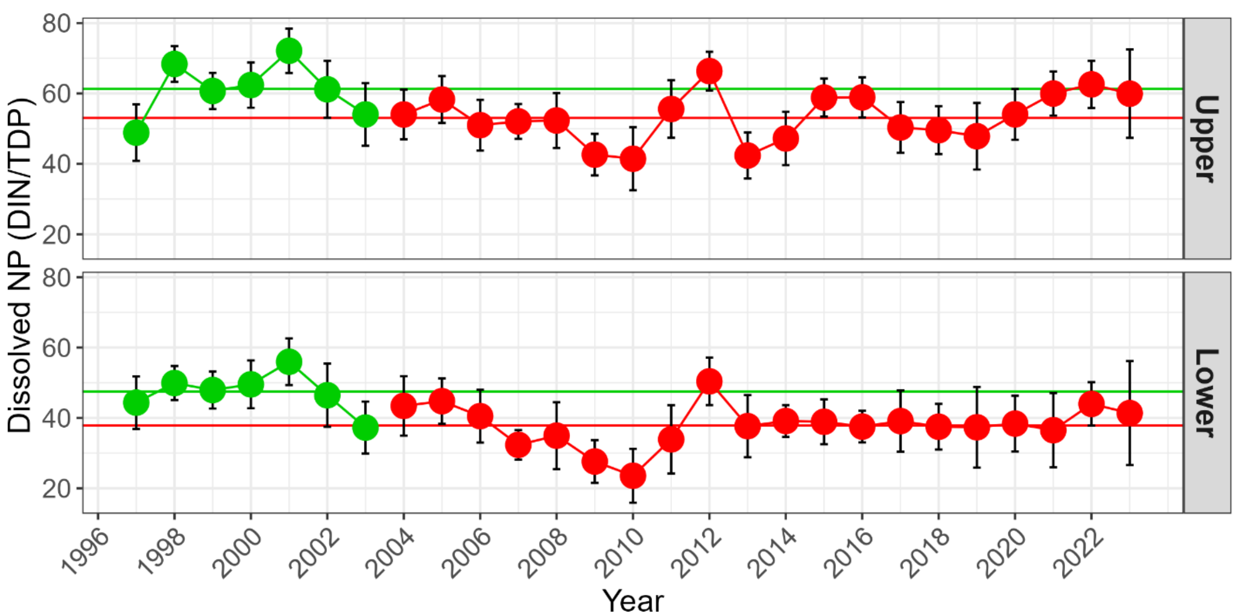

Figure 17. Arrow dissolved nitrogen to phosphorus (NP) ratio (DIN/TDP) annual mean (April – October), by basin. Sampling depth 0-30 m (green) and 0-20 m and 2023 (red). Horizontal lines are long term basin averages (by sampling depth). Means ± 2SE.

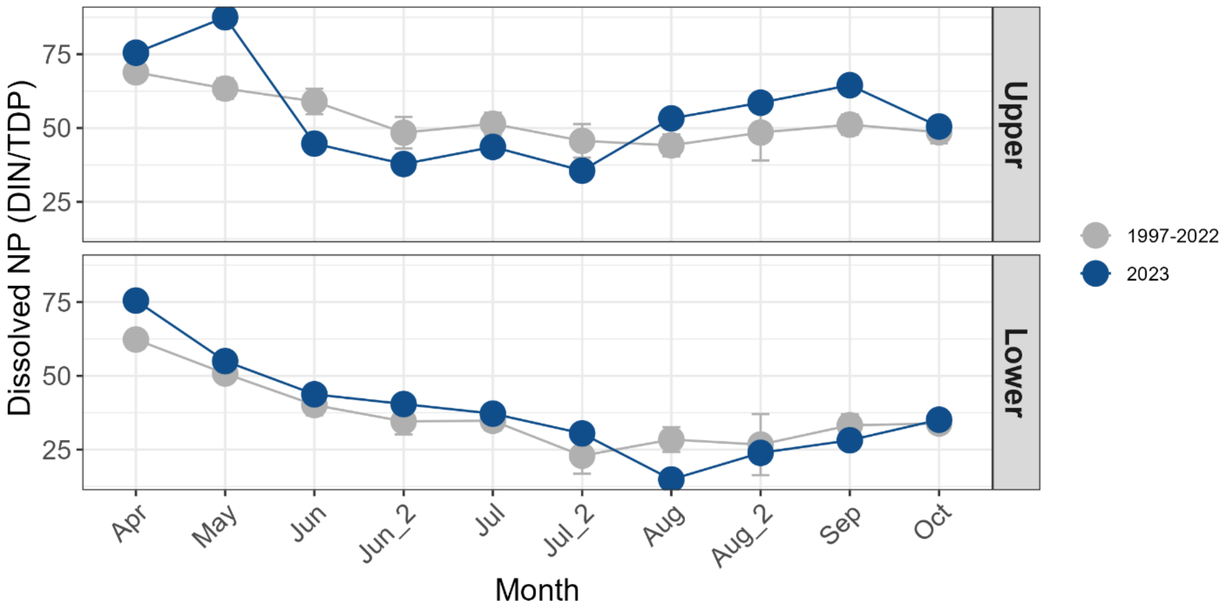

Figure 18. Arrow dissolved nitrogen to phosphorus (NP) ratio (DIN/TDP) monthly mean by basin (Upper and Lower) 2023 (blue) and 2004–2022 (grey). Jul_2 and Aug_2 sampling began in 2012. Means ±SE.

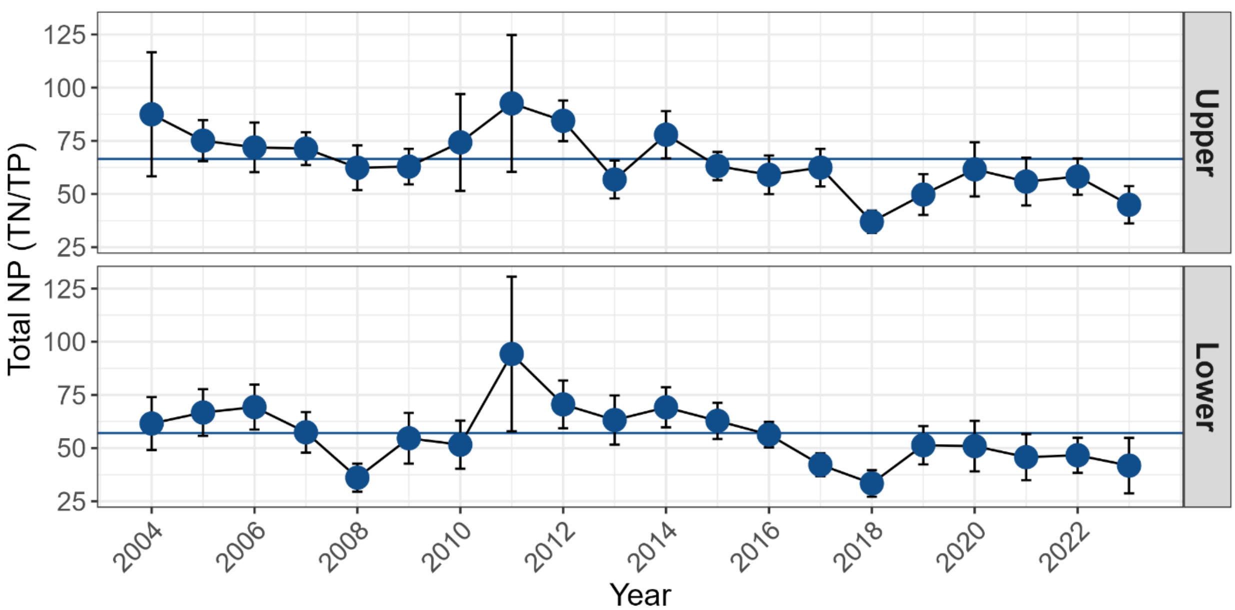

Figure 19. Arrow total nitrogen to phosphorus (NP) ratio (TN/TP) annual mean (April – October), by basin. TN sampling began in 2004. Means ± 2SE.

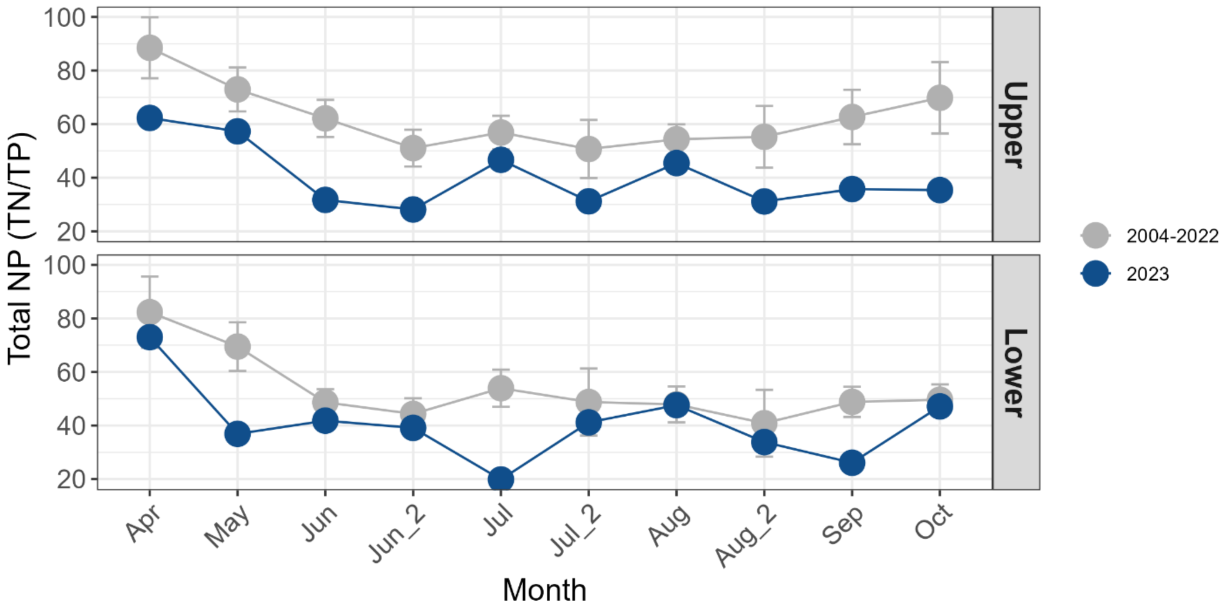

Figure 20. Arrow total nitrogen to phosphorus (NP) ratio (TN/TP) monthly mean by basin (Upper and Lower) 2023 (blue) and 2004–2022 (grey). Jul_2 and Aug_2 sampling began in 2012. Means ±SE.

Phytoplankton

Total phytoplankton abundance in 2023 was above average for both the Upper and Lower basins (Figure 21). The 2023 phytoplankton abundance trended seasonally with previous years, though higher abundances were observed in the summer and fall months in Upper and Lower Arrow, aside from in September in Lower Arrow, which was at the previous mean for that month (Figure 22).

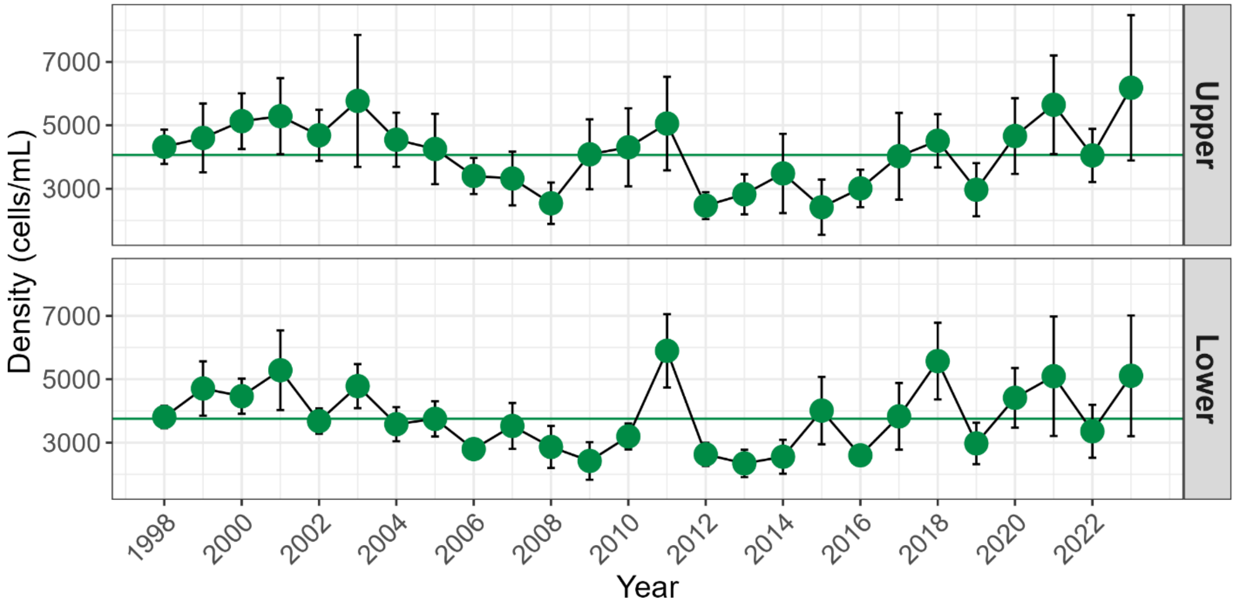

Figure 21. Arrow phytoplankton density (cells/ml) annual mean (April – October) by basin. Horizontal lines are long term basin averages. Means ± 2SE.

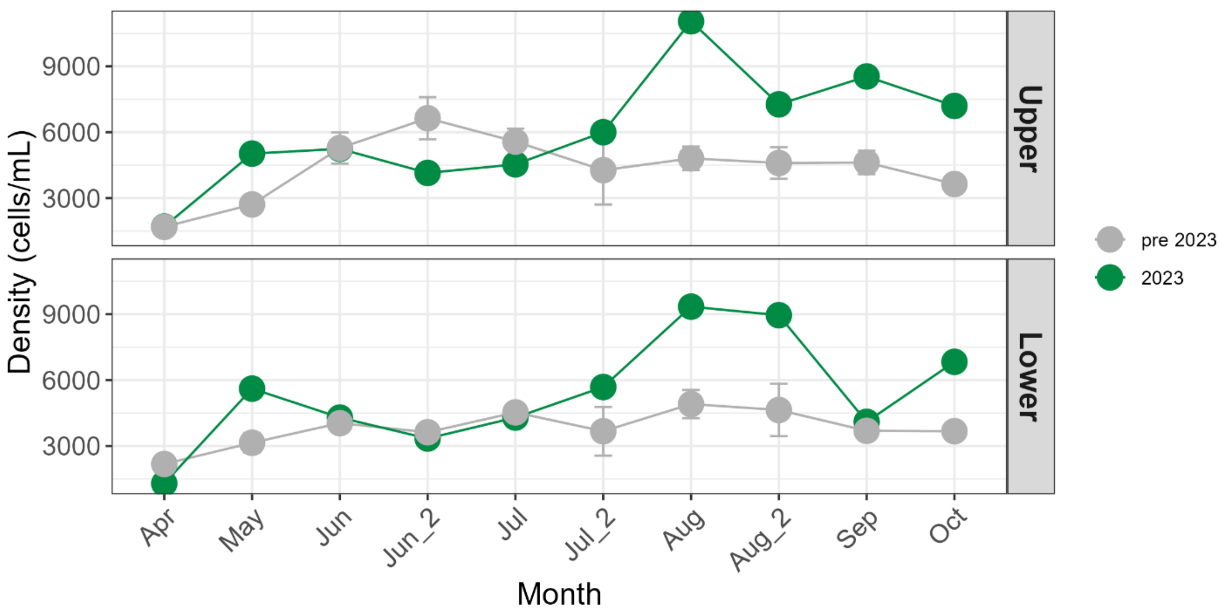

Figure 22. Arrow phytoplankton density monthly mean by basin (Upper and Lower) 2023 (green) and 1998–2022 (grey). Jul_2 and Aug_2 sampling began in 2012. Means ±SE.

Zooplankton

The Cladoceran species *Daphnia* is the preferred food source of kokanee. The *Daphnia* densities were above average in Upper and average in Lower Arrow in 2023 (Figure 23). In Upper Arrow, monthly densities followed a similar pattern to the previous year's monthly trends, however the densities observed in July were higher than historic monthly densities (Figure 24). In Lower Arrow, the densities followed the historic seasonal pattern (Figure 24). The size of daphnia is determined by the ratio of the biomass over density; in 2023, the size of Daphnia was near the long-term average (Figure 25). The first detection of *Daphnia* at concentrations >0.4 ind/L (a value of relevance to nerkid feeding; Scheuerell et al., 2005) was in July for both basins, as it was in the previous two years, following a four-year period (2017-2020) when it was generally later in the season (Figure 26).

Copepods are a smaller and more abundant zooplankton and are a food source to kokanee when *Daphnia* are unavailable. The 2023 copepod densities in Upper Arrow were near average, and in Lower Arrow slightly below average (Figure 27).

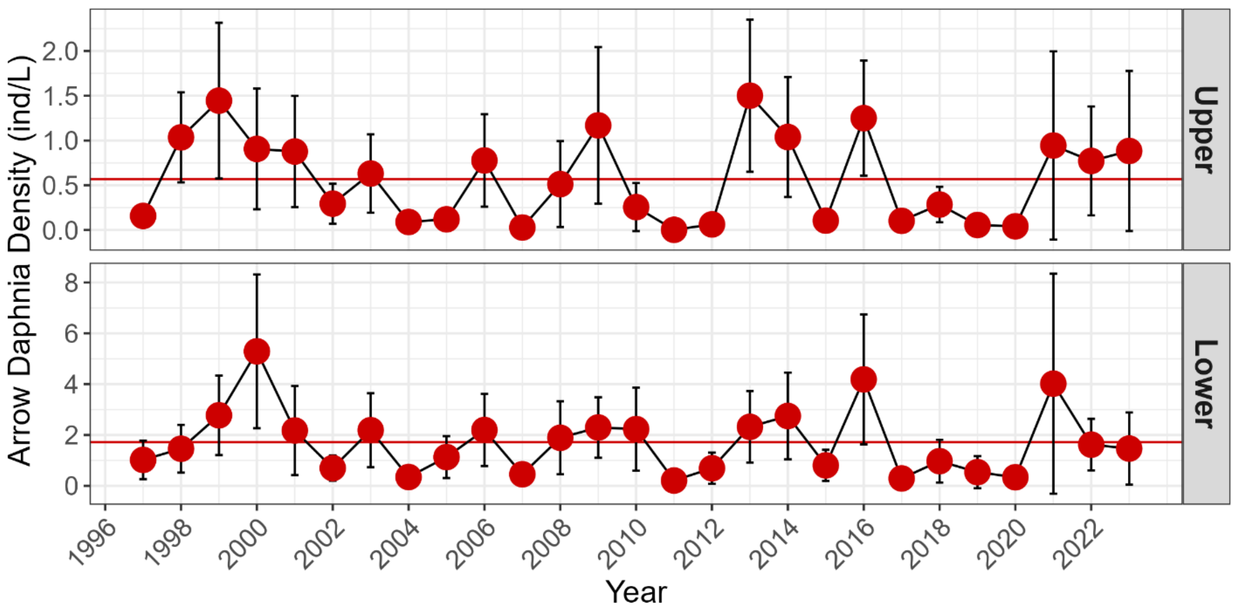

Figure 23. Arrow zooplankton *Daphnia* densities (ind/L) annual mean (April – October), by basin (note different scales). Horizontal lines are long term basin averages. Means ± 2SE.

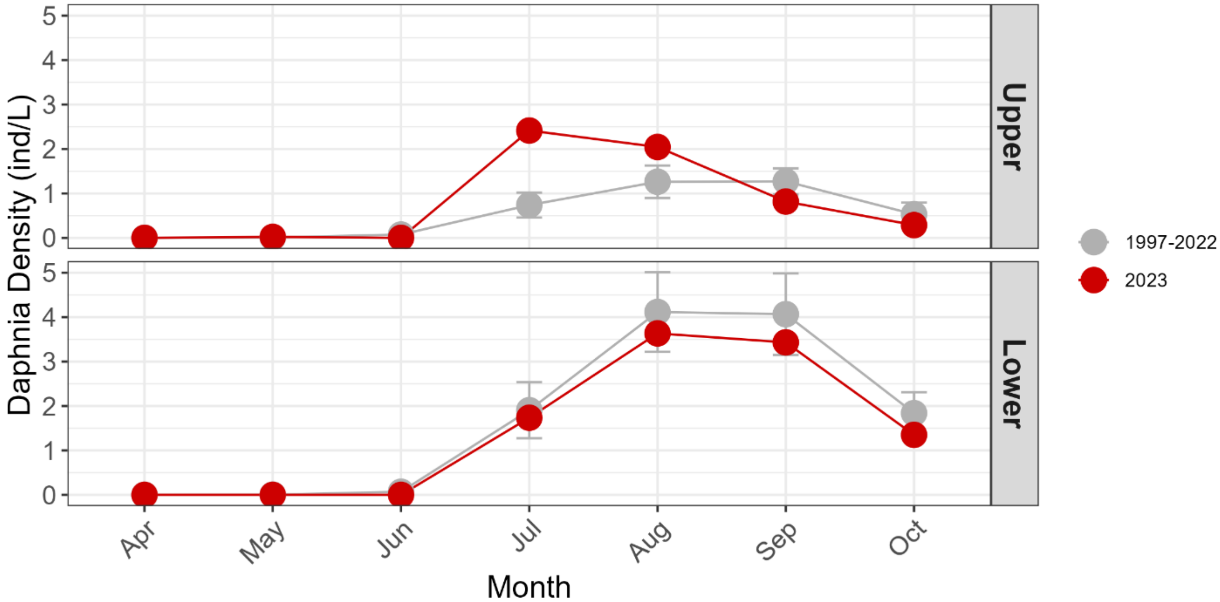

Figure 24. Monthly mean of *Daphnia* densities (ind/L) in Upper and Lower Arrow. Grey dots and error bars are 1997-2022 monthly means; red dots are 2023 data. Means ± 2SE.

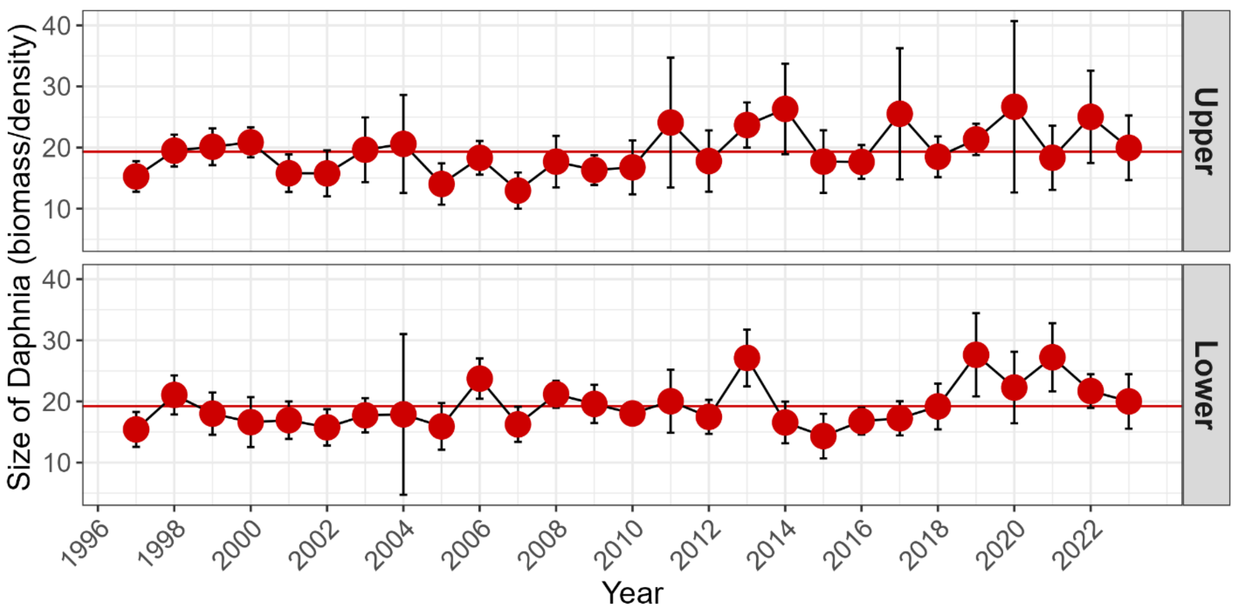

Figure 25. Arrow zooplankton *Daphnia* size (density/biomass) annual mean (April – October), by basin. Horizontal lines are long term basin averages. Means ± 2SE.

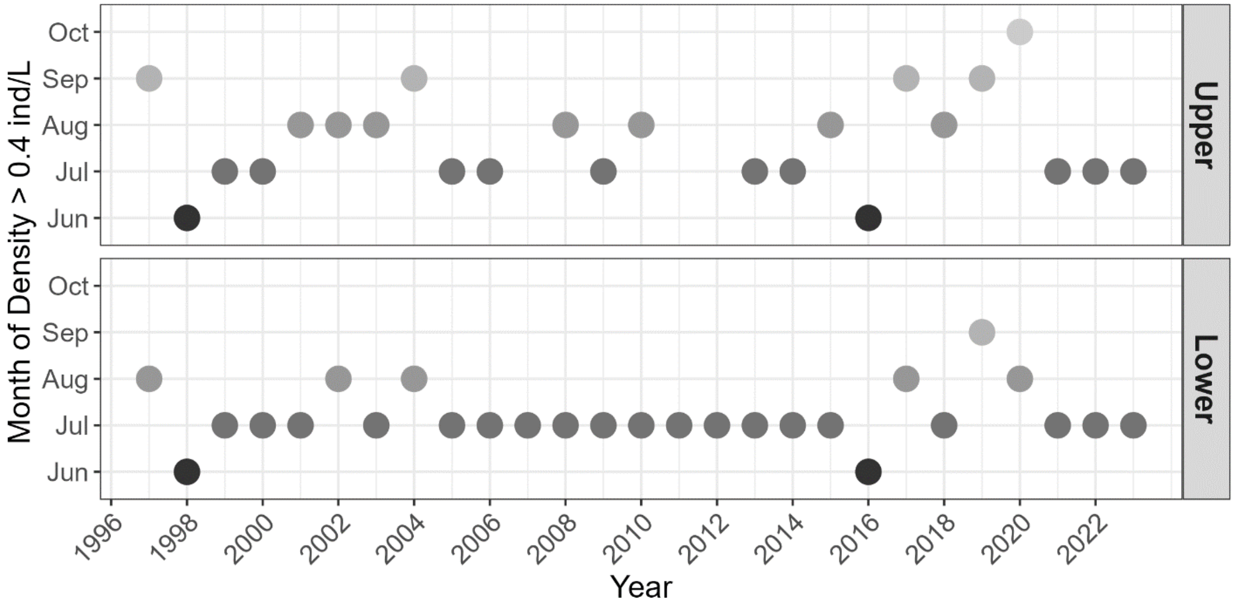

Figure 26. Month of first appearance of *Daphnia* densities above 0.4 ind/L by basin.

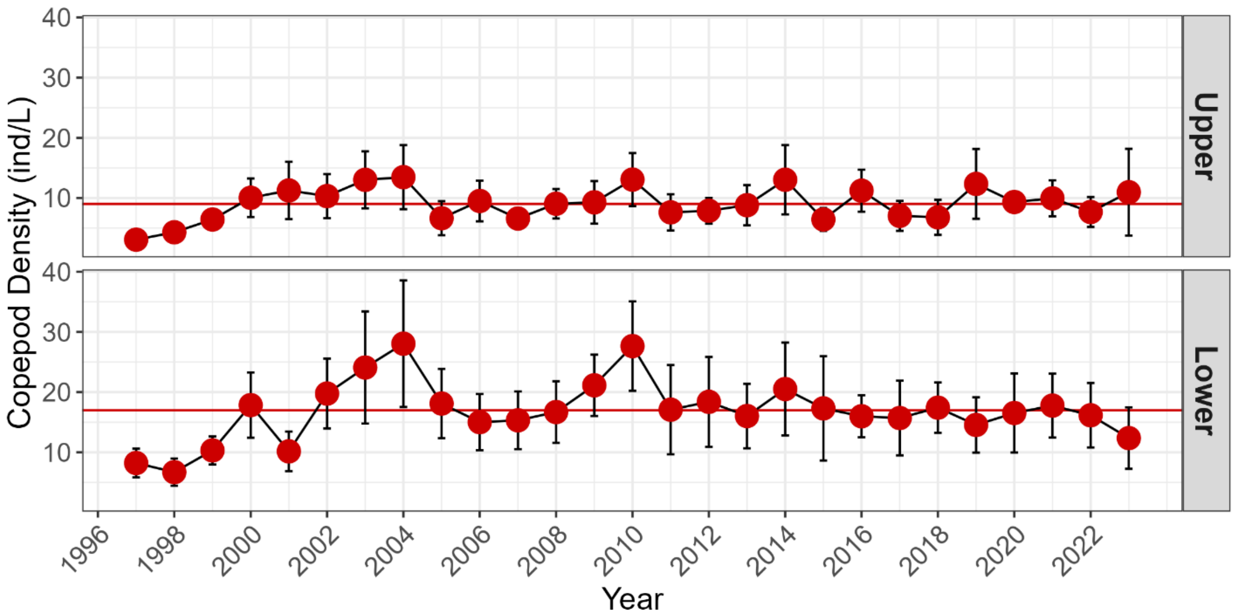

Figure 27. Arrow zooplankton copepod annual mean (April – October), by basin. Horizontal lines are long term basin averages. Means ± 2SE.

Mysids

In Upper Arrow, the 2023 April-October mean mysid density increased from 2022 but was still below the long-term mean. In Lower Arrow, mysid density was similar to 2022 and near the long-term mean (Figure 28). Mysid densities varied seasonally in both Upper and Lower Arrow basins and the highest results were observed in August and October in Upper Arrow and in June and August in Lower Arrow (Figure 29).

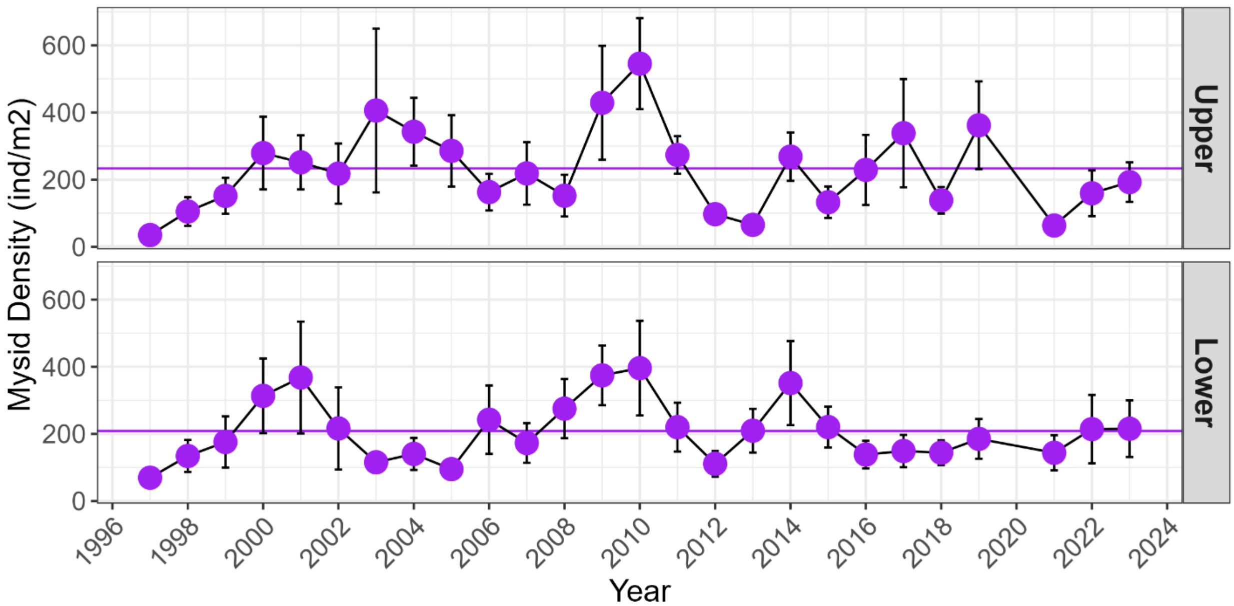

Figure 28. Arrow mysid densities (ind/m²) annual mean (April – October), by basin. The 2020 data is incomplete and not included in analysis. Horizontal lines are long term basin averages. Mean ± 2SE.

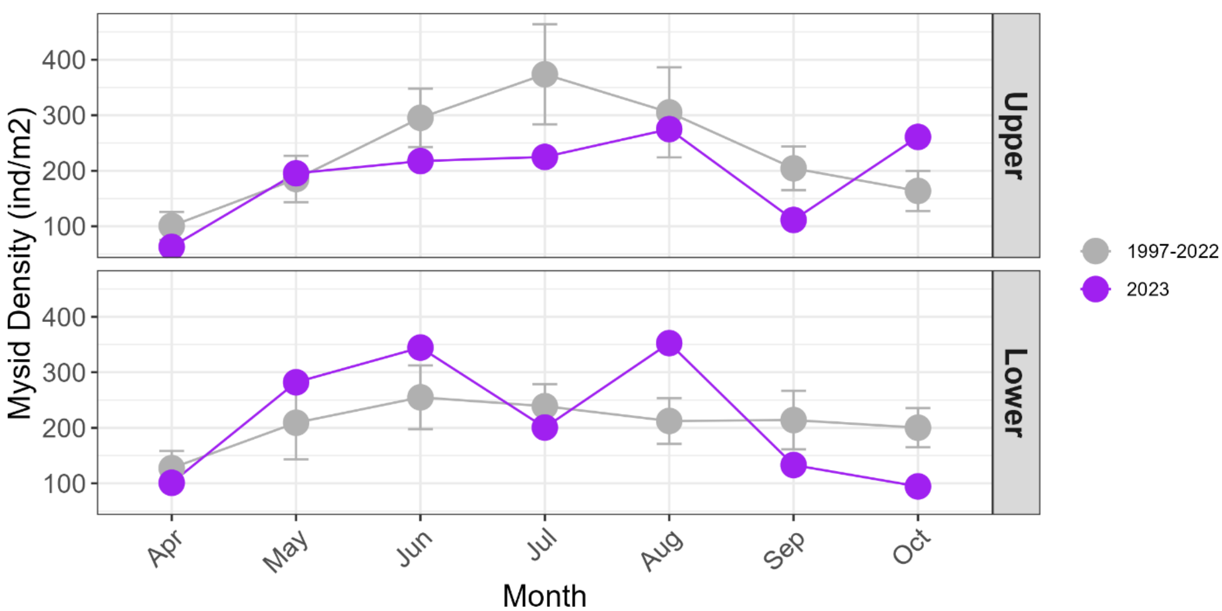

Figure 29. Monthly mean of mysid densities (ind/m²) in Upper and Lower Arrow. Grey dots and error bars are 1997-2022* monthly means; purple dots are 2023 data. The 2020 data is incomplete and not included in analysis. Means ± 2SE.

Kokanee

Escapement

Index tributary kokanee spawner counts in 2023 totaled 318,158 (Figure 30). The Upper Arrow count totaled 138,031, the majority of which (90,892) returned to Hill Creek. The Lower Arrow index tributary count totaled 180,127. Hydroacoustic data from the October 2023 survey of Arrow Lakes Reservoir suggests the spawner count in the fall of 2024 should be ~330,000, however forecasting spawner returns for Arrow has missed the mark substantially some years (e.g., 2012, 2017, 2021; data not shown).

Kokanee spawner ages were not available at the time of reporting, but length frequency analysis of fish measured at Hill Creek Spawning Channel in the fall of 2023 suggests a mix of age 2 and 3 spawners.

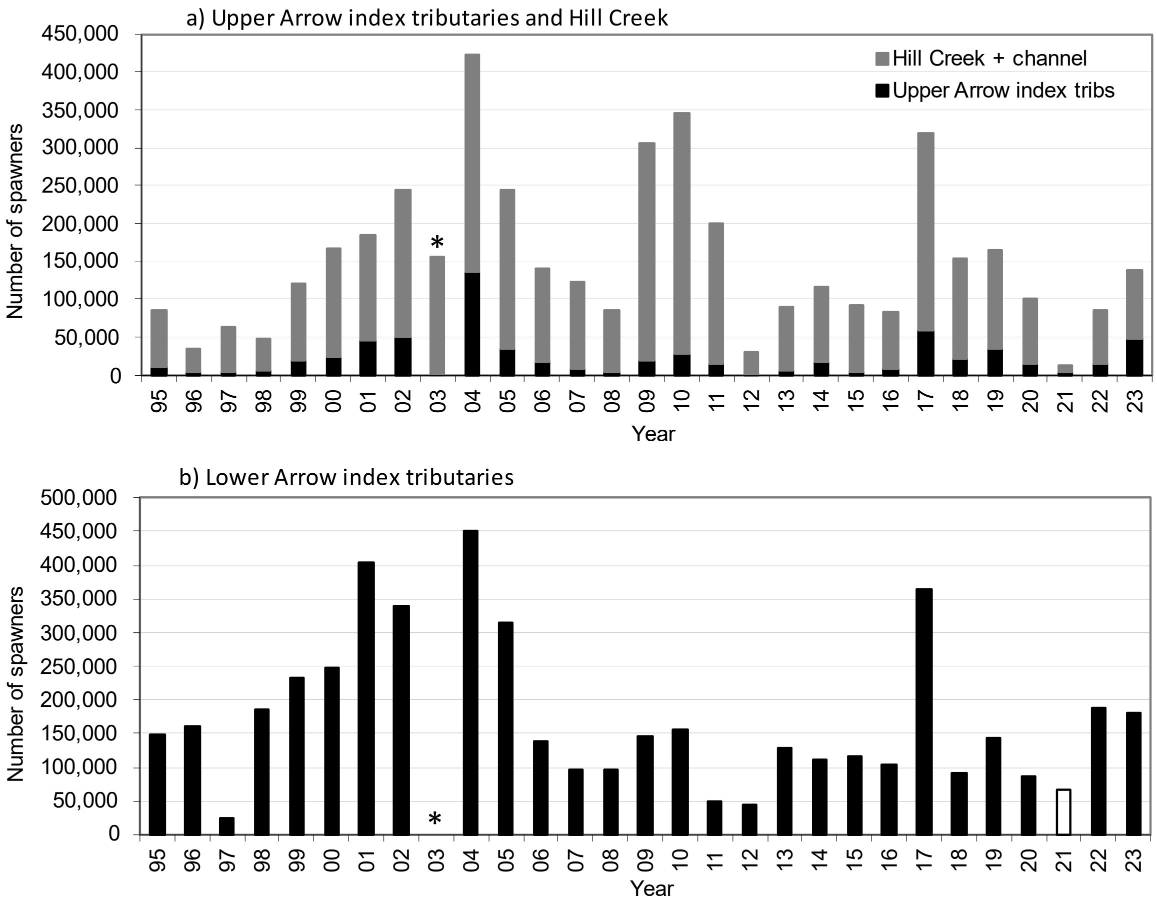

Figure 30. Kokanee escapement for index tributaries on Arrow Lakes Reservoir for a) Upper Arrow and b) Lower Arrow from 1995-2023. Estimates are the peak count multiplied by 1.5 except for the Hill Creek Spawning Channel which is a fence count. Index tributary counts were not completed in 2003 due to wildfires. 2021 estimates for index tributary counts (all except Hill Creek & Channel) were affected by poor water clarity.

In-Lake Abundance

The 2023 kokanee age 0 (fry) population for the combined basins was 6.3 million (Figure 31). The Upper Arrow fry abundance was 3.7 million compared to the post-NRP basin average of 4.5 million. The Lower Arrow fry abundance was 2.6 million compared to the basin average of 2.6 million. The 2023 age 1-3 kokanee population for the combined basins was 1.55 million (Figure 31). The Upper Arrow age 1-3 abundance was 0.95 million compared to the post-NRP basin average of 1.29 million. The Lower Arrow age 1-3 abundance was 0.63 million compared to the basin average of 0.83 million.

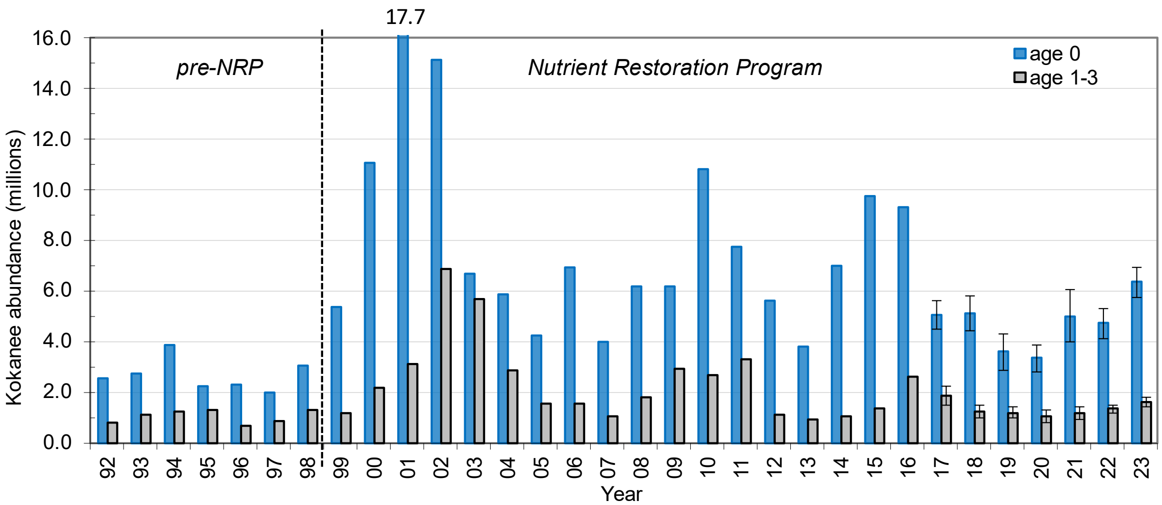

Figure 31. Kokanee abundance from fall acoustic surveys in Arrow Reservoir (combined Upper and Lower Arrow basins).

Survival

Kokanee cohort survival in 2023 was 24%, which was similar to the post-NRP average of 21%. Age 1-2+ survival was 49%, also near the long term mean of 51% (Figure 32).

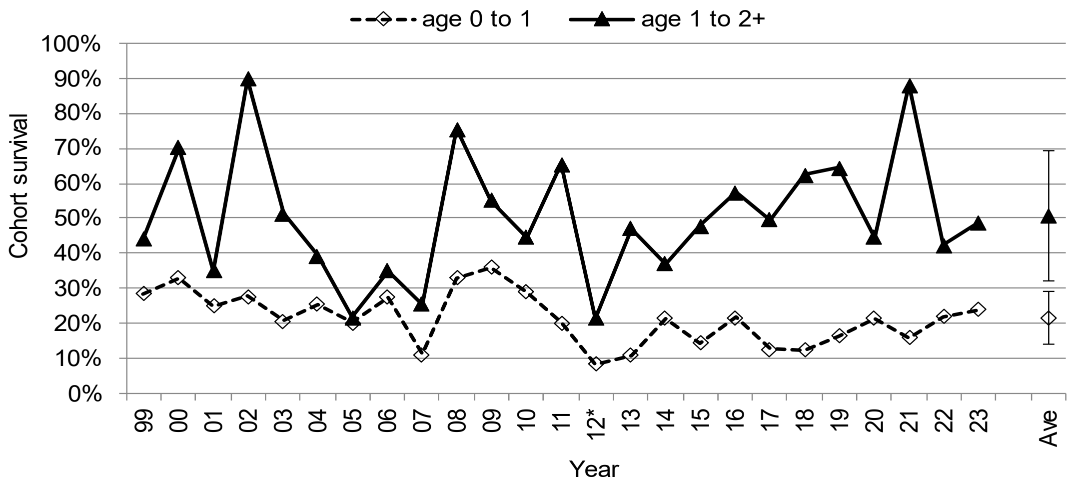

Figure 32. Trends in annual survival for in-lake kokanee cohorts for Arrow Lakes Reservoir (combined basins) and the post-NRP average (±SD). The age 2+ group includes the age 2 and older component estimated in-lake from fall hydroacoustic surveys as well as the estimate of age 2 spawners the same year. The year is labelled by the latter year as each value includes data from two consecutive years. *Survival from 2011 to 2012 was impacted by a large-scale mortality event in May 2012. 2023 estimates are preliminary.

Kokanee biomass

Kokanee biomass (combined in-lake and spawners) was 224 tonnes in 2023, which was 20% higher than the long term post-NRP mean of 186 tonnes and approximately 2.5X pre-NRP mean of 90 tonnes (Figure 33). Both in-lake and spawner biomass increased in 2023 over 2022.

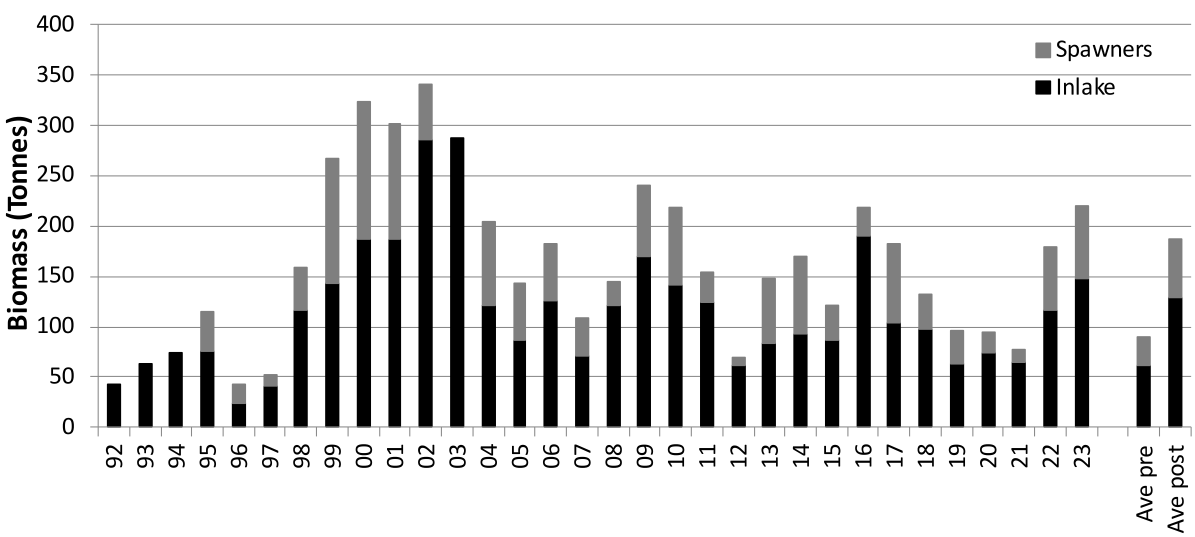

Figure 33. In-lake kokanee and spawner biomass estimates for Arrow reservoir. Averages are pre-NRP (1992-1998) and post-NRP (1999-2023). Data required to estimate spawner biomass from 1992-1994 are incomplete and the 2003 spawner biomass estimate is the average of 2002 and 2004 as no counts occurred. The pre-NRP spawner biomass average represents 1995-1998. 2023 estimates are preliminary.

Summary and Discussion

The data presented herein is a subset of the 2023 (F24) Arrow Lakes Reservoir NRP results from the extensive monitoring program. Further results and analysis will be presented in a comprehensive multi-year summary report (Province of BC, n.d.) that will be available online upon publication.

Nutrient additions, in the form of liquid agricultural grade fertilizer occurred in Upper Arrow following the same methods as recent years. In total, 42.9 MT of phosphorus and 204.9 MT of nitrogen were added to the Reservoir between late April and early September. The annual tonnes of phosphorus from fertilizer additions have been around 40 MT since 2016 (2023 was the 8th year of holding similar loading rates). The 2023 April-October daily mean outflow for Arrow was 1065 m^3/s and was below the 1997-2023 mean of 1122 m^3/s. Mean reservoir outflow in July and August (warm growing season) was on the 2011-2023 mean. Water clarity, measured as a Secchi depth was below average for both basins in 2023. Phosphorus and nitrogen values were similar to previous years and in the range of an oligotrophic system. Phytoplankton density was above average in both basins. For zooplankton, Daphnia was slightly above average in Upper Arrow and average in Lower Arrow. Copepods were near average in Upper Arrow, and lower in Lower Arrow in 2023. The timing of *Daphnia* detection was the same as 2021 and 2022, early compared to 2017-2020. Mysid densities in 2023 were average in both basins.

Kokanee returns to index tributaries in 2023 totaled approximately 320,000, which was near the post NRP average of 345,000. The length frequency plot for Hill Creek spawners suggests ~40% were age 2 and 60% were age 3, resulting in an age partitioned spawner replacement rate of ~0.7 for the 2019 brood year (when 307,000 spawners returned). The hydroacoustic data can provide insight into the following year spawner return, and the 2023 data suggests a return of 330,000 spawners in 2024. Should the 2024 spawner return materialize near forecast the spawner replacement rate would be ≥1 for the 2020 brood year, when 188,000 spawners returned.

Kokanee survival from the egg to fall fry stage is highly relevant to kokanee abundance and biomass across the lifespan of each cohort. Though not presented in this report, preliminary analysis indicates that egg to fall fry survival for 2022 spawners was near the value predicted by egg deposition. This marks the 3rd consecutive year where egg to fall fry survival was similar to or better[1] than predicted by egg deposition, which was likely a result of relatively large spawners and moderate late winter air temperatures, both of which are associated with egg to fall fry survival outcomes (Bray, Weir, Pieters, Brandt, & Harris, 2023). This, in combination with near average in-lake survival in 2022 and 2023 and average or better *Daphnia* outcomes (timing, density/biomass) since 2021 has contributed to the improvement in kokanee

[1] The 2021 egg year survival was far above predicted, however that estimate is confounded by the problematic 2021 spawner count when poor visibility resulted in an unprecise estimate of spawners.

abundance and biomass in 2023 in comparison to the low results observed during the 2019-2021 period.

Arrow Lakes Reservoir is a dynamic and complex system with interacting external variables. These variables include productivity (added nutrients), operations (Bray, Weir, Pieters, Brandt, & Harris, 2023), fry output from the spawning channel, mortality events (e.g., die off in 2012 (Bassett, Schindler, Sebastian, Weir, & Vidmanic, 2015) and weather-related drivers such as air temperature (Bray, Weir, Pieters, Brandt, & Harris, 2023), snowpack, precipitation, and wildfire smoke.

An independent review on the Arrow Lakes Reservoir and Kootenay Lake North Arm nutrient restoration programs was completed in 2022 (Hecky & Guilford, 2022). In this review, it was recommended that both NRPs continue as they are meeting the objectives of restoring productivity to these ecosystems. The methods for dispensing nutrients were deemed suitable, and some recommendations were made to improve the monitoring and reporting components of the program; see Hecky and Guildford (2022) for further details.

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Appendix 1. Personnel on Arrow Lakes Reservoir Nutrient Restoration Programs in 2023.

Project Focus	Personnel - Affiliation
Project co-ordination, management and scientific liaison	Marley Bassett - Resource Management, WLRS Rob Fox - Resource Management, WLRS Irene Manley - Resource Management, WLRS
Report compilation	Marley Bassett - Resource Management, WLRS Tyler Weir - Aquatic Ecosystems Branch, WLRS
Report editing and review	Marley Bassett – Resource Management, WLRS Tyler Weir – Aquatic Ecosystems Branch, WLRS Eva Schindler - Resource Management, MoF Mike Hounjet - Columbia Power, Castlegar Jen Walker-Larson – BC Hydro, Revelstoke
Fertilizer schedule, loading	Marley Bassett - Resource Management, WLRS Eva Schindler - Resource Management, WLRS
Fertilizer supplier	Nutrien Itafos
Fertilizer application	Crescent Bay Construction – Nakusp BC The Columbia Ferry - Waterbridge Ferries
Physical limnology, water chemistry, phytoplankton, zooplankton and mysid sampling	Kerry Reed - Reel Adventures Rob Fox – Resource Management, WLRS Aaron McGregor - Resource Management, WLRS Rob Webster - Resource Management, WLRS Karen Bray – BC Hydro Carson Kettlewell - Okanagan Nation Alliance Shelly Hackett - Okanagan Nation Alliance Ross Zeleznik - Okanagan Nation Alliance Patrick Zubick - Okanagan Nation Alliance Ali Schroeder – Nupqu Donovan Williams – Nupqu
Chemistry analysis	ALS Global staff - ALS Global
Chlorophyll analysis	ALS Global staff - ALS Global
Phytoplankton analysis	Advanced Eco-Solutions Inc.
Zooplankton and mysid analysis	Dr. Lidija Vidmanic, Limno-Lab Ltd., Vancouver
Kokanee acoustic surveys	Tyler Weir - Aquatic Ecosystems Branch, WLRS David Johner - Aquatic Ecosystems Branch, WLRS
Kokanee trawling and processing	Tyler Weir - Aquatic Ecosystems Branch, WLRS David Johner - Aquatic Ecosystems Branch, WLRS Rob Fox - Resource Management, WLRS Kerry Reed – Reel Adventures Ali Schroeder – Nupqu
Kokanee aerial spawner surveys	Mark Homis - Highland Helicopters Roman Sookorukoff – Highland Helicopters Marley Bassett - Resource Management, WLRS Shanon Basil - Yucwmenlúcwu - Caretakers of the Land
Kokanee ground spawner surveys	Tim Davis - Land Use Policy, Planning and Ecosystems Division, WLRS Kersti Vaino - Resource Management, WLRS Kristen Murphy - Resource Management, WLRS Kirsten Clarke - Resource Management, WLRS Blaire Smith - Resource Management, WLRS

	Steve Arndt - Resource Management, WLRS Shelley Hackett – Okanagan Nation Alliance Carson Kettlewell – Okanagan Nation Alliance Yvonne Gregory – Thomson River University Celeste Harvey – BCCF Karen Bray - BC Hydro Beth Manson - BC Hydro
Kokanee analysis and Reporting	Tyler Weir – Aquatic Ecosystems Branch, WLRS David Johner - Aquatic Ecosystems Branch, WLRS
Kokanee scale ageing	Morgan Davies - BC Provincial Aging Lab - FFSBC
Creel surveys	Operations and reporting: Irene Manley, Rob Fox and Steve Arndt – Resource Management, WLRS Creel Technicians: Mag-Con Environmental Kingfisher Silviculture Jessica Spencer Credence New Helena Garay Cody Peters Jacquie Armstrong Christina Dummer Nupqu Resource Limited Partnership Yucwmenlúcwu - Caretakers of the Land Ingersol Mountain Enterprises
Regional support	Matt Neufeld - Resource Management, WLRS Will Warnock - Resource Management, WLRS

Appendix 2. Sampling activities on Arrow Lakes Reservoir in 2023.

Parameter sampled 2023	Sampling frequency	Locations	Sampling technique
Temperature, dissolved oxygen, specific conductance	Monthly: April to October Twice monthly in June, July and August	AR2 and AR7	SeaBird profiles from surface to 5 m off the bottom. SeaBird profiles from surface to ~50 m
Transparency	Monthly: April to October Twice monthly in June, July and August	AR2 and AR7	Secchi disk
Epilimnion water chemistry TP, TDP, TN, NO3, silica	Monthly: April to October Twice monthly in June, July and August	AR2 and AR7	Integrated sampling tube at 0–20 m
Total and Dissolved Metals	June and September	AR2 and AR7	Integrated sampling tube at 0–20 m
Discrete Epilimnion Water Chemistry	Monthly: June to September	AR2 and AR7	Niskin water samples at 2, 5, 10, 15 and 20m

TP, TDP, TN, NO3, silica	Twice monthly in June, July and August		
Epilimnion Chlorophyll a (not corrected for phaeophytin)	Monthly: April to October Twice monthly in June, July and August	AR2 and AR7	Integrated sampling tube at 0–20 m
Discrete Epilimnion Chlorophyll a (not corrected for phaeophytin)	Monthly: June to September Twice monthly in June, July and August	AR2 and AR7	Discrete samples with Niskin sampler at 2, 5, 10, 15 and 20m
Epilimnion Phytoplankton	Monthly: April to October Twice monthly in June, July and August	AR2 and A7	Integrated sampling tube at 0–20 m
Discrete Epilimnion Phytoplankton	Monthly: June to September Twice monthly in June, July and August	AR2 and AR7	Discrete samples with Niskin sampler at 2, 5, 10, 15 and 20m
Macrozooplankton	Monthly: April to October May, August and October	AR2 and AR7 AR7	Three oblique Clarke-Bumpus net tows (3-minutes each) from about 20–0 m (150 µm net) 12 vertical Wisconsin net hauls (0-15, 0-20, 0-30, 0-40)
Mysid net sampling	Monthly: April to October	AR2 & AR7	Two replicate hauls with the mysid net from 5 m above bottom to the surface
Kokanee acoustic sampling	Fall survey	TR 3–18, TR 1 & 2 omitted.	Standard hydroacoustic methods; Beaton Arm transects (1 & 2) were omitted due to low water levels/unsafe access across Beaton Sill. Beaton habitat areas were added to transects 3 and 4 to account for habitat not surveyed.
Kokanee trawling	Fall pelagic trawling	AR3, AR6, AR7, AR8, TR10 AR1, AR2 omitted	Directed trawls focused on highest density locations to maximize catch.
Aerial kokanee spawner counts	September	Arrow tributaries (Bassett, Weir, & Fox, 2020)	Two standardized helicopter flights appr. one week apart to identify peak spawner numbers
Ground kokanee spawner counts	September		Two ground counts appr. one week apart to identify peak spawner numbers