ESTABLISHING BASELINES FOR WATER QUALITY AND ROTIFER COMMUNITIES IN FRAME LAKE, YELLOWKNIFE

by

Madeline Elizabeth Patenall

A Thesis Submitted to the Faculty of Science

In Partial Fulfilment of the Requirements for the

Degree of Honours Bachelor of Arts in the

Department of Biology

Wilfrid Laurier University

Waterloo, Ontario

©April 2023

Madeline Elizabeth Patenall

Abstract

Urbanization has altered terrestrial and aquatic habitats across Canada's north. Frame Lake in Yellowknife, Northwest Territories is an excellent example of a northern lake affected by poor urban planning. Development of the lake catchment has contributed to the lake's eutrophication and low dissolved oxygen levels, resulting in the loss of fish. Hypolimnetic aeration has been proposed as a rehabilitation method for Frame Lake; however, baseline data must be collected prior to the installation of the aerator to determine its effectiveness. We examined the seasonal variation of water quality and rotifer community metrics in Frame Lake. Our findings indicate that water quality metrics exhibit seasonal fluctuations that may be influenced by various factors, including ice cover development, mixing patterns, dissolved oxygen concentrations, internal loading, and anthropogenic factors such as road salts. Moreover, we provide insights into the seasonal dynamics and succession of rotifer communities in Canadian subarctic lakes, highlighting correlations with water quality variables. Our study generates novel high-frequency, multi-season baseline water quality and rotifer community data from an urbanized northern lake. Our study can inform future research assessing Frame Lake's rehabilitation and the efficacy of hypolimnetic aeration as a rehabilitation strategy. Given the increasing impact of urbanization on lakes across Canada's north, the assessment of hypolimnetic aeration as a rehabilitation strategy is particularly relevant.

Acknowledgements

Many incredible people and organizations supported this thesis. Looking back, I am overwhelmed by the support, encouragement, and opportunities I have received. First and foremost, I would like to thank Dr. Derek Gray. Dr. Gray has been a role model to me as a scientist and has supported my growth throughout this process. In addition to fostering my love of limnology, he has provided me with the opportunity to apply my knowledge and to experience Canada's north. Dr. Gray – I will never be able to thank you enough; you have opened many doors for me.

This project required significant amounts of fieldwork. I am thankful to those who joined me in the field, including Nicole Andreola, Nigel Rossouw, and Mike Palmer. Additionally, I would like to thank those who reviewed this thesis; Jess Kidd, Nicole Andreola, and Abbe Binning. Many thanks are also due to Dr. Erin Leonard and Dr. James Southworth, whose advice was invaluable in developing this thesis. I would also like to thank Dr. Scott Ramsay for bringing funding opportunities to my attention.

The financial support I received was instrumental in developing this project. I would like to thank Diavik Diamond Mines, owned by Rio Tinto, and the Natural Sciences and Engineering Research Council of Canada Undergraduate Student Research Award (NSERC USRA) for their financial support. The support allowed me to experience fieldwork and develop my research skills to complete this project.

The unwavering encouragement of my family and friends has been foundational in my achievements. I would like to give my deepest appreciation to my Mum and Dad (Deanne and James Patenall), who, in their own way, taught me the meaning of perseverance, resilience, and

grace. Finally, I would like to dedicate my thesis to my grandma, Hazel Male. Words cannot express my immense gratitude, admiration, and love for you.

Table of Contents

List of Figures

1 | Introduction

Urbanization and the development of infrastructure in northern Canada have altered both terrestrial and aquatic habitats. Lakes and ponds are experiencing changes in water quality, including temperature, residence time, and allochthonous nutrient loading from development in their lake catchments (Gavel et al., 2018; Gray et al., 2022). To understand how these changes will affect freshwater food webs, the relationships between water quality and the abundance and composition of aquatic species must be well understood (Cohen et al., 2021; Vucic et al., 2020). Previous research has indicated that northern lakes have experienced degradation from historical and ongoing factors such as poor urban planning and industrial pollution (Gavel et al., 2018; Palmer et al., 2019). Frame Lake in Yellowknife, Northwest Territories, is an excellent example (Gavel et al., 2018). Poor urban planning for Yellowknife, which surrounds Frame Lake, has been identified as a significant contributing factor responsible for the degradation of the lake's water quality. Development of the lake catchment, along with increased nutrient loading from unregulated dumping, has contributed to the lake's eutrophication (the gradual increase in nutrient concentrations) (Dirszowsky & Wilson, 2015; Gavel et al., 2018; Koch et al., 2000; Moore, 1981). Eutrophication can have many adverse effects on lakes, including changes to the species composition and diversity of a lake's food web (dos Santos et al., 2021).

One group of animals sensitive to changes associated with eutrophication are the rotifers. Rotifers are small (50-200 µm) metazoans belonging to the phylum Rotifera that are essential members of aquatic foodwebs (Wallace, 2002). Rotifers can be particularly useful for examining nutrient pollution, as they are bio-indicators of organic pollution (Duggan et al., 2002; Sládeček, 1983). As urbanization intensifies in Yellowknife and other northern regions, understanding how the associated changes will impact water quality and aquatic food webs is vital to inform management and rehabilitation strategies for urban lakes. This study aimed to analyze the adverse effects of poor urban planning and allochthonous sources of nutrient loading on Frame Lake while assessing rotifers as a bioindicator of water quality and the factors affecting their community composition and abundance.

1.1 | Effects of Poor Urban Planning on Frame Lake

Yellowknife has a history of poor urban planning. In 1896, gold was discovered in Yellowknife. The subsequent development of three large mines, Giant Mine, Con Mine and Discovery Mine, during the 1930s led to rapid urbanization. In 1967, the city experienced an influx of inhabitants after Yellowknife was named the territorial capital (Moir et al., 2016). The city of Yellowknife grew to enclose Frame Lake, located in the heart of the city. Due to its centralized location, the lake was once a recreational swimming attraction and the site of a fishing camp used by the Yellowknives Dene First Nations (Gavel et al., 2018). Unfortunately, in recent decades, the cumulative effects of the city's development and mining activities have led to the degradation of Frame Lake's water quality and food web, eliminating recreational and fishing opportunities.

Poor urban planning has degraded water quality in Frame Lake (Gavel et al., 2018). Previous studies have identified multiple sources of allochthonous nutrient loading to Frame Lake (Gavel et al., 2018; Healey & Woodall, 1973; Persaud et al., 2021). Work by Healey and Woodall (1973) outlined the practice of dumping snow scraped from the city's roads into the lake, likely contributing to Frame Lake's high ionic concentrations. Additionally, anecdotal accounts exist of mine wastes and sewage being dumped into the lake (Gavel et al., 2018; Persaud et al., 2021). These allochthonous sources of nutrients have deteriorated the lake's water quality (Dirszowsky & Wilson, 2015). For example, Gavel et al. (2018) examined hydroecological changes in Frame Lake in response to urbanization and possible illegal dumping. By assessing sediment cores from Frame Lake, three distinct Arcellinida sample assemblages appeared; assemblage 1 characterized conditions during the Holocene, assemblage 2 was associated with increased arsenic from mine waste influence, and assemblage 3, from more recent decades, was characterized by eutrophic conditions from nutrient-rich waters entering the lake. Assemblage 3 is noted to have developed in response to building 48th Street, which runs between Frame Lake and Niven Lake, during 1948-1964. In 1975, 48th Street was developed into a causeway, increasing the water residency time and disrupting the outflow of the lake to mainly seepage (Gavel et al., 2018; Healey & Woodall, 1973). Dirszowsky and Wilson (2015) found that the restriction of Frame Lake's outflow intensified nutrient pollution by reducing the ability of clean water to flush nutrients out of the lake.

Increased nutrient loads can lead to an abundance of algae and shift the types of algae present in a lake (Danylchuk & Tonn, 2003). As substantial quantities of algal biomass die and sink to the bottom of a lake, the organic material is broken down by heterotrophic bacteria in a process that utilizes large amounts of dissolved oxygen (Müller et al., 2012). Therefore, sediments with high organic matter concentrations have a high biochemical oxygen demand (Müller et al., 2012). In shallow eutrophic lakes, such as Frame Lake, the high sediment oxygen demand contributes to low oxygen conditions during winter ice cover when the mixing of atmospheric oxygen into the lake is restricted. As a result, winter dissolved oxygen levels can fall below fish survival thresholds, resulting in fish mortality (winterkill) (Müller et al., 2012). Frame Lake's anoxic conditions during months with ice cover are well documented, and fish species such as Lake Whitefish, Northern Pike and suckers that historically inhabited the lake are no longer present (Gavel et al., 2018; Healey & Woodall, 1973). In summary, poor urban planning in Yellowknife has caused increased nutrient loading into Frame Lake, significantly decreasing the lake's water quality.

1.2 | Rotifers as Bioindicators of Saprobity

While there are multiple methods to gauge nutrient and organic pollution levels in lakes, bioindicators are particularly useful in freshwater ecosystems (Paul & Kumari, 2020). Research by Sládeček (1983) found that rotifers are convenient bioindicators of saprobity – an estimate of organic pollution levels in a lake. Rotifers, microscopic (50-200 μm) pseudocoelomate animals belonging to the Phylum Rotifera, are essential links in aquatic food webs. Rotifers connect microscopic sources of organic matter, such as bacteria and algae, with the upper tiers of the trophic food web (dos Santos et al., 2021), such as predatory zooplankton and zooplanktivorous fish (Yoshida et al., 2003). Eutrophic conditions can affect the rotifer community in a lake, shifting the composition and abundance to species tolerant of low oxygen levels (dos Santos et al., 2021; Sládeček, 1983). Sládeček (1983) reviewed past literature to assess the composition and abundance of rotifer species concerning biochemical oxygen demand and organic pollution gradients. From the review, Sládeček (1983) developed the Saprobic Index, which lists species of rotifers and their assigned saprobic degree and valence. Five saprobic degrees exist, which indicate the intensity of water pollution. In order of degrading water quality, the degrees are: xenosaprobity, oligosaprobity, beta-mesosaprobity, alpha-mesosaprobity, and polysaprobity (Sládeček, 1983). Sládeček (1983) concluded that rotifers listed as xenosaprobic and oligosaprobic are strong indicators of oligotrophic conditions. In contrast, those listed as beta-mesosaprobic and alpha-mesosaprobic indicate eutrophic conditions (Sládeček, 1983). Notably, many species in the *Ascomorpha, Asplanchna, Atrochus, Bdelloidea, Collotheca, and Testudinella* genera are classified as indicators of eutrophic conditions (Sládeček, 1983).

1.3 | Temporal Changes in Rotifer Communities

In addition to organic pollution levels, changes in the physical environment, such as those that occur with seasonal changes, are also known to alter rotifer community composition and abundance (Yoshida, 2005). Groups of zooplankton and phytoplankton are known to exhibit seasonal changes. Notably, Sommer et al. (1986) developed a sequential description of these seasonal patterns by studying numerous lakes and proposed the Plankton Ecology Group (PEG) model. The PEG model is a template for the seasonal succession of planktonic events in freshwater ecosystems (Sommer et al., 1986). As described in the model, rotifer abundance is often expected to increase in the spring when algal food is abundant, then decrease when large zooplankton species become more prevalent due to competition and predation (Sommer et al., 1986). In the summer months, rotifer abundance is expected to increase when zooplanktivorous fish decrease the amount of competition and predation by larger zooplankton species. While Sommer et al. (1986) described the effects of competition and predation on rotifers, further work by Gilbert (1988) focused on how large zooplankton species, such as *Daphnia*, structure the rotifer community. They hypothesized that rotifers can commonly occur at high densities with small cladocerans but cannot become abundant members of zooplankton communities in the presence of large *Daphnia* due to suppression through competition. The authors' hypothesis was supported by laboratory experiments showing that *Daphnia* could suppress rotifer abundance through direct interference competition and indirect, exploitative competition for shared limiting resources (Gilbert, 1988). Gilbert (1988) also found that *Daphnia* numbers decreased and rotifer numbers increased when they added fish back to the experimental environment.

Sommer et al. (2012) further developed the PEG succession model by considering the effects of certain ecological interactions and life history characteristics, such as overwintering strategies and the loss of higher trophic level predation, which were underestimated in the original publication. Overwintering strategies are an important determinant of seasonal succession for rotifers. During the winter months, rotifer species exhibit multiple methods of overwintering. Most species, such as *Conochilus unicornis* and *Polyarthra vulgaris*, overwinter by forming a resting egg that will develop once environmental conditions are favourable (Larsson, 1978). Other species, such as *Kellicottia longispina*, remain in the water column to survive periods of ice cover (Larsson, 1978). Forming overwintering resting eggs is advantageous since they are more resistant to adverse conditions and, therefore, can lead to more abundant populations in spring and early summer (Larsson, 1978). In the original PEG model, the importance of ecological interactions among different types of zooplankton was not addressed for lakes lacking zooplanktivorous fish (Sommer et al. 1986). Prior to the expansion of the model, Yoshida et al. (2003) noted that predation and competition by other zooplankton strongly influenced rotifer abundance, especially in lakes lacking zooplanktivorous fish. In the expanded model, Sommer et al. (2012) suggested that lakes lacking predation by zooplanktivorous fish had higher summer abundances of herbivorous and predatory zooplankton. The resulting maintenance of competition and predation throughout the summer months prevents the rotifer community from becoming abundant (Sommer et al., 1986; Yoshida et al., 2003).

1.4 | Plans for Rehabilitation

The previous studies on rotifer communities suggest that Frame Lake’s eutrophic conditions and increased predation on rotifers from the lack of zooplanktivorous fish may affect the rotifer community's abundance and composition. A loss of abundance within the rotifer community will likely result in a cascade effect, affecting the upper trophic levels of the food web. If found, this may indicate concerns surrounding the plans for Frame Lake. Diavik

Diamond Mines, owned and operated by Rio Tinto, are pursuing a project to rehabilitate Frame Lake. The rehabilitation project aims to improve the water quality in the lake, such that natural ecosystem processes are restored, recreational uses of the lake can be supported, and a recreational fishery can be re-established. The primary intervention planned for Frame Lake is the installation of a hypolimnetic aerator during the summer of 2023 that can provide oxygen under the ice during the winter months. Previous research has demonstrated that poor urban planning and illegal dumping around the lake caused increased water residence time, nutrient loading, and sediment oxygen demand leading to anoxic conditions (Gavel et al., 2018; Healey & Woodall, 1973; Persaud et al., 2021). The installation of a hypolimnetic aerator will transport oxygen from the lake's surface to the hypolimnion. Oxygenating the hypolimnion, the lower layer of a stratified lake, will potentially allow oxygen levels to rise above the threshold required to support fish. In Canadian lakes with similar characteristics to Frame Lake, a hypolimnetic aerator has succeeded in raising dissolved oxygen levels (Ashley, 1983; Taggart, 1984). Studies in other lakes have demonstrated that hypolimnetic aerators can effectively reduce nutrient concentrations in the water column by reducing the release of phosphorus from the lake sediments (Ashley, 1983; Austin et al., 2019; Moore et al., 2012), giving hope that aeration may shift Frame Lake towards its natural trophic state.

1.5 | Research Justification

Although rehabilitation efforts aim to restore water quality and fish stocks, few background studies have been conducted to establish baseline conditions for the lake's food web. Our current understanding of the factors influencing seasonal rotifer community composition and abundance in northern lakes has significant gaps. There is a lack of data available for organisms of lower trophic levels, such as rotifers, in Canada's northern regions. While single-visit data is available from the summer months in many northern lakes (e.g., Vucic et al., 2020), there is an absence of high-frequency multi-season data that describes natural variability and seasonal changes. High-frequency multi-season sampling is needed to provide baseline data to understand and model the community composition of rotifers in Frame Lake. The baseline data is essential for comparing water quality metrics and lower trophic food web composition and abundance before and after the aerator installation.

1.6 | Objectives

The three objectives of my study are: 1) To examine the seasonal patterns in water quality; 2) To examine the seasonal patterns in the rotifer community composition and abundance; 3) To examine patterns in the rotifer community in relation to water quality metrics. In combination, these objectives will develop baseline data on Frame Lake's condition prior to the hypolimnetic aerator installation. This baseline data can then be compared to data collected after aerator installation to understand the effectiveness of hypolimnetic aeration as a strategy for rehabilitating urbanized northern lakes and inform on Frame Lake's rehabilitation progress. My study is observational rather than hypothesis driven; however, I made several predictions based on the relationships between rotifers and water quality: 1) Rotifer abundance and richness will reach maximums in early spring and late summer; 2) Throughout summer months, species characteristic of eutrophic conditions (*Ascomorpha*, *Asplanchna*, *Atrochus*, *Bdelloidea*, *Collotheca, and Testudinella* genera) will be most abundant but maintained at consistent levels through competition and predation by larger zooplankton due to the lack of zooplanktivorous fish; 3) In winter months *Kellicottia* genera will comprise the majority of the community, as they overwinter in the water column while other species overwinter as resting stages.

2 | Methods

This study was conducted in three main stages: firstly, collecting rotifer samples and gathering water quality metrics; secondly, processing the rotifer samples; and finally, performing statistical analyses.

2.1 | Rotifer Sample Collection

To evaluate rotifer community composition and abundance in Frame Lake, monthly rotifer samples were collected by taking three replicate samples at the lake's maximum depth (6.5 m) (Figure 1). Rotifer samples were collected by performing vertical tows with a 15 cm diameter, 64 µm mesh size zooplankton tow net. Samples were anesthetized with half a tablet of Alka-Seltzer before adding 70% ethanol to maintain the physical integrity of the animals for more accurate identifications (Peck et al., 2006). A mechanical propellor flowmeter attached to the mouth of the zooplankton net was used to determine the volume of water that passed through the net during each tow.

2.2 | Collection of Water Quality Metrics

At the point of maximum depth in Frame Lake (Figure 1), a Eureka Manta+35 multiparameter probe (Eureka Water Probes, Inc) was used to measure temperature, conductivity, turbidity, pH, dissolved oxygen, dissolved oxygen saturation, and chlorophyll-*a* levels. Measurements were recorded at 1 m intervals beginning at the surface. A Secchi disk was used to measure water clarity by deploying it over the shady side of the boat, recording the depths at which the disk disappeared and reappeared from view, and averaging those values. Surface water samples were also collected at the deepest point of Frame Lake (Figure 1). Water samples were brought to Taiga Environmental Laboratory, a lab in Yellowknife certified by the Canadian Association for Laboratory Accreditation, to measure major and minor ions, dissolved metals, dissolved organic carbon, total nitrogen, total phosphorus, total dissolved solids, and true colour. During winter periods with ice cover, an auger drilled access holes to collect water quality measurements and rotifer samples as described above. Ice depth measurements were recorded from the access holes.

2.3 | Rotifer Sample Processing

Rotifer samples were processed within the Gray Laboratory at Wilfrid Laurier University. Each sample was analyzed by filtering rotifers from the 70% ethanol preservative using a 35 μm sieve. Then 50 mL of water was added to the rotifers and mixed on a magnetic stir plate from which repeated 1 mL subsamples were placed in a Sedgwick Rafter Counting Cell. The counting cell was placed under a compound microscope at 40 times magnification and repeated subsamples were counted until at least one hundred individuals from the total sample were identified. Rotifers were identified to the genus level with “An Image-Based Key to the Zooplankton of North America” version 5.0 (Haney, 2013).

2.4 | Statistical Analyses

Community metrics were calculated, including total abundance, richness, diversity, and evenness. Rotifer species richness was measured by compiling a dataset containing a count of the different rotifer genera found in each sample. To compare species richness and diversity, indices which correct for differences in the sample size among the sampling dates were utilized. For richness, we used rarefaction to calculate values that reflect equal taxonomic and sampling effort for each sampling date, ensuring comparability (Hurlbert, 1971). Rarefaction accounts for differences in sampling effort by resampling abundance data for a particular site hundreds or thousands of times to determine the average number of species identified for a given number of individuals collected (Gotelli & Colwell, 2001). Rarefaction was conducted using the rarefy function in the Vegan package for R (Oksanen et al., 2022; R Core Team, 2022) based on Hurlbert's formulation (Hurlbert, 1971). Species richness refers to the number of unique species present in a community, whereas species evenness refers to the balance in terms of relative species abundances (Morris et al., 2014). Diversity indices consider both species richness and evenness in their formulas (Morris et al., 2014). One of the most frequently used indices is the Shannon-Wiener diversity index [1], where p_i represents the proportion of the entire population of species *i* and S represents the number of species encountered (Peet, 1974).

[1] $H' = -\sum_{i=1}^{S} p_i ln p_i$

A community exhibiting an even distribution would be comprised of a similar number of individuals for each species present. A community exhibiting an uneven distribution would be dominated by a few or one species. Pielou J's index [2] was calculated to describe community evenness, where H' is Shannon-Weiner diversity and S represents the total number of species in the community. J assumes a value between 0 and 1, where 1 represents complete evenness (Peet, 1974).

[2] $J = \frac{H'}{In\ (S)}$

To gain further insight, a principal component analysis (PCA) was used to examine differences in community structure among sampling dates. A PCA plot allows for the visualization of differences in species present and their relative abundance among sampling dates, with points located closer together having community structures that are more similar than points located further apart (Dytham, 2015).

Spearman correlations were used to examine correlations between water quality variables and rotifer metrics (Algina & Keslamn, 1999). Spearman correlation coefficient values vary between +1 and -1, with values closer to zero indicating a weak or nonexistent correlation.

Values closer to +1 and -1 indicate a more significant degree of association between the two variables (Algina & Keslamn, 1999). Spearman correlations were performed using the cor function in R with the method argument set to “spearman” (R Core Team, 2022).

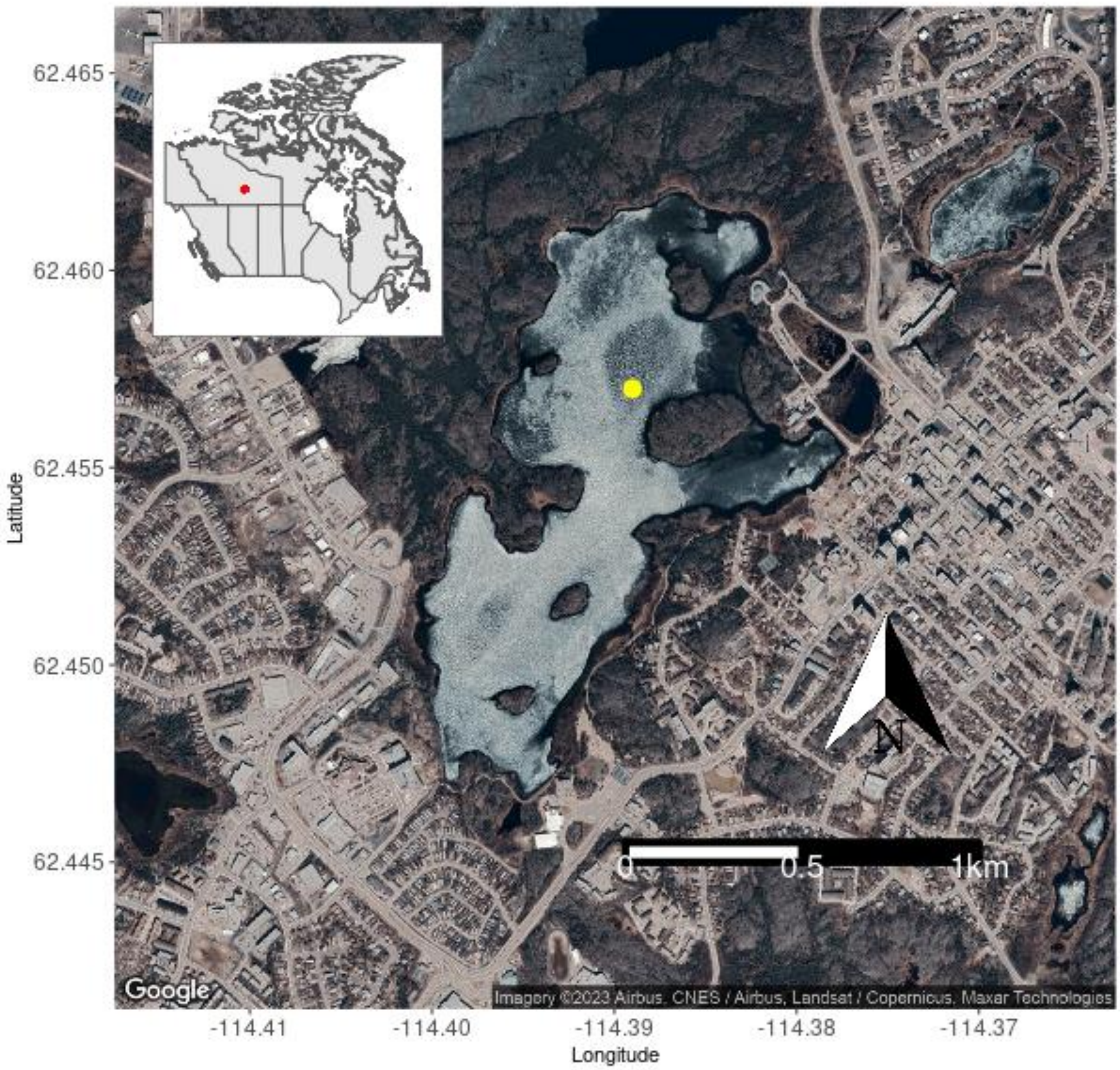

Figure 1. Map of Frame Lake in Yellowknife, Northwest Territories. The red dot indicates the location of Frame Lake within Canada. The yellow dot represents the point of maximum depth in Frame Lake, where rotifer and water sampling occurred, and where the aerator will be installed.

3 | Results

3.1 | Morphometry and Water Quality

Frame Lake was sampled nine times between April 2021 and November 2022. Sampling occurred throughout spring, summer, fall, and under ice cover in winter. Data was collected for 14 morphometric and water quality metrics (Table 1), however, data collection of total dissolved solids, turbidity, Secchi depth, and total phosphorus only began in 2022. Frame Lake varied significantly through time in terms of important water quality metrics, including Secchi depth (5.42-7.5 m), pH (6.93-10.24), calcium (19.3-112 mg/L), chloride (29.9-165 mg/L), magnesium (7.6-38.2 mg/L), dissolved organic carbon (10.9-28.2 mg/L), total dissolved solids (10-360 mg/L), turbidity (0.34-105.9 NTU), epilimnion water temperature (-0.59-19.56 °C), hypolimnion water temperature (2.89-19.56 °C), conductivity (32.6-980 µS/cm), dissolved oxygen (-0.8-7.95 mg/L), total nitrogen (0.49-3.43 mg/L), total phosphorus (0.0043-0.065 mg/L), chlorophyll-*a* (0.12-28.94 µg/L), true colour (5-8 TCU), and ice thickness (17.78-90 cm) (Table 1).

Seasonal trends in water chemistry metrics were evident at the minimum depth of measurement (1 m or less). Metrics such as total nitrogen and magnesium reached maximum concentrations in March and troughs in October (Figure 3, Figure 4). Similarly, dissolved organic carbon and calcium experienced troughs in October, however, they exhibited maximums in March (Figure 3, Figure 4). Chloride also exhibited maximums in March, but minimums occurred in early June (Figure 4). In early June, maximums in turbidity occurred and minimums occurred in October (Figure 2). Secchi depth also reached maximums in June, but another maximum was observed in November (Figure 3). Minimums for Secchi depth occurred in August when maximums in chlorophyll-*a* occurred (Figure 3). Interestingly, maximums in Secchi depth did not occur at the same time as minimums in chlorophyll-*a* (Figure 3).

Minimums in Secchi depth occurred in early June and November, while minimums in chlorophyll-*a* occurred in April (Figure 3). Maximums in the temperature of the epilimnion and hypolimnion were achieved in July (Figure 2). Minimum temperatures for the epilimnion were reached in November, while for the hypolimnion, minimums were reached in March (Figure 2). Conductivity and total phosphorus both reached maximums in August; however, total phosphorus reached a trough in June while conductivity reached a trough in July (Figure 2, Figure 3). Maximums in pH were observed in November and minimums in August (Figure 2). Total dissolved solids peaked in November with a trough in October (Figure 3). At the minimum depth of measurement, dissolved oxygen reached maximums in November under ice cover and minimums in April (Figure 2). However, it should be noted that at the maximum depth of measurement, maximums in dissolved oxygen occurred in October, and minimums occurred in March. During months with ice cover, ice thickness ranged from 17.78 cm in November to 90 cm in April (Table 1).

Temperature patterns in the lake indicate evidence of temperature stratification (Figure 5). The lake appeared polymictic, stratifying in some summer months and mixing before stratification set up again in November (Figure 5). During the winter months, reverse stratification occurred (Figure 5).

A Principal Component Analysis (PCA) was performed on the water quality data where the first two axes explained 85.9% of the variation among sampling dates (Figure 6). The PCA suggested that total nitrogen, magnesium, dissolved organic carbon, chloride, calcium, and conductivity are the most important contributors to the first principal component, while dissolved oxygen, pH, and temperature are the most important contributors to the second principal component (Figure 6). Total nitrogen, magnesium, dissolved organic carbon, chloride, calcium, and conductivity were highly correlated (Figure 6). Dissolved oxygen and pH are also correlated, while temperature was uncorrelated with the other variables (Figure 6). Data from spring months were correlated with high levels of total nitrogen, magnesium, dissolved organic carbon, chloride, calcium, and conductivity (Figure 6). Data from fall months were correlated with high levels of dissolved oxygen and pH, while data from summer months were correlated with high temperatures (Figure 6).

A correlation plot revealed that chloride, calcium, magnesium, total nitrogen, and dissolved organic carbon were all positively correlated with one another (Figure 7). Apart from dissolved organic carbon, conductivity was also positively correlated with these variables (Figure 7). Chlorophyll-*a* and water temperature were positively correlated, and both exhibited negative correlations to conductivity (Figure 7). Dissolved oxygen and pH were positively correlated, while dissolved oxygen was negatively correlated to chloride, calcium, magnesium, and total nitrogen (Figure 7).

3.2 | Rotifer Community Structure

The final rotifer data set was comprised of 24 rotifer genera (Appendix A). The total abundance of rotifers on each sampling date ranged from 1353 to 41,053 individuals L^{-1}, with a mean of 12,036 individuals L^{-1}. Maximums in rotifer abundance was observed in October and minimums in November (Figure 8). The rotifer community in Frame Lake exhibited seasonality. Rotifer abundance significantly increased from early spring to early summer (Figure 8). Decreases in rotifer abundance were observed in mid-summer through to winter (Figure 8). The diversity of the rotifer community in Frame Lake roughly tracked the seasonal changes observed in rotifer abundance (Figure 8). Rotifer diversity increased significantly from early spring through summer, reaching a maximum in mid-fall (Figure 8). Diversity fell significantly from mid-fall to late fall, reaching minimums where the community was mainly comprised of *Kellicottia* genera. The rotifer community in Frame Lake also exhibited seasonality in richness. Richness increased from early spring to mid-summer (Figure 8). A decrease in richness occurred mid-summer, only to increase again in late summer and early fall (Figure 8). Minimums in richness were observed in winter (Figure 8).

A PCA was performed on the rotifer abundance data where the first two axes explained 73.8% of the variation among sampling dates (Figure 9). The PCA suggested that *Keratella* and *Kellicottia* spp. were the most important contributors to the first principal component, while *Conochilus* spp. were the most important contributor to the second principal component (Figure 9). *Ascomorpha* spp. were correlated with sampling dates earlier in the year (Figure 9). *Conochilus* spp. were correlated with sampling dates mid-way through the year, and *Keratella and Kellicottia* spp. were correlated with sampling dates towards the end of the year (Figure 9). *Keratella* and *Kellicottia* spp. were highly correlated, while *Conochilus*, *Asplanchna*, and *Ascomorpha* spp. were uncorrelated (Figure 9). The PCA failed to reveal a consistent pattern between the relative abundance of different rotifer genera and seasons (Figure 9).

A correlation plot revealed that rotifer diversity was negatively correlated to dissolved organic carbon (Figure 7). Rotifer diversity and richness were positively correlated; however, no significant correlations existed between abundance and richness with the water quality metrics we assessed (Figure 7).

Water Quality Parameters	Minimum	Mean	Maximum
Secchi Depth (m)	5.42	6.63	7.50
pH	6.93	8.21	10.24
Calcium (mg/L)	19.30	53.21	112.00
Chloride (mg/L)	29.90	62.24	165.00
Magnesium (mg/L)	7.60	21.50	38.20
Dissolved Organic Carbon (mg/L)	10.90	19.34	28.20
Total Dissolved Solids (mg/L)	10.00	133.81	360.00
Turbidity (NTU)	0.34	4.86	105.90
Surface Temperature (°C)	-0.59	10.65	19.56
Bottom Temperature (°C)	2.89	8.29	19.56
Conductivity (µS/cm)	32.60	457.92	908.00
Dissolved Oxygen (mg/L)	-0.80	7.95	15.08
Total Nitrogen (mg/L)	0.49	1.76	3.43
Total Phosphorus (mg/L)	0.0043	0.025	0.065
Chlorophyll-*a* (µg/L)	0.12	2.48	28.94
True Colour (TCU)	5.00	6.68	8.00
Ice Thickness (cm)	17.78	52.03	90.00

Table 1. Minimum, mean, and maximum values for the physical and chemical water quality metrics.

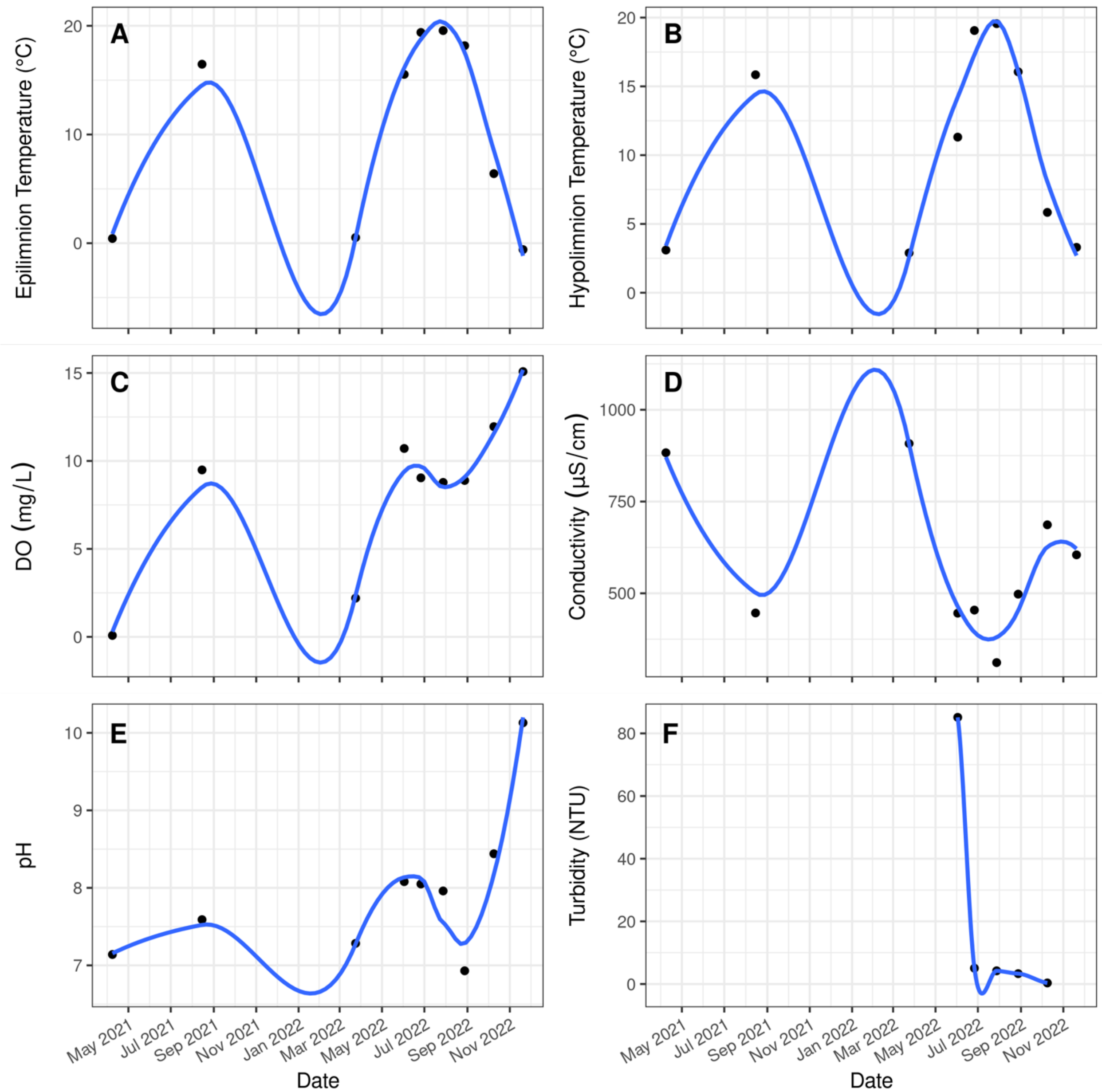

Figure 2. Data for epilimnion temperature (A), hypolimnion temperature (B), dissolved oxygen (C), conductivity (D), pH (E), and turbidity (F) at the minimum sampling depth available in Frame Lake.

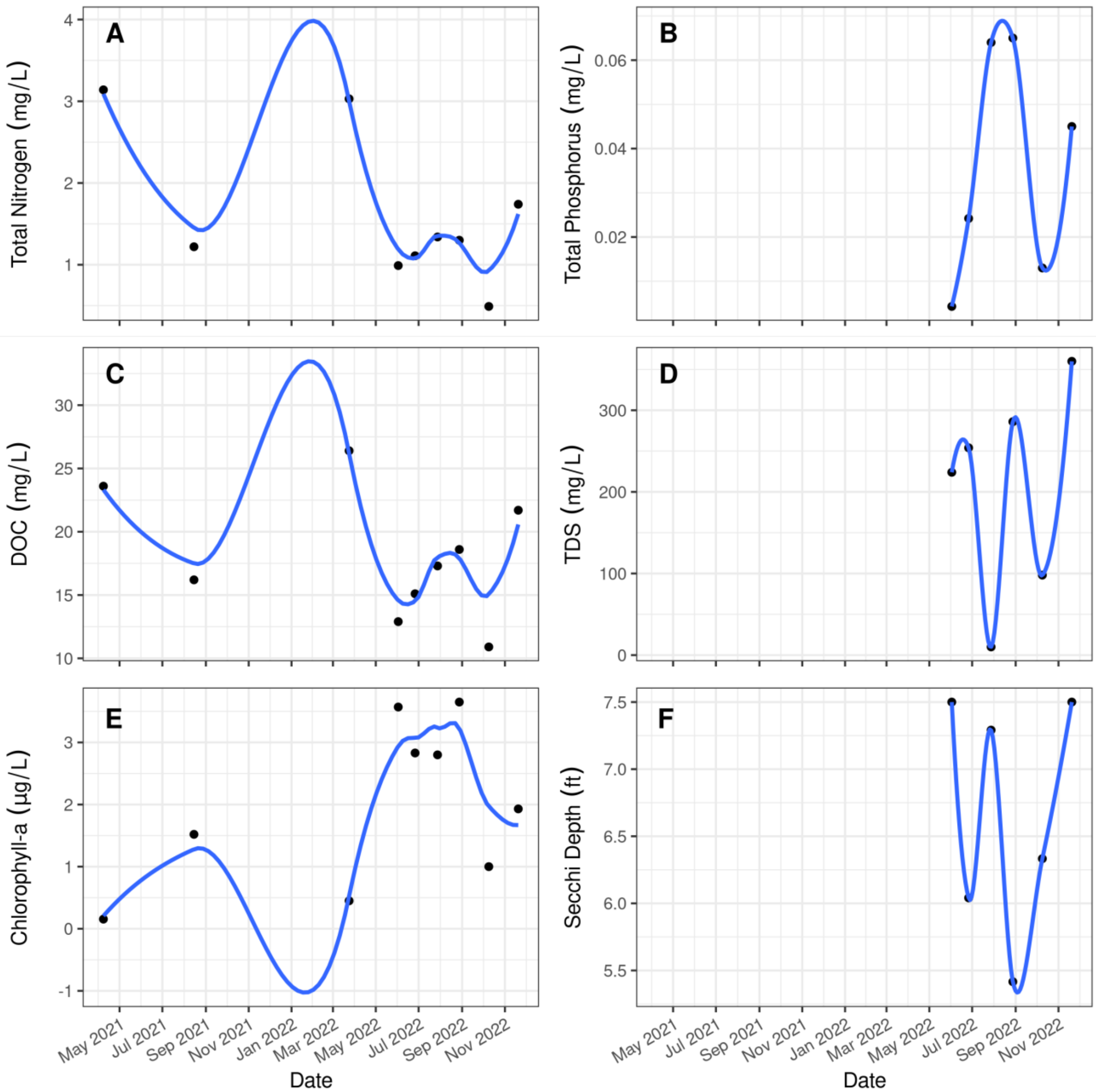

Figure 3. Data for total nitrogen (A), total phosphorus (B), dissolved organic carbon (C), total dissolved solids (D), chlorophyll-*a* (E), and Secchi depth (F) at the minimum sampling depth available in Frame Lake.

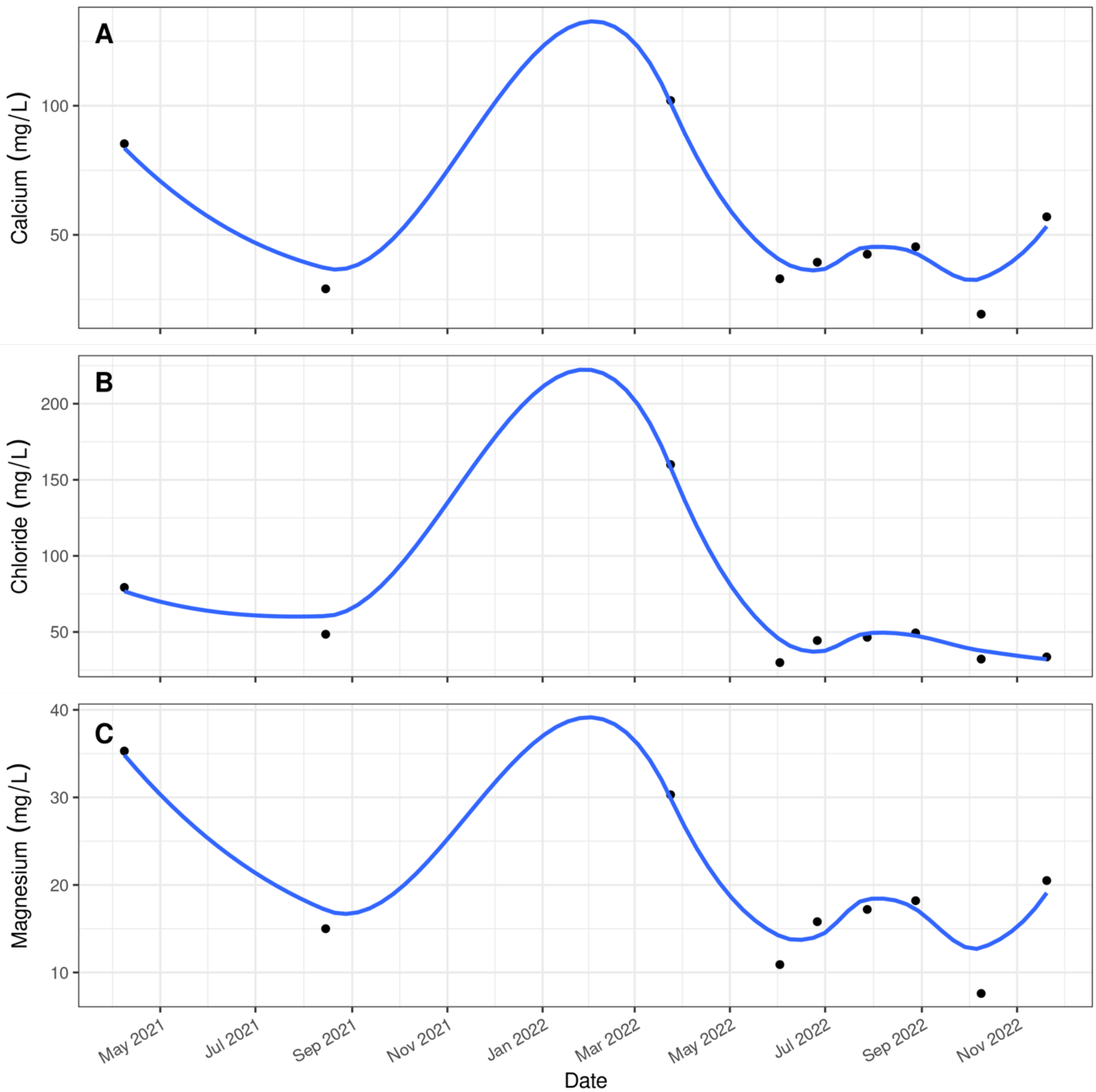

Figure 4. Data for calcium (A), chloride (B), and magnesium (C) at the minimum sampling depth available in Frame Lake.

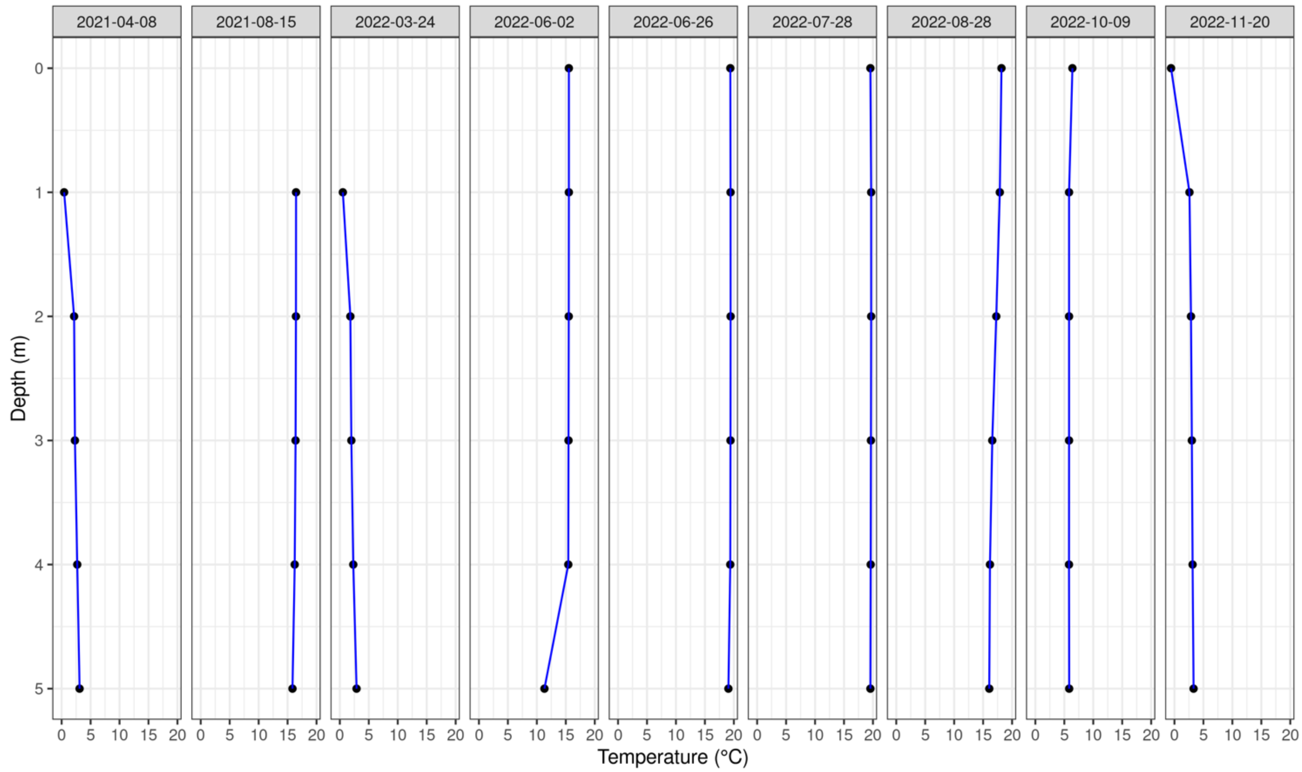

Figure 5. Temperature-depth plot on each sampling date for Frame Lake.

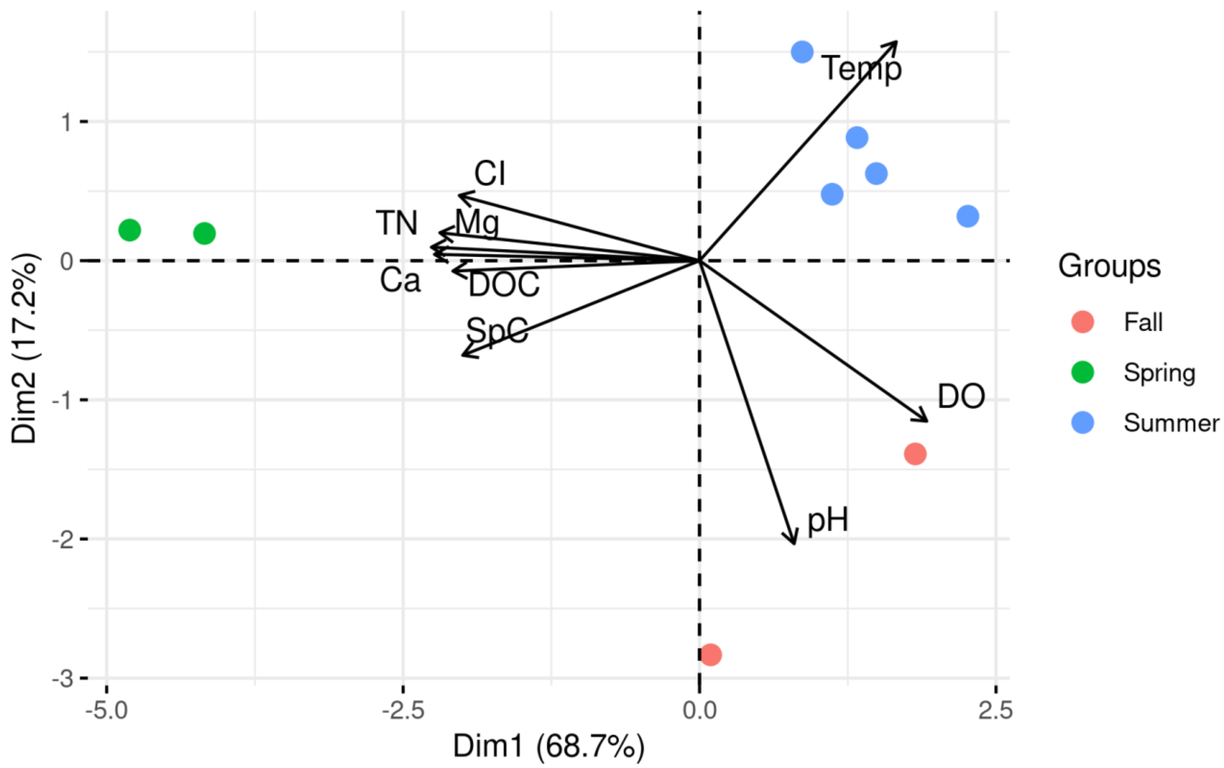

Figure 6. A Principal Component Analysis (PCA) plot for the physical and chemical water quality metrics. DO = dissolved oxygen, Cl = chloride, Mg = magnesium, TN = total nitrogen, Ca = calcium, DOC = dissolved organic carbon, SpC = specific conductivity.

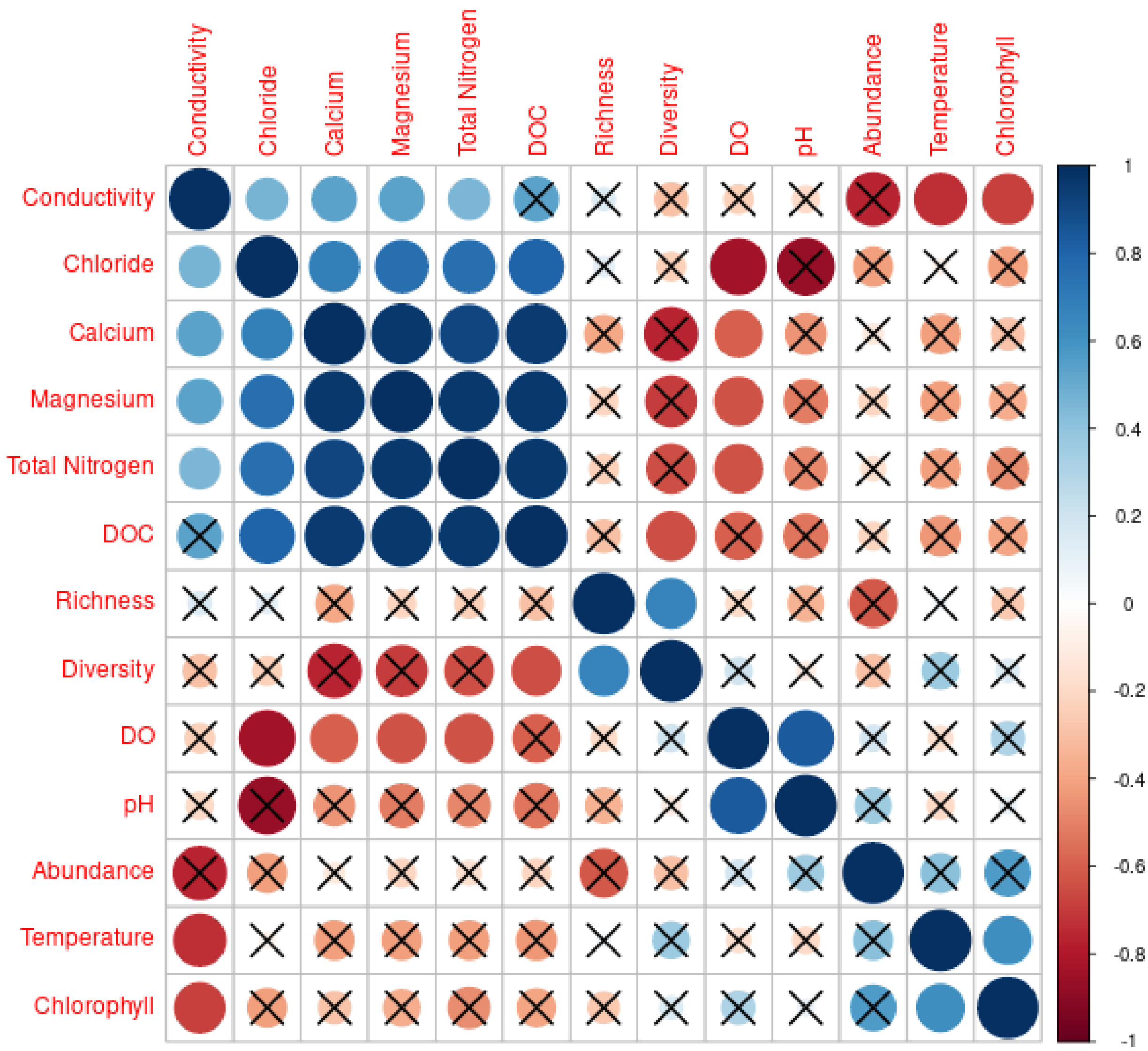

Figure 7. Correlation plot including the physical and chemical water quality and rotifer community metrics. DOC = dissolved organic carbon and DO = dissolved oxygen.

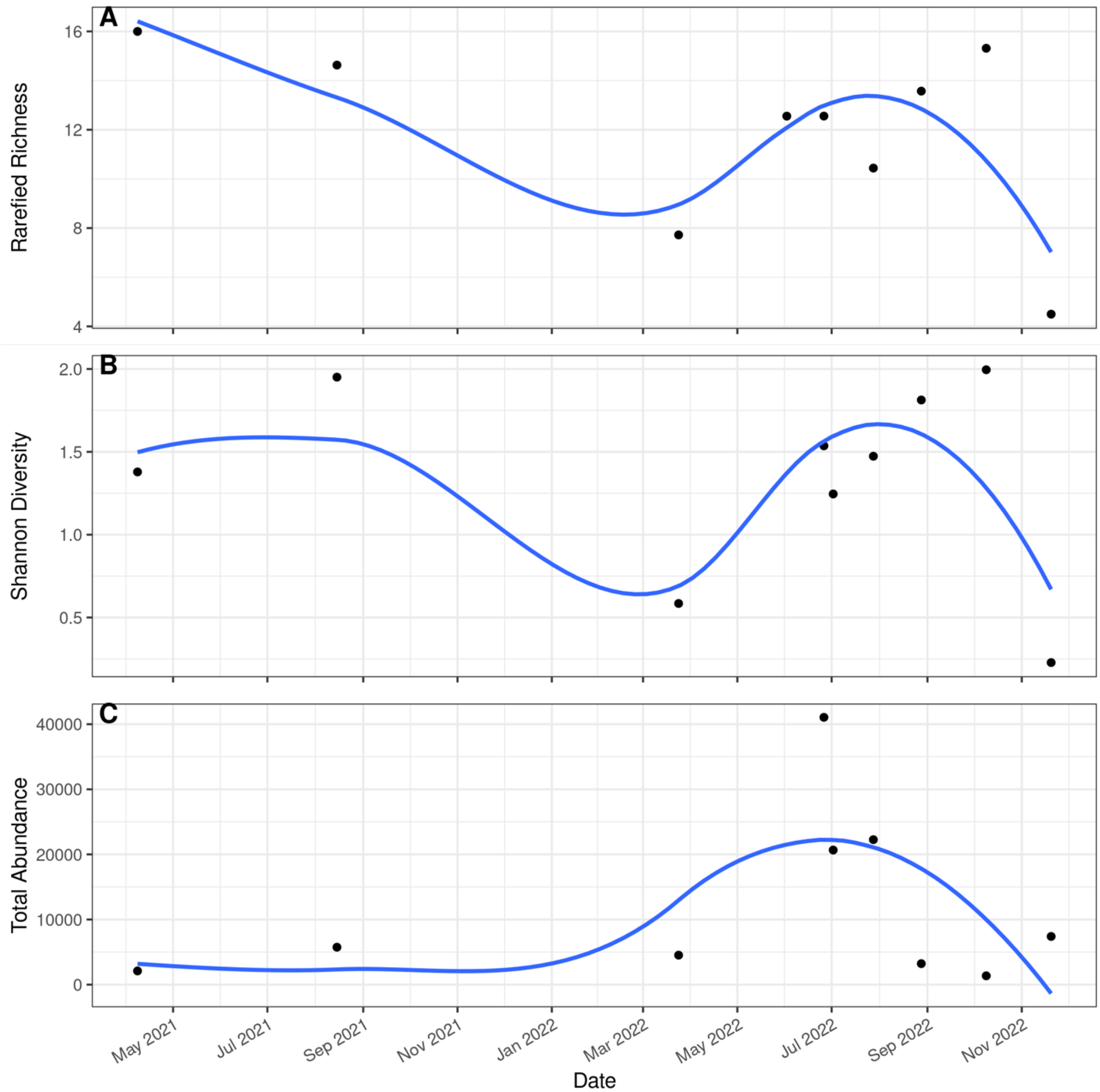

Figure 8. Plots of the richness (A), diversity (B), and abundance (C) of the rotifer community through time in Frame Lake.

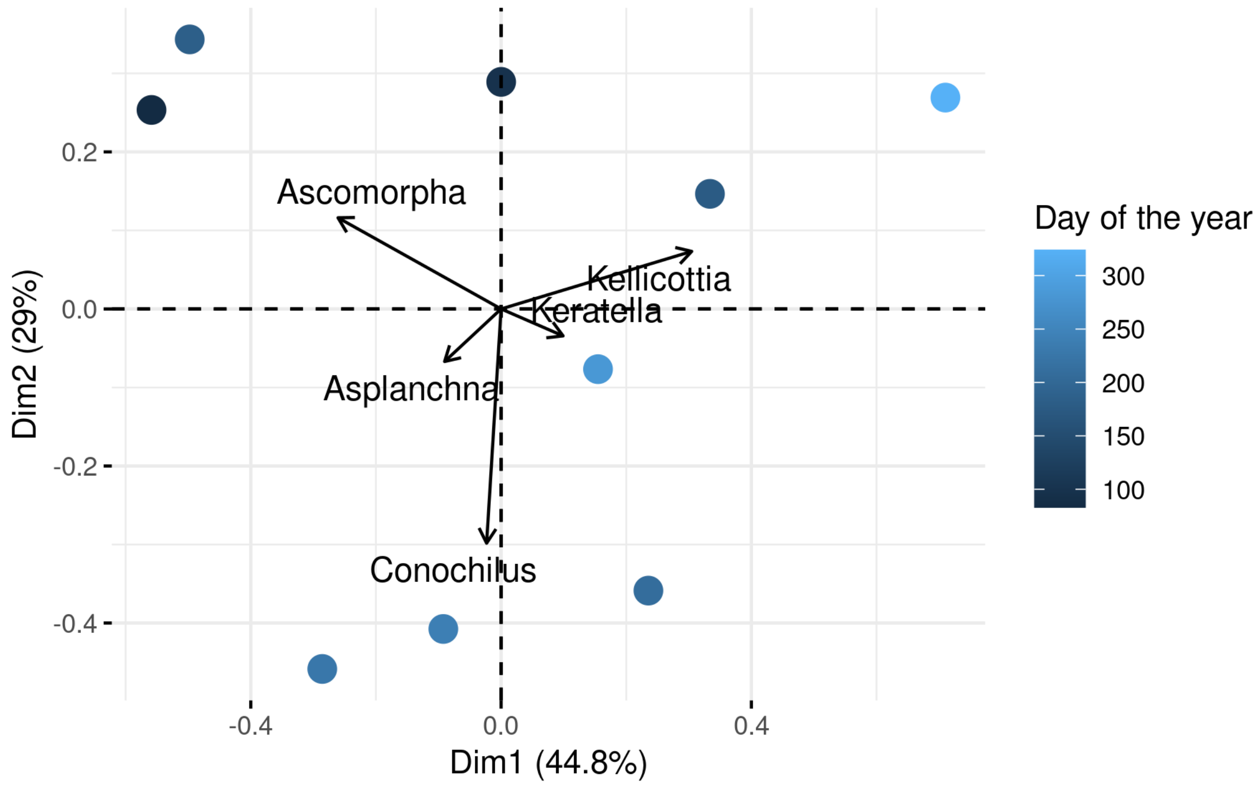

Figure 9. A Principal Component Analysis (PCA) plot for the rotifer genera present in Frame Lake. Each point represents a sampling date. The colour of each point indicates the day of the year on which the sample was collected.

4 | Discussion

Previous research has identified poor urban planning as a cause of allochthonous nutrient loading in Frame Lake, causing eutrophic and anoxic conditions (Dirszowsky & Wilson, 2015; Gavel et al., 2018; Koch et al., 2000; Moore, 1981; Palmer et al., 2019). While there are plans for Frame Lake's rehabilitation through hypolimnetic aeration, there is an absence of high-frequency multi-season water quality and rotifer community baseline data to compare to post-aerator conditions. Such a comparison is critical to understand the aerator's effectiveness and guiding further restoration efforts. Previous studies have assessed water quality and rotifer communities in Canada's northern lakes through one-time summer sampling (i.e., Chengalath & Koste, 1989; Cohen et al., 2021; De Smet & Beyens, 1995; Swadling et al., 2000; Vucic et al., 2020). However, the development of high-frequency multi-season data would enable the assessment of seasonal succession. Therefore, this study aimed to: 1) Examine seasonal patterns in water quality; 2) Examine seasonal patterns in rotifer community composition and abundance; and 3) Examine rotifer community patterns in relation to water quality metrics. This study presents six principal results: 1) hypoxia and anoxia following ice cover development; 2) seasonal changes in chlorophyll-*a*, total phosphorus, and total nitrogen; 3) seasonal and long-term changes in conductivity; 4) the presence of rotifers from a range of limnosaprobic degrees; 5) an absence of significant correlations between rotifer abundance, diversity, richness and water quality metrics; and 6) seasonal changes in the rotifer community of a subarctic lake. These results have allowed this study to make two important contributions to the field of limnology. Firstly, it provides new and unique high-frequency multi-season data on the variations in water quality of an urbanized northern lake. Secondly, it offers valuable insights into the seasonal succession of rotifer communities in northern regions. Additionally, these results have allowed this study to make contributions critical for Frame Lake's rehabilitation by establishing baseline data on the lake's water quality and rotifer communities.

4.1 | Water Quality

4.1.1 | Formation of Ice Cover Triggers Hypoxia and Anoxia

Frame Lake experiences periods of hypoxic and anoxic conditions following the formation of ice cover. Hypoxia, characterized by low dissolved oxygen concentrations, is generally defined as a condition in which oxygen levels fall to 3 mg/L or less (North et al., 2014; Vaquer-Sunyer & Duarte, 2008). In contrast, anoxia, the complete absence of dissolved oxygen, occurs when oxygen concentrations drop to 0.5 mg/L or less (North et al., 2014; Vaquer-Sunyer & Duarte, 2008). In early October, the water column in Frame Lake exhibited sufficient dissolved oxygen concentrations (11.95 mg/ L and above). Ice cover developed in late October into early November, concurrent with dissolved oxygen concentrations decreasing in the hypolimnion. The development of ice cover prevents the diffusion of atmospheric oxygen into the water and the wind-induced mixing of oxygen into the lower layers of the lake (Couture et al., 2015; Livingstone & Adrian, 2009; Muri & Brancelj, 2003). Based on the assessment of dissolved oxygen concentrations in April 2021 and March 2022, it is evident that Frame Lake's oxygen levels continue to deplete under ice cover, leading to anoxic conditions.

Reoxygenation of the water column likely depends on the timing of the ice breakup. March and April exhibited anoxic conditions; however, by early June, the water column was sufficiently oxygenated (10.71 mg/ L and above). In Yellowknife, ice breakup typically occurs in late April or early May when temperatures begin to rise above 0 °C. Exposed surface water allows for the diffusion of atmospheric oxygen into the water and wind-induced mixing to occur. In addition, snowmelt on top of ice cover or within Frame Lake's catchment would carry oxygenated water into the lake (Kumagai & Fushimi, 1995). Sampling was not possible during the ice breakup in May 2021 and 2022 due to unsafe sampling conditions. However, it is probable that an increase in dissolved oxygen concentrations would have been observed in this month. To validate our hypothesis regarding the timing of reoxygenation, additional sampling is necessary.

4.1.2 | Relationships Between Chlorophyll-*a*, Total Nitrogen, and Total Phosphorus: Insights from Lake Mixing Patterns

Increases in chlorophyll-*a* tracked increases in total nitrogen and phosphorus in summer months. The relationship between chlorophyll-*a* and nitrogen and phosphorus levels is one of the most well-known in limnology (Elser et al., 2007; Filstrup & Downing, 2017; Hecky & Kilham, 1988; Smith et al., 1999). In Frame Lake, the highest chlorophyll-*a* concentrations and lowest transparency (Secchi depth) coincided with increased total nitrogen and phosphorus. Lake turnover, which refers to mixing events induced by rising epilimnion temperatures, is crucial in redistributing nitrogen and phosphorus throughout the water column (Lung et al., 1976; Wilhelm & Adrian, 2008; Yang et al., 2020). Our results show summer changes in nitrogen and phosphorus concentrations; therefore, chlorophyll-*a* concentrations may relate to mixing processes. Examination of our temperature-depth plots suggests that Frame Lake is a polymictic lake exhibiting periods of thermal stratification and mixing (Figure 5). Thermal stratification was apparent in early June before an isothermal mixing period in late June and July (Figure 5). The warming temperatures in Yellowknife during June and July, along with the mechanical force produced by wind, has the potential to supply sufficient energy to thoroughly mix the water column (Bouffard et al., 2013). Water column mixing would effectively redistribute nitrogen and phosphorus from the hypolimnion to the upper layers of the water column. In August, weak thermal stratification is evident, and it is plausible that the peaks in phosphorus levels in August are also due to wind-induced mixing. Research conducted by Bouffard et al. (2013), Riley & Prepas (1984), and Yang et al. (2020) provides evidence for the role of mixing in redistributing nutrients to surface waters.

4.1.3 | Internal Loading as a Possible Driver of Seasonal Changes in Total Phosphorus and Total Nitrogen

The release of legacy phosphorus (internal loading) from the sediment in Frame Lake could also account for the peaks in total phosphorus observed during July. The literature widely cites that increases in phosphorus during the summer months can be caused by internal loading (Jeppesen et al., 1991; Kleeberg & Kozerski, 1997; Lung et al., 1976; Müller et al., 2016; Riley & Prepas, 1984; Romero et al., 2002). Research has demonstrated that sediment in freshwater lakes releases legacy phosphorus during the summer months when the water temperature increases and the pH of the water is alkaline (Boström et al., 1988; Wu et al., 2014). Shallow eutrophic lakes with high water residence time are particularly susceptible to internal phosphorus loading (Jeppesen et al., 1991; Romero et al., 2002). Our findings suggest that the elevated total phosphorus concentrations observed in the summer months in Frame Lake, which is classified as a shallow eutrophic lake with prolonged residence time, may be influenced by internal loading.

While summer peaks in total nitrogen may be attributed to lake turnover and mixing, the highest annual nitrogen concentrations were recorded during late spring when ice cover was still present. The peak concentrations of total nitrogen in Frame Lake were found to coincide with the lowest concentrations of dissolved oxygen in the water column. Dissolved oxygen concentrations exert a significant influence on a wide range of biogeochemical processes (Testa & Kemp, 2012). The cycling of nitrogen from lake sediments is one such example (Testa & Kemp, 2012). Prior research has reported inverse correlations between dissolved oxygen concentrations and elevated nitrogen cycling (Conley et al., 2007; Savchuk et al., 2008; Testa & Kemp, 2012). Specifically, a reduction in dissolved oxygen concentrations in a lake's hypolimnion results in greater rates of nitrogen release from sediments (Conley et al., 2007; Savchuk et al., 2008; Testa

& Kemp, 2012). The hypolimnion in Frame Lake achieved the lowest concentration of dissolved oxygen (anoxic) in April of 2021 and March of 2022. These months achieved the highest recorded levels of nitrogen. The co-occurrence of anoxia and high total nitrogen concentrations in Frame Lake may suggest that the discharge of legacy nitrogen from lake sediments is driving total nitrogen concentrations.

4.1.4 | Potential Influence of Snow and Ice Melt on Seasonal Changes in Conductivity

Frame Lake exhibits substantial seasonal changes in chloride (Cl), calcium (Ca), and magnesium (Mg). Higher Cl, Ca, and Mg concentrations are associated with spring, while lower concentrations are associated with summer. The highest concentrations of Cl, Ca, and Mg were observed in April 2021 and March 2022. As Cl, Ca, and Mg contribute to conductivity, the highest conductivity values were observed in April 2021 and March 2022. Interestingly, high conductivity was also observed in October 2022. The reason for spring increases in Cl, Ca, and Mg and fall increases in conductivity is unclear. However, one possible reason could be the input of Cl, Ca, and Mg from runoff influenced by road salt use. The City of Yellowknife applies a salt mixture, mainly in spring and fall, when temperatures return to the range for which road salt effectively reduces ice buildup (The City of Yellowknife, 2014). The City of Yellowknife applies salt to major roads, intersections, and areas adjacent to City properties (The City of Yellowknife, 2014). This includes the application of salts to many areas in Frame Lake's catchment, including the Northwest Territories Legislative Assembly, Prince of Wales Northern Heritage Center, and 48th Street on the north side, Franklin Avenue and many City buildings on the east side, the Ruth Inch Memorial Pool, Yellowknife Community Arena Complex and Stanton Memorial Hospital on the south side, and Old Airport Road on the southwest side. The most common road salts are chloride-based salts such as sodium chloride (NaCl), calcium chloride ($CaCl^2$) and magnesium chloride ($MgCl^2$) (Hintz & Relyea, 2019). With the application of road salts, snow and ice on roads, sidewalks, and parking or industrial lots accumulate ions from the salts, such as Cl, Ca, and Mg (Evans & Frick, 2001). With rising temperatures in spring, melting snow and ice transport these ions into waterways. (Evans & Frick, 2001). Larger lakes than Frame Lake, such as Lake Constance in Europe, have exhibited increased conductivity from the application of road salts in their catchments (Müller & Gächter, 2012).

4.1.5 | Exploring the Link Between Road Salt Application and Long-Term Conductivity Changes

Our results indicate that urbanization and road salt application may significantly affect Frame Lake's conductivity. While we have observed seasonal changes in conductivity that occur in Frame Lake within a year, there is evidence of long-term changes. Previous work by Pienitz et al. (1997) assessed the physical and chemical limnology of lakes northeast of Yellowknife unaffected by urbanization. By sampling twenty-four lakes in July of 1991, the study reported that lakes northeast of Yellowknife had consistently low conductivity. During July, the conductivity of these lakes ranged from 0 to 100 $\mu S/cm^{-1}$, with a mean value of 17.1 $\mu S/cm^{-1}$. Pienitz et al. (1997) discovered comparable results to those observed by Rawson (1960), Healey and Woodall (1973), and Welch and Legault (1986) regarding the conductivity of northern Canadian lakes. However, our results indicate Frame Lake has a mean conductivity of 441 $\mu S/cm^{-1}$ during July. A similar trend was observed in the case of Ca, where Pienitz et al. (1997) recorded significantly lower levels (2.2 mg/L^{-1}) in lakes northeast of Yellowknife during July compared to our findings for Frame Lake (42.5 mg/L^{-1}).

Our hypothesis regarding urbanization and the application of road salt having long-term effects on Frame Lake's conductivity is reinforced by the findings of Healey and Woodall

(1973). Healey and Woodall (1973) completed limnological surveys of multiple lakes around Yellowknife, including Frame Lake. In June and August of 1973, the mean conductivity of Frame Lake was reported to be 332 $\mu S/cm^{-1}$ (Healey & Woodall, 1973). In comparison, the mean conductivity of Frame Lake in June and August of 2022 was 467 $\mu S/cm^{-1}$. The long-term increase in conductivity we have observed may result from the gradual accumulation of road salt ions (Dugan et al., 2017). Year-after-year application of road salts has been demonstrated to increase conductivity in lakes, mainly through the accumulation of road salt related ions in lake sediments (Dugan et al., 2017). The continued use of road salts in areas within Frame Lake's catchment could further elevate the lake's conductivity. Increases in conductivity could have significant consequences for Diavik Diamond Mine's rehabilitation effort to restore natural ecosystem processes and a recreational fishery in Frame Lake. Increased conductivity, associated with increased Cl, Ca, and Mg concentrations, may also affect lake mixing and therefore dissolved oxygen concentrations in the hypolimnion (Tiwari & Rachlin, 2018).

4.2 | Rotifers

4.2.1 | Rotifers: Valuable Bioindicators of Water Quality Through Saprobity and Dissolved Oxygen Monitoring

The rotifer community in Frame Lake comprised genera from a range of limnosaprobic degrees. These included rotifers belonging to the oligosaprobic, beta-, and alpha-mesosaprobic categories (Sládeček, 1983). Typically, species listed as oligosaprobic are indicative of oligotrophic or high dissolved oxygen conditions, and those listed as beta or alpha-mesosaprobic indicate eutrophic or low oxygen conditions (Sládeček, 1983). The three most abundant genera of rotifers we observed included, *Kellicottia* spp., *Ascomorpha* spp., and *Conochilus* spp. The species that comprise the *Kellicottia* genera are all listed as oligosaprobic (Sládeček, 1983).

Higher abundances of *Kellicottia* spp. were observed in November when the highest dissolved oxygen concentration was recorded in the epilimnion of Frame Lake. Likely, the epilimnion remains well-oxygenated longer than the hypolimnion, where dissolved oxygen depletes first due to Frame Lake's high sediment oxygen demand. The well-oxygenated epilimnion would provide conditions appropriate for *Kellicottia* spp. to survive until later in the winter when the epilimnion becomes depleted of oxygen.

Species in the genera *Ascomorpha* exhibit a range of limnosaprobic degrees from oligotrophic to beta-mesosaprobic (Sládeček, 1983). *Ascomorpha* spp. were observed, most abundantly, in April 2021 and March 2022, which exhibited the lowest dissolved oxygen concentrations. The categorization of certain species of *Ascomorpha* spp. as beta-mesosaprobic, which represent low oxygen conditions, suggests that organic pollution may be present during months characterized by hypoxia and anoxia. This organic pollution is likely a result of internal loading from Frame Lake's sediments under anoxic conditions.

Additionally, Frame Lake contained genera of rotifers categorized as alpha-mesosaprobic, which can also indicate low oxygen conditions. These included rotifers of the genera *Testudinella* spp., *Brachionus* spp., and *Filinia* spp. Like beta-mesosaprobic rotifers, the presence of these alpha-mesosaprobic rotifers during months of low dissolved oxygen concentrations suggests the existence of organic pollution. The assessment of limnosaprobic categories of rotifers in Frame Lake suggests that the lake undergoes periods of oligotrophic conditions characterized by sufficient dissolved oxygen concentrations and eutrophic conditions characterized by low dissolved oxygen concentrations and organic pollutants. However, for a more informed conclusion, identification of the rotifer community in Frame Lake to the species level and further sampling during winter months is required.

4.2.2 | Rotifers in Relation to Water Quality Metrics

Of the water quality metrics assessed, dissolved organic carbon (DOC) was the only one to exhibit a significant correlation with a rotifer community metric. We observed a negative correlation between DOC and rotifer diversity. However, rather than a direct causal relationship, this correlation is more likely a result of seasonal changes in water quality in combination with the production of overwintering eggs by rotifers. The increase in DOC we observed is likely due to snowmelt runoff, which carries higher amounts of DOC into lakes than summertime runoff (Finlay et al., 2006). These increases in DOC occurred during late winter, coinciding with when most rotifers have produced overwintering eggs that have settled into the lake sediments and are not present in our samples. Therefore, increases in DOC coincide with decreases in rotifer diversity as only a few genera that overwinter in the water column, such as *Kellicottia* spp., are present in our samples (Larsson, 1978).

Additional observations on the relationships between water quality metrics and the rotifer community suggest that there may be relationships between rotifer abundance and temperature, chlorophyll-*a*, and magnesium. We are unable to confirm these correlations due to our small data set, but further sampling and processing may enable the corroboration of these relationships.

4.2.3 | Seasonal Dynamics of Rotifer Communities in Canada's Subarctic Region

In Frame Lake, rotifer community composition and abundance underwent seasonal changes. Previous work by Sommer et al. (1986) developed a sequential description of the seasonal patterns of succession planktonic organisms undergo, referred to as the PEG model. In the model, rotifer abundance is expected to increase in the spring when algal food is abundant, then decrease when large zooplankton species, such as *Daphnia*, become more prevalent due to competition and predation (Sommer et al., 1986). Contrary to the PEG model, in Frame Lake, we did not observe increases in rotifer abundance in spring or decreases in mid-summer. In early spring, we observed decreasing rotifer abundance from March to early June. Increases in rotifer abundance began mid-summer in June before a significant increase occurred to reach maximums in abundance in July.

We speculate that the differences in the timing of seasonal succession of rotifers in Frame Lake compared to the PEG model result from Frame Lake's location in the subarctic. In subarctic regions, stark seasonality in sunlight hours and the extended periods of ice cover restrict algae production to brief summer periods (Swadling et al., 2000). In Frame Lake, chlorophyll-*a*, which can be representative of algal abundance, steadily increased from March to June, similar to rotifer abundance. Likely, increases in rotifer abundance tracked increases in chlorophyll-*a* as algae is a significant food source of most rotifer genera (Sládeček, 1983). With food availability delaying increases in rotifer abundance, it is likely that larger zooplankton that consume rotifers also exhibit delayed maximums in abundance. Therefore, predation pressure from larger predatory zooplankton would occur later in the summer rather than mid-summer, as the PEG model outlined. Increased predation pressure by larger zooplankton would explain the decrease in rotifer abundance we observed from July through to October.

Rotifers were observed in the water column during periods of ice cover. In April and November, the most abundant rotifer was *Kellicottia* spp.. *Kellicottia* spp. have unique life cycles for rotifers as they do not produce resting eggs but rather overwinter in the water column (Larsson, 1978). Previous research has noted decreases in Kellicottia spp. during late-summer months due to predation (Larsson, 1978). Copepod zooplankton typically reach maximum size during late summer and can consume *Kellicottia* spp. (Larsson, 1978). These predaceous zooplankton develop resting eggs with the onset of decreased daylight hours and colder temperatures as an overwintering strategy (Glippa et al., 2013). Thus, with decreasing daylight hours and temperature in Yellowknife in November, the production of resting eggs likely decreases predation pressure from Copepods on *Kellicottia* spp.. Decreased predation pressure could explain why *Kellicottia* spp. dominated the rotifer community in November. *Kellicottia* spp. reaching maximums in abundance later than other rotifer genera is consistent with the findings reported by Larsson (1978).

4.2.4 | The Composition and Abundance of Rotifers in a Canadian Subarctic Lake

The composition of rotifers found in Frame Lake exhibits similarities to that of other subarctic lakes. The most frequently encountered rotifers in Frame Lake included *Kellicottia* spp., *Ascomorpha* spp., *Conochilus* spp., *Asplanchna* spp., and *Keratella* spp. A study by Swadling et al. (2000) assessed the summer rotifer community composition of lakes between the Northwest Territories and the Yukon. Swadling et al. (2000) outlined that the most frequently encountered genera were *Kellicottia* spp., *Conochilus* spp., *Keratella* spp., and *Polyartha* spp. Our findings are similar to that of Swadling et al. (2000) in that *Kellicottia* spp., *Conochilus* spp., and *Keratella* spp. were most commonly encountered. Our findings indicate that *Ascomorpha* spp. and *Asplanchna* spp. were more significant contributors to Frame Lake's rotifer community composition than *Polyartha* spp.; however, *Polyarthra* spp. was still observed.

A similar study by Duthie (1979) on lakes across Canada's subarctic region found that the most abundant rotifers included *Asplanchna* spp., *Keratella* spp., and *Kellicottia* spp. The findings of Duthie (1979) are consistent with our findings. Further research on rotifer communities in Canada's subarctic region during winter months would enable more insightful comparisons of the rotifer community composition and abundance in Frame Lake.

4.3 | Study Limitations

While this study developed novel high-frequency multi-season data on lower trophic organisms and the study design enabled us to test our hypotheses, some apparent limitations exist. We believe this study has four main limitations: duration, lake access, sample size, and rotifer identification. Firstly, the study's duration was restricted to eight months, which constrained the time allotted for data collection and exploring our research questions. To further reinforce our findings and gain more insight into the seasonality of rotifer communities, undertaking similar projects with an extended duration would be valuable.

Secondly, lake access hindered the consistency of month-to-month sampling. Accessing lakes in northern environments is complex and requires monitoring ice thickness to ensure safe sampling conditions. In Yellowknife, lake ice typically begins to break up between April and May. In 2021, sampling was able to occur in early April, prior to the ice breakup occurring. The breakup period in 2022 extended longer than in 2021, preventing safe lake access for sampling in April and May. Freeze-up generally occurs between October and November. In 2022, ice developed to a thickness suitable for safe sampling to occur by late November. The community composition of zooplankton typically undergoes the most dynamic changes during the transitions between fall-winter and winter-spring (Sommer et al., 1986). Collecting samples from Frame Lake during these periods would provide greater insight into the correlations between water quality and measures of the rotifer community, as well as seasonal community dynamics.

Limited study duration in combination with lake access led to a small sample size. Small sample size can lead to increased margins of error when estimating means (e.g., abundance or richness) and a decreased ability to detect significant correlations between the chemical and physical water quality metrics and the rotifer community (i.e., low statistical power). Again, a similar project adapted to a longer study duration would help to decrease margins of error and solidify significant correlations.

Lastly, the identification of rotifers to the species level would be advantageous. Previous work by Sládeček (1983) grouped several rotifer genera as indicators of organic pollution and low oxygen levels. Several instances exist where a complete genus of rotifers does not fall in the same saprobic classification. Identifying rotifers to the species level would allow for more exact comparisons with the saprobic values provided by Sládeček (1983), resulting in a better appreciation for the degree to which the rotifer communities reflect pollution levels in Frame Lake. Identifying rotifers to the species level would also prove beneficial as few studies have explored species composition in the subarctic region, especially in Canada.

4.4 | Promising Directions for Future Research

Future research should prioritize expanding our methodology to enhance the data set. Collecting more consistent high-frequency multi-season data over an extended duration would be beneficial. Consistent data collection would significantly increase the size of our data set, enhancing the statistical power of our analyses. Moreover, with a more extensive data set, we could validate the significant and promising correlations between water quality metrics and the rotifer community we observed.

To better understand the impacts of urbanization on water quality and rotifer communities in Frame Lake, future research should expand to assess comparable bodies of water in Yellowknife as control lakes. Including control lakes would provide a more comprehensive understanding of how urbanization affects Frame Lake. Additionally, control lakes would be advantageous for comparison once aeration has been installed in Frame Lake. By conducting such a study, we could obtain a more accurate assessment of aeration's effectiveness in mitigating urbanization's impacts on Frame Lake's water quality and rotifer communities.

Future studies should investigate the interactions between the focal species and other community members, including zooplankton that have been identified to affect rotifer communities through competition or predation, to better understand rotifer community dynamics. We would further understand Frame Lakes' ecosystem dynamics by examining zooplankton's role in shaping rotifer community structure.

Lastly, future studies should identify rotifers to the species level to obtain a more precise understanding of the rotifer community in Frame Lake. By identifying to the species level, we could more accurately quantify the species present and calculate the saprobic index for Frame Lake throughout all seasons. By implementing these strategies and expanding our methodology, we can gain a more comprehensive understanding of the composition and dynamics of the rotifer community. This, in turn, would facilitate a more accurate assessment of the overall health of Frame Lake and the impact of anthropogenic factors, such as urbanization.

4.5 | Conclusion: Synthesizing the Results and Implications

To conclude, this study has successfully established a baseline of high-frequency, multi-season data on the existing rotifer community and water quality of Frame Lake. The results suggest that Frame Lake experiences many seasonal fluxes in water quality metrics which may be influenced by the development of ice cover, mixing patterns, dissolved oxygen concentrations, internal nutrient loading, and anthropogenic factors such as road salt. Additionally, the assessment of the rotifer community indicates Frame Lake varies in limnosaprobic classification with seasonal changes. Assessment of the rotifer community also highlights correlations with water quality variables and provides insight into the seasonal dynamics and succession of rotifer communities in Canadian subarctic lakes.

This study has made two significant contributions to the field of limnology. Firstly, it provides new and unique high-frequency multi-season data on the seasonal variations in the water quality of an urbanized northern lake. Secondly, it offers valuable insights into the seasonal succession of rotifer communities in northern regions. These results have allowed this study to make contributions critical for Frame Lake's rehabilitation by establishing baseline data on water quality and rotifer communities in Frame Lake. Additionally, this study provides a solid foundation for future research to evaluate the efficacy of hypolimnetic aeration as a rehabilitation strategy. This is particularly relevant as urbanization continues to increase, leading to a rise in the number of urbanized lakes across Canada.

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Appendix

Genera	Mean	Standard Deviation	Minimum	Maximum
Anuraeopsis	23.53	94.65	0	487.45
Ascomorpha	3204.06	4659.90	0	18580.33
Asplanchna	577.73	719.38	0	2047.28
Bipalus	1.84	6.95	0	32.23
Brachionus	86.72	210.40	0	831.23
Collotheca	90.17	175.36	0	607.43
Conochilus	1470.10	3242.31	0	12618.91
Conochiloides	11.07	49.98	0	258.06
Euchlanis	33.42	149.55	0	774.18
Kellicottia	4492.69	9367.32	0	44357.66
Keratella	431.13	1228.22	0	6336.81
Lepadella	0.93	3.50	0	16.29
Monostyla	109.05	375.26	0	1939.53
Notholca	313.69	690.95	0	3047.83
Filina	12.65	42.45	0	202.48
Gastropus	213.85	573.49	0	2580.60
Ploesoma	66.78	143.18	0	588.50
Polyarthra	44.79	127.87	0	580.18
Synchaeta	3.28	12.10	0	53.50
Testudinella	596.50	1236.77	0	4433.20
Trichocera	174.60	492.72	0	2030.63
Trichotria	46.05	82.84	0	292.47
Tylotrocha	76.46	397.31	0	2064.48
Tylotrochidae	45.04	151.82	0	584.94

Appendix A. Mean, standard deviation, minimum, and maximum values for the rotifer genera found in Frame Lake.