# Temporal and Spatial Variability of the Zooplankton Community in Lake Couchiching, Orillia, Ontario: Influence of Water Quality Parameters

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## Abstract

Lake Couchiching, located in Ontario, is a vital freshwater ecosystem providing numerous ecological, recreational, and economic benefits. As human activities and property development increase in the region, it is important to understand their impact on water quality and zooplankton communities. This study explores spatial and temporal variation in water quality parameters and their influence on the structure of zooplankton communities (ZCS) in Lake Couchiching over an annual cycle.

Extensive field studies were conducted, and water samples were collected from multiple locations within the lake across various seasons throughout the year. The water quality parameters measured included chlorophyll-a, conductivity, pH, total phosphorus, and nitrate levels. Principal Component Analysis (PCA) identified the primary factors driving variability in the zooplankton community, and cluster analysis grouped similar sampling sites based on water quality characteristics.

Both natural factors and human activities drove these characteristics. Conductivity was significantly affected by water quality changes, except in areas directly impacted by effluent discharge from the Orillia Wastewater Filtration Plant. Seasonal variations were observed, with conductivity, total phosphorus, and nitrate levels changing significantly between summer and winter.

Changes in ZCS over time and differences among various locations within the lake were also examined. Statistical methods identified distinct ecological patterns, and specific zooplankton taxa correlated strongly with levels of certain water quality parameters. For example, the presence of taxa such as *Daphnia* spp and *Diacyclops* spp was closely associated with changes in pH and nutrient levels. Zooplankton diversity and abundance changed significantly between seasons, with higher diversity during the spring and summer.

Key zooplankton indicators, such as *Daphnia* spp and *Diayclops* spp, were identified as important indicators of water quality and ecosystem health. Areas with higher human activity showed lower zooplankton diversity, indicating the potential impacts of anthropogenic factors on ZCS. The results highlighted the importance of maintaining riparian zones and reducing

nutrient runoff to mitigate the adverse effects of human activities on the lake's ecological balance.

Overall, this study shows that ongoing human development in the region will likely exacerbate the impact on water quality and ZCS. Continuous monitoring and adaptive management strategies are imperative to preserve Lake Couchiching's ecological integrity. Implementing conservation practices, such as controlling nutrient inputs and protecting shoreline vegetation, will mitigate the impacts of development. These insights provide a foundational understanding for policymakers and stakeholders aiming to balance development and ecological preservation, ensuring the long-term health of this vital freshwater resource.

## Lay Summary

Lakehead University's Department of Biology mission statement is: "Faculty and students in the Department of Biology are bound together by a common interest in explaining the diversity of life, the fit between form and function, and the distribution and abundance of organisms." In line with this mission, this study investigates how environmental factors, specifically water quality parameters, affect zooplankton communities in Lake Couchiching. The research aims to understand spatial and temporal differences in water quality and their impact on zooplankton diversity and abundance. The main research questions addressed are:

(1) How does water quality vary over time and space in Lake Couchiching?
(2) Do zooplankton in the lake show consistent spatial and temporal changes?
(3) Which zooplankton species indicate different aspects of the zooplankton community structure (ZCS), and how are they affected by water quality?
(4) Are there associations between zooplankton species and the overall ZCS, which could help simplify ecological monitoring of the lake?

Through field sampling and laboratory analyses, this study reveals significant spatial-temporal variability in water quality parameters such as temperature, pH, and conductivity; these, in turn, influence zooplankton communities. Some zooplankton species strongly correlate with specific water quality conditions, making them potential bioindicators for monitoring lake health. For example, the presence of *Daphnia* spp demonstrates high water quality, while an increase in *Rotifera* was associated with nutrient-rich conditions, indicating inputs of fertilizer or organic wastes. The research also highlights the importance of seasonal monitoring, as zooplankton communities and water quality parameters undergo significant changes over the year. This research identifies valued insights into the ecological dynamics of Lake Couchiching and underscores the importance of sustaining water quality for the health of aquatic ecosystems. By understanding how zooplankton respond to changes in water quality, we can better manage and protect freshwater resources. The study emphasizes the need for continuous monitoring and adaptive management strategies to ensure the sustainability of lake ecosystems in the face of environmental changes.

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# 1.0 Chapter 1. Introduction: Background and Significance of Lake Ecology and Zooplankton Communities

## 1.1.0 Overview

Water contaminants derived from agriculture and farm fields, gardens, faulty septic systems, water treatment plants, industrial activities and biotic excretions pose significant challenges to the health of aquatic ecosystems (Cooke *et al.*, 2008). The escalating influence of climate change, particularly the onset of warmer temperatures, further intensifies the impacts of lake contaminants, which especially affect zooplankton diversity. Zooplankton are highly sensitive to slight changes in temperature and water quality, making them vulnerable at a finer scale (Cooke *et al.*, 2008).

At the epicentre of these impacts lie the zooplankton, an integral component of freshwater ecosystems. These microscopic organisms filter suspended particulate matter, graze on phytoplankton and excrete essential nutrients into the water system they inhabit. Small fish may consume them, and when they die, they add organic matter to the ecosystem, which supports energy flow. Water turbidity often results in the resuspension of sediments, organic matter and nutrients, leading to a shift in the redox conditions (de Carvalho *et al.*, 2019; Zhang *et al.*, 2019). Furthermore, factors like temperature fluctuations, dissolved oxygen (DO) levels, and sediment disturbances can alter the availability of dissolved contaminants in the water. Given the sensitivity of zooplankton to the chemical composition of the water, these changes might reshape the local zooplankton community.

Clearly, an understanding of the dynamics and composition of these microscopic organisms can offer insights into the functioning and health of the aquatic ecosystem. Here, we will explore the ecological significance of zooplankton and their role in the health of freshwater ecosystems.

### 1.2.1 What are zooplankton?

Zooplankton represent a diverse subset of the plankton community, characterized by their inability to move against the water flow. These microscopic organisms encompass a range of taxa, including protists, rotifers, copepods, cladocerans, ostracods, amphipods, isopods, and larval forms of various invertebrates and vertebrates (Holland *et al.*, 2012). Despite their short life, zooplankton hold a central trophic position in aquatic ecosystems. They perform essential roles, such as reducing microalgal densities, enhancing fish production, driving nutrient cycles, and assimilating contaminants (Holland *et al.*, 2012). Numerous studies on specific zooplankton taxa as quick responders to environmental stressors have further highlighted their significance (Adamczuk *et al.*, 2020; Holland *et al.*, 2012; Ochocka & Karpowicz, 2022).

These stressors range from hydrological alterations, climate change impacts on ecosystems, and human-mediated activities, resulting in changes in lake conditions. Notably, diversity shifts within the crustacean zooplankton community offer a sensitive indicator of water quality changes (Holland *et al.*, 2012). Thus, given the integral role and importance of zooplankton, it is essential to compare some of the major groups of the zooplankton community, namely the cladocerans, copepods, and rotifers.

### 1.2.2 Cladocerans

Cladocerans, commonly referred to as water fleas, are a group of small crustaceans vital to freshwater habitats. Over 650 species have been identified, with many still undescribed. Their evolutionary journey traces back to the Permian period (Kotov & Taylor, 2011), and they have since spread across various freshwater environments. Typically ranging between 0.2 and 3.0 mm in size, cladocerans possess a distinct forward-tilted head with a single median compound eye (Balcer *et al.*, 1984). The *Cladocera* includes three suborders: *Anomopoda, Ctenopoda,* and *Haplopoda*, with several families, such as *Bosmina* and *Leptodora*, categorized under these suborders due to their analogous phylogenetic traits. Notably, *Leptodora kindtii,* with its elongated form, can extend up to 18 mm in length (Forro *et al.*, 2008). Cladocerans have small mouthparts, including a unique labrum, paired mandibles, maxillae, and an unmatched labium. They consume a diet of organic detritus, algae (including scraping periphyton off surfaces), and bacteria while directly absorbing oxygen through their body surface.

Cladocerans show remarkable reproductive versatility. In favourable conditions, they rely on parthenogenesis, producing multiple generations of female clones, which is a simpler and energetically less costly strategy compared to sexual reproduction. As environmental conditions become challenging, Cladocerans shift to sexual reproduction. Females produce male offspring, which serve as sperm donors, and sexual mating results in the production of ephippia, robust dormant eggs that can outlast adverse conditions. These are long-lasting dormant eggs which can last through adverse conditions. The arrival of good environmental conditions results in the hatching of these eggs. This trait, the ability to switch between sexual reproduction and cloning, helps many cladoceran species to establish extensive and diverse distribution (Balcer *et al.*, 1984; Forro *et al.*, 2008; Smith, 2001).

Some cladoceran populations undertake daily vertical migration in the water column, modulating their position in response to light availability—a tactical maneuver to avoid predators. The determinants of these migration patterns are complex and influenced by factors such as age, size, food accessibility, oxygen levels, and environmental perturbations (Balcer *et al.*, 1984; Nowicki *et al.*, 2017; Storz & Paul, 1998).

Cyclomorphosis is an intriguing phenomenon observed in cladocerans, particularly among *Daphnia* species. This adaptive mechanism involves morphological transformations across generations due to asexual reproduction. Cyclomorphosis causes seasonal changes in physical traits, such as the development of "helmets" and spines, as a response to predation pressure and variations in water quality (Balcer *et al.*, 1984). These morphological adaptations enhance the survival of cladocerans in fluctuating environmental conditions.

### 1.2.3 Copepods

Copepods, belonging to the subclass Copepoda under the class Maxillopoda, are diverse crustaceans characterized by their jointed appendages and a cylindrical, ovate body structure (Damkaer, 2002). They are ubiquitously distributed, with more than ten thousand described species. There are ten orders of Copepoda, the most prominent being Calanoida, Cyclopoida, and Harpacticoida. Typically, copepods possess 5 to 6 pairs of thoracic appendages and a cephalothorax, which consists of 4 to 6 attached appendages. These creatures are versatile in their habitat preferences, with some species being planktonic, some benthic, and others even adopting a parasitic lifestyle.  Their presence is not limited to aquatic environments; they can also be found in terrestrial habitats (Thorp & Rogers, 2011).  Notably, copepods often prefer less perturbed zones within lakes, seeking stable conditions conducive to survival.

The life cycle of copepods is fascinating.  After the egg hatches, it produces a nauplius larva, which lacks a clearly defined abdomen despite having a distinct head and tail.  This larva undergoes several moulting phases until it eventually takes on an appearance resembling the adult form.  The nauplii were categorized as separate species until the metamorphic stages were identified in the late 1800s (Balcer *et al.*, 1984; Vuillemin, 2015).

Anatomically, copepods display several unique features. For instance, cyclopoids have shorter antennae than calanoids, with the first pair of antennae (antennules) being much longer than the second pair. The transparent cephalothorax of most copepods has a single, centrally located compound eye that is typically reddish.  Notably, some species of crustaceans that live underground may not have eyes. These crustaceans absorb oxygen directly through their body surface, eliminating the need for a heart and circulatory system (Barnes, 1980).

The copepods exhibit a variety of feeding habits.  Approximately three-tenths of copepod species are parasitic, obtaining their food directly from the host organisms (Kiørboe, 2011).  In contrast, non-parasitic copepods capture individual prey items, with some benthic variants feeding on organic detritus or bacteria. Reproduction in copepods begins with the male attaching to the female using his modified first pair of antennae and fifth leg. The male then produces a sperm packet, which he transfers to the female's genital opening. Reproductive strategies and timelines vary significantly across species and environmental conditions (Balcer *et al.*, 1984). For instance, *Diaptomus sicilis* is known for producing multiple egg sacs with many eggs, which indicates a strategy focused on high egg production.

In contrast, *Leptodiaptomus minutus* tends to produce fewer eggs, so more resources are invested in the development of each offspring. Environmental influences such as temperature, food availability, and predation pressure can influence these reproductive strategies (Balcer *et al.*, 1984). Understanding the reproductive behaviour of copepods is crucial for comprehending their population dynamics and their role in aquatic ecosystems.

### 1.2.4 Rotifers

Rotifers, belonging to the Phylum Rotifera, are unique microscopic organisms that serve a crucial function in freshwater ecosystems. Their corona, which resembles a crown, provides visual cues for identification. Their undifferentiated body structure, composed of a head, trunk, and foot, also serves as an identification feature. The corona, adorned with cilia in the head region, assists in movement through the water. Rotifers range from 40 µm to about 2mm and are characteristic of freshwater habitats.

The diversity within the Phylum Rotifera is vast, with approximately 2,030 species. They were then classified into three predominant groups: the marine Seisonida, with three species; the Monogononta, boasting 1,570 species; and the exclusively parthenogenic Bdelloidea, which has 461 species. Marine rotifers form a minority, constituting less than 5% of all known rotifer species (Barnes & Barnes, 2001). A fascinating adaptation of rotifers is their ability to produce diapausing or resting eggs, which are highly resilient to drought conditions.

Rotifers' diet includes algae, bacteria, particulate matter, and protozoans. They are known to ingest particles up to 10 µm in size. Their ecological roles are versatile. By feeding on algae, rotifers directly influence the community structure of the primary producers in aquatic systems. Moreover, like crustaceans, they are instrumental in nutrient recycling and enhancing light attenuation in their habitats (Barnes, 1980).

Studies on Bdelloid rotifer genomes have revealed intriguing findings. They possess two or more divergent copies of each gene, indicating a prolonged asexual evolutionary trajectory (Hespeels *et al.*, 2014; Welch *et al.*, 2004). From a reproductive standpoint, rotifers exhibit sexual dimorphism, with males consistently smaller than females. The magnitude of the size difference varies across species. Interestingly, the presence of males can vary throughout the year, particularly during the parthenogenic phase (Barnes, 1980). The genetic intricacies and reproductive behaviours of organisms like Bdelloid rotifers provide valuable insights into lake ecosystems, particularly in relation to environmental variability. As such, they play a critical role in studies of water quality in the lake.

### 1.3.1 Lake Water Quality

Aspects of chemical composition and physical attributes determine lake water quality, which is essential for its classification (Beamish & Harvey, 1972). Conductivity, which measures the ability of water to transmit electrical current and reflects the number of ions in solution, can indicate whether the water is brackish or fresh. Broadly, lakes are categorized based on their trophic status as follows (Mathur, 2015):

Oligotrophic Lakes: These lakes exhibit low productivity due to their limited nutrient content. The low nutrient levels result in minimal algal growth, leading to clear water, often deemed most suitable for drinking.

Mesotrophic Lakes: With moderate productivity and nutrient concentration, these lakes generally maintain clear water. However, an overproduction of planktonic algae can darken the water, occasionally resulting in algal blooms leading to fish mortality if Phosphate levels are relatively high compared to Nitrate levels, promoting the growth of (nitrogen-fixing) cyanobacteria.

Eutrophic Lakes: These lakes are high in nutrients and frequently experience algal blooms, reducing water transparency to less than 3 feet. Eutrophication, the enrichment of a body of water with nutrients, can be natural or caused by human activities. This nutrient enrichment leads to oxygen depletion, negatively affecting aquatic life (Bhateria & Jain, 2016; Dodds & Whiles, 2010).

Testing for various contaminants is imperative to ensure water quality, mainly when that water is destined for consumption or industrial use (Eliasz-Kowalska & Wojtal, 2020). Determining water quality involves both physical assessments, such as evaluating temperature, pH, turbidity, conductivity, transparency, and total dissolved solids (TDS), and chemical analyses that can determine the measures of oxygen consumption, such as biological oxygen demand (BOD), chemical oxygen demand (COD), and dissolved oxygen (DO), were analyzed along with other critical water quality constituents.

### 1.3.2 pH

There is an intricate link between lake water quality and pH level. According to Anacléto et al. (2018), the bedrock type, atmospheric deposition, and biological processes affect the pH level of freshwater bodies (Espeland & Wetzel, 2001). Acidic water can damage aquatic life. It can suppress primary productivity and, thus, disrupt the food chain (Adrian *et al.*, 2009; Beamish & Harvey, 1972).

Furthermore, pH fluctuations influence bedrock leaching into lake water, particularly in regions with carbonate formations. The dissolution of rocks like limestone through freshwater interaction can raise the water's pH, thereby increasing its alkalinity (Wetzel, 2001).

### 1.3.3 Water Temperature

Water temperature can significantly alter the ecosystem's chemical reactions and biotic growth rates in a lake system. Every species has a particular optimal temperature range for its growth (Sługocki & Czerniawski, 2018). Elevated temperatures decrease the solubility of gases like oxygen and carbon dioxide in water. Plants, algae, and cyanobacteria require dissolved carbon dioxide for photosynthesis, and reduced carbon dioxide levels can limit this process. Additionally, less dissolved oxygen is available for organisms that depend on it for cellular respiration. Higher temperatures can also increase metabolic rates, making organisms more vulnerable to diseases and toxins (Anacléto *et al.*, 2018; North *et al.*, 2014). Various factors such as weather anomalies, impoundment, warm water discharge, and groundwater inflow can induce temperature fluctuations in a lake system (Dodds & Whiles, 2010).

### 1.3.4 Biological Oxygen Demand (BOD)

BOD measures the oxygen consumption by microorganisms during the decomposition of organic matter in the water. Elevated BOD quickly reduces available oxygen, affecting higher trophic-level organisms. Effluents with high BOD can deteriorate water quality, potentially causing fish kills (Dai *et al.*, 2013).

### 1.3.5 Conductivity

Conductivity correlates with various water parameters, such as temperature, pH, and total dissolved solids (Eliasz-Kowalska & Wojtal, 2020). The geology of a particular area significantly influences water conductivity, with granite terrains typically exhibiting lower conductivity. In comparison, clay-rich regions tend to have higher conductivity due to having more dissolved materials. Human activities can increase water conductivity, particularly with excess fertilizers on agricultural land and in residential gardens, as well as from damage to sewage systems and the discharge of effluent (Mathur, 2015).

### 1.3.6 Total Dissolved Solids (TDS)

Total dissolved solids (TDS) in lakes represent the sum of all organic and inorganic substances dissolved in the water. Factors such as bedrock and soil composition, atmospheric deposition, and human activities—including agriculture, industry, and waste disposal—influence the TDS concentrations in water bodies (Bhateria & Jain, 2016; Welch *et al.*, 2004).

Although filtration can often capture suspended solids, dissolved solids can evade such procedures. Consequently, Total Dissolved Solids (TDS) are an essential indicator of water quality, impacting aquatic life and the ecosystem. High TDS levels can affect the osmoregulation of aquatic organisms, reduce water clarity, and alter the chemical balance of the ecosystem, leading to potential negative effects on biodiversity and overall aquatic health. TDS values in lakes and streams typically range between 50 to 250 mg/L. However, in calcium-rich or high-salinity areas, these values can surge to as much as 500 mg/L (Bhateria & Jain, 2016; Bridgewater *et al.*, 2017). Elevated levels of calcium and salinity increase water hardness, affecting the health and distribution of aquatic organisms. High salinity can also hinder the growth of freshwater species, disrupt osmoregulation, and reduce biodiversity in affected water bodies.

### 1.3.7 The Water Quality Index (WQI)

The Canadian Council of Ministers prepared the Water Quality Index (WQI; 2001) by combining three variance measures. This index ranges between 0 and 100, where 0 represents the poorest water quality, and 100 indicates the best possible quality. The WQI is invaluable for water resource management, water quality assessments, and watershed planning (Khan *et al.*, 2005). A higher WQI value signifies that the water is more suitable for its intended use, whether for drinking, recreation, or supporting aquatic life. In contrast, lower values indicate poor water quality, potentially posing risks to the aquatic environment and human health.

In the context of water quality assessment, zooplankton, as a vital component of the aquatic food web, plays a significant role in indicating the ecological health of a water body. Zooplankton's sensitivity to environmental changes and rapid response to various stressors make them ideal bioindicators. By monitoring zooplankton populations, researchers can gain insights into the overall health of aquatic ecosystems, more efficiently detecting issues such as pollution, nutrient imbalances, and habitat degradation.

### 1.4.1 Zooplankton as Indicators of Water Quality

Zooplankton, the microscopic organisms in aquatic ecosystems, are important indicators of the health and trophic state of the water body (Gannon & Stemberger, 1978). Their species composition, abundance, and behaviour provide valuable insights into environmental parameters such as nutrient conditions, pollution levels, and physio-chemical changes in the water column (Singh *et al.*, 2013; Thakur *et al.*, 2013). In oligotrophic (nutrient-poor) lakes, zooplankton communities typically consist of a diverse range of species but have low total biomass. In contrast, eutrophic (nutrient-rich) lakes tend to have fewer dominant species with high zooplankton biomass. These differences in community structures reflect changes in food availability, predation pressure, and habitat quality (Ferdous & Muktadir, 2009; Holland *et al.*, 2012).

Specific taxa from the order Cladocera and the suborders Calanoida and Cyclopoida within the order Copepoda are sensitive to pollutants and may decline or disappear in polluted waters, whereas other more resilient species may survive. Identifying the genus and species present can provide insights into water quality and pollution levels. An immediate decline in the population of sensitive species, paired with a rise in more resilient ones, can signal deteriorating water quality. Additionally, some species serve as bioindicators due to their high sensitivities or capacity to accumulate toxins. Assessing the periodic diversity and abundance of aquatic organisms provides a clearer understanding of the health of freshwater systems and can be a useful guide for developing appropriate management strategies (Gannon & Stemberger, 1978).

Cladocerans are a group of zooplankton used extensively as indicators of water quality. Shumate *et al.* (2002) emphasized the importance of the cladoceran *Chydorus* spp as an indicator of nutrient loading. Similarly, Jha and Barat (2003) highlighted *Miona* spp and *Daphnia* spp as useful indicators of pollution.

Because of their specific habitat preferences, copepods serve as essential markers for water quality. Gannon and Stemberger (1978) identified specific Copepoda species as indicators of oligotrophic conditions, while others indicated eutrophic conditions. An important observation by Thakur *et al.* (2013) showed that *Copepoda* density did not correlate with water temperature, suggesting their preference for stable environments.

With their rapid response to environmental changes, rotifers are invaluable as water quality indicators. Many species, such as *Brachionus angularis* and *Filinia longiseta*, indicate eutrophic conditions. A notable observation from Thakur *et al.* (2013) was the absence of certain rotifers in oligotrophic lakes, while their abundance in other lakes indicated eutrophic conditions. Zooplankton, in their various forms and as communities, give insight into the health and quality of aquatic ecosystems. Understanding the significance of their presence and behaviour can help guide effective water resource management and conservation strategies.

Zooplankton communities are affected by physical and chemical changes in the water body, such as temperature, pH, and changes in the level of dissolved oxygen. Some zooplankton are sensitive to pH variation and can, therefore, indicate abnormal pH levels (Smith, 2001).

In conclusion, zooplankton community composition and behaviour offer an indication for gauging the health of aquatic ecosystems. Their responses to environmental changes underscore their significance as bioindicators of water quality. At the same time, their community structure also provides valuable insights and certain groups within them are particularly important indicators of conditions. In addition to the water quality changes that can impact zooplankton communities in freshwater ecosystems, there are biological factors such as predation, competition, and the presence of invasive species. There are also physical factors such as UV incidence, water level fluctuation, sediment suspension, and lake water stratification that can influence a zooplankton community. The following section explores these factors and their influence on zooplankton communities in freshwater ecosystems.

## 1.5.1 Influence of Predation on Zooplankton Behaviour and Community Structure

Various biotic interactions, such as predation, food availability, disease, and competition, alongside environmental factors, intricately shape zooplankton behaviour and community structure. In ecosystems disturbed by human activities, these influences introduce additional layers of complexity. Overfishing, for instance, can cause a change in trophic structure, where eliminating top predators triggers an adverse surge in planktivorous fish, which in turn impacts zooplankton abundance (Almeda *et al.*, 2017; Xiong *et al.*, 2016). Their interaction with these predators can profoundly shape zooplankton communities. Lakes with abundant planktivorous fish are likely to suppress larger zooplankton species, leading to the prevalence of smaller zooplankton. They, in turn, can affect water clarity, as smaller zooplankton are less efficient at grazing on algae, potentially giving rise to algal blooms

(Thompson *et al.*, 2015). Li and Chen (2020) highlighted the significance of zooplankton as a water quality indicator in subtropical lakes. They noticed a strong influence of planktivorous fish on zooplankton, specifically rotifers, but found no significant correlation between zooplankton size distribution, richness, and trophic status. Clearly, then these interacting effects are complex.

### 1.6.1 The Impact of Invasive Species

Invasive species can lead to an extreme shift in zooplankton communities. Happel *et al.* (2015) studied the introduced species, *Bythotrephes longimanus,* from the order Cladocera in Lake Superior and Lake Michigan. They found that multiple factors, including fish predation, environmental conditions, and the presence of other non-native species, played crucial roles in influencing the abundance of zooplankton. Invasive species infiltrate and compete with native species for food and can also be voracious predators of native zooplankton. Such invasive species can alter zooplankton community structure and function, potentially affecting water quality and the broader aquatic food web (Happel *et al.*, 2015). Between 1995 and 1997, Hall *et al.* (2003) conducted a study to investigate changes in trophic conditions across habitats in Lake Ontario, focusing on the impact of invasive *Dreissena* mussels. The study revealed lower amounts of chlorophyll-a (Chl-a), reflecting the abundance of algae per unit of total phosphorus (TP) during the pre-Dreissena period in the nearshore areas. These findings contrasted with predictions made by models developed by researchers such as Azit Mazumder (1994) and Nicholls *et al.* (1999). These predictions suggest that a nutrient shunt may have occurred, with nutrients concentrated in the hypolimnion, resulting in lower phytoplankton production in the epilimnion. Consequently, zooplankton may have been forced to forage closer to the thermocline, where nutrient levels concentrate.

The overall implication of this shift is that it could decouple primary production from the epilimnion, affecting the food web by limiting food availability for surface-dwelling zooplankton and fish. Over time, this change could influence species distribution and productivity in the lake, potentially destabilizing nutrient cycling and ecosystem balance (Mazumder, 1994; Nicholls *et al.*, 1999).

### 1.7.1 Effects of Carbon, Phosphorus, and Nitrogen Limitations in Lake Systems

In aquatic ecology, the balance of nutrients, often described by the Redfield ratio, denotes the ratio of carbon (C), nitrogen (N), and phosphorous (P) atoms in phytoplankton. The canonical Redfield ratio is 106:16:1 for C:N:P (Islam *et al.*, 2019). This ratio is important because it represents the average requirements for these elements in phytoplankton, establishing a baseline to compare with nutrient availability in aquatic systems. Freshwater, temporal lakes, like Lake Couchiching, often exhibit variations in this ratio due to factors like watershed inputs, sediment interactions, and biological uptake (Gerten & Adrian, 2002). Deviations from the canonical Redfield ratio can indicate nutrient limitations, with a higher C:P ratio than the canonical value, potentially suggesting phosphorus limitation (Dodds & Whiles, 2010). Vanderploeg *et al.* (2012) examined the consequences of phosphorus reduction on zooplankton communities in the lake nutrient dynamics. Their findings indicated a shift in the zooplankton community composition due to changes in phosphorus levels. Cladoceran species, more reliant on phosphorus, declined, whereas copepods, less dependent on phosphorus, emerged as dominant.

The non-indigenous predatory species, *Bythotrephes longimanus*, intensified top-down control, influencing native zooplankton and predator dynamics. Studies such as those by Bourdeau *et al.* (2015) observed stability in Chl *a* and C ratios, suggesting there had been lower anthropogenic nitrogen contributions. However, the broader context of the Redfield ratio (C:N:P = 106:16:1) for phytoplankton (Falkowski, 2000) highlights the intricate interplay between bottom-up and top-down controls, particularly in relation to nutrient availability.

For the present study, understanding these nutrient dynamics and their deviations from the Redfield ratio will provide insights into the ecological balance of Lake Couchiching (Dodds & Whiles, 2010). Monitoring and analyzing these ratios could assist in predicting potential nutrient limitations, shaping management strategies, and assessing the impacts of anthropogenic activities on lake health.

## 1.8.1 Physical Parameters of Lakes

### 1.8.2 Effects of UV on the Diurnal Vertical Migration of Zooplankton

Many crustacean zooplankton species exhibit diel vertical migration (DVM), wherein their vertical distribution in the water column changes over the day (Fischer *et al.*, 2006). Species like *Daphnia catawba* are sensitive to Ultraviolet Radiation (UVR) and actively avoid it in laboratory and field experiments (Fischer *et al.*, 2006; Leech & Williamson, 2001; Rhode *et al.*, 2001). In the presence of UVR, zooplankton species such as *Daphnia catawba* and *Leptodiaptomus minutus* move deeper into the water column to avoid UVR (Leech *et al.*, 2005).

Fischer *et al.* (2006) conducted a mesocosm experiment in Lake Giles, Pennsylvania, to examine the impact of UVR on the DVM of crustacean zooplankton. They created mesocosms with varying UVR transmittance using different shading materials. The results indicated that *Daphnia catawba* moved to a deeper layer during the day in the presence of ambient UVR compared to the UVR-shielded treatment. Cooke *et al.* (2008) also examined how UVR and temperature affected DVM in Lake Giles. They found that *Daphnia catawba* and *Leptodiaptomus minutus* migrated to shallower depths in opaque UVR containers than in transparent ones. The distinction between the two species' responses was characterized by *Daphnia catawba's* negative phototactic response to UVR, resulting in deeper daytime migration. In contrast, *Leptodiaptomus minutus* primarily responded to UVR within the mixed layer and metalimnion, suggesting a less pronounced depth avoidance in comparison to *Daphnia*.

Furthermore, a study by Overholt *et al.* (2016) revealed that many freshwater calanoid copepods can detect and respond to UVR.  Depending on water transparency and pre-exposure conditions, their responses ranged from avoidance to attraction or no reaction.  Copepods react to UVR by orienting themselves based on the underwater light field and UVR spectral composition (Overholt *et al.*, 2016).

UV radiation significantly affects the vertical distribution and behaviour of zooplankton by serving as an environmental signal. Immediate behavioural responses to UV light are vital for zooplankton to avoid UV-induced harm. Additionally, zooplankton may migrate to deeper, darker waters to reduce visibility to predators, as brighter parts of the water column make them more susceptible to predation. These behaviours reflect how zooplankton react to multiple environmental factors, including visible light, temperature, and food availability (Kessler *et al.*, 2008). A deeper understanding of how zooplankton respond to UV radiation and how this sensitivity interacts with predator avoidance requires further research.

### 1.8.3 Water Retention time and thermocline effects on zooplankton distribution

The composition of zooplankton communities in different lake environments is crucial in assessing water quality and ecosystem health. Doubek *et al.* (2019) conducted a study to explore how water residence time (WRT), which refers to the time it takes water to flow through a lake or reservoir, influences zooplankton community structure. The study focused on natural lakes and reservoirs on a continental scale, analyzing data from the US Environmental Protection Agency's National Lakes Assessment and the US Army Corps of Engineer's National Inventory of Dams (Chow-Fraser *et al.*, 1998; Doubek *et al.*, 2019). The study uncovered distinct patterns in the communities of larger crustacean zooplankton. Specifically, natural lakes showed a greater abundance of these organisms than reservoirs. Among the various zooplankton species studied, calanoid copepods—predominant in these ecosystems—showed different population levels between the two types of water bodies. The research emphasized that Water Residence Time (WRT) – the duration of water staying in one place – was a key factor influencing differences in copepod abundance. In reservoirs, a shorter water residence time has a more noticeable impact on the density of calanoid copepods than in natural lakes. This observation underscores the importance of water flow rate in determining patterns of distribution and abundance of zooplankton species.

Water resource management can have significant implications for the composition and structure of zooplankton communities. Kitchen (1982) examined conflicts arising from water management practices in the Trent Severn Waterway (TSW) and their potential impact on zooplankton. Parks Canada manages the TSW, which has several lakes and water features, with the aim of balancing habitat preservation and recreational use. Improper water level management can lead to conflicts among stakeholders, including conservationists, recreational users, and local communities relying on the waterway for various needs. These conflicts can result in suboptimal water quality conditions, directly affecting zooplankton habitats and abundance.

Fluctuations in water levels are necessary for sustaining the ecological equilibrium of freshwater systems, as they impact habitat availability, nutrient cycling, and interactions among species. Kitchen (1982) and Bakker and Hilt (2016) provide a comprehensive understanding of how strategic water management supports both water quality and zooplankton diversity. They specifically examined how fluctuations help manage cyanobacterial blooms and indirectly influence zooplankton diversity. Their findings show that controlled water level changes can mitigate harmful algal blooms, creating a more favourable environment for diverse zooplankton communities. These preferred conditions highlight the importance of planned water management practices in maintaining water quality and biological diversity.

Understanding the intricacies of water management and its cascading effects on zooplankton communities is essential for developing effective conservation policies. By integrating the findings of Kitchen (1982) and Bakker and Hilt (2016), we can better appreciate the delicate balance required to sustain healthy aquatic ecosystems. Effective water management supports zooplankton diversity and enhances the ecological integrity of freshwater systems like the TSW.

The thermocline, a horizontal water boundary where the temperature shifts rapidly at a particular depth in the water column, can impact the zooplankton habitats in a lake. Cantin *et al.* (2011) explored three lake basins in Quebec with varying thermocline depths and found that thermocline depth significantly influenced zooplankton and phytoplankton distribution. In lakes with deeper thermoclines, zooplankton species, particularly those of different sizes, exhibit distinct distribution patterns. Larger species tended to reside deeper in the water column, while smaller species remained closer to the surface. This shift in the types and distribution of plankton suggests that thermocline depth plays a crucial role in structuring plankton communities, with deeper thermoclines favouring specific species adaptations. This shift emphasized the role of thermocline in determining the structure and distribution of aquatic communities. The depth of the thermocline affects the availability of nutrients, light, and oxygen, which in turn influences the habitat preferences and survival strategies of different zooplankton. As such, changes in thermocline depth can lead to cascading effects on the food web and overall ecosystem dynamics. With the ever-present and increasing threat of global climate change, the location and depth of the thermocline are likely to shift, which could have a profound impact on ecosystems, particularly in large freshwater systems like the Great Lakes. These changes will not only affect zooplankton distribution and behaviour but could also significantly alter water quality and overall ecosystem dynamics. A deeper examination of how these environmental shifts influence freshwater systems is essential.

## 1.9.1 Climate Change, Zooplankton, and Water Quality Parameters

The accelerating pace of global climate change has far-reaching implications for freshwater ecosystems. These changes can manifest in several ways, including alterations in water temperature, duration of ice cover, location of the thermocline, nutrient availability, and the presence and abundance of specific species (Adrian *et al.*, 2009). Gerten and Adrian (2002) noted that lakes in the northern hemisphere are experiencing warmer temperatures and reduced periods of ice cover. This warming can influence the metabolic rates of aquatic organisms, potentially affecting their growth, reproduction, and survival. The altered temperature and ice cover also influence phytoplankton, the primary producers in freshwater ecosystems. Warmer waters might favour certain species of phytoplankton over others, leading to shifts in community composition.

Furthermore, longer growing seasons due to reduced ice cover can lead to extended periods of phytoplankton blooms, which can have cascading effects on the food chain (Chen *et al.*, 2003). Changes in phytoplankton abundance and composition directly affect zooplankton as their food source. Shifts in phytoplankton communities can lead to mismatches between zooplankton hatching periods and the availability of their preferred food. This kind of shift can reduce zooplankton populations, further impacting food availability for predators like small fish (Bakker & Hilt, 2016; Gerten & Adrian, 2002). Warmer water holds less dissolved gas, including the CO2 needed by plants for photosynthesis and the oxygen required by zooplankton, fish, and other animals for respiration. Some zooplankton species might be more tolerant of these warmer conditions, while others may struggle, leading to shifts in community composition. As certain species become dominant and others decline or disappear, these changes can have broader implications for the food web and overall ecosystem health (Alofs *et al.*, 2014).

In conclusion, the intricate interactions between climate change and lake ecosystems require a comprehensive study. As Gerten and Adrian (2002) emphasized, understanding these interactions is important for predicting how lakes and their inhabitants will respond to the changing climate. Proactive measures based on such an understanding can help mitigate adverse effects and preserve the ecological balance of freshwater lakes.

### 1.9.2 Research Rationale

Due to its environmental complexity and significant human impacts, Lake Couchiching, Ontario, offers a unique setting for investigating zooplankton dynamics. This study aims to understand how water quality shapes the zooplankton community in this dynamic lake system. It experiences various human-induced stressors, including agricultural runoff and recreational activities, which can impact water quality.

The study will focus on the temporal and spatial distribution of zooplankton from Lake Couchiching. Zooplankton samples were obtained twice a month for the spring, summer, and fall of 2008 and 2013 from several locations in Lake Couchiching. The data analysis will capture seasonal (within a year) and long-term (over the five-year interval) variations in zooplankton distribution. The spatial analysis explores the zooplankton distribution in the lake (with sampling locations) and sheds light on the impacts of changes in water quality on zooplankton abundance and diversity.

The interaction between zooplankton and water quality is multifaceted, influenced by water chemistry, water residence time, water fluctuations, thermocline depth, climate change, and trophic interactions. Investigating these dynamics in Lake Couchiching provides valuable insights into the environment of these aquatic communities, thereby potentially supporting improved strategies for lake management and conservation (Bunnell *et al.*, 2014; Cantin *et al.*, 2011; Gerten & Adrian, 2002; Kitchen, 1982).

**Research Questions:**

What spatial and temporal differences can be identified in the water quality parameters in Lake Couchiching?

Does the zooplankton community structure exhibit consistent spatial and temporal patterns within the lake?

Which zooplankton taxa may be useful indicators of consistent changes in zooplankton community structure (ZCS) in Lake Couchiching, and how might changes in water quality parameters influence these taxa?

Are there identifiable associations between these zooplankton taxa and the overall ZCS that could guide long-term ecological monitoring of the lake?

Hypotheses tested:

**H1**: The spatial and temporal differences in water quality parameters within Lake Couchiching reflect the impacts of natural and anthropogenic factors affecting the lake ecosystem.

**H2**: The ZCS shows consistent temporal and spatial differences within this lake system.

**H3**: Specific zooplankton taxa change with water quality parameters, suggesting they can be used as reliable biological indicators of lake water quality.

**H4**: Specific water quality parameters and their interactions with other parameters consistently determine zooplankton community composition.

# 2.0 Chapter 2: General Methodology: Research Methodology and Experimental Design

## 2.1.1 Introduction

Lake Couchiching, located in south-central Ontario, Canada (44.6094° N latitude and 79.4198° W longitude), spans 45.4 square kilometres with a maximum depth of 12 meters. This freshwater body plays a critical ecological role, supporting diverse aquatic communities, including zooplankton. As a significant water source for the City of Orillia and surrounding communities, the lake's water quality and ecological health are vital to the region (Tourism Orillia, 2017).

The lake is part of the Trent-Severn Waterway, connecting it to a larger hydrological network via Lock 42 in Washago (Benkendorf *et al.,* 2023). Seasonal water level fluctuations, influenced by natural factors and waterway management by Parks Canada, affect the water quality and, consequently, the zooplankton distribution (Parks Canada Agency, 2022).

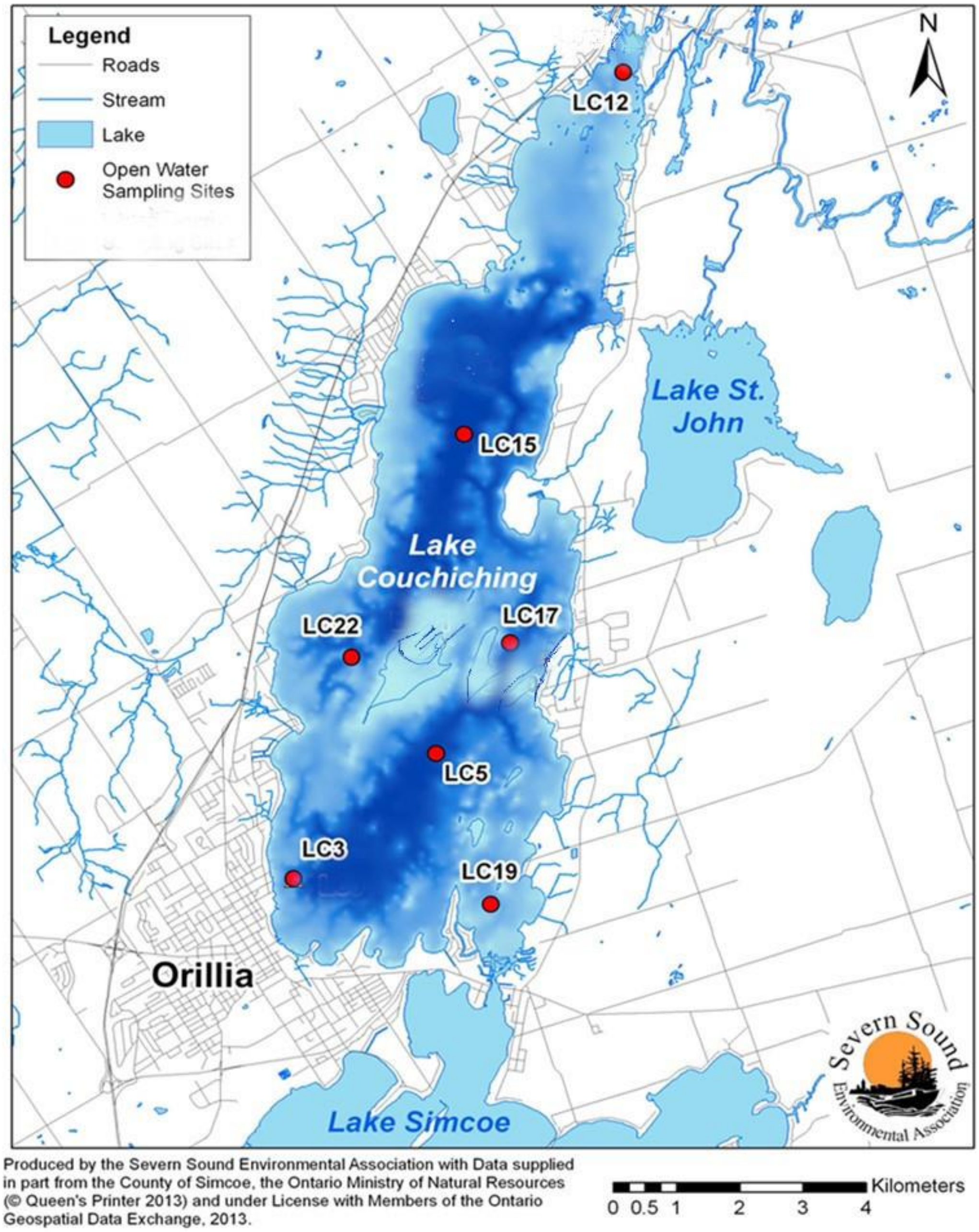
This study dissects the spatial and temporal variability of zooplankton community structure (ZCS) in relation to water quality parameters in Lake Couchiching. The findings offer valuable insights into the ecological processes of this dimictic lake system, supporting future management and conservation efforts.

### 2.1.2 Description of Study Area

Lake Couchiching spreads across the Townships of Ramara, Severn, and the City of Orillia. Lake Couchiching is approximately 15,000 meters long and 3,000 meters wide, with a mean depth that ranges from 6 meters to 12 meters (Kilgour *et al.,* 2000; Sherman, 2005). The lake is located north of Lake Simcoe and is part of the Trent-Severn Waterway (TSW). Water level fluctuations in the lake are influenced by natural factors and managed by Parks Canada to prevent flooding and ensure safe navigation (Parks Canada Agency, 2022).

The lake's watershed area is estimated to be approximately 64 square kilometres based on the data provided by the Severn Sound Environmental Association (SSEA). It includes several small streams that flow into the lake (Sherman, 2005). Water from Lake Simcoe flows into Lake Couchiching via Atherley Narrows, and water from Couchiching flows out to the Severn River through a northern channel. The immediate lake basin includes sand plains, drumlin clay plains, and limestone plains transitioning into the Precambrian Shield to the north (Chapman & Putnam, 1984).

Land use in the watershed comprises agricultural areas, urban centers (such as Orillia), and residential shorelines. There are permanent and seasonal residences, many of which rely on municipal services or private septic systems. Recreational watercraft and other activities occur regularly in the lake, especially during the summer, contributing to local disturbances (Kitchen, 1982).



Produced by the Severn Sound Environmental Association with Data supplied in part from the County of Simcoe, the Ontario Ministry of Natural Resources (© Queen's Printer 2013) and under License with Members of the Ontario Geospatial Data Exchange, 2013.

Figure 1. Map of sampling locations in Lake Couchiching. Seven Stations (LC3, LC5, LC12, LC15, LC17, LC19, and LC22) were sampled across various seasons in 2008 and 2013 to study the spatial distribution of the zooplankton community.

**Table 1.** Sampling locations, GPS coordinates, and sample counts for 2008 and 2013.

| Stn. | GPS Location | A08 | B08 | C08 | A13 | B13 | C13 |
|---|---|---|---|---|---|---|---|
| LC5 | E 628458.4525 N 4944112.853 | 1 | 4 | 0 | 2 | 3 | 1 |
| LC12 | E 631422.6826 N 4955470.431 | 3 | 7 | 2 | 4 | 6 | 2 |
| LC15 | E 628903.2677 N 4949431.039 | 1 | 4 | 0 | 2 | 3 | 1 |
| LC17 | E 629633.6045 N 4945957.536 | 3 | 7 | 2 | 4 | 6 | 2 |
| LC3 | E 626207.0302 N 4942031.258 | 3 | 7 | 2 | 4 | 6 | 2 |
| LC19 | E 629324.155 N 4941598.928 | 3 | 6 | 2 | 4 | 6 | 2 |
| LC22 | E 627126.4949 N 4945722.519 | 3 | 7 | 2 | 4 | 6 | 2 |

### 2.1.3 Depth of Sampling Locations

Sampling locations ranged from shallow sites (0.2 meters) to deeper zones (up to 12 meters). Stations LC12 and LC19 had a combined mean depth of 1.9 meters, with the shallowest site near the Severn River at the northern end of the lake. The deepest Stations included LC3, LC5, LC15, LC17, and LC22, with mean depths of 5.5 to 9.7 meters along a northward transect (Figure 1).

## 2.2.1 Sampling Methods

Sampling was conducted by the Severn Sound Environmental Association (SSEA), with zooplankton and water quality samples collected at seven Stations bi-weekly between May and October of 2008 and 2013. All zooplankton samples were collected using plankton nets, and water quality data were measured in situ. The SSEA handled both field sampling and transportation of samples to the lab for analysis.

### 2.2.2 Zooplankton:

In 2008, zooplankton were sampled using a Wisconsin-style plankton net with an 80 µm mesh and a 12 or 14-cm diameter mouth ring. In 2013, the equipment was updated to include a Tow Net with a 19 cm diameter mouth ring, also fitted with an 80 µm mesh. The net was lowered to a depth of approximately 1 meter above the lake substrate or twice the Secchi depth, whichever was less, and towed at a speed of 0.5 meters per second. After collection, the net and bucket were rinsed to ensure that all specimens were captured, and samples were preserved in 4% buffered formalin. All sampling was conducted between 7 AM and 3 PM to standardize the conditions under which samples were taken.

For shallow sites (such as LC5, where the depth was less than 1 meter), sampling methods were adapted to avoid disturbing the sediment. The net was carefully deployed just below the surface, and retrieval was conducted slowly to minimize sediment contamination. After collection, shallow samples were scrutinized during analysis to ensure that sediment did not interfere with zooplankton counts.

### 2.2.3 Calculation of Filtered Water Volume:

The volume of water filtered through the zooplankton net was calculated to standardize the sampling efforts and enable accurate comparisons of zooplankton density across various sampling Stations and periods. Thus, the volume of water filtered was calculated by using the following formula:

$$V=\pi r^2 h$$

*V* represents the volume of water filtered, $\pi$ is the mathematical constant, *r* is the radius of the net (half the net's mouth ring diameter), and *h* is the sample depth or tow-depth. The mouth ring diameter and sample depth differed between sampling events (see Table Q in Appendix B), necessitating adjustment to the radius for each calculation. Similarly, the sample/tow depth varied with sampling locations. The tow depth was recorded for each area and used in the volume calculation to ensure accuracy in determining the zooplankton density per $m^3$ water (Benoist *et al.*, 2019).

## 2.3.1 Lab Methods:

The zooplankton samples were analyzed for density, abundance, species richness, and diversity. All species were counted and identified to the species level and life stage using microscopic techniques and literature sources (An Image-Based Key to the Zooplankton of North America (n.d); Balcer *et al.*, 1984; Geraldes & Pasupuleti, 2016; Sherman, 2005; Witty, 2004; Zhang *et al.*, 2019). The "150/Sample Method," based on the methodology presented by Mack (2012), was followed to generate a statistically significant count of zooplankton. When dense, some samples were diluted to a specific volume using a graduated cylinder to facilitate the enumeration process. When dealing with dense zooplankton samples, the following tiered dilution approach was used to ensure clarity and accuracy in counting:

**50% dilution**: The initial approach involved halving the sample. It was achieved by taking 0.5 mL of the original sample and diluting it with 0.5 mL of deionized water (diluent), resulting in a dilution factor of 2.

**25% Dilution**: If halving was insufficient, the sample was diluted by quartering. It involved taking 0.25 mL of the original sample and adding 0.75 mL of diluent, yielding a dilution factor of 4.

**10% Dilution**: If quartering was insufficient, a ten-fold dilution was performed. Here, 0.1 mL of the original sample was combined with 0.9 mL of diluent, leading to a dilution factor of 10.

A maximum of 10 mL diluted sample was prepared during the dilution process. From this 10 mL diluted sample, 1 mL each was transferred into a Sedgewick-Rafter counter, sealed with a glass coverslip and observed under a microscope at 10x, 20x, and 40x as necessary (using the Nikon ECLIPSE Ts2R inverted microscope with Photometrics CoolSNAP DYNO CCD camera). This process continued until the total number of zooplankton reached a minimum of 150 counts across all taxa (excluding nauplii, given that they generally were seen in high abundance and all individuals were smaller than 200 µm). If 150 counts were achieved before using the whole 10 mL, the count was calibrated to represent the 10 mL volume. After dilution, up to three subsamples were required to achieve the target count of 150 or more zooplankton individuals (Mack *et al.*, 2012).

**Defective Samples:**

During both sampling periods, some samples were found to be defective or contaminated during transport, likely due to unintended air exposure, which compromised their integrity. Additionally, a few samples were lost or missing from their cohorts. These issues were identified during the enumeration process in the lab, and the affected samples were excluded from further analysis. No attempts were made to retake the missing samples, and this has been accounted for in the overall data analysis.:

**(1) Abundance**

The total number of zooplankton counted per sample

**(2) Species richness**

The number of specific species present in the sample

**(3) Species density**

Density (#ind/$m^3$) = Number of zooplankton /volume of water filtered

**(4) Species Diversity Index (SDI) - Shannon-Wiener Diversity Index**

*Formula:* $H=-\sum(Pi \times \ln Pi)$

Where:

- $H$ is the Shannon diversity index
- $Pi$ is the number of species $i$ relative to the total number of species
- The summation (Σ) is taken over all species, from the first to the last

### 2.3.2 Water parameters:

The parameters monitored at each sampling Station (Stations) included water quality parameters (WQPs) such as sample depth (Depth), Conductivity, pH, Secchi depth (Secchi), chlorophyll *a* (Chl *a*), and nutrients including Total Phosphorus (TP) and Total Kjeldahl Nitrogen (TKN). The vertical profiles of conductivity and pH at 1-meter intervals were recorded from the surface to 1 meter above the lake substrate at each of the sampling sites in both years using a calibrated YSI Multi-Parameter Water Quality Monitor (600QS-0-0). Water samples for Chl *a* and nutrients were collected using a van Dorn water sampler, targeting the euphotic zone, which represents the sunlit portion of the water column where photosynthesis occurs. Integrated depth composites were taken by combining samples from various depths within this zone to provide an overall representation of water quality and nutrient levels.

Nutrient analyses for TP and TKN were conducted at the Ontario Ministry of Environment's DESC lab using approved analytical techniques (MOECP, 2021). Chl *a* concentration was assessed at the MOE Rexdale lab using standard ministry-approved analytical methods. These measurements provided key insights into the lake's nutrient dynamics and their potential influence on zooplankton communities.

### 2.4.1 Data Analysis Overview

Various statistical methods were used to analyze the relationships between water quality parameters and the spatial and temporal dynamics of the zooplankton community. Principal Component Analysis (PCA) was employed to simplify the water quality data by identifying dominant patterns of variability. Generalized Linear Models (GLMs) were used to pinpoint significant factors affecting zooplankton density and diversity across different stations and seasons. Permutational Multivariate Analysis of Variance (PERMANOVA) was accomplished to assess the variability in zooplankton community composition and to determine the significance of changes observed across the study area. Visual tools such as PCA biplots and diversity trend graphs were also used to aid in interpreting the findings. These methods were chosen to clarify the key factors influencing the zooplankton community structure in Lake Couchiching. Statistical analyses were performed through the use of R version 4.2.2 (R Core Team, 2023), with further details, including the PERMANOVA analysis, available in Appendix D.

# 3.0 Chapter 3: Results of Water Quality Analysis and Zooplankton Dynamics

## 3.1.1 Introduction

A holistic interpretation of lake ecosystem dynamics is imperative to maintaining lake health and predicting disturbances and lake processes, which is a basis for strategic lake management. In this context, studies on Lake Couchiching's water quality parameters (WQPs) and their characteristics are vital for understanding the lake's ecological health and informing effective management strategies (Bunnell *et al.*, 2021). Human-induced changes, such as agricultural runoff, urbanization, and recreational activities, combined with natural disturbances like storms and seasonal weather patterns, affect the WQPs of the lake and, therefore, its biological components such as phytoplankton, zooplankton, and fish communities. The shape of the lake and its flow pattern further complicate the impacts mentioned above on its biological components (Gentine *et al.*, 2022).

Zooplankton, as sensitive bioindicators, play a key role in reflecting the ecological state of water bodies. Their responses to fluctuations in water temperature, nutrients, and water clarity provide valuable insights into changes in WQPs. Such environmental shifts can significantly impact zooplankton diversity, growth, and reproduction (Kovalenko *et al.*, 2023).

This study addresses the gap in understanding how natural and anthropogenic factors affect water quality and, subsequently, their impact on zooplankton communities in Lake Couchiching, a unique and complex ecosystem. Although the interplay of these factors is understood in general for freshwater bodies, their specific implications within the context of Lake Couchiching remain underexplored. Therefore, this study investigated the effects of WQPs and their spatial and temporal variations in Lake Couchiching and how these factors impacted the zooplankton communities in the lake. These study findings will offer valuable insights specific to Lake Couchiching and may also enhance our understanding of other similar lakes.

The hypothesis, inspired by Barbiero *et al.* (2018, 2019), is that significant variations in WQPs across locations and times within Lake Couchiching will have a marked impact on zooplankton populations.

## 3.2.1 Methods

The General Methodology section details the collection of water samples during different seasons, standardized laboratory analyses for the zooplankton community, and statistical analyses using both parametric and non-parametric tests.

## 3.3.1 Results

### 3.3.2 Temporal and Spatial Variances of Water Quality Parameters in Lake Couchiching - Principal Component Analysis

The WQP data from 2008 and 2013 was analyzed using Principal Component Analysis (PCA). The PCA identified the first principal component (PC1), segmented as physical-environmental variables, accounting for 29.69% of the variance. Conversely, the second principal component (PC2), representing chemical-environmental variables, contributed 25.94%. Together, these two principal components explained 55.62% of the total variance over the study period.

### 3.3.3 Principal Component Biplot Analysis

In this section, we analyze the seasonal variation in WQPs from Lake Couchiching for the years 2008 and 2013. We conducted a PCA to identify patterns and differences in WQPs across seasons (Seasons). The PCA biplot (Figures 2, 3. 4, and 5) provides a visual representation of these patterns.

Each point in the biplot represents a unique observation of WQPs measured during spring (Spring), summer (Summer), and Autumn (Fall). The first two principal components, PC1 (Dim1) and PC2 (Dim2) captured a significant portion of the variation in the data. Ellipses around clusters of points for each Season represent the 95% confidence intervals, highlighting the distribution and variability of the data observed in each Season.

The PCA biplot revealed significant relationships between WQP variables and the PCs. Secchi depth (Secchi) and depth (Depth) of Stations align more with Dim1, while pH and conductivity (Conductivity) are strongly associated with Dim2.

Notably, there was a negative correlation between chlorophyll-a (Chl *a*) and Secchi for PC1. Moreover, Chl *a*, Total Kjeldahl Nitrogen (TKN), and Total Phosphorous (TP) were negatively correlated with Conductivity and pH for PC2, emphasizing their inverse relationship with this component. These variables showed a higher correlation with the second principal component, emphasizing the distinct influences on the principal components identified in the PCA (Figure 2).

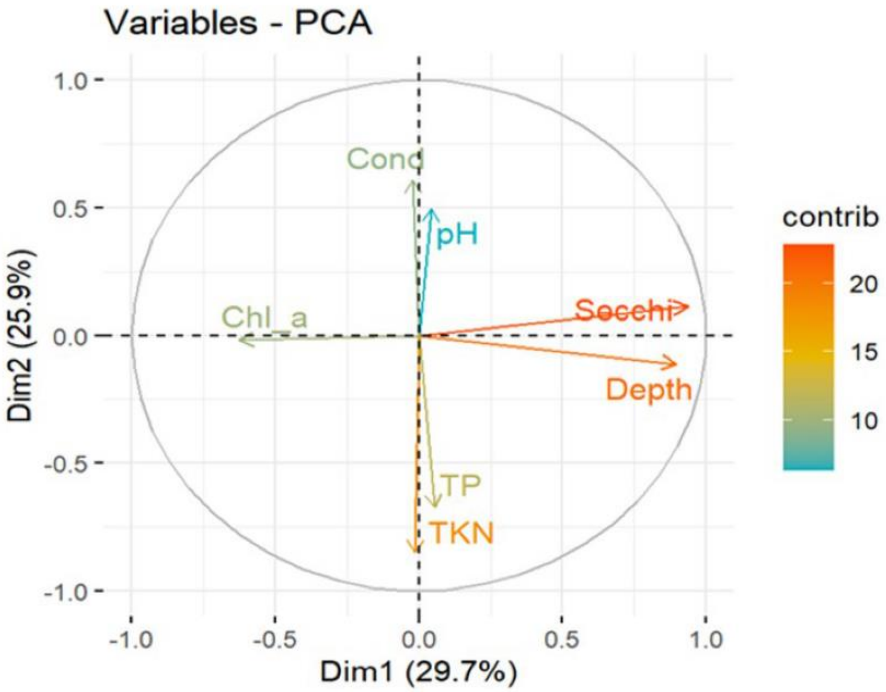


**Figure 2: WQP PCA Biplot—**The PCA biplot displays the contributions of various water quality parameters across the first two principal components (PC1(Dim1) and PC2(Dim2)), with a colour gradient representing the contribution of each parameter to the component. Warmer colours indicate higher contributions, highlighting the most influential parameters in the dataset. This method of visualization is supported by the approach outlined by Quinn and Keough (2002), emphasizing the clarity in representing influential variables in multivariate datasets.

### 3.3.4 Principal Component Analysis of Individual Water Quality Parameters Over Seasons and Years (the whole study period) (Cos2 values)

Depth and Secchi displayed high cos2 values on PC1 (0.8029, 0.8768), suggesting they are well-represented and are critical factors in the physical characterization of aquatic habitats. The TKN also showed a high cos2 value on PC2 (0.7221), indicating its strong influence on the physical variables in this system (Figure 3).

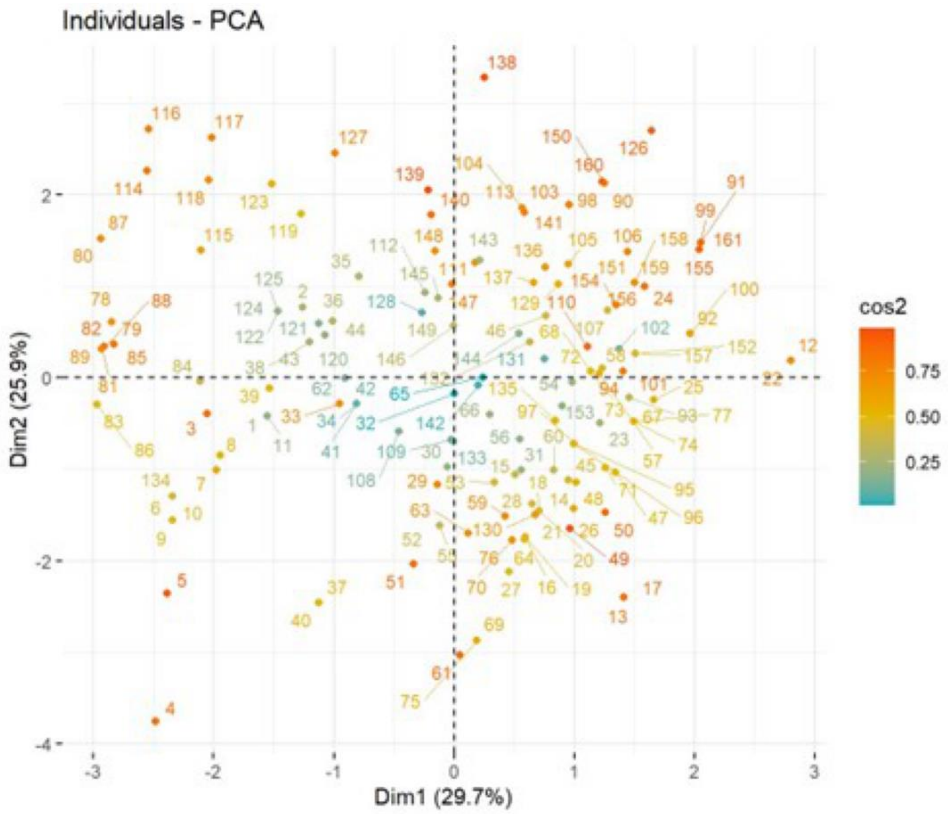


**Figure 3: Principal Component Analysis of Water Quality Parameters in Lake Couchiching—** The scatter plot presents a PCA based on WQPs collected from Lake Couchiching. Each dot represents an individual observation, uniquely identified by numbers, consisting of a complete set of WQPs measured at a specific time and place. The axes Dim1 (29.7% variance) and Dim2 (25.9% variance) illustrate the primary directions of data variability, highlighting significant patterns in water quality due to changing environmental conditions. The blue-to-red gradient indicates the cos2 value for each observation, with red showing a high degree of representation. Dashed lines denote the central tendency of the data along each principal component. This analysis is fundamental for identifying overall trends and relationships in the lake's WQPs.

### 3.3.5 Principal Component Analysis of Water Quality Parameter Categorized by Year and Season in Lake Couchiching

This analysis revealed patterns of individual WQPs based on Year and Season variations, with ellipses indicating temporal shifts and seasonal differences. The PCA categorized by Year and Season showed distinct clusters, suggesting potential temporal shifts in individual WQPs between 2008 and 2013 and across Seasons (Figure 4).

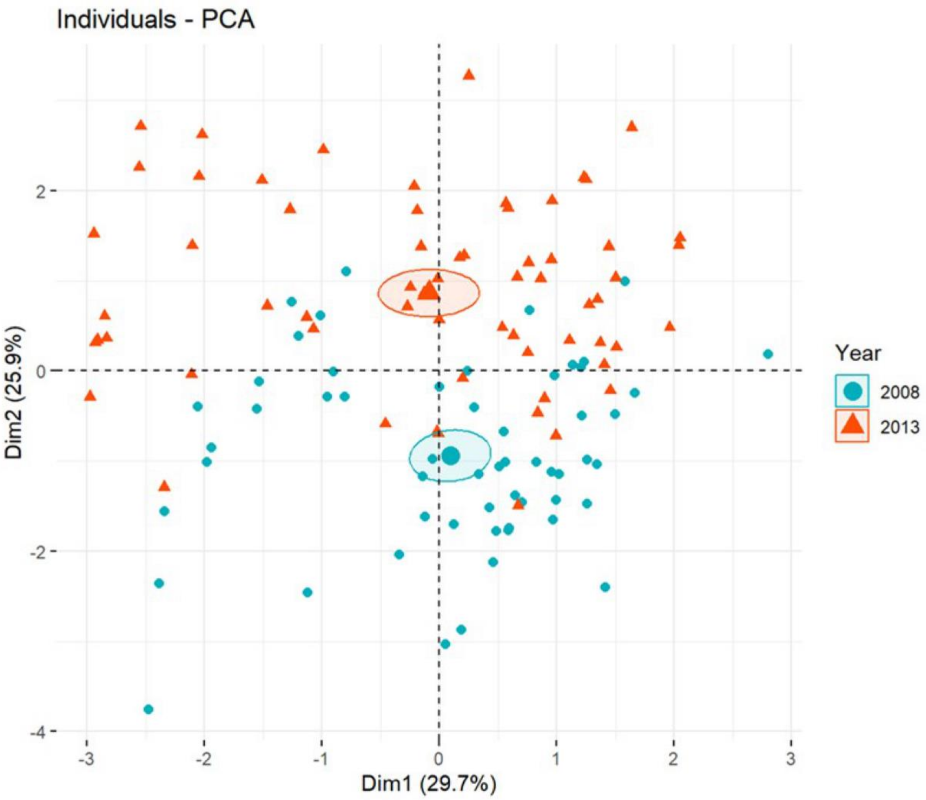


**Figure 4: PCA of Individual WQPs by Year—**This biplot represents the PCA of individual WQPs in Lake Couchiching, categorized by the Year of data collection. Each dot corresponds to a unique set of WQPs measured at a specific time, with the first two principal components (Dim1 and Dim2) captured on the axes, illustrating 29.7% and 25.9% of the variance, respectively. The colour-coded dots reflect the Year each measurement was taken, aiding in the differentiation of temporal patterns. Ellipses around clusters of points indicate the 95% confidence intervals.

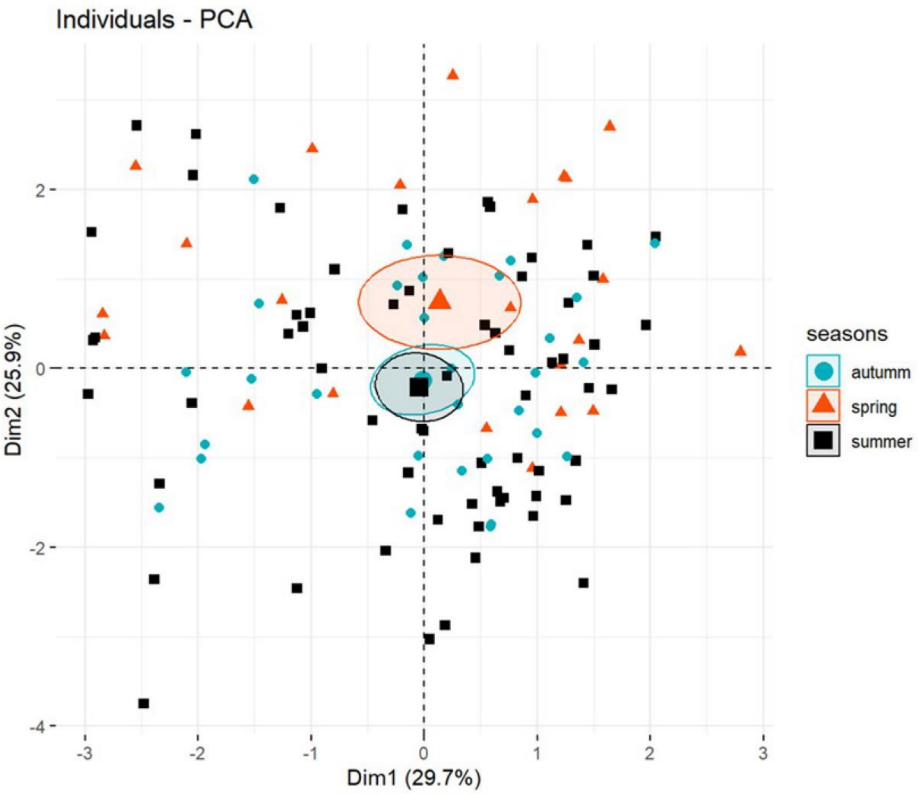


**Figure 5: PCA of Individual WQPs by Seasons**—This biplot illustrates the PCA of individual WQPs from Lake Couchiching, categorized by Season, for 2008 and 2013. Each point represents a unique observation of WQPs measured during spring, summer, and fall. Ellipses around clusters of points for each Season represent the 95% confidence intervals, emphasizing the distribution and variability of the data observed across Seasons.

### 3.3.6 Principal Component Analysis of Individual Water Quality Parameters Categorized by Sampling Stations (spatial) in Lake Couchiching

To assess the distribution and variability of WQPs in Lake Couchiching, we conducted a PCA using data combined from all Seasons for each Station. The resulting spatial biplot (Figure 6) provides insights into the pattern of WQPs across Stations.

Each data point in the biplot represents an individual WQP measurement, highlighting the combined data from the two years under study. Clusters within the biplot indicate spatial similarities or differences among Stations, revealing spatial trends in the WQP dataset. This analysis is crucial for understanding how water quality differs among locations within the lake, which is essential for targeted environmental management and ecological assessments.

The spatial biplot (Figure 5) reveals distinct clusters of Stations based on their WQP measurements. Certain Stations may cluster together, indicating similar water quality characteristics, while others are more dispersed, reflecting different environmental influences such as high inputs from runoff, sewage, or clean water flushes. These spatial differences can inform management strategies by identifying areas with specific water quality issues that require attention.

The biplot in Figure 6 represents a PCA of WQPs collected from sampling Stations across Lake Couchiching. The plot illustrates spatial variability in the measured parameters as overlapping and distinct clusters. Specifically, Stations LC12 and LC19 were quite distant from the other sites, suggesting unique water quality characteristics at these locations (Figure 6). In contrast, the clusters formed by data from Stations LC3, LC22, and LC17, represented by overlapping ellipses that indicate 95% confidence limits, show no significant differences from those formed by LC5 and LC15, indicating similar water quality profiles. Notably, the clusters for LC3, LC22, and LC17 are distinct from those of LC12 and LC19, emphasizing the spatial heterogeneity in water quality across the lake. This analysis provided insight into the distribution and variability of water quality, which is crucial for environmental management and conservation efforts.

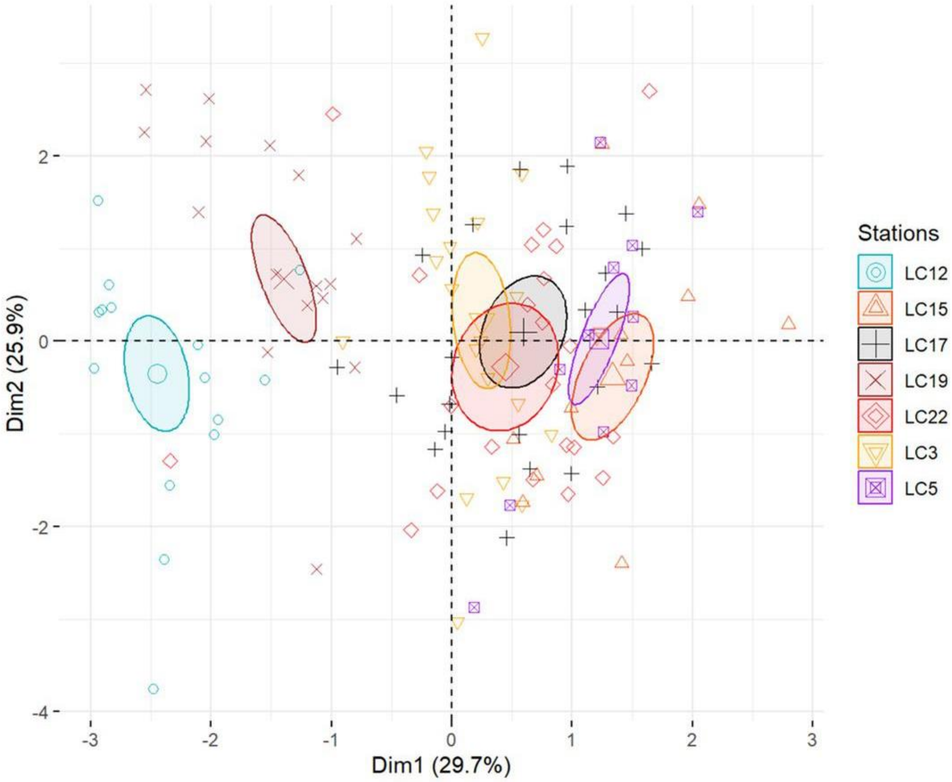


**Figure 6: Spatial Biplot of Combined Data (pooled for both Years) Analysis Using Individual Water Quality Parameters in Lake Couchiching—** This spatial biplot illustrates the WQPs for Stations across the first two principal components. Each data point represents the average of WQP measurements for the 2008 and 2013 Seasons at each Station. These averages were taken across all three Seasons (spring, summer, and fall) to represent overall trends for each Year. Clusters within the biplot indicate spatial similarities or differences, highlighting the spatial trends in the WQP dataset. This visualization aids in understanding the spatial distribution and variability of water quality, which is essential for targeted environmental management and ecological assessments in Lake Couchiching.

### 3.3.7 Spatial-Temporal Differentiation of Water Quality Profiles in Lake Couchiching Using Cluster Analysis

Following the PCA, K-means cluster analysis was used to segment further the WQPs in Lake Couchiching.  The optimum number of clusters, determined utilizing the gap statistic, was three. These clusters, containing 75, 36, and 50 observations, exhibited distinct ecological profiles based on the WQPs.

### 3.3.8 Cluster Characteristics

**Cluster 1**: Featured an average Depth of 6.39 meters, Secchi depth of 4.63 meters, pH of 8.15, Conductivity of 366.45 µS/cm, Chl *a* of 0.79 µg/L, TP of 9.24 µg/L, and TKN of 414.36 µg/L.

**Clusters 2 and 3**: Demonstrated unique mean values for these parameters, indicative of varying ecological conditions.

The within-cluster sum of squares featured a high degree of compactness within each cluster, with values of 21073.78 for Cluster 1, 19003.84 for Cluster 2, and 17852.09 for Cluster 3, suggesting internal Cluster consistency. Figure 7 illustrates that these clusters account for 78.5% of the total variance, reinforcing the robustness of the clustering.

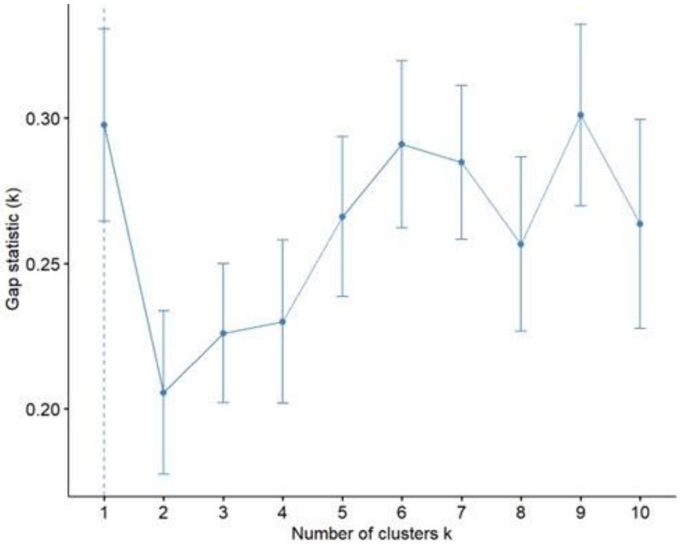


**Figure 7**: **Gap Statistic Plot—**This graph indicates the optimal number of clusters for the dataset established on the Gap statistic values, with error bars representing the estimate's uncertainty. The peak in the Gap statistic values suggests the most appropriate number of clusters, aiding in the identification of natural groupings within the dataset.

### 3.3.9 Cluster Plot Analysis

The gap statistic, which evaluates the dispersion of data points within our dataset compared to a null reference distribution, guided the decision to define three clusters. The resulting cluster plot, shown in Figure 8, depicts these clusters in a three-dimensional PCA space, with each cluster colour-coded.

1. The blue cluster represents an ecological zone with specific WQPs and environmental conditions. It primarily occupies the negative side of Dim1 and extends across Dim2. This zone corresponds to a particular ecological habitat or microenvironment within the lake.
2. The yellow cluster occupies a different ecological region on the positive side of both Dim1 and Dim2. This region exhibits its unique ecological characteristics and may correspond to another distinct habitat within the lake.
3. The green cluster, positioned on the positive side of Dim1, overlaps with the other clusters, suggesting a transitional ecological area with a blend of features from neighbouring zones. This overlapped area may indicate an ecotone, where ecological boundaries meet and interact.

These clusters provided valuable ecological insights into the distinct niches and transitional zones within Lake Couchiching.

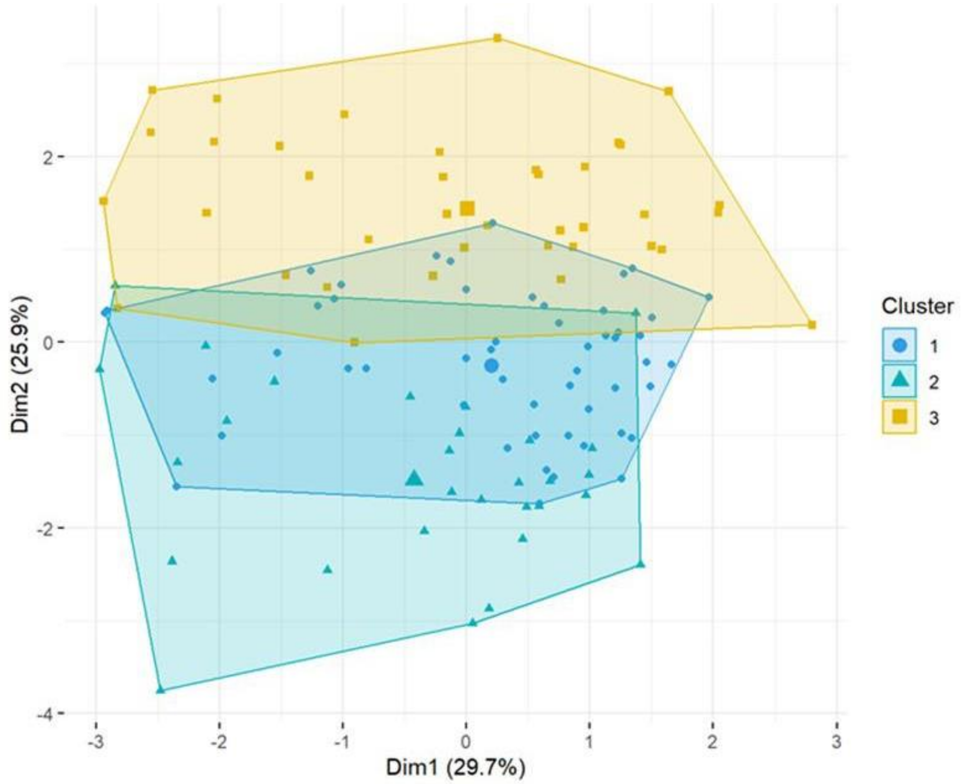


**Figure 8: Cluster Plot—**This is a three-dimensional cluster plot from the PCA showing the spatial distribution and convex hulls of three identified clusters based on the first two principal components. Each point represents an observation of the water quality parameters, and the convex hulls highlight the boundaries of each cluster.

## 3.4.1 Analyzing the Effects of an Individual Water Parameter in Lake Couchiching

### 3.4.2 General Linear Model Analysis of Depth

The General Linear Model (GLM) investigated the temporal and spatial variations in Depth, a critical WQP, across Stations, Seasons, and Years. The model demonstrated an excellent fit and substantial explanatory power ($F_{(29,\ 111)} = 130.1$, $p < 0.001$), with an $R^2$ of 0.9573 and an Adjusted $R^2$ of 0.9486, indicating that these factors explained a considerable proportion of the variance in Depth.

The analysis revealed that Depth variability has changed over the years, suggesting inconsistent temporal patterns. Stations LC17 and LC22 showed notable effects of Depth on WQPs (LC17: $\beta$ = -359.9, $p$ = 0.016973; LC22: $\beta$ = 319.0, $p$ = 0.033963. Seasonal influences were also significant, with Depth fluctuating during Spring ($\beta = 348.72$, $p = 0.005$) and Summer ($\beta = 313.54$, $p = 0.0008$), indicating actual changes in water levels at the sites. These fluctuations may be influenced by natural factors like inflow, outflow, and weather conditions, as well as human interventions such as flood mitigation and water flow control measures managed by Parks Canada. These combined factors underscore the dynamic nature of lake Depth across Seasons.

The interaction effects, such as those between Year and specific Stations (LC17 and LC22) and Year and Seasons (Spring and Summer), added complexity to the Depth dynamics.   The interactions between LC15 with Spring and LC17 with Summer were also significant (Year × LC17: $\beta = 0.18153$, $p = 0.015$; Year × LC22: $\beta = -0.15623$, $p = 0.037$; Year × Spring: $\beta = -0.17333$, $p = 0.005$; Year × Summer: $\beta = -0.15592$, $p = 0.0008$; LC15 × Spring: $\beta = 1.18808$, $p < 0.038$; LC17 × Summer: $\beta = 1.00795$, $p = 0.019$). These results highlighted the complex interplay of temporal and spatial factors influencing Depth and impacting water quality at distinct locations and times.

**Type II ANOVA Analysis**

The Type II ANOVA analysis further dissected the role of Year, Station, and Season on Depth variation.  We found that all predictors significantly influenced Depth except the Stations and Seasons interaction (Year: $F_{(1, 111)} = 14.8355$, $p < 0.001$; Station: $F_{(6, 111)} = 611.2615$, $p < 0.001$; Seasons: $F_{(2, 111)} = 19.0733$, $p < 0.001$; Year x Station: $F_{(6, 111)} = 4.7274$, $p = 0.0002$; Year x Seasons: $F_{(2, 111)} = 6.7516$, $p = 0.0015943$), with noteworthy interaction effects between Year and Station.  The box plots for Depth Variations (Figures 9 and 10) show the variability in the Depth at which samples were taken across different Stations and over time. These Depth profiles highlight the unique sampling

Depths chosen at each Station rather than the overall water Depth at the site, ensuring a consistent methodology for assessing WQPs at various Depths.

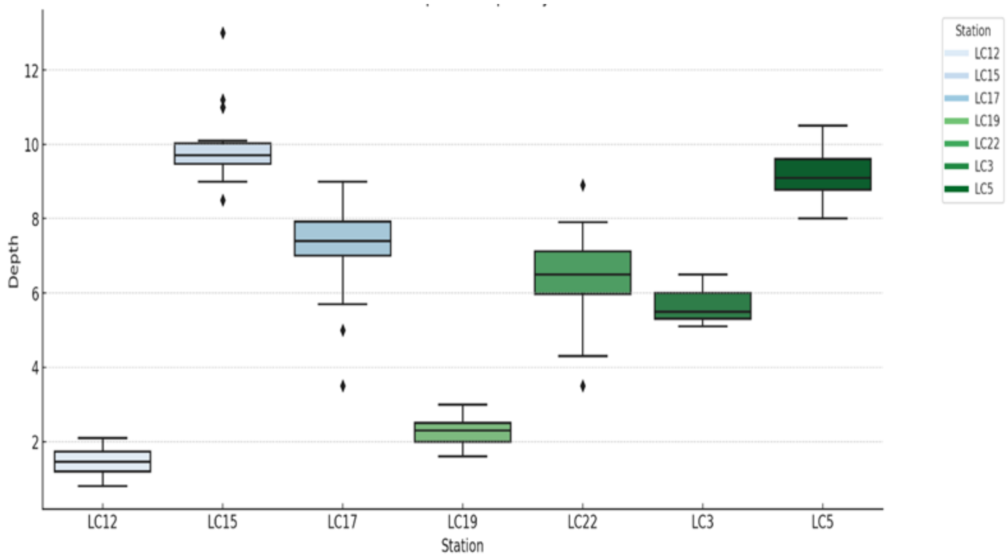


**Figure 9: Box Plots of Depth Variations—**This box plot visually displays the variations in Depth measurements across the seven Stations. The tiny purple diamonds represent outliers that may indicate fluctuating water Depth or data anomalies. This plot provides insights into the differences in water transparency in different parts of the lake.

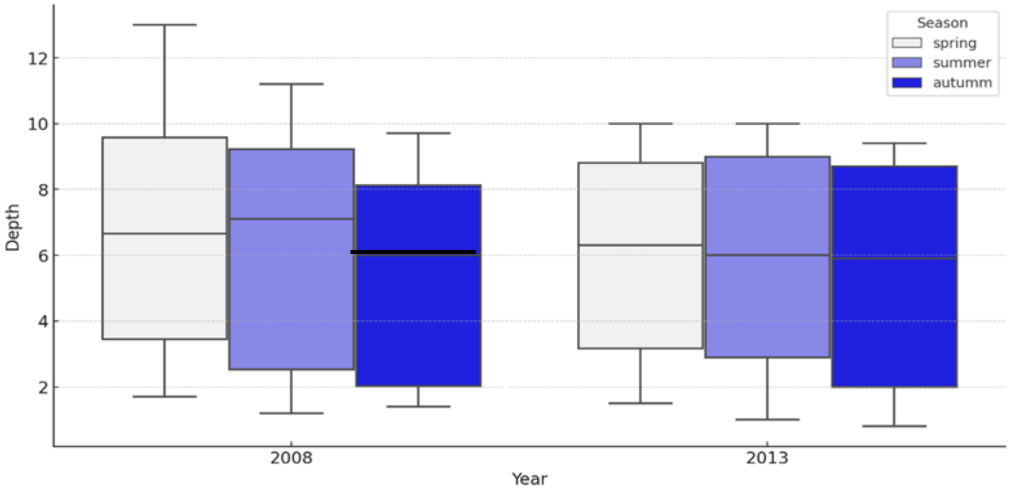


**Figure 10: Depth Variations by Year and Seasons—** These box plots illustrate the variations in Depth measurements (in metres) across the three Seasons (spring, summer, and fall) and between the Years 2008 and 2013. The y-axis includes Depth in metres (m), referring to the actual Depth at which the water samples were taken. The legend further clarifies that "Depth" refers to the sampling Depth, not the total water column Depth at each Station.

### 3.4.3 Depth Correlation with Other Water Quality Parameters

A scatterplot matrix offers a comprehensive view of the relationships between water Depth and various WQPs, including Secchi, pH, Chl *a*, and Conductivity (Figure 11). These scatterplots demonstrate a robust positive correlation between water Depth and Secchi. At the same time, they also show moderate to negligible correlations with parameters like pH and Chl *a,* providing a better understanding of how Depth interacts with various aspects of water quality.

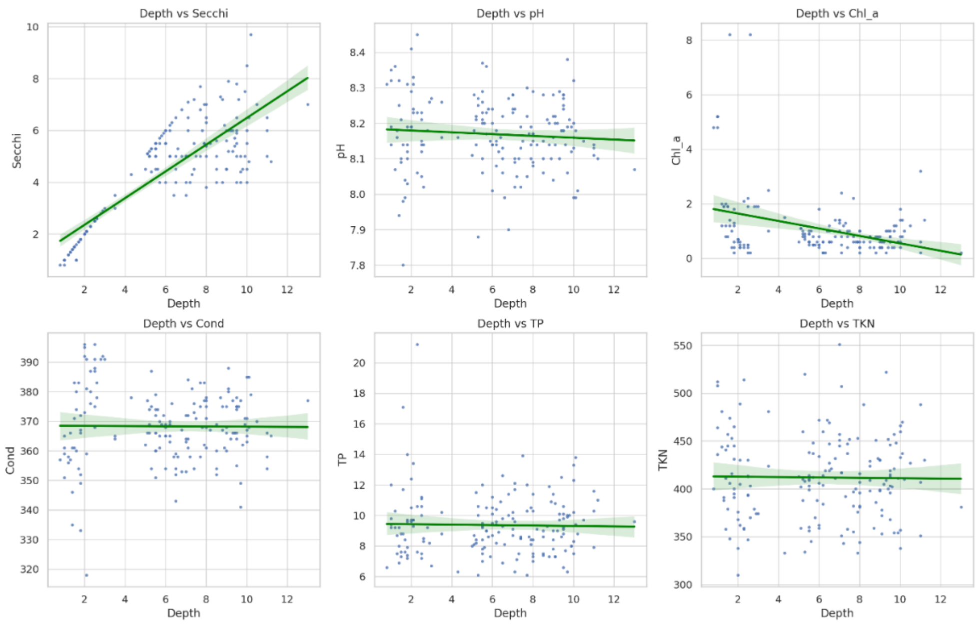


**Figure 11: Scatterplot Matrix of Depth Correlations with WQPs**—The scatterplot matrix depicts the intricate relationships between water Depth and other WQPs, such as Secchi, pH, and Chl *a*. The moderate positive correlation between Depth and Secchi ($R^2 = 0.6864$, $p < 0.001$) underscores Depth's significant impact on water clarity. The various correlations with other parameters, like Chl *a*, emphasize the complexity of aquatic ecosystem dynamics, while the other parameters showed no significant correlation.

## 3.5.1 General Linear Model Analysis of Secchi Depth

The GLM analysis revealed a significant model fit ($F_{(29, 111)} = 24.73$, $p < 0.001$) for Secchi, accounting for a considerable variance ($R^2 = 0.866$, Adjusted $R^2 = 0.831$). Specific Stations, such as LC15 and LC5, significantly influenced Secchi, indicating the spatial variability in water clarity.

### Type II ANOVA Analysis

While examining the influence of various predictors on Secchi in Lake Couchiching, the Type II ANOVA analysis stressed that the Year alone was not a significant predictor of Secchi variation. However, the analysis revealed substantial differences in Secchi values among Stations ($F_{(6, 111)} = 110.1055$, $p < 0.001$), showing significant spatial differences in water clarity within the lake.

The effects of Seasons on Secchi were significant ($F_{(2, 111)} = 6.6455$, $p = 0.001879$). Interaction effects between Year and Stations ($F_{(6, 111)} = 1.8523$, $p = 0.095406$) and between Year and Seasons ($F_{(2, 111)} = 3.4502$, $p = 0.035181$) on Secchi were observed, indicating that the impact of the Year on Secchi might vary depending on the specific Station and Season.

Additionally, the interaction between Stations and Seasons showed significance approaching the alpha threshold (F(12, 111) = 1.7437, p = 0.066857), implying that seasonal changes in Secchi depth might differ across Stations.

### 3.5.2 Box Plots for Secchi Variations by Stations, Seasons, and Year

The box plots show the variations in Secchi across Stations and Years. These plots demonstrated the spatial and temporal dynamics of lake water clarity. The variations in water clarity across Stations and Years in Lake Couchiching were analyzed using box plots (Figures 12 and 13). These plots visually represent the distribution of Secchi measurements, highlighting the spatial and temporal dynamics of lake water clarity. Secchi depth is a key indicator of water clarity, influenced by factors such as algal growth, sedimentation, and WQPs.

The box plots revealed significant differences in Secchi across Stations and Years. For instance, certain Stations exhibited consistently lower Secchi values, indicating poorer water clarity, while others showed higher Secchi, reflecting clearer water. Temporal trends were also evident, with 2008 and 2013 displaying notable changes in water clarity, likely due to anthropogenic and environmental influences or management practices.

The average Secchi during 2008 was 4.4018 meters, with a maximum of 6.7 meters at Station LC22 in October 2008 and a minimum of 1.6 meters at LC12 in July 2008. In 2013, the average increased to 4.5726 meters, with a maximum of 8.5 meters at LC15 in May and a minimum of 0.8 meters at Station LC12 in September, demonstrating significant annual variations.

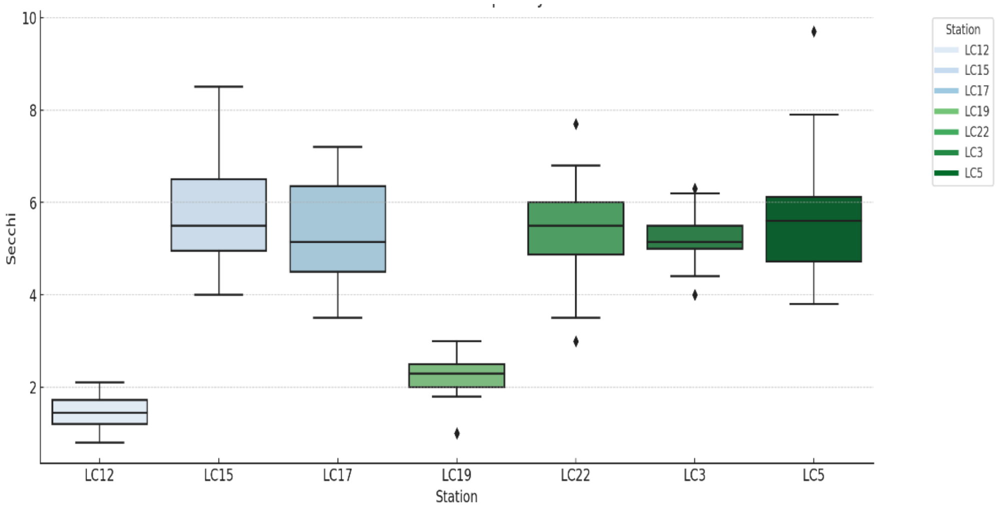


**Figure 12: The box plot of Secchi Depth by Sampling Stations**— The box plots illustrate variations in water clarity among locations. Stations like LC15 and LC17 exhibited higher median Secchi, indicating clearer waters, while LC22 and LC5 showed similar median values, suggesting comparable water clarity. Outliers may indicate periods of exceptional clarity or potential data anomalies. This plot provides insights into the spatial variability of water transparency across the lake.

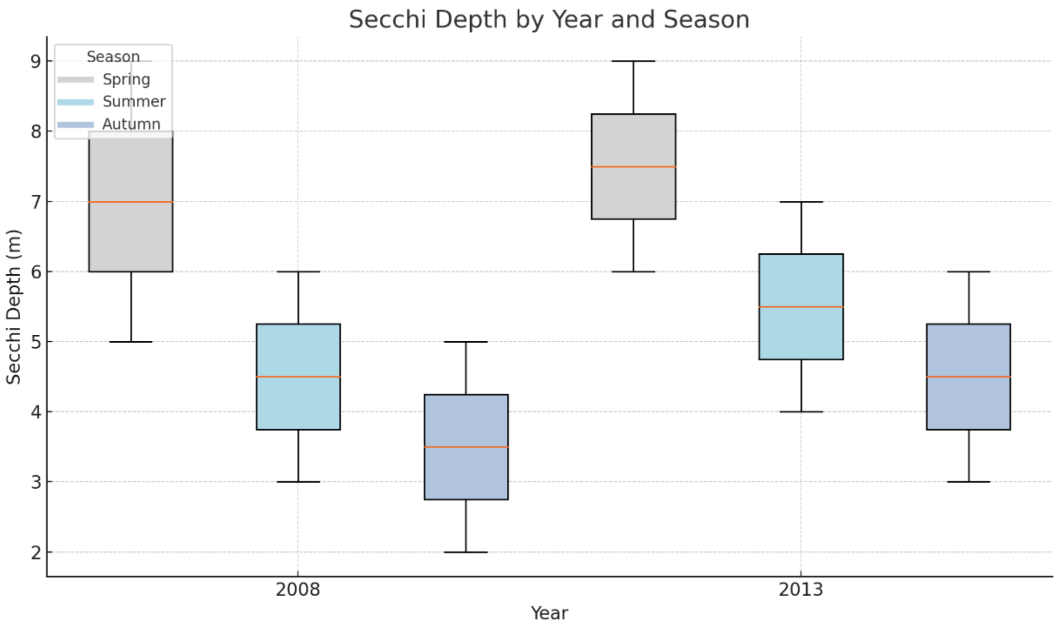


**Figure 13: Secchi Depth Box Plots Seasonal Variations—**The box plots illustrate variations in Secchi (in meters) across the three Seasons (Spring, Summer, and Autumn (Fall)) and between the years 2008 and 2013. The thin horizontal red lines within each box represent the median Secchi for each season, providing a clear visual of water clarity trends.

### 3.5.3 Secchi Depth Correlation with Other Water Quality Parameters:

The correlation between Secchi and other WQPs, including pH and Chl *a,* revealed a weak positive correlation between Secchi and Conductivity, indicating a significant influence of the concentration of dissolved ions on Secchi depth.

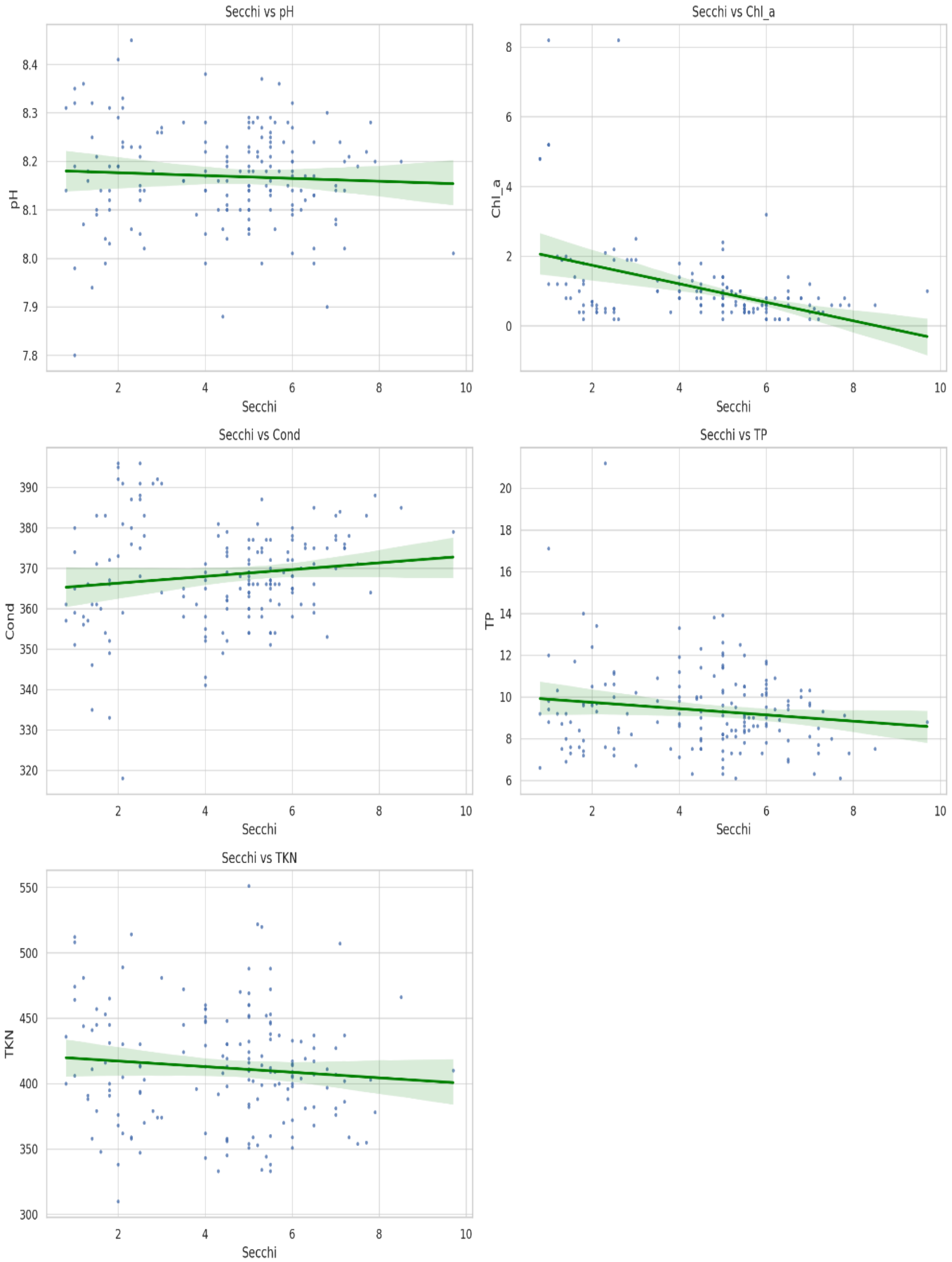


**Figure 14: Correlation of Secchi Depth and Water Quality Parameters—**A moderate negative correlation was observed with Chl *a* ($R^2 = 0.1867$, $p < 0.001$), indicating a notable relationship between water clarity and algal concentration. Relationships with pH, Conductivity, TP, and TKN were weak or not statistically significant.

## 3.6.1 General Linear Model Analysis of pH

The GLM analysis of pH demonstrated a significant model fit ($F_{(29,111)} = 5.52$, $p < 0.001$; $R^2 = 0.653$, adjusted $R^2 = 0.624$, capturing approximately 60% of the variance in pH data. This finding suggested a substantial difference between the two years, indicating increased pH levels over time, with minimal variations observed between Stations or Seasons.

**Type II ANOVA Analysis**

The Type II ANOVA analysis highlighted that the Year significantly influenced pH levels (F(1, 111) = 57.5822, p < 0.001), underscoring a notable increase in pH between 2008 and 2013. However, the analysis did not reveal significant variations in pH among Stations, suggesting consistent pH levels throughout the lake.

Interaction effects were examined between Year and Stations, Year and Seasons, and Seasons and Stations, but these interactions did not show significant impacts on the pH. These results suggest that while the Year and Seasons independently affected pH, their interactive effects with Stations did not contribute significantly to variation in the lake's pH.

## 3.6.2 Box Plots for pH Variations by Stations, Seasons, and Years

Figures 15 and 16 illustrate pH variations across Stations, Seasons, and Years. These plots highlighted the variability in the pH in Lake Couchiching. LC12 and LC19 showed more pH variation than other Stations.

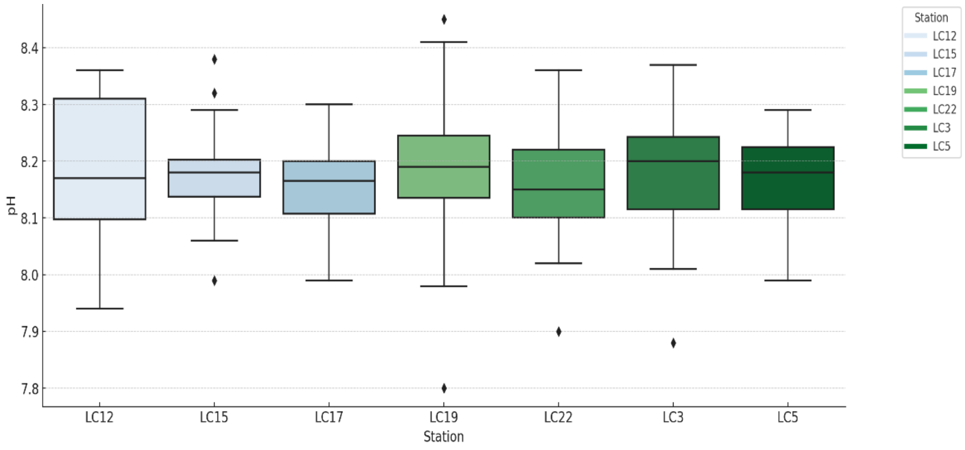


**Figure 15: Box Plot of pH by Station—**The outliers indicate sampling Stations with extreme pH values, potentially influencing the chemistry of this aquatic ecosystem.

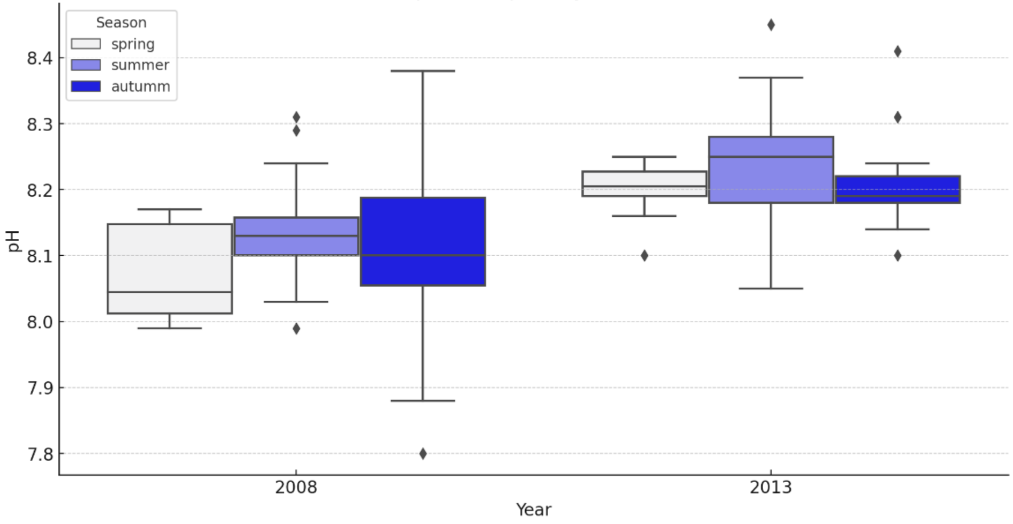


**Figure 16: pH box plots by season and year—**This plot shows seasonal and annual pH fluctuations. The fall of 2008 revealed considerable variation in pH. Outliers in specific Seasons or Years may suggest unusual pH conditions during those periods.

### 3.6.3 pH Correlation with Other Water Quality Parameters

Figure 17 demonstrates the pH correlation analysis results with other WQPs. The analysis revealed a negligible to weak correlation between pH and parameters like Chl *a*.

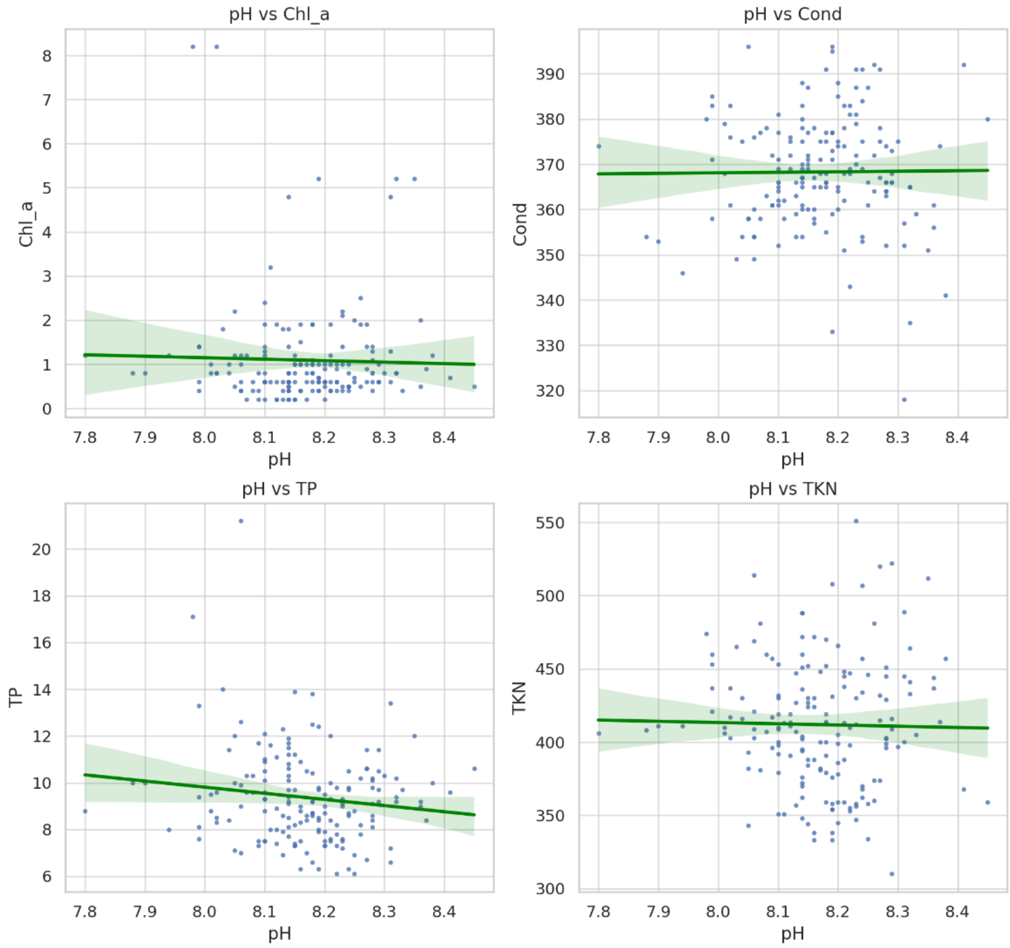


**Figure 17: Correlations between pH and Other Water Quality Parameters—** This Figure presents the relationships between water pH and other water quality parameters: Chl *a* conductivity, TP, and TKN. pH showed a weak negative correlation with Chl *a* and no significant correlation with Conductivity. Additionally, there were weak negative correlations with TP and TKN, indicating minimal variations in these parameters with changes in pH.

### 3.7.1 General Linear Model Analysis of Chlorophyll-*a*

The GLM analysis of Chl *a* indicated a satisfactory model fit ($F_{(29,\ 111)} = 2.657$, $p < 0.001$). It explained about 40% of the variance in Chl *a* ($R^2 = 0.4097$, Adjusted $R^2 = 0.255$). Notable effects were observed at specific Stations. LC15 and LC19 capture their distinct influence on Chl *a*. These results reflect the spatial variability in phytoplankton distribution and its potential impact on the aquatic food web.

**Type II ANOVA Results**

The Type II ANOVA analysis revealed a significant influence of the Year on Chl *a* ($F_{(1, 111)}$ = 2.8998, $p$ = 0.091), indicating a temporal trend in phytoplankton biomass variation. Furthermore, Stations significantly influenced Chl *a*, highlighting the importance of spatial factors in phytoplankton distribution within the lake.

The interaction effects revealed significant findings. The interaction between years showed a prominent effect on Chl *a* ($F_{(6, 111)}$ = 4.1964, $p < 0.001$), indicating that the relationship between the Year and Chl *a* varied significantly across Stations. However, interactions between Year and Seasons and Seasons and Stations did not significantly impact *Chl a*.

### 3.7.2 Box Plots for Chlorophyll-*a* Variations by Stations, Seasons, and Years

The box plots in Figures 18 and 19 showed the variations in Chl *a* across Stations (Figure 18) and over the three Seasons in each of the two Years in Lake Couchiching, providing critical insights into the spatial and temporal variations in algal biomass.

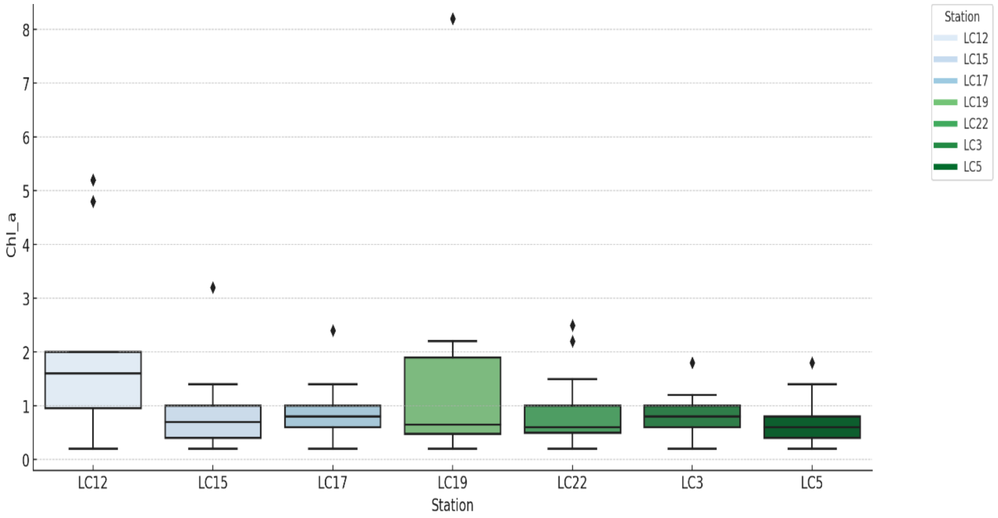


**Figure 18: The box plot of Chlorophyll-*a* by Stations—**Outliers indicated exceptionally high Chl *a*, potentially suggesting intense algal blooms.

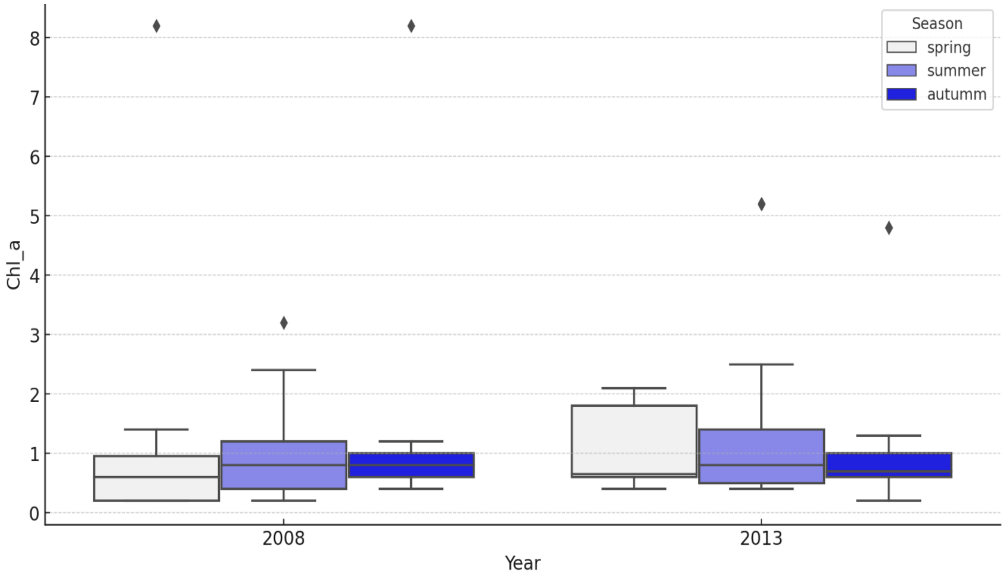


**Figure 19: These box plots show seasonal and annual fluctuations in Chl *a*—**Outliers in specific Seasons or Years may suggest unusual algal bloom events.

### 3.7.3 Chlorophyll-*a* Correlation with Other Water Quality Parameters

As shown in Figure 20, the Chl *a* correlation analysis with other WQPs indicated moderate positive correlations with TP and TKN and a slightly negative correlation with Conductivity. This result suggests that higher levels of Chl *a* are often linked to increased nutrients in Lake Couchiching. The negative correlation with Conductivity is interesting, as one might expect conductivity to increase with higher nutrient inputs. They could be due to the specific ionic composition of the water or seasonal influences that affect nutrient levels and conductivity differently. Further investigation into the drivers of this relationship is warranted.

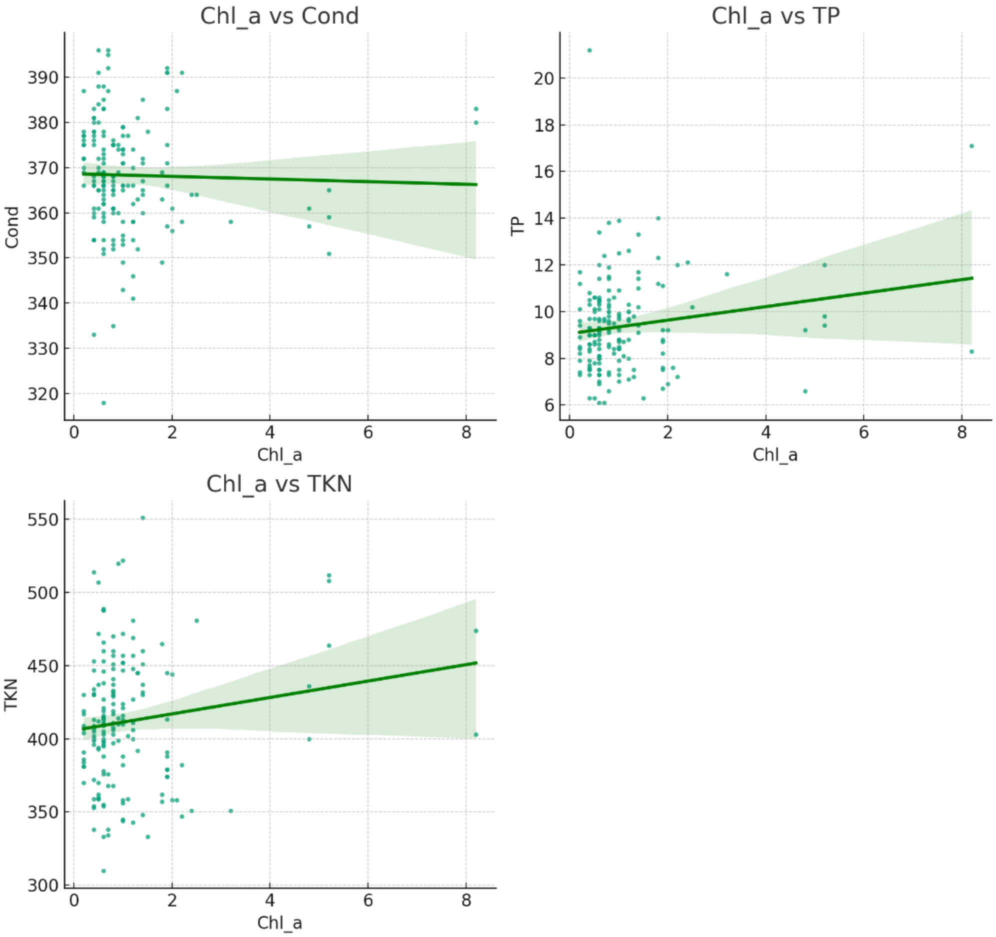


**Figure 20: Scatter Plot Matrix Correlations Chl *a* with other WQPs—** Moderate positive correlations with TP and TKN suggested that elevated Chl *a* was associated with enhanced nutrient availability for algae and cyanobacteria.

## 3.8.1 General Linear Model Analysis of Conductivity

The Conductivity analysis investigated variations in dissolved salts and minerals in the lake. The GLM analysis highlighted a significant difference between Years for Conductivity levels ($R^2$ = .7552, Adjusted $R^2$ = .6912, $F_{(29, 111)}$ = 14.23, $p < .001$). This trend suggested an increase in the lake's ion concentration from 2008 to 2013 (see Figure 21), which could have substantial ecological implications, particularly for phytoplankton and zooplankton species.

**Type II ANOVA Analysis**

The Type II ANOVA results showed a pronounced effect of Year on Conductivity ($F_{(1, 111)}$ = 64.6849, $p < 0.001$), again showing an increasing trend of Conductivity over time. Seasonal variations also significantly affected Conductivity, underlining the dynamic nature of the lake's water quality across the sampling periods.

The interaction between Year and Seasons was significant ($F_{(2, 111)}$ = 5.046, $p = 0.007989$), indicating that changes over the three Seasons accompanied the increase in Conductivity between 2008 and 2013. The interaction between Stations and Seasons showed significant relationships, indicating that conditions varied not only among Seasons but also among Stations. This variability was consistent across the Stations, suggesting that seasonal changes influence spatial differences in conductivity.

### 3.8.2 Box Plots for Conductivity Variations By Stations, Seasons, and Years

The box plots in Figure 21 show the variability in Conductivity over Seasons and between the two Years at Lake Couchiching, highlighting the lake's dynamic water chemistry. The detailed analysis, as shown in Figure 22, revealed seasonal Conductivity trends: In 2008, Spring showed a mean Conductivity of 375.36 µS/cm (*SD* = 7.50), decreasing to 364.00 µS/cm in Summer (*SD* = 11.71) and 356.89 µS/cm in Fall (*SD* = 9.74). Similarly, 2013 exhibited the same pattern of decreasing conductivity over the year, with Spring having the highest mean of 382.21 µS/cm (SD = 5.39), followed by a decline in Summer to 370.94 µS/cm (SD = 10.26) and a slight further decrease in Fall to

372.00 µS/cm (SD = 11.73). This consistent seasonal trend highlights a clear decline in Conductivity from Spring to Fall.

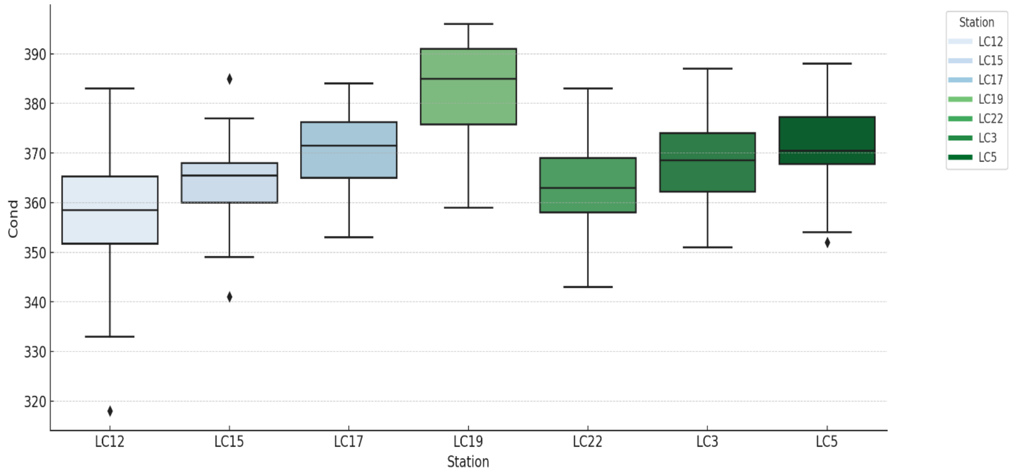


**Figure 21: The box plot of Conductivity by Stations—**Notable outliers at specific Stations, like LC15, indicated exceptional Conductivity values.

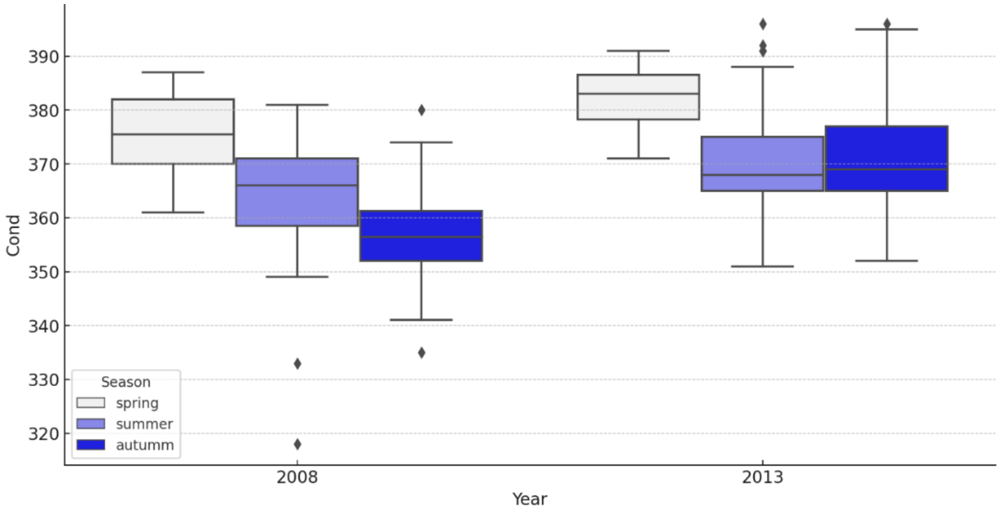


**Figure 22: Box Plot of Conductivity by Seasons and Years**—This plot revealed changes in water chemistry and environmental factors. Outliers represented in specific Seasons or Years may suggest unusual conditions during those periods.

### 3.8.3 Correlation of Conductivity with Other Water Quality Parameters

As shown in Figure 23, the correlation analysis between Conductivity and other WQPs showed a moderate negative correlation with TKN ($R^2 = 0.1419$ and $p < 0.001$).

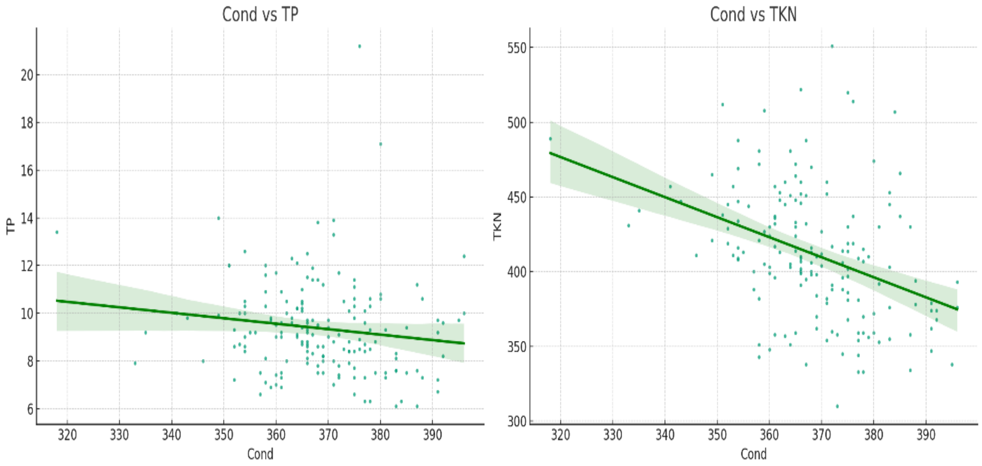


**Figure 23: Scatter Plot Matrix Correlations with Conductivity—**This plot revealed a moderate negative correlation between Conductivity and TKN ($R^2 = 0.1419$, $p < 0.001$). The analysis also revealed a weak negative correlation with TP, suggesting a minimal impact of these parameters on Conductivity.

## 3.9.1 General Linear Model Analysis of Total Phosphorous

The GLM analysis of TP in Lake Couchiching showed a moderate model fit ($R^2 = 0.3663$, Adjusted $R^2 = 0.2008$, $F_{(29,\ 111)} = 2.213$, $p = 0.001678$). The model highlighted that Season, particularly Summer, significantly influenced TP. It suggests a potential increase in nutrient input during warmer months, which in turn affects phytoplankton populations—the primary food source for zooplankton—rather than the zooplankton consuming TP directly.

**Type II ANOVA Analysis**

The Type II ANOVA analysis revealed a significant difference between years on TP ($F_{(1,\ 111)} = 30.4804$, $p < 0.001$), with TP levels being lower in 2013 than in 2008. Seasonal changes and Stations also significantly affected TP, indicating the influence of Seasons and sampling locations on nutrient dynamics within the lake ($F_{(2,\,111)} = 8.4679$, $p < 0.001$; $F_{(6,\,111)} = 9.4040$, $p < 0.001$).

Interaction effects between the Year and Stations and Year and Seasons on TP were significant ($F_{(6,\,111)} = 1.8869$, $p < 0.001$; $F_{(2,\,111)} = 2.8097$, $p < 0.001$). However, the interaction between Stations and Seasons was insignificant.

### 3.9.2 Box Plots for Total Phosphorous Variations by Stations, Seasons, and Years

The TP box plots showed variation with Stations (Figures 24 and 25). Outliers suggested potential pollution events or high nutrient inputs at certain Stations. Furthermore, the box plot representing TP by Seasons and Year highlighted temporal changes in nutrient loading patterns. In 2008, Spring exhibited a mean TP of 8.97 µg/L (*SD* = 0.996); in Summer, it increased to 11.05 µg/L (*SD* = 2.33). In contrast, in 2013, lower TP concentrations were seen in each Season: Spring at 7.31 µg/L (*SD* = 1.01), Summer at 9.08 µg/L (*SD* = 1.35) and Fall at 8.66 µg/L (*SD* = 1.27).

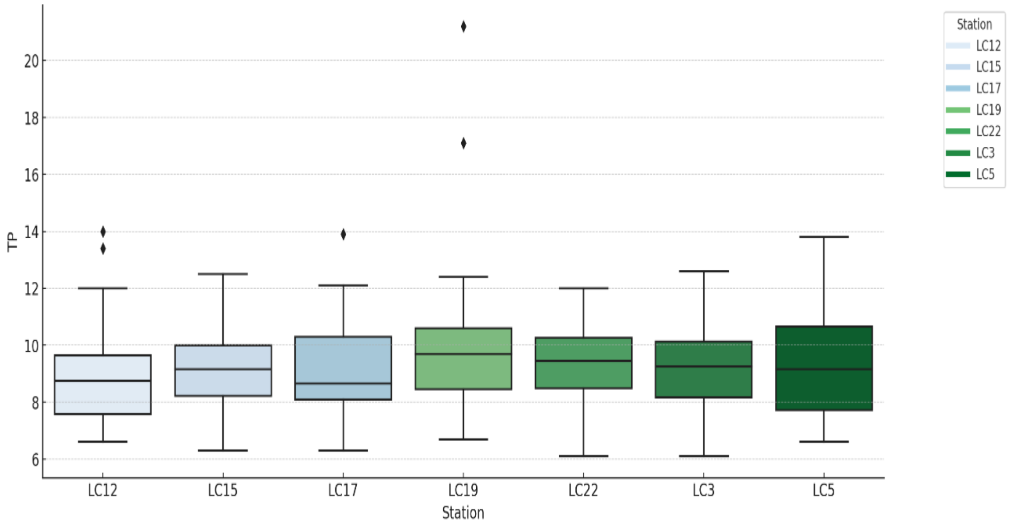


**Figure 24: Box Plot showing variations in TP among Stations**—Outliers at LC19 indicated a Station with exceptionally high TP, potentially suggesting pollution events or high nutrient inputs.

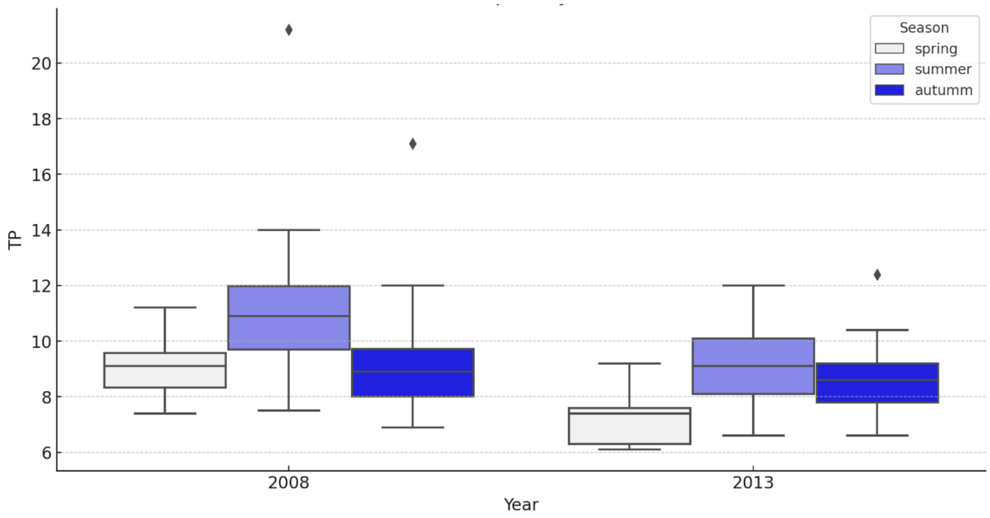


**Figure 25: Box Plot of seasonal and annual fluctuations in TP**—Outliers in Seasons or Years suggest unusual nutrient input events.

### 3.9.3 Total Phosphorous Correlation with Other Water Quality Parameters

The correlation analysis between TP and other WQPs revealed a complex relationship, as shown in Figure 26. A positive correlation with TKN ($R^2 = 0.1488$, $p < 0.001$) indicated increasing TKN with an increase in TP, emphasizing the intricacy of these parameters in the water quality of Lake Couchiching.

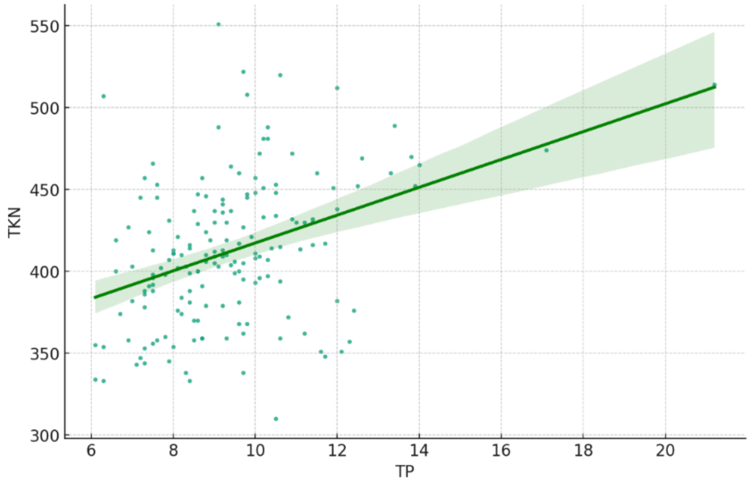


**Figure 26: Correlation Between TP and TKN**—This Figure illustrated a positive correlation between TP and TKN, with an $R^2$ value of 0.1488 and a significance level of $p < 0.001$.

## 3.10.1 General Linear Model Analysis of Total Kjeldahl Nitrogen

The GLM analysis for TKN demonstrated a modest fit ($R^2 = 0.2867$, Adjusted $R^2 = 0.1003$, $F(29, 111) = 1.538$, $p = 0.05811$), indicating that the model captured some variability in TKN. While the GLM suggested that the effect of Year on TKN was not statistically significant, the Type II ANOVA analysis below revealed significant differences between the two years for TKN. The different statistical methods may highlight various aspects of the data, with the ANOVA capturing a more pronounced Year effect. At the same time, the GLM emphasizes the influence of seasonal and Station-specific factors on TKN distribution. For instance, TKN levels showed differences between Years and among Seasons and Stations, underscoring the importance of localized and temporal factors in influencing nitrogen levels in Lake Couchiching.

**Type II ANOVA Analysis**

The Type II ANOVA analysis revealed a significant difference in TKN levels between 2008 and 2013 ($F(1, 111) = 13.8764$, $p = 0.000309$), with levels being lower in 2013 than in 2008. The influence of different Stations was insignificant, suggesting minimal or no spatial variation in TKN across the lake. Seasonal changes significantly affected TKN ($F(2, 111) = 4.4753$, $p = 0.013515$), highlighting the important role of seasonality in TKN variation, while spatial differences are minimal.

## 3.10.2 Box Plots for Total Kjeldahl Nitrogen Variations by Stations, Seasons, and Years:

The box plot of TKN by Stations showed variations in TKN with no significant spatial differences (Figure 27). Outliers, especially at LC3, LC15, LC17, and LC19, suggested high TKN concentrations. Figure 28 for TKN by Seasons and Year indicated seasonal and annual fluctuations. In 2008, TKN concentrations were fairly similar in Spring (mean: 411.5 µg/L, *SD* = 22.93), Summer

(428.13 µg/L, SD = 45.40), and Fall (422.5 µg/L, *SD* = 20.68). By 2013, all Seasons showed lower concentrations: Spring (380.71 µg/L, *SD* = 53.62), Summer (409.84 µg/L, *SD* = 52.36), and Fall (391.43 µg/L, *SD* = 27.41), respectively.

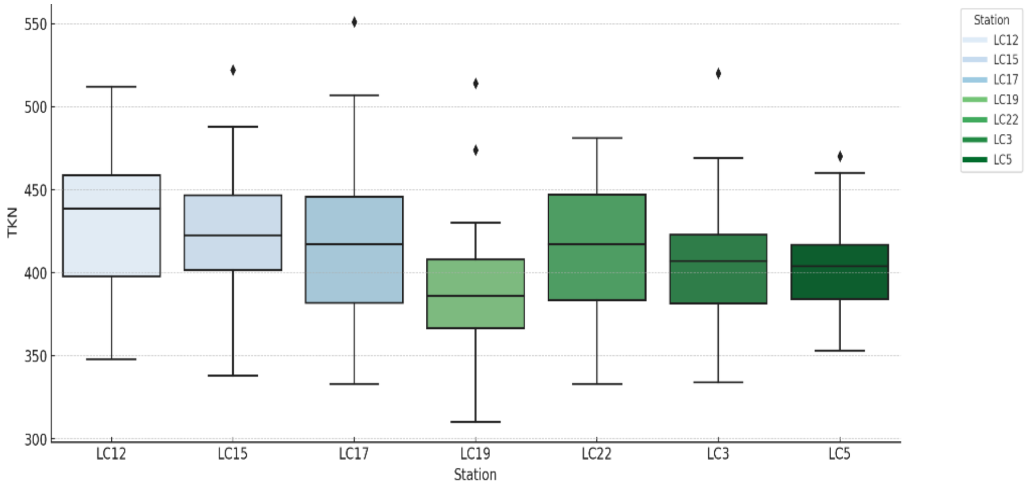


**Figure 27: Box Plot of TKN by Station**—This plot shows TKN variations with no significant difference among Stations reflecting differences in nitrogen sources. Outliers at LC3, LC15, LC17, and LC19 showed Stations with an exceptionally high TKN, potentially suggesting pollution events or high nitrogen inputs.

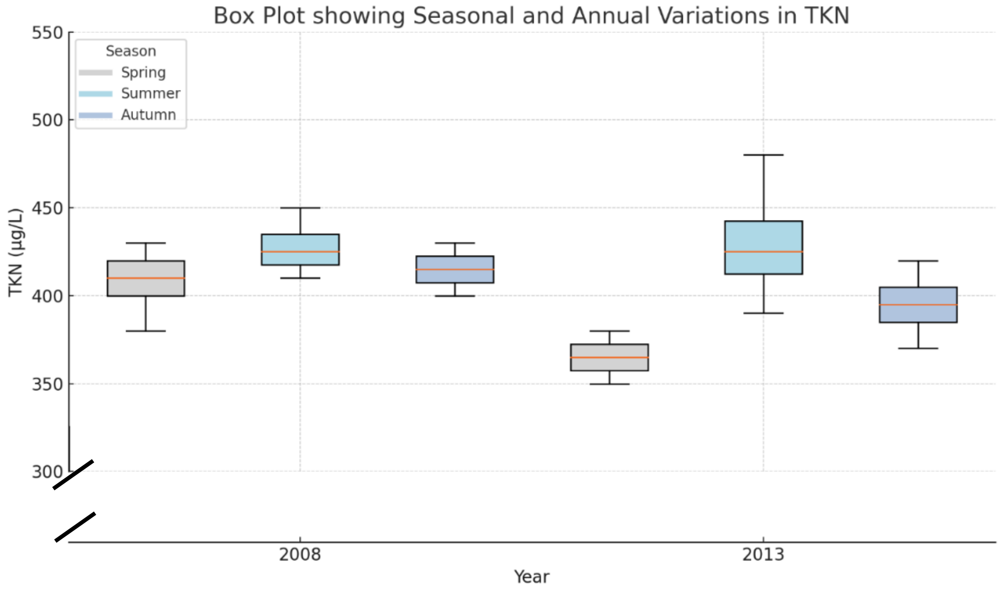


Figure 28: Box Plot showing seasonal and annual fluctuations in TKN

## 3.11.1 Summary

This chapter explored the spatial and temporal variations in the water quality of Lake Couchiching for the years 2008 and 2013. The findings demonstrated significant variability in the WQPs, which are likely to be influenced by natural and anthropogenic factors. By using the GLMs (Benjamini & Hochberg, 1995), it was found that Depth ($F(29, 111) = 130.1$, $p < 0.001$, $R^2 = 0.9573$) and Secchi depth ($F(29, 111) = 24.73$, $p < 0.001$, $R^2 = 0.866$) were the two most significant predictors of water quality parameters in Lake Couchiching. The analysis revealed notable spatial patterns in the variability of WQPs, with certain areas exhibiting higher variability due to localized factors, while the temporal changes highlighted seasonal impacts. Additionally, the study captured differences between years, showing how WQPs changed from 2008 to 2013. These results underscore the complexity of the lake's ecosystem and set the stage for understanding the corresponding impacts of these parameters on the ZCS. The topic will be explored further in the subsequent chapter.

# 4.0 Chapter 4 Results of Spatial-Temporal Patterns in Zooplankton Community Structure

## 4.1.1 Introduction

The relationship between the zooplankton community structure (ZCS) and Water Quality Parameters (WQPs) in Lake Couchiching presents both benefits and challenges. On the one hand, the spatial-temporal variations in WQPs—such as nutrient levels, pH, and temperature—serve as the primary drivers of changes in zooplankton composition. Zooplankton species respond differently to environmental factors, with certain taxa thriving under specific conditions while others diminish. On the other hand, zooplankton can also influence WQPs, particularly through their grazing on phytoplankton, which impacts nutrient cycling, water clarity, and other key water quality metrics. Thus, the relationship is dynamic, with both cause and effect at play: while WQPs shape the zooplankton community, the zooplankton, in turn, indirectly modify some aspects of water quality.

Razak and Sharip (2019) emphasized the importance of WQP dynamics in managing aquatic ecosystems. In Lake Couchiching, the structure and formation of the ZCS are directly influenced by the WQPs at play. Changes in factors like temperature, pH, dissolved oxygen, and nutrient levels drive the dynamics of the zooplankton community. These fluctuations in WQPs shape the ZCS, which in turn acts as an indicator of the overall health and balance of the lake's ecosystem.

For instance, changes in the abundance and diversity within the ZCS can signal shifts in nutrient availability or water clarity, which, in turn, can influence the entire food web. Razak and

Sharip (2019) emphasized the significance of understanding WQP dynamics for effective aquatic ecosystem management, highlighting that monitoring these parameters helps detect early signs of ecological imbalance and allows for timely intervention measures.

In Lake Couchiching, data were collected twice a month during three seasons (Spring, Summer, and Fall) in both 2008 and 2013, providing a robust dataset to monitor the ZCS and WQPs. Despite the five-year gap between sampling years, this frequent sampling schedule allowed for a detailed understanding of the spatial-temporal variability in water quality and zooplankton dynamics. The insights gained from these monitoring efforts are crucial for developing targeted conservation strategies and ensuring the long-term sustainability of the lake's ecosystem. However, continuous monitoring across more years would further enhance the ability to detect long-term ecological trends.  By integrating the findings of spatial-temporal variations in WQPs with the ZCS data, researchers and environmental managers can better understand the intricate relationships between these factors within the lake's ecosystem, thereby facilitating more informed decision-making processes.

This chapter examines how WQPs shape the zooplankton community in terms of composition, abundance, and diversity across various temporal and spatial scales. While WQPs such as nutrient concentrations, pH, and temperature primarily drive changes in the zooplankton community, it is important to note that zooplankton may also exert some influence on WQPs through processes like grazing on phytoplankton. However, the primary focus here is on understanding how environmental factors influence zooplankton rather than the reverse. For instance, Hu *et al.* (2019) studied the influence of depth-related variations and conductivity levels on ZCS.  The study revealed that zooplankton distribution patterns and community dynamics are intricately tied to WQPs. Such insights emphasize the importance of WQPs on lake ecosystems and the need for detailed studies on ecological parameters (Hu *et al.*, 2019; Zhang *et al.*, 2019).

The spatial aspects of WQPs in lakes may relate to differences in depth, littoral versus pelagic zones, and inflow-outflow dynamics, which can also influence the structure of zooplankton communities. Logez *et al.* (2016) and McClymont (2017) studied zooplankton species that exhibit distinct preferences for water depths driven by factors such as light availability, predation pressure, and the availability of nutrients required for phytoplankton growth (which indirectly influences zooplankton food sources, such as phytoplankton abundance).

They also emphasized the role of shoreline proximity in determining ZCS, with certain zooplankton species thriving well in sheltered littoral zones while others, like copepods, dominate in open pelagic waters.

The temporal and spatial variations in WQPs create a mixture of ecological niches within lake systems, as demonstrated by several recent studies (Anderson *et al.*, 2021; Shchapov & Ozersky, 2023; Shi *et al.*, 2020). These studies explained how seasonal temperature and nutrient level shifts may interact with factors like lake stratification and physiochemical gradients to determine patterns of zooplankton distribution.

Modern study methods have been vital in understanding the temporal and spatial dynamics of WQPs and their influence on ZCS. As described by Amato *et al.* (2020) and Lan *et al.* (2021), time-series analyses and spatial mapping techniques have offered valuable information on the cyclical and spatial distribution of zooplankton communities in lake ecosystems. Moreover, Amato *et al.* (2020) developed predictive models that helped to forecast changes in ZCS depending on shifts in WQPs.

## 4.2.1 Methodology

The General Methodology section described the methods used for collecting water samples from the sampling Stations (Stations) during the study period and the standardized laboratory protocols for ZCS estimations. It also described the statistical analyses, both parametric and non-parametric tests, used to assess the trends in the data.

## 4.3.1 Results

### 4.3.2 Testing Assumptions for PERMANOVA

Before running the PERMANOVA, homogeneity tests were carried out on the ZCS data to ensure they met the normality assumptions. Similarly, data on environmental variables were also tested to ensure they followed a normal distribution. The betadisper from the vegan package in R was used to test the homogeneity in multivariate dispersions among ZCS groups.

A permutation test was used to evaluate the uniformity of multivariate dispersions $F(4, 114) = 0.5338$, $p = 0.724$). Since the p-value exceeded the 0.05 significance threshold, the null hypothesis could not be rejected because these spatial groupings had no significant differences in multivariate dispersion. The permutation test was deemed robust in assuming homogeneity in variances. The data met normality assumptions, as confirmed by QQ plots. Each QQ plot represented a ZCS variable, including density, or number per unit volume (Avg_Dens), abundance (Abund), species richness (Richness), and the Shannon-Weiner Diversity Index (SDI).

Next, I omitted the missing values from the dataset to ensure PERMANOVA data suitability, as shown by the R console output [1] 0.

### 4.3.3 PERMANOVA Analysis of Zooplankton Community Structure (ZCS)

The PERMANOVA analysis revealed significant effects and interactions of sampling Stations (Stations), seasons (Seasons), and years (Years) on the ZCS across Lake Couchiching. Key findings of Station locations and seasonal effects included significant variations in ZCS across Stations ($R^2 = 0.165$, $p < .001$) and seasons ($R^2 = 0.146$, $p < .001$) (Table 2).

The interaction effects between Year and Station ($R^2 = 0.048$, $p = .038$) and between Season and Year ($R^2 = 0.064$, $p < .001$) on ZCS were significant, suggesting the occurrence of both spatial and temporal differences in ZCS. However, the interaction of Station with Season showed no significant impact ($p = .139$) on ZCS.

**Table 2.** Zooplankton Community Structure PERMANOVA Results: This table summarizes the PERMANOVA analysis results of zooplankton community structure (ZCS) metrics in Lake Couchiching. The analysis includes data on Abundance (Abund), Average Density (Avg_Dens), Shannon Diversity Index (SDI), and Species Richness (Richness). These metrics provide insights into the zooplankton community's variations in composition and diversity, which were examined across spatial and temporal scales.

| | Df | SumOfSqs | R2 | F | Pr(>F) | |
|---|---|---|---|---|---|---|
| S_Station | 6 | 4.0163 | 0.16501 | 6.6438 | 0.001 | *** |
| seasons | 2 | 3.5464 | 0.1457 | 17.5993 | 0.001 | *** |
| Year | 1 | 1.2736 | 0.05232 | 12.6405 | 0.001 | *** |
| S_Station:Year | 6 | 1.1569 | 0.04753 | 1.9138 | 0.038 | * |
| seasons: Year | 2 | 1.5612 | 0.06414 | 7.7479 | 0.001 | *** |
| S_Station:seasons | 12 | 1.6016 | 0.0658 | 1.3247 | 0.139 | |
| Residual | 111 | 11.1836 | 0.45948 | | | |
| Total | 140 | 24.3397 | 1 | | | |

- "***" indicates $p < 0.001$.
- "*" indicates $p < 0.05$.
- Blank under 'Significance' indicates non-significance.

## Post-hoc analysis

The tables below show the comprehensive post hoc analysis using MANOVAs with Wilks' test. There were noticeable year-to-year seasonal differences (*p* =.001) between 2008 and 2013 (Tables 3 and 4), revealing the ZCS's sensitivity to temporal environmental changes. There were apparent spatial differences in ZCS with Stations (*p* =.0014 between certain Station pairs), though not all showed significant differences (Table 5).

**Table 3.** Multivariate post-hoc analysis results for zooplankton community variables across seasons, using Wilks' test.

| Seasons | | |
|---|---|---|
| | Fall | Spring |
| Spring | 0.001 | - |
| Summer | 0.001 | 0.001 |

**Table 4.** Multivariate post-hoc analysis results for zooplankton community variables across years using Wilks' test.

| Year | |
|---|---|
| | 2008 |
| 2013 | 0.001 |

**Table 5.** Multivariate post-hoc analysis results for zooplankton community variables across Stations using Wilks' yest. The table reveals significant differences among Stations except between LC17 and LC22, LC3 and LC22, and LC3 and LC17.

| Stations | | | | |
|---|---|---|---|---|
| | LC12 | LC17 | LC19 | LC22 |
| LC17 | 0.0014 | - | - | - |
| LC19 | 0.0014 | 0.0014 | - | - |
| LC22 | 0.0014 | 0.52 | 0.0014 | - |
| LC3 | 0.0014 | 0.1537 | 0.0014 | 0.3956 |

### 4.3.4 Data handling and sensitivity analysis for improving PERMANOVA robustness

In this study, restructuring the dataset was crucial due to missing values that would normally be required for PERMANOVA models. To address this, I developed two structurally distinct datasets. First, the conservative dataset excluded Stations LC5 and LC15 (because they had missing data points) to minimize potential biases and ensure balanced group distribution across Years, Seasons, and Stations. Removing these two Stations was critical to producing an equal number of samples per site and enhancing the robustness of PERMANOVA analysis. Second, the inclusive or original dataset included all Stations but omitted only the records with missing data. Although this approach offers a broader view by incorporating data from all Stations, including LC5 and LC15, it is more susceptible to biases due to incomplete and unbalanced data and reduced analytical power.

A sensitivity analysis compared the efficacy of the conservative dataset against the inclusive dataset. This analysis was essential in validating analytical assumptions and ensuring the reliability of the variability findings. The study revealed that the datasets displayed similar spatial and temporal variability across all ZCS metrics, including Abund, Richness, Avg_Dens, and SDI. The consistent results across the datasets indicated that the adjustments in dataset structuring effectively mitigated potential biases (detailed test results are presented in Tables A to D in Appendix A).

Given its higher reliability, the conservative dataset was selected for detailed PERMANOVA, ad hoc tests, and PCA. This choice ensured that the analysis minimized bias, providing a solid basis for valid ecological interpretations. Meanwhile, the inclusive dataset is utilized in Chapter 5 for CCA graphical analyses, offering additional insights into Stations LC5 and LC15 by incorporating a broader range of data points.

### 4.4.1 Abundance

The box plots (Figure 29) represent the abundance distribution from the original dataset across Years, Seasons, and Stations. The plots illustrate temporal and spatial variations, with a significant observation at Station LC22, where on June 3rd, 2013, the zooplankton count peaked at 4590.0. This value exceeded the station's interquartile range (IQR), where the median was 1698.0.

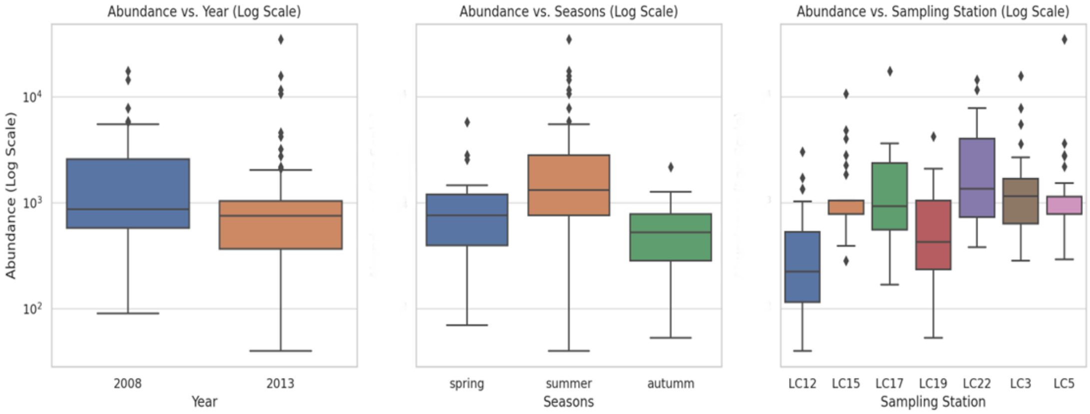


**Figure 29: Zooplankton Abundance Box Plots Using the Original Dataset—**These box plots show an abundant distribution between years and among seasons and stations.

### 4.4.2 PERMANOVA Results

The results of the PERMANOVA analysis showed spatial variation in Abund with Station ($F_{(6, 111)} = 6.5792$, $p < .001$). Significant interaction results were observed between Year and Stations ($F_{(2, 111)} = 1.9321$, $p < .025$) and between Year and Seasons (Year $F_{(2, 111)} = 7.7271$, $p <$ .00, Table 6). These results indicated that zooplankton abundance differed spatially between the two years and among seasons, as well as Stations in the lake.

**Table 6. PERMANOVA Analysis of Abundance Based on the Conservative Dataset—** This table presents the results of a PERMANOVA conducted to assess the effects of Station, season, and Year on Abund, as well as the interactions between these factors.

| | Df | SumOfSqs | R2 | F | Pr(>F) | |
|---|---|---|---|---|---|---|
| S-Station | 6 | 4.0806 | 0.16415 | 6.5792 | 0.001 | *** |
| Seasons | 2 | 3.5653 | 0.14342 | 17.2453 | 0.001 | *** |
| Year | 1 | 1.2744 | 0.05127 | 12.3283 | 0.001 | *** |
| S-Station:Year | 6 | 1.1984 | 0.04821 | 1.9321 | 0.025 | * |
| seasons: Year | 2 | 1.5975 | 0.06426 | 7.7271 | 0.001 | *** |
| S-Station:seasons | 12 | 1.6683 | 0.06711 | 1.3449 | 0.112 | |
| Residual | 111 | 11.4742 | 0.46158 | | | |
| Total | 140 | 24.8587 | 1 | | | |

- "***" indicates $p < 0.001$.
- "*" indicates $p < 0.05$.
- Blank under 'Significance' indicates non-significance.

### Abundance Pairwise Comparisons T-test

Table 8 shows spatial variability in Abund among Stations. It highlighted the influences of localized environmental conditions. Noteworthy significant differences were observed between LC12 and LC17 ($p < .001$), LC03 and LC12 ($p < .001$), LC17 and LC19 ($p = .03603$), LC19 and LC22 ($p = .00184$), and LC3 and LC19 ($p = .01506$) showing the spatial diversity and complexity of the lake's ecological structure.

**Table 7. Abundance Pairwise Comparisons T-Test Analysis Among Lake Stations—**This table shows the results of pairwise comparisons using t-tests to assess significant Abund differences between lake Stations. Each cell shows the p-value by comparing the Stations.

| | LC12 | LC17 | LC19 | LC22 |
|---|---|---|---|---|
| LC17 | 0.00046 | - | - | - |
| LC19 | 0.33894 | 0.03603 | - | - |
| LC22 | 0.000019 | 0.71956 | 0.00184 | - |
| LC3 | 0.00038 | 0.78073 | 0.01506 | 0.76167 |

### 4.5.1 Average Density

The average density box plots in Figure 30 illustrate the distribution of Avg_Dens by Year, Season, and Station. These plots show central tendency and spread, revealing the temporal and spatial patterns. The recorded value peaked at 0.25518 at LC15, significantly higher than the Station's IQR average of 0.10046615.

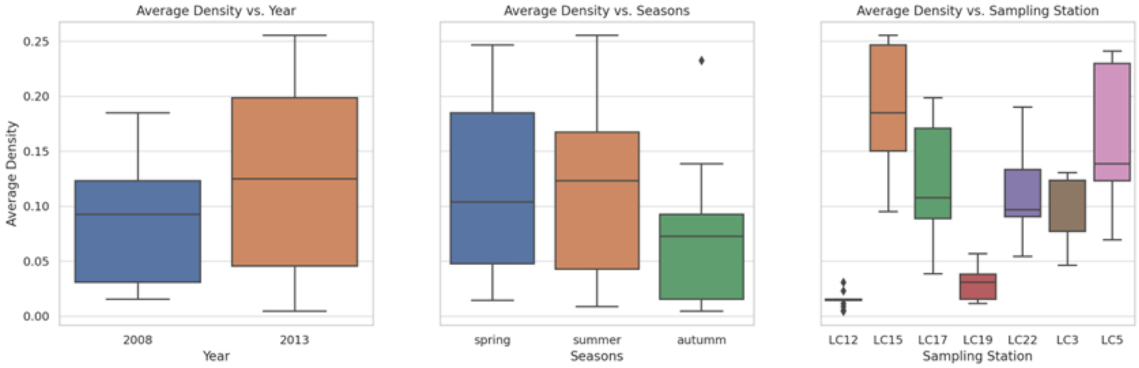


**Figure 30: Average Density Box Plots Using the Original Dataset—**These box plots show the distribution of Avg_Dens across Years, seasons, and Station, with considerable variation for Station LC5, LC15, and LC17 on August 13th, 2013, with the lowest medians at LC12 and LC19.

### 4.5.2 PERMANOVA Results

The PERMANOVA results of Avg_Dens indicate distinct spatial-temporal distribution patterns (Table 8). Pronounced effects were observed for Station, Seasons, Year and their interactions ($F_{(6, 111)} = 168.3950$, $p = .001$, $F_{(2, 111)} = 29.2396$, $p = .001$, $F_{(1, 111)} = 25.5993$, $p = .001$, $F_{(6, 111)} = 5.8717$, $p = .001$, $F_{(2, 111)} = 10.6551$, $p = .001$, $F_{(12, 111)} = 1.2284$, $p = .001$ for Station, Seasons, Year and their interactions, respectively). Furthermore, significant interaction effects were detected between location and time. Like Abund, these findings revealed that Avg_Dens significantly varied across Lake Couchiching's horizontal gradient, reflecting the dynamic nature of its ecosystem.

**Table 8.** Average Density PERMANOVA Results.

| | Df | SumOfSqs | R2 | F | Pr(>F) | |
|---|---|---|---|---|---|---|
| S_Station | 6 | 13.9776 | 0.74799 | 168.395 | 0.001 | *** |
| Seasons | 2 | 0.809 | 0.04329 | 29.2396 | 0.001 | *** |
| Year | 1 | 0.3541 | 0.01895 | 25.5993 | 0.001 | *** |
| S_Station:Year | 6 | 0.4874 | 0.02608 | 5.8717 | 0.001 | *** |
| seasons: Year | 2 | 0.2948 | 0.01578 | 10.6551 | 0.001 | *** |
| S_Station:seasons | 12 | 1.2284 | 0.06574 | 7.3998 | 0.001 | *** |
| Residual | 111 | 1.5356 | 0.08217 | | | |
| Total | 140 | 18.687 | 1 | | | |

- "*"** denotes **p < 0.001**, indicating a highly significant result.
- **"*"** denotes **p < 0.05**, indicating a significant result.
- **"N.S."** indicates a **non-significant result**.

**Average Density Pairwise Comparisons T-test**

There was no significant difference in the yearly variation of Avg_Dens, suggesting stability in zooplankton density over these Years. However, the seasonal analysis uncovered substantial differences as the Avg_Dens in Summer was markedly higher than in Spring (*p* = .0026) and Fall (*p* = .0233). Spring and Fall showed similar density levels (*p* = .8293), indicating similarity between these Seasons. Spatially, heterogeneity in Avg_Dens was distinct among different sampling Stations.

**Table 9.** Average Density Pairwise Comparison Using the T-test Analysis:

| | LC12 | LC17 | LC19 | LC22 |
|---|---|---|---|---|
| LC17 | 0.000000025 | - | - | - |
| LC19 | 0.00053 | 0.000000055 | - | - |
| LC22 | 0.000000025 | 0.24669 | 0.00000004 | - |
| LC3 | 0.000000024 | 0.19498 | 0.000000059 | 0.19498 |

### 4.6.1 Shannon Weiner Diversity Index

Figure 31 shows the temporal and spatial patterns of SDI during the study. A key finding was observed on June 24th, 2008. The SDI at Station LC12 recorded a value of 1.0425003, surpassing the Station's IQR average of 0.5199807. Several outliers seen beyond the interquartile range may signify deviations from the trend observed in the normal SDI boxplot.

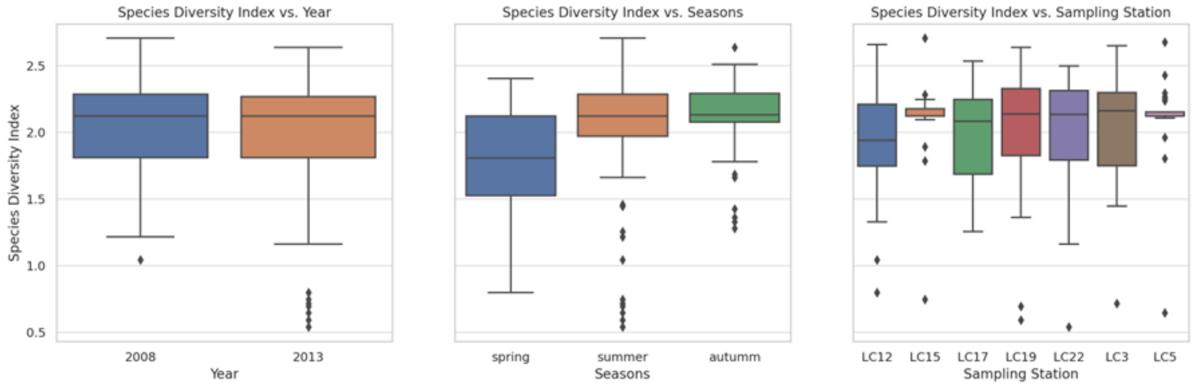


**Figure 31: Shannon Diversity Index Box Plots Using the Original Dataset Showing Temporal and Spatial Variations—** These plots demonstrate the peak observed at Station LC12 on June 24th, 2008.

### 4.6.2 PERMANOVA Results

The SDI PERMANOVA analysis results in Table 10 highlight seasonal impacts on zooplankton diversity ($F_{(2, 111)} = 3.5103$, $p < 0.05$). This analysis revealed no significant spatial and annual effects, suggesting that diversity fluctuated mostly according to Season. However, it remained relatively consistent across all sampling Stations in 2008 and 2013.

**Table 20.** Shannon Diversity Index PERMANOVA Analysis Results:

| | Df | SumOfSqs | R2 | F | Pr(>F) | |
|---|---|---|---|---|---|---|
| S_Station | 6 | 0.03646 | 0.01295 | 0.291 | 0.964 | |
| Seasons | 2 | 0.14659 | 0.05204 | 3.5103 | 0.029 | * |
| Year | 1 | 0.03475 | 0.01234 | 1.6644 | 0.202 | |
| S_Station:Year | 6 | 0.07513 | 0.02667 | 0.5997 | 0.747 | |

| | | | | | | |
|---|---|---|---|---|---|---|
| seasons: Year | 2 | 0.12376 | 0.04394 | 2.9636 | 0.043 | * |
| S_Station:seasons | 12 | 0.08237 | 0.02924 | 0.3287 | 0.988 | |
| Residual | 111 | 2.31769 | 0.82282 | | | |
| Total | 140 | 2.81675 | 1 | | | |

- "***" denotes $p < 0.001$, indicating a highly significant impact.
- "*" signifies $p < 0.05$, suggesting a significant impact.
- A blank under 'Significance' indicates a non-significant result.

**Shannon Diversity Index Pairwise Comparisons with T-test**

A univariate post hoc analysis indicated notable seasonal differences in the SDI. Specifically, the spring season displayed a distinct diversity profile, significantly different from the fall and summer seasons ($p$ = .014 for both comparisons). In contrast, the similarity in SDI between summer and fall ($p$ = .806) suggested a consistent diversity pattern during these seasons. Moreover, the diversity was inconsistent across Stations for 2008 and 2013. Table 11 displays spatial analysis across Stations, revealing heterogeneity in zooplankton diversity, with significant differences among the Stations (all adjusted $p$ = 0.0014).

**Table 11.** Shannon Diversity Index Univariate Pairwise Comparison Using T-test:

| | LC12 | LC17 | LC19 | LC22 |
|---|---|---|---|---|
| LC17 | 0.0014 | - | - | - |
| LC19 | 0.0014 | 0.0014 | - | - |
| LC22 | 0.0014 | 0.52 | 0.0014 | - |
| LC3 | 0.0014 | 0.1537 | 0.0014 | 0.3956 |

## 4.7.1 Species Richness

Species Richness peaked at 30.0 at LC5 on August 19th, 2008, exceeding the interquartile range (IQR) average of 7.0. The IQR captures the central 50% of the data, showing the range from the 25th to the 75th percentile, which helps highlight the central tendency and dispersion in the data. Figure 32 shows the central tendencies and dispersions in the Species Richness data across Stations and periods.

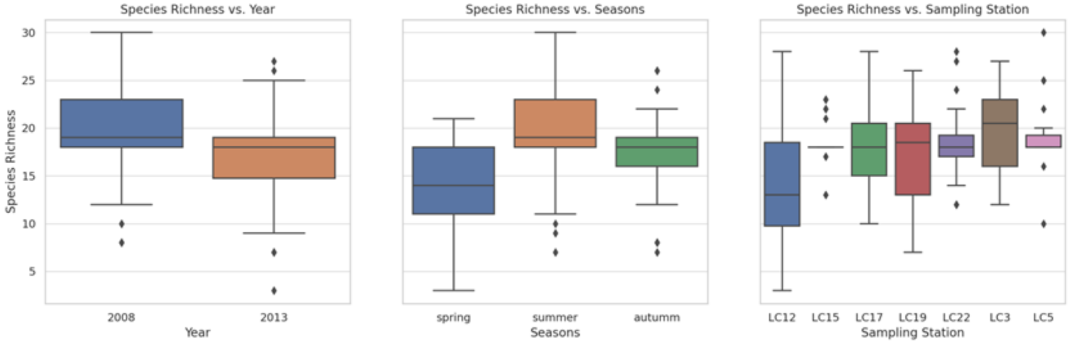


**Figure 32: Species Richness Box Plots Using Inclusive Dataset—**The box plots show the distribution of Species Richness with considerable differences among Stations. There is a significant peak at Station LC5 on August 19th, 2008. This value is considerably higher than the IQR for this Station.

### 4.7.2 PERMANOVA Results

The Species Richness PERMANOVA results revealed that sampling Station, Seasons, and Year significantly affected Species Richness (Table 12). The impact of Seasons was pronounced ($F_{(2, 111)}$ = 23.0773, $p < .001$). It highlighted the dynamic nature of temporal changes in Richness. As a result, the interaction term seasons-year was statistically significant.

**Table 12.** Zooplankton Richness PERMANOVA results:

| | Df | SumOfSqs | R2 | F | Pr(>F) | |
|---|---|---|---|---|---|---|
| S_Station | 6 | 0.4923 | 0.13741 | 5.5724 | 0.001 | *** |
| Seasons | 2 | 0.6796 | 0.18968 | 23.0773 | 0.001 | *** |
| Year | 1 | 0.3404 | 0.095 | 23.1167 | 0.001 | *** |
| S_Station:Year | 6 | 0.05 | 0.01394 | 0.5655 | 0.817 | N.S. |
| seasons: Year | 2 | 0.1903 | 0.0531 | 6.4606 | 0.002 | ** |
| S_Station:seasons | 12 | 0.196 | 0.05469 | 1.109 | 0.338 | N.S. |
| Residual | 111 | 1.6345 | 0.45617 | | | |
| Total | 140 | 3.5831 | 1 | | | |

- "***" denotes p < 0.001, indicating a highly significant impact.

- ** signifies p< 0.01, indicating a significant impact.
- "*" signifies p < 0.05, suggesting a significant impact.
- N.S. under 'Significance' indicates a non-significant result.

**Taxonomic Richness - Pairwise Comparisons Using T-tests**

The post-hoc tests indicated significant differences between Years in terms of Richness (*p* = .00027). The seasonal analysis showed significant differences in Richness between Spring and Summer (*p* < .001), Spring and Fall (*p* = .0259), and Summer and Fall (*p* = .0022). Spatially, there was homogeneity in species richness among sampling Stations (Table 13).

**Table 13.** Richness Pairwise Comparison Using T-test:

| | LC12 | LC17 | LC19 | LC22 |
|---|---|---|---|---|
| LC17 | 0.326 | - | - | - |
| LC19 | 0.873 | 1 | - | - |
| LC22 | 0.248 | 1 | 1 | - |
| LC3 | 0.084 | 1 | 1 | 1 |

## 4.8.1 Integrated Analysis of Zooplankton Community Patterns

Each ZCS metric offers a unique ecological perspective on the lake. The significant variations in ZCS observed over time and between Stations underlined the zooplankton community's natural responses to changes in environmental conditions and habitats. The null hypothesis proposed that no significant differences would be observed in the ZCS between Stations, Seasons, or between the two Years. However, the variations observed in the PERMANOVA analysis of Abund, Avg_Dens, SDI, and Richness reject the null hypothesis, indicating that ZCS showed significant variability across spatial and temporal scales within this lake system.

### 4.9.1 Principal Component Analysis of Zooplankton Community Structure

The initial two principal components identified by the PCA captured the most significant portion of the variability in the dataset (Abund PC1 = 38%, Avg_Dens PC2 = 35%) (Figure 33). The seasonal plots (Figures 35 to 37) displayed clustering according to the Stations, especially between LC12 and LC19, which supported the significant interaction observed in the PERMANOVA analysis.

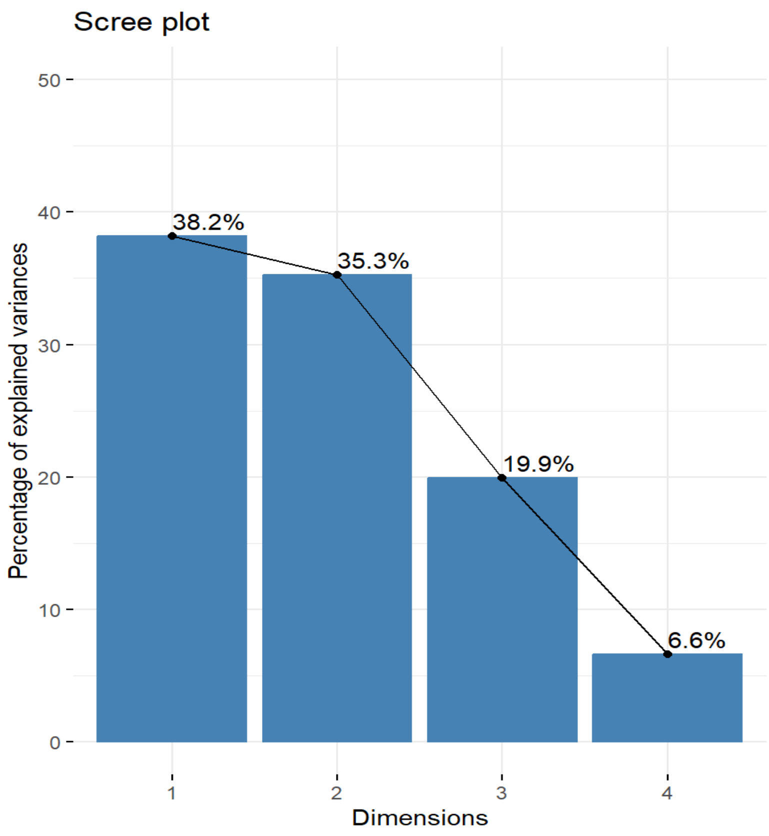


**Figure 33: The PCA Scree Plot of Zooplankton Community Structure Metrics—** This plot shows the percentage of variance explained by each principal component.

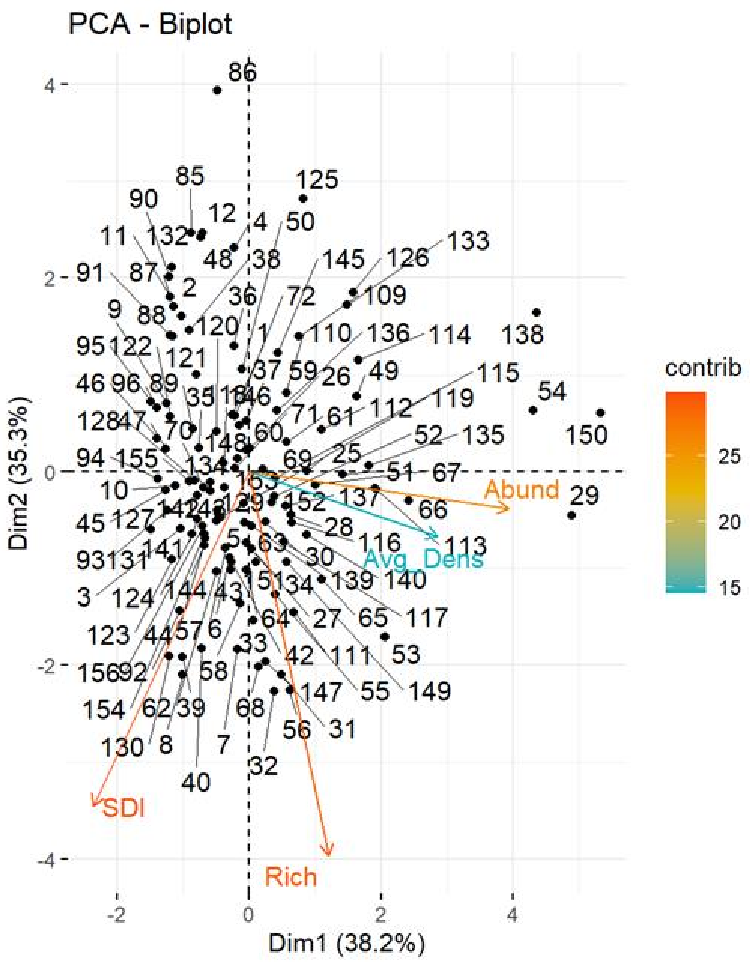


**Figure 34: PCA Biplot Indicating Individual Contributions to Zooplankton Community Structure (ZCS) Across PC1 (Dim1) and PC2 (Dim2) —** This plot illustrates the contributions of each variable to the first two principal components, highlighting correlations and potential ecological gradients within the ZCS. PC1 represents contributions from Abundance, Shannon Diversity Index (SDI), and Richness, while PC2 captures contributions from Average Density (Avg_Dens).

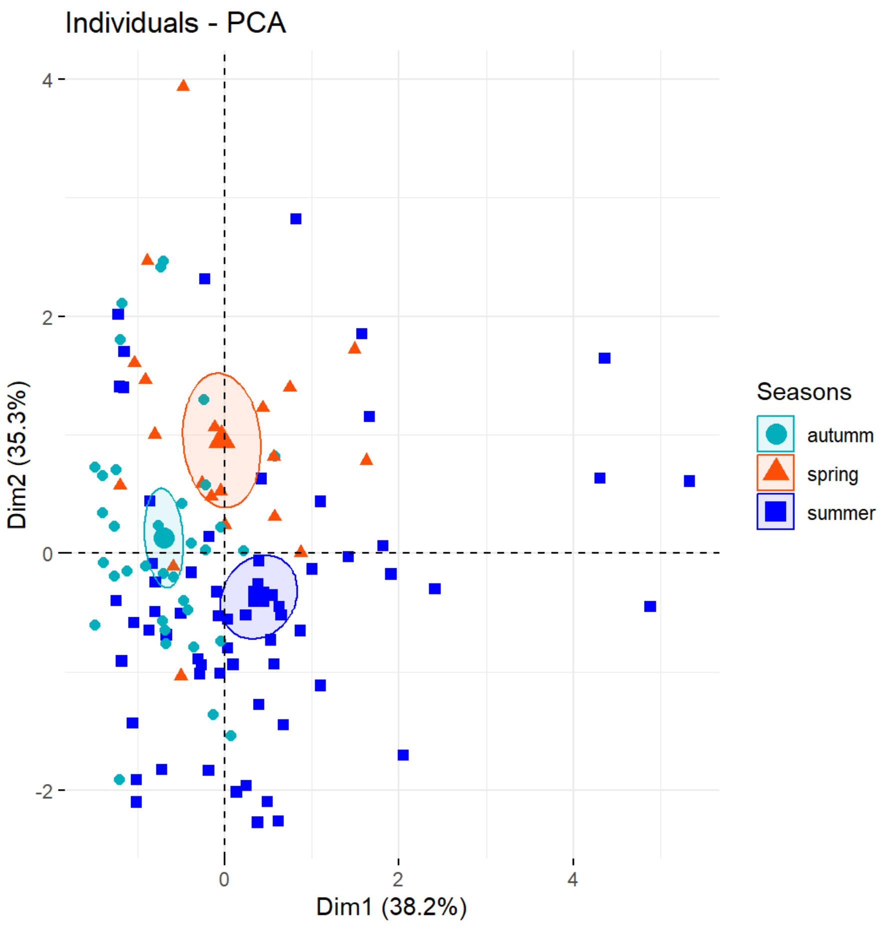


**Figure 35: PCA Biplot of Seasonal Patterns of Zooplankton Community Structure**—The PCA scores are coloured by Season, highlighting variations in ZCS metrics such as abundance (Abund), average density (Avg_Dens), Shannon Diversity Index (SDI), and species richness. This biplot illustrates the seasonal influences on zooplankton community composition.

**Figure 34: PCA Biplot of Zooplankton Community Structure Across Sampling Stations—** This plot shows the PCA scores coloured by Station, revealing spatial differences in the zooplankton community based on the conservative dataset using the metrics (Abund, Avg_Dens, SDI, and Richness).

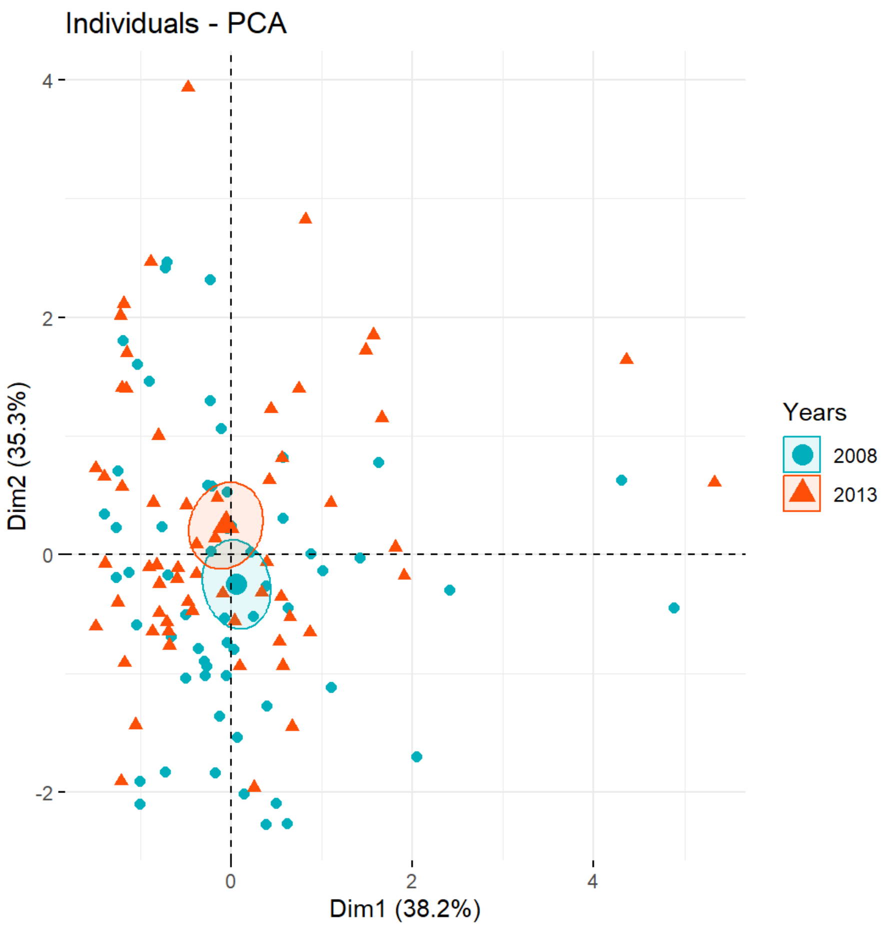


**Figure 35: PCA Biplot for Zooplankton Community Structure Across Years—**The PCA scores are coloured by year, illustrating temporal changes or stability in the ZCS over time and the long-term trends or shifts in community composition based on the conservative dataset using Abund, Avg_Dens, SDI, and Richness metrics.

### 4.10.1 Summary

This chapter investigated changes in the ZCS over time and space within Lake Couchiching in 2008 and 2013. The data revealed distinct patterns and shifts in zooplankton populations, showing their relationship with the variations in water quality parameters, as discussed in Chapter 3. Using the PCA and Permutational Multivariate Analysis of Variance (PERMANOVA; Anderson, 2001), significant differences in ZCS across Seasons, locations, and

Years were identified (PERMANOVA: $R^2 = 0.165$, $F(6, 111) = 6.64$, $p < 0.001$; seasons: $R^2 = 0.146$, $F(2, 111) = 17.60$, $p < 0.001$; years: $R^2 = 0.052$, $F(1, 111) = 12.64$, $p < 0.001$).

The connection between zooplankton and water quality was established through detailed statistical analysis and inspection of the data. Specific metrics, such as Abund and Richness, showed strong correlations with WQPs like pH and nutrient levels through a cross-comparison between WQP PCA and ZCS PCA, indicating their potential as bioindicators. This relationship was identified by examining the spatial and temporal distribution of zooplankton alongside variations in WQPs, utilizing PCA to highlight the primary factors driving these patterns (Zhang *et al.*, 2019), and PERMANOVA to confirm the statistical significance of these associations (Anderson 2001).

The analysis highlighted how seasonal and annual changes affected the zooplankton community, demonstrating the interplay between water quality and biological responses. These analyses provided crucial insights into the ecological dynamics of the lake. They established a foundation for a more detailed analysis of the interactions between ZCS and water quality parameters (WQPs) in Chapter 5.

# 5.0 Chapter 5: Interpretation of Findings: Water Quality and Zooplankton Interactions

## 5.1.1 Introduction

This chapter directly explores the relationship between Zooplankton Community Structure and water quality parameters. These findings will provide crucial ecological insights for maintaining a healthy level of zooplankton diversity in a water body. Understanding the role of ZCS can benefit lake systems, including Lake Couchiching.

### 5.1.2 Hypothesis tested

It is expected that a notable correlation exists between Zooplankton Community Structure (ZCS) and zooplankton taxa (Hypothesis A) and between ZCS metrics (abundance (Abund), average density (Avg_Dens), Shannon Weiner Diversity Index (SDI), and species richness (Richness) and water quality parameters (WQPs) (Hypothesis B). An extension of this hypothesis is that significant relationships exist between specific zooplankton taxa and WQPs, reflecting the complex interdependencies between the presence/absence and abundance of these taxa and the ecosystem.

## 5.2.1 Methods

### 5.2.2 Sampling and Analytical Approach

This study used generalized linear models (GLMs) and Negative Binomial regression techniques to examine the connections between taxa and WQPs in Lake Couchiching. The sampling strategy ensured appropriate spatial and temporal representations, facilitating a detailed analysis of zooplankton community dynamics.

For the GLM analysis, the data from sites LC5 and LC15 were omitted due to missing data points (conservative dataset). This choice aligned with best practices in ecological research for dealing with missing data (Benjamini & Hochberg, 1995; Osman *et al.*, 2018; Quinn & Keough, 2002). Additional sensitivity analyses affirmed the consistency of the observed patterns across this conservative and the more inclusive datasets (those that included the samples from sites LC5 and LC15).

The GLMs and negative binomial models enabled a detailed examination of complex zooplankton community metrics such as abundance (Abund), average density (Avg_Dens), Shannon Weiner Diversity Index (SDI), and taxonomic richness (Richness) and their association with WQPs like depth (Depth), Secchi depth (Secchi), pH, chlorophyll-a (Chl-a), Conductivity, total phosphorous (TP), and Total Kjeldjahl Nitrogen (TKN). This methodology, grounded in established practices (Benjamini & Hochberg, 1995), addressed the complex interactions between WQPs and ZCS variables commonly found in Lake Couchiching. Table 14 shows the taxa groups and their corresponding species names.

**Table 14.** Taxa Names for Map Categorization by Copepoda (Cyclopoids and Calanoids), Cladocera, Rotifera, and Other Zooplankton

| **Copepods (Cyclopoids)** |
|---|
| |
| *Acanthocyclops vernalis* |
| *Cyclops scutifer* |
| *Diacyclops nanus* |
| *Eucyclops agilis* |
| *Diacyclops thomasi* |
| *Microcyclops varicans* |
| *Mesocyclops edax* |
| *Tropocyclops prasinus mexicanus* |
| Cyclopoid (nauplius stage) — Cyclopoid nauplius stage |
| **Copepods (Calanoids)*:*** |

| |
|---|
| Calanoid (copepodite stage) — *Calanoid* copepodite stage |
| *Leptodiaptomus* spp. |
| *Epischura* spp. |
| *Limnocalanus macrurus* |
| *Skistodiaptomus oregonensis* |
| Calanoid (nauplius stage) — Calanoid nauplius stage |
| Harpacticoida (order *Harpacticoida*) |
| |
| **Cladocerans** |
| |
| *Athlebridae* spp. |
| *Acroperus harpae* |
| *Alona* spp. |
| *Bosmina longirostris* |
| *Ceriodaphnia lacustris* |
| *Ceriodaphnia sphaerula* |
| *Daphnia mendotae* |
| *Daphnia longiremis* |
| *Daphniasoma birgeii* |
| *Daphniasoma brachyurastrum* |
| *Eubosmina coregoni* |
| *Holopedium gibberum* |
| *Leptodiaptomus kindtii* |
| *Pleuroxus hamatus* |
| *Polyphemus pediculus* |
| *Sida crystallina* |
| *Ilyocryptus* spp. |
| ***Rotifers:*** |
| *Asplanchna* spp. |
| *Brachionus calyciflorus* |
| *Filinia* spp. |
| *Kellicottia bostoniensis* |
| *Kellicottia longispina* |
| *Keratella quadrata* |
| *Keratella cochlearis* |
| *Keratella earlinae* |
| *Keratella tecta* |
| *Lecane lunaris* |
| *Lecane mira* |
| *Monostyla lunaris* |
| *Monostyla bulla* |
| *Pleurotrocha* spp. |

| |
|---|
| *Monostyla stenroosi* |
| *Synchaeta* spp. |
| *Conochilus* spp. |
| *Gastropus* spp. |
| *Lepadella* spp. |
| *Pleuroxus truncatus* |
| *Monostyla quadridentata* |
| *Tylotrocha* spp. |
| *Euchlanis* spp. |
| *Trichocerca* spp. |
| *Notholca* spp. |
| *Navicula* spp. |
| *Pompholyx sulcata* |
| *Trichotria* spp. |
| *Stephanoceros fimbriatus* |
| *Hexarthra mira* |
| *Bipalpus hudsoni* |
| **Other Zooplankton Types:** |
| *Chaoborus* spp. |
| Hydracarina |
| Molluscs (phylum Mollusca) |
| Ostracoda (class of crustaceans) |
| Carapaces (dorsal exoskeleton part of unknown taxa) |
| Free-floating eggs (of unknown taxa) |
| Egg-bearing individuals (species-specific, clarify if known) |

## 5.3.1 Results

### 5.3.2 Statistical analysis of taxa contribution to ZCS

Two statistical tests were conducted to evaluate zooplankton taxa as bioindicators of the WQPs. First, differences between the two years (2008 and 2013), across three seasons (Spring, Summer, and Fall), and between Stations (LC3, LC5, LC12, LC15, LC17, LC19, and LC22) were examined to explore the relationship between ZCS and WQPs. Then, the best model for characterizing each zooplankton species and type was selected based on the AICc and delta AICc values, along with Akaike weights (Wi), to assess the influence of zooplankton taxa on ZCS.

In this context, a statistically significant coefficient for *Tropocyclops prasinus mexicanus* (T_mex) indicates that the presence or absence of this species has a measurable impact on the ZCS. For example, suppose *T. prasinus mexicanus* negatively influences overall zooplankton abundance or density. In that case, it may act as a dominant competitor, out-competing other species and leading to a reduction in ZCS. A negative impact on the Shannon Diversity Index would suggest that an increase in the abundance of *T. prasinus mexicanus* results in a less diverse zooplankton community due to competitive exclusion or predation on other species.

In terms of species richness, *T. prasinus mexicanus* may dominate to the extent that fewer other species can coexist or thrive in the same environment. This chapter will provide key examples of key species, including *T. prasinus mexicanus*, and their contributions to ZCS (Balcer et al., 1984).

### 5.3.2 Summary of Results for the Best Model Based on Copepoda

Structmod1a was the best model fit for Copepoda, with the lowest AIC value of 2668.584, the lowest corrected AIC value (AICc) of 2671.021, and the highest weight (Wi) of 0.407829 (Table 15B). Among the significant taxa, *Diacyclops nanus* and *Leptodiaptomus* spp had a positive impact on ZCS ($\beta = 38.342$, SE = 11.733, $t = 3.268$, $p = 0.00139$, **, $\beta = 16.725$, $p < 0.001$, *** for *Diacyclops nanus* and *Leptodiaptomus* spp, respectively), suggesting a critical role for these species in shaping community dynamics (Table 15A). This table summarizes the results from the multiple GLMs, showing the influence of various Copepoda taxa on the combined ZCS metrics.

**Table 15A.** GLM Results on the Influence of Copepoda Taxa on ZCS Metrics. This table presents the results of multiple Generalized Linear Models (GLMs) that analyzed the influence of various Copepoda taxa on each ZCS metric (abundance, average density, Shannon Diversity Index, and richness). Each row represents a Copepoda taxon and its estimated effect on the combined ZCS metrics, including abundance, average density, Shannon Diversity Index (SDI), and richness.

| **Coefficients:** | **Estimate** | **Std.** | **t value** | **Pr(>\|t\|)** | **Significance Level** |
|---|---|---|---|---|---|
| (Intercept) | -97.376 | 357.486 | -0.272 | 0.78575 | |
| *Acanthocyclops vernalis* | -7.032 | 13.231 | -0.531 | 0.59601 | |
| *Cyclops scutifer* | 9.1 | 5.528 | 1.646 | 0.10214 | |
| *Diacyclops nanus* | 38.342 | 11.733 | 3.268 | 0.00139 | ** |
| *Diacyclops thomasi* | -6.176 | 2.059 | -3 | 0.00324 | ** |
| *Mesocyclops edax* | -4.984 | 7.127 | -0.699 | 0.48557 | |
| *Tropocyclops prasinus mexicanus* | -16.204 | 5.977 | -2.711 | 0.00761 | ** |
| Calanoid (copepodite stage) | 9.008 | 8.803 | 1.023 | 0.30803 | |
| *Leptodiaptomus* spp. | 16.725 | 2.408 | 6.944 | 1.63E-10 | *** |
| *Epischura* spp. | 116.078 | 46.662 | 2.488 | 0.01413 | * |
| Harpacticoid (order Harpacticoida) | -21.132 | 202.297 | -0.104 | 0.91696 | |

In this table, the significance levels are indicated by asterisks in the p-value column as follows:

- *: p-value < 0.05 (significant)
- **: p-value < 0.01 (highly significant)
- ***: p-value < 0.001 (very highly significant)

**Table 15B.** ZCS bioindicator model selection using AICc, Delta AICc, and Akaike Weight Values. The table reveals Structmod1a as the best model based on its AICc, delta AICc, and Akaike weight values (Wi).

| | Df | AIC | AICc | deltaAICc | Wi |
|---|---|---|---|---|---|
| Structmod1a | 12 | 2668.584 | 2671.021 | 0 | 0.407829 |
| Structmod1d | 8 | 2670.472 | 2671.563 | 0.541942 | 0.311026 |
| Structmod1f | 6 | 2671.138 | 2671.765 | 0.743957 | 0.281145 |

Taxa included in the model were selected based on the Variance Inflation Factor (VIF) analysis. VIFs were calculated to detect multicollinearity among the taxa. Taxa with high VIF values were excluded to reduce multicollinearity, ensuring more reliable estimates for the remaining taxa. The best model, Structmod1a, was selected based on its lowest

AICc value (2671.021) and the highest Akaike weight (Wi = 0.407829). The model ultimately retained 12 taxa that were most influential on ZCS metrics. Taxa with insignificant contributions or high multicollinearity were excluded from the final model.

### 5.3.3 Summary of Results for the Best Cladocera Model

Structmod2b was the best model fit for Cladocera with the lowest AIC value of 2661.822, lowest corrected AIC value (AICc) of 2663.196, and the highest weight (Wi) of 0.6619301 (Table 16B). Amongst the significant taxa, *Daphniasoma birgeii* had a pronounced significant positive impact on ZCS ($\beta$= 41.07, $SE$= 4.8228, $t$= 8.516, $p < 0.001$, ***), indicating *Diaphnosoma bergeii* as the major Cladoceran bioindicator species shaping the ZCS in Lake Couchiching (Table 16A).

**Table 16A.** GLM results on Cladocera taxa influence on ZCS metrics

| Coefficients: | Estimate | Std. Error | t value | Pr(>\|t\|) | Significance Level |
|---|---|---|---|---|---|
| (Intercept) | 704.4192 | 325.6032 | 2.163 | 0.0323 | * |
| Bos_long | 0.7891 | 1.7856 | 0.442 | 0.6592 | |
| C_lacustris | -26.9203 | 19.7483 | -1.363 | 0.1751 | |
| C_sphaer | 205.5286 | 116.4607 | 1.765 | 0.0799 | . |
| D_mend | 39.6994 | 16.569 | 2.396 | 0.018 | * |
| D_birgeii | 41.07 | 4.8228 | 8.516 | 3.10E-14 | *** |
| H_gibber | -190.0733 | 80.5403 | -2.36 | 0.0197 | * |
| S_crysta | -799.5965 | 1147.0436 | -0.697 | 0.487 | |

In this table, the significance levels are indicated by asterisks in the p-value column as follows:

- *: p-value < 0.05 (significant)
- **: p-value < 0.01 (highly significant)
- ***: p-value < 0.001 (very highly significant)

**Table 16B.** ZCS Cladocera bioindicator model selection using AICc, Delta AICc, and Akaike Weight Values: The table reveals Structmod2b as the best model based on its AICc, delta AICc and Akaike weight values.

| | Df | AIC | AICc | deltaAICc | Wi |
|---|---|---|---|---|---|
| Structmod2b | 9 | 2661.822 | 2663.196 | 0 | 0.6619301 |

| | | | | | |
|---|---|---|---|---|---|
| Structmod2a | 10 | 2663.678 | 2665.371 | 2.17503 | 0.2231056 |
| Structmod2c | 8 | 2665.606 | 2666.697 | 3.501077 | 0.1149643 |
| Structmod2d | 7 | 2666.431 | 2667.273 | 4.077896 | 0.6619301 |
| Structmod2e | 6 | 2666.892 | 2667.519 | 4.323098 | 0.2231056 |
| Structmod2f | 5 | 2667.513 | 2667.958 | 4.762271 | 0.1149643 |

### 5.3.4 Summary of Results for the Best Model Based on Rotifera

Structmod3a was the best model fit for Rotifera with the lowest AIC value of 2232.683, lowest corrected AIC value (AICc) of 2246.063, and the highest weight (Wi) of 1.00E+00 (Tables 17A and 17B). *Conochilus* spp and *Anuraeopsis navicular* represented the best predictors for this model, having significant outcomes ($\beta = 641.98096$, *SE*= 87.06543, *t*= 7.374, $p < 0.001$, ***, $\beta$= 1.1283, *SE*= 0.03942, *t*= 28.6 $p < 0.001$, *** for Conoch_spp and A_navi, respectively).

**Table 17A.** GLM Results on Rotifera Taxa Influence on ZCS Metrics.

| Coefficients: | Estimate | Std. Error | t value | Pr(>\|t\|) | Significance level |
|---|---|---|---|---|---|
| (Intercept) | 986.55341 | 141.93337 | 6.951 | 1.54E-10 | *** |
| *Monostyla stenroosi* | 3.46968 | 1.95118 | 1.778 | 0.0777 | . |
| *Conochilus* spp. | 1.1283 | 0.03942 | 28.62 | < 2e-16 | *** |
| *Lepadella* spp. | 52.38698 | 70.07587 | 0.748 | 0.4561 | |
| *Pleuroxus truncatus* | 18.49405 | 71.54565 | 0.258 | 0.7964 | |
| *Navicula* spp. | 641.98096 | 87.06543 | 7.374 | 1.68E-11 | *** |
| *Pompholyx sulcata* | 261.23604 | 211.64156 | 1.234 | 0.2193 | |
| *Trichotria* spp. | -175.12362 | 115.34827 | -1.518 | 0.1314 | |
| *Stephanoceros fimbriatus* | 326.27302 | 195.60472 | 1.668 | 0.0977 | . |
| *Bipalpus hudsoni* | -60.06779 | 101.91644 | -0.589 | 0.5566 | |

In this table, the significance levels are indicated by asterisks in the p-value column as follows:

- *: p-value < 0.05 (Significant)
- **: p-value < 0.01 (highly significant)
- ***: p-value < 0.001 (very highly significant)

**Table 17B**. ZCS Rotifera bioindicator model selection using AICc, Delta AICc, and Akaike Weight Values: The table reveals Structmod3a as the best model based on its AICc, delta AICc and Akaike weight values.

| | df | AIC | AICc | deltaAICc | Wi |
|---|---|---|---|---|---|
| Structmod3a | 27 | 2232.683 | 2246.063 | 0 | 1.00E+00 |

| | | | | | |
|---|---|---|---|---|---|
| Structmod3b | 17 | 2459.029 | 2464.004 | 217.9408 | 4.73E-48 |
| Structmod3c | 16 | 2460.055 | 2464.442 | 218.379 | 3.80E-48 |
| Structmod3d | 16 | 2460.055 | 2464.442 | 218.379 | 3.80E-48 |
| Structmod3f | 14 | 2461.624 | 2464.958 | 218.8943 | 2.94E-48 |
| Structmod3e | 15 | 2463.332 | 2467.172 | 221.1089 | 9.70E-49 |
| Structmod3h | 12 | 2466.441 | 2468.879 | 222.8155 | 4.13E-49 |
| Structmod3i | 11 | 2467.033 | 2469.079 | 223.016 | 3.74E-49 |
| Structmod3j | 10 | 2467.492 | 2469.184 | 223.1212 | 3.55E-49 |
| Structmod3g | 13 | 2468.289 | 2471.156 | 225.0923 | 1.32E-49 |
| Structmod3k | 9 | 2513.412 | 2514.786 | 268.7229 | 4.44E-59 |
| Structmod3p | 4 | 2741.075 | 2741.369 | 495.3056 | 2.79E-108 |
| Structmod3o | 5 | 2743.013 | 2743.458 | 497.3944 | 9.82E-109 |
| Structmod3n | 6 | 2744.387 | 2745.014 | 498.9509 | 4.51E-109 |
| Structmod3m | 7 | 2746.058 | 2746.9 | 500.8369 | 1.76E-109 |
| Structmod3l | 8 | 2747.851 | 2748.942 | 502.8791 | 6.33E-110 |

### 5.3.5 Summary of Best Models for Other Zooplankton

The model, Structmod4d, with the lowest AIC and AICc values (2597.286 and 2597.912, respectively) and the highest weight (Wi = 0.541670988) (Table 18B), was the best fit for other zooplankton in Lake Couchiching. *Chaoborus* spp., molluscs, and free-floating eggs had statistically significant impacts on the model. effects on ZCS ($\beta$= 446.2553, *SE*= 137.2173, *t*= 3.252, *p*= 0.00144, **, $\beta$= 1.9883, *SE*= 0.2449, *t*= 8.12, *p* < 0.001, ***, $\beta$= 26.476, *SE*= 2.3762, *t*= 11.142, *p* < 0.001, *** for Chaob_spp, Molluscs, and FreeEgg, respectively) (Table 18A).

**Table 18A.** GLM Results on Rotifera Taxa Influence on ZCS Metrics.

| Coefficients: | Estimate | Std. Error | t value | Pr(>\|t\|) | |
|---|---|---|---|---|---|
| (Intercept) | 232.5481 | 239.4139 | 0.971 | 0.33311 | |
| Chaob_spp | 446.2553 | 137.2173 | 3.252 | 0.00144 | ** |
| Molluscs | 1.9883 | 0.2449 | 8.12 | 2.50E-13 | *** |
| Ostrocod | -73.0105 | 131.1699 | -0.557 | 0.57871 | |
| FreeEgg | 26.476 | 2.3762 | 11.142 | < 2e-16 | *** |

In this table, the significance levels are indicated by asterisks in the p-value column as follows:

- *: p-value < 0.05 (Significant)
- **: p-value < 0.01 (highly significant)
- ***: p-value < 0.001 (very highly significant)

**Table 18B**. Other Zooplankton taxa bioindicator model selection using AICc, Delta AICc, and Akaike Weight Values: The table reveals Structmod4d as the best model fit for this category based on its AICc, delta AICc and Akaike weight values.

| | df | AIC | AICc | | Wi |
|---|---|---|---|---|---|
| Structmod4d | 6 | 2597.286 | 2597.912 | 0 | 0.541670988 |
| Structmod4c | 7 | 2599.096 | 2599.938 | 2.025535 | 0.196741646 |
| Structmod4b | 8 | 2598.913 | 2600.004 | 2.091881 | 0.190322206 |
| Structmod4a | 9 | 2600.84 | 2602.214 | 4.301429 | 0.063051023 |
| Structmod4e | 5 | 2605.846 | 2606.29 | 8.377604 | 0.008214137 |

These results show other zooplankton taxa that significantly contributed to ZCS. So *Diacyclops nanus, Leptodiaptomus* spp*, Diaphnosoma bergeii, A. navicula, Conochilus* spp*, Chaborus* spp*,* Molluscs*, and* FreeEggs played significant roles in determining ZCS in Lake Couchiching confirming the hypothesis that specific taxa may play a significant role in determining ZCS.

## 5.4.1 WQP Effects on ZCS Metrics

### 5.4.2 Model of WQP Effects on Zooplankton Abundance

This section focuses on the effects of WQPs on zooplankton abundance**.** Conductivity was a significant predictor of abundance, showing a negative relationship (Estimate = -0.2679, SE = 0.1291, t = -2.075, p = 0.0380) (Appendix A Table E). Additionally, significant interaction effects were observed between Secchi and TP (Estimate = 0.04860, SE = 0.02374, t = 2.048, p = 0.0406). Other interactions, such as pH (Estimate = 0.7434, SE = 0.4369, t = 1.702, p = 0.0888) and Conductivity (Estimate = 0.0006408, SE = 0.0003049, t = 2.102, p = 0.0355), showed near-significance, indicating that the interaction between these factors is important for explaining zooplankton abundance. However, Depth and other individual variables were not significant. The AIC of the model was 2335.9, indicating a reasonable fit, though not the best

### 5.4.3 Model of WQP Effects on Average Density

The GLM analysis of WQP impacts on Avg_Dens did not identify any significant predictors. Variables such as Depth, Secchi, pH, and others showed no strong relationships with Avg_Dens (all p-values > 0.1). Despite the lack of significance, the AIC value was 98.79, suggesting that the model fits the data well in terms of balancing model complexity and goodness of fit. This low AIC implies that while predictors were not significant individually, the overall model may still explain the patterns in the data reasonably well (Appendix B Table F).

### 5.4.4 Model of WQP Effects on Shannon Weiner Diversity Index

No significant predictors for the SDI were identified in the model. Variables such as Depth, Secchi depth, Conductivity, and Chl a showed no significant effect on SDI (all p-values > 0.5). This result suggests that the tested WQPs did not strongly influence the SDI. The AIC value was 409.68, indicating a moderate fit, meaning the model explains some of the variation but not strongly (Appendix B Table G).

### 5.4.5 Model of WQP Effects on Species Richness

The GLM analysis of WQP effects on Richness showed some significant and near-significant relationships. pH was nearly significant (Estimate = -2.354, SE = 1.212, t = -1.943, p = 0.0521), and the interaction between pH and TP was significant (Estimate = 0.2445, SE = 0.1244, t = 1.965, p = 0.0494). TP was also nearly significant (Estimate = -1.934, SE = 1.003, t = -1.929, p = 0.0537), suggesting that nutrient levels and pH may play a role in influencing species richness. The AIC value for this model was 854.95, which suggests a moderate fit (Appendix B Table H).

The GLM results uncovered significant associations between pH, TP, and ZCS variables, supporting the hypothesis that ZCS showed spatial and temporal shifts influenced by environmental variables such as water depth, clarity, and nutrient levels. These insights are important for developing effective management and conservation strategies to maintain Lake Couchiching's ecological health.

## 5.5.1 Spatial Analysis of Zooplankton Community Structure in Lake Couchiching: Canonical Correspondence Analysis (Part 1 of 3)

### 5.5.2 Influence of Environmental Variables

Figure 37 and Tables 19 and 20 present the outcomes of the Canonical Correspondence Analysis (CCA) of zooplankton composition in relation to environmental variables. CCA Axis 1 showed a significant impact from depth and Secchi depth on zooplankton community composition, indicating that these variables are key drivers of zooplankton distribution. CCA Axis 2, on the other hand, reflects the influence of Richness and TP, suggesting that nutrient levels and species diversity play secondary roles in shaping zooplankton distribution in Lake Couchiching.

The scores for environmental variables, based on Figures 37 to 39, illustrate their distinct relationships with ZCS at each Station (for the additional tables, see Appendix B, Tables I & J). As illustrated in Figure 39, the vectors for Secchi and Conductivity point in the same direction along positive CCA1 and CCA2, indicating a complex relationship between water clarity and nutrient availability. While Secchi depth reflects transparent water, conductivity often correlates with pollution or nutrient loading. The similar magnitude and direction of these vectors suggest that *Leptodiaptomus* spp (Lept_spp) and other zooplankton thrive in conditions where there is enhanced water clarity despite elevated conductivity. This preference in water quality may indicate that clearer water and nutrient-rich environments, often associated with pollution, may favour certain zooplankton taxa, resulting in shifts in community composition.

### 5.5.3 Spatial Variance of ZCS

This study revealed spatial heterogeneity in zooplankton assemblages across Lake Couchiching. For example, Station LC19 could be characterized as an ecotone, showing a transition in species composition with a community of filter feeders and predators. Similarly, Station LC3 appeared to provide a refuge from predators, allowing large-bodied Cladocera species to thrive undisturbed, particularly during periods of water mixing (Figures 38 and 39).

### 5.5.4 Spatial CCA Results

The Canonical Correspondence Analysis (CCA) plots illustrated zooplankton distribution in relation to environmental gradients in various sampling Stations, such as LC3, LC12, and LC19, with additional plots in Appendix C Figures A to D . Taxa like calanoid copepodites and *Ceriodaphnia lacustris* were identified as potential bioindicators due to their distinct positioning according to Depth and Conductivity gradients.

The biplot shows WQP gradients associated with LC5 along CCA Axis 1, which are Depth (0.224187) and Secchi (0.222499), both of which are positively correlated. At the same time, pH (-0.48146) and TP (0.460241) also show strong associations. CCA Axis 2 is influenced by Conductivity (0.307279), TKN (0.440349), and Richness (-0.72659), with notable directional associations. Species at this Station demonstrated interesting adaptive traits based on these gradients.

For example, calanoid and cyclopoid copepods preferred more transparent water, as indicated by their association with the Secchi vector. Cladocera species (e.g., *Alona* spp., *Bosmina longirostris*) showed a broader distribution, indicating less dependence on a particular level of transparency. At the bottom left, Rotifera taxa (e.g., *Keratella cochlearis*) preferred more turbid water with moderate nutrient levels. In contrast, the rotifers belonging to *Conochilus* spp. were positively correlated with both water transparency and pH, suggesting a preference for clearer water with higher pH levels. *Ceriodaphnia sphaericus* showed a negative correlation with both CCA1 and CCA2, indicating a preference for shallow regions with higher levels of TP and TKN. These species thrive in nutrient-rich, shallow waters despite the potential for increased predation pressure in such environments. Thus, the biplot highlighted the importance of water clarity and nutrient levels in shaping the zooplankton community at Station LC5 (see Appendix C Figure D).

Overall, the observed spatial and temporal variation in WQPs and ZCS supported the hypotheses that specific taxa correlate with particular WQPs and ZCS metrics in Lake Couchiching.

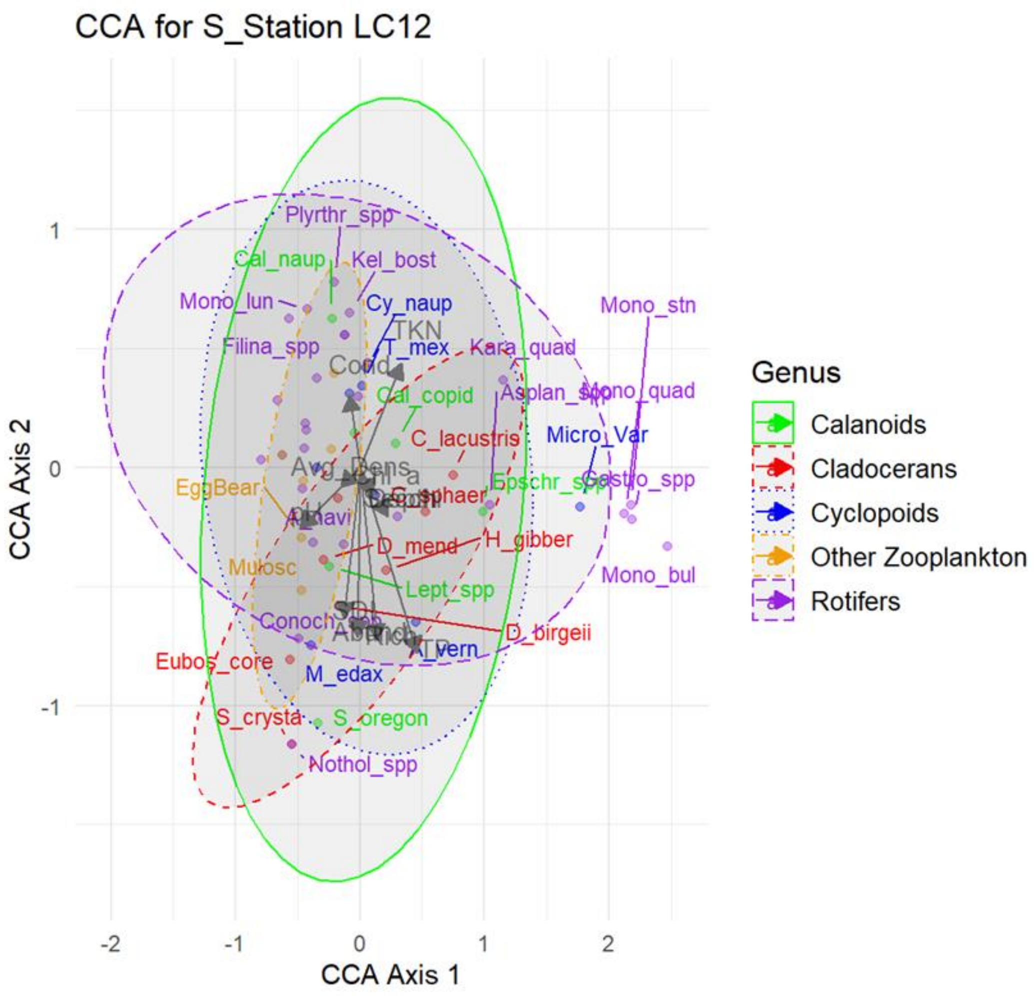


**Figure 36: CCA biplot for Station LC12**—This biplot shows the relationship between taxa and environmental variables, showcasing the influence of pH and conductivity on patterns of zooplankton distribution.

**Table 19.** The table shows the Eigenvalues and the significant explanatory power of the first ten CCA axes in species environmental variable correlation.

| | Eigenvalue | Proportion Explained | Cumulative Proportion |
|---|---|---|---|
| CCA1 | 0.7374 | 0.3803 | 0.3803 |
| CCA2 | 0.4563 | 0.2354 | 0.6157 |
| CCA3 | 0.2757 | 0.1422 | 0.7579 |
| CCA4 | 0.15436 | 0.07962 | 0.83751 |
| CCA5 | 0.10263 | 0.05294 | 0.89044 |
| CCA6 | 0.0758 | 0.0391 | 0.9295 |
| CCA7 | 0.05116 | 0.02639 | 0.95593 |
| CCA8 | 0.0432 | 0.02228 | 0.97821 |

| | | | |
|---|---|---|---|
| CCA9 | 0.02896 | 0.01494 | 0.99315 |
| CCA10 | 0.013274 | 0.006846 | 1 |

**Table 20.** LC12 Biplot Scores for Crucial Environmental Variables: This table summarizes critical environmental variables' scores on the first two canonical axes (CCA1 and CCA2), indicating how each variable is related to the zooplankton community distribution at LC12.

| Variable | CCA1 | CCA2 |
|---|---|---|
| Depth | 0.224187 | -0.20486 |
| Secchi | 0.222499 | -0.20515 |
| pH | -0.48146 | -0.25411 |
| Conductivity | -0.0857 | 0.307279 |
| Chl_a | 0.104378 | -0.11655 |
| TP | 0.460241 | -0.77797 |
| TKN | 0.331361 | 0.440349 |
| Abund | -0.01811 | -0.71484 |
| Avg_Dens | -0.15509 | -0.08258 |
| SDI | -0.13072 | -0.63261 |
| Rich | 0.145221 | -0.72659 |

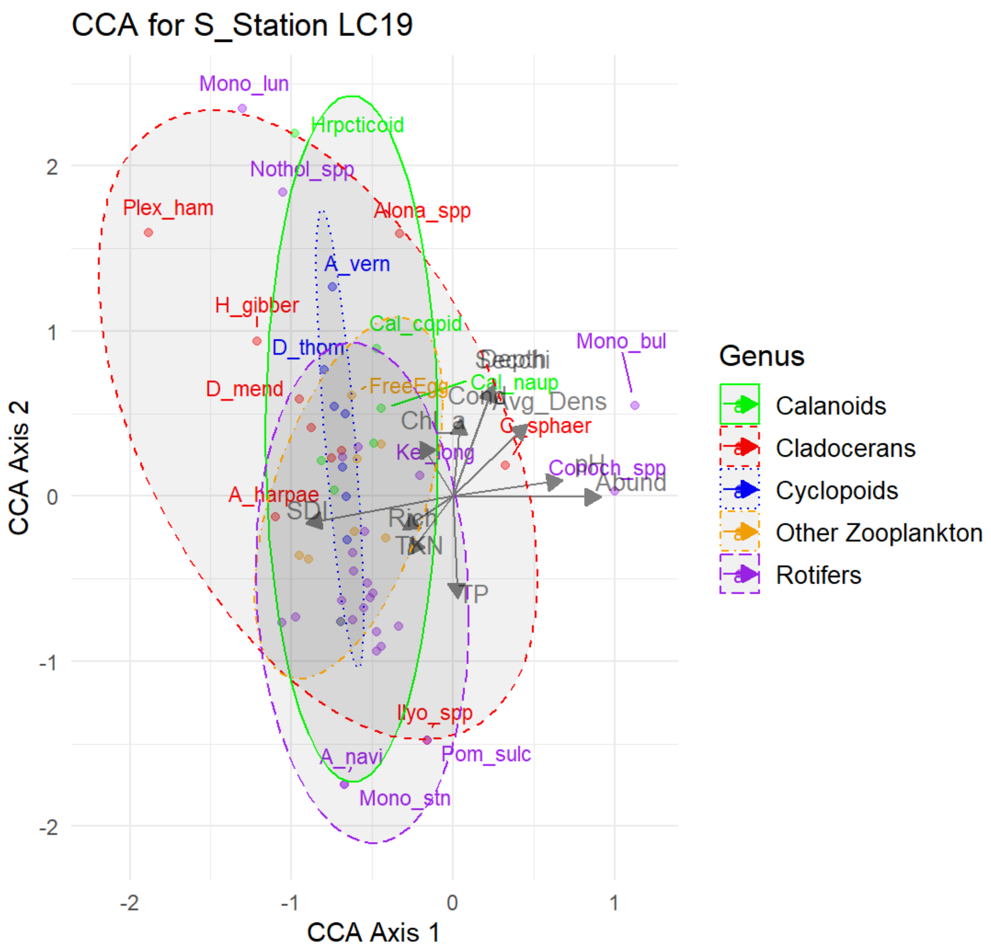


**Figure 37: CCA biplot for Station LC19—**Features the relationship between zooplankton species and environmental variables at Station LC19, showcasing the influence of total phosphorus and chlorophyll-*a* on zooplankton distribution.

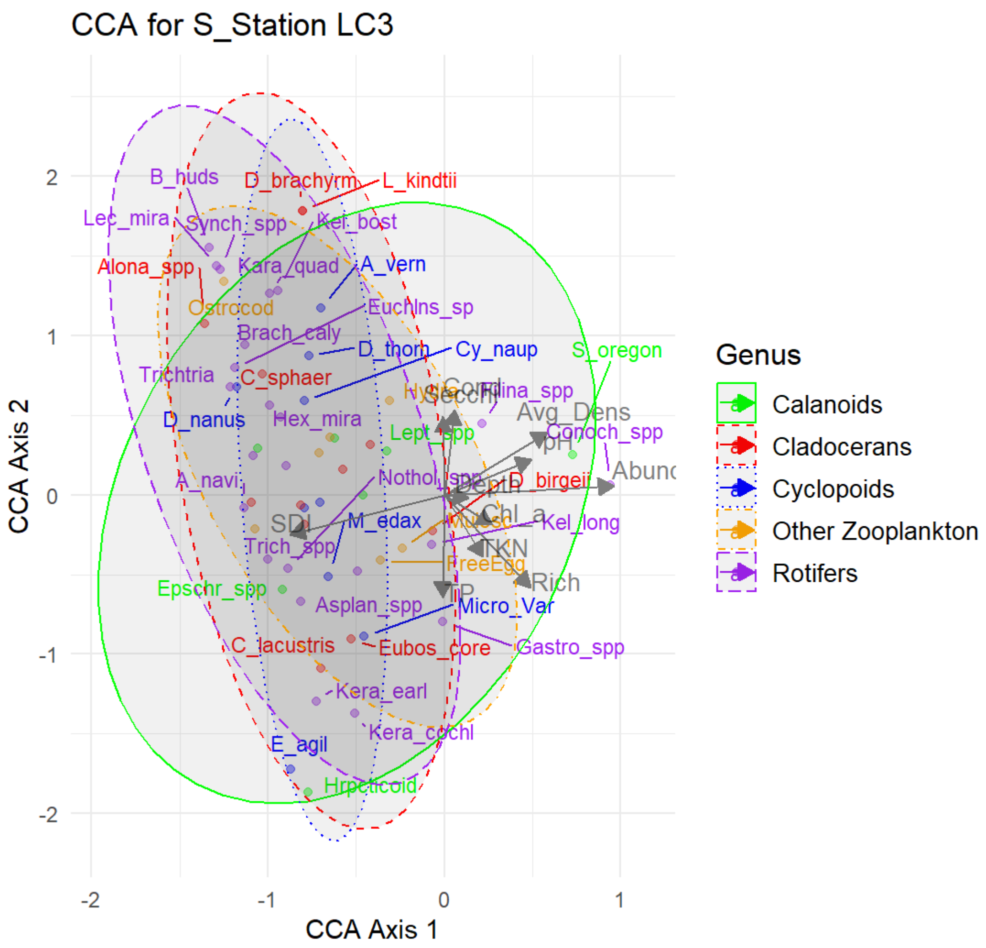


**Figure 38: CCA biplot for Station LC3**—This biplot illustrates the relationship between zooplankton species and environmental variables at Station LC3, highlighting the species strongly influenced by water depth and pH.

### 5.5.5 Seasonal Dynamics of Zooplankton Community Structure in Lake Couchiching: Canonical Correspondence Analysis Results (Part 2 of 3)

The eigenvalues for the first two canonical axes, CCA1 (0.1984) and CCA2 (0.1875) demonstrated a strong relationship between zooplankton communities and environmental variables (refer to Appendix B, Tables K to M). CCA1 and CCA2 accounted for approximately 24.91% and 23.54% of the constrained variance, respectively (see Figures N, O, and P in Appendix B). Seasonal CCA results revealed strong associations between zooplankton community composition and environmental variables, particularly in Spring. Depth, pH, and SDI were the primary drivers. Taxa like *Acanthocyclops vernalis*, *Cyclops scutifer*, and *Diacyclops nanus* showed a positive affinity for Depth and pH, while these parameters negatively affected species like *Eucyclops agilis* and *Microcyclops varicans* (see Figure N in Appendix B).

The Summer analysis showed a profound influence of water clarity and nutrient levels on zooplankton dynamics for calanoid copepods and *Leptodora* spp. These changes were aligned closely with changes in water clarity. *Leptodiaptomus* spp and Harpacticoid Copepods responded to changes in nutrient levels (see Figure O in Appendix B ).

The Fall CCA illustrated that Chl *a* and TKN significantly influenced zooplankton taxa, with species like *Eubosmina coregoni* and *Holopedium gibberum* favouring nutrient-rich conditions (see Figure P in Appendix B). This seasonally adjusted perspective underscores the adaptability of zooplankton to changing nutrient and productivity levels in Lake Couchiching. These CCA results suggested that seasonal variations in a number of environmental conditions shape the ZCS in Lake Couchiching.

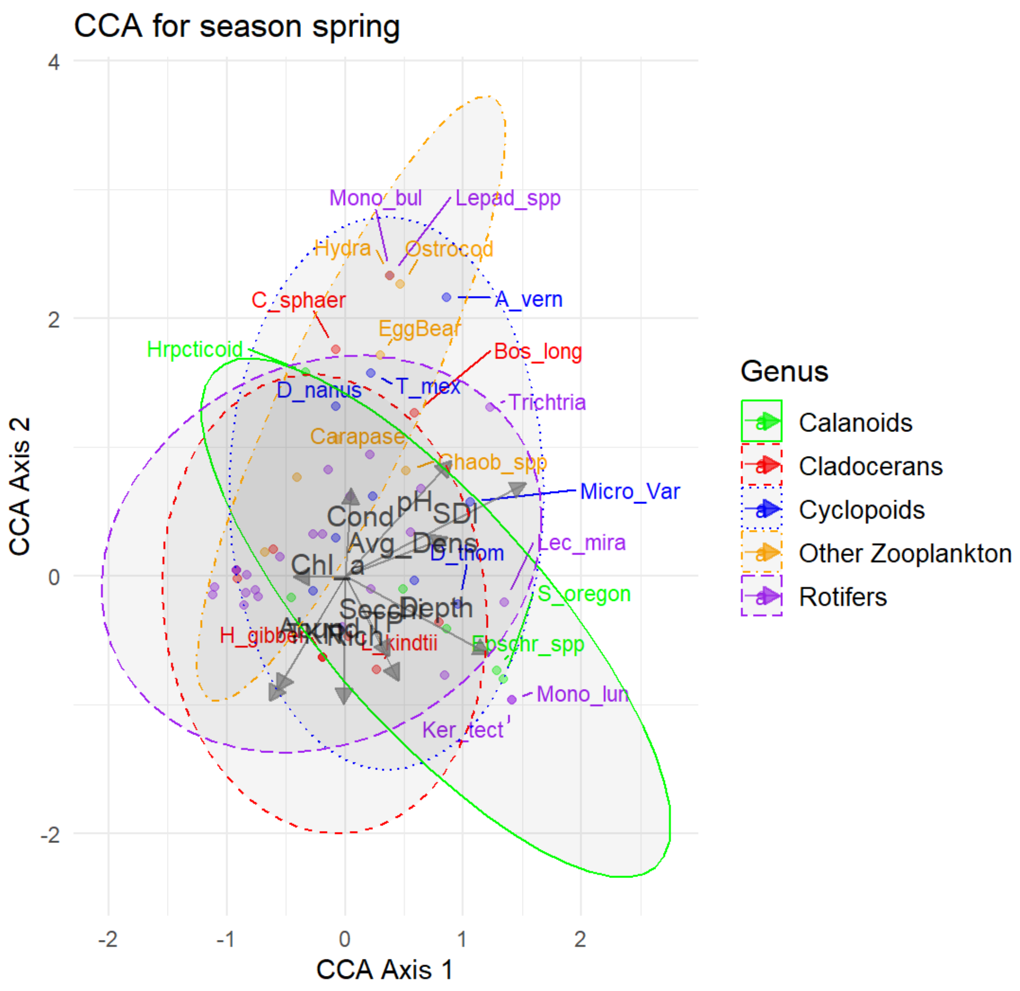


**Figure 39: Seasonal CCA Biplot for Lake Couchiching**—This biplot represents the relationship between taxa and environmental variables in Spring, highlighting the influence of Conductivity on zooplankton distribution patterns.  The influence of Chl *a* is present but appears less pronounced.

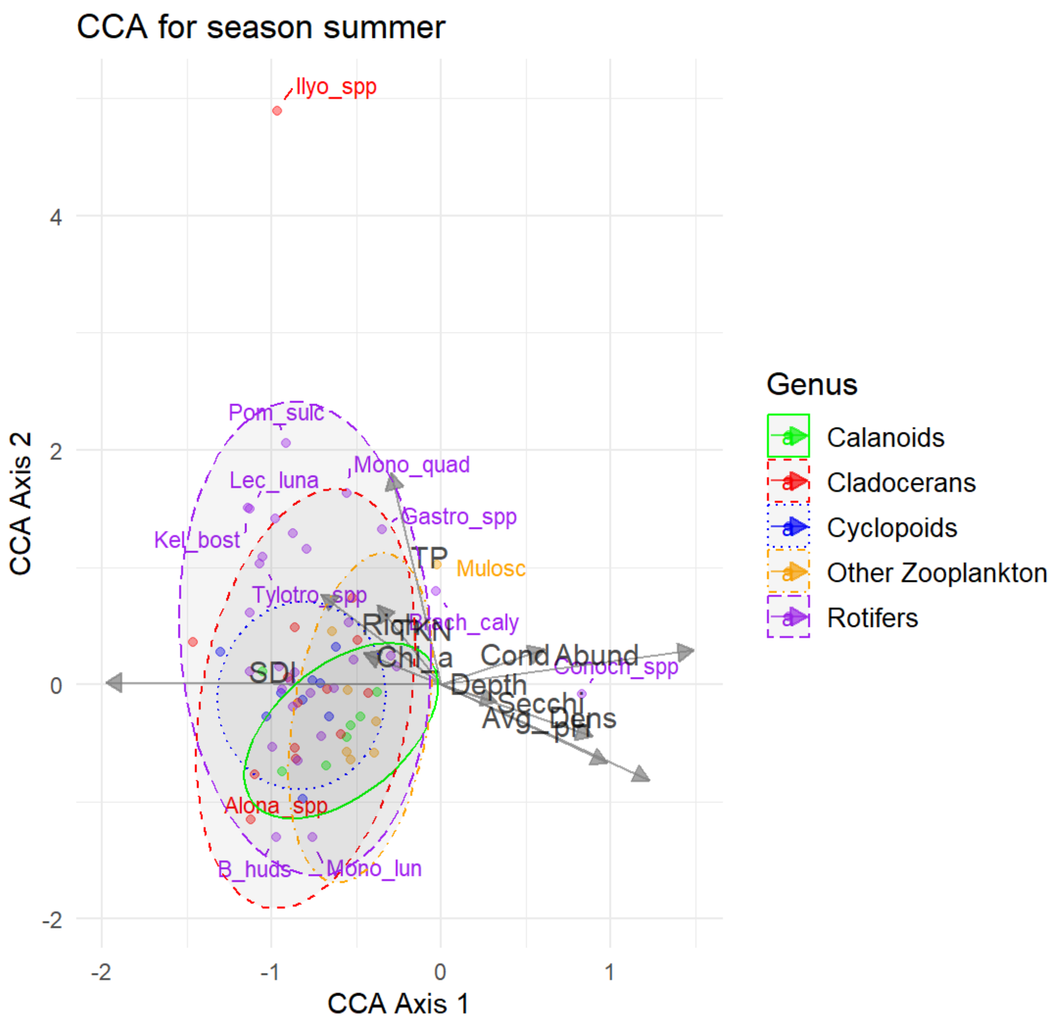


**Figure 40: Seasonal CCA Biplot for Lake Couchiching**—This biplot represents the relationship between taxa and environmental variables in Summer, highlighting the influence of Conductivity, Chl *a*, and other factors such as TP and Depth on zooplankton distribution patterns.

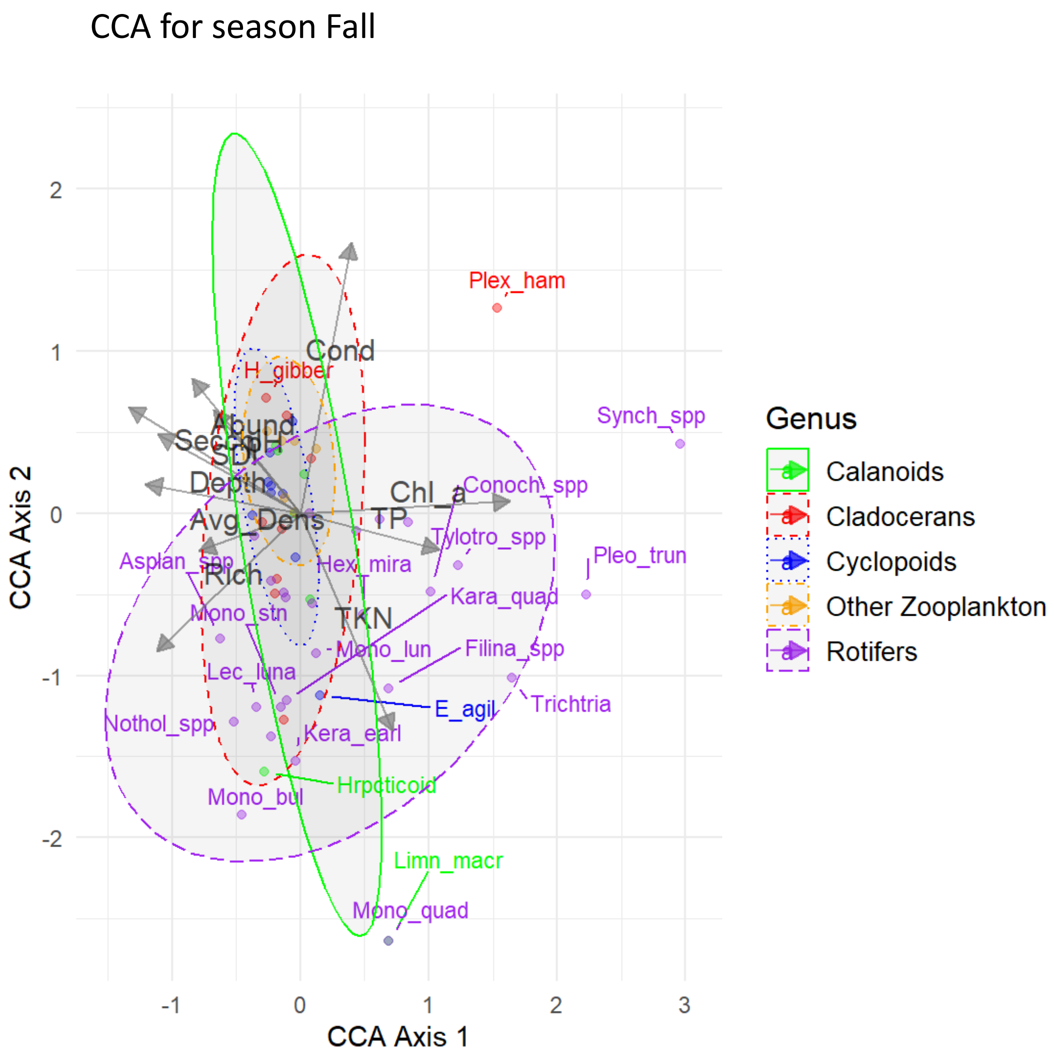


**Figure 41: Seasonal CCA Biplot for Lake Couchiching—**This biplot represents the relationship between taxa and environmental variables in Fall, highlighting the influence of Conductivity, Chl *a*, and other factors such as TP, TKN, and Depth on zooplankton distribution patterns**.**

### 5.5.6 Annual Variability in Zooplankton Community Structure and Environmental Variables in Lake Couchiching: Canonical Correspondence Analysis (Part 3 of 3)

The Canonical Correspondence Analysis (CCA) model explained 50.72% of the variation in zooplankton community structure (ZCS), with a constrained inertia of 0.9161. The results indicated the predictive power and statistical significance of environmental variables in explaining differences in ZCS between 2008 and 2013.

The Canonical Correspondence Analyses (CCA) for 2008 and 2013 illustrate distinct relationships between the zooplankton community composition and environmental variables. These biplots show clear differences between the two years in terms of the zooplankton community in response to environmental changes.

In 2008, Depth and pH were identified as significant environmental drivers influencing zooplankton communities (Figure 42). Taxa such as *Acanthocyclops vernalis* (A_vern), *Cyclopoid copepods* (Cy_copid), and *Diacyclops nanus* (D_nanus) were positively correlated with increased depth and pH levels. Conversely, *Eudiaptomus agilis* (E_agil) and *Microcyclops varicans* (Micro_Var) were negatively correlated with the same environmental parameters. The clustering of plotted taxa acronyms such as A_vern, Cy_copid, and D_nanus near these environmental vectors indicated their positive responses to these conditions.

In 2013, as in 2008, water Depth and pH continued to play crucial roles in determining ZCS (Figure 43). However, the responses of particular taxa showed some contrasts between the two years. These contrasts may reflect ecological or biological changes over the five years. For instance, the CCA for 2013 shows that taxa such as *Daphnia galatea mendotea* (D_mend) and Mollusca exhibited a positive affinity towards the environmental vectors, while taxa like *Chaoborus* spp. (Chaob_spp) showed significant shifts in their distribution. These changes suggest adaptations or responses to altered environmental conditions, highlighting the dynamic nature of the lake's ecosystem. The robust fit of the CCA model to the observed data, with an AIC of 840.56, underscores the model's value in detecting these significant changes.

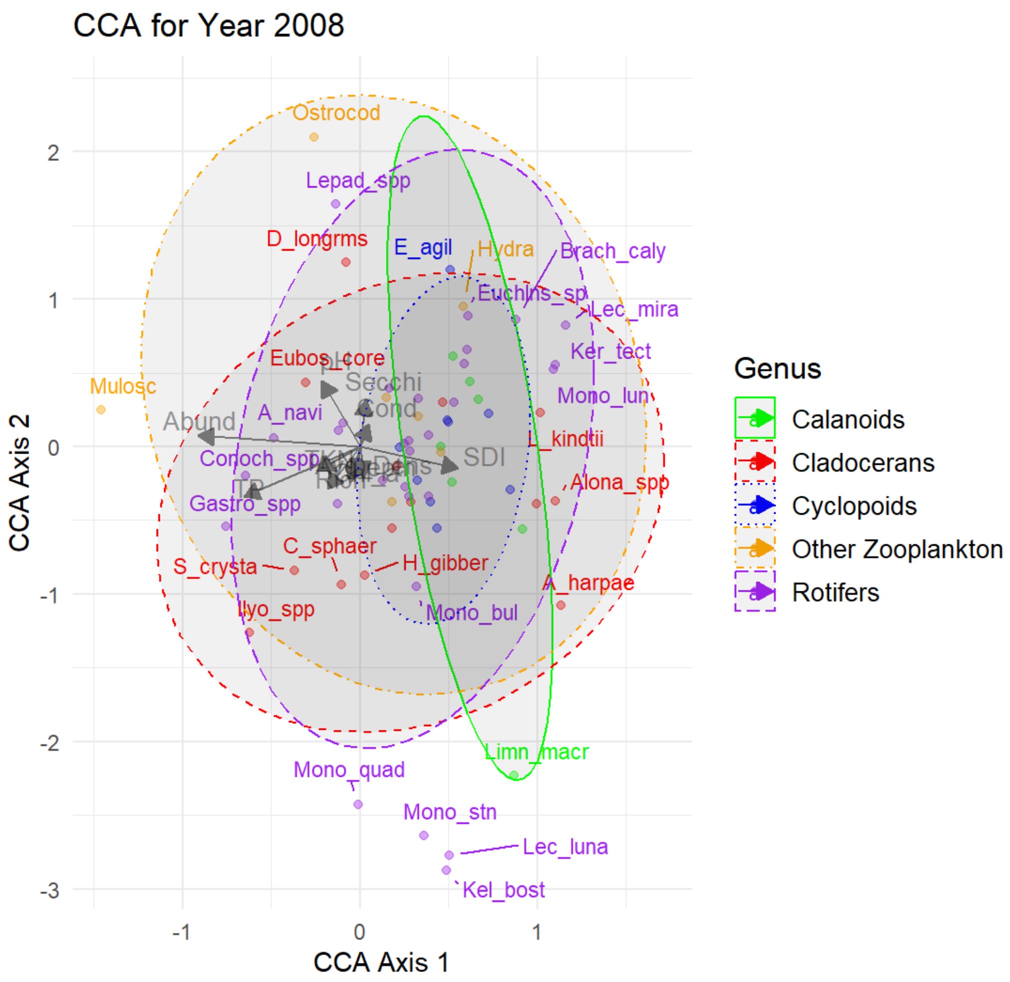


**Figure 42: Annual CCA biplot for Lake Couchiching**—This biplot depicts the complex relationships between taxa and environmental variables in 2008.

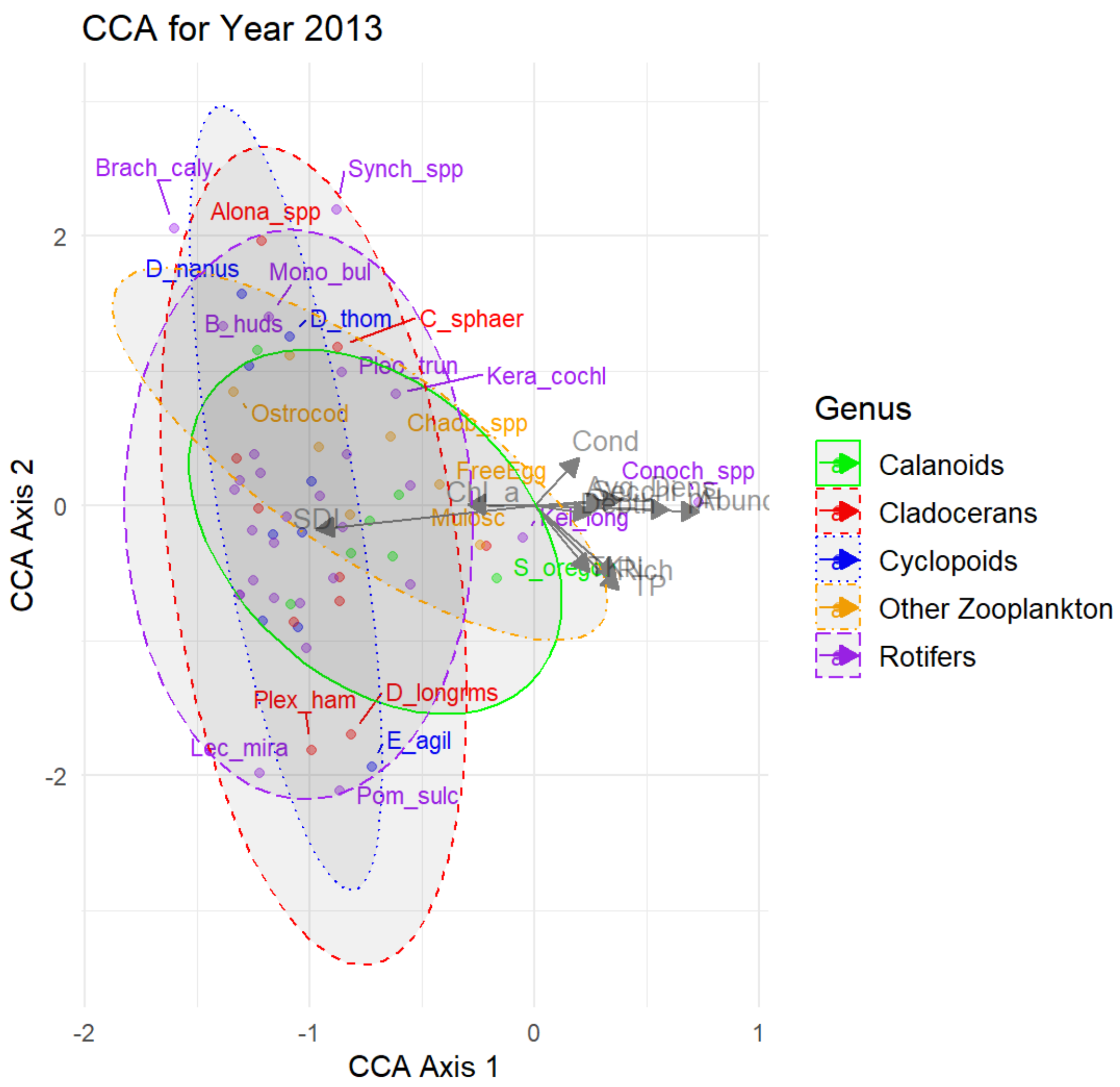


**Figure 43: Annual CCA biplot for Lake Couchiching**—This biplot shows the complex relationships between taxa and environmental variables in 2013.

## 5.6.1 Summary

This chapter explored the complex relationships between ZCS and WQPs in Lake Couchiching. We identified key indicators of water quality and ecosystem health by examining specific taxa and their responses to varying environmental conditions. Generalized Linear Model (GLM) analyses (Benjamini & Hochberg, 1995) revealed significant predictors for ZCS metrics, such as a negative impact of Depth on Avg_Dens (Estimate = -0.4728, SE = 0.1718, t = -

2.753, p = 0.00683); that is, the Avg_Dens of zooplankton is lower at greater depths. In addition, there were significant interactions between Secchi and TP and Abund (Estimate = 0.075692, SE = 0.025452, t = 2.974, p = 0.00294). Canonical Correspondence Analysis (CCA; ter Braak, 1986) further highlighted the strong relationships between zooplankton taxa and environmental gradients, explaining a substantial portion of the variance (CCA1 eigenvalue = 0.6421, explaining 35.55% of the variance). These findings enhance our understanding of the lake's ecological balance and contribute valuable knowledge to guide future monitoring and conservation efforts.

# 6.0 Chapter 6: Discussion and Conclusion of Spatial-Temporal Patterns in Water Quality and Zooplankton Interactions: Their Implications in Lake Ecology and Future Directions

## 6.1.1 Discussion

This chapter explores further the spatial and temporal variations in water quality parameters (WQPs) and zooplankton community structure (ZCS) in Lake Couchiching. The findings indicated significant temporal (between Years and among Seasons) and spatial (according to Stations) relationships between WQPs and ZCS, offering valuable insights for better lake management. Specifically, we tested the following aspects:

(a) significant spatial-temporal variability in WQPs,
(b) significant temporal and spatial changes in ZCS,
(c) specific zooplankton taxa and their relationship with WQPs, and
(d) associations between zooplankton and ZCS metrics.

## 6.1.2 Depth Preferences and Zooplankton Communities

This study revealed significant relationships between depth (Depth) and various zooplankton taxa, indicating species-specific Depth preferences for their distribution and abundance. Similar findings were reported by Bakker and Hilt (2016), Barbiero et al. (2019), and Doubek et al. (2019), all of whom demonstrated that Depth influences ZCS through environmental factors like predation pressure, light availability, and temperature stability.

For example, Bakker and Hilt (2016) found that certain cladoceran species preferred deeper waters in stratified lakes due to reduced predation and more stable thermal conditions. Likewise, Barbiero et al. (2019) reported depth-related variations in copepod communities across the Great Lakes, suggesting that Depth influences food availability and physicochemical parameters critical to zooplankton survival. This study's findings, such as the positive relationship between *Daphnia galeata mendotae* and Depth (*Estimate* = 0.564, $SE = 0.198$, $z = 2.848$, $p = 0.004$), are consistent with this research, indicating a preference for deeper waters where conditions such as reduced predation and stable temperatures prevail.

In contrast, the present study found that *Hydracarina* (water mites), though not technically zooplankton, were included due to their ecological overlap. *Hydracarina* showed a negative correlation with Depth ($\beta = -0.7226$, $SE = 0.2503$, $z = -2.887$, p = 0.0039), suggesting a preference for shallower waters, possibly due to higher prey availability and optimal light conditions, as Doubek et al. (2019) also observed.

Additionally, molluscs, including invasive species like zebra mussels, showed a positive relationship with depth ($\beta = 0.0944$, $SE = 0.0041$, $z = 22.858$, $p < 0.001$). These deeper waters offer more stable environmental conditions and reduced disturbances, allowing molluscs to thrive. These findings align with Paterson et al. (2019), who noted the critical role of molluscs in maintaining water clarity through filtration. However, invasive species like zebra and quagga mussels can disrupt local ecosystems.

These findings underline the importance of depth as a critical factor for understanding zooplankton dynamics. Vertical stratification within the water column creates distinct environmental layers, influencing species-specific habitat preferences. This study supports the notion that depth-related factors are vital for developing targeted lake management strategies to maintain ecological integrity.

### 6.1.3 Secchi Depth

Water transparency, measured by Secchi depth (Secchi), emerged as a critical factor influencing zooplankton communities, showing strong correlations with species diversity, richness, abundance, and average density. Increased Secchi depth, indicating clearer water, is often associated with higher zooplankton diversity and abundance due to improved light penetration and enhanced primary productivity. These influences are supported by findings from Barbiero et al. (2018), Gentine et al. (2022), Hall et al. (2003), Zou et al. (2022), and Paterson et al. (2019), who observed that clearer waters promoted larger zooplankton populations in various lake systems.

For example, Barbiero et al. (2018) found that greater water clarity in Lake Michigan supported higher primary production, which in turn sustained larger zooplankton populations. Similarly, studies by Hall et al. (2003) and Paterson et al. (2019) demonstrated that clear water conditions are linked to greater species richness and diversity in North American lakes.

In the present study, Secchi depth was positively correlated with the abundance of Cyclopoid copepodites ($\beta = 0.164$, $SE = 0.011$, $z = 15.269$, $p < 0.001$), *Diaptomus* *thomasi* ($\beta = 0.153$, $SE = 0.009$, $z = 16.145$, $p < 0.001$), and *Tylotrocha* spp ($\beta = 0.973$, SE $= 0.435$, $z = 2.239$, $p = 0.025$). These results align with Johnson et al. (2011), who found that clearer waters often support higher zooplankton densities. However, the relationship between Secchi depth and zooplankton abundance may vary by region. For instance, Johnson et al. (2011) observed no significant relationship between Secchi depth and copepod abundance in lakes along the Gulf of Maine and the Scotian Shelf, highlighting the influence of local environmental factors.

It is important to recognize that clearer water does not always indicate better water quality. In some cases, reduced turbidity may result from pollutants that inhibit algal growth, such as certain toxins or nutrient imbalances. For example, nutrient-poor but chemically polluted lakes may appear clear while suffering from reduced ecological health due to the absence of productive algal communities (Barbiero et al., 2018). Thus, while increased Secchi often benefits zooplankton diversity and abundance; these findings are vital to interpreting alongside other WQPs.

Maintaining balanced water transparency is critical for the health of aquatic ecosystems. Although clearer water generally supports higher species richness and abundance, monitoring should include other water quality factors, such as nutrient levels and potential pollutants, to avoid misinterpreting the ecological status of a lake. Effective management practices should aim to reduce excessive turbidity while also preventing harmful pollution, ensuring healthy, diverse, and resilient zooplankton populations (Barbiero et al., 2018; Gentine et al., 2022; Hall et al., 2003; Paterson et al., 2019; Zou et al., 2022).

### 6.1.4 pH

The alkaline conditions of Lake Couchiching were found to influence the distribution of zooplankton species, with some taxa showing a preference for higher pH levels. Studies by Doubek et al. (2019), Hu et al. (2019), Lamothe et al. (2018), and Venkataramana et al. (2017) have similarly reported that pH significantly impacts zooplankton community dynamics. In the present study, *Mesocyclops* spp. and *Keratella cochlearis* exhibited positive associations with pH ($\beta = 0.214$, $SE = 0.067$, $z = 3.194$, $p = 0.001$ and $\beta = 0.281$, SE = 0.085, $z = 3.306$, $p = 0.001$, respectively). These conclusions align with previous studies, which suggest that higher pH levels enhance zooplankton activity and distribution.

Doubek et al. (2019) and Hu et al. (2019) also reported that *Daphnia* spp thrive in slightly alkaline conditions. In the current study, *Daphnia* spp showed a preference for higher pH levels, supporting findings that alkaline environments improve survival and reproductive rates in these species. This trend is likely due to the solubility of calcium carbonate, which is essential for exoskeleton development in *Daphnia* spp and other cladocerans (Hu et al., 2019).

The geological composition of the Lake Couchiching watershed, particularly its limestone-rich areas, plays a key role in contributing to the lake's elevated pH levels. Figure 44 illustrates the geological map of the watershed, identifying areas where bedrock outcrops and clay-rich soils influence water chemistry. This geological-pH relationship is crucial in shaping the zooplankton community. For example, *Keratella cochlearis* and *Mesocyclops* spp. were found to have higher abundances in areas with increased pH, emphasizing the significance of alkaline conditions for zooplankton metabolism and enzyme activity (Venkataramana et al., 2017).

Doubek et al. (2019) further explored the ecological impacts of pH on lake ecosystems, highlighting the survival and flourishing of *Eudiaptomus* spp., which showed increased reproductive and growth rates in alkaline waters. They hypothesized that higher pH levels might reduce the solubility of harmful metals, thereby decreasing water toxicity and improving nutrient availability, fostering more favourable conditions for zooplankton. This consistency across studies illustrates that alkaline conditions favour the growth and reproduction of certain zooplankton species.

In addition to pH, other local environmental factors, such as competition, predation pressures, and water body chemistry, may also explain differences in species-specific responses to pH. Understanding these relationships is fundamental for predicting changes in zooplankton community dynamics. Therefore, effective monitoring and management strategies that address pH fluctuations in water systems are essential for maintaining a healthy zooplankton community, which, in turn, supports the overall health of aquatic ecosystems.

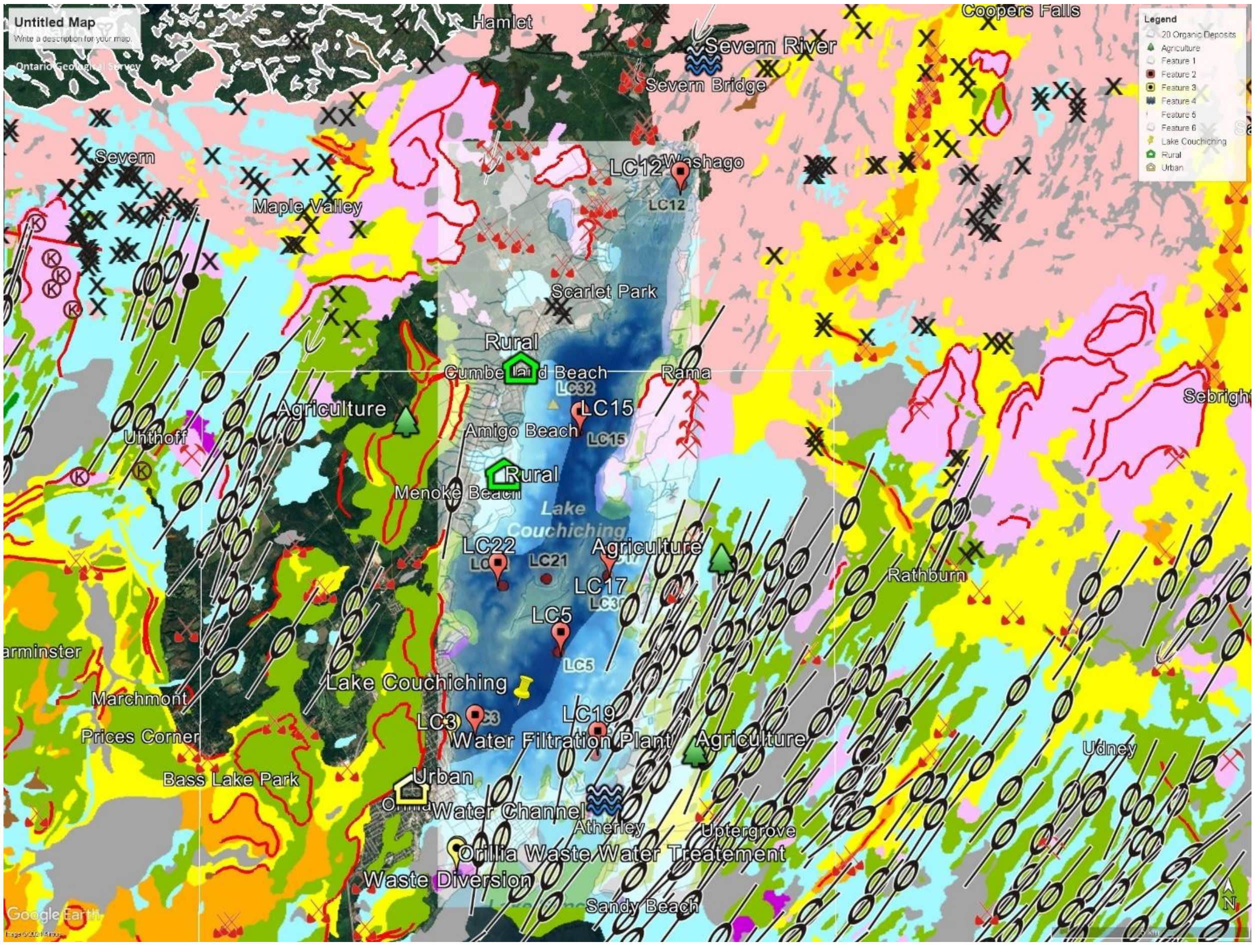


**Figure 44: Geology and Land Use Map of Lake Couchiching Watershed**–
This map displays the geological and land use features surrounding Lake Couchiching, highlighting key environmental factors that influence the lake's water chemistry and zooplankton dynamics. The slashes with circles on the eastern side indicate the drumlin/clay plains, which contribute to slower water infiltration and increased surface runoff, affecting the lake's alkalinity. The X symbols represent outcrops of bedrock, likely influencing mineral deposits in runoff water. Agricultural areas, water treatment facilities, urban zones, and waste diversion points are also identified, which play a role in nutrient loading and the overall ecological balance of the lake**.**

### 6.1.5 Conductivity

Changes in conductivity influenced the zooplankton community in Lake Couchiching, highlighting their sensitivity to fluctuations in ionic concentrations. Conductivity measures the concentration of dissolved salts and minerals, such as calcium, chloride, sodium, and potassium, which affect aquatic organisms' osmoregulatory processes (Cunillera-Montcusí et al., 2022; Hu et al., 2019; Yuan et al., 1994).

Zooplankton, such as *Bosmina longirostris* and *Polyarthra* spp, typically regulate their internal ionic concentrations to maintain balance in freshwater habitats where external salinity is low. In high-conductivity environments, zooplankton expend more energy on osmoregulation, which can cause physiological stress, reduce reproductive success, and ultimately lower survival rates.

In this study, conductivity was negatively associated with *Bosmina longirostris* ($\beta = -0.337$, $SE = 0.112$, $z = -3.009$, $p = 0.003$) and *Polyarthra* spp ($\beta = -0.217$, $SE = 0.062$, $z = -3.484$, $p = 0.0005$). These results suggest that elevated conductivity levels caused osmotic stress, impairing the ability of these species to reproduce and survive.

Yuan et al. (1994) found that conductivity changes, driven by seasonal runoff and agricultural discharges, significantly impacted zooplankton in the East China Sea region. Similarly, in this study, increased conductivity was harmful to *Bosmina longirostris* and *Polyarthra* spp populations.

Cunillera-Montcusí et al. (2022) also found that *Bosmina* spp and *Polyarthra* spp were particularly sensitive to elevated ionic concentrations. Hu et al. (2019) observed similar declines in zooplankton diversity and abundance in areas with elevated conductivity due to agricultural runoff.

These studies underscore the strong sensitivity of freshwater zooplankton to conductivity changes. High conductivity levels, whether from natural changes or anthropogenic activities, increase ionic concentrations, leading to osmotic stress. This stress forces zooplankton to expend energy on osmoregulation rather than feeding and reproduction, reducing survival and altering community composition.

Monitoring conductivity is essential for managing freshwater ecosystems, as it can help predict shifts in zooplankton populations and inform strategies to reduce ionic stress, such as managing runoff and nutrient inputs.

### 6.1.7 Total Phosphorus

Elevated total phosphorus (TP) levels support higher Chl *a* concentrations, which in turn increase abundance (Bai *et al.*, 2022; Barbiero *et al.*, 2018; Crossman *et al.*, 2016; Geraldes & Pasupuleti, 2019; Hall *et al.*, 2003). The present study showed a positive correlation between TP and the average density of zooplankton ($\beta = 0.423$, SE = 0.118, z = 3.585, $p < 0.001$).

In the current study, a strong positive correlation was observed between the density of *Filinia longispina* and the concentration of TP ($\beta = 0.392$, $SE = 0.094$, $z = 4.170$, $p < 0.001$). *Asplanchna* spp also showed a positive response to increased TP levels. These findings suggest that higher TP concentrations, often resulting from nutrient enrichment, enhance growth conditions for these zooplankton species by promoting phytoplankton growth, which serves as their primary food source. While moderate nutrient enrichment benefits zooplankton populations, excessive nutrient inputs may lead to eutrophication, potentially disrupting ecosystem health (Carpenter & Brock, 2006; Geraldes & Pasupuleti, 2016).

Bai *et al.* (2022) investigated the response of zooplankton communities to nutrient gradients in freshwater systems. They found that rotifers, including *Filinia longispina*, were exceptionally responsive to elevated nutrient levels, thriving in enriched conditions due to their ability to exploit rapid increases in phytoplankton biomass. Crossman *et al.* (2016) focused on the impact of nutrient loading on aquatic food webs. They reported that *Asplanchna* spp, a predatory rotifer, showed increased densities in environments with high TP concentrations. Their study suggested that *Asplanchna* spp benefited from the cascading effects of nutrient enrichment on the food chain, as increased primary production led to greater prey availability. Similar results were reported by Barbiero *et al.* (2018) and Johnson *et al.* (2011).

Thus, the observed zooplankton trends in abundance and community dynamics in response to elevated TP levels can be attributed to several factors. First, higher TP levels typically lead to more abundant phytoplankton, providing a richer food source for zooplankton. This increased food availability supports larger zooplankton populations. Second, nutrient-rich environments may offer more favourable conditions for the reproduction and growth of specific zooplankton species, enhancing their survival and proliferation. Finally, species like *Filinia longispina* and *Asplanchna* spp may possess specific traits that allow them to thrive in nutrient-enhanced waters, potentially outcompeting other taxa less suited to such conditions. These factors collectively contributed to positive associations between TP levels and zooplankton densities. Therefore, effective nutrient management practices are essential to control TP levels and maintain balanced zooplankton communities, thereby supporting the overall health of aquatic ecosystems.

Additionally, the balance of nitrogen and phosphorus is crucial in regulating primary productivity and the onset of harmful algal blooms. The N ratio can help determine whether nitrogen or phosphorus is limiting for phytoplankton growth. An N ratio lower than 16:1 typically indicates nitrogen limitation, while a higher ratio suggests phosphorus limitation. This nutrient balance plays a significant role in managing the composition of phytoplankton and, consequently, zooplankton populations(Bai et al., 2022; Bakker & Hilt, 2016). Figure 45 shows the N ratio across stations and seasons, demonstrating the temporal variability in nutrient dynamics. The figure highlights significant fluctuations in N ratios, particularly during spring and summer, when nutrient uptake and primary production are most active.

### 6.1.8 Total Kjeldahl Nitrogen (TKN) and Zooplankton Dynamics

Elevated Total Kjeldahl Nitrogen (TKN) levels are associated with increased nutrient inputs, supporting greater zooplankton abundance and influencing community composition (Gerten & Adrian, 2002; Barbiero *et al.*, 2019). Positive correlations were observed between TKN and the density of *Asplanchna priodonta* ($\beta = 0.451$, SE = 0.134, $z = 3.366$, $p < 0.001$) and TKN and the density of *Keratella cochlearis* ($\beta = 0.334$, SE = 0.107, $z = 3.121$, $p = 0.002$).

These findings suggest that nutrient enrichment, indicated by higher TKN levels, enhances primary productivity, which in turn boosts phytoplankton biomass, a primary food source for zooplankton, thereby increasing zooplankton densities. In temperate lakes, Barbiero *et al.* (2019) found that increased TKN levels correlated with a surge in *Daphnia magna* populations due to enhanced algal blooms. *Daphnia magna* is a species sensitive to changes in nutrient levels, and the enriched algal blooms stimulated by increased TKN provided a rich food source, facilitating their population growth.

Hernandez *et al.* (2018) found that high TKN levels were linked to changes in the diurnal migration patterns of zooplankton, suggesting behavioural changes in response to increased predator activities influenced by populated larger-sized zooplankton. These changes were attributed to increased predator-prey interactions, as nutrient enrichment supported diverse and abundant zooplankton populations, attracting more predators. This study highlighted the complex ecological interactions driven by nutrient inputs beyond simple increases in zooplankton density. Lee and Choi (2015) discovered that increased nutrient levels led to greater species richness, competition, and predation pressure among zooplankton. However, their results did not entirely align with our study, where, although high nutrient levels were associated with increased zooplankton abundance, they were also associated with lower species diversity.

This comprehensive analysis underscores the significant role of TKN as a driver of zooplankton community dynamics in freshwater ecosystems. Understanding these nuanced interactions—how TKN influences zooplankton quantitatively and qualitatively—is crucial for managing nutrient dynamics in aquatic environments. Moreover, these insights help predict ecosystem responses to nutrient changes, helping to initiate effective management and conservation strategies to maintain aquatic biodiversity and ecological balance across freshwater systems. To further understand how nutrient dynamics, specifically the balance between nitrogen and phosphorus, impact algal blooms and zooplankton dynamics, we examined the N ratio across all Stations and Seasons (Figure 47). The N ratio provides insight into whether nitrogen or phosphorus is the limiting nutrient for primary productivity, and imbalances can indicate the likelihood of harmful algal blooms, particularly cyanobacterial blooms. The N ratio across Lake Couchiching's Stations shows seasonal and spatial variability. As seen in the spring and summer months, certain stations—such as LC19 and LC22—exhibit N ratios below 16:1, indicating nitrogen limitation, which may promote cyanobacterial growth. These findings suggest that these areas could be at higher risk for cyanobacterial blooms, which could significantly impact zooplankton community dynamics by altering the food web structure(Bai et al., 2022; Bakker & Hilt, 2016).

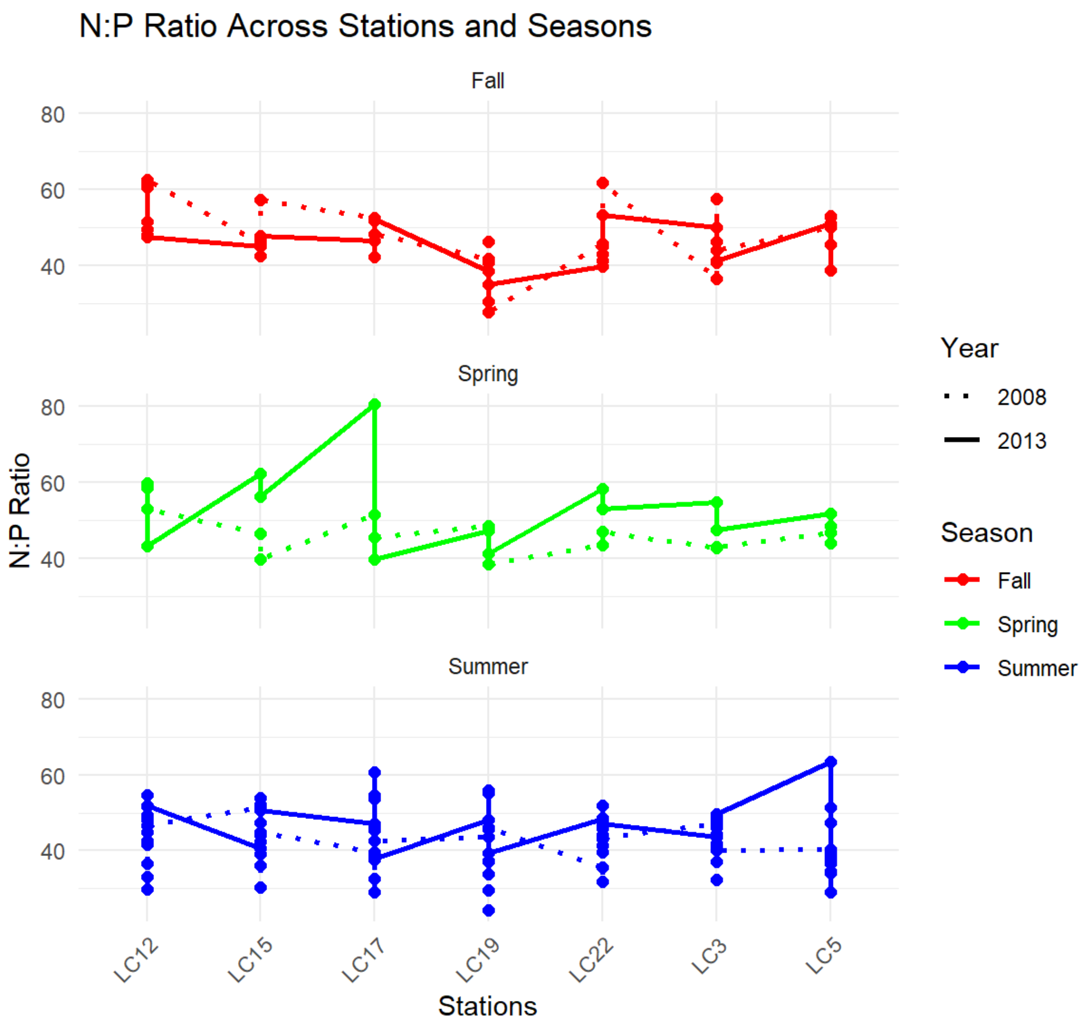


**Figure 45: N Ratio Across Stations and Seasons-** Figure 47 illustrates the N ratio across various sampling stations and seasons in 2008 and 2013. The solid lines represent data from 2013, while dotted lines indicate 2008. Each season is color-coded: red for Fall, green for spring, and blue for summer. Stations LC3, LC5, and LC22 showed N ratios below 40 in Fall 2008, suggesting no potential risk for cyanobacterial blooms, particularly where phosphorus levels remained low. Conversely, higher N ratios observed in Spring 2013, especially at LC17, point towards nutrient conditions that could favour eukaryotic algal growth.

The N ratio diagram demonstrates how nutrient dynamics vary spatially and temporally across the lake, with specific patterns that may correspond to the onset of algal blooms under favourable conditions. These trends reinforce the need for seasonal nutrient management and monitoring to prevent harmful blooms and ensure water quality.

## 6.2.1 Associations Between WQPs and Particular Taxa

### 6.2.2 Cladocerans

Johnson et al. (2011) observed that most taxa of cladocerans did not show a significant relationship with Chl a, a finding consistent with the observations in this study.  Specifically, we found that *Acroperus harpae* was negatively associated with Chl *a* (*Estimate* = -1.224, *SE* = 0.404, *z* = -3.035, *p* = 0.002).  This negative association was interpreted as potentially resulting from competition with other zooplankton, intense intra-specific competition for algae as a food source, or issues in the sampling strategy. Additionally, higher *Chl a* concentration may not favor *Acroperus harpae*, as they could lead to increased competition for food resources. This species tends to prefer shallow waters with dense plant cover and higher water clarity (increased Secchi depth), where higher plant biomass contributes to nutrient levels that support both *A. harpae* and its food sources, fostering its presence in these habitats.

Barbiero *et al.* 2019 explored the dynamics between zooplankton communities and Chl *a* in temperate lakes, noting that certain cladocerans, such as *Daphnia* spp, responded positively to increases in Chl *a* during spring and fall but not during the peak of summer algal blooms.  This finding supports the notion that seasonal dynamics in environmental parameters significantly affected the relationship between zooplankton and Chl *a.*  Gerten and Adrian (2002) investigated the impact of Chl *a* on zooplankton in eutrophic systems and found that different taxa responded differently to nutrient enrichment and increased phytoplankton growth.  Some taxa showed positive associations with eutrophication, likely due to increased direct feeding on algae. In contrast, others, like some cladocerans, did not show any clear pattern, which could suggest complex ecological interactions such as indirect negative effects of cyanobacterial toxins (commonly misidentified as algal toxins in the past) or changes in water quality associated with high cyanobacterial density.

The negative association of *Acroperus harpae* with Chl *a* in both the current study and Johnson *et al.*'s (2011) study contrasts with the more variable responses observed by Gerten and Adrian (2002).  This contrast highlights the fact that while some taxa may show clear patterns, others exhibit complex interactions that can differ based on local environmental conditions.  The findings presented by Gerten & Adrian (2002) suggest that the presence of cyanobacterial toxins or changes in water quality associated with high algal density may lead to different responses among zooplankton taxa, an aspect not directly explored in the current study or by Johnson *et al.* (2011).

### 6.2.3 Copepods

The responses of copepods to WQPs differed among taxa.  Cyclopoid copepodites (*Estimate* = 0.164, *SE* = 0.011, $z$ = 15.269, $p < 0.001$) and adult cyclopoids, specifically *Diacyclops thomasi* (*Estimate* = 0.153, *SE* = 0.009, $z$ = 16.145, $p < 0.001$), showed positive relationships with Secchi.  Calanoid copepods, such as *Leptodiaptomus* spp., exhibited positive correlations with Secchi depth (Estimate = 0.112, SE = 0.012, z = 9.333, p < 0.001), indicating a preference for clearer waters. This finding aligns with Johnson et al. (2011), who observed that clearer waters often support higher densities of these taxa. In contrast, *Diaptomus nanus* ($\beta = -0.170$, SE = 0.024, $z = -6.953$, $p < 0.001$) preferred less transparent waters. This difference suggests that some copepod species are generalists and may thrive in turbid conditions, likely benefiting from reduced predation and increased food availability.

This study showed a negative relationship between copepods and Chl *a*. For example, *Diaptomus thomasi* ($\beta = -1.367$, $SE = 0.030$, $z = -45.950$, $p < 0.001$) and *Senecella oregonensis* ($\beta = -1.322$, $SE = 0.122$, $z = -10.861$, $p < 0.001$) exhibited a negative relationship with higher Chl *a* concentrations, possibly attributed to the presence of harmful factors such as cyanobacterial species, which can produce toxins or changes in water quality conditions. The suggestion that higher Chl *a* concentration could lead to reduced oxygen levels may be related to oxygen depletion caused by cyanobacterial blooms, which can reduce oxygen levels during decay (Johnson *et al.*, 2011).

Smith *et al.* (2014) noted that certain copepod species, such as *Cyclops vicinus*, showed positive correlations with Chl *a* during moderate algal growth but avoided peak algal bloom conditions. This finding aligns with the mixed responses observed in the current study, where some species thrived in more transparent waters while others preferred turbid conditions.

### 6.2.4 Rotifers

Rotifers exhibited a range of responses to WQPs. *Tylotrocha* spp and *Euchlanis* spp responded positively to increasing Secchi depth (e.g., *Tylotrocha* spp: *Estimate* =

0.973, *SE* = 0.435, *z =* 2.239*, p* = 0.025), indicating a preference for transparent water conditions (Johnson *et al.*, 2011). This positive association suggests that these species benefit from increased light penetration, which enhances primary productivity and food availability.

Several rotifer species showed negative responses to high Chl *a*. For example, *Pleurotrocha* spp, *Euchlanis* spp, and *Trichotria* spp exhibited negative correlations with Chl *a* (e.g., *Pleurotrocha* spp.: *Estimate* = -0.225, *SE* = 0.101*, z* = -2.230, *p* = 0.026) (Barbiero *et al.*, 2019). This negative response may be due to the detrimental effects of dense algal blooms on water quality, particularly the reduced oxygen levels that occur when algae die and decay, consuming oxygen during decomposition, and the presence of harmful cyanobacterial toxins.

Conversely, *Notholca* spp showed a positive response to Chl *a* (*Estimate* = 0.367, *SE* = 0.117*, z* = 3.138, *p* = 0.002), suggesting that some rotifers thrive in environments with higher primary productivity, benefiting from the increased food supply. The balance between nitrates and phosphates in the water may influence this response. Cyanobacteria, unlike green algae, can fix nitrogen from the atmosphere when phosphates are in excess, giving them a competitive advantage in such environments. Toxic algal blooms often occur when cyanobacteria dominate, as certain species produce powerful cyanotoxins. Smith *et al.* (2014) observed that rotifer species such as *Keratella cochlearis* responded positively to Chl *a,* similar to the positive response of *Notholca* spp, indicating that some rotifers benefit from higher primary productivity, likely when cyanobacteria are not yet dominating the system.

## 6.2.5 Other Zooplankton

**Hydracarina**

The current study revealed the significant role of environmental parameters (pH, Conductivity, Chl *a*, TP, and TKN) in driving zooplankton community dynamics. To better understand how environmental factors influence the zooplankton community, it is important to examine the broader ecological context. This study included life stages of other aquatic organisms that are not zooplankton as adults but whose juvenile stages are part of the zooplankton community, such as Hydracarina (water mites), molluscs, and *Chaoborus* spp (phantom midge larvae). Although the adult stages of these organisms are not traditionally classified as zooplankton, their larval stages, which often perform filter-feeding, are ecologically significant in freshwater ecosystems. These juvenile stages play important roles in nutrient cycling and habitat interactions. They are influenced by similar environmental factors, making them relevant components for understanding the ecological dynamics of freshwater systems.

This study found a significant negative correlation between the presence of Hydracarina and Depth, suggesting that they prefer shallower waters ($\beta = -0.7226$, $SE = 0.2503$, $z = -2.887$, $p = 0.0039$). Their preference for shallow water can be attributed to higher prey availability, optimal light conditions, and more stable temperatures, which are vital for ectothermic organisms like Hydracarina (Venkataramana *et al.*, 2017).

Molluscs showed a significant positive relationship with Depth, indicating their preference for deeper waters ($\beta = 0.0944$, $SE = 0.0041$, $z = 22.858$, $p < 0.001$). Several factors could influence this preference for greater depths. The reduced predation risk in deeper waters provides a safer habitat for molluscs, allowing them to thrive. Specifically, lower light penetration at these depths may reduce the likelihood of detection by predators. Stable environmental conditions, such as consistent temperature and oxygen levels, also contribute to the suitability of deeper waters for molluscs, supporting their growth and survival.

Nowicki *et al.* (2017) showed *Chaoborus* spp had a significant positive response to Chl *a*, suggesting a preference for areas with higher phytoplankton concentrations ($\beta = 0.271$, $SE = 0.093$, $z = 2.914$, $p = 0.0036$). Higher Chl *a* levels typically indicate greater phytoplankton density, providing a richer food source and more suitable habitat conditions for *Chaoborus* spp (Zhang *et al.*, 2019). This preference for high Chl *a* area indicates that *Chaoborus* spp are well-adapted to tolerating eutrophic conditions, where nutrient levels are high, benefitting from dense algal blooms.

Adding Hydracarina, Molluscs, and *Chaoborus* to this study broadened the scope of understanding freshwater ecosystem dynamics and enhanced the ability to make informed management decisions. Understanding the interactions among these organisms and zooplankton can help predict changes in community structure in response to environmental stressors and help guide effective conservation strategies.

## 6.3.1 Changes in Zooplankton Community Structure (ZCS)

### 6.3.2 Abundance and Average Density

Correlations were found between nutrient levels and both Abund and Avg_Dens. For instance, TP and TKN positively correlated with Abund ($\beta = 0.392$, $SE = 0.094$, $z = 4.170$, $p < 0.001$, $\beta = 0.334$, $SE = 0.107$, $z = 3.121$, $p = 0.002$, respectively). These results agree with Xiong *et al.* (2019) and Yang *et al.* (2017), who observed similar positive correlations between nutrient levels and zooplankton abundance.

Maintaining good water clarity is crucial for the health and diversity of aquatic ecosystems. Enhanced water transparency can positively impact zooplankton species richness and overall abundance in lake systems. Effective management practices that reduce excessive turbidity and control nutrient inputs are essential for maintaining clear water conditions and fostering healthy, diverse, and abundant zooplankton populations. Although increased nutrient levels can lead to a higher overall abundance of zooplankton, this can also result in a reduction in diversity because certain species thrive in nutrient-rich conditions, often outcompeting more sensitive species (Barbiero *et al.*, 2019; Zhang *et al.*, 2019). Consequently, the ecosystem may become dominated by a few resilient species, potentially disrupting the ecological balance and reducing the overall resilience of the aquatic community (Hernandez *et al.*, 2018; Nowicki *et al.*, 2019).

### 6.3.3 Diversity Indices and Species Richness

A lower level of species diversity (SDI) in high-nutrient areas indicates potential dominance by a few species, as observed by Johnson *et al.* (2011) and Rusak *et al.*

(2008). High nutrient levels can lead to competitive exclusion, reducing overall diversity. In contrast, higher Richness at Stations like LC3 suggests that diverse ecological niches can mitigate the adverse effects of nutrient enrichment on diversity. This observation is supported by Yang *et al.* (2017), who found that nutrient-rich environments can sometimes support a diverse range of species due to the availability of more ecological niches.

Although high nutrient levels often reduce diversity due to the dominance of a few species, heterogeneous habitats with varied resources and conditions can support a richer species assemblage. Managing habitat complexity and promoting ecological diversity can help mitigate the adverse effects of nutrient enrichment.

### 6.3.4 Temporal and Spatial Changes

Temporal and spatial changes in ZCS highlight the influence of varying WQPs. For example, LC12, a shallow water Station, showed increased biotic activity during summer, coinciding with higher Chl *a* levels and algal blooms. Similar effects were noted by Nowicki *et al.* (2019) and Zhang *et al.* (2019). Seasonal variations significantly influenced community structure, as evidenced by the dynamic responses of zooplankton populations to environmental changes in Lake Couchiching. Hernandez *et al.* (2018) also observed seasonal patterns of changes in zooplankton communities, with changes corresponding to changes in temperature and nutrient availability. An understanding of these changes in water quality, driven by seasonal changes and human activities, is crucial for understanding how temporal variations in the environment impact ecological interactions and the stability of zooplankton communities.

## 6.4.1 Station-Specific Patterns and Ecological Implications

### 6.4.2 Diversity and Abundance

Stations like LC3 and LC5, which are adjacent to built-up areas and are therefore influenced by urban runoff and nutrient-rich conditions, showed high SDI and Abund (Barbiero *et al.*, 2019; Nowicki *et al.*, 2019). Urban runoff enhances primary production, supporting diverse zooplankton communities. This high SDI and Abund suggested that these Stations provided a wider variety of ecological niches, enabling the coexistence of more diverse zooplankton species.

In contrast, some Stations exhibited low SDI but had high Abund due to contrasting influencing factors. For example, LC15 is impacted by adjacent agricultural runoff and showed low SDI but had a high abundance of opportunistic species. This kind of effect was also seen in studies by Johnson *et al.* (2011) and Rusak *et al.* (2008). It reflected how nutrient inputs may differentially favour certain species, thereby reducing species diversity.

Smith *et al.* (2014) found that urban runoff created nutrient hotspots that promoted high biodiversity. They also suggested that managing urban runoff and maintaining ecological niches can enhance biodiversity in impacted areas. In contrast, Gerten and Adrian (2002) noted that agricultural runoff often leads to the dominance of nutrient-tolerant species, reducing overall community diversity. These authors concluded that targeted nutrient management in agricultural areas is crucial to maintaining ecological balance and preventing the dominance of opportunistic species.

### 6.4.3 Dominance of Particular Taxa

The bubble chart in Figure 46 visualizes the relationships between zooplankton taxa and environmental variables (Depth, Secchi, Conductivity (Cond), and Total Phosphorus (TP)) across Stations. The size of the bubbles represents the strength of significance, with larger bubbles indicating higher significance. Red bubbles represent a negative correlation (relationship = -1), while blue bubbles represent a positive correlation (relationship = 1).

For example, the blue bubble for Depth at LC17 shows a strong positive correlation with *Diaphanasoma birgeii*, a species known to prefer the western side of lakes. In contrast, *Diaphanasoma birgeii* exhibits a positive correlation with TP at LC12, indicating that higher nutrient levels may favour its presence at this station. Similarly, at LC12, *Acroperus harpae* shows a positive correlation with Conductivity, suggesting that areas with higher conductivity support its growth. The smaller red bubble for Depth at LC12 indicates a lower significance and a negative relationship with *Holopedium gibberum*. The red bubble for Depth at LC19 suggests a negative correlation, indicating that *Holopedium gibberum* may avoid shallow areas at that station, likely moving further offshore as TP concentrations increase with depth.

**Table 21. Zooplankton Taxa Matched to Bubble Chart Numeric Values**- This table provides the numeric labels for the taxa presented on the Y-axis of the bubble chart (Figure 48). These values correlate the zooplankton species with their respective positions in the chart, allowing a direct reference to the relationships illustrated between environmental variables and taxa across various stations.

| | |
|---|---|
| *Diaphanasoma birgeii (D_birgeii)* | 1 |
| *Diaphanasoma birgeii (D_birgeii)* | 2 |
| *Holopedium gibberum (H_gibber)* | 3 |
| *Holopedium gibberum (H_gibber)* | 4 |
| *Diaphanasoma birgeii (D_birgeii)* | 5 |
| *Diaphanasoma birgeii (D_birgeii)* | 6 |
| *Acroperus harpae (A_harpae)* | 7 |
| *Diaphanasoma birgeii (D_birgeii)* | 8 |
| *Cyclopoid copepodites* | 9 |
| *Diacyclops nanus* | 10 |
| *Diacyclops Thomasi* | 11 |
| *Pleurotrocha* spp. | 12 |
| *Asplanchna* spp. | 13 |
| *Hydracarina* | 14 |
| *Molluscs* | 15 |
| *Diaphanasoma birgeii (D_birgeii)* | 16 |
| *Acroperus harpae (A_harpae)* | 17 |
| *Pleurotrocha* spp. | 18 |

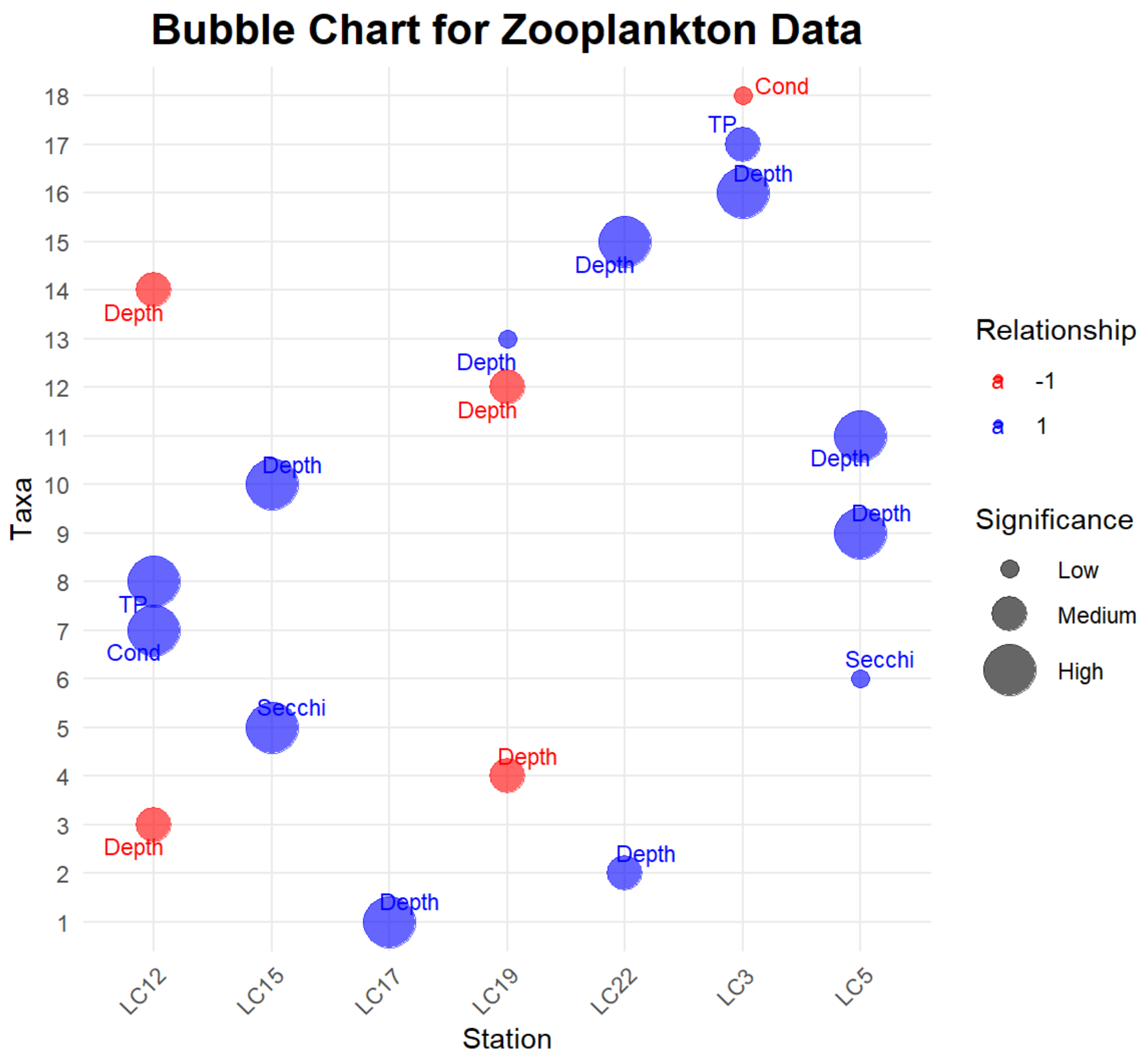


**Figure 46. Bubble Chart Depicting Zooplankton Taxa and Environmental Variable Relationships**– This chart shows the relationships between zooplankton taxa and environmental variables (Depth, Secchi, Conductivity, and TP) across sampling stations. Larger bubbles indicate higher significance, with red representing negative correlations and blue representing positive correlations. For instance, Depth at LC17 shows a strong positive correlation with *Diaphanasoma birgeii*, while Depth at LC12 shows a negative relationship with *Holopedium gibberum*. The red bubble at LC19 suggests *Holopedium gibberum* avoids deeper areas, likely due to increasing TP with depth.

### 6.4.5 Impact of Harmful Algal Blooms (HABs) on Zooplankton Community Structure (ZCS)

The potential for Harmful Algal Blooms (HABs) to influence ZCS is an important aspect of lake ecology. Several different types of algae, particularly cyanobacteria, are known to produce toxins that can significantly impact aquatic ecosystems. In freshwater systems, cyanobacteria such as *Microcystis*, *Dolichospermum* (previously *Anabaena*), *Planktothrix*, *Microseira*, *Nostoc*, and *Microcoleus* are common toxin-producing genera (EPA, 2023). These organisms can produce cyanotoxins, which may accumulate in the water column and affect higher trophic levels, including zooplankton.

Cyanotoxins can alter zooplankton populations directly through toxicity or indirectly by disrupting food web dynamics. For example, zooplankton species that feed on cyanobacteria may experience reduced survival or reproduction due to the ingestion of toxins. Furthermore, the increased density of cyanobacteria during HABs can lead to water quality degradation, reduced transparency, and decreased availability of preferred food sources like green algae, further altering zooplankton distribution and abundance (Barbiero et al., 2019).

This relationship between harmful algal blooms and ZCS highlights the need for regular monitoring of both WQPs and algal dynamics in lakes. Effective management strategies that reduce nutrient inputs and control cyanobacterial growth are crucial for mitigating the impact of HABs and maintaining a balanced zooplankton community, which is integral to the overall health of aquatic ecosystems.

## 6.5.1 Conclusion of Findings and Interpretation

### 6.5.2 Water Quality Parameters (WQPs) by Time and Space in Relation to ZCS

The analysis revealed significant associations between WQPs and the ZCS, particularly with Depth and Secchi. These factors emerged as critical determinants of zooplankton distribution, affecting both species abundance and diversity (Barbiero et al., 2019; Zhang et al., 2019). Regular monitoring of these parameters is essential for detecting shifts in the ZCS, which can serve as early indicators of broader environmental changes.

The Depth and light penetration were found to strongly influence ZCS, with certain taxa responding more favourably to variations in these parameters. These water quality influences are consistent with previous studies, which emphasize that spatial and temporal monitoring of WQPs, particularly nutrient inputs and water clarity, is essential for maintaining zooplankton biodiversity and lake health (Nowicki et al., 2019). Effective lake management should prioritize monitoring of WQPs to sustain optimal conditions for the zooplankton community, which plays a critical part in the overall ecological balance of aquatic systems.

**Hypothesis 1 (H1):**

The present study anticipated significant spatial-temporal variations in water quality due to natural and human factors in Lake Couchiching, which would, in turn, influence the zooplankton community structure (ZCS). The results confirmed this hypothesis, demonstrating significant variability in water quality across Stations and times. This variability was closely linked to changes in ZCS, supporting the alternate hypothesis that both natural and human-induced water quality changes are key drivers of spatial and temporal shifts in zooplankton communities.

### 6.5.3 Zooplankton Community Structure (ZCS) by Time and Space

Higher zooplankton abundance in nutrient-rich areas indicated eutrophication processes (Barbiero *et al.*, 2019; Zhang *et al.*, 2019). Cluster analysis identified distinct ecological zones and transition zones of water quality conditions and zooplankton communities in Lake Couchiching, comparable to the earlier findings of Nowicki *et al.* (2019) and Zhang *et al.* (2019) in other freshwater bodies. The results of Canonical Correspondence Analysis (CCA) illustrated the spatial distribution of zooplankton as influenced by environmental factors. These results align with those of Hernandez *et al.* (2018) and others, which showed that nutrient enrichment significantly impacted ZCS. Identifying ecological zones and understanding the distribution of environmental variables are crucial for effective ecosystem management.

**Hypothesis 2 (H2):**

The null hypothesis proposed that no significant differences would be observed in changes in ZCS over time or across different locations, indicating no spatial or temporal ecological patterns. However, the results of this study allowed us to reject the null hypothesis. Significant temporal and spatial variations were identified in our analysis which revealed notable temporal and spatial variations in ZCS, confirming the alternate hypothesis that these patterns reveal ecological dynamics within the zooplankton community, which are influenced by water quality parameters (e.g., nutrient levels) and other environmental factors.

### 6.5.4 Model Selection and Interpretation

Integrated findings from WQPs and ZCS analyses highlighted significant relationships between zooplankton communities and WQPs. The sensitivity of zooplankton to environmental variables may require adaptive management strategies. Targeted nutrient management practices are essential to mitigate anthropogenic impacts and enhance water quality. These insights underline the importance of ongoing monitoring and adaptive management strategies to preserve healthy and diverse lake ecosystems.

These findings are consistent with those of Xiong *et al.* (2019) and Yang *et al.* (2017), who also emphasized the need for adaptive management strategies in response to environmental degradation. Establishing and implementing targeted nutrient management practices can mitigate the impacts of eutrophication and support sustainable lake management.

**Hypothesis 3 (H3):**

The null hypothesis would be that specific zooplankton taxa do not correlate with water quality at a particular location and thereby influence the Zooplankton Community Structure (ZCS). The present study showed that specific zooplankton taxa are indeed correlated with water quality parameters, validating the alternate hypothesis that these zooplankton taxa can influence ZCS at a specific locality.

**Hypothesis 4 (H4):**

The null hypothesis, that there are no associations between specific zooplankton taxa and Zooplankton Community Structure (ZCS) metrics, was rejected. The present study identified significant associations between the zooplankton community and ZCS metrics, supporting the alternate hypothesis that these associations do indeed provide valuable ecological insights for lake monitoring and management.

## 6.6.1 Final Commentary

This study investigated the complex relationships between WQPs and ZCS, providing a solid foundation for future research and informed management practices, and that frequent monitoring and adaptive management strategies are essential for preserving the health and biodiversity of freshwater ecosystems.  These insights and conclusions agree with those of Barbiero *et al.* (2019) and Gerten and Adrian (2002), who also highlighted the importance of frequent monitoring and adaptive management strategies in maintaining freshwater ecosystem health.

## 6.7.1 Limitations of the Study

One limitation of this study is the seasonal scope of the data because data collection was primarily conducted during Spring and Summer.  Future studies should include more comprehensive year-round sampling to capture the subtleties of seasonal changes.  Additionally, although the spatial coverage included multiple Stations, finer-scale sampling (and more frequent sampling at a specific location) could reveal more localized patterns in zooplankton distribution and WQPs.  A more detailed characterization of land use in different areas of the Lake Couchiching watershed would be particularly useful as it might help explain the differences between sites in terms of their nutrient concentrations and other environmental metrics. Also, a map of the surrounding surface geology would help to understand and explain the variation of pH measurements in the study. Our data collection methods also have a potential bias because samples were taken primarily during daylight hours, which may not capture the full range of zooplankton activity, such as diurnal variation in depth and other activities.

### 6.8.1 Future Research and Community Collaboration:

Future research should focus on long-term monitoring to track the impact of climate change on WQPs and ZCS in Lake Couchiching.  Experimental studies manipulating nutrient inputs could provide insights into causal relationships between nutrient levels and zooplankton dynamics.  Additionally, incorporating advanced modelling techniques could help predict future changes in lake ecosystems under various management scenarios, which would provide more solid guidance for management strategies in the future.

The Severn Sound Environmental Association (SSEA) plays a vital role in environmental protection and water quality monitoring in the region. Though their primary focus is on Severn Sound, their expertise and existing programs offer an excellent foundation for future collaborations aimed at expanding monitoring efforts across the broader watershed, including Lake Couchiching.

Furthermore, developing a cultural partnership with the Chippewas of Rama First Nation presents an invaluable opportunity for advancing local water stewardship. Engaging youth and elders from the community in water sampling and conservation activities would strengthen the combination of traditional ecological knowledge with modern scientific methods. Such partnerships could deepen understanding of Lake Couchiching’s ecosystem and foster a collaborative approach to sustainable lake management that acknowledges both cultural heritage and environmental protection.

Incorporating these partnerships would enhance local community involvement and open avenues for long-term environmental monitoring and protection strategies, ensuring a holistic approach to lake conservation.

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# Appendix A: Supplementary Data Tables

**Table A.** PERMANOVA Analysis of Abundance Based on the Conservative Dataset: This table presents the results of the PERMANOVA (Permutational Multivariate Analysis of Variance) conducted to assess the effects of Station (Station), season, and year on abundance (Abund) as well as the interactions between these factors. The analysis uses degrees of freedom (Df), the sum of squares (SumOfSqs), the proportion of variance explained (*$R^2$*), F-values, and p-values to evaluate statistical significance.

| | Df | SumOfSqs | R2 | F | Pr(>F) | |
|---|---|---|---|---|---|---|
| S_Station | 6 | 4.0806 | 0.16415 | 6.5792 | 0.001 | *** |
| Seasons | 2 | 3.5653 | 0.14342 | 17.2453 | 0.001 | *** |
| Year | 1 | 1.2744 | 0.05127 | 12.3283 | 0.001 | *** |
| S_Station:Year | 6 | 1.1984 | 0.04821 | 1.9321 | 0.025 | * |
| seasons: Year | 2 | 1.5975 | 0.06426 | 7.7271 | 0.001 | *** |
| S_Station:seasons | 12 | 1.6683 | 0.06711 | 1.3449 | 0.112 | |
| Residual | 111 | 11.4742 | 0.46158 | | | |
| Total | 140 | 24.8587 | 1 | | | |

In this table, the significance levels are indicated by asterisks in the p-value column as follows:

- *: p-value < 0.05 (Significant)
- **: p-value < 0.01 (Highly Significant)
- ***: p-value < 0.001 (Very Highly Significant)

**Table B.** Abund Sensitivity Analysis Without Interaction Terms Using the Inclusive Dataset: This table displays abundant results from the inclusive dataset without interaction terms for comparison.

| | Df | SumOfSqs | R2 | F | Pr(>F) | |
|---|---|---|---|---|---|---|
| S_Station | 4 | 3.7604 | 0.18097 | 7.8561 | 0.001 | *** |
| seasons | 2 | 2.7608 | 0.13287 | 11.5357 | 0.001 | *** |
| Year | 1 | 0.9746 | 0.0469 | 8.1445 | 0.001 | *** |
| Residual | 111 | 13.2828 | 0.63925 | | | |

**Table C.** Abund Sensitivity Analysis Based on 2013 Data: This table details the Abund sensitivity analysis of 2013 and highlights similar significant spatial and seasonal variations.

| | Df | SumOfSqs | R2 | F | Pr(>F) | |
|---|---|---|---|---|---|---|
| S_Station | 4 | 3.4502 | 0.34051 | 7.4829 | 0.001 | *** |
| seasons | 2 | 0.5729 | 0.05654 | 2.4852 | 0.028 | * |
| Residual | 53 | 6.1093 | 0.60294 | | | |
| Total | 59 | 10.1325 | 1 | | | |

**Table D.** Abund Sensitivity Analysis at Station LC17: This table shows the sensitivity analysis results focusing on Abund at Station LC17.

| | Df | SumOfSqs | R2 | F | Pr(>F) | |
|---|---|---|---|---|---|---|
| seasons | 2 | 0.7444 | 0.23551 | 3.7105 | 0.013 | * |
| Year | 1 | 0.41023 | 0.12978 | 4.0896 | 0.033 | * |
| Residual | 20 | 2.00622 | 0.63471 | | | |
| Total | 23 | 3.16085 | 1 | | | |

- "***" denotes $p < 0.001$, indicating a highly significant impact.
- "*" signifies $p < 0.05$, suggesting a significant impact.
- A blank under 'Significance' indicates a non-significant result.

# Appendix B: Model Selection Tables

**Table E.** Summary of GLM Results Showing the Influence of WQPs on Abund:

| Predictor | Coefficient | Std. Error | t-value | p-value |
|---|---|---|---|---|
| (Intercept) | 52.252753 | 41.948573 | 1.246 | 0.21290 |
| Depth | 10.199301 | 4.769490 | 2.138 | 0.03248* |
| Secchi | -18.700161 | 6.757867 | -2.767 | 0.00565** |
| pH | -7.182552 | 4.628752 | -1.552 | 0.12073 |
| Cond | 0.028542 | 0.035705 | 0.799 | 0.42406 |
| Chl_a | 18.943240 | 9.467260 | 2.001 | 0.04540* |
| TP | -6.348208 | 3.962535 | -1.602 | 0.10914 |
| TKN | 0.003350 | 0.003489 | 0.960 | 0.33704 |
| pH:TP | 0.835579 | 0.444839 | 1.878 | 0.06033 . |
| Depth: Secchi | -0.011885 | 0.020309 | -0.585 | 0.55839 |
| Depth: pH | -1.117651 | 0.543925 | -2.055 | 0.03990* |
| Depth: Cond | -0.002387 | 0.005225 | -0.457 | 0.64777 |
| Depth: Chl_a | -0.133836 | 0.127631 | -1.049 | 0.29435 |
| Chl_a:TP | 0.027721 | 0.032057 | 0.865 | 0.38718 |
| Secchi:pH | 2.083310 | 0.760997 | 2.738 | 0.00619** |
| Secchi:Chl_a | 0.238559 | 0.185136 | 1.289 | 0.19755 |
| Secchi:Cond | 0.003208 | 0.008452 | 0.380 | 0.70425 |
| Secchi:TP | 0.075692 | 0.025452 | 2.974 | 0.00294** |
| pH:Chl_a | -1.522520 | 0.824893 | -1.846 | 0.06493 . |
| Cond: Chl_a | -0.016276 | 0.009370 | -1.737 | 0.08238 . |
| Chl_a:TKN | -0.002278 | 0.002430 | -0.938 | 0.34836 |
| Cond: TP | -0.001272 | 0.002833 | -0.449 | 0.65353 |

In this table, the significance levels are indicated by asterisks in the p-value column as follows:

- *: p-value < 0.05 (Significant)
- **: p-value < 0.01 (Highly Significant)
- ***: p-value < 0.001 (Very Highly Significant)

**Table F.** Summary of GLM Results Showing the Influence of Taxa on Avg_Dens:

| Predictor | Coefficient | Std. Error | t-value | p-value |
|---|---|---|---|---|
| (Intercept) | 0.5982 | 1.509 | 0.396 | 0.69259 |
| Depth | -0.4728 | 0.1718 | -2.753 | 0.00683** |
| Secchi | 0.0586 | 0.2433 | 0.241 | 0.81020 |
| pH | -0.0668 | 0.1665 | -0.401 | 0.68930 |
| Cond | -0.000046 | 0.001285 | -0.036 | 0.97141 |
| Chl_a | -0.2395 | 0.3402 | -0.704 | 0.48272 |

| | | | | |
|---|---|---|---|---|
| TP | 0.0756 | 0.1426 | 0.530 | 0.59695 |
| TKN | -0.000147 | 0.000126 | -1.177 | 0.24157 |
| pH:TP | -0.0078 | 0.0160 | -0.487 | 0.62722 |
| Depth: Secchi | 0.000657 | 0.000731 | 0.898 | 0.37109 |
| Depth: pH | 0.0501 | 0.0196 | 2.559 | 0.01175* |
| Depth: Cond | 0.000216 | 0.000188 | 1.149 | 0.25283 |
| Depth: Chl_a | -0.000012 | 0.004596 | -0.003 | 0.99792 |
| Chl_a:TP | -0.000303 | 0.001153 | -0.263 | 0.79304 |
| Secchi:pH | -0.000290 | 0.0274 | -0.011 | 0.99156 |
| Secchi:Chl_a | 0.0042 | 0.006664 | 0.632 | 0.52855 |
| Secchi:Cond | -0.000147 | 0.000464 | 0.324 | 0.7465 |
| Secchi:TP | -0.000705 | 0.000916 | -0.769 | 0.44314 |
| pH:Chl_a | 0.0237 | 0.0296 | 0.799 | 0.42569 |
| Cond: Chl_a | 0.000032 | 0.000337 | 0.097 | 0.92300 |
| Chl_a:TKN | 0.000074 | 0.000087 | 0.850 | 0.39688 |
| Cond: TP | -0.000026 | 0.000102 | -0.263 | 0.79307 |

In this table, the significance levels are indicated by asterisks in the p-value column as follows:

- *: p-value < 0.05 (Significant)
- **: p-value < 0.01 (Highly Significant)
- ***: p-value < 0.001 (Very Highly Significant)

**Table G.** Summary of GLM Results Showing the Influence of Taxa on the SDI:

| **Predictor** | **Coefficient** | **Std. Error** | **t-value** | **p-value** |
|---|---|---|---|---|
| **(Intercept)** | -5.0408313 | 23.0309434 | -0.219 | 0.8271 |
| **Depth** | -2.1840734 | 2.6209054 | -0.833 | 0.4063 |
| **Secchi** | 4.6945558 | 3.7128772 | 1.264 | 0.2086 |
| **pH** | 0.3348311 | 2.5412400 | 0.132 | 0.8954 |
| **Cond** | 0.0105963 | 0.0196030 | 0.541 | 0.5898 |
| **Chl_a** | 0.7108513 | 5.1909051 | 0.137 | 0.8913 |
| **TP** | 0.5448253 | 2.1761318 | 0.250 | 0.8027 |
| **TKN** | -0.0009760 | 0.0019155 | -0.510 | 0.6113 |
| **pH:TP** | -0.0300401 | 0.2442865 | -0.123 | 0.9023 |
| **Depth: Secchi** | -0.0247545 | 0.0111585 | -2.218 | 0.0284* |
| **Depth: pH** | 0.3489551 | 0.2989175 | 1.167 | 0.2454 |
| **Depth: Cond** | -0.019564 | 0.027754 | -0.705 | 0.4822 |
| **Depth: Chl_a** | 0.0161030 | 0.0701208 | 0.230 | 0.8188 |
| **Chl_a:TP** | -0.0110938 | 0.0176004 | -0.432 | 0.6665 |
| **Secchi:pH** | -2.862548 | 0.4181529 | -0.708 | 0.4803 |
| **Secchi:Chl_a** | 1.013492 | 0.982998 | 1.031 | 0.3046 |
| **Secchi:Cond** | 0.005089 | 0.044893 | 0.113 | 0.9099 |

| | | | | |
|---|---|---|---|---|
| **Secchi:TP** | -0.040326 | 0.135176 | -0.298 | 0.7660 |
| **pH:Chl_a** | -6.175307 | 4.372474 | -1.412 | 0.1605 |
| **Cond: Chl_a** | -0.103837 | 0.049691 | -2.090 | 0.0388* |
| **Chl_a:TKN** | -0.002359 | 0.012882 | -0.183 | 0.8550 |
| **Cond: TP** | -0.020102 | 0.015044 | -1.336 | 0.1840 |

In this table, the significance levels are indicated by asterisks in the p-value column as follows:

- *: p-value < 0.05 (Significant)
- **: p-value < 0.01 (Highly Significant)
- ***: p-value < 0.001 (Very Highly Significant)

**Table H.** Summary of GLM Results Showing the Influence of Taxa on Richness:

| Predictor | Estimate | Std. Error | t-value | p-value |
|---|---|---|---|---|
| (Intercept) | -7.044140 | 222.649330 | -0.032 | 0.9748 |
| Depth | 3.893594 | 25.337340 | 0.154 | 0.8781 |
| Secchi | 22.188568 | 35.893867 | 0.618 | 0.5376 |
| pH | -13.673395 | 24.567182 | -0.557 | 0.5789 |
| Cond | 0.318547 | 0.189510 | 1.681 | 0.0954* |
| Chl_a | 89.564637 | 50.182553 | 1.785 | 0.0768* |
| TP | -14.288906 | 21.037535 | -0.679 | 0.4983 |
| TKN | 0.005087 | 0.018518 | 0.275 | 0.7840 |
| pH:TP | 2.819372 | 2.361615 | 1.194 | 0.2349 |
| Depth: Secchi | -0.209528 | 0.107874 | -1.942 | 0.0545* |
| Depth: pH | 0.603603 | 2.889755 | 0.209 | 0.8349 |
| Depth: Cond | -0.019564 | 0.027754 | -0.705 | 0.4822 |
| Depth: Chl_a | -0.469344 | 0.677886 | -0.692 | 0.4901 |
| Chl_a:TP | -0.073517 | 0.170150 | -0.432 | 0.6665 |
| Secchi:pH | -2.862548 | 4.042451 | -0.708 | 0.4803 |
| Secchi:Chl_a | 1.013492 | 0.982998 | 1.031 | 0.3046 |
| Secchi:Cond | 0.005089 | 0.044893 | 0.113 | 0.9099 |
| Secchi:TP | -0.040326 | 0.135176 | -0.298 | 0.7660 |
| pH:Chl_a | 0.1021029 | 0.4522906 | 0.226 | 0.8218 |
| Cond: Chl_a | -0.103837 | 0.049691 | -2.090 | 0.0388* |
| Chl_a:TKN | -0.002359 | 0.012882 | -0.183 | 0.8550 |
| Cond: TP | -0.020102 | 0.015044 | -1.336 | 0.1840* |

In this table, the significance levels are indicated by asterisks in the p-value column as follows:

- *: p-value < 0.05 (Significant)

- **: p-value < 0.01 (Highly Significant)
- ***: p-value < 0.001 (Very Highly Significant)

**Table I.** Station Eigenvalues and Species Environment Correlations: This table concisely overviews the analysis's quantitative backbone, emphasizing the significant explanatory power of the first ten CCA axes.

| | Eigenvalue | Proportion Explained | Cumulative Proportion |
|---|---|---|---|
| CCA1 | 0.7374 | 0.3803 | 0.3803 |
| CCA2 | 0.4563 | 0.2354 | 0.6157 |
| CCA3 | 0.2757 | 0.1422 | 0.7579 |
| CCA4 | 0.15436 | 0.07962 | 0.83751 |
| CCA5 | 0.10263 | 0.05294 | 0.89044 |
| CCA6 | 0.0758 | 0.0391 | 0.9295 |
| CCA7 | 0.05116 | 0.02639 | 0.95593 |
| CCA8 | 0.0432 | 0.02228 | 0.97821 |
| CCA9 | 0.02896 | 0.01494 | 0.99315 |
| CCA10 | 0.013274 | 0.006846 | 1 |

**Table J.** LC12 Biplot Scores for Key Environmental Variables: This table will summarize the scores of key environmental variables on the first two canonical axes (CCA1 and CCA2), indicating how each variable is related to the zooplankton community distribution at LC12.

| Variable | CCA1 | CCA2 |
|---|---|---|
| Depth | 0.224187 | -0.20486 |
| Secchi | 0.222499 | -0.20515 |
| pH | -0.48146 | -0.25411 |
| Cond | -0.0857 | 0.307279 |
| Chl_a | 0.104378 | -0.11655 |
| TP | 0.460241 | -0.77797 |
| TKN | 0.331361 | 0.440349 |
| Abund | -0.01811 | -0.71484 |
| Avg_Dens | -0.15509 | -0.08258 |
| SDI | -0.13072 | -0.63261 |
| Rich | 0.145221 | -0.72659 |

**Table K.** Seasons Eigenvalues and Species Environment Correlations presents a concise overview of the analysis's quantitative backbone, emphasizing the significant explanatory power of the first two CCA axes.

| Axis | Eigenvalue | Proportion Explained | Cumulative Proportion |
|---|---|---|---|
| CCA1 | 0.1984 | 0.1179 | 0.1179 |
| CCA2 | 0.1875 | 0.1114 | 0.2294 |
| CCA3 | 0.11886 | 0.07064 | 0.29999 |
| CCA4 | 0.09315 | 0.05536 | 0.35534 |
| CCA5 | 0.06435 | 0.03824 | 0.39359 |
| CCA6 | 0.05813 | 0.03455 | 0.42813 |
| CCA7 | 0.03056 | 0.01816 | 0.4463 |
| CCA8 | 0.01817 | 0.0108 | 0.4571 |
| CCA9 | 0.011557 | 0.006868 | 0.463965 |
| CCA10 | 0.00904 | 0.005372 | 0.469337 |
| CCA11 | 0.006729 | 0.003999 | 0.473336 |
| CA1 | 0.15516 | 0.09221 | 0.56555 |
| CA2 | 0.14921 | 0.08867 | 0.65422 |
| CA3 | 0.09889 | 0.05877 | 0.71298 |
| CA4 | 0.0835 | 0.04962 | 0.76261 |
| CA5 | 0.06772 | 0.04025 | 0.80285 |
| CA6 | 0.05908 | 0.03511 | 0.83797 |
| CA7 | 0.04091 | 0.02431 | 0.86228 |
| CA8 | 0.0342 | 0.02032 | 0.8826 |
| CA9 | 0.02499 | 0.01485 | 0.89745 |
| CA10 | 0.02216 | 0.01317 | 0.91062 |
| CA11 | 0.02036 | 0.0121 | 0.92272 |
| CA12 | 0.01846 | 0.01097 | 0.93369 |
| CA13 | 0.01637 | 0.00973 | 0.94342 |
| CA14 | 0.013469 | 0.008004 | 0.951428 |
| CA15 | 0.01236 | 0.007345 | 0.958773 |
| CA16 | 0.012 | 0.00713 | 0.9659 |
| CA17 | 0.010396 | 0.006178 | 0.972082 |
| CA18 | 0.007954 | 0.004727 | 0.976809 |
| CA19 | 0.007468 | 0.004438 | 0.981247 |

| | | | |
|---|---|---|---|
| CA20 | 0.005723 | 0.003401 | 0.984649 |
| CA21 | 0.005479 | 0.003256 | 0.987904 |
| CA22 | 0.004683 | 0.002783 | 0.990687 |
| CA23 | 0.00405 | 0.002407 | 0.993094 |
| CA24 | 0.003263 | 0.001939 | 0.995033 |
| CA25 | 0.002589 | 0.001539 | 0.996572 |
| CA26 | 0.002203 | 0.001309 | 0.997881 |
| CA27 | 0.001445 | 0.0008589 | 0.9987397 |
| CA28 | 0.001252 | 0.0007437 | 0.9994834 |
| | | CA29 | 0.000869 |

**Table L.** Spring Biplot Scores for Key Environmental Variables: This table summarizes the scores of key environmental variables on the first two canonical axes (CCA1 and CCA2), indicating how each variable is related to the zooplankton community distribution for the Spring season.

| Variable | CCA1 | CCA2 |
|---|---|---|
| Depth | 0.610249 | -0.30323 |
| Secchi | 0.186978 | -0.31133 |
| pH | 0.450483 | 0.448547 |
| Cond | 0.027439 | 0.341703 |
| Chl_a | -0.21651 | -0.00222 |
| TP | 0.2262 | -0.40617 |
| TKN | -0.3193 | -0.487 |
| Abund | -0.28584 | -0.44558 |
| Avg_Dens | 0.432872 | 0.151668 |
| SDI | 0.765554 | 0.361451 |
| Rich | -0.00512 | -0.49954 |

**Table M.** Summer Biplot Scores for Key Environmental Variables: This table summarizes the scores of key environmental variables on the first two canonical axes (CCA1 and CCA2), indicating how each variable is related to the zooplankton community distribution for the Summer season.

| Variable | CCA1 | CCA2 |
|---|---|---|
| Depth | 0.165112 | -0.07503 |
| Secchi | 0.445855 | -0.22029 |
| pH | 0.61542 | -0.40713 |
| Cond | 0.305677 | 0.150883 |

| | | |
|---|---|---|
| Chl_a | -0.22955 | 0.135109 |
| TP | -0.1491 | 0.902025 |
| TKN | -0.18788 | 0.339154 |
| Abund | 0.745482 | 0.146041 |
| Avg_Dens | 0.491088 | -0.33553 |
| SDI | -0.98944 | 0.009462 |
| Rich | -0.3548 | 0.386994 |

**Table N.** Fall Biplot Scores for Key Environmental Variables: This table will summarize the scores of key environmental variables on the first two canonical axes (CCA1 and CCA2), indicating how each variable is related to the zooplankton community distribution for the Fall season.

| Variable | CCA1 | CCA2 |
|---|---|---|
| Depth | -0.60467 | 0.091004 |
| Secchi | -0.67011 | 0.327958 |
| pH | -0.33939 | 0.318911 |
| Cond | 0.19716 | 0.835099 |
| Chl_a | 0.814917 | 0.037723 |
| TP | 0.541041 | -0.11295 |
| TKN | 0.357568 | -0.67009 |
| Abund | -0.42194 | 0.41671 |
| Avg_Dens | -0.39675 | -0.11602 |
| SDI | -0.55695 | 0.242895 |
| Rich | -0.56153 | -0.42588 |

**Table O.** Summary of Eigenvalues and Annual Species-Environment Correlations: This table details the eigenvalues, the proportion of variance explained, and the cumulative proportion, offering a quantitative backdrop to the visual insights provided by the biplot.

| Axis | Eigenvalue | Proportion Explained | Cumulative Proportion |
|---|---|---|---|
| CCA1 | 0.6421 | 0.3555 | 0.3555 |
| CCA2 | 0.09989 | 0.05531 | 0.41082 |
| CCA3 | 0.05354 | 0.02964 | 0.44046 |
| CCA4 | 0.04751 | 0.0263 | 0.46676 |
| CCA5 | 0.02219 | 0.01229 | 0.47904 |
| CCA6 | 0.01892 | 0.01048 | 0.48952 |
| CCA7 | 0.012253 | 0.006784 | 0.496305 |

| | | | |
|---|---|---|---|
| CCA8 | 0.007927 | 0.004389 | 0.500694 |
| CCA9 | 0.006563 | 0.003633 | 0.504328 |
| CCA10 | 0.003515 | 0.001946 | 0.506274 |
| CCA11 | 0.001697 | 0.0009397 | 0.5072134 |
| CA1 | 0.14282 | 0.07907 | 0.58629 |
| CA2 | 0.08738 | 0.04838 | 0.63467 |
| CA3 | 0.07661 | 0.04241 | 0.67708 |
| CA4 | 0.06625 | 0.03668 | 0.71376 |
| CA5 | 0.05083 | 0.02814 | 0.7419 |
| CA6 | 0.04754 | 0.02632 | 0.76822 |
| CA7 | 0.03621 | 0.02005 | 0.78827 |
| CA8 | 0.03465 | 0.01918 | 0.80745 |
| CA9 | 0.03211 | 0.01778 | 0.82523 |
| CA10 | 0.02895 | 0.01603 | 0.84126 |
| CA11 | 0.02555 | 0.01415 | 0.85541 |
| CA12 | 0.02485 | 0.01376 | 0.86916 |
| CA13 | 0.02265 | 0.01254 | 0.88171 |
| CA14 | 0.01881 | 0.01041 | 0.89212 |
| CA15 | 0.017164 | 0.009503 | 0.90162 |
| CA16 | 0.016861 | 0.009335 | 0.910955 |
| CA17 | 0.01535 | 0.0085 | 0.91946 |
| CA18 | 0.014022 | 0.007763 | 0.927218 |
| CA19 | 0.01305 | 0.007225 | 0.934443 |
| CA20 | 0.011712 | 0.006484 | 0.940928 |
| CA21 | 0.01019 | 0.00564 | 0.94657 |
| CA22 | 0.009637 | 0.005335 | 0.951903 |
| CA23 | 0.009064 | 0.005018 | 0.956921 |
| CA24 | 0.007781 | 0.004308 | 0.961229 |
| CA25 | 0.007141 | 0.003954 | 0.965183 |
| CA26 | 0.006723 | 0.003722 | 0.968905 |
| CA27 | 0.005842 | 0.003235 | 0.97214 |
| CA28 | 0.00499 | 0.002763 | 0.974902 |
| CA29 | 0.00485 | 0.002685 | 0.977588 |
| CA30 | 0.004806 | 0.002661 | 0.980249 |
| CA31 | 0.004319 | 0.002391 | 0.98264 |
| CA32 | 0.004027 | 0.00223 | 0.98487 |

| | | | |
|---|---|---|---|
| CA33 | 0.003562 | 0.001972 | 0.986842 |
| CA34 | 0.003077 | 0.001704 | 0.988546 |
| CA35 | 0.002679 | 0.001483 | 0.990029 |
| CA36 | 0.002538 | 0.001405 | 0.991434 |
| CA37 | 0.002159 | 0.001195 | 0.99263 |
| CA38 | 0.001949 | 0.001079 | 0.993709 |
| CA39 | 0.001706 | 0.0009442 | 0.9946529 |
| CA40 | 0.001565 | 0.0008664 | 0.9955193 |
| CA41 | 0.001482 | 0.0008204 | 0.9963396 |
| CA42 | 0.001195 | 0.0006615 | 0.9970012 |
| CA43 | 0.000976 | 0.0005403 | 0.9975415 |
| CA44 | 0.000824 | 0.0004559 | 0.9979974 |
| CA45 | 0.000724 | 0.0004009 | 0.9983983 |
| CA46 | 0.000612 | 0.000339 | 0.9987372 |
| CA47 | 0.000537 | 0.0002973 | 0.9990345 |
| CA48 | 0.000451 | 0.0002495 | 0.999284 |
| CA49 | 0.00037 | 0.0002051 | 0.9994891 |
| CA50 | 0.000229 | 0.0001268 | 0.9996158 |
| CA51 | 0.000189 | 0.0001049 | 0.9997207 |
| CA52 | 1.72E-04 | 9.54E-05 | 1.00E+00 |
| CA53 | 1.08E-04 | 5.99E-05 | 1.00E+00 |
| CA54 | 8.32E-05 | 4.61E-05 | 1.00E+00 |
| CA55 | 6.04E-05 | 3.35E-05 | 1.00E+00 |
| CA56 | 5.80E-05 | 3.21E-05 | 1.00E+00 |
| CA57 | 1.30E-05 | 7.18E-06 | 1.00E+00 |
| CA58 | 4.89E-06 | 2.71E-06 | 1.00E+00 |
| CA59 | 4.26E-06 | 2.36E-06 | 1.00E+00 |
| CA60 | 2.70E-07 | 1.50E-07 | 1.00E+00 |

**Table P.** Year 2008 Biplot Scores for Key Environmental Variables: This table summarizes the scores of key environmental variables on the first two canonical axes (CCA1 and CCA2), indicating how each variable is related to the zooplankton community distribution for the Year 2008.

| Variable | CCA1 | CCA2 |
|---|---|---|
| Depth | 0.024994 | -0.20998 |
| Secchi | 0.032323 | 0.319073 |
| pH | -0.21495 | 0.445534 |
| Cond | 0.052218 | 0.154531 |
| Chl_a | -0.05439 | -0.24378 |
| TP | -0.6566 | -0.34087 |
| TKN | -0.24381 | -0.16518 |
| Abund | -0.9129 | 0.073891 |
| Avg_Dens | -0.01875 | -0.19738 |
| SDI | 0.552706 | -0.14581 |
| Rich | -0.18585 | -0.28714 |

**Table Q.** Detailed Analysis of Water Filtration: This table details the quantity of water filtered across various Stations over different years and seasons using nets with mouth ring diameters of 12 cm, 14 cm, or 19 cm.

| **Station** | **Date** | **Diameter (m)** | **Sample Depth (m)** | **Calculated Volume ($m^3$)** |
|---|---|---|---|---|
| LC12 | 2008-05-13 | 0.14 | 1.5 | 0.023091 |
| LC12 | 2008-05-27 | 0.14 | 1 | 0.015394 |
| LC12 | 2008-06-11 | 0.14 | 1 | 0.015394 |
| LC12 | 2008-06-24 | 0.12 | 1 | 0.01131 |
| LC12 | 2008-07-08 | 0.14 | 2 | 0.030788 |

| | | | | |
|---|---|---|---|---|
| LC12 | 2008-07-22 | 0.14 | 1 | 0.015394 |
| LC12 | 2008-08-05 | 0.14 | 1 | 0.015394 |
| LC12 | 2008-08-19 | 0.14 | 1 | 0.015394 |
| LC12 | 2008-09-02 | 0.14 | 1 | 0.015394 |
| LC12 | 2008-09-16 | 0.14 | 1 | 0.015394 |
| LC12 | 2008-09-30 | 0.14 | 1 | 0.015394 |
| LC12 | 2008-10-14 | 0.14 | 1 | 0.015394 |
| LC15 | 2008-05-13 | 0.14 | 9 | 0.138544 |
| LC15 | 2008-05-27 | 0.14 | 12 | 0.184726 |
| LC15 | 2008-06-11 | 0.14 | 10 | 0.153938 |
| LC15 | 2008-06-24 | 0.12 | 10 | 0.113097 |
| LC15 | 2008-07-08 | 0.14 | 8 | 0.12315 |
| LC17 | 2008-05-13 | 0.14 | 7 | 0.107757 |
| LC17 | 2008-05-27 | 0.14 | 7 | 0.107757 |
| LC17 | 2008-06-11 | 0.14 | 7 | 0.107757 |
| LC17 | 2008-06-24 | 0.12 | 7 | 0.079168 |
| LC17 | 2008-07-08 | 0.14 | 7 | 0.107757 |
| LC17 | 2008-07-22 | 0.14 | 8 | 0.12315 |
| LC17 | 2008-08-05 | 0.14 | 6 | 0.092363 |
| LC17 | 2008-08-19 | 0.14 | 5 | 0.076969 |
| LC17 | 2008-09-02 | 0.14 | 6 | 0.092363 |
| LC17 | 2008-09-16 | 0.14 | 6 | 0.092363 |
| LC17 | 2008-09-30 | 0.14 | 4 | 0.061575 |
| LC17 | 2008-10-14 | 0.14 | 2.5 | 0.038485 |
| LC19 | 2008-05-13 | 0.14 | 2 | 0.030788 |
| LC19 | 2008-05-27 | 0.14 | 2 | 0.030788 |
| LC19 | 2008-06-11 | 0.14 | 2 | 0.030788 |
| LC19 | 2008-06-24 | 0.12 | 2 | 0.022619 |
| LC19 | 2008-07-08 | 0.14 | 2 | 0.030788 |
| LC19 | 2008-07-22 | 0.14 | 2 | 0.030788 |
| LC19 | 2008-08-05 | 0.14 | 2 | 0.030788 |
| LC19 | 2008-08-19 | 0.14 | 1 | 0.015394 |
| LC19 | 2008-09-02 | 0.14 | 1 | 0.015394 |
| LC19 | 2008-09-16 | 0.14 | 1.5 | 0.023091 |
| LC19 | 2008-09-30 | 0.14 | 1 | 0.015394 |
| LC22 | 2008-05-13 | 0.14 | 6.5 | 0.10006 |
| LC22 | 2008-05-27 | 0.14 | 5 | 0.076969 |
| LC22 | 2008-06-11 | 0.14 | 6 | 0.092363 |
| LC22 | 2008-06-24 | 0.12 | 7 | 0.079168 |
| LC22 | 2008-07-08 | 0.14 | 7 | 0.107757 |
| LC22 | 2008-07-22 | 0.14 | 8 | 0.12315 |

| | | | | |
|---|---|---|---|---|
| LC22 | 2008-08-05 | 0.14 | 7 | 0.107757 |
| LC22 | 2008-08-19 | 0.14 | 6 | 0.092363 |
| LC22 | 2008-09-02 | 0.14 | 6 | 0.092363 |
| LC22 | 2008-09-16 | 0.14 | 6 | 0.092363 |
| LC22 | 2008-09-30 | 0.14 | 6 | 0.092363 |
| LC22 | 2008-10-14 | 0.14 | 5.5 | 0.084666 |
| LC3 | 2008-05-13 | 0.14 | 5 | 0.076969 |
| LC3 | 2008-05-27 | 0.14 | 5 | 0.076969 |
| LC3 | 2008-06-11 | 0.14 | 5 | 0.076969 |
| LC3 | 2008-06-24 | 0.12 | 5 | 0.056549 |
| LC3 | 2008-07-08 | 0.14 | 5 | 0.076969 |
| LC3 | 2008-07-22 | 0.14 | 6 | 0.092363 |
| LC3 | 2008-08-05 | 0.14 | 5 | 0.076969 |
| LC3 | 2008-08-19 | 0.14 | 5 | 0.076969 |
| LC3 | 2008-09-02 | 0.14 | 5 | 0.076969 |
| LC3 | 2008-09-16 | 0.14 | 5 | 0.076969 |
| LC3 | 2008-09-30 | 0.14 | 5 | 0.076969 |
| LC3 | 2008-10-14 | 0.14 | 4.5 | 0.069272 |
| LC5 | 2008-05-13 | 0.14 | 9 | 0.138544 |
| LC5 | 2008-05-27 | 0.14 | 9 | 0.138544 |
| LC5 | 2008-06-11 | 0.14 | 8 | 0.12315 |
| LC5 | 2008-06-24 | 0.12 | 9 | 0.101788 |
| LC5 | 2008-07-08 | 0.14 | 9 | 0.138544 |
| LC12 | 2013-05-07 | 0.19 | 0.5 | 0.014176 |
| LC12 | 2013-05-22 | 0.19 | 0.5 | 0.014176 |
| LC12 | 2013-06-03 | 0.19 | 0.4 | 0.011341 |
| LC12 | 2013-06-17 | 0.19 | 0.3 | 0.008506 |
| LC12 | 2013-07-03 | 0.19 | 3 | 0.085059 |
| LC12 | 2013-07-16 | 0.19 | 0.2 | 0.005671 |
| LC12 | 2013-07-30 | 0.19 | 0.5 | 0.014176 |
| LC12 | 2013-08-13 | 0.19 | 0.5 | 0.014176 |
| LC12 | 2013-08-27 | 0.19 | 0.5 | 0.014176 |
| LC12 | 2013-09-10 | 0.19 | 0.8 | 0.022682 |
| LC12 | 2013-09-24 | 0.12 | 0.4 | 0.004524 |
| LC12 | 2013-10-08 | 0.12 | 0.5 | 0.005655 |
| LC15 | 2013-05-22 | 0.19 | 8.7 | 0.24667 |
| LC15 | 2013-06-17 | 0.19 | 8.2 | 0.232494 |
| LC15 | 2013-07-16 | 0.19 | 8.6 | 0.243835 |
| LC15 | 2013-08-13 | 0.19 | 9 | 0.255176 |
| LC15 | 2013-09-10 | 0.19 | 8.7 | 0.24667 |
| LC15 | 2013-10-08 | 0.12 | 8.4 | 0.095002 |

| | | | | |
|---|---|---|---|---|
| LC17 | 2013-05-07 | 0.19 | 6.1 | 0.172953 |
| LC17 | 2013-05-22 | 0.19 | 6.9 | 0.195635 |
| LC17 | 2013-06-03 | 0.19 | 7 | 0.19847 |
| LC17 | 2013-06-17 | 0.19 | 7 | 0.19847 |
| LC17 | 2013-07-03 | 0.19 | 6.9 | 0.195635 |
| LC17 | 2013-07-16 | 0.19 | 6.7 | 0.189964 |
| LC17 | 2013-07-30 | 0.19 | 6 | 0.170117 |
| LC17 | 2013-08-13 | 0.19 | 6 | 0.170117 |
| LC17 | 2013-08-27 | 0.19 | 5.8 | 0.164447 |
| LC17 | 2013-09-10 | 0.12 | 6.7 | 0.075775 |
| LC17 | 2013-09-24 | 0.12 | 6.4 | 0.072382 |
| LC17 | 2013-10-08 | 0.12 | 6.3 | 0.071251 |
| LC19 | 2013-05-07 | 0.19 | 1.3 | 0.036859 |
| LC19 | 2013-05-22 | 0.19 | 1.8 | 0.051035 |
| LC19 | 2013-06-03 | 0.19 | 1.5 | 0.042529 |
| LC19 | 2013-06-17 | 0.19 | 2 | 0.056706 |
| LC19 | 2013-07-03 | 0.19 | 1.9 | 0.05387 |
| LC19 | 2013-07-16 | 0.19 | 1.3 | 0.036859 |
| LC19 | 2013-07-30 | 0.19 | 1.1 | 0.031188 |
| LC19 | 2013-08-13 | 0.19 | 1.5 | 0.042529 |
| LC19 | 2013-08-27 | 0.19 | 1.5 | 0.042529 |
| LC19 | 2013-09-10 | 0.12 | 1 | 0.01131 |
| LC19 | 2013-09-24 | 0.12 | 1 | 0.01131 |
| LC19 | 2013-10-08 | 0.12 | 1 | 0.01131 |
| LC22 | 2013-05-07 | 0.19 | 6.7 | 0.189964 |
| LC22 | 2013-05-22 | 0.19 | 3.3 | 0.093564 |
| LC22 | 2013-06-03 | 0.19 | 6.2 | 0.175788 |
| LC22 | 2013-06-17 | 0.19 | 5 | 0.141764 |
| LC22 | 2013-07-03 | 0.19 | 5 | 0.141764 |
| LC22 | 2013-07-16 | 0.19 | 4.7 | 0.133259 |
| LC22 | 2013-07-30 | 0.19 | 4.7 | 0.133259 |
| LC22 | 2013-08-13 | 0.19 | 6 | 0.170117 |
| LC22 | 2013-08-27 | 0.19 | 2 | 0.056706 |
| LC22 | 2013-09-10 | 0.12 | 5.2 | 0.058811 |
| LC22 | 2013-09-24 | 0.12 | 4.8 | 0.054287 |
| LC22 | 2013-10-08 | 0.12 | 4.9 | 0.055418 |
| LC3 | 2013-05-07 | 0.19 | 4.3 | 0.121917 |
| LC3 | 2013-05-22 | 0.19 | 4.5 | 0.127588 |
| LC3 | 2013-06-03 | 0.19 | 4.6 | 0.130423 |
| LC3 | 2013-06-17 | 0.19 | 4.5 | 0.127588 |
| LC3 | 2013-07-03 | 0.19 | 4.5 | 0.127588 |

| | | | | |
|---|---|---|---|---|
| LC3 | 2013-07-16 | 0.19 | 4.5 | 0.127588 |
| LC3 | 2013-07-30 | 0.19 | 4.3 | 0.121917 |
| LC3 | 2013-08-13 | 0.19 | 4.5 | 0.127588 |
| LC3 | 2013-08-27 | 0.19 | 4.1 | 0.116247 |
| LC3 | 2013-09-10 | 0.12 | 4.2 | 0.047501 |
| LC3 | 2013-09-24 | 0.12 | 4.2 | 0.047501 |
| LC3 | 2013-10-08 | 0.12 | 4.1 | 0.04637 |
| LC5 | 2013-05-22 | 0.19 | 8.1 | 0.229658 |
| LC5 | 2013-06-17 | 0.19 | 8.5 | 0.240999 |
| LC5 | 2013-07-16 | 0.19 | 8.3 | 0.235329 |
| LC5 | 2013-08-13 | 0.19 | 7 | 0.19847 |
| LC5 | 2013-09-10 | 0.12 | 8 | 0.090478 |
| LC5 | 2013-10-08 | 0.12 | 7.8 | 0.088216 |

# Appendix C Figures: Canonical Correspondence Analysis (CCA) Plots

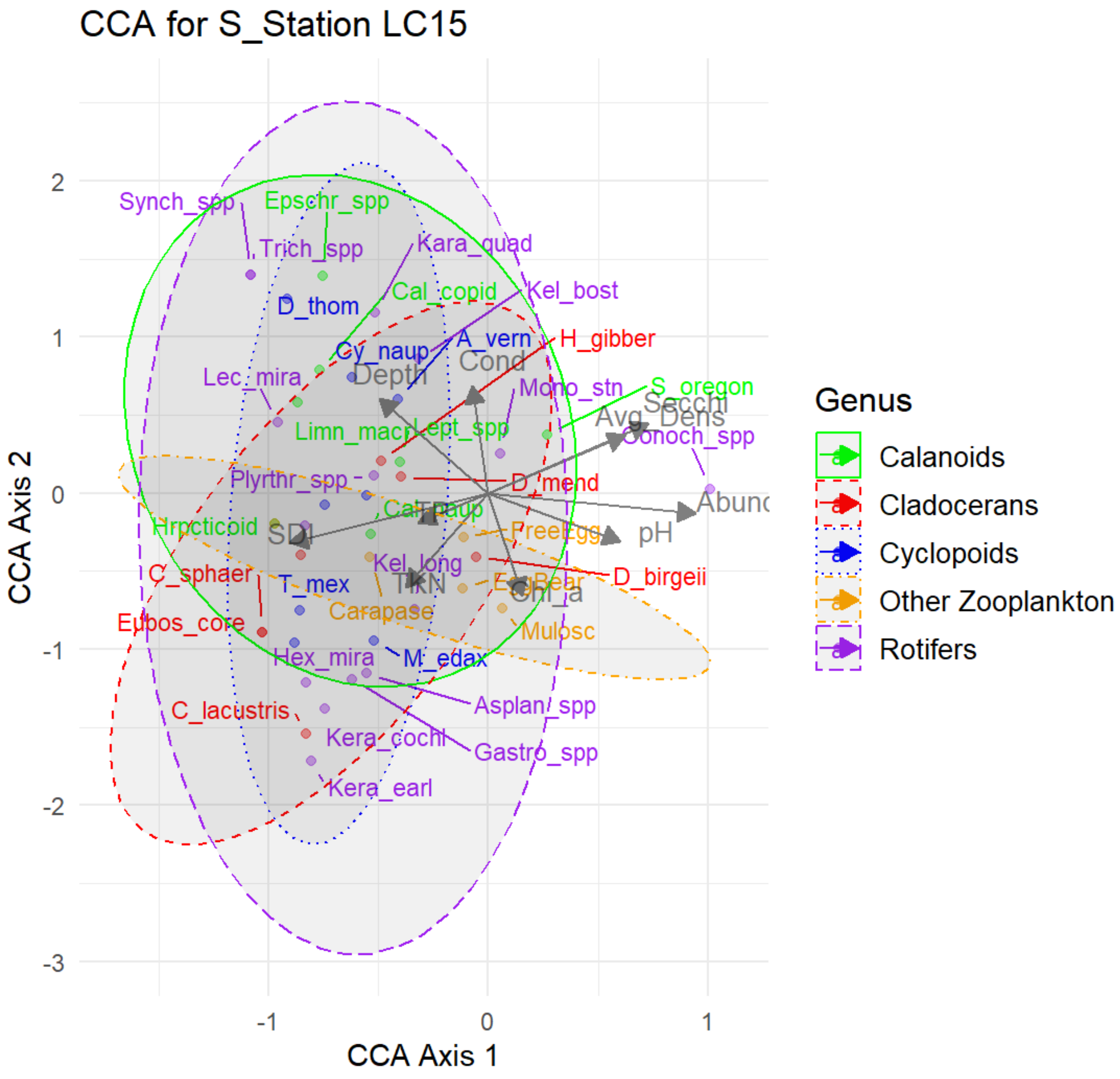

**Figure A. Biplot for Station LC15 Caption**— Depicts the relationship between zooplankton species and environmental variables at Station LC15, focusing on the influence of TP and TKN.

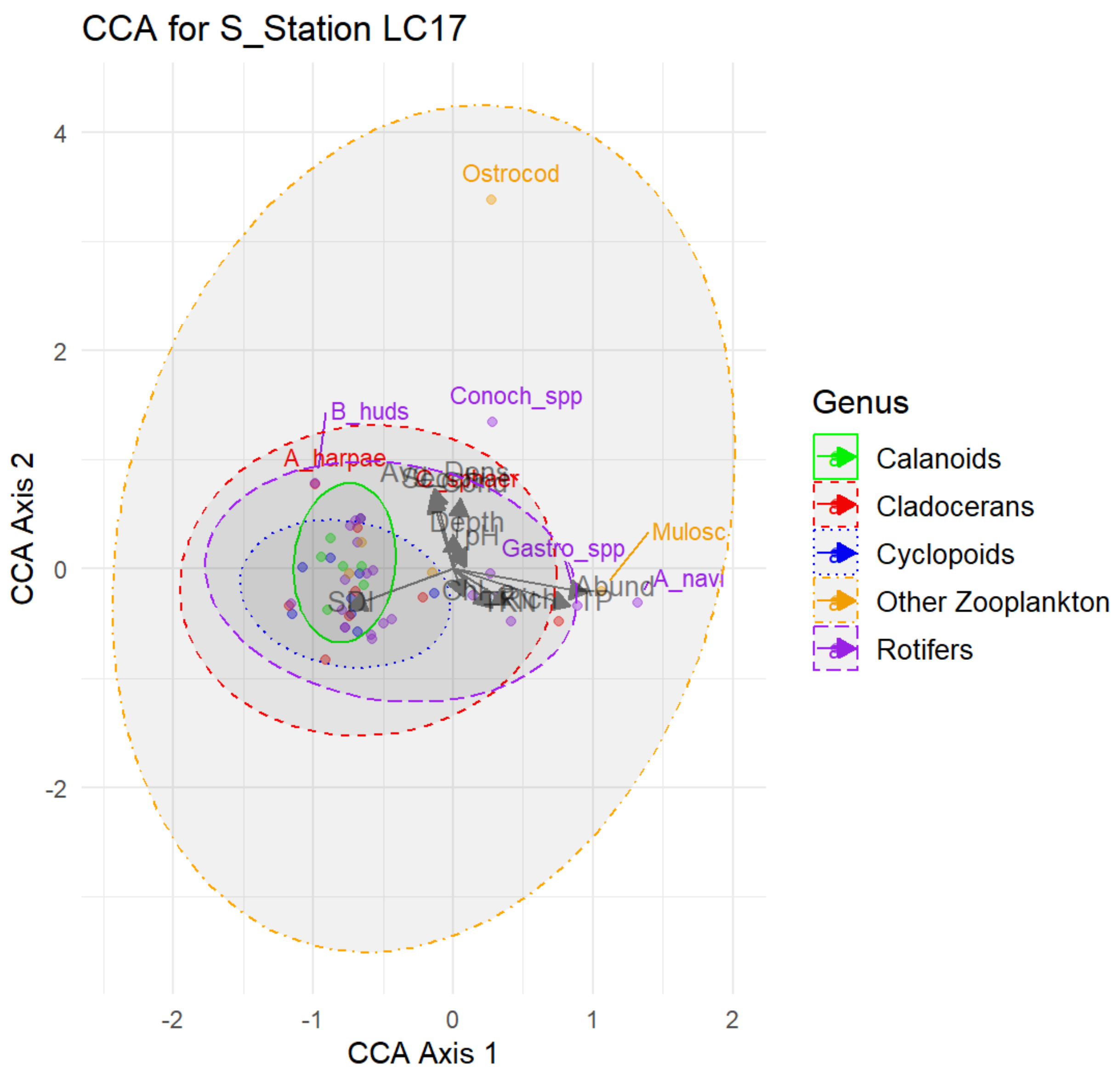

**Figure B. Biplot for Station LC17 Caption**—Demonstrates the interaction between zooplankton species and environmental variables at Station LC17, emphasizing the importance of Chl_a and pH.

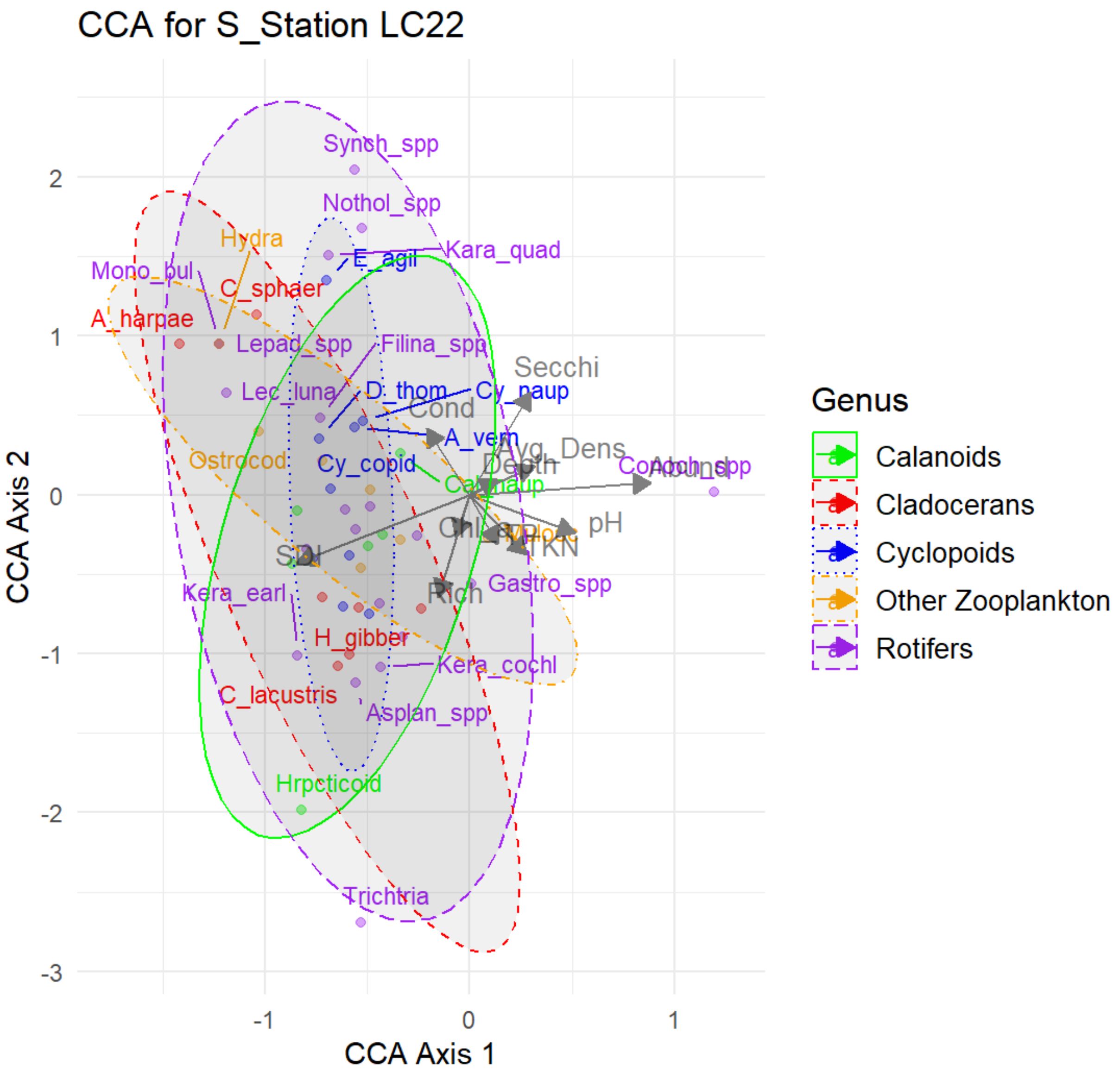

**Figure C. Biplot for Station LC22 Caption**—Biplot showing the interaction between zooplankton species and environmental variables at Station LC22, focusing on the impact of Secchi depth and Total Phosphorus.

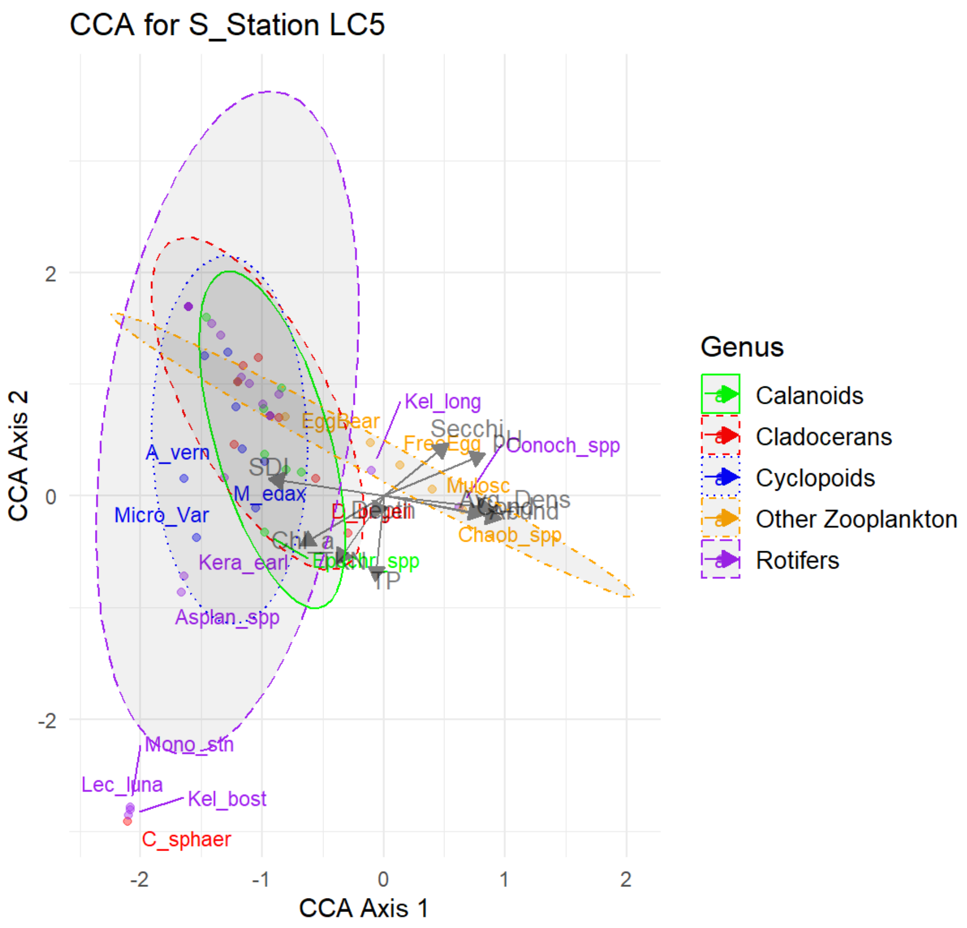

**Figure D Biplot for Station LC5 Caption**—Illustrates the relationship between zooplankton species and environmental variables at Station LC5, emphasizing the influence of conductivity and chlorophyll-a levels.

## Appendix D Methodology: Detailed Statistical Description

### Data Preprocessing and Structuring

This study faced significant challenges regarding sample loss and data imbalances across the two sampling years. Initially, down-sampling was considered to ensure equal representation among Stations and temporal scales (Year, Season), a strategy commonly employed in ecological research to manage data constraints (Bourel et al., 2021). However, the missing data, particularly at Stations LC5 and LC15, required a revision of the data structuring approach to better suit the present analytical needs. Two distinct datasets were developed to address the missing data issue:

**Conservative Dataset**: It excluded all records from Stations LC5 and LC15, eliminating the problems generated by missing data. This approach ensured a balanced dataset, but it omitted potentially valuable data from these Stations.

**Inclusive Dataset**: This dataset, which included all available records, even from LC5 and LC15, was designed to ensure the thoroughness and comprehensiveness of our research. It made the study more comprehensive but required careful handling of missing entries to mitigate potential biases.

Each dataset was crafted to mitigate specific limitations. The conservative dataset reduced the risk of biases associated with missing data, while the inclusive dataset, although more comprehensive, was susceptible to potential biases due to incomplete records. These adaptations were essential to maintain the integrity of the ecological findings and ensure that no single group was overrepresented such that it would influence the overall analysis (Anderson, 2001; Benkendorf et al., 2023; Quinn & Keough, 2002).

### Data Categorization and Grouping

Data were categorized and grouped based on important criteria such as sampling Station, Season, and Year. This structured approach allowed for the creation of subsets of data that maintained internal consistency and coherence, facilitating more precise trend detection and pattern analysis. The significance of data categorization and grouping lies in its ability to detect trends and identify subtle variations in water quality and zooplankton community structures (ZCS) that may have been obscured in a more aggregated dataset. Additionally, grouping datasets allowed for a more targeted application of analytical techniques, providing deeper insights into the ecological dynamics specific to each subset. This process improved the interpretation of results, helping to attribute observed trends to specific environmental or temporal factors. Overall, data categorization and grouping were essential to enhance the analytical power of the study and lay a foundation for subsequent analyses, uncovering important insights into the lake's ecosystem dynamics.

### Sensitivity Analysis for PERMANOVA Optimization

The PERMANOVA was performed on two different dataset structures, which were devised to address the issue of missing values in the original dataset. A sensitivity analysis assessed the impact of these structures on the statistical outcomes by comparing significance values, variance, and effect sizes between the balanced (conservative) and inclusive datasets.

**Variance and Effect Sizes:** Comparing variance and effect sizes before and after data balancing revealed minimal changes, indicating that the models were stable across most dataset structures.

**Bias Checks:** Statistical measures such as means and variances were scrutinized across the conservative and inclusive datasets. The consistency observed in most of these comparisons suggested that the dataset modifications did not introduce bias.

Therefore, the findings from the sensitivity analysis confirmed the robustness of the ecological interpretations. It demonstrated that the conservatively balanced dataset was particularly effective in maintaining accurate findings and ensuring valid ecological interpretations (Benkendorf et al., 2023).

### Descriptive Statistical Analyses

Descriptive statistical tests were conducted to check the distribution and variability of the water quality parameters and ZCS across various Stations. The data was summarized by calculating the mean standard deviation and identifying the minimum and maximum values to provide an overview of each variable's spread and central tendencies (Quinn & Keough, 2002).

### Principal Component Analysis for Temporal and Spatial Visualization of Water Quality Parameters and Zooplankton Community Structure

Separate Principal Component Analyses (PCAs) were conducted on two distinct sets of variables: WQPs including Depth, Secchi, pH, Conductivity, Chl_a, TP, TKN, and ZCS metrics comprising richness (Richness), abundance (Abund), Species Diversity Index (SDI), and average density (Avg_Dens). Data normalization was applied to each dataset before the PCA to ensure comparability across different metrics.

For WQPs and ZCS indices, only principal components with eigenvalues exceeding the Kaiser criterion (greater than 1) were retained for further analysis. This decision aligned with the established practices for determining the number of components to keep (*Principal Component Analysis*, 2002; Quinn & Keough, 2002). A Varimax orthogonal rotation facilitated a more precise interpretation of the principal components. This rotation simplifies the loading structure, making it easier to identify the contribution of each variable to the respective components (Pejman et al., 2009; Quinn & Keough, 2002).

The application of PCA allowed dimensionality reduction in the datasets, distilling the most influential factors that define patterns within the ecological data. These analyses provided insights into the underlying relationships between water quality and the ZCS in Lake Couchiching (Pejman et al., 2009; *Principal Component Analysis*, 2002; Quinn & Keough, 2002).

General Linear Models to Assess Spatial and Temporal Variations in Water Quality Parameters:

The General Linear Model (GLM) was used to evaluate the influences of temporal and spatial factors, including the Year, Season, and Station, on the WQPs. The GLM was chosen based on its ability to handle parametric data while maximizing the analytical power. GLMs were applied to each WQP individually to delineate specific temporal and spatial patterns and whether or not they were independent of one another.

A key advantage of GLMs in this context was their flexibility in accommodating the parametric assumptions met by the data, which included normality, homogeneity of variance, and independence of observations. Diagnostic plots were examined for each model to ensure these assumptions were satisfied. The significance level for all GLMs was set at $p < 0.05$. Additionally, the Variance Inflation Factor (VIF) was calculated for each predictive factor; a VIF of less than five was required to confirm that multicollinearity did not compromise the models' integrity.

After identifying significant effects using GLMs, post hoc analyses were conducted to explore pairwise comparisons among different group levels. This step was critical for understanding the differences that drove the GLM results. We employed the Holm-Bonferroni method to control for the potential inflation of Type I errors due to multiple comparisons. This adjustment method systematically corrects p-values, enhancing the statistical rigour of the tests (Quinn & Keough, 2002).

These analyses were designed to investigate the specific effects of various WQPs, such as temperature, pH, Conductivity, and nutrient levels while considering critical temporal-spatial factors such as Year, Station, and Season. This approach ensures a full understanding of how each variable interacts and influences the overall outcomes. Subsequently, the robustness of the pairwise comparisons was ensured by using the Tukey Honest Significant Difference (HSD) method, which was particularly effective at maintaining control over the family-wise error rate, thereby providing statistical validity to the findings. By following these stringent criteria, the GLMs provided A useful structure for analyzing the factors that affect various temporal and spatial factors on WQPs in Lake Couchiching. Ultimately, these analyses were designed to investigate the specific effects of multiple WQPs while considering critical temporal and spatial factors. This approach ensured a thorough understanding of how these variables interact and influence the overall outcomes.

### Spatial and Temporal Factors Affecting Zooplankton Community Structure: Permutation Multivariate Analysis of Variance

In this study, Permutation Analysis of Variance (PERMANOVA) was a suitable analytical tool to investigate the spatial and temporal determinants impacting the ZCS in Lake Couchiching. Using a Bray-Curtis dissimilarity matrix, the analysis integrated key ecological metrics, including species Abund, Avg_Dens, SDI, and Richness, as outlined by Anderson (2001) and Anderson and Walsh (2013). The statistical rigour was ensured by mitigating the risk of Type 1 error. The analysis encompassed 999 permutations, with a significance benchmark set at $p < 0.05$. Furthermore, the Holm-Bonferroni method was employed to adjust multiple comparisons, thereby augmenting the reliability of the results (Anderson, 2001). A separate PERMANOVA was conducted for each ZCS variable, ensuring a comprehensive examination of the factors influencing community structure.

### Multivariate Post-Hoc Analysis to Compare Individual Samples:

After the PERMANOVA, post-hoc pairwise comparisons between sampling stations were conducted using Wilks' lambda. The **pairwise.perm.manova** function in R was employed with 999 permutations for each comparison. A pairwise Wilcoxon test was also conducted using the pairwise

**Wilcox.test** function in R. This non-parametric test, suitable for comparing two independent samples, provided a matrix of p-values, indicating statistical significance for each pair of group comparisons. The Holm-Bonferroni correction, integrated within both functions, was applied to adjust p-values for multiple tests, thereby maintaining the integrity of the statistical conclusions and reducing the likelihood of false positives. Combining both PERMANOVA and pairwise Wilcoxon tests, this comprehensive approach ensured a robust analysis of the ZCS variations across spatial and temporal scales in Lake Couchiching.Univariate Post-hoc Analysis for Identifying Distinct Ecological Influences:

In the subsequent research phase, a univariate PERMANOVA analysis was applied to individual variables within the ZCS of Lake Couchiching. This methodical approach, intended to isolate and understand the distinct ecological influences on each ZCS component, began with carefully selecting variables based on earlier insights provided by sensitivity analysis. Each variable was prepared and scrutinized to meet PERMANOVA's prerequisites, ensuring data integrity and homogeneity of variance. The study, conducted for each variable separately, was designed to discern and quantify the unique contributions to the ZCS, with a stringent validation of assumptions underscoring the reliability of our findings. Results were integrated into the broader ecological framework of the study to assess better the robustness of the current level of environmental monitoring in Lake Couchiching.

### Model Selection for Assessing the Influence of Water Quality Parameters on Zooplankton Community Structure:

Generalized Linear Models were employed due to their robustness in handling the diverse distribution of ecological data, such as counts of zooplankton taxa, which often deviate from a normal distribution. GLMs extend linear models by linking a function of the response variable mean to the predictors, thereby accommodating data distributions like Poisson, binomial, or negative binomial distributions, which are frequently encountered in ecological research (Quinn & Keough, 2002). Before the GLM analysis, log or Box-Cox transformations were performed to meet the normality and homoscedasticity model assumptions. Predictors were normalized to ensure a uniform scale across all models, following recommended practices (Quinn & Keough, 2002). Then, model selection was steered by the Akaike Information Criterion (AIC) or the corrected AIC (AICc) for smaller sample sizes, mainly when the observation-to-parameter ratio was less than 40 (Richards, 2005).

This approach ensured the selection of parsimonious models, avoiding overfitting while retaining explanatory power. The Variance Inflation Factor (VIF) detected multicollinearity among predictors, with a threshold of five. Statistical significance was evaluated using a p-value threshold of 0.05 to assess statistical significance, and Bonferroni adjustments were applied to address the risks of making multiple comparisons. Interaction terms were considered when they significantly improved AIC values, revealing interdependencies within the data. Dispersion checks in count data models informed the potential shift to a negative binomial distribution if overdispersion was present. Hence, the entire GLM process—from transformation and normalization through model selection and validation—was designed to ensure a transparent analysis, enabling a confident interpretation of the impacts of WQPs on ZCS. A thorough sensitivity analysis was essential to the modelling process, ensuring the robustness of the results against variations in data treatment and model parameters.

The following aspects were examined:

**Taxa and WQP Inclusion**: Iterative inclusion and exclusion examined the influence of individual zooplankton taxa and WQPs on the model outputs. This step allowed the identification of the importance of specific WQPs on zooplankton taxa models.

**ZCS and Taxa Inclusion**: Zooplankton Community Structure and taxa inclusion were tested iteratively, including and excluding individual zooplankton taxa. This process was crucial in understanding the relative impact of specific zooplankton taxa on community structure models.

Several GLM models were evaluated based on whether their key metrics changed substantially during these tests. If a model's key metrics did not change significantly, it was considered robust and consistent even when different zooplankton taxa were included or excluded, indicating that the model can withstand variations in the input data. Our approach is based on the principles outlined by Quinn and Keough in 2002, emphasizing the importance of robustness in ecological models.

### Visualizing Canonical Correlation Analysis Results

The biplots from the Canonical Correlation Analysis (CCA) displayed the sampling sites, species, and WQPs within a shared ordination space. In these biplots, the direction of the environmental vectors suggested their correlation with the ordination axes, while the vector length indicated the strength of their impact on species distributions (Quinn & Keough, 2002).

### Tools and Software

The PCA was executed using the statistical program R (R Core Team, 2021), utilizing the factoextra, broom, ggfortify, plotly, tidyverse, and dplyr packages for enhanced visualization and interpretation (Wickham et al., 2019; Sievert, 2020). Subsequent statistical tests were conducted with the MASS package (Venables & Ripley, 2002).

Spatial and temporal patterns were examined using GLMs with the **ggpubr** package (Kassambara, 2017). The PERMANOVA was run with **RVAideMemoire** and **adonis2** to assess zooplankton community structure (Hervé, 2020), followed by model selection for optimal fit to uncover the best taxa representation in ZCS and the WQPs that influence zooplankton taxa.

CCA was carried out using **vegan** and **car** packages for comprehensive diagnostics (Fox & Weisberg, 2019; Oksanen et al., 2020). The **ggplot2** package was used to generate visual diagnostics (Wickham, 2016), And **pandas** in Python was used to manage data manipulation (Fortin, 2020). **Microsoft Excel** was used to create and organize the data tables.

The post hoc analysis used the emmeans package in R to understand the variations in WQPs across different sampling stations (**Stations**) between years (2008 and 2013) and seasons. The analysis provides insights into the average WQP (EMMeans) and their statistical differences (contrasts) over these categories (Searle et al., 1980).