Spatial Heterogeneity of Zooplankton and AquaBOT Water Quality Measurements on Lake Geneserath, Beaver Island, Michigan

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A thesis submitted to the faculty of The University of the South in partial fulfillment of the requirement for honors in the Department of Biology

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Abstract

Understanding the spatial heterogeneity of zooplankton is important for identifying patterns in freshwater ecosystems and assessing ecosystem function and management. Lake Geneserath, Beaver Island, Michigan is an inland freshwater lake that is irregularly shaped and has become increasingly eutrophic, especially since the mid 20th century. Previous studies show correlations between zooplankton spatial heterogeneity and water quality measurements, but there exists a gap in the knowledge of how these patterns manifest in an irregularly-shaped lake that is undergoing eutrophication such as Lake Geneserath. New technologies such as the AquaBOT aquatic drone from Oak Ridge National Laboratory can provide insights on water quality in freshwater ecosystems. I collected zooplankton samples (n = 45) and AquaBOT measurements (n = 1933) simultaneously from Lake Geneserath. I divided sampling between the four main regions of the lake: the narrow, developed North Arm; the undeveloped East Shore; the developed West shore; and the developed South End. I found that zooplankton abundance was significantly higher in the narrow North Arm of the lake compared to the other regions. Rotifer diversity was negatively correlated with photosynthetically active radiation. The variability of zooplankton and water quality revealed that the narrow North Arm of the lake is different from every other region in Lake Geneserath, representing a novel ecological observation where higher zooplankton abundance, lower dissolved oxygen, lower conductivity, and higher turbidity occurred specifically within a narrow, protected section of an irregularly-shaped lake.

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Introduction

Zooplankton play important biological roles in freshwater lake ecosystems: they are an intermediary part of the food chain and can act as indicators of freshwater ecosystem health. Previous studies have found that zooplankton biomass and zooplankton community composition can be indicators of eutrophication, when a body of water changes trophic states due to an excess of nutrients entering the watershed (Gazonato Neto et al. 2014). Measuring zooplankton diversity and abundance can reveal insights on trophic state, eutrophication, climate change, and nutrient loading in lakes (Jeppesen et al. 2011). An aspect influencing zooplankton's ecological roles is spatial heterogeneity, which refers to the uneven distributions of organisms across their environment. Understanding the horizontal spatial heterogeneity of zooplankton is vital for comprehending ecosystem formation and function, as these organisms consume algae and bacteria while serving as prey for other zooplankton, fish, insects, and more (US EPA 2013).

Spatial heterogeneity is foundational in ecological phenomena and theories such as spatial dependence from the Environmental Control Model from the 1950s. This model posits that structures of ecological communities are founded on spatial structure and environmental factors (Bray and Curtis 1957; Legendre 1993). Applying these ideas to zooplankton distribution improves our understanding of how distribution patterns interact with lake ecosystem dynamics. For example, zooplankton communities can be shaped by water qualities such as temperature, turbidity, pH, dissolved oxygen, and nutrient levels (Table 1) (Abdulwahab and Rabee 2015; Duggan et al. 2002; Santangelo et al. 2008). Nutrient levels limit phytoplankton populations, therefore limiting zooplankton in top-down and bottom-up effects (Sun et al. 2022). In large zooplankton communities such as those in large lakes, factors like water movement and wind create uneven distribution. In small zooplankton communities, however, small-scale biotic effects such as food availability and competition create community structure and uneven gradients, (Merrix-Jones et al. 2013). A 2000 study in Loch Ness, UK found that the greatest factors influencing the horizontal distribution of zooplankton are wind-induced water movements, allochthonous material from rivers, and the productivity gradient of nitrate-nitrogen, suggesting that land use changes such as nutrient deposition can impact zooplankton distribution (George 2000). In lakes with little human impact, zooplankton species composition is correlated with environmental gradients like conductivity, hypolimnetic stratification, and primary production (Dodson et al. 2009).

This study was conducted on Lake Geneserath, an inland lake of Beaver Island, Michigan (Figure 1). Lake Geneserath is a meso-oligotrophic lake, with chlorophyll at 1.32 ug/L, phosphorus at 13.3 ug/L, and 29 plankton per L (Devan & McNaught, 2022). A previous study by Sawyers et al. (2016) identified recent and historic eutrophication in the lake with data from the year 1200 CE to present day. The researchers took sediment cores from the two main basins of Lake Geneserath and analyzed nutrient and diatom changes over time. The study showed a period of minimal disturbance prior to ca. 1450 CE. The second period was characterized by little eutrophication before the Little Ice Age between 1450 to 1650, which corresponded with climate changes and the first uses of Beaver Island by Native Americans and French fur traders. This eutrophication eventually reversed: between 1650 to 1848, there was little human disturbance and little eutrophication, allowing the lake to transition to a lower trophic state. Between the years of 1848-1949, there was an initial period of eutrophication occurring at the same time as European colonization of Beaver Island. However, the greatest levels of eutrophication have occurred from 1950 to the present, with higher levels of phytoplankton production, phosphorus input, and organic matter accumulation. This corresponds with human manipulation of the habitat, including housing developments and stocking the lake with fish such as walleye (*Sander vitreus*). The authors hypothesize that these changes in nutrient levels suggest that Lake Geneserath is transitioning to a higher trophic status which could cause future anoxia, or the complete lack of oxygen in the water.

The lake has a surface area of 490 acres with two distinct sections: the main body and the North Arm (Cashmann, n.d., Figure 2). The North arm is particularly constricted from the rest of the lake which creates a bottleneck (Figure 2). During preliminary site surveys, I observed a notable abundance of aquatic vegetation in the North Arm, in contrast to other regions of the lake. This observation prompted further inquiry into potential differences in water quality and the abundance and diversity of zooplankton among the various regions. There remains a gap in understanding how spatial heterogeneity in zooplankton communities correlates with water quality variations within Lake Geneserath and if this varies among regions of the lake. Studies have highlighted the influence of environmental heterogeneity on zooplankton diversity in other freshwater systems (Chaparro et al. 2015), yet we lack specific data on how these spatial patterns manifest in Lake Geneserath. Addressing this knowledge gap is crucial for developing targeted conservation and management strategies for the lake's ecosystem as it becomes increasingly eutrophic.

This study sought to investigate the spatial heterogeneity of zooplankton in Lake Geneserath, and to compare it to water quality measurements taken by the AquaBOT. The AquaBOT, a remotely-controlled aquatic drone from the Oak Ridge National Laboratory originally made for streams, had not been utilized to study lake ecosystems before this study (Griffiths et al. 2022). I also hypothesized that zooplankton will be spatially heterogeneous in Lake Geneserath, which will correspond with hot spots of nutrients near buildings on the shoreline. A secondary objective was to create maps of zooplankton distribution and water quality measurements in Lake Geneserath to visually represent patterns of distribution in each region. Based on initial surveys, I hypothesized there would be regional differences in water quality and zooplankton abundance across the lake.

Figure 1: Location of Beaver Island, Michigan and Lake Geneserath. Red dot denotes the location of Lake Geneserath.

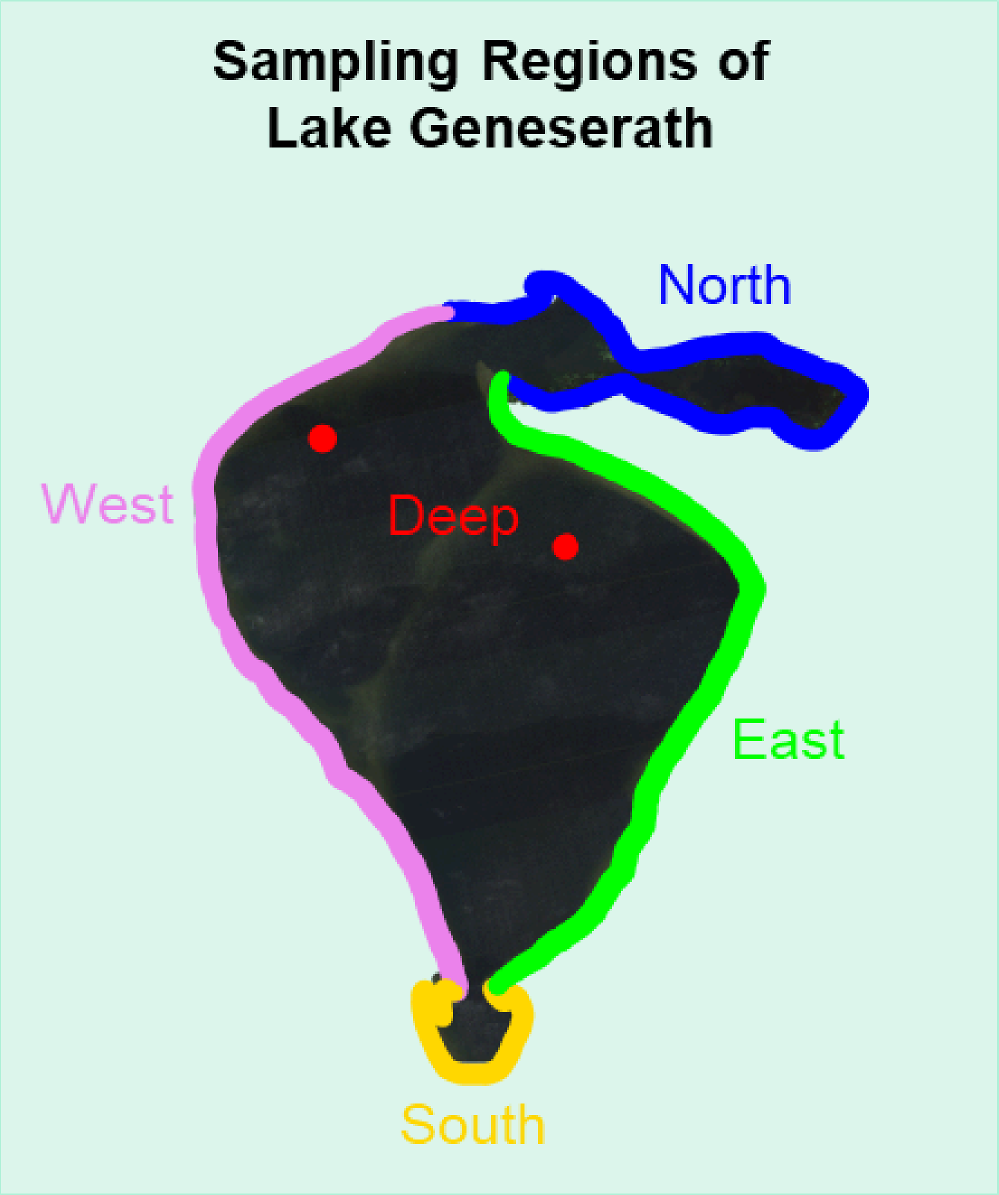

Figure 2: Sampling regions of Lake Geneserath (North, East, South, West, Deep).

Table 1: Variables measured with units and previous literature on correlations with zooplankton abundance and/or diversity

Variable	Unit	Previous Literature
Water temperature	Degrees Celsius (°C)	Freshwater zooplankton abundance and diversity are positively correlated with water temperature up to a certain threshold, beyond which further temperature increases may lead to a decline in overall diversity (Rasconi et al. 2015).
Photosynthetically Active Radiation (PAR)	Micromoles of photons per square meter per second (μmol s^{-1} m^{-2})	Elevated PAR levels stimulate phytoplankton growth, increasing the food supply for zooplankton. Enhanced resource availability can lead to higher zooplankton abundance and diversity (Striebel et al. 2012).
Dissolved oxygen	Milligrams per liter (mg/L)	Higher DO supports greater zooplankton abundance and diversity. Well-oxygenated waters promote primary productivity, which increases food availability for zooplankton. Low DO below 8 mg/L can be detrimental to zooplankton survival (Zhao, Fan, and Zhao 2021).
Specific conductivity	Siemens per centimeter (S/cm)	Higher conductivity is associated with higher salinity, which some freshwater zooplankton cannot tolerate (Hall and Burns 2002).
Turbidity	Nephelometric Turbidity Units (NTU)	Turbidity decreases light availability and can change the structure and function of communities, thereby decreasing diversity and abundance of zooplankton (Goździejewska, Kruk, and Bláha 2024).
Water depth	Meters (m)	Zooplankton in Lake Superior are more abundant in shallow areas compared to offshore ones (Shchapov and Ozersky 2023).
Time of day	Hours, minutes, seconds (HH:MM:SS)	Diel vertical migration patterns which change based on the time of day could impact the location of zooplankton in the water column. Zooplankton migrate down the water column at dawn and up the water column at dusk to minimize interactions with predators and exposure to UV light (Williamson et al. 2011).

Presence of houses	Yes, No	Increased residential development along lake shorelines can negatively impact zooplankton abundance and diversity due to factors such as nutrient runoff, habitat modification, and pollution (Shen et al. 2021).

Methods

Site Description

The study was conducted at Lake Geneserath (45.5954, -85.5369), the largest inland lake of Beaver Island, Lake Michigan (Figure 1). Lake Geneserath supports a variety of wildlife including *Esox lucius* (northern pike), *Micropterus dolomieu* (smallmouth bass), *Micropterus salmoides* (largemouth bass), *Lepomis macrochirus* (bluegill), *Gavia immer* (common loon), *Haliaeetus leucocephalus* (bald eagles) and *Chelydra serpentina* (snapping turtles). Locals and visitors use it as a recreational area for swimming, boating, and fishing (Cashmann n.d.). The North Arm has the lake's main public access point which consists of a boat ramp, a dirt parking lot, and a grassy area with picnic tables. The North Arm is the shallowest section of the lake and has 13 buildings, mainly houses and sheds, on the southern side of the arm. The East shore of the main body has 34 structures including large houses that are far apart with rocky, shallow shorelines. The Southern end has the highest housing density, with 16 waterfront structures close in proximity to one another. The West side is completely undeveloped with a shallow shoreline. The deepest point of the lake is 14 meters deep and is in the Eastern basin. Much of the lake is less than six meters deep. My team and I had access to three boat launches, so we sampled the North Arm, West shore, and East shore/South end regions on three separate days. I took at least ten zooplankton samples per region, and two samples from the deep basins, with a total of 45 samples (Figure 3).

Zooplankton Sampling

We collected all field data between June 11 and June 15, 2024 between the hours of around 10:00 am to 3:00 pm. We sampled only on days with little to no wind. To collect zooplankton, I took samples about every 100 meters along the shoreline by lowering a 30-cm diameter, 60-micron plankton collection net 1 m below the water and pulling it to the surface. All samples were taken at least 1 m from the shore and in at least 1 m of water depth. I then filtered the zooplankton into 125ml collection bottles. I added a quarter tablet of Alka Seltzer to each collection bottle to anesthetize the zooplankton in the field. I then added a small amount of sugar-formalin solution (solution was 400g sugar in 1000 mL of 37% formaldehyde solution) for preservation, approximately one part solution to nine parts water and zooplankton. I also collected samples on more offshore areas, traveling about 20 meters away from the shoreline with the Zodiac and canoe with the AquaBOT.

In total, I collected 43 samples along the perimeter of the lake, including at least 10 from each region (North arm, East shore, West shore, South end) and two samples in deep, offshore areas (Figure 2). At each sample site, I marked the location using Avenza Maps and used a measuring tape with a weight to take a depth reading by dropping the disk until it reaches the bottom of the lake. We also made notes of the site description, like vegetation analysis and what the bottom of the lake looks like (sandy, rocky, etc). The presence of houses was noted based on visual assessment: houses on Lake Geneserath are generally far apart, so if a house was present directly on shore parallel to where we were sampling, we denoted this as “yes”.

In the laboratory, I added Eosin-Y dye to zooplankton samples at least 12 hours before counting them to dye the plankton dark pink. Before counting each sample, I filtered zooplankton from the formaldehyde solution using a 44 micron mesh sieve, then diluting to a volume that was determined based on zooplankton mass, recording the dilution for each sample for calculations later. To make the study blind, I covered the site labels on the bottles and selected each bottle randomly; I only revealed the site after counting was complete. I counted copepods and cladocerans under a dissecting microscope in a 5ml sample on a spinning counting tray. I counted rotifers in a 1 ml counting slide. I repeated counting of 5 ml or 1 ml samples until there were at least 100 zooplankton of the top two zooplankton genera in the sample. I used a button counter and identified the zooplankton to the smallest discernible taxonomic group according to my knowledge and ability. For crustaceans, I classified zooplankton to the genus level with the exception of nauplius larvae (larval stage), calanoid (order), cyclopoid (order), and harpacticoid (order). For rotifers, I classified zooplankton to the level of genus.

AquaBOT Sampling

In a team with two other student researchers, I collected AquaBOT measurements and simultaneously with zooplankton samples. The AquaBOT takes measurements on the surface of the water every 30 seconds using two sensors. One sensor measures photosynthetically active radiation (PAR) and air temperature and is affixed to the top of the AquaBOT. The AquaBOT has locations for two sondes. We attached a YSI EXO3 Multiparameter Sonde that measures water temperature, dissolved oxygen, specific conductivity, and turbidity. One of my colleagues manually sampled nitrate, phosphorus, and ammonium. The AquaBOT was attached to a canoe because one of the propellers was not functional. The team paddled the canoe around the perimeter approximately three to five meters from the shoreline, and I followed behind in a Zodiac boat. At the end of each session, AquaBOT data was transmitted to the LoggerLink app and exported to external drives.

Statistical Analysis

First, dilutions and counts of zooplankton were used to calculate total zooplankton per liter, total crustaceans per liter, and rotifers per liter to standardize volume across all samples. I calculated crustacean and rotifer diversity using the Shannon-Wiener Index to estimate zooplankton biodiversity by the smallest discernible taxonomic group. AquaBOT measurements were linked to zooplankton samples and compared using Kruskal-Wallis tests of all variables (Crustacean diversity, rotifer diversity, rotifers per liter, crustaceans per liter, total zooplankton per liter, rotifer genus richness, crustacean genus richness, total richness, air temperature, Photosynthetically Active Radiation (PAR), water temperature, specific conductivity, turbidity, dissolved oxygen, depth, nitrate, ammonium, phosphorous) in RStudio to look for significant correlations. Bray-Curtis non-metric multidimensional scaling ordinations were conducted with rotifers, crustacea, and regions in RStudio after transforming the data. A principal component analysis was conducted in RStudio using the FactoExtra package. All maps including heat maps of zooplankton and water qualities were created in ArcGIS Pro using site data.

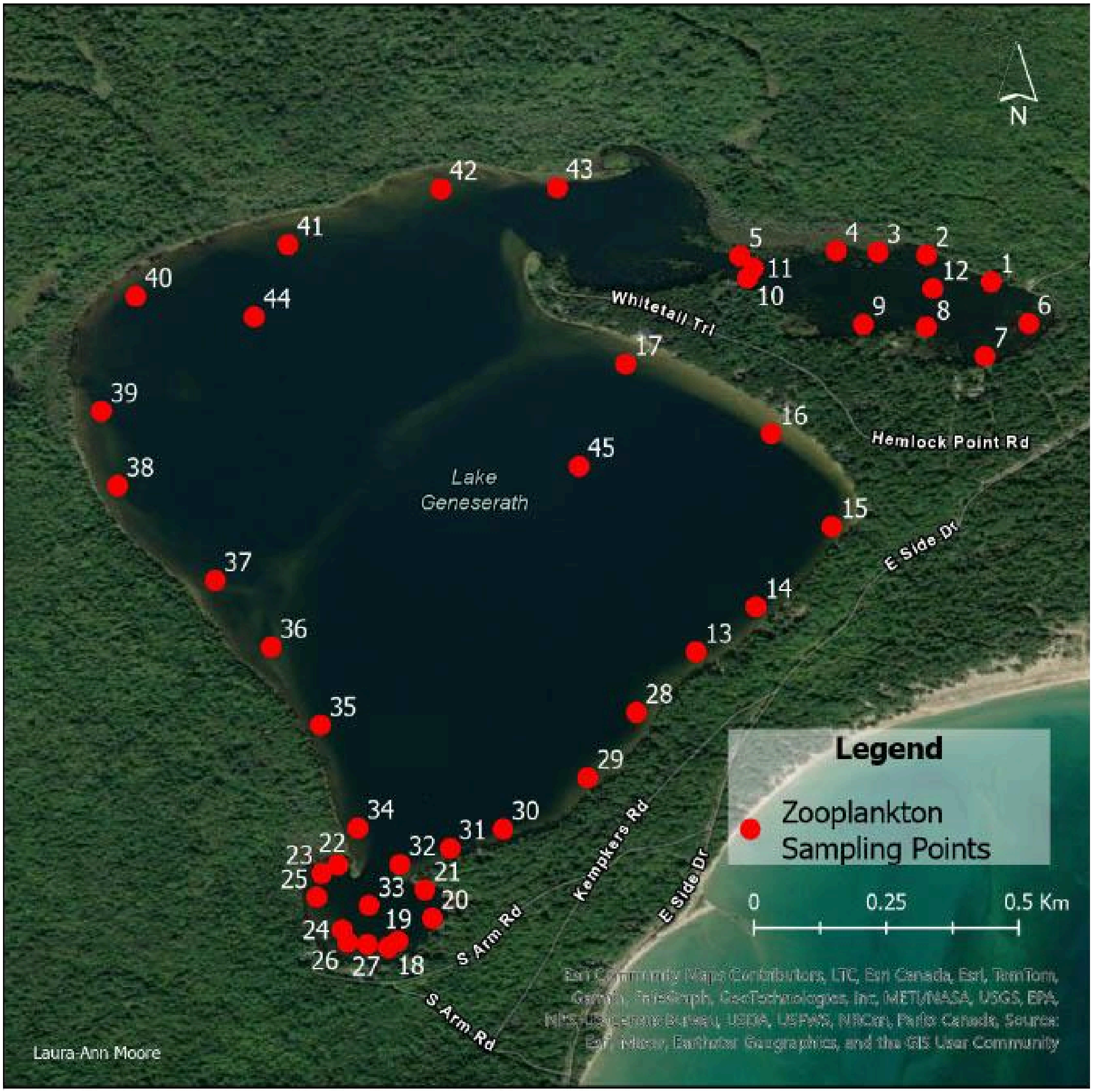

Figure 3: Locations of zooplankton sampling sites on Lake Geneserath, Beaver Island, Michigan.

Results

The main goal of this study was to map zooplankton distribution, water qualities, and the presence of houses across Lake Geneserath, and to find any correlations between these variables or any differences among regions of the lake. Zooplankton were sampled and quantified, the AquaBOT automatically took water quality measurements, and the presence of houses on the shoreline was noted.

Zooplankton were concentrated in the North Arm of Lake Geneserath, with an average of 675.2 zooplankton per liter in the North, compared to 118, 74.5, 120.4, and 201.9 zooplankton per liter in the East, South, West, and Deep regions of the lake, respectively (Figure 4, Figure 5, n = 45). Zooplankton abundance was significantly higher in the North Arm compared to the East, West, and South (Figure 5). Zooplankton abundance per site was six times higher in the North Arm compared to the other regions of the lake, on average.

Crustacea found in Lake Geneserath include *Sida, Diaphanosoma, Daphnia, Chydorus, Ceriodaphnia, Holopedium, Bosmina,* Calanoid*,* Harpacticoid*,* Cyclopoid*,* and nauplius larvae. A non-metric multidimensional scaling showed that the plankton community in the North Arm was more closely associated with *Sida*, *Daphnia*, *Diaphanosoma*, *Ceriodaphnia*, and *Bosmina* crustaceans compared to other regions (Figure 6, Bray-Curtis nMDS, Log10 data transformation, Dimensions = 3, Stress = 0.0632, n = 45).

Rotifera found in Lake Geneserath include *Trichocerca, Conochilus, Synchaeta, Polyarthra, Keratella, Asplanchna, Kellicottia, Lecane, Monostyla, Notholca,* and *Lepadella.* With rotifers, the North Arm was more closely associated with *Trichocerca* and *Conochilus* zooplankton (Figure 7, Bray-Curtis nMDS, Log10 data transformation, Dimensions = 3, Stress = 0.0601, n = 45). With both stress levels being below 0.1, this indicates that the ordination is a good fit for the data and that the North Arm has different zooplankton present compared to other regions.

The AquaBOT results show that dissolved oxygen was lower in our AquaBOT paths of the North Arm of Lake Geneserath (Figure 8, $n = 1933$). Furthermore, dissolved oxygen was significantly different in the North Arm compared to the East, North, and South (Table 2, $n = 45$, Kruskal-Wallis Test, $p < 0.001$; Dunn Test: East - North $p = 0.000682$, North - South $p = 0.03697$, North - West $p = 4.39e-06$). Specific conductivity was also lower in our AquaBOT paths of the North Arm (Figure 9, $n = 1933$). Specific conductivity was significantly different in the North Arm compared to the East, North, and South (Table 2, $n = 45$, Kruskal-Wallis Test, $p < 0.001$; Dunn post-hoc test, Deep - North: $p = 0.004$, East - North: $p = 0.0176$, North - South: $p = 0.0145$, North - West: $p = 1.53e-06$). A principal component analysis of all water quality variables showed that specific conductivity and dissolved oxygen together explained 28.5% of variation in water quality in the lake (Figure 10, Figure 11). A box plot and Kruskal-Wallis test demonstrate that these metrics vary by region, with the North Arm having lower conductivity and dissolved oxygen than the rest of the regions (Figure 12, Kruskal-Wallis test and Dunn post-hoc test. Chi-squared = 28.55, df = 4, p-value = 9.649e-06. East-North: $p = 0.0195$, North-South: $p = 0.0043$, North-West: $p = 1.87e-06$).

Ammonium levels showed regional differences between East and South, and between West and South (Table 2, $n = 44$, Kruskal-Wallis Test, p-value = 0.002981, East-West p-adj. = 0.0445, and West-South p-adj. = 0.0453). There was a difference in ammonium level by presence of houses, with areas without houses having higher ammonium concentrations (mg/L) (Figure 13, two-sample t-test, $p = 0.0167$). Rotifer genera richness was higher where there were no houses on the shoreline compared to areas where there were (Figure 14, two-sample t-test, p =

0.033). Rotifer H’ diversity was negatively correlated with photosynthetically active radiation (Figure 15, Spearman correlation, p = 0.024, n = 45).

I found differences in zooplankton number and type in the North Arm of Lake Geneserath compared to the other regions of the lake. The North Arm also showed lower specific conductivity and lower dissolved oxygen, with these variables explaining 28.5% of variation in water quality in the lake.

Table 2: Variables measured with units and correlations to zooplankton diversity and abundance.

Kruskal-Wallis Test with Dunn post-hoc test (n = 45). P-value for significance was equal to 0.05 divided by the number of tests run (n = 10), so p = 0.005. When there are significant differences between the regions, p-values adjusted to account for multiple hypotheses were used from the Dunn post-hoc test with p = 0.05.

Variable	Unit	Differences among regions of Lake Geneserath
Zooplankton Abundance	Zooplankton per liter	Differences found between North-East (p-adj. = 1.425039e-02), North-South (p-adj. = 3.411817e-05), and North-West (p-adj. = 4.493052e-04). Kruskal-Wallis chi-squared = 26.617, df = 4, p-value = 2.376e-05.
Water temperature	Degrees Celsius (°C)	None. Kruskal-Wallis chi-squared = 11.168, df = 4, p-value = 0.02474.
Photosynthetically Active Radiation (PAR)	Micromoles of photons per square meter per second (μmol s^{-1} m^{-2})	None. Kruskal-Wallis chi-squared = 7.1164, df = 4, p-value = 0.1299.
Dissolved oxygen	Milligrams per liter (mg/L)	Differences found between North-East (p-adj. = 6.823388e-04), North-West (p-adj. = 4.394187e-06), and North-South (p-adj. =3.697310e-02). Kruskal-Wallis chi-squared = 30.666, df = 4, p-value = 3.581e-06.
Specific conductivity	Siemens per centimeter (S/cm)	Differences found between North-South (p-adj. = 1.452823e-02), North-West (p-adj. = 1.533131e-06), North-Deep (p-adj. = 4.013551e-03).

		Kruskal-Wallis chi-squared = 32.927, df = 4, p-value = 1.236e-06.
Water depth	Meters (m)	None. Kruskal-Wallis chi-squared = 6.2079, df = 4, p-value = 0.1842.
Turbidity	Nephelometric Turbidity Units (NTU)	Differences found between North-South (p-adj. = 0.000148640), and North-East (p-adj. = 0.003937829) Kruskal-Wallis chi-squared = 22.311, df = 4, p-value = 0.0001737.
Nitrate	Milligrams per liter (mg/L)	None. Kruskal-Wallis chi-squared = 5.4148, df = 4, p-value = 0.2473.
Phosphorus	Milligrams per liter (mg/L)	None. Kruskal-Wallis chi-squared = 3.4488, df = 4, p-value = 0.4857
Ammonium	Milligrams per liter (mg/L)	Differences between East-West (p-adj. = 0.0445), and West-South (p-adj. = 0.0453). Kruskal-Wallis chi-squared = 16.029, df = 4, p-value = 0.002981.

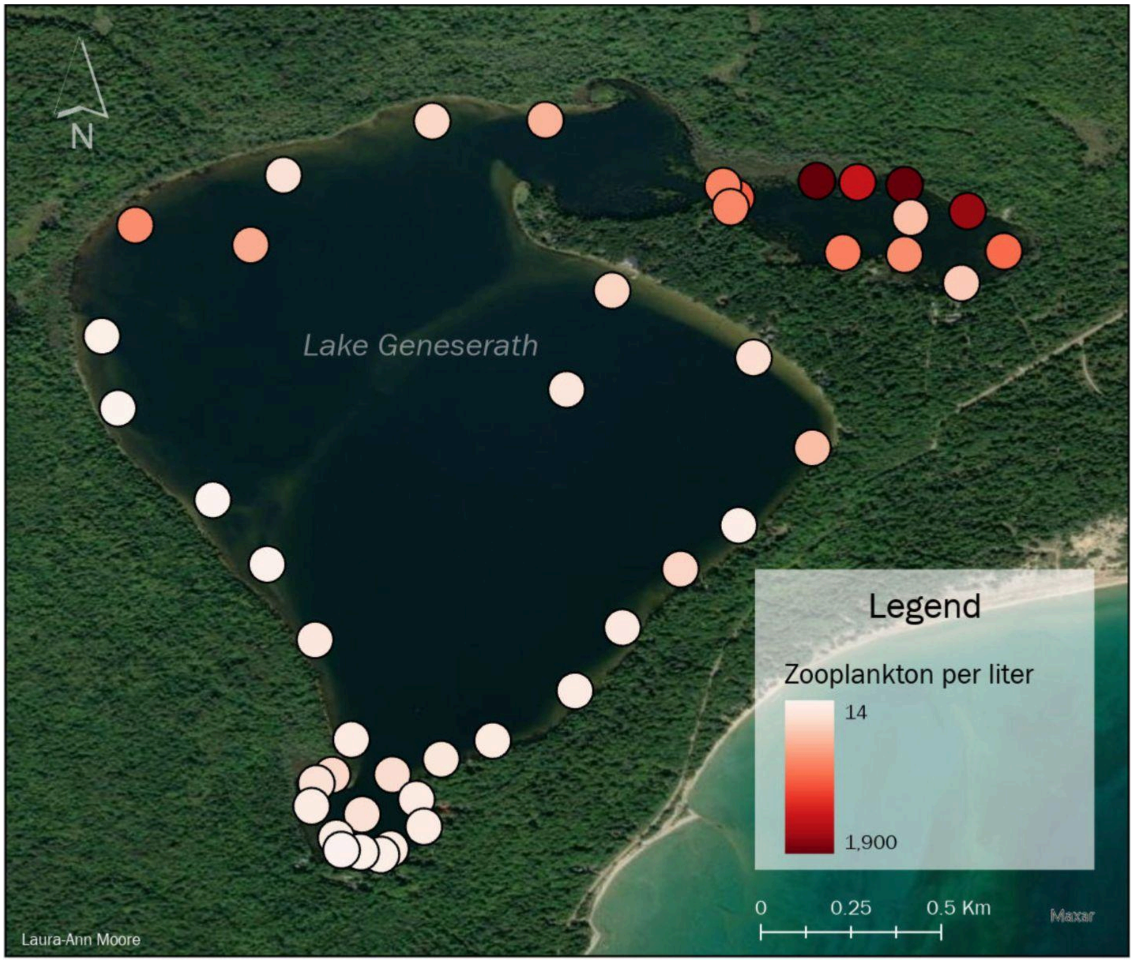

Figure 4: Heatmap of zooplankton concentration in Lake Geneserath.

Color represents zooplankton per liter at each point sampled (n = 45), showing a concentration of zooplankton in the North Arm of the lake. The color spectrum has white representing the lowest zooplankton abundance and deep red representing highest abundance.

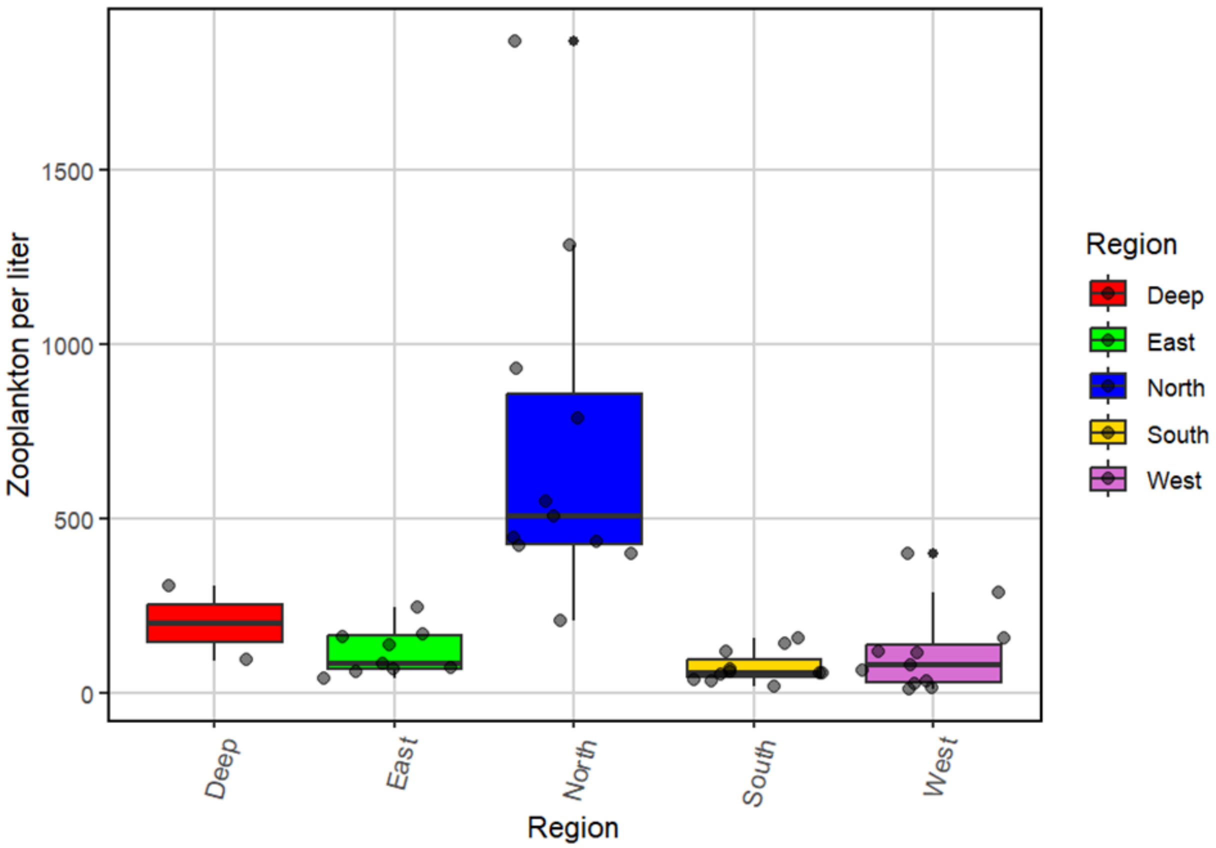

Figure 5: Boxplot of Zooplankton Abundance by Region.

Kruskal-Wallis test and Dunn post-hoc test (chi-squared = 26.617, df = 4, p = 2.376e-05, n = 45). Significant differences found include between East and North (p = 0.0143), South and North (p = 3.41e-05), and West and North (p = 0.000449).

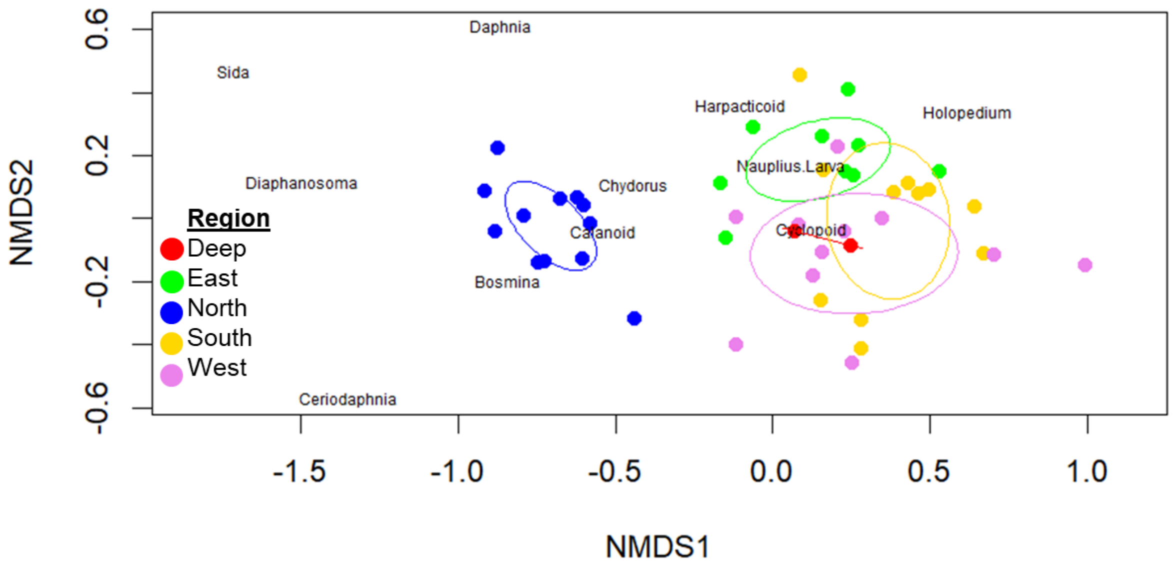

Figure 6: Nonmetric multidimensional scaling graph of crustacean by smallest discernible classification on Lake Geneserath.

Each region is represented by color-coded ellipses and points for each crustacean classification (Stress = 0.0632, n = 45).

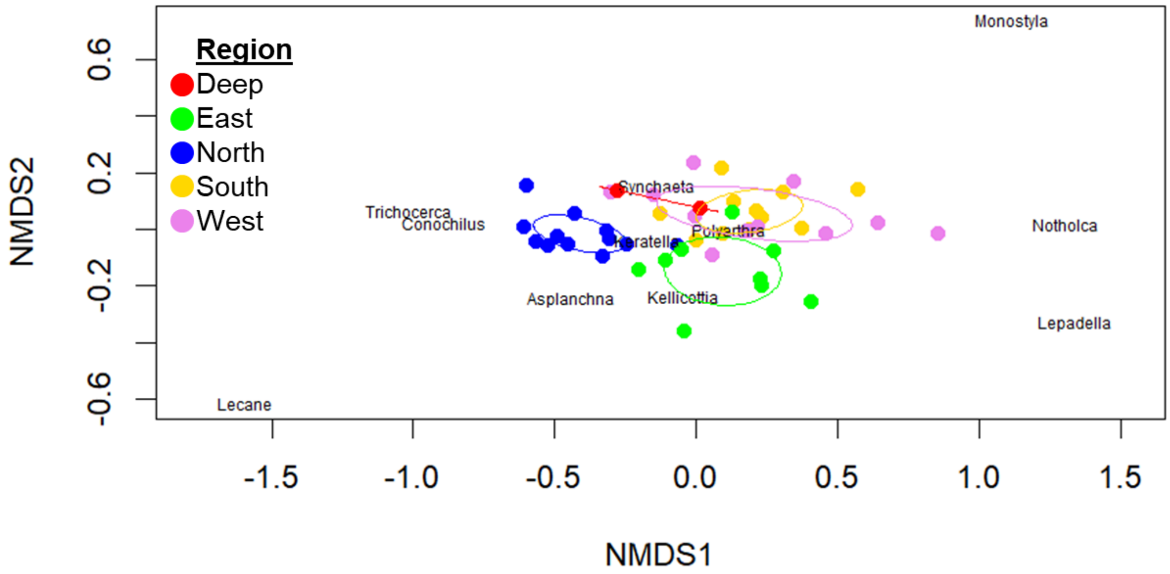

Figure 7: Nonmetric multidimensional scaling graph of rotifer by genus on Lake Geneserath.

Each region is represented by color-coded ellipses and points for each rotifer genus (Stress = 0.0601, n = 45).

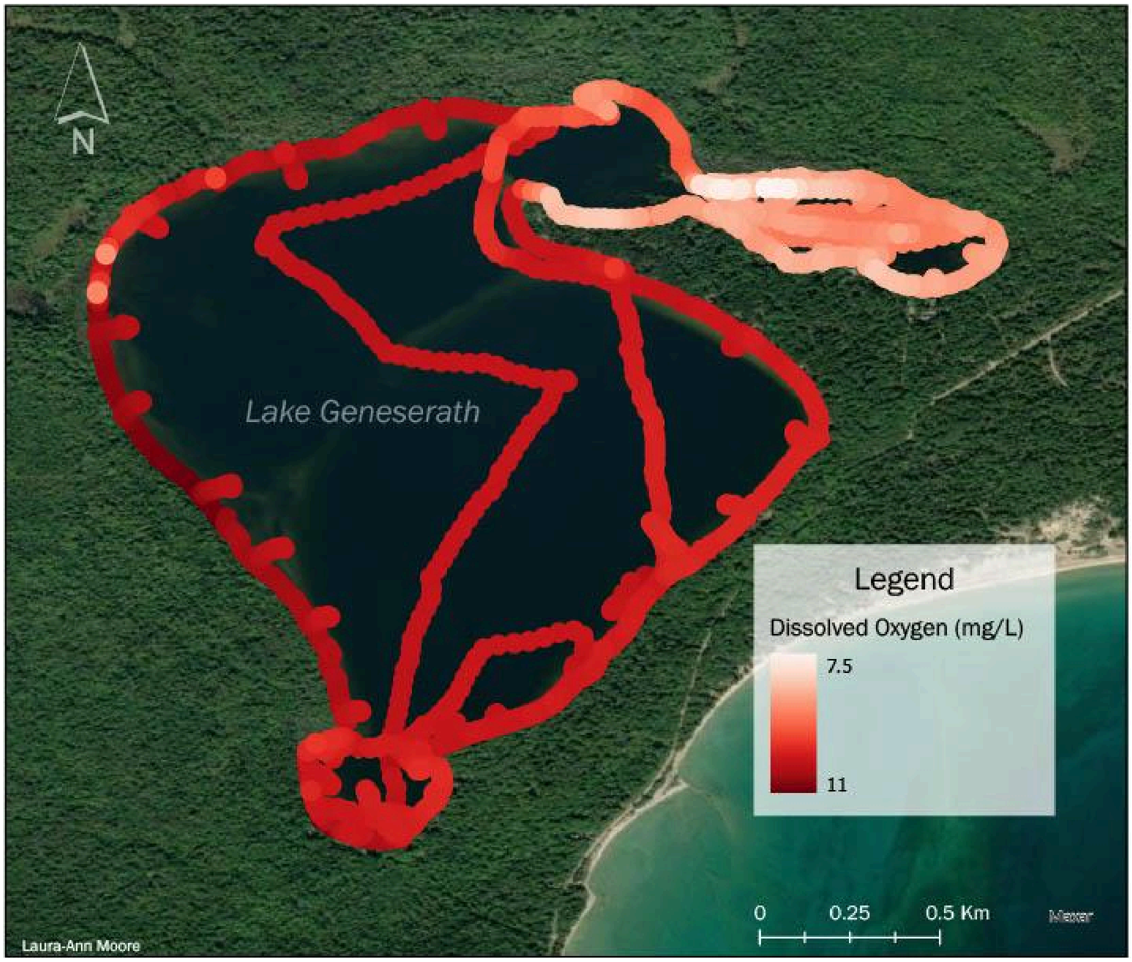

Figure 8: Heatmap of dissolved oxygen in Lake Geneserath.

Color represents dissolved oxygen at each point sampled (mg/L, n = 1933), showing that dissolved oxygen is lower in the North Arm of the lake. The color spectrum has white representing the lowest DO levels and deep red representing highest DO levels.

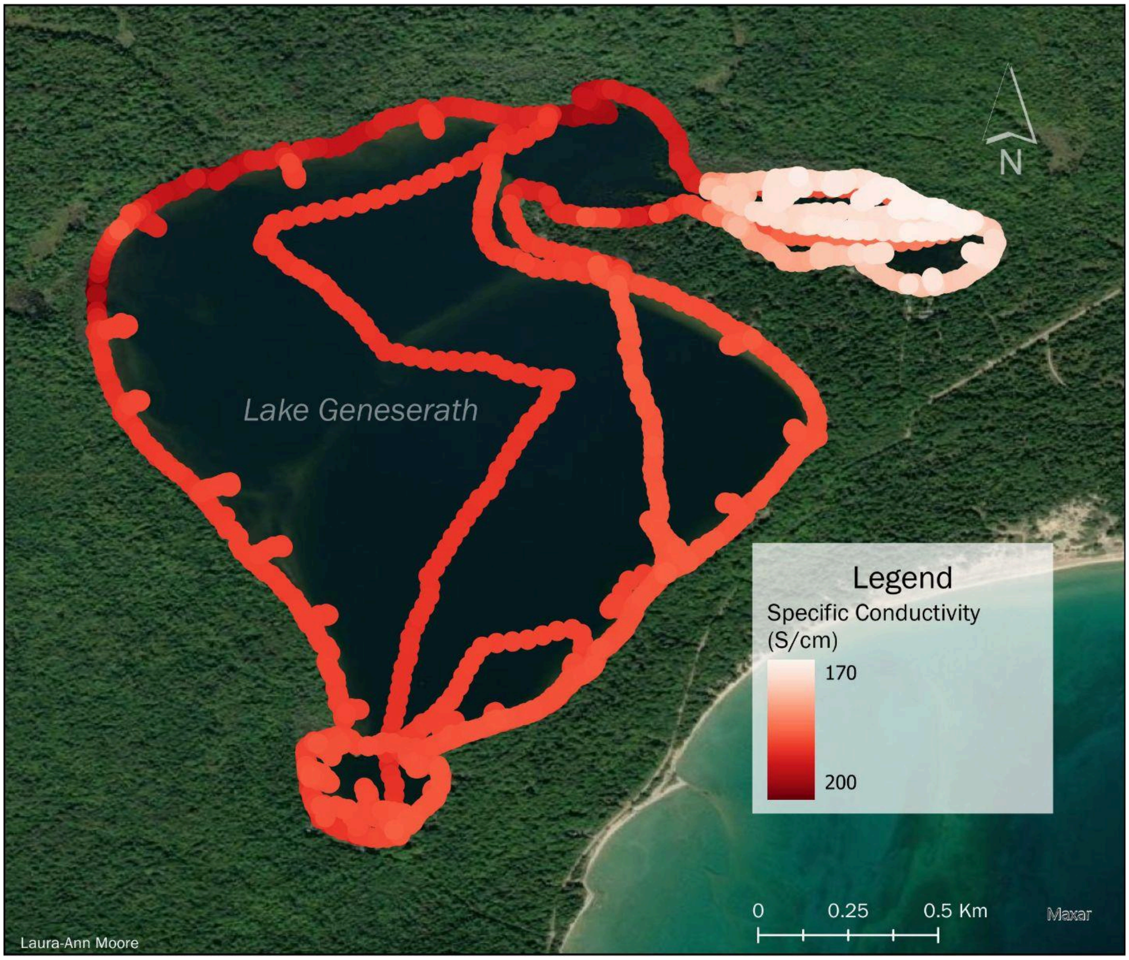

Figure 9: Heatmap of specific conductivity in Lake Geneserath.

Color represents dissolved oxygen at each point sampled by the AquaBOT (S/cm, n=1933), showing that specific conductivity is lower in the North Arm of the lake. The color spectrum has white representing the lowest conductivity levels and deep red representing highest conductivity levels.

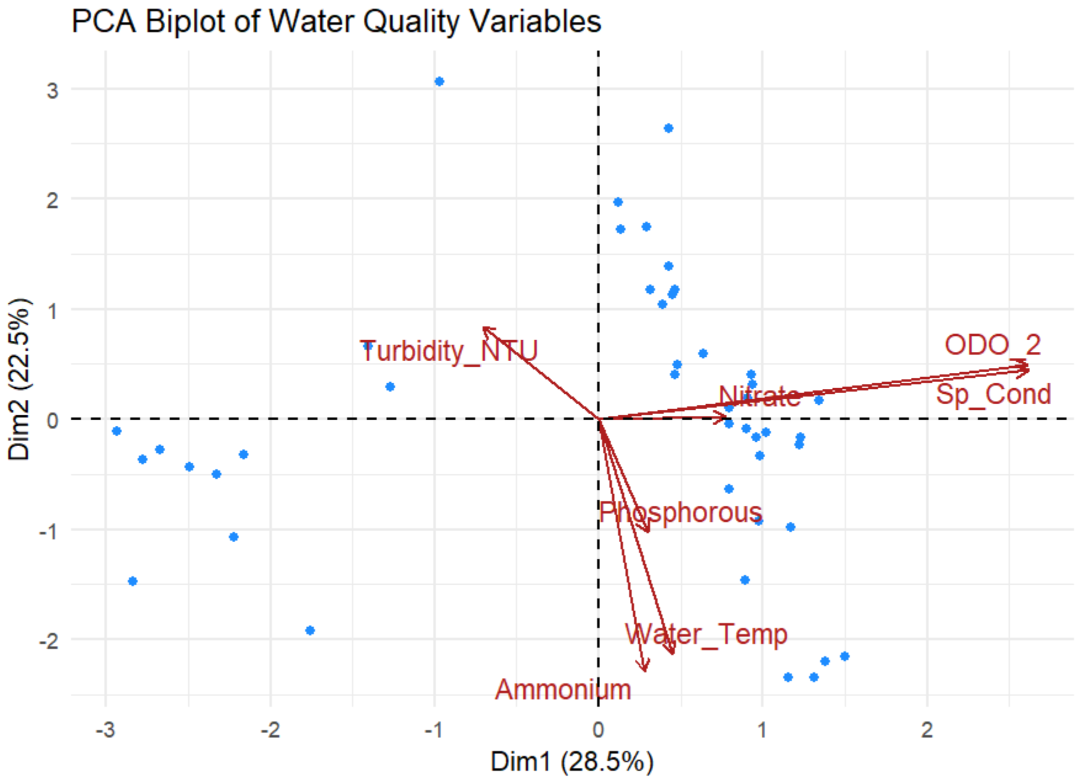

Figure 10: Biplot of Principal Components Analysis of Water Quality variables.

Principal Component 1 (Dim1) was strongly associated with specific conductivity and dissolved oxygen, while Principal Component 2 (Dim2) was primarily associated with water temperature and ammonium. The two components together explained 51% of the total variance (PC1 = 28.5%, PC2 = 22.5%). Model fit was adequate (RMSR = 0.15; chi squared = 39.02, $p < 0.00001$).

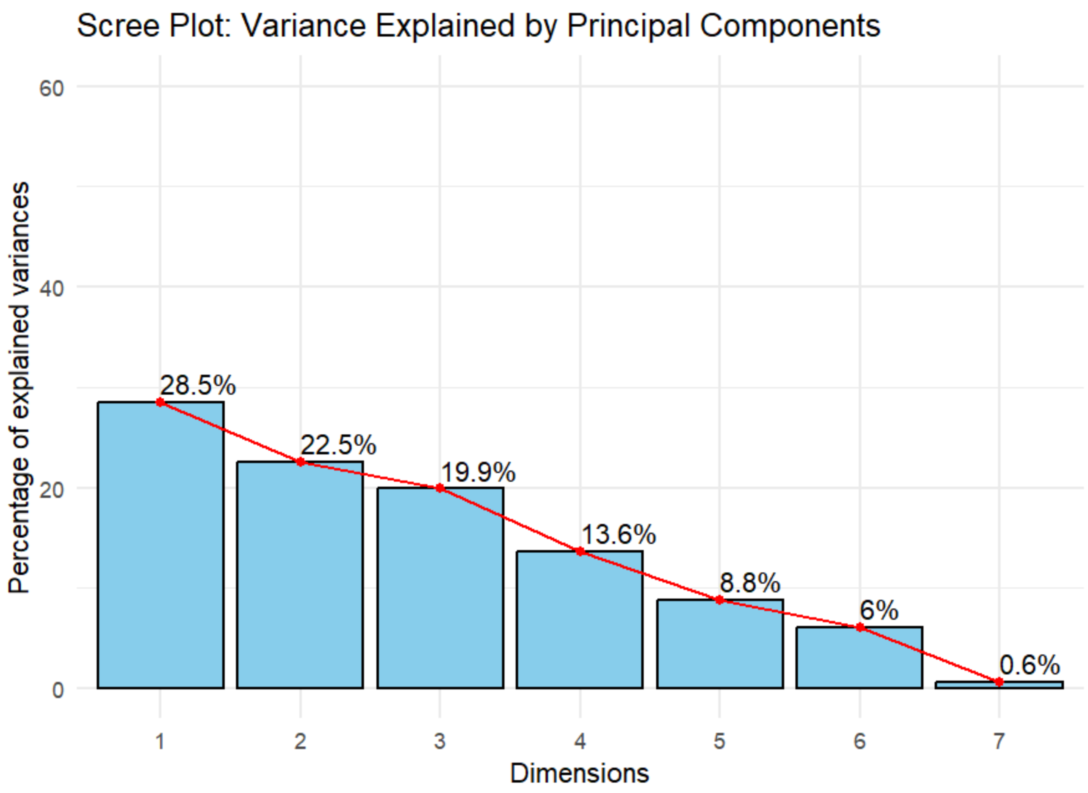

Figure 11: Scree plot of Principal Components Analysis of Water Quality Variables.

Scree plot showing the proportion of variance explained by each principal component in the PCA of water quality variables. The bars represent the individual variance contributions of each PC, with the red line indicating the cumulative variance. The first two PCs explain a cumulative total of approximately 51% of the total variance.

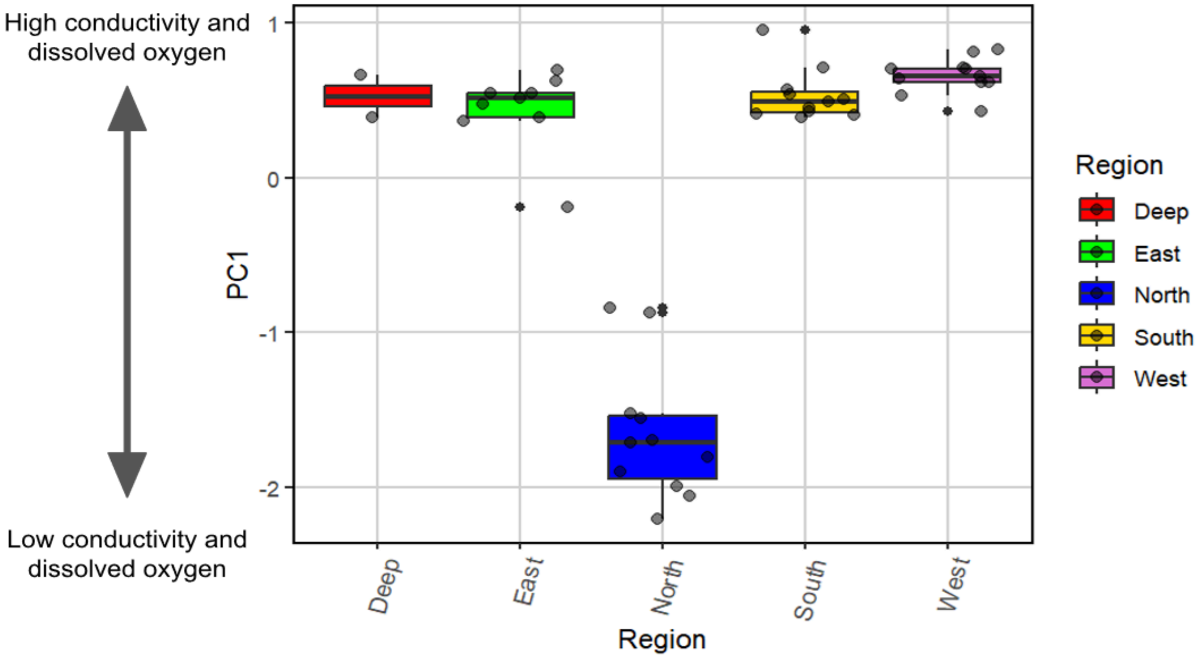

Figure 12: Boxplot of Water Quality Principal Component 1 by Region

Kruskal-Wallis test and Dunn post-hoc test (chi-squared = 28.55, df = 4, p-value = 9.649e-06). Significant differences were found between East and North (p = 0.0195), North and South (p = 0.0043), and North and West (p = 1.87e-06).

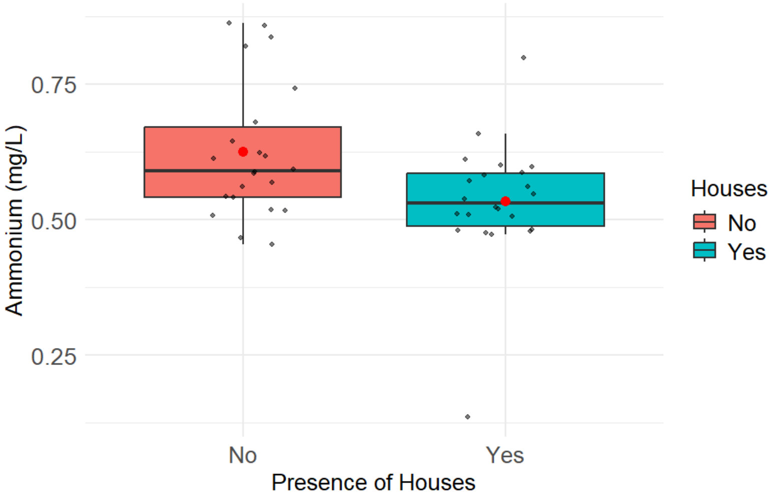

Figure 13: Boxplot of ammonium levels compared to the presence of houses on Lake Geneserath.

Welch Two Sample t-test, t = -2.489, df = 41.808, p-value = 0.01688, n = 45.

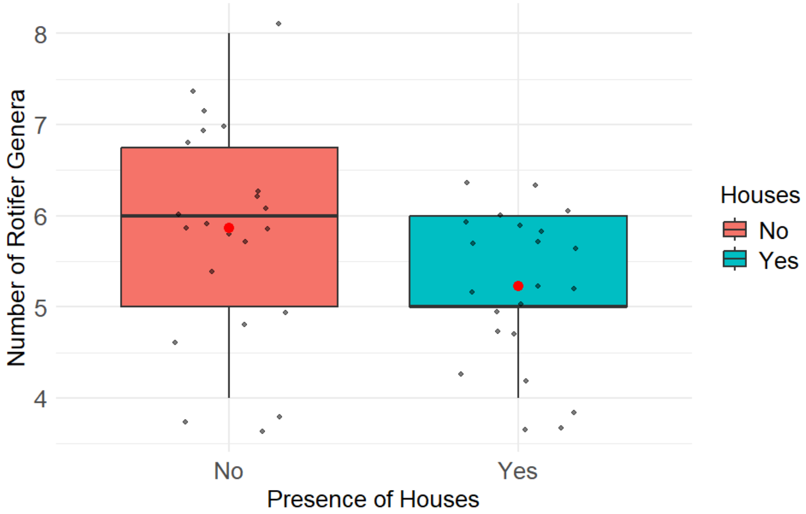

Figure 14: Boxplot of rotifer genera richness compared to the presence of houses on Lake Geneserath (n = 45).

Welch Two Sample t-test, t = -2.4088, df = 40.726, p-value = 0.02061, n = 45.

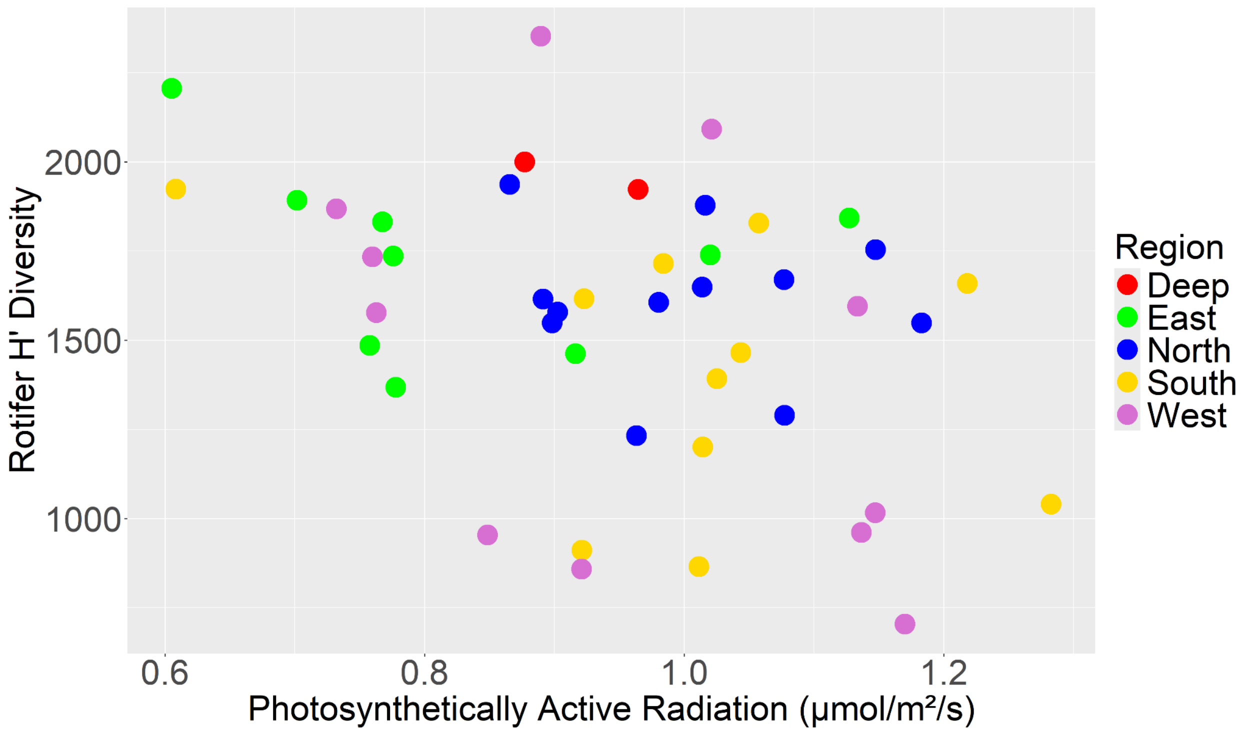

Figure 15: Scatterplot showing negative correlation between photosynthetically active radiation (m^{-2} s^{-1}) and rotifer H' diversity.

Each point represents a sample site (n = 45), color-coded by region (Deep, East, North, South, West). Spearman correlation, p = 0.024, Spearman's rho = -0.3357, n = 45.

Discussion

In Lake Geneserath, there was a significant difference in zooplankton abundance in the North Arm of Lake Geneserath compared to the other regions of the lake. Zooplankton abundance was negatively correlated with dissolved oxygen and specific conductivity. Looking for nutrient hotspots that correlated with zooplankton diversity and abundance was one of the goals of this study, but no hotspots were located.

Zooplankton were found to be spatially heterogeneous, with the North Arm containing six times more zooplankton on average per site than the rest of the lake (Figure 4, Figure 5). Furthermore, different rotifer and crustacea groups were regionally associated in Lake Geneserath, and the North Arm sites showed a close association with one another in respect to crustacea groups compared to the rest of the lake (Figure 6, Figure 7). The lake's irregular shape is likely contributing to these patterns. A previous study found that when comparing 624 lakes in Canada, lake morphometry was the most influential factor correlating with zooplankton diversity. Specifically, large, deep, irregularly-shaped lakes had the highest zooplankton diversity (Paquette et al. 2022). However, no other study has reported higher zooplankton abundance specifically within a narrow section of an irregularly-shaped lake, making this a novel ecological observation.

When looking at all factors measured by the AquaBOT, the four factors showed significant differences among regions of Lake Geneserath were dissolved oxygen, specific conductivity, ammonium, and water temperature, whereas PAR, turbidity, water depth, nitrate, and phosphorous showed no significant differences (Table 2). Dissolved oxygen and specific conductivity explained 28.5% of the variance in water quality, with the lowest dissolved oxygen and specific conductivity occurring in the North Arm (Figure 10, Figure 11, Figure 12). This co-occurred with greater zooplankton abundance in the North Arm (Figure 4, Figure 8, Figure 9). The negative correlation between zooplankton abundance and dissolved oxygen was unexpected. Previous literature generally shows positive correlations between zooplankton abundance and dissolved oxygen (Bowszys et al. 2020; Karpowicz et al. 2020). In general, higher oxygen levels can support greater biomass of zooplankton. One possible explanation for this pattern is that with greater observed plant material and algae in the North Arm, there will be greater decomposition which can cause lower dissolved oxygen levels. All dissolved oxygen measurements in Lake Geneserath were above 5 mg/L, meaning that the location can still support life and is not limiting zooplankton abundance (Bozorg-Haddad et al. 2021). When considering specific conductivity, other literature has mixed results, with some studies showing a negative correlation between conductivity and zooplankton abundance (Ersoy et al. 2022, Soto and De los Rios 2006). In general, zooplankton are sensitive to changes in specific conductivity because conductivity is an indicator of salinity changes in a lake.

The North Arm is fairly protected from the main body of the lake, which would cause less mixing. The North Arm is shallow compared to the deep basins of the main body, and had more observed signs of eutrophication (high plant material, high zooplankton abundance, lower DO) than the main body. Furthermore, dissolved oxygen may be lower in the North Arm due to less mixing with the main body of the lake: the oxygenated water in the main body rarely mixes with the less oxygenated water in the Arm. Together, these variables reveal how the North Arm most likely has little mixing with the main body of the lake and creates an environment suitable for zooplankton.

The data indicate that multiple factors contribute to the spatial heterogeneity of zooplankton, supporting existing literature that highlights how zooplankton distribution is shaped by a multitude of interacting influences. The North Arm of Lake Geneserath is different from the other regions in regard to dissolved oxygen and specific conductivity, both of which can shape spatial heterogeneity of zooplankton. In the narrow, protected section of a large, meso-oligotrophic lake, I observed how water qualities likely reveal limited mixing with the rest of the lake and contribute to a suitable habitat for zooplankton. In terms of eutrophication of Lake Geneserath, the data suggest that the North Arm is more eutrophic than the main basins due to its higher zooplankton abundance and lower dissolved oxygen. This information can improve conservation and management of the lake as it demonstrates how there are different types of habitat present in one contiguous lake.

In respect to shoreline houses, there was a significant difference in ammonium levels, with ammonium being lower in front of houses (Figure 13). The highest ammonium readings were taken on the East shore, where a marsh area was observed as well as a creek coming into Lake Geneserath. The East shore is undeveloped, while all other areas of the lake have housing, which could contribute to this pattern. Nutrient input may be coming from this marsh area and stream which is part of an undeveloped area, causing these differences in the “house” variable.

I observed a significant difference in rotifer richness in relation to the location of houses on the shoreline of Lake Geneserath: rotifer genera richness was higher where there were no houses on the shoreline (Figure 14). While there is a substantial body of research on factors influencing rotifer diversity, including habitat structure and land use, there are no studies specifically examining the impact of shoreline housing on rotifer richness. A study on ponds in Germany found that land use, particularly surrounding agricultural areas, significantly affected rotifer diversity and abundance (Onandia et al. 2021). However, future research is needed to understand why this pattern has emerged between rotifer richness and shoreline development, especially since it does not appear to be correlated with any water quality variables. Measuring the “house” variable as a binary categorical variable was a limitation in my study: this measurement was subjective and thus weakens the interpretation of the data. In the future, I would measure it as the distance our sample site is from a house or development.

My analysis revealed a significant negative relationship between PAR and rotifer diversity, calculated using the Shannon-Wiener diversity index (Figure 15). This suggests that as light availability increases, rotifer communities become less diverse. However, time of day had no significant effect on rotifer diversity, indicating that the observed changes were not merely a product of temporal variation but were more directly linked to PAR levels. Unlike diel vertical migration, which is driven by predator avoidance and light exposure (Williamson et al. 2011), the observed correlation suggests that certain rotifers may exhibit spatial avoidance of high-light environments rather than just temporal shifts. The literature supports the hypothesis that ultraviolet radiation from the sun can be damaging to certain zooplankton as rotifers are transparent and do not have pigment protection from sunlight. Certain *Asplanchna* rotifers have shorter lifespans under high UV light (Sawada & Enesco 1984). Some rotifers cannot digest food under high UV radiation in laboratory settings (Feng et al. 2007). It is possible that some rotifer genera are avoiding UV light effects by migrating down in the water column in sunny areas but are more present in shady areas. While the correlation between PAR and rotifer diversity was statistically significant ($p = 0.02465$), it explained only 14.55% of the variation in rotifer diversity, suggesting that other environmental or biological factors may also play crucial roles.

The AquaBOT is a useful tool with many potential applications beyond the reasons for which it was originally created. Originally made for detecting nutrient hotspots in small streams in agricultural areas, the AquaBOT has now been used in a meso-oligotrophic lake. We found the

AquaBOT to be convenient, quick, and simple to use for water quality testing. New and emerging technologies such as the AquaBOT can change field work by reducing the time, costs, and labor associated with field work. The AquaBOT took measurements at a total of 1,933 individual locations on Lake Geneserath, a feat that would be tedious and nearly impossible with human labor alone. This broad-picture sampling can provide insights for management, especially in regard to zooplankton abundance which may indicate more eutrophic areas with greater abundances of zooplankton predators such as fish. Investigating the spatial heterogeneity of predators to zooplankton could provide a more complete picture of ecosystem dynamics in irregularly shaped lakes.

There are some limitations to the study methods that may impact the application of its results. For instance, I only sampled the top meter of the water. Zooplankton can be vertically stratified (Williamson et al. 2011), meaning this methodology is missing the vertical aspect of zooplankton spatial heterogeneity. Another limitation was the timing of sampling. Due to logistical restraints, only one to two sections of the lake could be sampled each day. There were three boat launches on Lake Geneserath: one in the South end, one on the East shore and one in the North Arm. Sampling was broken up into multiple days, which means that weather was variable across samples and between regions of the lake. While we did not sample on highly windy days due to safety concerns, wind levels were variable on sampling days which could cause mixing on the top of the lake. Furthermore, sampling occurred in a one week period because the AquaBOT was on lease to the Central Michigan University Biological Station for only two weeks. Zooplankton abundance and diversity exhibit significant seasonal variation; therefore, this study represents only a limited representation of these dynamics.

Future research on zooplankton spatial heterogeneity in freshwater ecosystems, particularly in irregularly shaped and meso-oligotrophic lakes undergoing eutrophication like Lake Geneserath, should focus on several key areas. First, exploring other underlying mechanisms driving the observed differences in zooplankton abundance and diversity, such as water circulation, nutrients, and habitat structure, would provide valuable insights on the relationship with lake morphometry. Second, investigating the spatial heterogeneity of predators to zooplankton could provide a more complete picture of ecosystem dynamics in irregularly shaped lakes. Third, seasonal studies are needed to assess how these patterns change over time as I only collected field data in June. Comparative studies across other irregularly shaped lakes could provide clarity on the generalizability of my findings. These research directions will not only advance ecological knowledge but also inform effective lake management and conservation strategies.

The use of advanced technologies, like the AquaBOT aquatic drone, should be expanded to collect higher-resolution, real-time data, which could be integrated with artificial intelligence to improve predictive models of zooplankton distribution. I also recommend that the AquaBOT be used in lakes that have greater levels of development or are part of watersheds that include agricultural land. This could provide insights on how anthropogenic modifications to ecosystems impact watersheds at a fine-scale. Utilizing the AquaBOT to find nutrient hotspots in lake ecosystems can indicate causes of eutrophication such as runoff and pollution that can be addressed by management and policy.

References

Abdulwahab, Shayma, and Adel M. Rabee. 2015. ‘Ecological Factors Affecting the Distribution of the Zooplankton Community in the Tigris River at Baghdad Region, Iraq’. *Egyptian Journal of Aquatic Research* 41 (2): 187–96. https://doi.org/10.1016/j.ejar.2015.03.003.

Bowszys, Magdalena, Renata Tandyrak, Iwona Gołaś, and Ewa Paturej. 2020. ‘Zooplankton Communities in a River Downstream from a Lake Restored with Hypolimnetic Withdrawal’. *Knowledge & Management of Aquatic Ecosystems*, no. 421, 12. https://doi.org/10.1051/kmae/2020005.

Bozorg-Haddad, Omid, Mohammad Delpasand, and Hugo A. Loáiciga. 2021. ‘10 - Water Quality, Hygiene, and Health’. In *Economical, Political, and Social Issues in Water Resources*, edited by Omid Bozorg-Haddad, 217–57. Elsevier. https://doi.org/10.1016/B978-0-323-90567-1.00008-5.

Bray, J. Roger, and J. T. Curtis. 1957. ‘An Ordination of the Upland Forest Communities of Southern Wisconsin’. *Ecological Monographs* 27 (4): 325–49. https://doi.org/10.2307/1942268.

Cashmann, William. n.d. ‘Lake Geneserath’. Beaver Island. Accessed 21 March 2025. https://www.beaverisland.net/Places/Inland_Lakes/Lake_Geneserath/lake_geneserath.htm.

Chaparro, G., P. Kandus, and I. O’Farrell. 2015. ‘Effect of Spatial Heterogeneity on Zooplankton Diversity: A Multi-Scale Habitat Approximation in a Floodplain Lake’. *River Research and Applications* 31 (1): 85–97. https://doi.org/10.1002/rra.2711.

Dodson, Stanley I., Amy L. Newman, Susan Will-Wolf, Mara L. Alexander, Michele P. Woodford, and Scott Van Egeren. 2009. ‘The Relationship between Zooplankton Community Structure and Lake Characteristics in Temperate Lakes (Northern Wisconsin, USA)’. *Journal of Plankton Research* 31 (1): 93–100. https://doi.org/10.1093/plankt/fbn095.

Duggan, Ian C., John D. Green, and Russell J. Shiel. 2002. ‘Distribution of Rotifer Assemblages in North Island, New Zealand, Lakes: Relationships to Environmental and Historical Factors’. *Freshwater Biology* 47 (2): 195–206. https://doi.org/10.1046/j.1365-2427.2002.00742.x.

Energy, UT-Battelle LLC for the US Department of. 2022. ‘Environment — Clean Water Bots’. 4 April 2022. https://www.ornl.gov/news/environment-clean-water-bots.

Ersoy, Zeynep, Meritxell Abril, Miguel Cañedo-Argüelles, Carmen Espinosa, Lidia Vendrell-Puigmitja, and Lorenzo Proia. 2022. 'Experimental Assessment of Salinization Effects on Freshwater Zooplankton Communities and Their Trophic Interactions under Eutrophic Conditions'. Environmental Pollution 313 (November):120127. https://doi.org/10.1016/j.envpol.2022.120127.

Feng, Lei, Xuexi Tang, You Wang, Hiu Xiao, Xianghong Meng, and Xiguang Chen. 2007. 'Effect of UV-B Radiation on Ingesting and Nutritional Selecting Behavior of Rotifer Brachionus Urceus'. *Wuhan University Journal of Natural Sciences* 12 (2): 361–66. https://doi.org/10.1007/s11859-006-0042-0.

Florida, USF Water Institute, School of Geosciences, University of South. n.d. 'Learn More: Dissolved Oxygen - Sarasota County Water Atlas - Sarasota.WaterAtlas.Org'. Accessed 11 July 2024. https://sarasota.wateratlas.usf.edu/library/learn-more/learnmore.aspx?toolsection=lm_dissolvedox.

Gazonato Neto, Antonio José, Lidiane Cristina da Silva, Angelo Augusto Saggio, and Odete Rocha. 2014. 'Zooplankton Communities as Eutrophication Bioindicators in Tropical Reservoirs'. Biota Neotropica 14 (December):e20140018. https://doi.org/10.1590/1676-06032014001814.

George, D. G., and I. J. Winfield. 2000. 'Factors Influencing the Spatial Distribution of Zooplankton and Fish in Loch Ness, UK'. *Freshwater Biology* 43 (4): 557–70. https://doi.org/10.1046/j.1365-2427.2000.00539.x.

Goździejewska, Anna Maria, Marek Kruk, and Martin Bláha. 2024. 'The Zooplankton Adaptation Patterns along Turbidity Gradient in Shallow Water Reservoirs'. *Ecohydrology & Hydrobiology* 24 (1): 188–200. https://doi.org/10.1016/j.ecohyd.2023.08.005.

Greer, Adam T., Adam D. Boyette, Valerie J. Cruz, Mustafa Kemal Cambazoglu, Brian Dzwonkowski, Luciano M. Chiaverano, Steven L. Dykstra, Christian Briseño-Avena, Robert K. Cowen, and Jerry D. Wiggert. 2020. 'Contrasting Fine-Scale Distributional Patterns of Zooplankton Driven by the Formation of a Diatom-Dominated Thin Layer'. *Limnology and Oceanography* 65 (9): 2236–58. https://doi.org/10.1002/lno.11450.

Griffiths, Natalie. n.d. 'Spatially Resolved Measurements of Water Quality Indicators within in a Bioenergy Landscape'.

Griffiths, Natalie A., Peter S. Levi, Jeffery S. Riggs, Christopher R. DeRolph, Allison M. Fortner, and Jason K. Richards. 2022. 'Sensor-Equipped Unmanned Surface Vehicle for

High-Resolution Mapping of Water Quality in Low- to Mid-Order Streams'. *ACS ES&T Water* 2 (3): 425–35. https://doi.org/10.1021/acsestwater.1c00342.

Hall, C. J., and C. W. Burns. 2002. 'Effects of Temperature and Salinity on the Survival and Egg Production of Gladioferens Pectinatus Brady (Copepodas: Calanoida)'. *Estuarine, Coastal and Shelf Science* 55 (4): 557–64. https://doi.org/10.1006/ecss.2001.0923.

Jeppesen, Erik, Peeter Noges, Thomas A. Davidson, Juta Haberman, Tiina Noges, Katlin Blank, and Torben L. Lauridsen. 2011. 'Zooplankton as Indicators in Lakes: A Scientific-Based Plea for Including Zooplankton in the Ecological Quality Assessment of Lakes According to the European Water Framework Directive (WFD)'. *Hydrobiologia* 676 (1). https://doi.org/10.1007/s10750-011-0831-0.

Julies, Elsabe M., and Isak K. Kaholongo. 2014. 'Relationship between Dissolved Oxygen and the Vertical and Longitudinal Distribution of Zooplankton off the Namibian Coast'. *International Science and Technology Journal of Namibia*, April, 078–089.

Karpowicz, Maciej, Jolanta Ejsmont-Karabin, Joanna Kozłowska, Irina Feniova, and Andrew Dzialowski. 2020. 'Zooplankton Community Responses to Oxygen Stress'. *Water* 12 (March):706. https://doi.org/10.3390/w12030706.

Kelderman, Peter, Philiphi De Rozari, Saumyasib Mukhopadhyay, and R Ang'weya. 2012. 'Sediment Dynamics in Shallow Lake Markermeer, The Netherlands: Field/Laboratory Surveys and First Results for a 3-D Suspended Solids Model'. Water Science and Technology : A Journal of the International Association on Water Pollution Research 66 (August):1984–90. https://doi.org/10.2166/wst.2012.325.

Kim, Hee-Jin, Jae-Seong Lee, and Atsushi Hagiwara. 2018. 'Phototactic Behavior of Live Food Rotifer Brachionus Plicatilis Species Complex and Its Significance in Larviculture: A Review'. Aquaculture 497 (December):253–59. https://doi.org/10.1016/j.aquaculture.2018.07.070.

Legendre, Pierre. 1993. 'Spatial Autocorrelation: Trouble or New Paradigm?' Ecology 74 (6): 1659–73. https://doi.org/10.2307/1939924.

Merrix-Jones, Faye, Stephen Thackeray, Isabelle Durance, and Steve Ormerod. 2013. 'Spatial Structure in the Zooplankton of a Newly Formed and Heavily Disturbed Urban Lake'. Fundamental and Applied Limnology / Archiv Für Hydrobiologie 183 (July):1–14. https://doi.org/10.1127/1863-9135/2013/0459.

Onandia, Gabriela, Sebastian Maassen, Camille L Musseau, Stella A Berger, Carla Olmo, Jonathan M Jeschke, and Gunnar Lischeid. 2021. 'Key Drivers Structuring Rotifer Communities in Ponds: Insights into an Agricultural Landscape'. Journal of Plankton Research 43 (3): 396–412. https://doi.org/10.1093/plankt/fbab033.

Paquette, Cindy, Irene Gregory-Eaves, and Beatrix E. Beisner. 2022. ‘Environmental Drivers of Taxonomic and Functional Variation in Zooplankton Diversity and Composition in Freshwater Lakes across Canadian Continental Watersheds’. Limnology and Oceanography 67 (5): 1081–97. https://doi.org/10.1002/lno.12058.

Rasconi, Serena, Andrea Gall, Katharina Winter, and Martin J. Kainz. 2015. ‘Increasing Water Temperature Triggers Dominance of Small Freshwater Plankton’. PLoS ONE 10 (10): e0140449. https://doi.org/10.1371/journal.pone.0140449.

Robertson, Wendy Marie, Daria B. Kluver, Roderick W. Lammers, Natalie A. Griffiths, Chloe Majeske Neal, and Amanda K. Suchy. n.d. ‘Home Chill Home: Leveraging Aquatic Drone Technology to Understand Spatial Variation in Water Quality Parameters of Coldwater Streams (Michigan, USA)’. Accessed 17 February 2025. https://www.authorea.com/doi/full/10.22541/essoar.173867564.49642022?commit=70da8c4209ee6fd24f7105ca669ed00b91982f12.

Santangelo, Jayme M., Reinaldo L. Bozelli, Adriana de M. Rocha, and Francisco de A. Esteves. 2008. ‘Effects of Slight Salinity Increases on Moina Micrura (Cladocera) Populations: Field and Laboratory Observations’. Marine and Freshwater Research 59 (9): 808–16. https://doi.org/10.1071/MF08026.

Sawada, M., and H. E. Enesco. 1984. ‘Effects of U.V. Radiation on the Lifespan of the Rotifer Asplanchna Brightwelli’. Experimental Gerontology 19 (5): 289–96. https://doi.org/10.1016/0531-5565(84)90001-9.

Sawyers, Jane E., A. Scott McNaught, and Donna K. King. 2016. ‘Recent and Historic Eutrophication of an Island Lake in Northern Lake Michigan, USA’. Journal of Paleolimnology 55 (2): 97–112. https://doi.org/10.1007/s10933-015-9867-x.

Shchapov, Kirill, and Ted Ozersky. 2023. ‘Opening the Black Box of Winter: Full-Year Dynamics of Crustacean Zooplankton along a Nearshore Depth Gradient in a Large Lake’. Limnology and Oceanography 68 (7): 1438–51. https://doi.org/10.1002/lno.12355.

Shen, Jiachen, Ge Qin, Rendong Yu, Yuxuan Zhao, Jiqiang Yang, Shuqing An, Run Liu, Xin Leng, and Yun Wan. 2021. ‘Urbanization Has Changed the Distribution Pattern of Zooplankton Species Diversity and the Structure of Functional Groups’. Ecological Indicators 120 (January):106944. https://doi.org/10.1016/j.ecolind.2020.106944.

Soto, Doris, and Patricio De los Rios. 2006. ‘Influence of Trophic Status and Conductivity on Zooplankton Composition in Lakes and Ponds of Torres Del Paine National Park (Chile)’. Biologia 61 (5): 541–46. https://doi.org/10.2478/s11756-006-0088-7.

Striebel, Maren, Gabriel Singer, Herwig Stibor, and Tom Andersen. 2012. '"Trophic Overyielding": Phytoplankton Diversity Promotes Zooplankton Productivity'. *Ecology* 93 (12): 2719–27. https://doi.org/10.1890/12-0003.1.

Sun, Xuewei, Huayong Zhang, Zhongyu Wang, Tousheng Huang, and Hai Huang. 2022. 'Phytoplankton Community Response to Environmental Factors along a Salinity Gradient in a Seagoing River, Tianjin, China'. *Microorganisms* 11 (1): 75. https://doi.org/10.3390/microorganisms11010075.

Trudnowska, Emilia, Slawomir Sagan, Slawomir Kwasniewski, Miroslaw Darecki, and Katarzyna Blachowiak-Samolyk. 2015. 'Fine-Scale Zooplankton Vertical Distribution in Relation to Hydrographic and Optical Characteristics of the Surface Waters on the Arctic Shelf'. *Journal of Plankton Research* 37 (1): 120–33. https://doi.org/10.1093/plankt/fbu087.

US EPA, ORD. 2015. 'Dissolved Oxygen'. Data and Tools. 4 November 2015. https://www.epa.gov/caddis/dissolved-oxygen.

US EPA, OW. 2013. 'Indicators: Zooplankton'. Overviews and Factsheets. 21 November 2013. https://www.epa.gov/national-aquatic-resource-surveys/indicators-zooplankton.

Williamson, Craig E., Janet M. Fischer, Stephen M. Bollens, Erin P. Overholt, and Joanne K. Breckenridge. 2011. 'Toward a More Comprehensive Theory of Zooplankton Diel Vertical Migration: Integrating Ultraviolet Radiation and Water Transparency into the Biotic Paradigm'. *Limnology and Oceanography* 56 (5): 1603–23. https://doi.org/10.4319/lo.2011.56.5.1603.

Yang, Li-Juan, Ya Tao, Xia Jiang, Ying Wang, Ye-Hao Li, Long Zhou, Pu-Ze Wang, et al. 2023. 'Interactive Effects of Nutrients and Salinity on Zooplankton in Subtropical Plateau Lakes with Contrasting Water Depth'. *Frontiers in Environmental Science* 11 (February). https://doi.org/10.3389/fenvs.2023.1110746.

Yuan, Lester L. 2021. 'Continental-Scale Effects of Phytoplankton and Non-Phytoplankton Turbidity on Macrophyte Occurrence in Shallow Lakes'. Aquatic Sciences 14:10.1007/s00027-020-00769–1. https://doi.org/10.1007/s00027-020-00769-1.

Zhang, Siyong, Wenqin Lu, Zhongze Zhou, and Wenwen Chen. 2022. 'Spatial Differences in Zooplankton Community Structure between Two Fluvial Lakes in the Middle and Lower Reaches of the Yangtze River: Effects of Land Use Patterns and Physicochemical Factors'. *Diversity* 14 (11): 908. https://doi.org/10.3390/d14110908.

Zhao, Na, Zemeng Fan, and Miaomiao Zhao. 2021. 'A New Approach for Estimating Dissolved Oxygen Based on a High-Accuracy Surface Modeling Method'. Sensors (Basel, Switzerland) 21 (12): 3954. https://doi.org/10.3390/s21123954.

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