How do depth and water chemistry influence diversity and community composition in stratified stormwater ponds?

EEB397 Final Report

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Introduction

Aquatic ecosystems encapsulate any environment in water where species interact with the chemical and physical of the water and are typically divided into marine and freshwater ecosystems. The presence of water has always served as a necessity for human populations and through urbanization, these aquatic systems are being physically altered (Tucci 2017; Molden 2007). The influence of urbanization on freshwater ponds can be mostly characterized as consequences of urban infrastructures and urban processes (Marsalek 2003; Fanton et al. 2023). More specifically, the former pertains to the effects instilled strictly from the installation of structures and their existence, whereas the latter to how the urban systems function.

One consequence induced by urbanization is the reduction of pervious surfaces (Hibbs and Sharp 2012). Roads, sidewalks, and other concrete structures are among examples of impervious surfaces, however, recent efforts have explored the possibility of pervious concrete to improve stormwater runoff management (Hibbs and Sharp 2012; Azad, Sheikh, and Hai 2024). To account for the increase in impervious surfaces in urban areas, researchers have also explored incorporating green spaces wherever possible to reduce stormwater runoff (Zimmermann et al. 2016). Although increasing the effective area of green spaces may reduce runoff, this approach fails to address managing any runoff that is not attenuated by the green spaces. Furthermore, urban runoff in particular is heavily polluted, carrying heavy metals, litter, and sediment (Malaviya and Singh 2012; Müller et al. 2020). As urban runoff is displaced to larger freshwater bodies, the carried pollutants can be detrimental to the receiving waterways (Li et al. 2010).

In 1994, stormwater ponds were first proposed as a solution to deal with stormwater runoff, and as of 2022, there are over 9000 publicly managed stormwater pond facilities that are used across Canada, demonstrating the widespread incorporation of this infrastructure to manage runoff (Environment 1994; Drake and Guo 2008; Statistics Canada 2022). Stormwater ponds are excellent for managing urban runoff as they effectively store runoff and simultaneously treat the runoff by enabling suspended solids to settle before the runoff is slowly released into further waterways (Nayeb Yazdi et al. 2021). While stormwater ponds have proven to be effective for water management, these ponds are often as effective as the monitoring and management programs behind them, since accumulated sediment must be cleared out (Drake and Guo 2008; Gu et al. 2017). More specifically, as suspended solids continue to accumulate in stormwater ponds, they become less efficient at treating received runoff as solids may become suspended once again and released into waterways (Gu et al. 2017). Lastly, stormwater ponds are rather appealing within urban settings and double as recreational green spaces for nearby residents, which can be especially useful in urban areas where green spaces are not widely available (Polta 2004).

However, recreational use is not the only extended feature of stormwater ponds, rather these ponds also serve as a habitat for animals within urban settings. Hassall and Anderson 2015 found that invertebrate biodiversity in stormwater ponds was comparable to that of invertebrates in unmanaged wetlands, indicating that stormwater ponds now serve as a replacement for previously suitable habitats that have been removed in the establishment of cities. This makes stormwater ponds quintessential for urban conservation practices. Bishop et al. 2000 were the first to survey and assess what type of wildlife resides within stormwater ponds. Since then, others have continued to study the relationship between invertebrates and stormwater ponds, specifically how it may impact diversity (e.g., Meland et al. 2020, Vehkaoja, Niemi, and Väänänen 2020, and Le Viol et al. 2009).

Briefly stepping away from diversity in stormwater ponds, stormwater ponds are also known to undergo intense stratification, which induces layers with distinct water chemistry within stormwater ponds. Loewen and Jackson 2024 found that salinity, temperature, and water transparency (turbidity) are the primary drivers of stratification in urban stormwater ponds, which refuted the ongoing conception that depth gradients were largely induced by depth and area. Notably, stratification in stormwater ponds may come in the form of several non-mutually exclusive gradients such as a thermocline (temperature) and an oxycline (dissolved oxygen). Moreover, it is well understood that macroinvertebrate taxonomic families have specific tolerance ranges to aquatic environmental conditions (e.g., Berezina 2003, Dlamini et al. 2010) and further, that within their tolerance ranges, they may prefer certain environmental conditions (Everaert et al. 2014). This motivates the hypothesis that the environmental differences induced by stratification may drive variation in macroinvertebrate communities along a depth gradient. In general, previous literature that has explored macroinvertebrate communities in stormwater ponds did not include the influence of a depth gradient where stratification occurs within the stormwater pond.

The primary objective of this study is to explore how depth and water chemistry predict diversity and community composition. Note, that stratification is directly characterized by the relationship between depth and water chemistry. To effectively address this aim, it is important to determine how stratification is impacting the selected ponds and how diversity changes with depth within the ponds. As discussed above, previous literature suggests that stratification should be occurring within these ponds, thus it is expected that stratification of some form is observed in this study. Furthermore, assuming stratification greatly impacts the water chemistry along a depth gradient and consequently alters the environmental niche, it is expected that diversity in some capacity changes with depth. There are two main predictions concerning how community structures may be impacted by stratification (see Figure 1). The former conjects that communities will consist of the same species along a depth gradient however in lesser quantities, whereas the latter proposes that different communities will contain different species.

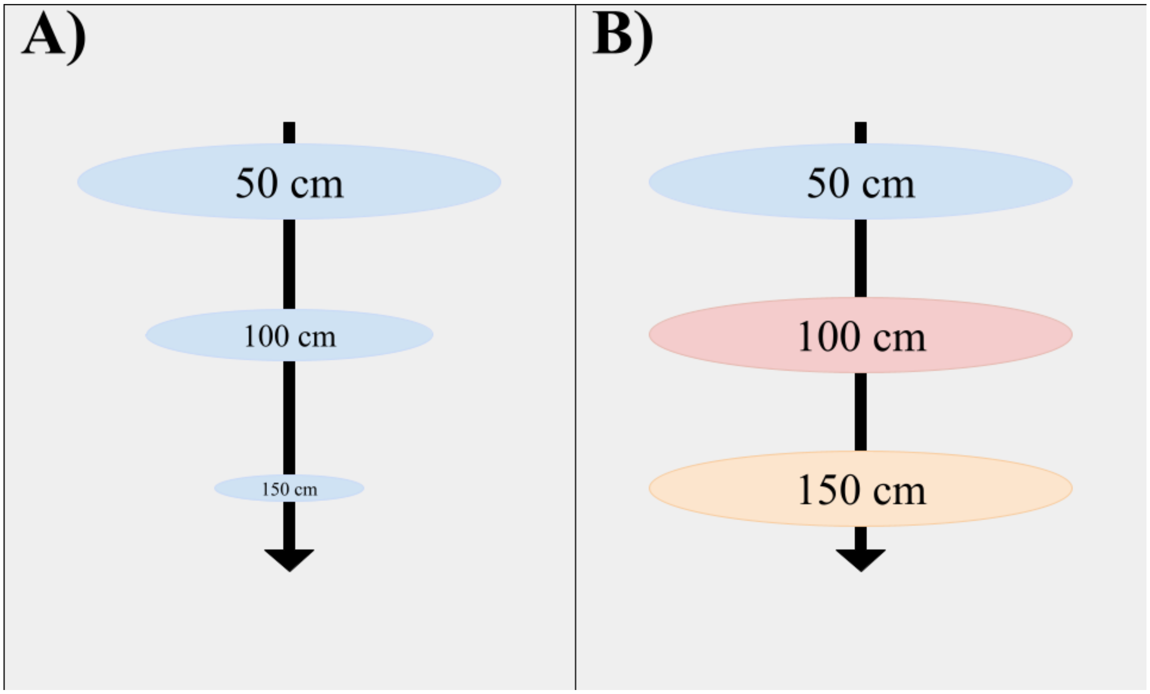


Figure 1: Visualization of the two primary predictions regarding invertebrate community composition along a depth gradient. In A), each ellipse is the same colour but decreases in size (similar composition with fewer specimens down the depth gradient), whereas in B), each ellipse is a different colour which represents different community composition.

Methods

This study was conducted from July to August 2023 in Brampton, Ontario, CA. The city of Brampton is in the Peel Region of the Greater Toronto Area (GTA) and is northwest of Toronto. Brampton experienced a population growth of 13.3% and 10.6% from 2011 to 2016 and 2016 to 2021, respectively (Canada 2016; Canada 2021). Moreover, Brampton is ranked as the ninth-largest city in Canada. Currently, the city of Brampton manages over 180 stormwater ponds across the region, three of which were selected for this study (see Figure 2; City of Brampton 2024). Briefly, these ponds were selected with the foreknowledge that they were i) at least 150cm deep and ii) relatively close to one another. The figure below depicts the location of the three ponds relative to one another.

To collect invertebrates along a depth gradient, three colony plates were inserted at depths of 50cm, 100cm, and 150cm, respectively. The construction of said colony plates is depicted in Figure 3. Furthermore, two sets of plates (referred to as Site A and Site B), were placed at each depth along each pond. This yielded a total sample size of 18 colony plates. The colony plates were placed on the same day in early July and collected on the same day in early August. To ensure colony plates would remain in their location, they were weighted down using a brick that was attached to the bottom. Similarly, to ensure colony plates could be recollected, ropes of length matching the plate's assigned depth were attached to the colony plates. These ropes were tied onto a buoyant handle.

Vertical profiles were conducted twice throughout this study, once in the middle of July and the other, in the middle of August. Throughout these profiles, water chemistry data on temperature, dissolved oxygen, conductivity, and turbidity were collected at 10cm depth increments. Unfortunately, in ponds that are approximately 150cm deep, it was not feasible to collect data along

Figure 2: Images taken from Google Earth. Captures of the individual ponds are scaled to one another.

a full gradient (i.e., from 0cm to 150cm). This will be further discussed in the *Discussion* section of this paper. Moreover, in some instances, data beyond the depth of 150cm was collected, however, these observations were omitted from the analysis as they remained outside the focal depth range of this study. It should also be noted that profiles were conducted during the morning; water chemistry within stormwater ponds can often vary within a singular day.

During the colony plate collection segment of this study, individual plates were scrapped into the jars and thereafter filled with ethanol to preserve collected macroinvertebrates. Every macroinvertebrate collected was identified at the family taxonomic level and total abundance was documented for each colony plate. Lastly, all analysis and visualization were conducted using R v4.3.0 and ggplot2 (Wickham 2016).

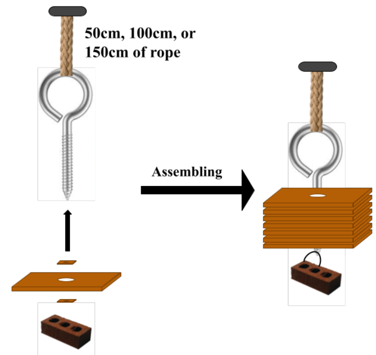
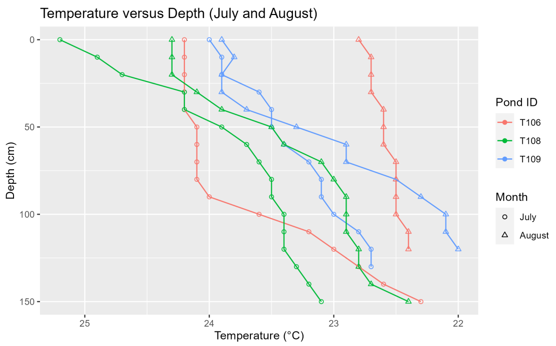


Figure 3: Diagram representing the components used to assemble colony plates.

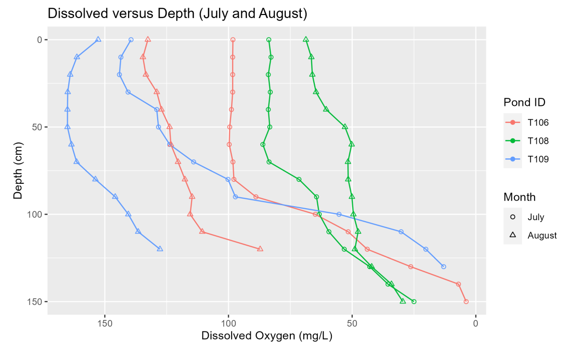
Results

Stratification

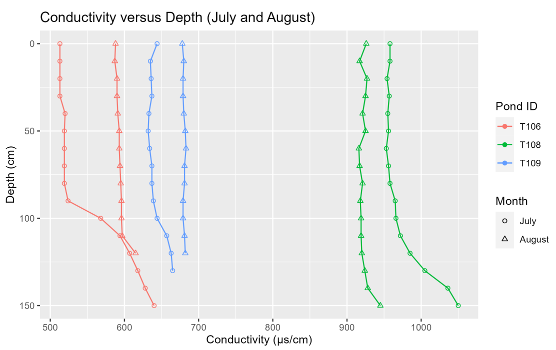
While previous literature found evidence of stratification within the ponds used within this study, it was important to verify the effects of stratification during the time of this study. To quantify the effects of stratification, random intercept models were derived using depth, month, and the interaction of depth and month as fixed effects, and ponds as a random effect to explain the measured



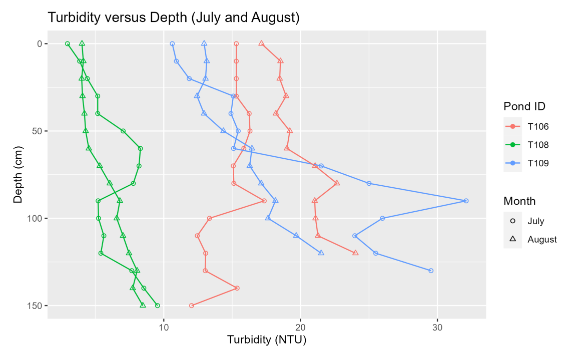
(a) Temperature measurements along a depth gradient of 0cm to 150cm, from July and August. Note that the *y*-axis is inverted to mimic progressing down the depth gradient. Lines are grouped by depth and month.



(b) Dissolved oxygen measurements along a depth gradient of 0cm to 150cm, from July and August. Note that the *y*-axis is inverted to mimic progressing down the depth gradient. Lines are grouped by depth and month.



(c) Conductivity measurements along a depth gradient of 0cm to 150cm, from July and August. Note that the *y*-axis is inverted to mimic progressing down the depth gradient. Lines are grouped by depth and month.



(d) Turbidity measurements along a depth gradient of 0cm to 150cm, from July and August. Note that the *y*-axis is inverted to mimic progressing down the depth gradient. Lines are grouped by depth and month.

Figure 4: Water chemistry measurements along depth gradients.

aspects of water chemistry (Eq. 1). Namely in Eq. 1, the Y_i term refers to the i-th chemical

$$Y_i = \alpha_{0i} + \alpha_{1i} X_1 + \alpha_{2i} X_2 + \alpha_{3i} X_1 X_2 \tag{1}$$

property of water documented during vertical profiles (i.e., temperature, dissolved oxygen conductivity, and turbidity), $\alpha_{0i}, \alpha_{1i}, \alpha_{2i}, \alpha_{3i}$ the estimated intercept and slopes associated with the i-th water property, and X_1 and X_2 depth and month, respectively. Using this model, water temperature reported a decrease of -0.0118 °C/cm (p-value 8.43e-3), a decrease of -0.712 °C from July to August (p-value 6.11e-7), with the interaction of depth and month having no statistical significance (p-value 0.955). Dissolved Oxygen reported a decrease of 0.942 mg/cm·L (p-value 1.73e-7), month did not have a statistically significant effect (p-value 0.782), while the interaction of depth and month had an effect 0.311 cm·month (p-value 5.32e-3). Conductivity reported an increase of 1.223 μs/cm^2 (p-value 5.22e-8), an increase of 51.871 μs/cm from July to August (p-value 7.20e-6), with an interaction of depth and month having an effect of -0.627 cm·month (p-value 1.14e-5). Turbidity reported an increase of 0.0334 NTU/cm (p-value 0.200), an increase of 0.221 NTU from July to August (p-value 0.872), with the interaction of depth and month having no statistical significance (p-value 0.7527). Generally, we can see that temperature and dissolved oxygen decrease with depth, whereas conductivity and turbidity increase with depth. The results from the four models indicate that temperature (thermocline), dissolved oxygen (oxycline), and conductivity (conductivity gradient) are undergoing stratification in the ponds selected for this study (see Figure 4).

Diversity and Depth

As covered in the previous section, the three ponds selected for this study exhibit evidence of a thermocline, oxycline, and conductivity gradient. This motivates exploring how diversity is impacted by depth. Diversity will be characterized by species richness (SR), sample size (SS), Simpson's index, Simpson's Evenness, Shannon's index, and Shannon's Evenness. A summary of these measurements can be found in Table 1. Briefly, these indices cover an array of concepts intrinsic to diversity such as number of species, size of population, and relative abundances. To quantify the

effects of depth on diversity, linear models were derived using depth as a fixed effect to explain the measured aspects of water chemistry (Eq. 2). Namely in Eq. 2, the Y_i' term refers to the i-th

$$Y_i' = \beta_{0i} + \beta_{1i} X \tag{2}$$

diversity measurement, $\beta_{0i}, \beta 1i$ the intercept and slope associated with the i-th diversity measure-

Depth	Mean SR	Mean SS	Mean Simp. Index	Mean Simp. Even.	Mean Shan. Index	Mean Shan. Even.
50	7.167	283.333	1.820	0.255	0.789	0.386
100	5.333	133.833	1.723	0.327	0.766	0.459
150	4.667	108.000	2.082	0.471	0.887	0.593
Pond	**Mean SR**	**Mean SS**	**Mean Simp. Index**	**Mean Simp. Even.**	**Mean Shan. Index**	**Mean Shan. Even.**
T106	6.500	167.667	1.972	0.314	0.899	0.487
T108	6.333	88.167	1.967	0.329	0.934	0.520
T109	4.333	269.333	1.688	0.409	0.609	0.432

Table 1: Mean values computed for selected diversity measurements. Note that the upper table includes computations grouped by depth, whereas the bottom table includes computations grouped by pond.

ment, and X is depth. Species richness reported a decrease of 0.025 species/cm (p-value 0.0199). Sample size reported a decrease of 1.75 specimens/cm (p-value 0.0220). Simpson Evenness reported an increase of 0.00173 per centimeter (p-value 1.28e-2) and Shannon Evenness reported 0.00147 per centimeter (p-value 9.65e-5). Neither Simpson's Index nor Shannon's Index had any statistically significant effects relating to depth. Generally, these models suggest that diversity decreases with depth. This is seen as both the number of taxonomic families and the overall sample size decrease with depth. Noting that the Simpson and Shannon index were not directly explained by depth, but their measurements of evenness were influenced by depth. In the table below, diversity estimates generated from statistically significant models are delineated for each depth that hosted colony plates. Recalling the hypotheses depicted in Figure 1, there is evidence that invertebrate communities decrease along the depth gradient (supporting A), however, verifying how the species within these communities vary will affirm this characterization.

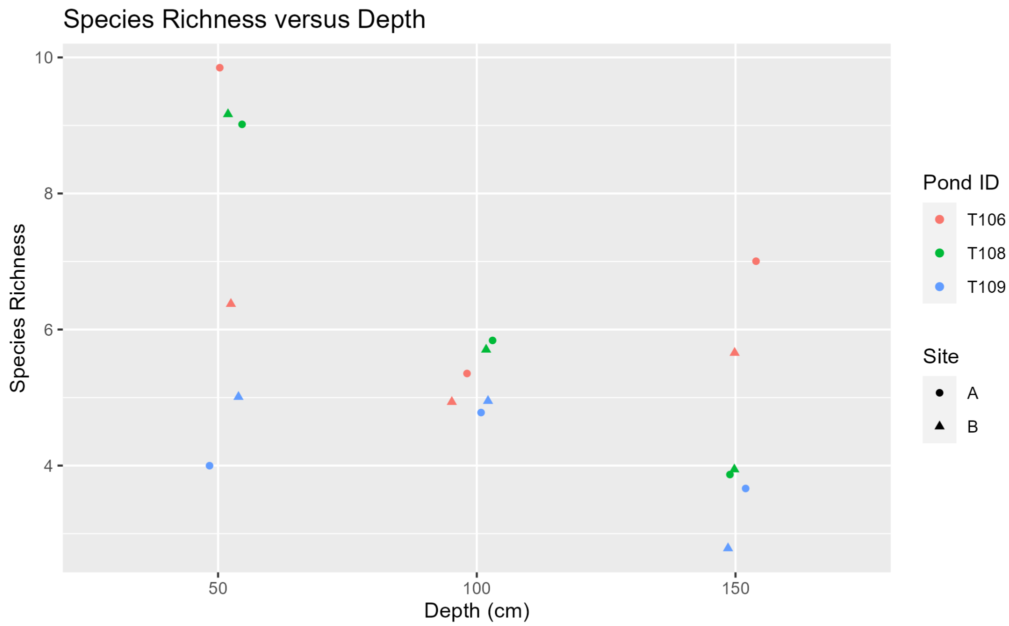


Figure 5a: Species richness plotted against Depth (centimeters). Each observation is coloured by Pond and shaped by Site. Note, that depth is not continuous but discrete (representing colony plate depths of 50cm, 100cm, and 150cm).

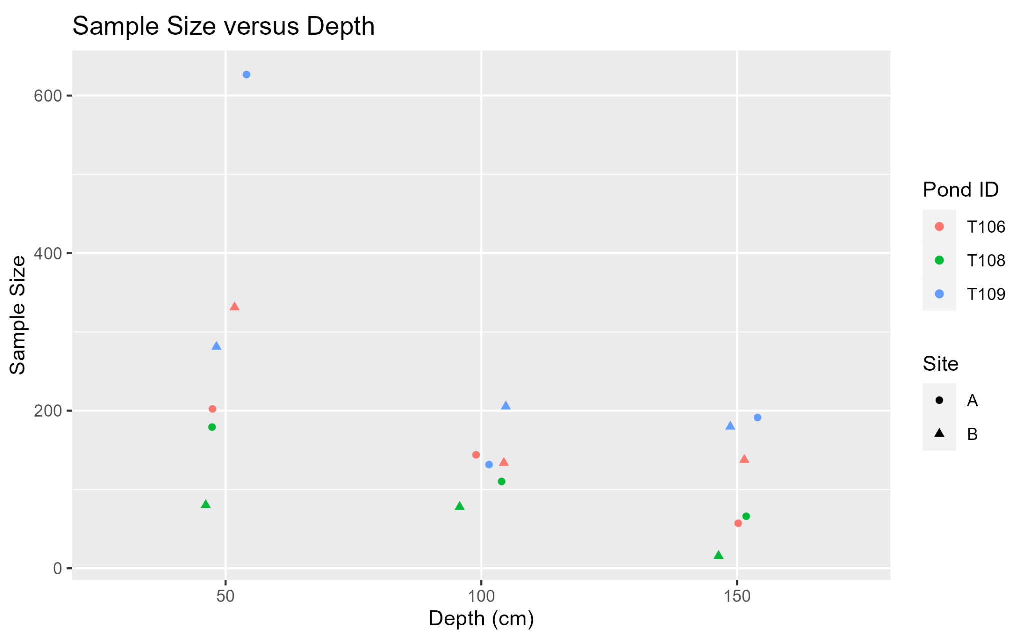


Figure 5b: Sample size plotted against depth (centimeters). Each observation is coloured by Pond and shaped by Site. Note, that depth is not continuous but discrete (representing colony plate depths of 50cm, 100cm, and 150cm).

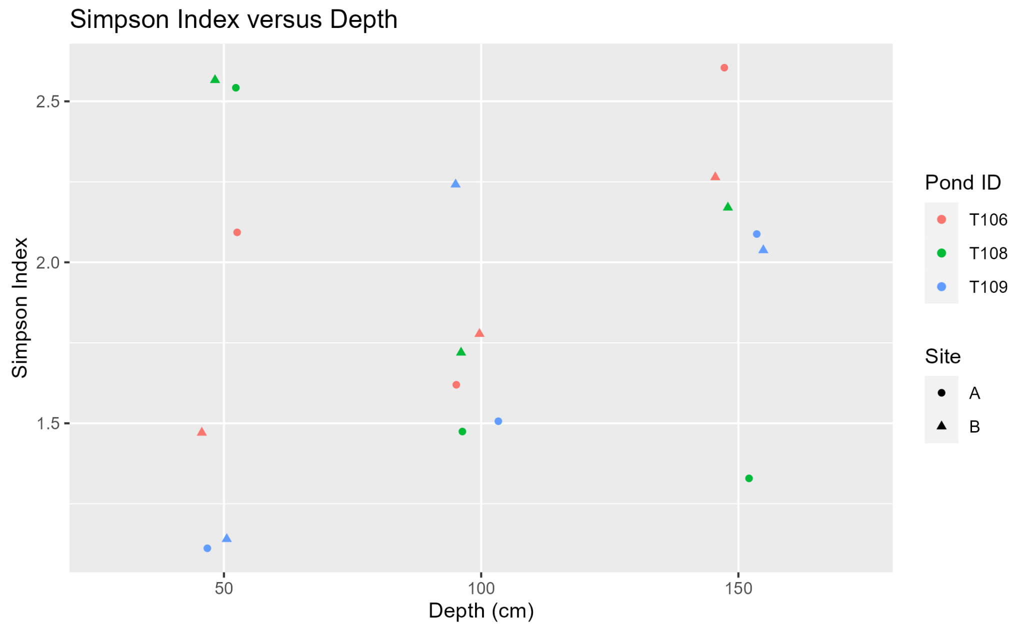


Figure 5c: Simpson Index plotted against depth (centimeters). Each observation is coloured by Pond and shaped by Site. Note, that depth is not continuous but discrete (representing colony plate depths of 50cm, 100cm, and 150cm).

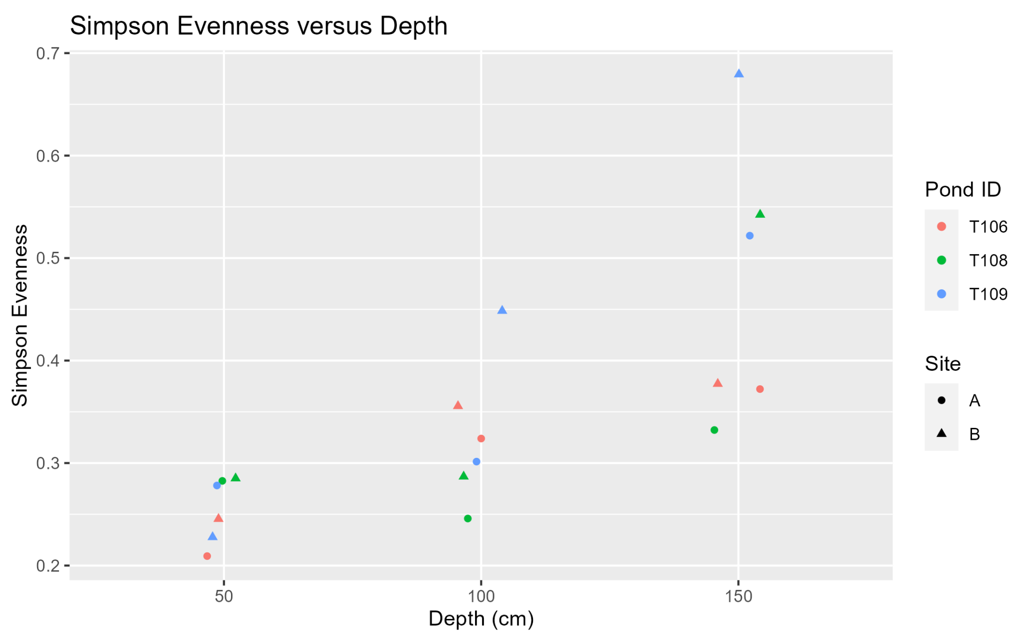


Figure 5d: Simpson evenness plotted against depth (centimeters). Each observation is coloured by Pond and shaped by Site. Note, that depth is not continuous but discrete (representing colony plate depths of 50cm, 100cm, and 150cm).

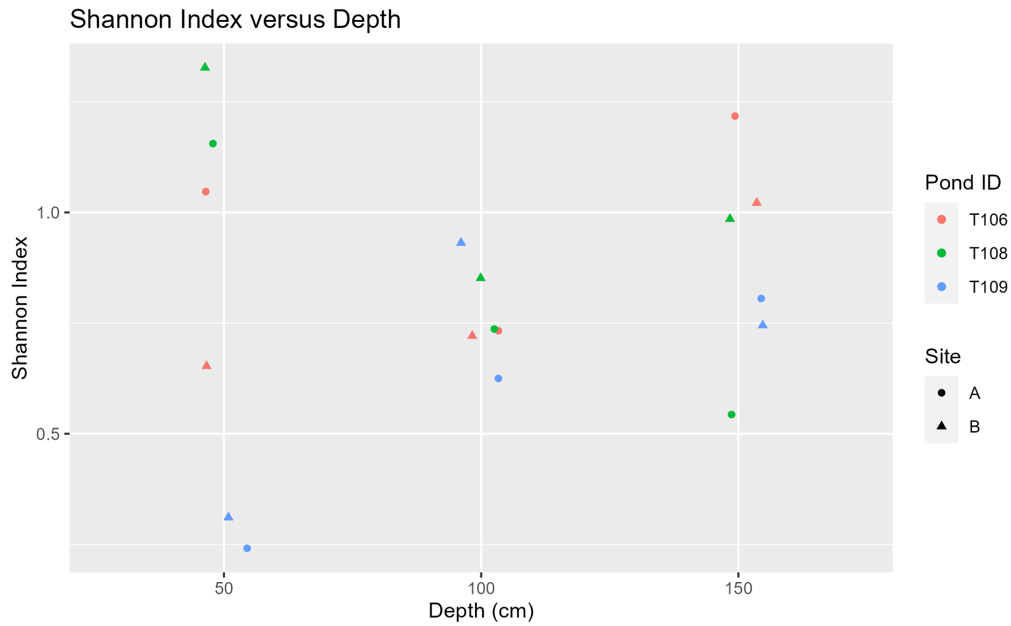


Figure 5e: Shannon Index plotted against depth (centimeters). Each observation is coloured by Pond and shaped by Site. Note, that depth is not continuous but discrete (representing colony plate depths of 50cm, 100cm, and 150cm).

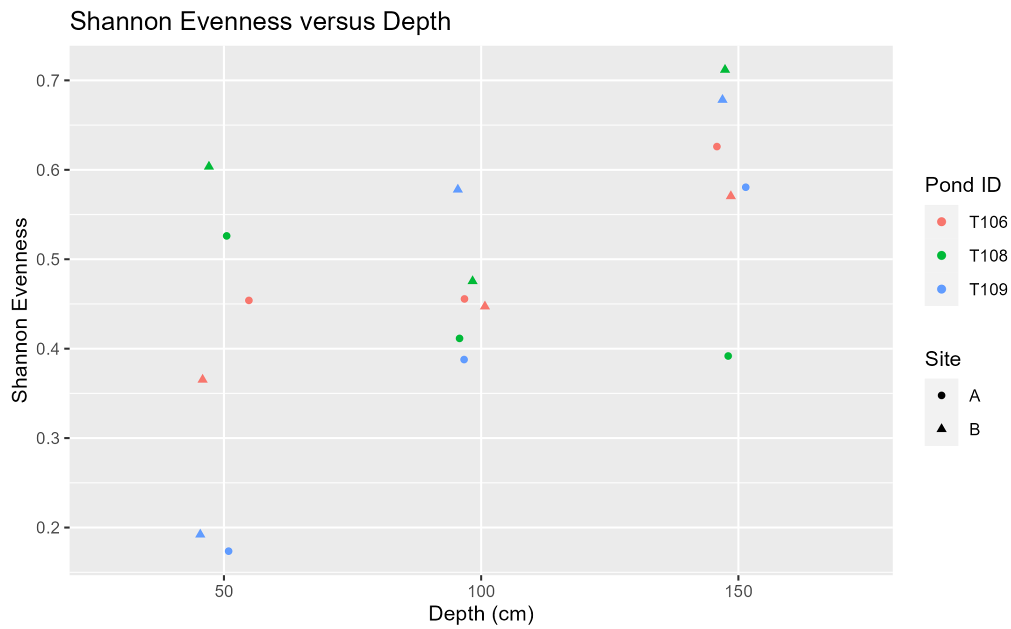


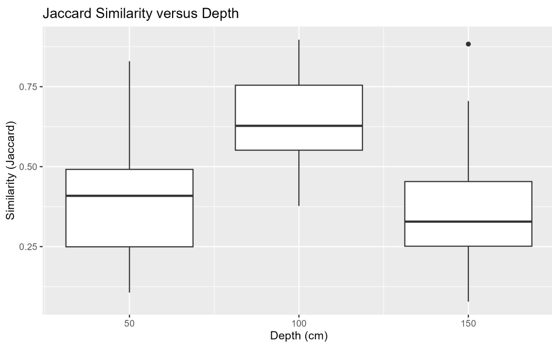
Figure 5f: Shannon evenness plotted against depth (centimeters). Each observation is coloured by Pond and shaped by Site. Note, that depth is not continuous but discrete (representing colony plate depths of 50cm, 100cm, and 150cm).

Depth	SR (Estimate)	SS (Estimate)	Simp. Even. (Estimate)	Shan. Even. (Estimate)
50	7.972	262.739	0.320	0.521
100	6.722	175.089	0.406	0.594
150	5.472	87.439	0.493	0.667

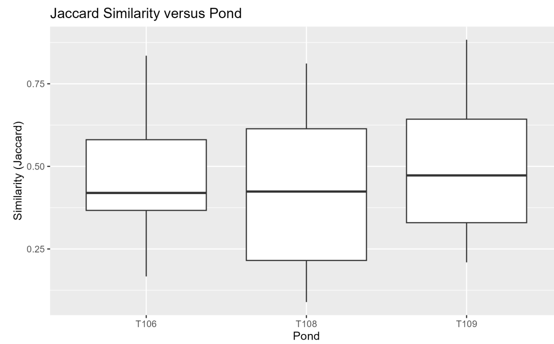
Table 2: Estimated diversity measurements derived from linear models at depths where colony plates were inserted in this study.

Depth, Water Chemistry, and Community Composition

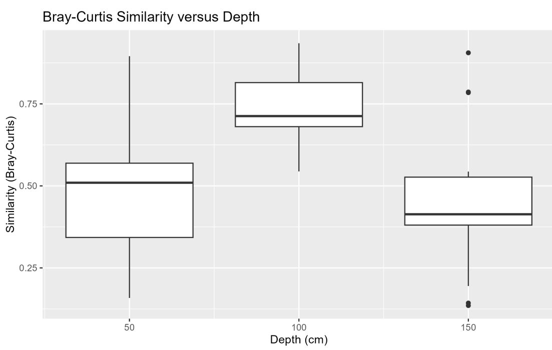
Samples were first compared using measurements of similarity to quantify variation in macroinvertebrate community composition. Notably, comparisons were done using Jaccard's Similarity and Bray-Curtis's Similarity. When comparing communities within depths, the mean Jaccard's Similarity is 0.327, 0.603, and 0.332, for depths 50cm, 100cm, and 150cm respectively. In contrast, when comparing Jaccard's Similarity within ponds, the mean Jaccard's Similarity is 0.377, 0.395, and 0.439, for ponds T106, 108, and 109 respectively. Thus, communities at 100cm depth are more similar when grouping by depth, and communities in the pond T109 are more similar when grouping by depth. However, when comparing with Bray-Curtis's Similarity, the mean Bray-Curtis's Similarity is 0.471, 0.744, and 0.464, for depths 50cm, 100cm, and 150cm respectively, and 0.531, 0.538, and 0.572, for the ponds T106, T108, and T109, respectively. Using Bray-Curtis's Similarity, the differences in similarity between the 100cm grouping and the other depths are greater in magnitude than the observed values for Jaccard's Similarity. Furthermore, the similarity is almost now uniform using the Bray-Curtis distance when comparing within ponds (roughly between 53% and 57.3%). To further analyze these relationships, dissimilarity matrices from both indices were analyzed using a Principal Coordinate Analysis (PCoA). The PCoA on Jaccard's Dissimilarity reveals that the first axis explains 62.2% of the variation and the second axis explains 12.9% of the variation (totals 75.2% of the variation). As for Bray-Curtis's Dissimilarity, the first axis explains 76.5% of the variation and the second axis explains 12.2% of the variation (totals 88.7% of the variation). These axes are plotted in Figure 8. From these plots, the ellipses for 50cm and 100cm



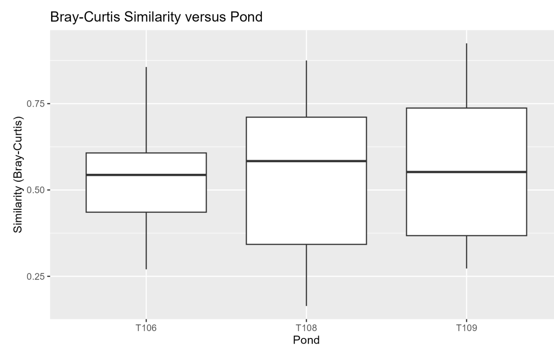
(a) Jaccard's Similarity comparing samples within the same depth.



(b) Jaccard's Similarity comparing samples within the same pond.



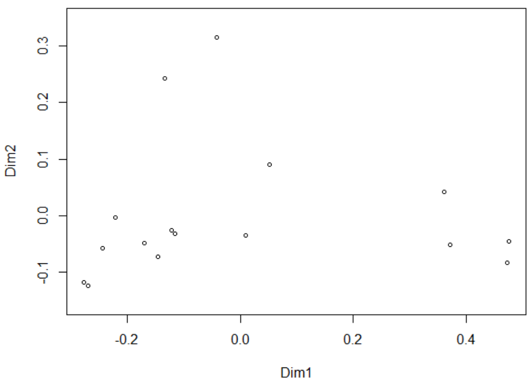
(c) Bray-Curtis's Similarity comparing samples within the same depth.



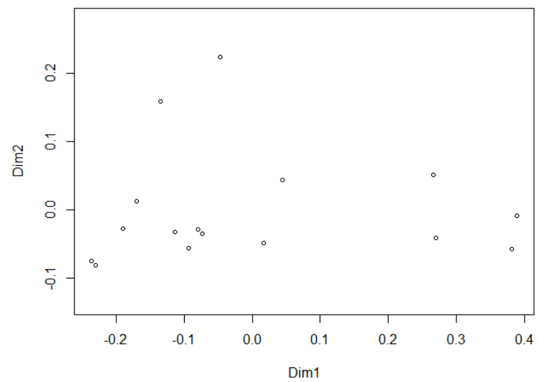
(d) Bray-Curtis's Similarity comparing samples within the same pond.

Figure 6: Similarity measurements (Jaccard's Similarity and Bray-Curtis Similarity) derived by comparing within ponds and within depths.

when grouped by depth are quite comparable, and the grouping for 150cm is largely contained with the other two ellipses. Moreover, the ellipsis for the pond T108 is contained in the ellipsis for the pond T109, with the pond T106 being quite variable across the second axis and outlying the other two ellipses. Additionally, both Jaccard's Dissimilarity and Bray-Curtis's Dissimilarity are best explained by depth, temperature, and dissolved oxygen. For Jaccard's Dissimilarity, depth had an 8.327 AIC (p-value 0.040), temperature had an 8.461 AIC (p-value 0.045), and dissolved oxygen had a 10.268 AIC (p-value 0.005), whereas with Bray-Curtis's Dissimilarity, depth had a -3.810 AIC (p-value), temperature had a -3.335 AIC (p-value), and dissolved oxygen had a -1.067 (p-value). Using linear models to explore diversity indices in terms of depth, temperature, and



(a) Ordination plots for Jaccard's Dissimilarity.



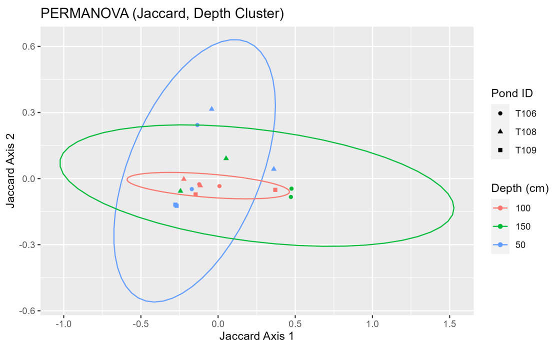
(b) Ordination plots for Bray-Curtis's Dissimilarity.

Figure 7: Ordination plots for both dissimilarity indices.

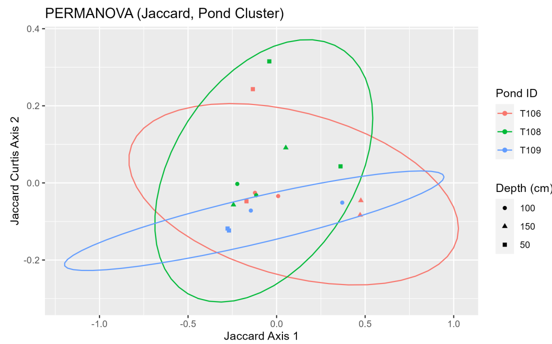
dissolved oxygen, only depth and dissolved oxygen had statistically significant effects on diversity. For Simpson's Index, there is a decrease of 0.0212 per standardized depth unit (*p*-value 1.04e-4) and a decrease of -0.754 per standardized dissolved oxygen unit (*p*-1.087e-3), as for Shannon's Index, there is a decrease of 0.0125 per standardized depth unit (*p*-value 6.97e-3) and a decrease of 0.487 per standardized dissolved oxygen unit (*p*-value 2.42e-3). The selected effects had no statistically significant difference on observed sample size, however, for species richness there was a decrease of -0.1 per standardized depth unit (*p*-value 3.01e-4) and a decrease of 2.75 per standardized dissolved oxygen unit (*p*-value 1.18e-4). Lastly, the only statistically significant effect on evenness observed was for dissolved oxygen and Shannon evenness (*p*-value 0.0115).

Discussion

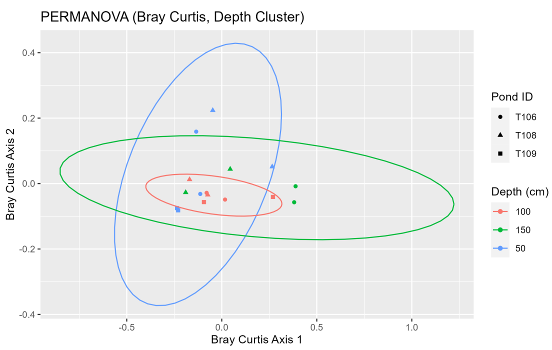
The results from this study suggest that community composition is influenced primarily by depth and dissolved oxygen, with temperature also explaining a certain portion of the observed variance. While temperature was not a statistically significant effect in our analyses of community compo-



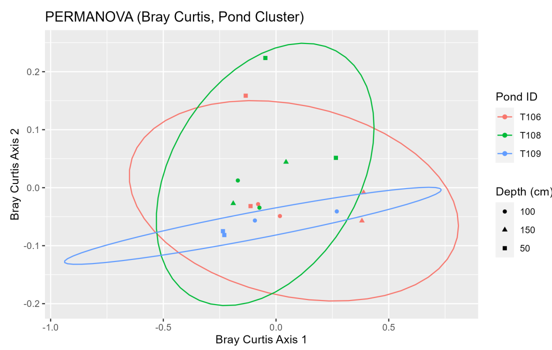
(a) PERMANOVA on Jaccard's Dissimilarity grouping by depth.



(b) PERMANOVA on Jaccard's Dissimilarity grouping by pond.



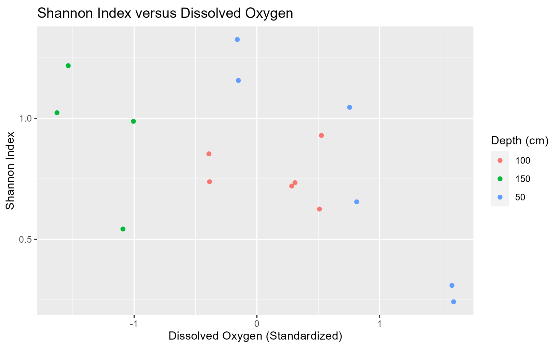
(c) PERMANOVA on Bray-Curtis's Dissimilarity grouping by depth.



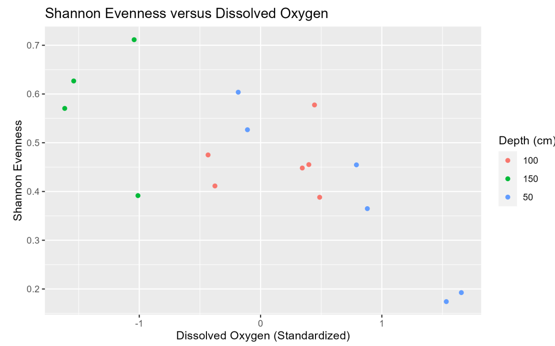
(d) PERMANOVA on Bray-Curtis's Dissimilarity grouping by pond.

Figure 8: Analyzing the Jaccard and Bray-Curtis distances for dissimilarity using the two axes that explain the most variation.

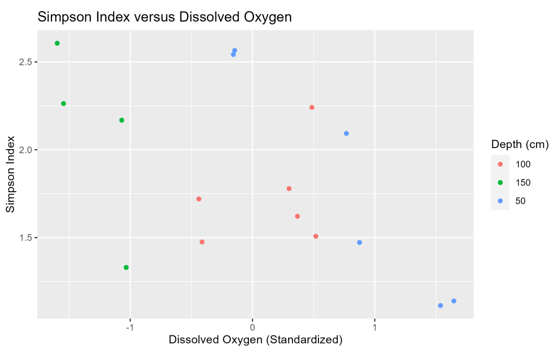
sition concerning depth and water chemistry, it was often quite close to being significant (*p*-value between 0.1 and 0.05). Moreover, both temperature and dissolved oxygen exhibited heavy stratification (see Figure 4). Croijmans, De Jong, and Prins 2021 noted that temperature and dissolved oxygen are the main drivers of macroinvertebrate biodiversity and that dissolved oxygen tended to be a better predictor for richness, which matches the observed results. Davis 1975 conducted a thorough review of the role dissolved oxygen occupies within macroinvertebrate community compositions. This review suggests that when dissolved oxygen levels are unfavorable to some taxonomic families, either tolerant species will occupy these spaces within the community and perhaps become more numerous, or, the community structure will be altered without the presence of species that are sensitive to dissolved oxygen levels (Davis 1975).



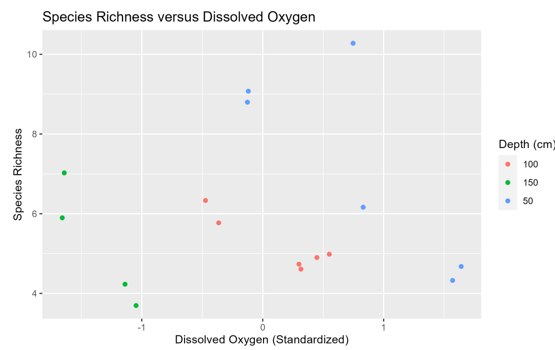
(a) Shannon Index versus standardized dissolved oxygen by depth.



(b) Shannon Evenness Index versus standardized dissolved oxygen by depth.



(c) Simpson Index versus standardized dissolved oxygen by depth.



(d) Species richness versus standardized dissolved oxygen by depth.

Figure 9: Analyzing statistically significant effects (depth and dissolved oxygen) on measurements of diversity.

Returning to hypothesis depicted in Figure 1, across all samples *Chironomidae* and *Oligochaeta* were the primary taxonomic families found, with *Ceratopogonidae*, *Coenagrionidae*, *Caenidae*, and *Hydrachnida*. Every other taxonomic family that was observed in the samples either occurred in a singular sample or consistently low quantities (across a few samples). Consequently, the primary and secondary taxonomic families delineated above are the families that largely makeup community composition in these samples. In the data, most of these families are consistently present but in lesser quantities along a depth gradient. This suggests that hypothesis A), which conjects that community composition is similar along the depth gradient with the overall biomass decreasing with depth, matches our observations.

While this study supports that stratification influences invertebrate communities in stormwater ponds, many extensions of this study could prove worthwhile. For starters, the selected measurements considered in vertical profiles are consistent with those that drive the lack of vertical mixing, however, there are other forms of depth gradients that may occur in stormwater ponds (Loewen and Jackson 2024). Moreover, while some stormwater ponds can be quite shallow, a key aspect in the analysis of invertebrate data along a depth gradient is having complete vertical profiles to explain trends with invertebrates. This can be ensured by either reducing the furthest depth of colony plates or equivalently utilizing different ponds. Notably, the former suggestion may be preferable to ensure more general predictions are derived, though this may not be quintessential as even shallow ponds may undergo intense stratification (Loewen and Jackson 2024). Moreover, many of the taxonomic families collected within this study tend to be characterized as sprawlers. These are macroinvertebrate families that are not particularly actively mobile. Exploring techniques to ensure active families that may be influencing community structure but are not collected within samples may provide a more thorough understanding of the relationship between stratification and macroinvertebrates. As stormwater ponds become more widely used across urban environments and the effects of stratification in stormwater ponds are better understood, continuing to explore how stratification shapes invertebrate communities will be quintessential for management practices.

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Code Availability

The code used for this study's analysis is available at `https://github.com/dumassam/StormwaterInverts`. Required packages are listed in the README.md file.

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