Liminal Habitats: An Investigation of Stormwater Management Facilities in Urban and Suburban Kitchener-Waterloo

by

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A thesis

presented to the University of Waterloo

in fulfilment of the

thesis requirement for the degree of

Master of Science

in

Biology

Waterloo, Ontario, Canada, 2025

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Author's Declaration:

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

Abstract
Stormwater Management Ponds (SWMPs) are a tool to protect neighbourhoods from floods and collect pollutants before they enter the natural environment. Despite these facilities being infrastructure, they inadvertently become habitat for an array of taxa, notably macroinvertebrates. My research has three primary goals: to understand the language used in municipal documents to inform how SWMPs are viewed by the municipal governments in the Kitchener-Waterloo Region; to understand the broader implications of SWMP research; and to investigate the drivers of biodiversity in SWMPs. Firstly, I confirm that SWMPs are predominantly seen as pieces of infrastructure rather than habitat by the municipalities in the Kitchener-Waterloo region. Secondly, I found that SWMPs harbour similar levels of biodiversity compared to control ponds. The majority of the literature focuses on single-taxa investigations, predominantly those of odonates and plant diversity. Thirdly, I investigated biodiversity in SWMPs in the Kitchener-Waterloo area. I investigated the attributes of the ponds and discovered that turbidity and the surrounding land cover impact biodiversity within the ponds. Additionally, I found that facility type impacts biodiversity, where engineered wetlands harboured higher diversity and evenness of macroinvertebrate communities. I compared Kitchener-Waterloo's SWMPs to other lentic systems across the province, finding that the macroinvertebrate communities in Kitchener-Waterloo's SWMPs are similar. Based on my research, I recommend implementing engineered wetlands in place of traditional wet ponds in urbanized areas. As well, I recommend municipalities incorporate biodiversity initiatives in their design manuals for SMWP infrastructure. Finally, I advocate for a re-signification of the SWMP and acknowledgement that SWMPs provide habitat in urban areas for macroinvertebrates.

Acknowledgements

This research was supported by the Government of Canada's Climate Action and Awareness Fund. My research will contribute to the overall Residential Development Impact Scorecard for the Environment RISE project. This interdisciplinary initiative aims to provide input and develop solutions for complex environmental challenges facing Canada.

I would like to thank my supervisor, Dr. Rebecca Rooney, for taking a significant risk in accepting a multidisciplinary student who wanted to focus on urban ecosystem research. I would also like to thank my two committee members, Dr. Michael Drescher and Dr. Andrew Doxey. Thank you for your feedback throughout this process. Thank you to the extended faculty members in both the Faculty of Science and the Faculty of Arts for enabling me to think critically as a communicator and ecologist. Thank you for allowing me to broaden the interdisciplinary gap that is critical to understanding the world around us better.

I want to thank my fabulous lab mates (Gab Izma, Jersey Fontz, Grace Lew-Kowal, Claire Schon, Rachel McNamee, Josh Pickering, and Andrii Kramarenko) for their uplifting support throughout this challenging process. I would also like to thank the fabulous lab technicians (Ryan Graham, Robyn Larkin, Kim Bartlett, Hannah Thibault, Indigo Sibanda, Kayla Martin, Emily Cummins, Kirsten Nikel, Megan Jordan) who helped to make this all possible. I would also like to thank the "Bat-Girlies" (Michaela Contursi, Sepidar Golestaneh, and Beatriz Nogueira E Figueira) and my former office colleagues (Cailyn Zamora, Cody Collis) for the countless amounts of coffee and kikiing over these couple years.

Additionally, I would like to extend my thanks to the City of Kitchener and the City of Waterloo. I have lived in this region for over 10 years, and the cities have allowed me to flourish

and think critically about how we find nature within our urban areas. For everything these cities have given me, I hope this research gives back to the community.

Lastly, I would like to give my thanks to my family and close friends. Thank you for truly believing in me when, at times, I did not believe in myself. Your love has transformed me into a more robust and caring researcher.

Merci à tous ✌

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List of Abbreviations

AIC – Akaike Information Criterion

ANOSIM – Analysis of Similarities

Chl-*a* – chlorophyll-*a*

DO – Dissolved Oxygen

FNU – Formazin Nephelometric Unit

H' – Shannon Diversity

J – Pielou's Evenness

NMDS – Non-metric MultiDimensional Scaling

OBBN – Ontario Benthos Biomonitoring Network

PC – Phycocyanin

RISE – Residential development Impact Scorecard for the Environment

SWMP – Stormwater Management Pond

Chapter 1: Introduction & Textual Analysis

In Canada, the rapid expansion of cities due to urbanization (Statistics Canada, 2022) has led to a reduction in the amount and quality of habitat available for various biological communities, resulting in biodiversity loss (Grimm et al., 2008). However, anthropogenic alterations to the landscape have also created habitats that are not analogous to their prior structures, forming what could be considered "novel ecosystems" (Hobbs et al., 2009). These novel ecosystems, especially in urban environments, play a crucial role in understanding the global implications of human activities on the environment. Some scholars even classify these new ecosystems as "anthropogenic biomes" or "anthromes," where land development for human use becomes a replacement ecosystem for local biological communities (Ellis & Ramankutty, 2008). The anthromes that will be the focus of my research are stormwater management ponds (SWMPs).

1.0 What is a Stormwater Management Pond?

SWMPs have some characteristics equivalent to natural wetlands and other lentic ecosystems. For instance, they both have open water with littoral zones, they both collect and settle solids from the water column, and they both can harbour an array of biological communities (e.g., Hassall & Anderson, 2015, find managed and unmanaged ponds can harbour similar levels of biodiversity). However, SWMPs are built infrastructure that humans intensively manage. Likewise, SWMPs unintentionally provide habitat for aquatic and semi-aquatic species. Not all SWMPs are designed to be the same, but they share common goals. First, they are designed and constructed to detain run-off during storm events to prevent flooding. Considerations for this style of SWMP is a wet pond design with deeper zones to contain a higher volume of runoff (Government of Ontario, 2003) Second, they are designed and

constructed to improve the water quality of urban and suburban run-off via the sedimentation of suspended particles. Included in removing excess suspended solids are categorical target thresholds for long-term sediment removal, including basic (60% of suspended solids), normal (70% of suspended solids), and enhanced (80% of suspended solids) (Government of Ontario, 2003). Therefore, a SWMP's main objective is to protect private property from flooding, not to provide habitat itself.

SWMPs primarily receive stormwater from impervious surface runoff, which is then transported via underground pipes to the pond. Management of the ponds may include riparian area management (i.e. mowing and landscaping work around the pond), routine dredging of their sediment to remove accumulated solids, and application of biocide to remove public health threats such as West Nile virus vectored by mosquitoes (Toronto and Region Conservation Authority, 2025). These management practices can alter the water quality and biotic community, disturbing the habitat for the animals currently occupying the ponds.

1.1 What is in a Stormwater Management Pond?

Based on an assessment of the biophysical characteristics of SWMPs, these ponds are not analogous to natural wetlands despite superficial similarities and the presence of some wetland species (Rooney et al., 2015). Despite the habitat differences between natural wetlands and SWMPs, the current literature investigating SWMP diversity has focused on single taxa occupying the aquatic portion of the pond and has overwhelmingly focused on macroinvertebrates (Hassall & Anderson, 2015; Hill et al., 2015; Holtmann et al., 2018) and amphibian populations (Antonin et al., 2022; Sievers et al., 2018, 2019). What we do know indicates that at least some wetland biota use SWMPs. For example, frogs and salamanders are known to occupy sedimentation ponds in Australia (Sievers et al., 2018). In France, Le Viol et al.

(2012) state that SWMPs are key habitats for amphibian populations, finding higher species richness in SWMPs beside highways compared to ponds further away from highways. Holtmann et al. (2018) suggest that SWMPs promote higher levels of biodiversity in German cities, finding that habitat heterogeneity in SWMPs can promote dragonfly and damselfly richness. In Canada, Perron and Pick (2020) found that plant richness in SWMPs is higher due to the presence of increased non-native plant species compared to less densely populated, less invaded rural ponds. They find that a higher richness of wetland plant species supported an abundance of dragonfly and damselfly adults and recommend planting native to support odonates in SWMPs.

Although SWMPs provide valuable habitat for wetland species in urban areas, several concerns exist regarding their habitat. Pollutants such as excess nutrients from fertilizer runoff can contribute to the eutrophication of ponds, resulting in toxic algal blooms (Glibert et al., 2001). Increased road salt application can increase chloride concentrations, making SWMPs less favourable to salt-sensitive species (Gallagher et al., 2011). Due to factors not limited to pond surface area, conductivity, pH, and others, the combination of physical pond characteristics and water quality may result may be dominated by more pollution-tolerant taxa (Meland et al., 2020). While noting that SWMPs hold considerable species richness for amphibians, Sievers et al. (2018) insist that SWMPs may become “ecological traps” (sensu Robertson & Hutto, 2006) where SWMPs may cue suitable habitat but do not offer stable environmental conditions (Schlaepfer et al., 2002). This concern is also evident at the molecular level, where road pollutants that accumulate in SWMPs can cause DNA damage in pollution-sensitive taxa, such as dragonfly and damselfly nymphs (Meland et al., 2019).

Moreover, SWMPs may be sources of invasive species, such as feral Goldfish (McIsaac, 2022) or Starry Stonewort (Harrow-Lyle & Kirkwood, 2021) to name a few. Birch et al. (2022)

describes the expansion of stormwater pond creation, finding that cities across Southwestern Ontario rapidly replace extensive natural wetlands with smaller stormwater management facilities. Thus, an altered landscape resulting from suburban expansion and continued development may impact biodiversity in urban areas, as SWMPs displace natural wetland habitats (Gagné & Fahrig, 2007; McKinney, 2002; Paul & Meyer, 2001). SWMPs are not suitable compensation for natural wetlands that are destroyed, but they may provide some habitat as an anthrome in urban areas that are otherwise inhospitable to wetland biota.

1.2 How are these Anthromes Maintained in Ontario?

In Canada, SWMP regulations originate from Provincial Governments; for our geography, the Province of Ontario administers engineering targets and design criteria for developers when building stormwater infrastructure. When a developer creates a suburban or urban development, they are required by legislation, specifically the *Ontario Water Resources Act* (Ontario Water Resources Act, 1990), to offset rainwater run-off. Engineering targets that developers are required to design for focus on protecting natural resources and heritage features from the negative impacts of stormwater run-off generated by these developments. The targets include specific criteria, such as protecting groundwater, preserving the flow of water in the landscape, safeguarding private property from flooding, and preserving downstream habitats for aquatic life (Ontario Ministry of Environment, 2003). As a result, SWMPs intercept road salt (Castillo et al., 2018), heavy metals (Huber & Helmreich, 2016), gasoline and oil products (Mijangos et al., 2010) and pesticides (Izma et al., 2024) from urban developments that would otherwise move into downstream aquatic environments.



Figure 1: Image of rainbow film being released as sediment is disrupted from an autumn sampling event. While this type of film can be produced by iron-oxidizing bacteria, the pond's catchment area includes a large parking lot for a major shopping centre, which features a gas station, an automotive service centre, and is adjacent to a highway. Additionally, we noted leaking from a highly rusted waste container with rust stains running in the direction of the pond. The smell emanating from the sediment was particularly noxious, with a scent reminiscent of gasoline and decaying matter.

Although SWMPs are inhabited by wetland species, they are technically considered infrastructure and designed to receive rain runoff, which is designated as "sewage" under the *Ontario Water Resources Act*. Therefore, the language in the act can create a management conflict of competing priorities. An exemplary case study is the recent relocation of endangered mollusks in the City of Hamilton. Delsey Pond, a former natural wetland complex converted into a SWMP in 2005 after an environmental assessment by the City of Hamilton, identified issues related to erosion and flood potential that could damage nearby private property (Stephen & Skrypniak, 2003). Geographically, this pond is close to the western inlet of Lake Ontario. Following Hamilton's stormwater pond management guidelines(City of Hamilton, 2007), the Delsey Pond was being dredged to remove accumulated sediment and restore the SWMP's

floodwater storage capacity. However, a provincially listed species-at-risk mussel, the Lilliput Mussel (Government of Ontario, 2023) was detected in the Delsey Pond. In 2021, Ontario's Ministry of Environment charged the City of Hamilton and its contractors for disturbing Lilliput habitat by dredging the Delsey Pond SWMP (Campbell, 2021), which interfered with the City's ability to maintain the SWMP as infrastructure. While not all SWMPs are home to species at risk, the Delsey Pond case study illustrates the tension between the role SWMPs occupy as infrastructure and their role as habitat for wetland species in urban environments.

As regulated under the *Ontario Water Resources Act* (Ontario Water Resources Act, 1990), the implementation of SWMPs is a matter of public-private partnership between municipalities and landowners who then develop the land, where the Province, in conjunction with engineering standards, does not limit the developer in the application of baseline implementations. In this guidance document, the Province intends for municipalities to design their own stormwater management manuals, expressing that municipalities can innovate on new solutions tailored to their regions, suggesting that at the local level, there is the flexibility to design SWMPs in new neighbourhood developments that could enhance habitat for wetland biota in urban landscapes within SWMPs themselves.

2.0 Quantitative Text Analysis of Stormwater Management Master Plan Documents

2.1 Why I am Including a Text Analysis in a MSc Thesis

Interdisciplinary research is critical to understanding the world around us. Prior to my current research in the Department of Biology, I was a member of the Department of English at the University of Waterloo. Before that, I was an undergraduate student in the Faculty of Science. I have accrued a broad set of skills that provide me with insights that many scientists

might not initially gravitate toward. However, as scientists, we can become more interdisciplinary and broaden the tools we use when we initially analyze a problem. Stormwater management is political and understanding how stormwater management is understood textually can help distinguish how municipalities view these infrastructure assets. In this text analysis, I will identify how three cities in the Kitchener-Waterloo Region communicate their SWMP policies. Through this text analysis, I will present how the language in these documents communicates to the public how stormwater management is implemented. As well, the text analysis will shape how I frame my hypotheses in Chapters 2 & 3.

2.2 Introduction to Text Analysis

Text analysis incorporates a broad set of tools that use textual data (e.g. documents, webpages, speech, etc.) and perform various qualitative and quantitative analyses (Bernard & Ryan, 1998). The aims of text analysis can range based on the analysis being performed. Often, text analysis is performed in the humanities and social sciences (O'Connor et al., 2011). In ecology, text analysis is underutilized. Due to the large amount of textual data available through publications, policy documents, and more, text analysis can be a powerful tool to understand relationships across research. Importantly, text analysis is not a replacement for literature reviews and meta-analyses; text analysis can be a complementary tool for an ecologist.

2.3 Background on Stormwater Management Policy in Ontario

Our language connects us to the landscape in various ways. Like water, the variety of paths for language to flow is paramount to our understanding of the world around us. Complex systems like watersheds and their connecting flows are essential to the overall landscape. Water, therefore, is a constant presence that influences our connection within our urban environment.

Globally, wetland landscapes and ecosystems have been reduced by 64% with growing pressures to support human needs (Davidson, 2014). By 2030, it is estimated that over 60% of the world's population will live in urban environments (United Nations, 2016). In an urban landscape, stormwater management tools such as SWMPs act as artificial bodies of water, slowing the flow of overland run-off, preventing flooding, and allowing pollutants to settle before flowing into creeks, rivers, and lakes (Government of Ontario, 2003). The importance of management, design, and investment in stormwater infrastructure lies in mitigating property damage for urban communities in flood-prone areas.

In the aftermath of Hurricane Hazel in 1954, the provincial government amended the Conservation Authorities Act of 1946 to give conservation authorities powers to mitigate future flooding events (Conservation Authorities Act, 1990). Adjusted for inflation, the damages accrued from Hurricane Hazel cost over $1 billion (Environment and Climate Change Canada, 2023). In conjunction with conservation authorities, municipalities SWMPs to prevent watershed degradation and control flooding during severe rain events. The Ministry of Environment describes the goals of the official stormwater management planning and design manual as requiring municipalities to mitigate the consequences of urbanization, citing the major goals of stormwater management policy to lessen the impact of flooding and loss of property (Government of Ontario, 2003). As it relates to environmental initiatives such as the ecological health of urban streams and ponds, the document also mentions goals related to habitat quality of downstream waters, stating, “The goal of stormwater management is to protect the aquatic ecosystem, as well as the stream’s aesthetic and recreational values, by maintaining a stable fluvial systems” (Government of Ontario, 2003). Similarly, the Ministry document identifies the potential power of SWMPs in enhancing habitat in urban areas, under section 4.6 titled *End-of-*

Pipe Stormwater Management Facilities, subsection 4.6.1 states to maximize diversity and, "enhance biodiversity on a watershed-wide scale, but also contribute to the system's resiliency and ability to maintain itself," (Government of Ontario, 2003). The document includes subheadings for developers to use when designing their pond systems, such as the recommendations to include planting local vegetation, to design corridors between aquatic and terrestrial habitats, as well as additional design augmentations for ecological functions. The updated measures are detailed as a "tool for understanding the performance requirements of stormwater management projects," and encourage developers to use "innovation" in their SWMP design (Government of Ontario, 2003).

The ways we communicate about SWMPs can impact the implementation of flood mitigation and ecosystem protection; however, the way we identify SWMPs as infrastructure or habitat dictates the way we situate ourselves in our built landscape. SWMPs are ontologically tangled objects caught between predefined ideologies. Are SWMPs identified as critical habitat and critical infrastructure? Are they only seen as facilities for runoff capture? I explore the three Stormwater Management Master Plans from the three major cities in the Region of Waterloo: Kitchener (City of Kitchener, 2016), Waterloo (City of Waterloo, 2019), and Cambridge (City of Cambridge, 2011). I examined how the documents discuss property protection and habitat protection. While there are hundreds of municipalities, as well as regions and counties in the Province of Ontario, this analysis focuses on the cities in the Region of Waterloo. I contained my analysis Kitchener, Waterloo, and Cambridge as the Region of Waterloo is where I researched SWMPs. As there are many municipalities who may take different approaches, my choice to focus on these cities aid in understanding how the SWMPs I researched in Chapter 3 are discussed at the municipal level.

2.4 Methods

The focus of this text analysis are the cities in the Region of Waterloo, which include Kitchener, Waterloo, and Cambridge. Stormwater management master plan documents were collected from municipal websites that featured dedicated stormwater management web pages. After collecting the PDFs of master plans, I first cleaned the PDF documents to remove title pages, images, figures, and appendices. These portions of the document are removed due to their repetitive bigrams that may skew the corpus. Next, I formatted PDFs into text files to create a corpus. A corpus is a collection of all the words within the document which will be analyzed.

I analyzed the corpus using R (R Core Team, 2021) in R Studio (Posit team, 2025) with the text-analysis package *quanteda* (Benoit et al., 2018). *quanteda* utilizes natural language processing, where words are transformed into tokenized vectors that can then be tested statistically. I further cleaned the corpus by removing punctuation, numbers, and converting all tokens to lowercase; however, I did not remove initialisms (e.g., SWM), as these initialisms provide context within the document.

After cleaning the corpus, I created a document feature matrix that structures the tokens into a numerical value, allowing for various data transformations. This includes stemming words (example: “biolog” from “biology” or “biological”), and the count of n-grams (example: “Stormwater” AND “Pond”). I conducted a co-occurrence analysis on two tokens: “habitat” and “property” to identify thematic context and semantic relationships within the corpus. Co-occurrence identifies a word in a string that occurs more often than would be expected by chance. I ranked these tokens based on their frequency and the strength of occurrence across the documents to form a regional approach.

2.5 Results

The primary documents were created for the cities through consultation with two companies: Aquafor Beech Ltd. (City of Kitchener & City of Waterloo) and AMEC Earth and Environmental (City of Cambridge). Kitchener and Waterloo's documents were published more recently, in 2016 and 2019; Cambridge's plan was published in 2011. Each document contains recommendations for the cities to implement in their stormwater management goals. All documents primarily focus on the protection of private property. The documents lay out primary goals the cities are aiming for as it relates to stormwater management. For the City of Kitchener, the main goals of its document include integrated approaches with other urban goals, such as stormwater integration in parks, connecting ponds with its transit and cycling master plans, erosion mitigation, and natural heritage protection (including protection of the Grand River). The City of Waterloo takes a similar approach, stating its goals as preventing municipal flooding, mitigating the warming of natural creeks, and addressing the health impacts on humans and animals. Unlike Kitchener, Waterloo does not broadly approach stormwater management from a comprehensive scope, mainly focusing on market-based approaches for private properties to "beautify" their stormwater management, improving conveyance controls on major roadways, and creating new catchment areas that can support larger park infrastructures. The City of Cambridge primarily focuses on infrastructure goals, including maintaining aging assets, creating a database of assets, and financing maintenance of current and future assets. All documents imply the need for long-term management of stormwater assets and should be prioritized as guiding principles for cities. Kitchener, for example, details how their stormwater management master plan document will guide its stormwater management into 2030. Similarly, Waterloo's

master plan aims to accomplish its stormwater management goals by 2033. Cambridge does not have a set timeline to accomplish its stormwater management goals.

A majority of the corpora emphasize the importance of stormwater management, with the bi-gram “Stormwater” and “Management” being the highest-ranked n-gram, occurring 567 times across the documents. Significant themes that appear in the corpus include a predominant focus on climate change and adaptation. The most common stormwater feature mentioned in the corpus is wet ponds, which are highly ranked within the document, whereas constructed wetlands occur less frequently and with a lower rank.

Table 1: Examples of frequency analysis using bigram counts. Ranking is subject to the total occurrence of the bigram across the total corpus.

Token 1	Token 2	Occurrence	Rank in Corpus
Stormwater	Management	567	1
Climate	Change	99	18
Wet	Pond	79	24
Private	Property	66	32
Stormwater	Infrastructure	62	35
Natural	Heritage	29	125
Heritage	Landscape	20	214
Pond	Quality	20	218
Constructed	Wetland	19	228
Rehabilitation	SWM	19	234
Aquatic	Habitat	18	242
Ecological	Restoration	14	339
Habitat	Conditions	13	396
Terrestrial	Habitat	12	480

The co-occurrence of the tokens “habitat” and “property” revealed differing relationships to stormwater, where stormwater was more closely associated with property than with habitat. “Property” was often associated with words such as “business”, “owners”, “residential”, and “value” (Figure 2). This signals the semantic relationships between private property and the municipalities’ stormwater management focus, specifically their role in protecting these. Shifting to “habitat”, words associated include “water”, “quality”, “erosion”, “connectivity”, signals the key issues the master plan documents in the protection of downstream environments (Figure 3). However, the token relationship does not suggest a thematic context of SWMPs being considered as habitat, but rather the further emphasis they are seen as infrastructure.

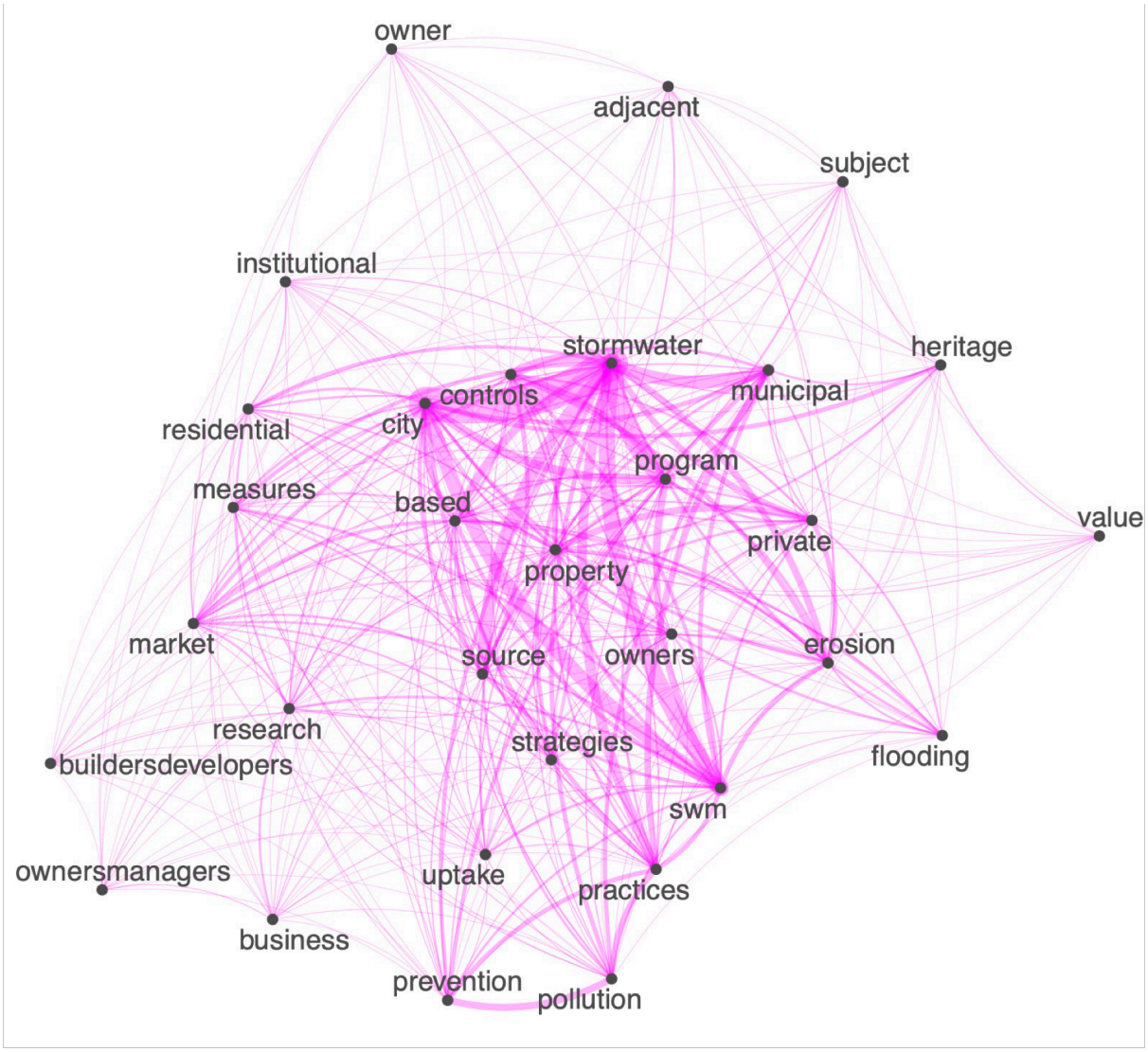


Figure 1: Feature Co-occurence Matrix (FCM) of the token "Property"

Figure 2: Feature collocation networks of token "property "generated from Stormwater Masterplans corpus using the quanteda *package in R. Nodes represent terms in the corpus, and edges represent co-occurrence relationships between terms calculated using a lambda value. The thickness of each edge corresponds to the frequency of collocation within the specified context window, where larger lambda values display increased thickness.*

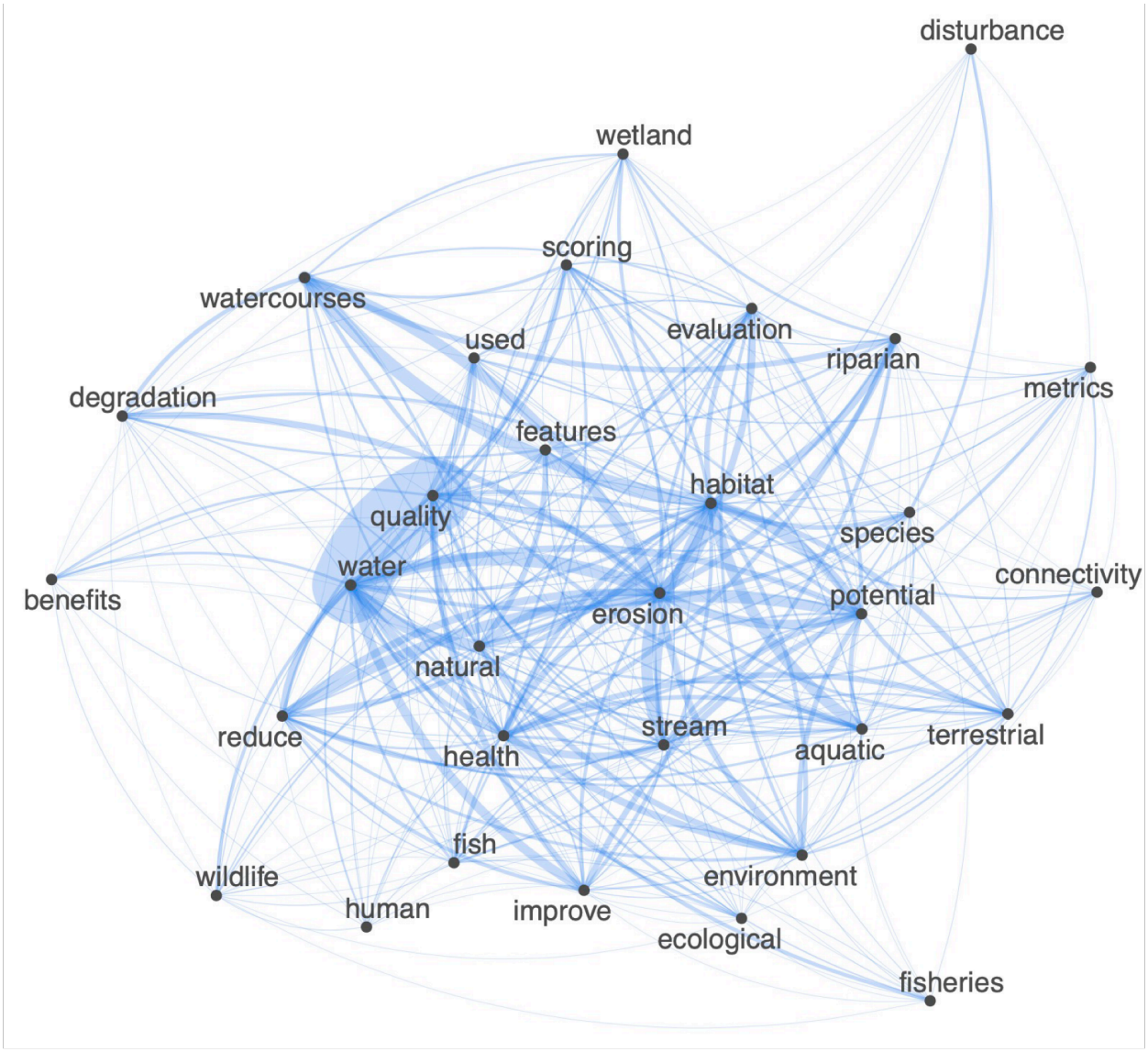


Figure 2: Feature Co-occurence Matrix (FCM) of the token "habitat"

Figure 3: Feature collocation networks of token "habitat" generated from Stormwater Masterplans corpus using the quanteda package in R. Nodes represent terms in the corpus, and edges represent co-occurrence relationships between terms calculated using a lambda value. The thickness of each edge corresponds to the frequency of collocation within the specified context window, where larger lambda values display increased thickness.

Unsurprisingly, the planning documents focus more on property than habitat. Total occurrences of bi-grams including "property" occur more frequently and are higher ranked (mean rank = 4365.5) than bigrams containing habitat (mean rank = 5930.5), with a ranked distance of 1565. Within each of the documents, Kitchener mentions the token "habitat" 30

times; Waterloo and Cambridge mention the token 102 times and 3 times, respectively. Waterloo is the only city to mention habitat more times than the token "property," where it appears 100 times in the document; Kitchener and Cambridge mention the token 88 times and 31 times, respectively.

2.6 Discussion

The municipal documents themselves reflect some interest in correcting infrastructure opportunities for future redevelopment of stormwater assets, such as pond and urban stream restoration. For instance, the municipal documents acknowledge the challenges of urban development, stating that it leads to a "loss of fish and wildlife habitat, and natural features." The documents display an acknowledgement of natural systems being considered as beneficial pieces of green infrastructure. Still, the text provided in the municipal manuals adheres closely to the minimum criteria for pond design dictated by the Province. Most importantly, the documents are formatted as a set of themes regarding the creation of ponds as a form of infrastructure, interpreted as a minimum standard. This approach, where municipalities follow minimum design standards, may homogenize SWMP design across Kitchener, Waterloo, and Cambridge.

Additionally, the documents themselves identify the challenges which come with stormwater management development in urban areas. Included in the implementation of stormwater conveyance are terrestrial subwatershed health metric (Bryan & Henshaw, 2002) that classify surrounding land areas using guidelines provided by Environment and Climate Change Canada (ECCC, a Federal Agency); it is noted in the guide that meeting the required minimums may not be possible in the contexts of stormwater infrastructure in urban areas as the habitat metrics such as natural cover (i.e. the total cover of wetlands, riparian area, wood lots, forest

cover) may not even be present in highly urbanized areas. For example, Kitchener's recommendations include the assessments of heritage features including terrestrial habitats and creeks as natural. This language implemented by the City of Kitchener further segregates a SWMP away from natural heritage features that provides habitat for wetland species in urban landscapes and does not acknowledge SWMP assets or include them in a broader integrated urban habitat.

One instance in the Master Plan document for the reimagining of SWMPs is written in the City of Waterloo's document, "[The City of Waterloo] is encouraged to look within and beyond their urban and geographical boundaries to neighbouring lands and consider how increasing landscape connectivity and representation of a diversity of ecological communities can provide an overall benefit for the ecology of the City of Waterloo," (City of Waterloo, 2019) However, the City of Waterloo's approach to focus on persuading private property owners to take on stormwater management can create a fractured system of conveyance and ecological measures. For instance, Waterloo emphasizes the priority of property owners to implement biorientation features (e.g. rain gardens and bioswales), tree planting, and other low impact developments (LID) that may provide dual benefits of flood mitigation and habitat creation for animals in their suburban areas. Despite the push for private adoption of these strategies, implementation by property owners is a considerable challenge. For example, adoption of LIDs by property owners in Maryland only accounted for 2.5% of households (Newburn et al., 2014); the authors also report that the increased cost of implementing LIDs discouraged owners from adding additional stormwater measures to their property. This is supported by research at the University of Waterloo where cost was associated with the decreased implementation of LID by property owners (Smith et al., 2019). Following market-based approaches, the cities do include

tax credit incentives by including a stormwater fee reduction. While the Province provides municipalities with the opportunity to introduce innovations into their stormwater planning documents, the text analysis reflects the municipalities' intention to implement the minimum guidelines for stormwater management outlined in the *Ontario Water Resources Act*.

Despite the open-ended nature of innovation included in the manual, the documents clearly describe the ponds as infrastructure. One example of this is the formation of naming these assets, for instance, “engineered wetlands” and “constructed wetlands,” which imply that despite the design being a wetland, they are altered anthropogenically and can be considered a *simulacra* of a natural pond itself (sensu Baudrillard, 1981). However, the design manuals are documents intended to display the minimum requirements for stormwater pond systems; they disseminate the criteria across all jurisdictions in the Province to establish a common design methodology. Due to differing landscapes and ecologies, for municipalities to “innovate” their stormwater management systems means adapting to their local watershed, local geography, and local ecology. As the municipal documents themselves does not include best design practices for geological morphologies and specified habitats for aquatic and riparian areas around the pond, the implementation of any innovations will require updated manuals. Bradford & Gharabaghi, in their analysis of Ontario’s SWPD manual, likens the document to a cookbook, stating that “the manual’s lack of specificity leads to ‘cookie-cutter designs,’” where the development of these ponds favours homogeneous design and lacks integration into the watershed and local communities (Bradford & Gharabaghi, 2004). As stormwater is legislated at the provincial level and implemented by municipalities, Ontario’s SWMP manual serves as the minimum standard for all municipalities, regardless of their geographic location.

Figures of speech are contained in this document, such as prescribing a reduction of "car habitat". "Habitat", in the context of ecological discourse, is a collection of the biotic and abiotic factors that support the life of an organism. Habitat, in the context of stormwater management in Ontario, is a metonymy of a metonymy. For instance, the Provincial document cites the reduction of "car habitat" to improve stormwater quality, as runoff from roads and highways facilitates the transfer of pollution into the ponds (Bradford & Gharabaghi, 2004). While disregarding the original meaning of habitat, the document identifies that if X habitat is reduced, there will be a reduction in Y variable. Reduce car habitat and reduce pollution; reduce aquatic habitat and reduce biodiversity.

2.7 Text Analysis Conclusions

Stormwater management documents from the cities in the Region of Waterloo dictate their context as pieces of infrastructure rather than identifying the facilities themselves as critical habitat within an urban space. Despite adhering to the minimum guidelines set by the province of Ontario, municipalities should consider innovating their stormwater pond designs and updating their stormwater masterplan documents. While innovation may present itself as a hollow and vague rhetoric, implementing clear biodiversity initiatives into municipal stormwater master plans and design documents is twofold. Firstly, implementing biodiversity guidelines into municipal SWMP design manuals can enable municipalities to transform (or, better yet, reimagine) their infrastructure assets into habitats themselves. Like other biodiversity programs in the region, such as Kitchener's Community Canopy Project (City of Kitchener, 2025) and the region's "Bee Region" program (Region of Waterloo, 2022), extending habitat restoration projects from the terrestrial to the aquatic environment fills a critical gap to promote biodiversity

in the cities. Secondly, the implementation of biodiversity initiatives for SWMPs in the region adds co-benefits to naturalization projects of the creek system. For example, naturalization of Schnider's Creek and Shoemaker Creek (City of Kitchener, 2023) will restore flow, improved water quality, and new habitat after many years of concrete channelling. By focusing on creating biodiversity initiatives in SWMPs, the cities in the Region of Waterloo integrate SWMPs into a more naturalized infrastructure system that also provides ecosystem services.

3.0 Thesis Objectives

Specifically, I am interested in how the neighbourhood's design surrounding SWMPs impacts the biodiversity of species occupying SWMPs. In other words, does land cover surrounding stormwater management facilities influence the biological diversity of organisms living in SWMPs? Can neighbourhoods be designed to enhance SWMP biodiversity, or are the critical factors outside the influence of individual developers, either on too broad a scale or due to engineering regulations?

In Chapter 2, I conducted a meta-analysis reviewing the scientific literature to investigate the drivers of biodiversity in SWMPs. I also establish which factors have been the focus of SWMP biodiversity studies (e.g., pond surface area, road density, impervious cover, etc.). Further, I display how biodiversity has been quantified in the studies and identify the taxa have been the focus of SWMP research (e.g., anurans, odonates). I also compare biodiversity in SWMPs to the various response variables the papers use to explain biodiversity trends in SWMPS. I hypothesized that SWMPs support lower diversity. Overall, I found SWMPs and comparison ponds harbour similar levels of biodiversity. The potential predictors of biodiversity investigated by authors of the reviewed studies were of inconsistent influence, leading to no clear driver of biodiversity in SWMPs.

In Chapter 3, I examine the determinants of biodiversity in two types of SWMPs: wet ponds and engineered wetlands. The definitions of engineered wetland and constructed wetland are used interchangeably across Waterloo and Kitchener. Going forward, I will be using "engineered wetland". I predicted that engineered wetlands will have higher biodiversity than wet ponds. I also predicted that SWMPs in Kitchener-Waterloo would have different community composition when compared to other wetlands and ponds in the province. In October of 2024, I collected benthic macroinvertebrate samples in both wet ponds and engineered wetlands and identified taxa. I followed the Ontario Benthic Biomonitoring Network (OBBN) protocol for wetlands to collect my samples. I also measured water quality including temperature, dissolved oxygen, conductivity, pH, phycocyanin concentration (PC), chlorophyll-*a* concentration (Chl-*a*), and turbidity to determine if these variables influenced biodiversity in SWMPs. Additionally, I used OBBN to investigate whether the widely-used manual for predicting water quality in streams and lakes can serve as a representative tool for use in novel ecosystems such as SWMPs. Firstly, I examined the biodiversity index values used in OBBN methods for various attributes of stormwater facilities. I found that facilities predominantly surrounded by natural land cover harboured higher taxa richness than ponds surrounded by suburbs and commercial land cover. Additionally, I found turbidity had a significant effect on richness, but due to multicollinearity I found the result spurious. Secondly, I found that engineered wetlands harboured higher Shannon-Weiner diversity and higher Pielou's Evenness when compared to wet ponds, indicating pond design can impact biodiversity in urban areas. Lastly, I compared the ponds sampled in Kitchener-Waterloo to other small lentic systems in the province to identify any differences in community composition and found the communities to be similar.

Chapter 2: Pondering Ponds – Unpacking Urban Biodiversity Through a Meta-Analysis of Stormwater Systems

1.0 Introduction

Land-use is a primary drivers of biodiversity loss worldwide (Díaz et al., 2019). When land use is altered for human activity, the resulting loss of natural land cover and decrease in habitat quality threaten the biota that inhabit the area (McKercher et al., 2024). Aquatic ecosystems, such as wetlands, are significantly impacted by urban development, creating challenges to support urban aquatic biodiversity. When a residential or commercial development is constructed, builders must include stormwater management features to collect runoff from impervious surfaces, mitigate flood risk, remove pollutants before they enter the downstream aquatic environment, and reduce downstream erosion. Building suburbs and expanding road infrastructure that connects to other suburban areas require stormwater management ponds (SWMPs). Unintentionally, SWMPs present themselves as habitat for many types of amphibians, birds, and insects; in urban areas they become novel ecosystems. These stormwater management features are implemented in accordance with the engineering guidelines established by the local or regional governing bodies.

In Ontario, wetlands are rapidly replaced by developments that often necessitate the construction of SWMPs; these ponds are typically smaller than the wetlands that characterized the pre-development landscape (Birch et al., 2022). Suburban residents living near SWMPs appreciate the visual appeal of these ponds, despite some studies indicating that they may support lower biodiversity compared to natural wetlands (Rooney et al., 2015). Internationally, SWMPs are implemented across many developed regions, including Canada (Marsalek & Schreier, 2009), the United States (Council et al., 2009), Australia (Roy et al., 2008), and across

Europe (Backhaus & Fryd, 2013). For example, in France, the highway infrastructure regulation *European Union directive 91/271/CEE, French law 92/3* requires developers to install SWMPs along all highways to catch runoff and detain pollutants from the road before entering the environment (Council Directive 91/271/EEC of 21 May 1991 Concerning Urban Waste-Water Treatment, 1991). Due to infrastructure regulation and guidelines, SWMPs will continue to be installed across the urban landscape.

Despite SWMPs being human-made pieces of infrastructure, they are inhabited by a diverse array of biota. Macroinvertebrates, for example, are often found in SWMPs in assemblages that may be related to landscape factors (Holtmann et al., 2018, 2019b). Amphibian colonization of SWMPs has also been observed, with some observers noting several species occupying ponds (Clevenot et al., 2022; Le Viol et al., 2012; McIsaac, 2022). Plants have also been reported to colonize SWMPs, where they can create various microhabitats within the ponds themselves (Holtmann et al., 2019a). However, the apparent benefits of SWMPs promoting biodiversity are not without trade-offs. For instance, pollutants retained in SWMPs can damage dragonfly DNA (Meland et al., 2019) as well as biofilms that some macroinvertebrates graze (Izma et al., 2024). For amphibians, SWMPs have been argued to form ecological traps and may impede amphibian reproductive success (Clevenot et al., 2018; Sievers et al., 2018). As for plants, SWMPs can act as reservoirs for invasive species, negatively impacting biodiversity (McKercher et al., 2024).

My meta-analysis aims to evaluate whether SWMPs harbour similar, higher, or lower levels of biodiversity when compared to other ponds. In this meta-analysis, I review the literature to understand what key variables contribute to biodiversity in SWMP and which taxa are the primary focus of researchers. Due to the landscape context of SWMPs, these ponds often occur

in urban areas, typically being found in developments adjacent to suburbs, roadways, and agricultural lands. I use the meta-analysis to quantitatively test for a difference in biodiversity between SWMPs and "control ponds". It is important to note that SWMPs may appear analogous to natural systems, but contribute to the landscape via "ecomimicry" where the specific infrastructure mimics the natural analog (sensu Chambers, 2011). "Control pond" in the instance of this meta-analysis may refer to a natural pond or another pond within the vicinity. Linguistically, the various definitions as they relate to "control" are a challenge, which I will discuss later in the chapter. My meta-analysis aims to inform urban planners, land-use managers, landscape architects, and developers how SWMPs may influence biodiversity in landscapes where development has significantly altered the ecosystem.

2.0 Methods

2.1 Literature Review & Methodology

I conducted a literature review on biodiversity and SWMPs using Web of Science. I conducted the initial literature review in June 2023. I continued to search for updated literature by searching for new papers on two occasions in June 2024 and September 2024. I searched the Web of Science collection using two topic field searches combined with the Boolean operator "AND". The first field used the search string: stormwater NEAR/3 (pond OR urban OR "artificial pond" OR "detention pond"). The second topic field used the search string: biodivers* OR "diversity index" OR Shannon OR ecolog* OR bioassess*. The two search strings used syntax and context search parameters to help assign relevance to papers in the Web of Science database. For example, the operator "NEAR/3" searches for papers where the word "Stormwater" is within a three-word limit of "pond," allowing for my search to require a more

precise context of stormwater pond research. As there are many papers in the Web of Science collection focusing on the engineering design of SWMPs, it was essential to include contextual search operators to establish a solid basis for the initial search. The second string included search criteria such as “diversity index” and “Shannon”, as these are popular measures of biodiversity. This would also weed out papers that may mention “biodiversity” as a rhetorical *pathos* rather than a point of evidence. In total, my search resulted in 388 papers identified in the Web of Science database.

Next, I screened the abstracts of the studies from my initial search and restricted the papers that did not meet the criteria of the meta-analysis goals using the PRISMA workflow (Page et al., 2021) (Figure 4). I excluded documents such as engineering design reviews, literature reviews, and those that did not focus on the correct habitat form (i.e., a paper on stormwater management that studied a creek instead of SWMPs), as well as documents that mentioned biodiversity but did not directly measure it. Overall, I excluded 258 papers, assessing 129 studies for eligibility within my meta-analysis. For the full-text assessment, I refined my selection by removing papers that lacked identifiable measures of biodiversity, those with incorrect “control pond” comparators, those without institutional access, those without accessible supplemental data, and those whose authors did not respond to further information requests. In total, I identified 18 papers to include in the meta-analysis.

From the 18 papers, I collected data including the main taxonomic group researched, the country in which the paper was conducted, the number of samples collected, the area surveyed, the explanatory variable investigated, the measure of biodiversity used within the paper, and whether the authors compared their SWMPs to natural ponds or other “control” ponds. I also

include a field where authors noted lower, similar, or higher levels of biodiversity, along with the significance level.

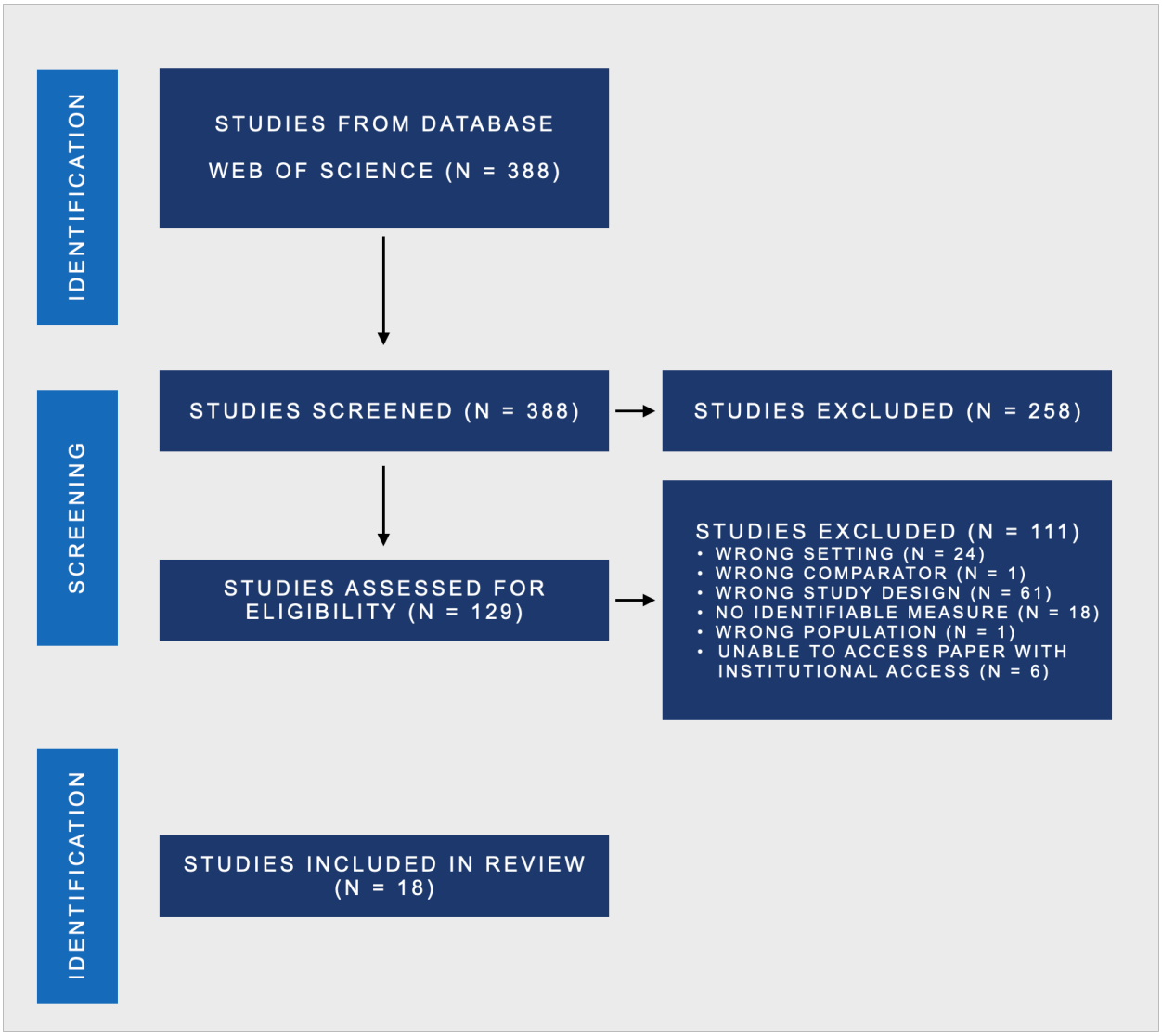


Figure 4: PRISMA workflow conducted in the meta-analysis

I extracted data from tables and appendices using direct measures if they were written and displayed by the authors. To analyze the data, I used R Studio (R Core Team, 2021) with the R packages *metafor* (Viechtbauer, 2010), *ggplot2* (Wickham et al., 2019) and *tidyverse* (Wickhamet al., 2019) for data cleaning, data analysis, and data modelling.

To calculate the effect size and outcome measures of biodiversity levels, I used the escal() function to calculate the means and standard deviations of the experimental and control variables. The function escal() transforms the data into a vector that allows for the calculation of the standardized mean difference (SMD) to be inferred (Hedges & Olkin, 1985; Wasserman, 1988). When calculating the SMD, the *metafor* package uses Hedge's G value to compute it, where the SMD is the difference of means between the two experimental groups divided by the pooled standard deviation, correcting for positive bias that may arise due to sample approximation and variation in sample estimates. In the meta-analysis, when the SMD is negative, the biodiversity of the stormwater pond is poorer than that of the comparator. When running the analysis, I used a random effects method to account for differences in variance within the selected studies. Due to the nature of the selected studies, the actual effect may be influenced by differences in study design, comparators, and sample sizes of the studies, as well as the total number of studies within the meta-analysis, which can all impact the outcome of the model. Unlike a fixed effects method, whose variance is assumed to be sample error within studies, a random effects model takes a more conservative approach where variance is accounted for among studies (Borenstein et al., 2010).

Next, I used the function influence () to account for any weight in my random effects analysis, which would help mitigate the impact of papers with greater variability. Depending on the study included in the overall analysis, some studies may skew the results due to larger weight coefficients. To maintain a balanced analysis, an influence check is necessary to ensure quality control of data input (e.g., misplaced decimal markers, incorrect study outcomes, etc.). After completing the random effects model, I then completed a moderator analysis and meta-regression as a *post-hoc* test to account for any heterogeneity within the variables tested. Using a

moderator analysis and meta-regression allows for a more detailed look at which factors may be significant in causing a change to the true effect within the analysis (Cheung, 2008; Hedges & Vevea, 1998; Nakagawa & Santos, 2012).

Lastly, I performed a publication bias analysis to examine potential contradictions that may arise in the meta-analysis itself (Afonso et al., 2024). Publication bias can also be defined as results that, when reported, may lead to false conclusions and misrepresent the true effect (Halpern & Berlin, 2005). To report publication bias, I ran an Egger's regression test (Egger et al., 1997) to investigate asymmetry using a funnel plot. I then used the trimandfill() function to validate asymmetry and confirm the Egger's regression and examine for any underlying asymmetry (Duval, 2005) and publication bias.

3.0 Results

3.1 General Overview

Globally, many publications focusing on biodiversity in SWMPs are published in highly developed, high-income economies, with the majority of studies occurring in Europe and Canada (except for one publication included in the meta-analysis from South Korea). Overall, a majority of the publications were released in the 2010s, with some research published into the 2020s (Figure 5) Among the countries, Canada (n = 4), Denmark (n = 4), and France (n = 4) had the most publications included in the studies (Figure 6). Within the studies, 66% of the publications investigated invertebrates (n = 12), followed by amphibians (n = 4), plants (n = 1), and bacteria (n = 1). Absent from the meta-analysis are publications focusing on birds, reptiles, and mammals. An overwhelming majority of publications used richness as their key metric (n = 15)

to explain biodiversity, whereas studies using the Shannon Index accounted for a small minority (n = 3).

On average, about 33 ponds (mean = 33.778) were observed across all studies, with one study investigating a maximum of 82 SWMPs (Jumeau et al., 2020) and another investigating a only 4 SWMPs (Choi et al., 2022).

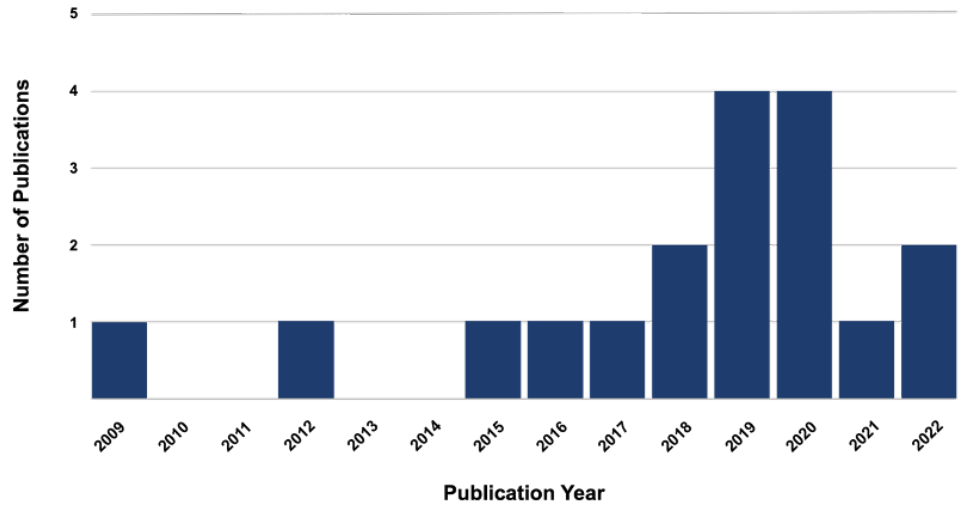


Figure 5: Bar plot of publications by year

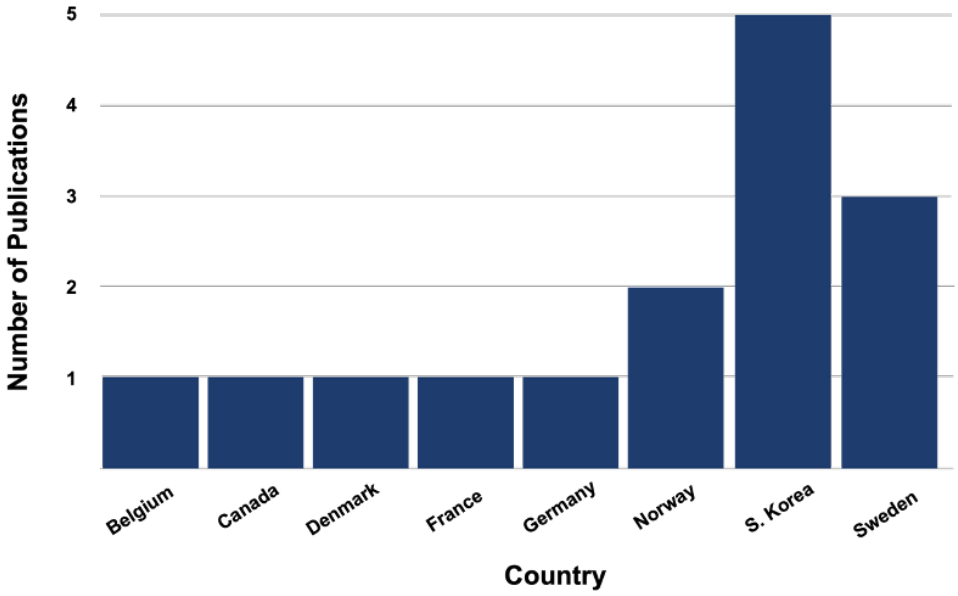


Figure 6: Bar plot of publications by country. European countries compose a majority of the studies in the meta-analysis.

Of all the studies, only two publications claimed that SWMPs harboured higher levels of biodiversity (Holtman et al., 2019a; Meland et al., 2020), whereas six publications claimed lower levels of biodiversity (Choi et al., 2022; Clevenot et al., 2022; Cours et al., 2021; Holtmann, et al., 2019b; Jumeau et al., 2020; Koziel et al., 2019; Perron & Pick, 2020a) than in the "control ponds"; most publications included in the meta-analysis reported similar levels of biodiversity (Hassall & Anderson, 2015; Holtmann et al., 2017, 2018; Johansson et al., 2019; Le Viol et al., 2009, 2012; Perron & Pick, 2020b; Stephansen et al., 2016; Woodcock et al., 2010), with authors not finding significant differences in biodiversity.

3.2 Random Effects Meta-Analysis

I conducted a random effects meta-analysis on 18 studies. The results of this random-effects meta-analysis reveal no significant difference in biodiversity between SWMPs and their comparator (g = 0.0196, p = 0.9230). In the model, there is substantial heterogeneity (Q= 145.3803, p-value < 0.0001, df = 17) (Figure 7). Estimated heterogeneity, τ^2 = 0.5938 (SE = 0.2501), suggests substantial variance among the studies. The true effect across all studies, τ = 0.7706, presents the standard deviation between studies, indicating the variability resulting from differences between studies. The proportion of total variability due to heterogeneity, I^2 = 86.62% (total heterogeneity / total variability), is considerable, suggesting high levels of heterogeneity in the effect size across studies, which reinforces the notion that studies do not estimate the same effect. The ratio of total variability to sampling variability, H^2 = 7.47, suggests significant between-study variation. The results of my influence test revealed that no individual study was an outlier in being overrepresented in my analysis.

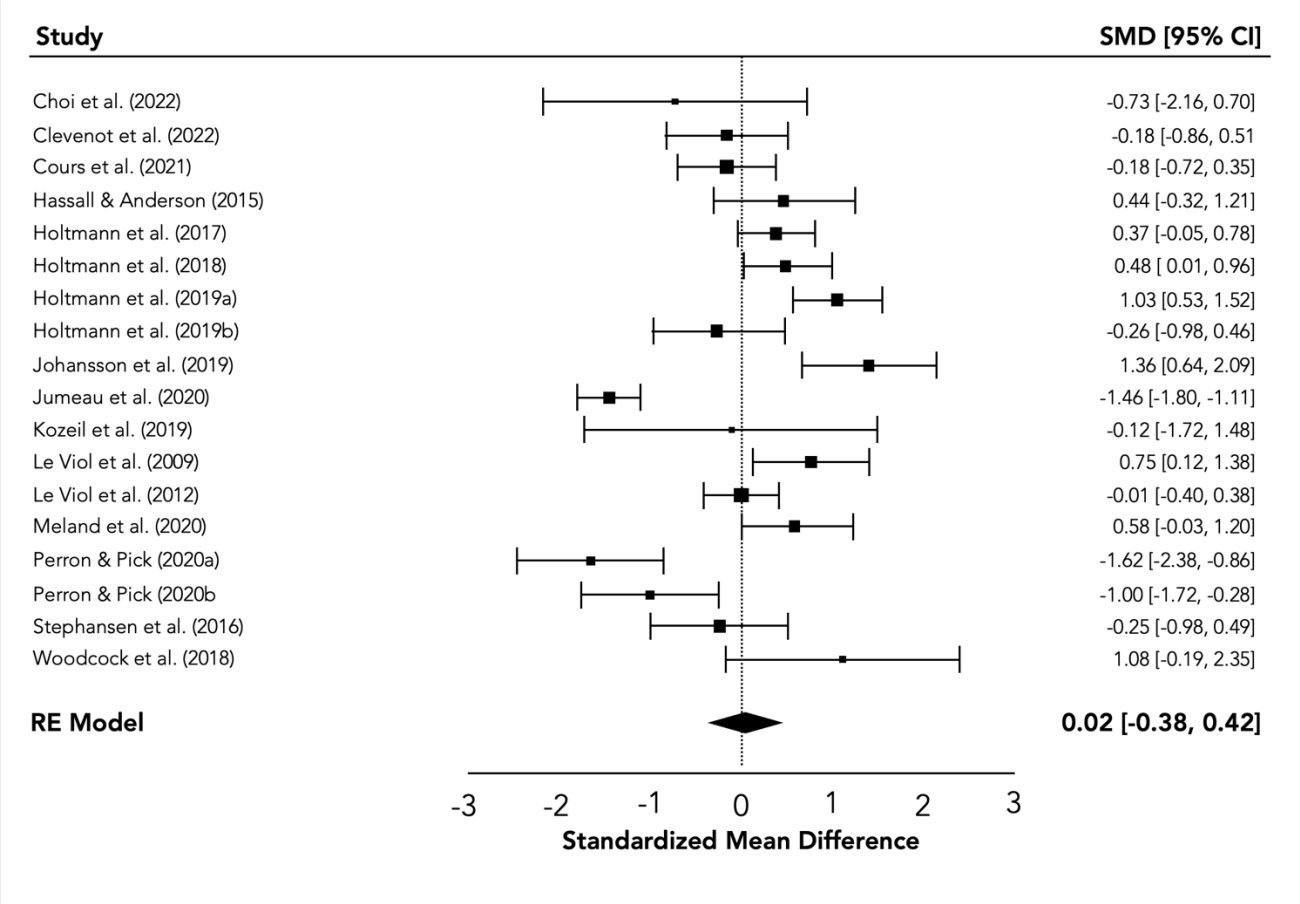


Figure 7: Forrest plot of all studies in random effects meta-analysis. Larger points on the plot represent papers contributing more weight to the pooled estimate.

Regarding the different moderators within the model, I tested several variables using moderator analysis and meta-regression to determine if there are any significant relationships between moderators across studies. There is weak evidence to suggest that water quality impacts biodiversity in SWMPs (g = -1.2678, n = 2, p = 0.0517, SE = 0.6516); however, this is within the margin of significance (p >0.05) (Figure 8). Testing taxa as a moderator, there was no significance between taxa across studies (QM = 2.9194, p = 0.5714, df = 4) (Figure 9). I also tested whether comparing SWMPs to the control pond, being a natural pond, made a significant difference; it did not impact diversity (QM= 1.8251, p = 0.6095, df = 3). These model results

suggest that SWMPs may not differ significantly in harbouring levels of biodiversity compared to control ponds.

WATER QUALITY IS WEAKLY ASSOCIATED WITH LOWER BIODIVERSITY

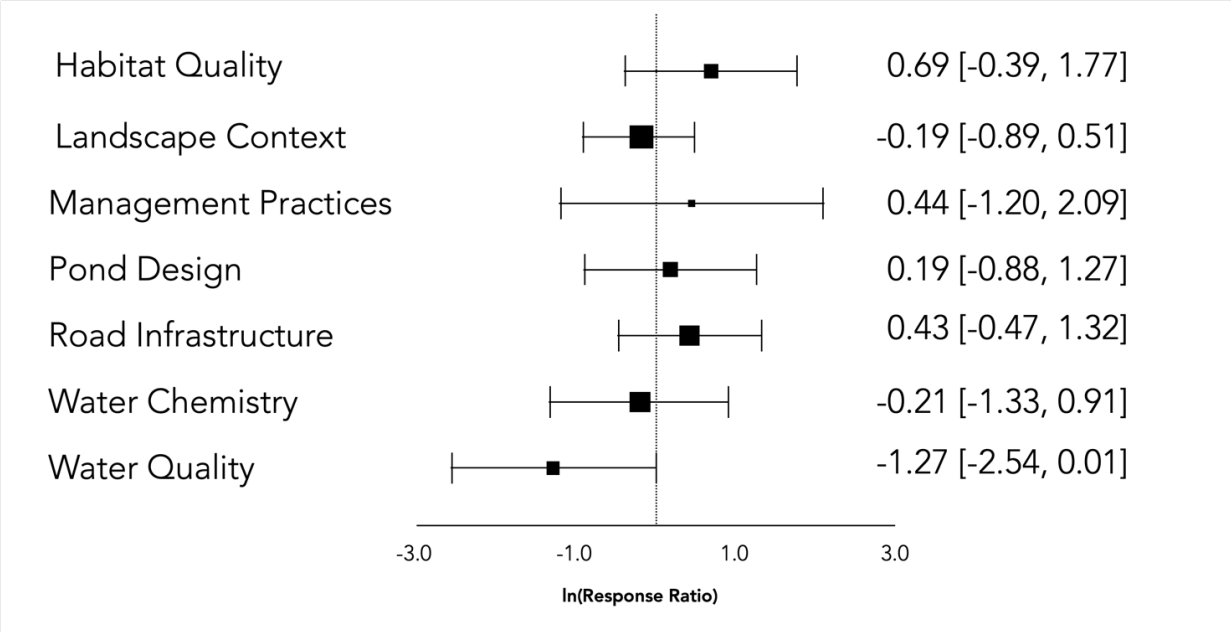


Figure 8: Forest plot of mixed meta-regression of the moderators "explanatory variables" authors used to test for biodiversity.

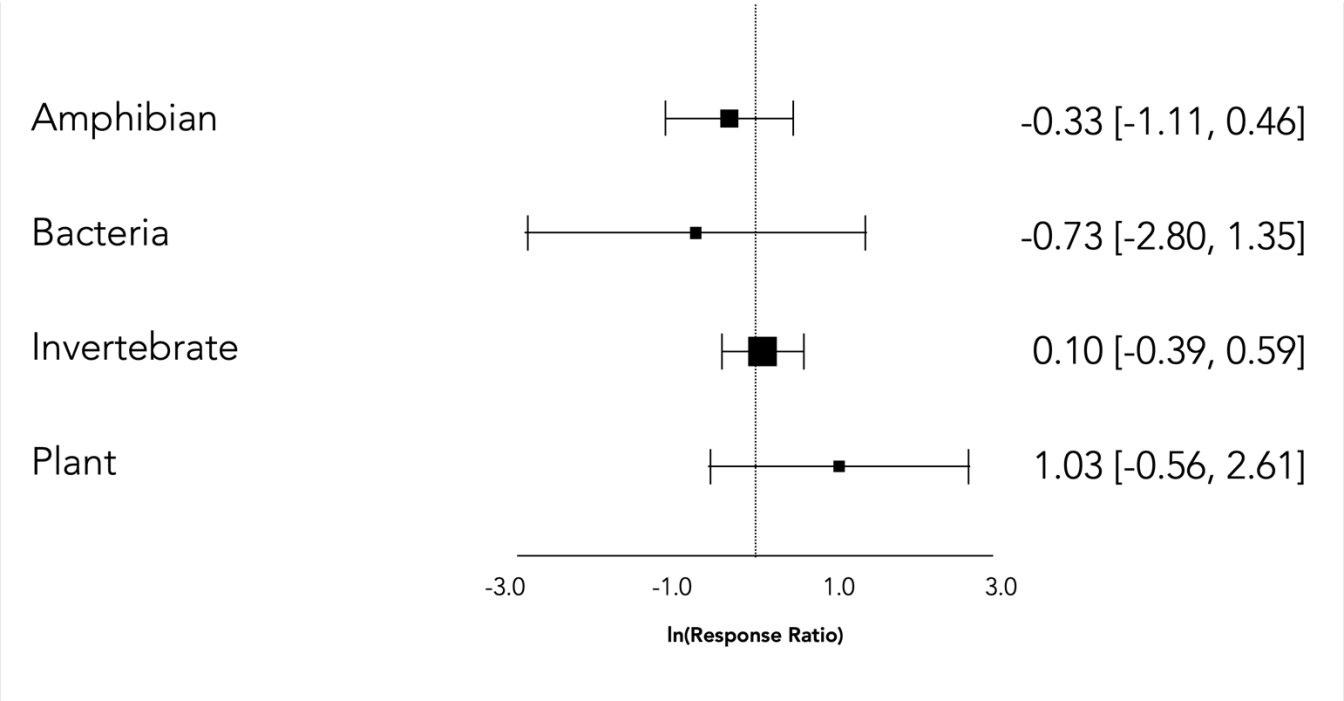


Figure 9: Forest plot of mixed meta-regression testing moderators "taxa."

3.3 Publication Bias

To test for publication bias, I conducted an Egger's regression test for asymmetry in the funnel plot. The funnel plot exhibits considerable symmetry (Figure 10, observed significance = 0.0352, p = 0.9719), with three publications falling outside the 95% confidence interval on both the left and right sides, suggesting that publication bias within the analysis is unlikely. However, when conducting a Fail-safe N Test using the Rosenthal approach did not find the need for additional studies to change the conclusion of the meta-analysis (observed significance level = 0.4577, fsn = 0).

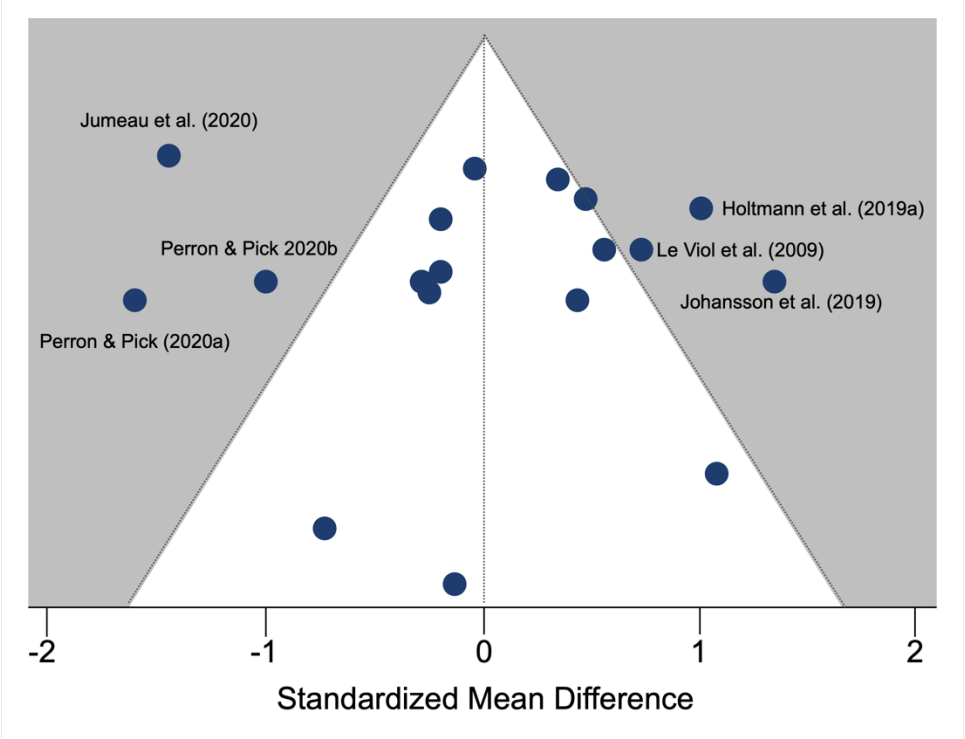


Figure 10: Funnel Plot testing for publication bias. Labels show publications that fall outside the confidence intervals.

4.0 Discussion

Through this meta-analysis, I conclude that there is no significant difference in biodiversity levels between SWMPs and control ponds. Due to the nature of the publications being tested, I can also conclude that the methods of comparing SWMPs to control ponds were also not a significant factor in predicting biodiversity. One main challenge in testing the biodiversity across papers is the choice of control in the context of the researcher's goals in maintaining a unified control. Across the set of publications, control ponds varied greatly, including natural ponds and ponds of unknown origin. Reconciling this, I took a random effects approach to the meta-analysis to account for the differences with heterogeneous controls.

In a recent systematic review and meta-analysis published by Ferzoco & McCauley (2024), the authors came to similar conclusions, stating the importance of SWMPs in urban

ecological conservation. In comparison, their meta-analysis only accounted for 11 publications, whereas this meta-analysis included 18 publications. It is worth noting that, due to the recent interest in SWMPs as novel ecosystems, there is considerable overlap between the studies. Additionally, Ferzoco & McCauley (2024) include a qualitative analysis to explore the broader goals ecologists are interested in. Across our analyses, we independently come to the same conclusions that SWMPs provide similar levels of biodiversity to control ponds. Regarding "control ponds," one major challenge in this meta-analysis was accounting for the "control" authors used. "Control pond" in the instance of this meta-analysis may refer to a natural pond or "another" pond. For instance, "control pond" in Le Viol et al. (2009, 2012) used "surrounding ponds" as their control, stating their control ponds should not be considered as either "unaltered" or "natural." Hassall & Anderson (2015) differentiate their ponds as "managed" and "unmanaged." A study that compared SWMPs to natural ponds was Meland et al. (2020); they found higher diversity in SWMPs but attribute this to a higher number of pollution tolerant species. Due to the differences in "control" pond across studies along with the small number of studies, care should be taken when interpreting the results of my meta-analysis.

Similarly, there is an abundance of literature attributed to three main authors: Holtmann et al., Le Viol et al., and Perron & Pick. This raises the question about the independence of papers included in the meta-analysis. With the Holtmann et al. studies, the authors do sample different taxa in their papers. The authors use the same landscape and select from a pool of SWMPs across all their studies. Despite the geographic area being the same across all studies (this research was conducted in Münster and the authors selected ponds from 79 available ponds), the authors described their site selection as random. Similarly, the authors did sample in different years and different time periods during the year where Holtmann et al. (2017) sampled

amphibians in SWMPs in March to May 2014 and randomly selected 46 ponds; Holtmann et al. (2018) sampled odonates in April to September 2015 and randomly selected 35 ponds; Holtmann et al. (2019a) sampled plants in April to September 2016 and randomly selected 35 ponds; Holtmann et al. (2019b) sampled odonates in April to September 2015 and randomly selected 30 ponds. Due to Holtmann et al. studies being conducted in different years, different seasons, and different taxa may introduce meaningful independence across the studies. Similarly, Le Viol et al. (2009, 2012) sampled ponds along the A11 highway in France but conducted studies on different taxa and in different time frames with amphibian surveys in March and April 2006, and macroinvertebrates in June and July in 2006. Le Viol et al. also measured different number of ponds and different sections of the A11 highway where Le Viol et al. (2009) sampled 25 ponds within 50m of the highway along a 56km section, and Le Viol et al. (2012) sampled 58 ponds within 50m of the A11 highway along a 100 km section. However, Perron & Pick (2020a, 2020b) did sample the same 41 ponds in Ottawa in the same summer temporal period but differed in scope of what explains the difference in diversity (Peron & Pick, (2020a) focused on water quality whereas (2020b) focused on landscape context) which may explain why these two papers fall outside the confidence intervals in Figure 9 and may influence the results of the meta-analysis. As it relates to Holtmann et al. and Le Viol et al., potential dependence among effect sizes arising from shared authorship or regional context should be noted. As such, effect sizes were treated as independent due to differences in site selection, sampling seasons, and taxa. I acknowledge that shared methodological approaches and regional context may introduce some degree of non-independence, which is partially accounted for through the use of random-effects modeling.

4.1 Pond Design & Road Infrastructure

In publications that found lower levels of biodiversity, land use management, water quality, water chemistry, and pond design were all identified as significant factors contributing to the reduction of biodiversity. Road infrastructure has been noted to impact biodiversity (Abra et al., 2025). Clevenot et al. (2022) describe ponds along French highways as harbouring lower levels of amphibian richness. Due to the highway infrastructure, SWMPs are required to funnel runoff during rain events. However, the authors find that isolated ponds near highways are less likely to harbour high levels of amphibian diversity, as the highway landscape inhibits the connectivity between these ponds. Publishing a year earlier, Jumeau et al. (2020) found that amphibian diversity in SWMPs is impacted primarily by land use and pond design; they also find more pollutant-intolerant species, such as newts, in ponds within a landscape context of deciduous forests. The authors highlight the ecological potential of SWMPs in highly developed landscapes.

4.2 Water Quality and Chemistry

Water quality and chemistry were also determinants of biodiversity in the collected publications. In the context of my analysis, I decided to separate water quality publications by how they measure the water's suitability for habitat, whereas water chemistry papers investigated and quantified specific compounds in the water. Choi et al. (2022) evaluated runoff into SWMPs by comparing land-use and rain events to assess water inflow quality, finding that total suspended solids (TSS), conductivity, water temperature, and season significantly influence the bacterial community and greatly impact the microorganism composition found in the ponds. Cours et al. (2021) find that water chemistry have impacts on ostracod richness when ammonium

and total phosphorus levels are higher. While the findings of these papers indicate the importance of water quality and water chemistry within the pond, there is an indication that it depends on the hydroperiod of the ponds themselves. For instance, Choi et al. (2022) find that bacterial communities in soil are more stable than those in water due to fluctuations in water quality from stormwater sources, suggesting that the biota inhabiting the water column may be more prone to environmental stress.

Additionally, Cours et al. (2021) state that the landscape context of the pond can be influential but find water chemistry is a stronger predictor of community structure in SWMPs. The authors sampled ponds in three different levels of urbanization and did not find a strong effect on community structure. They do suggest that the increase in ammonium and phosphorus in their ponds may be due to proximity to agricultural lands, rather than urbanization influencing community assemblages as the cause of community influence. However, the pathway of surface runoff into SWMPs is not delineated by topography alone. A series of culverts, drains, and pipes, in a storm sewer network allow for water to enter a SWMP in ways natural flow would not allow. The land cover types comprising the sewershed reflect the sources of contaminants that runoff picks up before entering the SWMP. For example, ponds that are surrounded by agricultural lands can differ in contaminant signature from ponds surrounded by urban development (Izma et al., 2025)

4.3 Habitat Quality and Landscape Context

The landscape context surrounding SWMPs is not only a source of contaminants through the sewershed, but it also contributes to habitat quality by influencing ecological connectivity. Many of the organisms residing in SWMPs require access to terrestrial habitats for at least a

portion of their life cycle, such as dragonflies (Holtmann, 2018) and amphibians (Holtmann, 2017). Holtmann et al. (2017) describe SWMPs with greater riparian habitat as having slightly higher levels of amphibian species richness than ponds with less riparian habitat, both within the pond and surrounding the pond. The authors, in a subsequent study (Holtmann et al., 2018), also find habitat heterogeneity to be an indicator of higher plant species richness. The authors (Holtmann et al., 2019b) further illustrate the importance of management and habitat heterogeneity, focusing on dragonfly diversity, and find that regular management of riparian areas influences microhabitats within the ponds, resulting in higher dragonfly richness at SWMPs compared to the control ponds (note: A control pond in Holtmann's papers are defined as the next pond in the vicinity of each chosen SWMP, the authors do not differentiate the origin of control pond).

Perron & Pick (2020b) supports this finding, arguing that SWMPs with higher macrophyte richness have a positive influence on odonate richness compared to natural ponds. The authors sampled plant communities and used a Floristic Quality Index as well as richness to measure the plant community composition across SWMPs and natural ponds and concluded that despite SWMPs having higher macrophyte richness than natural ponds, the FQI was significantly lower due to increased plant richness from invasives. The authors in Clevenot et al. (2022) find that fewer amphibian species use SWMPs when natural ponds are available within a highway landscape. Within their study, the authors compare the connectivity using a metric to place each pond within the wider landscape context using a "degree of node" framework (Rayfield et al., 2011; Wintle et al., 2019). They find that species richness in some SWMPs may be higher than in marginal ponds (ponds that are slightly connected but not isolated), as connectivity to other habitat patches may be lower than in SWMPs with higher connectivity to other aquatic spaces.

The authors argue that the isolation of SWMPs to natural aquatic habitats is a result of SWMPs being the only available aquatic habitat within the landscape, whereas ponds with higher connectivity act more like corridors for amphibians to traverse and find suitable habitat. As the authors suggest, isolated ponds and marginally connected ponds may become sink ecosystems in the long term. Importantly, Johanssen et al. (2019) find that SWMPs in Sweden harbour a large number of dragonfly taxa, suggesting that SWMPs may play a crucial role in conserving diversity in urban areas. The authors investigated landscape variables such as the geographical distance between one pond and another, pond management, and more. They find that the distance between ponds and the floristic quality within and surrounding the ponds fostered higher beta diversity. The authors suggest plant maintenance in ponds to increase biodiversity. Additionally, Hassall & Anderson (2015) find that SWMPs, when compared to natural analogs have similar levels of biodiversity and community structure, even if the SWMPs have relatively poor water quality. For example, they cite Navis et al., (2013) who suggest torpor, a state of reduced metabolic activity, as a mechanism invertebrates may use to avoid toxicity from polluted SWMPs.

4.4 Potential Mechanisms for the Results

4.4.1 Connectivity as a Means for Dispersal

Many of the papers included in the meta-analysis primarily focus on differences between SWMPs and control ponds as they relate to the habitat conditions within and surrounding the ponds. A mechanism of taxa expansion is the concept of dispersal, where species move from one site to another (Vellend, 2016). Natural waterbodies in the vicinity of SWMPs can serve as sources of colonists to establish populations in SWMPs. Regional diversity (i.e., gamma

diversity) acts as a reservoir for species to disperse across the landscape in search of new aquatic habitats.

As cited in several studies (Clevenot et al., 2022; Jumeau et al., 2020), connectivity and the ability of an organism to find the SWMP are important for population establishment. Some organisms, such as dragonflies and damselflies, may fly from one pond to another in hopes of reduced competition in new ponds (Holtmann et al., 2019). Anecdotally, it is reported that the transfer of invertebrate and amphibian eggs from birds, such as herons, may occur and form populations (Clevenot et al., 2022, Jumeau et al., 2020). Despite human interventions to keep these species out of SWMPs, such as using guards in outlets and drains, as well as fencing and concrete barriers that block these species from entering the pond, one can only reiterate that "life finds a way."

4.4.2 Habitat and Landscape Management Practices

Biological management of SWMPs was also noted as potentially influencing biodiversity in SWMPs. Mowing and planting useful plant species is common maintenance protocol within guidelines for building a SWMP (Government of Ontario, 2003). The additional planting of aquatic species is also important but may not be as well implemented due to increased colonization of SWMPs by invasive species (Sinclair et al., 2020). Due to the nature of SWMPs as pieces of infrastructure, there is an opportunity to design and manage riparian area in SWMPs. Despite some ponds having high levels of species richness in their riparian areas (Holtmann et al., 2019), the management practices across municipalities and natural resource management agencies across geographies may result in uneven approaches if SWMPs are to be considered critical to urban biodiversity. In relation to Canadian SWMPs, species such as goldfish

(*Carassius auratus*) and common reed (*Phragmites australis*) can inhabit SWMPs and alter ecosystem dynamics (Rooney et al., 2015). Additionally, the integration of biodiversity management, such as incorporating habitat design into the planning and management guidelines of SWMPs, may provide guidance to revitalize SWMPs into higher quality habitats.

4.5 Future Development Opportunities for SWMPs

While many publications in the meta-analysis advocate for increased ecological management of SWMPs and designing for biodiversity in mind, such recommendations include increasing vegetation community diversity across ponds (as suggested by Johanssen et al., 2019, Perron & Pick, 2020b), implementing heterogeneous habitat zones (as indicated by Holtmann et al., 2019a), improving connectivity (Clevenot et al., 2022), and more. However, there is a knowledge gap regarding the effects of management on promoting biodiversity, particularly in the context of the impact of dredging on biological communities. Dredging is the process of removing accumulated sediment and other debris from the bottom of a pond, thereby restoring its original capacity. The removal of sediment where benthic macroinvertebrates live has been mentioned as a disturbance that may impact the community composition of SWMPS. Two papers included in the meta-analysis mention dredging as a management practice that may impact amphibian community composition in SWMPs. Le Viol et al. (2009) mention dredging as a temporary disturbance that should be accounted for in management recommendations. Similarly, Jumeau et al. (2020) express a similar sentiment, commenting on a review by Clevenot et al. (2018) that suggests avoiding pond dredging during amphibian breeding season. As ponds are drained and accumulated sediment is removed, the effects of such management practices should be better studied and monitored for potential longer-term effects. Therefore,

municipalities, sewage works, landscape architects, and planners have an opportunity to expand and broaden their management of SWMPs. Specifically in Ontario, municipal authorities are responsible for the long-term management of SWMPs. Municipalities can create biodiversity goals in mind when approving new development projects. Additionally, the development of new neighbourhoods and the creation of SWMPs are built by the developer, who installs the SWMP. Educating and incentivizing building with biodiversity in mind can be an alternative strategy to foster biodiversity in urban landscapes.

4.6. Limitations and Future Opportunities

In the past decade, ecologists have become increasingly interested in understanding how SWMPs can unintentionally become aquatic ecosystems. However, the are limitations within the research, as well as opportunities for future research.

To begin, a significant gap in the meta-analysis is the scarcity of mammalian research. Aquatic environments are also important for various mammals, including muskrats, beavers, stoats, gophers, and coyotes. Anecdotally, when I was collecting invertebrates for my analysis in Chapter 3, many community members mentioned coyote sightings at their local SWMP. As well, species can even alter hydrologic efficacy and impact the effectiveness of the infrastructure, such as beavers and muskrats altering the physical and hydro morphology of the ponds (Ledford et al., 2020). Additionally, beavers and other mammals can change the biogeochemical makeup of ponds and downstream habitat (Sheppy et al., 2024). Further investigation into the use of SWMPs by mammals will broaden the understanding of these aquatic realms in the urban landscape.

Additionally, studies included in the meta-analysis focused on short-term community dynamics rather than long-term monitoring of community changes. Studies have rarely investigated SWMPs for more than one season, and most research has occurred during the summer months. Despite this, storm runoff is known to cause fish die-offs in early spring due to rapid changes in water quality resulting from snowmelt and spring rains, a phenomenon referred to as "stormwater-driven mortality syndrome" (Chow et al., 2019). For example, Perron & Pick (2020a) state that they only tested water quality twice in one season, not accounting for changes in quality due to drought or rainfall events. Future researchers have the opportunity to investigate long-term dynamics and how seasonality alters community structure in SWMPs.

Lastly, management practices between jurisdictions can vary greatly. As established in the meta-analysis, there is a limited number of publications examining of the biodiversity levels of SWMPs. However, from a management perspective, there is a deficit of papers that investigate the practices that may impact the biological community. One instance of significant disturbance is the practice of dredging of SWMPs. Draining, removing accumulated sediment, and rehabilitating the riparian area during maintenance events may temporarily reduce the biodiversity of the biological community inhabiting the SWMPs, but the long-term impacts and recovery rates are poorly understood.

5.0 Conclusion

SWMPs are key components in a city's infrastructure toolbox for mitigating flooding and reducing erosion. However, SWMPs can also be important aquatic ecosystems that exist within heavily developed areas, providing habitat for a broad range of life. Cities will continue to build and upgrade their stormwater infrastructure as new challenges arising from climate change increase pressures on water management (Moore et al., 2016). While SWMPs are not intended to

provide habitat, they become habitat unintentionally. In places where natural ponds may not be as abundant, SWMPs may become important features in promoting biodiversity in urban areas.

Chapter 3: Land Use and Stormwater Facility Type Influence Biodiversity in Urban Landscapes

1.0 Introduction

In Canada, nearly 75% of people live in urbanized areas (Government of Canada, 2022). New housing developments are needed to accommodate the growing number of residents. However, urban and suburban sprawl are significant concerns for municipalities, as the development of low-density housing (i.e., single detached dwellings) expands the footprint of built-up land cover in the landscape (Fonberg & Schellenberg, 2019). Low-density housing both increases service costs for municipalities, and impacts the environment by increasing the impervious surface cover (Miller et al., 2014). A significant concern with landscape changes for suburban residential development is the loss of critical farmland (Fischel, 1982) and of natural heritage features such as wetlands (Sithole & Goredema, 2013, Birch et al., 2022).

One specific service required for low-density residential developments is adequate stormwater infrastructure. Specifically in Ontario, where this chapter's research was conducted, each municipality has a responsibility to design and enforce stormwater management under the *Ontario Water Resources Act* (Ontario Water Resources Act, 1990). Stormwater infrastructure in these developments aims to reduce the risks of flooding, reduce erosion, and capture pollutants before they enter the wider environment (Ontario Water Resources Act, 1990). Stormwater infrastructure in Ontario often takes form as a stormwater management pond (SWMP), which serves to minimize the loss of property in the event of widespread flooding. As a secondary objective, through their detention of run-off, SWMPs allow for the settlement of suspended solids before it is returned to a creek, a river, or a lake (Government of Ontario, 2003).

While the development of suburban infrastructure can influence the wider landscape, it presents a novel opportunity to re-imagine SWMPs as urban aquatic habitats. SWMPs have been identified as novel ecosystems (Foltz & Dodson, 2009), with a marginal increase in publications in the 2010s that investigate how these ecosystems function. In the previous chapter, I conducted a meta-analysis that concluded SWMPs can support similar levels of biodiversity compared to other control ponds. These findings are consistent with a similar literature review and meta-analysis conducted by Ferzoco and McCauley (2024), which found that SWMPs can harbour a considerable variety of species.

There are two types of stormwater management infrastructure that residential developments use to improve water quality while also preventing erosion and flooding from surface runoff: wet ponds and engineered wetlands (Ontario Water Resources Act, 1990). Wet ponds are designed to retain stormwater in a permanent pool, allowing suspended solids to settle and water to be released slowly. Wet ponds are often deep, with a regulated maximum depth of 3.3 m, and they are often designed to lack aquatic plants which might reduce their storage volume (Government of Ontario, 2003). Engineered wetlands are similar to wet ponds in that they maintain a permanent pool of water, but they are limited to a depth of 2.1 m (Government of Ontario, 2003). Engineered wetlands are designed to mimic natural wetlands to enhance water quality in stormwater through a diverse array of plants to absorb excess nutrients and trap suspended solids (Government of Ontario, 2003).

Both wet ponds and engineered wetlands require regular maintenance, such as dredging accumulated sediments, to ensure the infrastructure operates as designed. While the infrastructure detains water for a period of time before entering the wider ecosystem into creeks, rivers, and lakes, SWMPs can harbour toxic algal blooms of cyanobacteria (de la Cruz et al.,

2017) and can act as reservoirs for invasive species distribution (Sinclair et al., 2020). These ponds illustrate that, while they provide infrastructure and ecosystem services, they also pose new unintentional challenges for municipalities to address. In Chapter 2, I concluded that research on stormwater pond biodiversity tends to focus on either amphibians (Class, comprising frogs and salamanders) or odonates (insect Order, including dragonflies and damselflies). Some studies took a broader view of biodiversity and examined aquatic macroinvertebrates as a community (Hassall & Anderson, 2015). Aquatic macroinvertebrates make excellent bioindicators in aquatic ecosystems because of their demonstrated sensitivity to water quality and other outcomes of anthropogenic disturbances (Holt & Miller, 2010)

In this chapter, I explore potential correlates of macroinvertebrate biodiversity in stormwater management infrastructure within the Southwestern Ontario cities of Kitchener and Waterloo (moving forward, I will be referring to the cities as Kitchener-Waterloo). Firstly, I compared biodiversity response variables such as richness, Shannon Diversity (*H'*), and Pielou's Evenness (*J*) against a series of predictor variables using Ontario Benthic Biomonitoring Network (OBBN) protocol. Secondly, I use invertebrate biodiversity and OBBN-derived indices of habitat quality to compare the two major types of stormwater management infrastructure: wet ponds versus engineered wetlands. I also compared the community composition of macroinvertebrates in stormwater management ponds to other small lentic study sites in Ontario.

2.0 Methods

2.1 Study Area

The study area is located in the Southwestern Ontario cities of Kitchener and Waterloo (collectively known as Kitchener-Waterloo) (Appendix 1). Kitchener-Waterloo is situated on the

Haldimand Tract and is the tenth largest metropolitan area in Canada. Adjacent to the Grand River, Kitchener-Waterloo is in the largest watershed in Southern Ontario. Kitchener-Waterloo is located in the Waterloo Moraine, which accumulates and discharges freshwater, and features several large creek systems throughout the city (Veale et al., 2014).

SWMPs were chosen in conjunction with Dr. Maria Strack and Akshara Withanage (Withanage, 2025). Considerations included catchment area, neighbourhood, and pond type. In total, 24 facilities were included in the survey, comprising eight engineered wetlands and 16 wet ponds. Thirteen of the stormwater management ponds are located in Kitchener, and 11 are located in Waterloo. Descriptions and features of the stormwater management ponds were collected from the cities' Open Data Portals (Region of Waterloo, 2018; City of Waterloo, 2019; City of Kitchener, 2019) as well as SWMP design plans and additional documentation available through data sharing agreements with the cities.

To compare Kitchener-Waterloo's ponds to other small lentic systems, I initially searched OBBN's database to find if other datasets had been uploaded. Accessing data on OBBN's ArcGIS repository did not have any available data on ponds, lakes, and wetlands in Southwestern Ontario. Supplementing this, I found three datasets to compare to my ponds Kitchener-Waterloo's. Firstly, I compared a dataset from Hassall & Anderson (Hassall & Anderson, 2015) who researched benthic macroinvertebrate communities across SWMPs in Ottawa, ON. As well I compared a dataset by Hogg (2006) who assessed the Whitfield Wetland Complex and compiled a biophysical inventory of benthic macroinvertebrates in Peterborough, ON. Finally, I included data from the University of Waterloo's benthic collection from ERS 340 class sampling of the University of Waterloo's Environmental Reserve Wetland and Columbia Lake on the University of Waterloo Campus in Waterloo, ON (Esmail, 2022). Due to OBBN's repository lacking

wetland data, supplementing using Hassall & Anderson, Hogg, and Esmail allowed me to compare and contrast my SWMPs assemblages.

2.2 Benthic Macroinvertebrate Collection

Field sampling was conducted in October 2024. Benthic macroinvertebrates were collected following the wetland protocol of the Ontario Benthic Biomonitoring Protocol (OBBN) (Jones, Somers, Craig, & Reynoldson, 2007), during a period of no rain to maintain consistent water quality measurements. Dates were chosen in autumn to maximize richness, as there is a higher prevalence of identifiable nymphs (Jones, Somers, Craig, & Reynoldson, 2007) and summer conditions may be more accurately reflected (Jones, Somers, Craig, & Reynoldson, 2007). Following OBBN protocol, three replicates (segments of the pond) are chosen to collect macroinvertebrates. Benthic macroinvertebrates were collected using a 500-micron mesh D-net following a jab-and-sweep method to collect benthic into a representative sample that integrated all available habitat types. Macroinvertebrates were collected, composited and then live-sorted in the field until a minimum of 100 animals were obtained. All samples yielded at least 100 individuals. They were immediately preserved in 70% ethanol.

Macroinvertebrates were returned to the lab and identified mainly to order following Merrit and Cummins taxonomic guide (Merrit & Cummins 2019). Samples were identified and enumerated under a dissecting microscope using a 10 x 10 cm gridded petri dish with the aid of the Tab Carter & Doran key for freshwater macroinvertebrates in Ontario (Carter & Doran, 2005). For quality control purposes, a second independent individual confirmed all identifications, and reclassified 12 individuals which were identified and corrected. These reclassifications include one misidentified aquatic caterpillar (Lepidoptera) individual, and the

remaining individuals were misidentified as leeches (Hirudinae) when they were flat worms (Turbellaria). Details are provided in the appendix under supplementary data.

Counts of macroinvertebrates were used to compute several common indices of environmental condition and habitat quality within the Ontario Benthos Biomonitoring Network methodology, including Shannon Diversity, Pielou's Evenness, and more (Table 2).

2.3 Physical Landscape and Water Quality Measurements

Water quality measures for each stormwater management pond were measured using a YSI Exo Sonde (Yellow Springs, Ohio, USA) to capture water quality data, including temperature (ºC), pH, dissolved oxygen (mg/L), conductivity (µS/cm), turbidity (Formazin Nephelometric Unit, "FNU"), phycocyanin (µg/L), and chlorophyll-*a* (µg/L).

Additional measures of habitat quality, included in the OBBN protocol were collected simultaneously with macroinvertebrate sample collection. These included substrate type, macrophyte and algal cover estimates. Macrophytes and algae were classified as either "absent", "present", or "abundant" (Stanfield, 2005; Stanfield & Jackson, 2011). Macrophytes were broken down by growth form into broadleaf emergent, narrow-leaf emergent, submersed aquatic plants, and free-floating plants. Algae were categorized into four types: floating, filamentous, slime, and attached algae. Land cover surrounding each stormwater pond was classified as either deciduous forest, coniferous forest, wetland, meadow, scrubland, suburb, commercial, cultivated, or varied, based on an aerial image analysis of images taken by the Region of Waterloo in 2024, imported into ArcGIS (Region of Waterloo, 2024). Substrate was collected in the field during kick net sampling of invertebrates and noted by the dominant and the second dominant substrate type for each subsample. Like macrophyte and algae abundance, substrate was classified into several

classifications, including clay, silt, sand, gravel, cobble, boulder, bedrock, and an additional "organic" classification. I define "organic" as a non-mineral substrate that includes leaf detritus and other vascular plant matter that has accumulated on the pond bottom. I included this classification due to the accumulation of organic material at the bottom of the pond, which can provide important context for benthic macroinvertebrate foraging and habitat.

Land cover type was extracted from each cardinal direction extending beyond the stormwater pond open water to one of three nested buffer bands: 1.5-10 m, 10-30 m, 30-100 m. Dominant land cover was assigned based on the banding scheme, with the most extensive land-cover class within each unit designated as the overall dominant land cover. During fieldwork, when collecting invertebrate samples, this land cover classification was validated. The land cover categories recommended by Stanfield (2005) were expanded to include "suburb", "commercial/industrial", and "cultivated" to account for the urban context of my thesis research. I defined "suburb" as land that is predominantly occupied by housing and other neighbourhood-based infrastructure, including road infrastructure, single-family housing, townhouses, condominium buildings, and schools. These neighbourhoods have high amounts of housing, significant road cover, and lawns and are further defined by their lack of natural coverage. I define commercial and industrial classifications as places with high levels of impervious cover, such as parking lots and roads, large buildings (such as fulfillment centres and shopping centres). Commercial areas are also identified by their lack of natural cover. I define the cultivated land cover as farm fields, often growing operations of corn or soy. In the Waterloo Region, agricultural land use surrounds the Cities of Kitchener and Waterloo.

Pond design features such as the open water area, permanent pond volume, catchment area, and open water perimeter were provided through data sharing agreements and data through

the regional open data portal. As well as data from stormwater proposal build plans shared from the cities, this also included vector data from the cities (City of Kitchener, 2018; City of Waterloo, 2018; Region of Waterloo, 2018). Vector data was bound to the water's edge, where the surface of the water meets the land; this did not include riparian area. Several common measures of patch shape from landscape ecology were included to represent variations in pond design (McGarigal & Marks, 1995), such as pond compactness, perimeter-area ratio, shape index, and fractal dimension index.

Table 2: Metrics used within the chapter and their associated formulas.

Metric	Formula	Citation
Shannon Diversity Index (H')	$H' = -\sum_{i=1}^{S} p_i \ln(p_i)$	(Shannon & Weaver, 1949)
Pielou's Evenness (J)	$J = \frac{H'}{\ln(S)}$	(Pielou, 1975)
OBBN metrics (e.g. %EPT, %diptera, %insects, etc.)	$\left(\frac{\sum of\ x\ individuals}{\sum of\ total\ individuals}\right)$	(Jones et al., 2007)
Hilsenhoff Biotic Index	$HBI = \frac{\sum(n_i a_i)}{N}$	(Hilsenhoff, 1988)
Bray-Curtis Dissimilarity	$BC_{jk} = 1 - \frac{2C_{jk}}{S_j + S_k}$	(Bray & Curtis, 1957)
Shape Index	$SI = \frac{P}{2\sqrt{\pi A}}$	(Patton, 1975)
Compactness Index	$CI = \frac{4\pi A}{P^2}$	(Forman & Godron, 1986, Baker & Cai, 1992)
Fractal Dimension Index	$FD = \frac{2\log(P)}{\log(A)}$	(Krummel et al., 1987; Mandelbrot, 1967)

2.4 Statistical Analysis

Data was compiled using Microsoft Excel and imported into R (R Core Team, 2021) RStudio (Posit Team, 2025). Several packages for data analysis include vegan (Oksanen et al., 2025), tidyverse (Wickham et al., 2019), dplyr (Wickham et al., 2023); AICcmodavg package for determining AIC model competition values (Mazerolle, 2025); factoextra (Kassambara & Mundt, 2020), and factomine (Lê et al., 2008) to calculate values in the Non-metric MultiDimensional Scaling ordination (NMDS). Visualization of the data was performed using the ggplot2 package (Wickham et al., 2025).

Firstly, I examined the multicollinearity among my explanatory variables to identify highly correlated variables, using a correlation matrix to identify which pairs of explanatory variables exhibited a high degree of correlation ($r > 0.70$). For such strongly correlated pairs of variables, I chose to exclude strongly related from my linear modelling as using variables that are colinear may result in multicollinearity, and may impact model predictions (Kim, 2019). I made this choice based on the pairwise correlation between variables. For instance, because my explanatory variables of turbidity, PC and Chl-*a* variables exceeded my threshold value ($r > 0.70$), I decided to keep turbidity as a model to use in this analysis. Additionally, Shape Index, Compactness Index, and Fractal Dimensional Index were colinear with area and perimeter ($r > 0.70$), I decided to keep area and perimeter as models to use in this analysis. Next, I used linear models to determine relationships between my biodiversity variables, such as Richness, Shannon diversity, and Pielou's Evenness, with my linear models consisting of water quality, land cover, macrophyte abundance, algae abundance, pond area, pond perimeter, permanent pond volume, pond characteristics, and habitat characteristics. Upon completing the linear models, I then employed an Akaike information criterion (AIC) method (Akaike, 1974) using AICcmodavg

package (Mazerolle, 2025) to determine which linear model about macroinvertebrate diversity in SWMPs is best supported by the data.

Secondly, I compared the SWMP type (wet pond versus engineered wetland) by their physical and water quality parameters, and well as OBBN biotic indices using Welch's t-tests to account for the uneven sample size of facility types using base R (R Core Team, 2021).

Thirdly, I conducted multivariate analysis to evaluate the associations between community composition and various water quality, habitat quality, and surrounding land cover data, as well as to compare community composition in wet ponds and engineered wetlands. To contextualize the community composition patterns characterized by the OBBN protocol in my wet ponds and engineered wetlands, in comparison to small lentic sites where OBBN was applied in Ontario, I performed a Non-Metric Multidimensional Scaling (NMDS) ordination using *vegan* (Oksanen et al., 2025). I used a Bray-Curtis dissimilarity matrix to input ordination data to determine the distance between community assemblages. Additionally, I conducted an analysis of similarity (ANOSIM) (Clarke & Green, 1988; Clarke, 1993) with 999 permutations using the *vegan* package (Oksanen et al., 2025) to determine whether the community assemblages in wet ponds and engineered wetlands supported distinct or similar macroinvertebrate communities.

3.0 Results

Across all sites, a total of 3278 individual macroinvertebrates were collected. On average, 10 taxa were present at a pond, ranging from 7 to 15 taxa. In total, 25 taxa were identified to the lowest possible taxonomic resolution across all 24 ponds. Mayflies (Ephemeroptera), midges (Chironomidae), and damselflies (Zygoptera) were present in 100% of sites. Worms (Oligochaeta; present in 91% of sites), true bugs (Hemiptera; 87%), dragonflies (Anisoptera,

83%), no-seeums (Ceratopogonidae; 66%), water beetles (Coleoptera; 66%), water snails (Gastropoda; 53%), mites (Hydrachnidia; 50%), flat worms (Turbellaria; 33%), and molluscs (Bivalvia; 12%) were common.

3.1 Comparing Biodiversity Index Values to Attributes of the Stormwater Facilities

The best-supported model of taxonomic richness was predicted by turbidity. This accounted for 84% of the cumulative model weight (DeltaAIC = 0, AICcWt = 0.84, $R^2 = 0.34$). I will discuss this specific result in the discussion as this may be specious (Table 3).

Despite the high delta AICc value for dominant land cover, the linear model did show significant difference between dominant land cover types and richness ($F_{4, 19} = 3.82$, $p = 0.019$) (Figure 11)

Table 3: AICc Table for the LM Models with Richness. K represents the number of parameters in the model where categorical variables such as Dom. Land Cover defaulting to dummy variables in R (Burnham & Anderson, 2002; Ong, 2022). AICc is the test score corrected for a small sample size. Delta AICc is the difference in AIC scores between different models. The weight of the AICc represents the model's ability to predict variation in richness. Log likelihood describes the likelihood of the model given the data.

LM Models with Richness							
	K	**AICc**	**Delta_AICc**	**ModelLik**	**AICcWt**	**LL**	**Cum.Wt**
Turbidity	3.00	99.81	0.00	1.00	0.84	-46.31	0.84
Dom. Land Cover	6.00	105.60	5.79	0.06	0.05	-44.33	0.88
Pond Area	3.00	105.95	6.14	0.05	0.04	-49.38	0.92
Perimeter	3.00	106.11	6.30	0.04	0.04	-49.46	0.96
Conductivity	3.00	108.81	8.99	0.01	0.01	-50.80	0.97
DO	3.00	109.56	9.75	0.01	0.01	-51.18	0.98
pH	3.00	109.65	9.83	0.01	0.01	-51.22	0.98
Pond Type	3.00	109.78	9.97	0.01	0.01	-51.29	0.99
Macrophyte Cover	4.00	109.90	10.09	0.01	0.01	-49.90	0.99
Water Temp	3.00	110.02	10.21	0.01	0.01	-51.41	1.00
Algae Cover	5.00	111.62	11.81	0.00	0.00	-49.14	1.00
Substrate	6.00	116.89	17.08	0.00	0.00	-49.97	1.00
Multivariate Model	18.00	117.30	17.49	0.00	0.00	-43.22	1.00

Shannon diversity (H') was also supported primarily by the turbidity model (DeltaAIC = 0, AICcWt = 0.27, R^2 = 0.12), accounting for 27% of the cumulative weight. Alternative models with subsequent support from the data included pond types (DeltaAIC = 0.45, AICcWt = 0.21, R^2 = 0.10) with 21% of the cumulative weight, pond area (DeltaAIC = 0.85, AICcWt = 0.17, R^2 = 0.089) with 17% of the cumulative weight, and pond perimeter (DeltaAIC = 1.68, AICcWt = 0.12, R^2 = 0.06) with 12% of the cumulative weight (Table 4).

Table 4: AICc Table for the LM Models with Shannon. K represents the number of parameters in the model where categorical variables such as Dom. Land Cover defaulting to dummy variables in R (Burnham & Anderson, 2002; Ong, 2022). AICc is the test score corrected for a small sample size. Delta AICc is the difference in AIC scores between different models. The weight of the AICc represents the model's ability to predict variation in richness. Log likelihood describes the likelihood of the model given the data.

LM Models with Shannon							
	K	**AICc**	**Delta_AICc**	**ModelLik**	**AICcWt**	**LL**	**Cum.Wt**
Turbidity	3.00	28.76	0.00	1.00	0.27	-10.78	0.27
Pond Type	3.00	29.21	0.45	0.80	0.21	-11.00	0.48
Pond Area	3.00	29.61	0.85	0.65	0.17	-11.20	0.65
Perimeter	3.00	30.44	1.68	0.43	0.12	-11.62	0.77
Conductivity	3.00	31.12	2.36	0.31	0.08	-11.96	0.85
pH	3.00	32.58	3.83	0.15	0.04	-12.69	0.89
Water Temp	3.00	32.88	4.13	0.13	0.03	-12.84	0.92
DO	3.00	32.90	4.14	0.13	0.03	-12.85	0.96
Macrophyte Cover	4.00	33.18	4.43	0.11	0.03	-11.54	0.99
Algae Cover	5.00	36.48	7.72	0.02	0.01	-11.57	0.99
Dom. Land Cover	6.00	36.48	7.72	0.02	0.01	-9.77	1.00
Substrate	6.00	40.08	11.33	0.00	0.00	-11.57	1.00
Multivariable Model	18.00	171.36	142.60	0.00	0.00	0.72	1.00

Pielou's evenness (J) was best supported by the pond type model (DeltaAIC = 0, AICcWt = 0.27, R^2 = 0.12) accounting for 40% of the cumulative weight (Table 5).

Table 5: AICc Table for the LM Models with Shannon. K represents the number of parameters in the model where categorical variables such as Dom. Land Cover defaulting to dummy variables in R (Burnham & Anderson, 2002; Ong, 2022). AICc is the test score corrected for a small sample size. Delta AICc is the difference in AIC scores between different models. The weight of the AICc represents the model's ability to predict variation in richness. Log likelihood describes the likelihood of the model given the data.

LM Models with Pielou's	K	AICc	Delta_AICc	ModelLik	AICcWt	LL	Cum.Wt
Pond Type	3.00	-19.54	0.00	1.00	0.40	13.37	0.40
Macrophyte Cover	4.00	-17.32	2.22	0.33	0.13	13.71	0.53
Pond Area	3.00	-16.64	2.90	0.23	0.09	11.92	0.62
Turbidity	3.00	-16.44	3.10	0.21	0.08	11.82	0.71
Conductivity	3.00	-16.25	3.30	0.19	0.08	11.72	0.78
pH	3.00	-15.92	3.62	0.16	0.07	11.56	0.85
Perimeter	3.00	-15.86	3.68	0.16	0.06	11.53	0.91
DO	3.00	-14.96	4.58	0.10	0.04	11.08	0.95
Water Temp	3.00	-14.87	4.67	0.10	0.04	11.03	0.99
Algae Cover	5.00	-11.54	8.00	0.02	0.01	12.44	1.00
Substrate	6.00	-8.49	11.05	0.00	0.00	12.72	1.00
Dom. Land Cover	6.00	-8.23	11.31	0.00	0.00	12.59	1.00
Multivariable Model	18.00	126.24	145.78	0.00	0.00	23.28	1.00

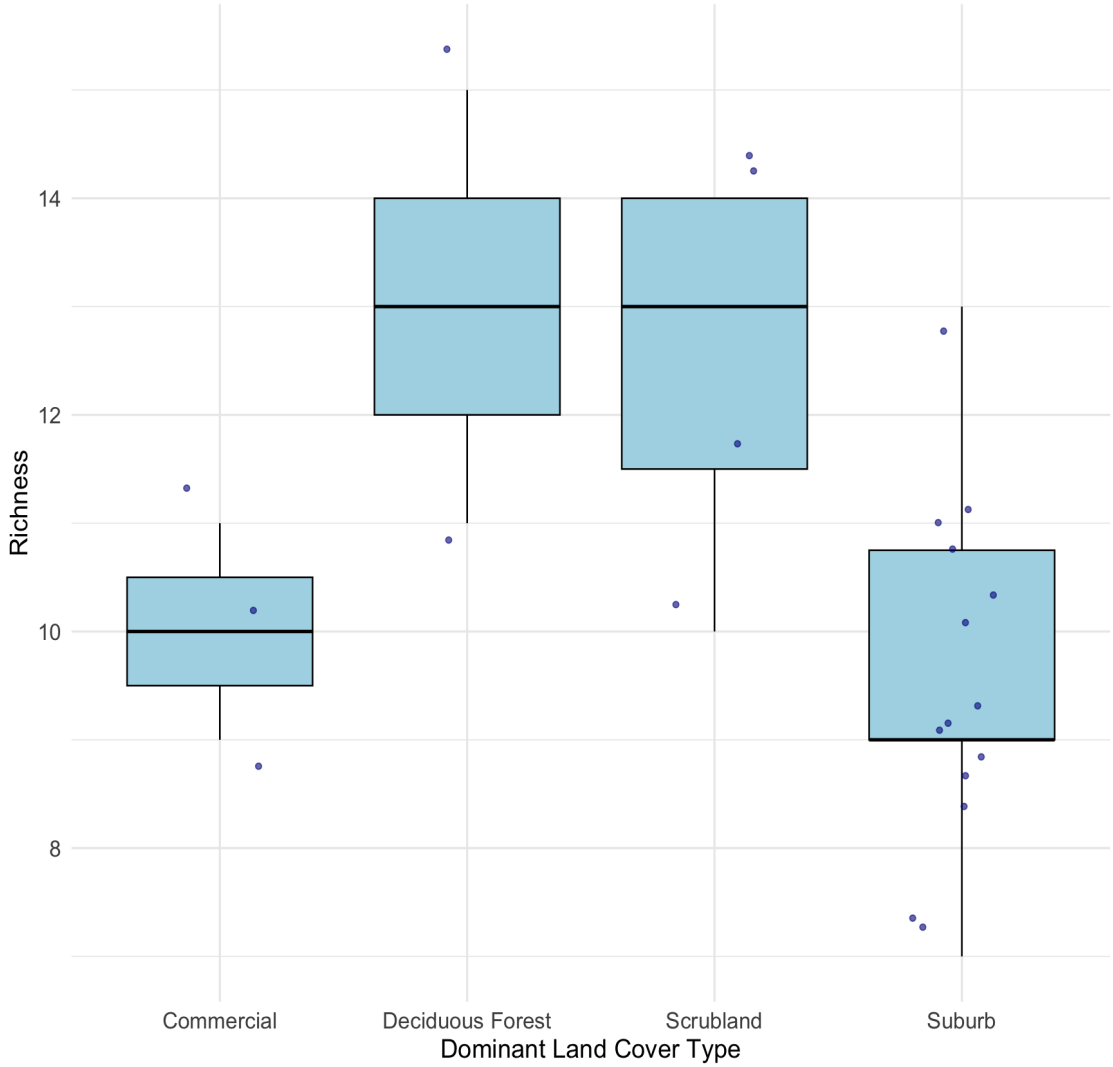


Figure 11: Box plot of richness based on Dominant Land Cover type surrounding the SWMPs in Kitchener Waterloo. Ponds surrounded by natural land cover supported higher richness.

3.2 Comparing Wet Ponds & Engineered Wetlands

Referencing Table 6, richness of macroinvertebrate taxa was not significantly different between wet ponds and engineered wetlands (t = -0.472, p = 0.644, df = 13.52, Table 6). Shannon-Weiner diversity (*H'*) was higher in engineered wetlands (t = -2.316, p = 0.030, df = 21.87, Table 6). Shannon-Weiner diversity was lower in wet ponds (*H'* = 1.457; SE = 0.111;

Figure 12, Table 6) than in engineered wetlands (*H'* = 1.788, SE = 0.100, Figure 12, Table 6). In corroboration, Pielou's evenness (*J*) was also significantly higher in engineered wetlands (*J* = 0.759) than wet ponds (*J* = 0.622, t = -2.630, p = 0.015, df = 21.97, Figure 13, Table 6). Continuing these findings, the % dominant taxa, where the most dominant taxa can skew distribution to one, was significant (t = 3.067, p = 0.006, df =21.60), where wet ponds had a higher % dominant taxa (51.5%, SE = 0.049), whereas engineered wetlands had lower % dominant taxa (34.0%, SE = 0.028).

Although *H'* and *J* differed between stormwater management pond types, I did not observe a difference between these indices' physical characteristics, such as pond area (t = -0.094, p = 0.927, df = 13.90 or perimeter (t = 0.121, p = 0.910, df = 3.60). Additionally, both wet ponds and engineered wetlands exhibited equivalent compactness, shape complexity, and fractal complexity, as well as catchment areas. Most OBBN metrics and biotic indices, such as Hilsenhoff Biotic Index, were not significantly different between the two stormwater management pond types (Table 6).

Table 6: Welch's t-test comparing indices between SWMP types (Wet Pond, Engineered Wetland).

	Wet Pond Mean	Wet Pond SE	E. Wetland Mean	E. Wetland SE	t	p	df	Sig
Pond Area (m^2)	5295.25	1269.13	5503.25	1824.35	-0.09	0.93	13.90	ns
Pond Perimeter (m)	358.57	41.34	397.81	77.48	0.12	0.91	3.60	ns
Permanent Pool Volume (m^3)	2886.20	451.74	2702.00	1450.60	-1.30	0.27	3.35	ns
Shape Index	1.46	0.06	1.62	0.08	-1.63	0.14	7.58	ns
Compactness ratio	0.04	0.00	0.03	0.00	1.85	0.09	10.44	ns
Fractal Dimension Index	1.39	0.01	1.43	0.02	-1.01	0.34	8.63	ns
Catchment Area (HA)	33.33	4.25	23.47	5.89	1.07	0.31	9.02	ns
Water Temp (ºC)	11.55	0.57	10.16	0.58	1.72	0.10	18.77	ns
DO (mg/L)	11.02	0.87	9.01	0.72	1.42	0.17	18.67	ns
pH	7.68	0.18	7.51	0.20	0.58	0.57	16.19	ns
Conductivity (µs/cm)	860.11	144.75	658.56	67.62	0.48	0.64	21.89	ns
Turbidity (FNU)	11.27	2.78	14.95	4.67	0.77	0.45	14.63	ns
PC (µg/L)	1.14	0.22	1.40	0.26	-0.97	0.35	17.31	ns
Chl-*a* (µg/L)	15.97	3.66	19.99	4.99	-1.16	0.26	18.12	ns
Richness	10.31	0.54	10.75	0.75	-0.47	0.64	13.52	ns
H'	1.46	0.11	1.79	0.10	-2.32	**0.03**	21.87	*
J'	0.62	0.04	0.76	0.03	-2.63	**0.02**	21.97	*
%EPT	0.40	0.07	0.21	0.05	1.38	0.20	9.52	ns
%diptera	0.18	0.03	0.20	0.03	-0.02	0.98	5.88	ns
%insects	0.81	0.05	0.75	0.07	0.92	0.39	7.52	ns
%gastropoda	0.05	0.03	0.03	0.01	-0.95	0.41	3.31	ns
%worms	0.11	0.03	0.12	0.04	-0.32	0.76	5.79	ns
%chironomidae	0.16	0.03	0.17	0.03	-0.10	0.92	5.92	ns
%odonata	0.15	0.03	0.19	0.06	-0.17	0.87	7.66	ns
%Amphipoda	0.03	0.01	0.01	0.01	-0.65	0.56	3.15	ns
%hemiptera	0.05	0.01	0.07	0.04	0.04	0.97	7.04	ns
%predators	0.24	0.04	0.31	0.05	0.48	0.64	9.46	ns
%scrapers	0.01	0.00	0.01	0.01	1.51	0.16	9.37	ns
%gatherers	0.06	0.01	0.06	0.01	-0.48	0.64	9.97	ns
%filterers	0.22	0.04	0.23	0.03	-0.99	0.40	3.00	ns
%tolerant	0.48	0.06	0.59	0.06	0.65	0.53	9.74	ns
%intolerant	0.52	0.06	0.41	0.06	0.65	0.53	9.74	ns
%dominant	0.51	0.05	0.34	0.03	3.07	**0.01**	21.60	**
HBI	5.16	0.27	5.60	0.21	-1.47	0.16	21.91	ns
Water Quality	Poor		Poor					

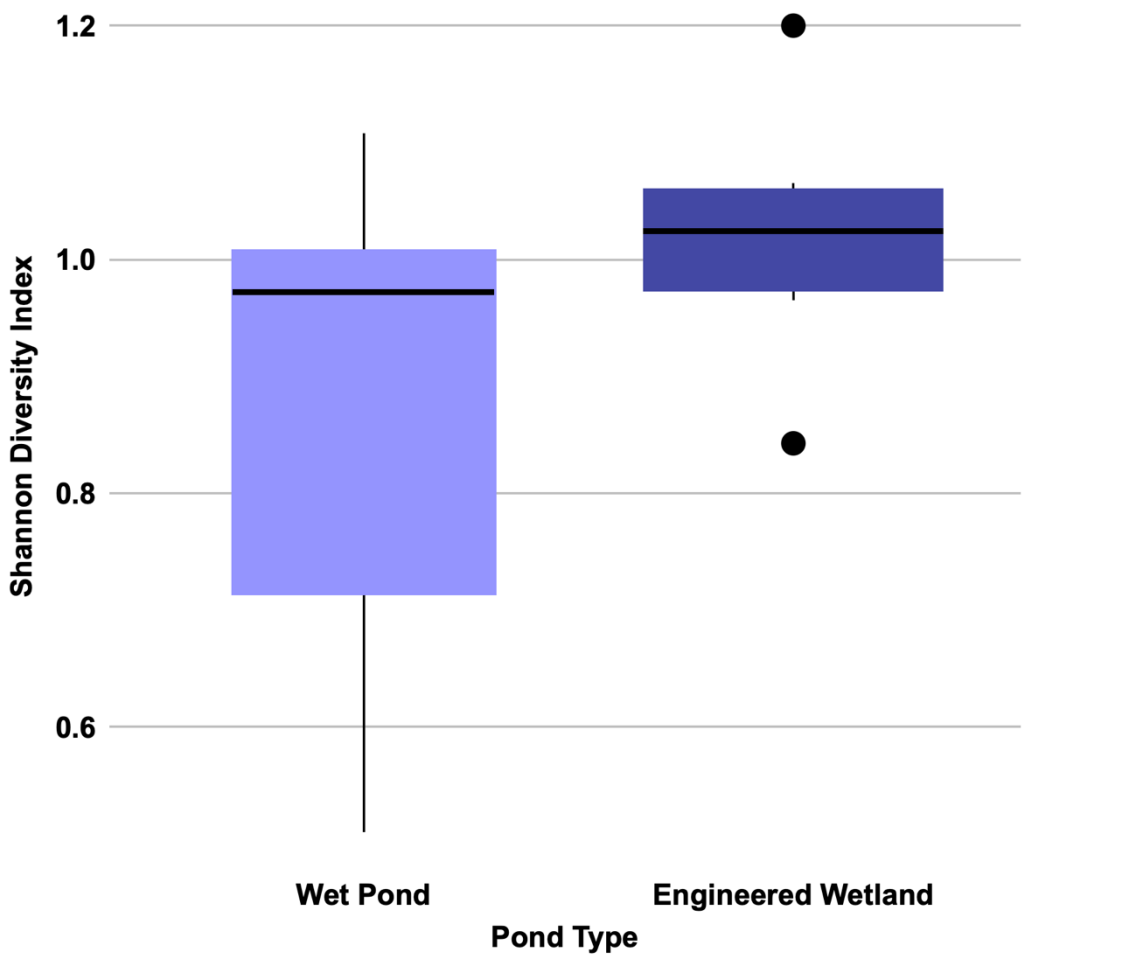


Figure 12: Box plot of Shannon Diversity by Pond Type. Engineered wetlands have higher Shannon Diversity compared to wet ponds.

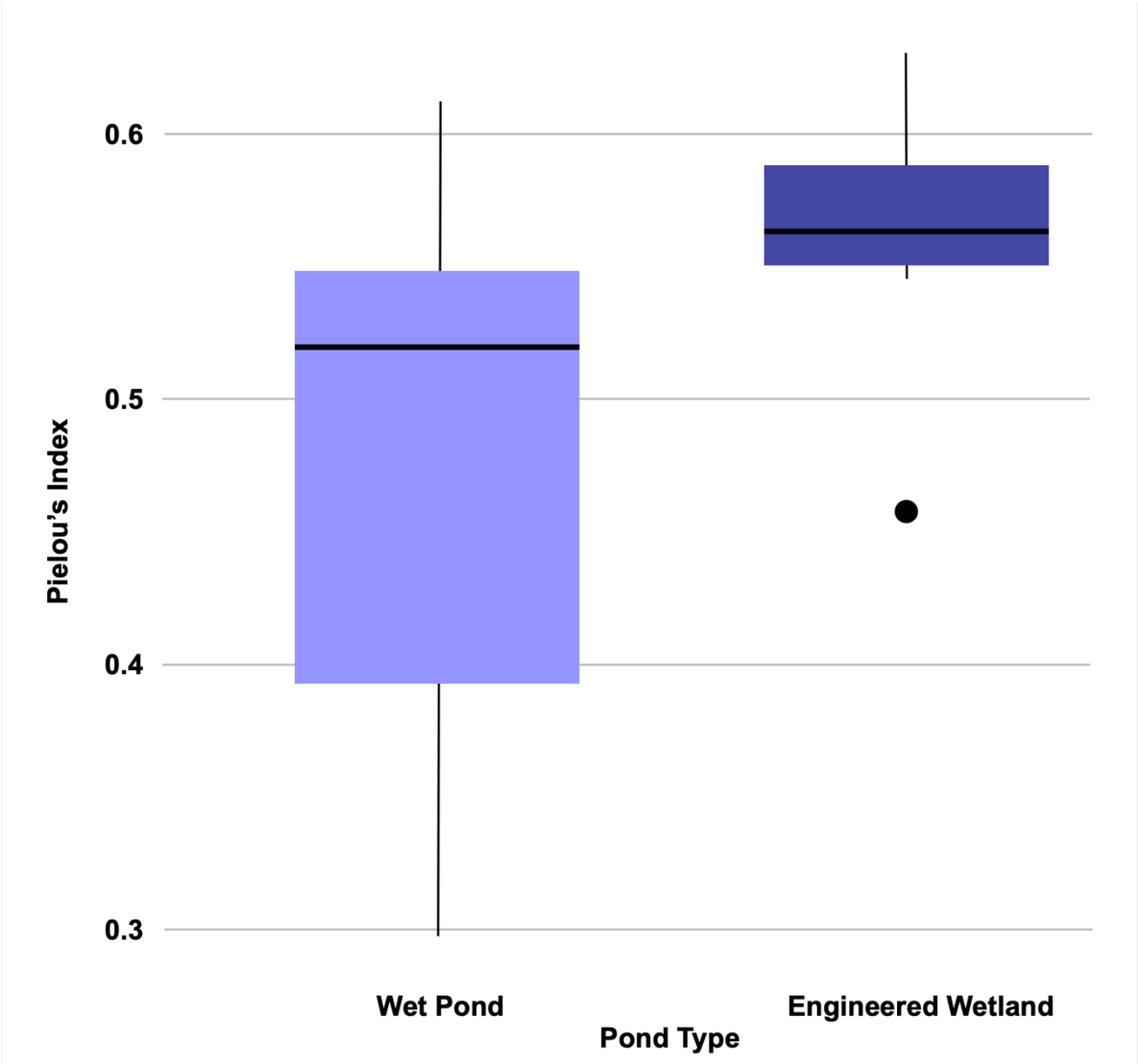


Figure 13: Box plots of Pielou's Evenness by pond type. Engineered wetlands exhibited higher evenness compared to wet ponds.

3.3 Contextualizing OBBN Results from Kitchener-Waterloo Stormwater Management Ponds

First, I assessed the dimensionality for my NMDS ordination using a scree plot of stress versus dimensionality to determine the optimal dimensions needed for reliable ordination. Stress in the model drops significantly after one dimension and plateaus around three dimensions, indicating that a two-dimensional analysis (k = 0.16) is sufficient and reliable for the NMDS (Figure 14). Additionally, a Shepard diagram illustrated a strong fit between ordination distances and dissimilarities in the model, where the non-metric fit (R^2 of 0.974) preserved relative distances among samples (Figure 15).

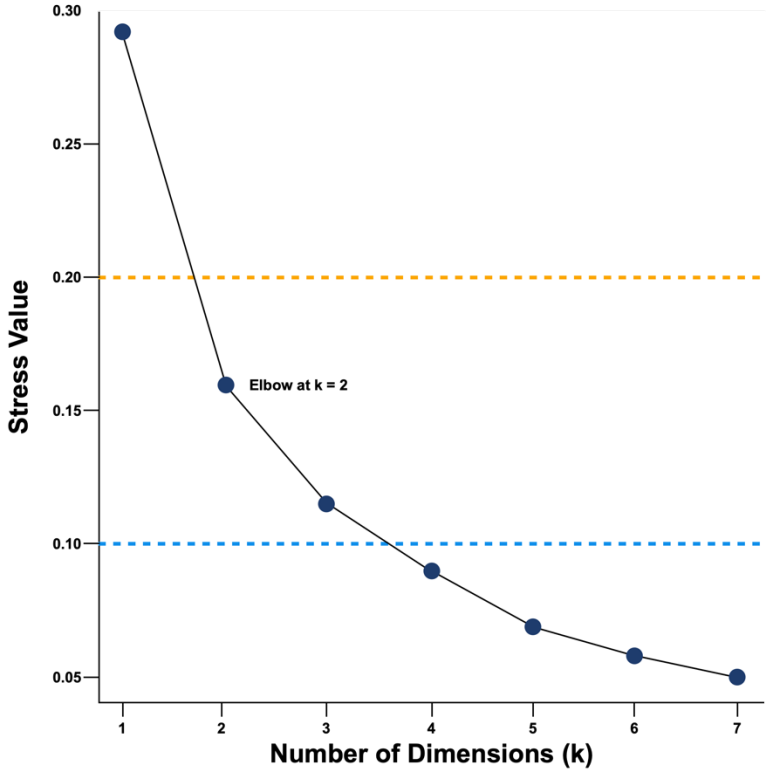


Figure 14: Scree Plot and of NMDS dimensionality. Elbow at k=2, where stress is equal to 0.16 shows a two-dimensional solution is optimal in representing the ordination data.

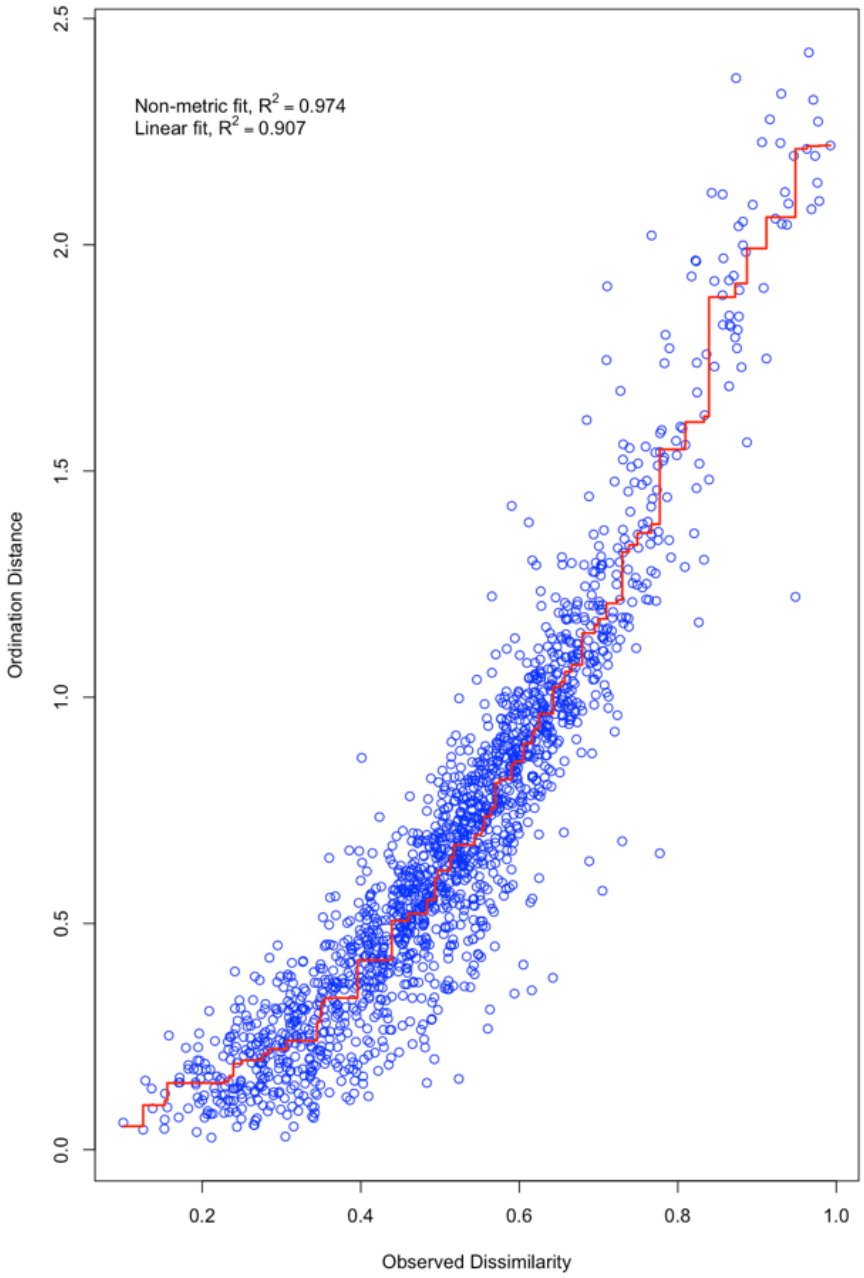


Figure 15: The Shepard plot confirms a strong fit for the ordination data.

I observed a high degree of overlap in community composition between wet ponds and engineered wetlands (Figure 16), particularly when considered in relationship to other published

studies. Corroborating this, an ANOSIM with 999 permutations revealed no significant dissimilarity in their community composition ($R = -0.01061$, $p = 0.526$) (Figure 17).

The stormwater ponds in my study in Kitchener-Waterloo were characterized by taxa often considered sensitive to pollution, such as Ephemeroptera (HBI Value = 3) and Odonata (HBI Value = 4), although they also had a higher relative abundance of Oligochaeta, which are considered pollution-tolerant (HBI Value = 7) (Figure 16). SWMPs in Kitchener-Waterloo tended to have fewer Bivalvia and Amphipoda than the other small lentic systems (Figure 16). This was particularly true in comparison to the UW Environmental Reserve and the Peterborough wetland inlet and outlet, where Chironomidae is abundant (HBI Value = 7). Interestingly, the 95% confidence ellipses around the wet pond and engineered wetlands in my study are relatively small compared to the other studies, indicating that the community composition among my study sites was relatively homogenous, signalling that the SWMPs sampled in Kitchener-Waterloo had lower beta diversity compared with other invertebrate communities captured using the same OBBN field sampling method in Ottawa and Peterborough. However, overall community composition in my stormwater ponds was certainly within the realm of other studies using the same OBBN field methods have observed (Figure 16). The greatest differences I observed were between the Kitchener-Waterloo ponds and UW Environmental Reserve Wetland ($R = 0.934$, $p = 0.001$), the Kitchener-Waterloo ponds and Peterborough's Wetland ($R = 0.642$, $p = 0.001$), the Kitchener-Waterloo ponds and Ottawa's ponds ($R = 0.598$, $p = 0.001$), and the Kitchener-Waterloo ponds and Columbia Lake ($R = 0.417$, $p = 0.001$) reflecting the greater homogeneity in community composition among the stormwater ponds I sampled in my study and the relatively greater heterogeneity in community composition among sites sampled in the other studies (Figure 17).

Due to the high abundance of predator taxa such as dragonflies and damselflies in Kitchener-Waterloo's SWMPs, this suggests the ecological condition of the ponds in Kitchener-Waterloo are relatively good compared with other sites across the province that have employed OBBN methods. Additionally, the high level of worms in Kitchener-Waterloo's SWMPs may suggest more sediment and organic substrates at the bottom of ponds compared to other lentic systems. Contrasting the SWMPs in Kitchener-Waterloo, the facilities documented in Peterborough harboured more pollution-tolerant taxa such as Amphipoda (HBI Value = 8) and Chironomidae, suggesting poorer ecological condition. The increased percentage of gatherers, which feed on fine organic matter, as well as the increased percentage of Diptera and Chironomidae, may signal poor ecological conditions in ecosystems where they dominate. %filterer and taxa like Bivalvia, which filter organic particulates from the water column, were highly abundant in the Peterborough wetlands, along with other pollution-tolerant species that may thrive in poorer ecological conditions.

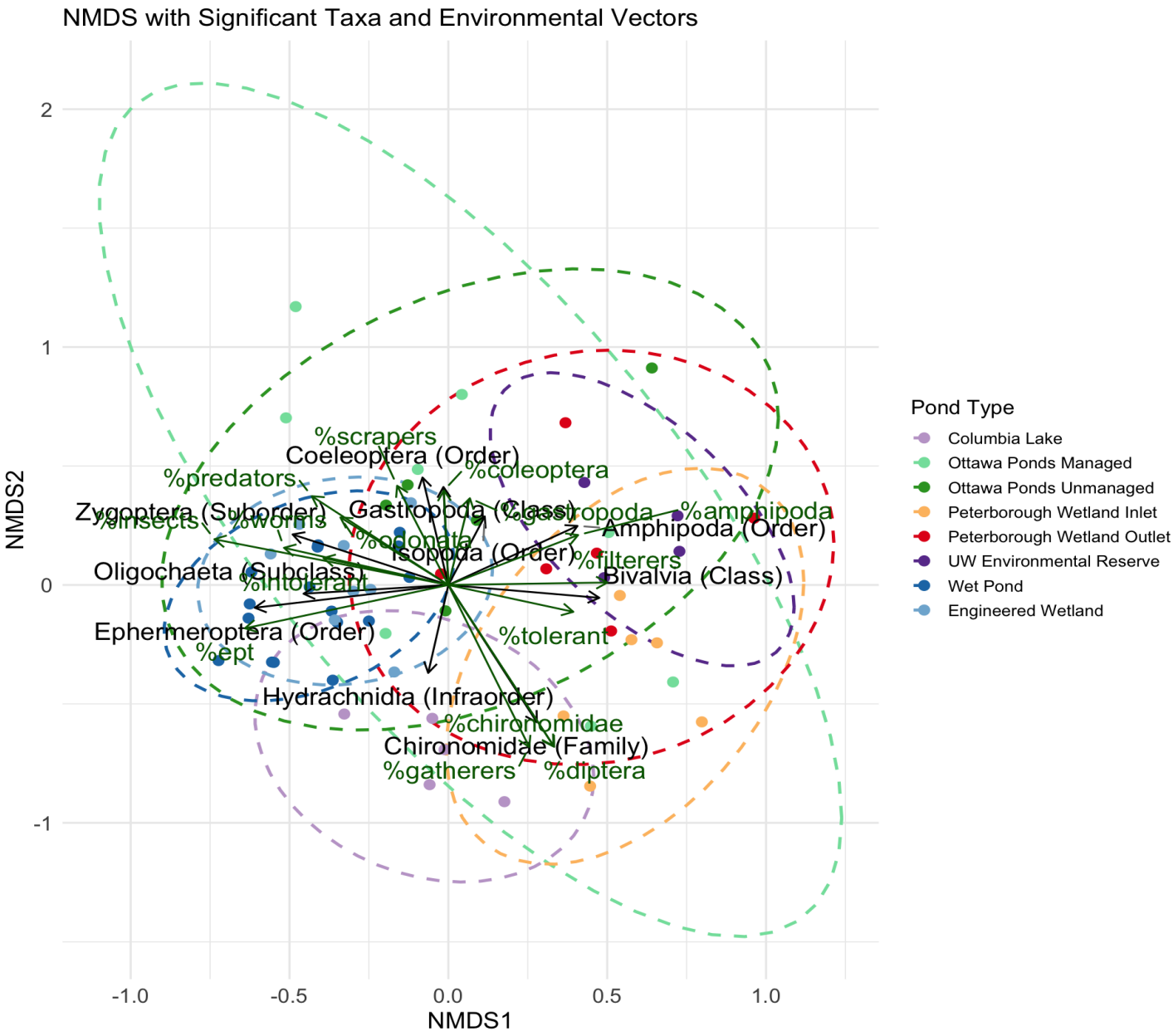


Figure 16: NMDS plot of taxa compared across all Kitchener-Waterloo sites and sites from other published studies that used OBBN in shallow lentic systems. Ellipses surrounding the site points represent a confidence level of 95%. Larger ellipses represent greater variability in community composition among sites or stations, whereas smaller ellipses display more similar community. Overlapping groups display more similarity in community composition than groups at farther distances.

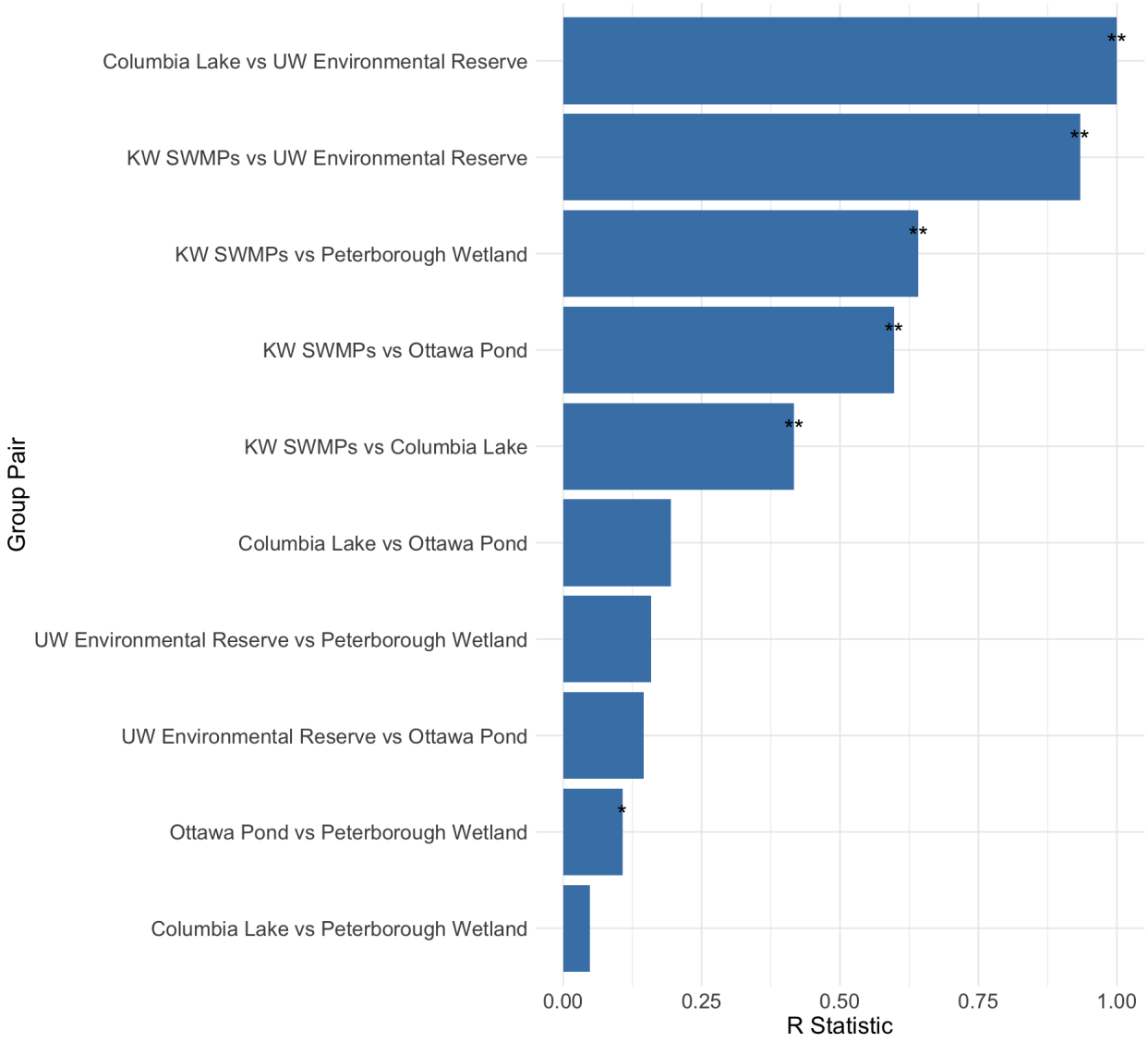


Figure 17: Pairwise ANOSIM values with significance. Differences in SWMPS sampled in Kitchener-Waterloo are similar in community structure to other stormwater management systems (Ottawa ponds) as well as lakes and wetlands in the same region (Columbia Lake and UW Env. Reserve).

Overall, the most abundant taxa of Chironomidae ($R^2 = 0.410$; $p = 0.001$), Ephemeroptera ($R^2 = 0.381$; $p = 0.001$), Amphipoda ($R^2 = 0.227$; $p = 0.001$), and Zygoptera ($R^2 = 0.286$; $p = 0.001$) accounted for the most variance in community composition (Figures 18 & 19).

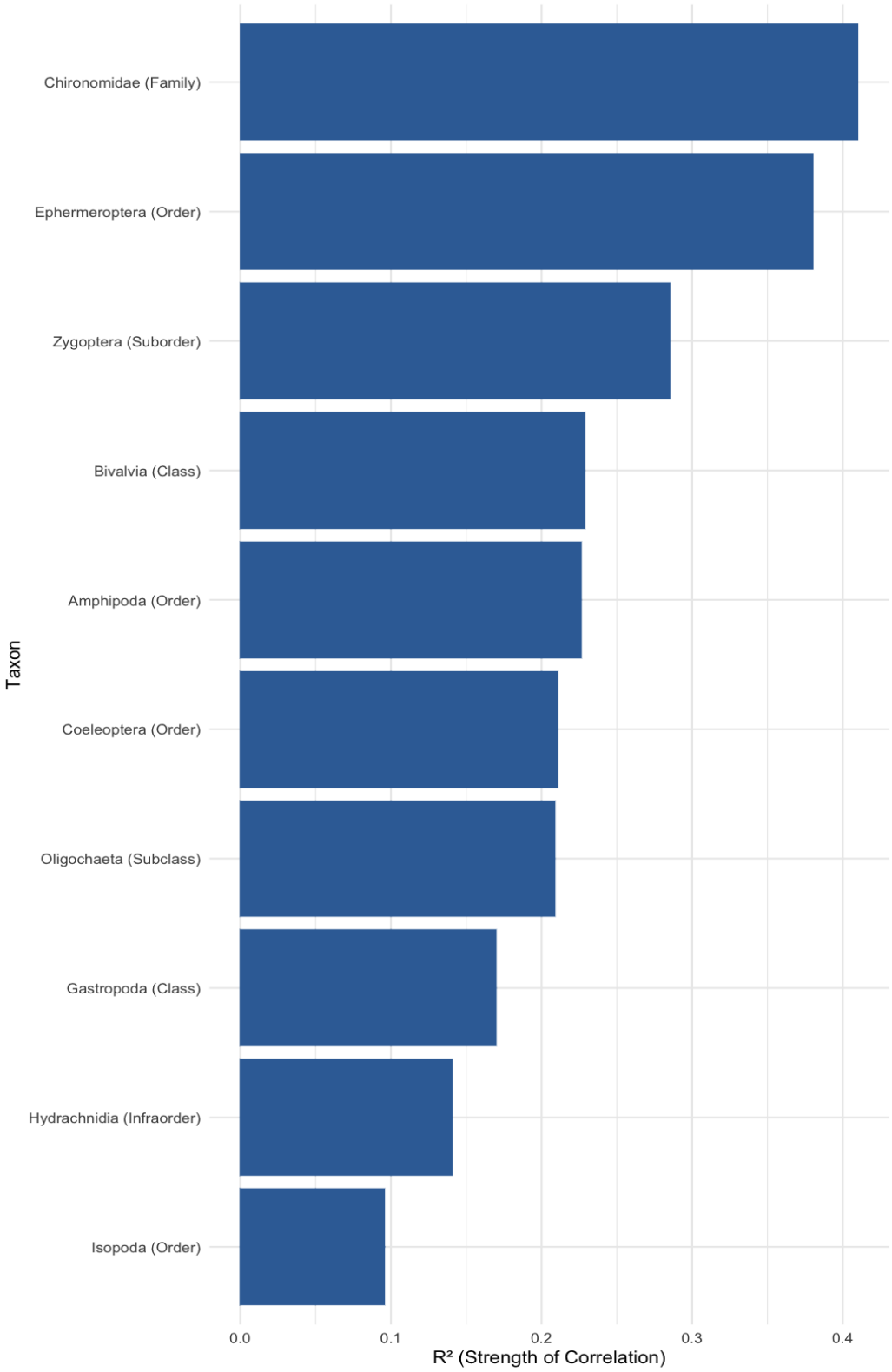


Figure 18: Taxa contribution to the NMDS ordination. Most abundant taxa contribute to the strength of the correlation in the NMDS plot.

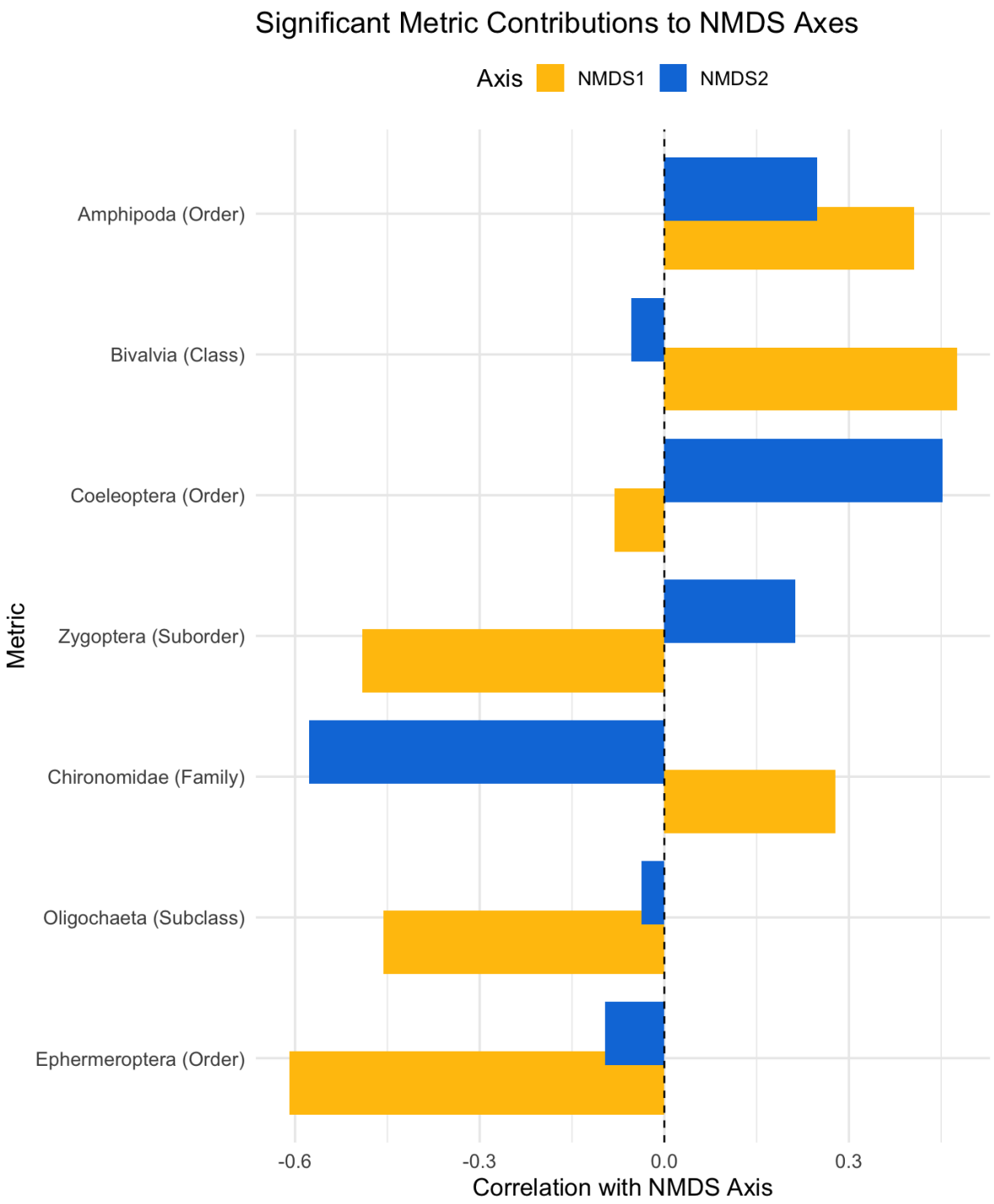


Figure 19: Significant metrics driving taxa community similarity across the NMDS dimensions. Taxa such as Amphipoda, Zygoptera, and Chironomidae influence the dimensions of the NMDS.

4.0 Discussion

The findings in this study show that turbidity (a parameter of water quality), pond design (pond type, pond area, pond perimeter), and landscape context (dominant land cover) influence biodiversity in stormwater management ponds. Additionally, the study also displays that the community composition of ponds in Kitchener-Waterloo is similar across different lentic systems, helping to confirm the meta-analysis findings that biodiversity is similar across pond types. A novel aspect of this study examines the specific differences in pond design, specifically investigating the differences between wet ponds and engineered wetlands. I conclude that engineered wetlands exhibit significantly higher Shannon diversity and Pielou's evenness, but significantly lower % dominants compared to wet ponds. However, when considered in comparison to other available studies using OBBN to characterize the invertebrate community in stormwater ponds and wetlands in Ontario, my wet ponds and engineered wetlands were similar in terms of invertebrate community composition and exhibited relatively low beta diversity.

4.1 Biodiversity indices, values, and attributes of the stormwater facilities

The water quality metric turbidity did correlate with richness and Shannon diversity, but may be a specious correlation. Turbidity can be attributed to several factors, including runoff, bacterial and algal growth, and suspended sediment, all of which impact water quality. Turbidity, phycocyanin, and chlorophyll-*a* exhibited multicollinearity leading to my choice of excluding phycocyanin and chlorophyll-*a* in my model competition. High turbidity is a known stressor for many macroinvertebrates (Forio et al., 2023). In some instances, turbidity can result from increases in chlorophyll-*a* concentrations, as harmful algal blooms caused by increased nutrient loads into the pond may compromise water quality by depleting dissolved oxygen, thereby reducing biodiversity (Heil & Muni-Morgan, 2021). As it impacts macroinvertebrates, algal

blooms can impact water quality, interfering with the chemosensory organs some snails use to find food and hiding places from predatory fish (Turner & Chislock, 2010). Dragonfly and damselfly larvae are also impacted by turbidity whose visual predation is impacted by more turbid water (Bashir et al., 2020). Turbidity caused by silt and other fine sediments can cause abrasion on body parts (Culp et al., 1986), clogging of gills (MacIsaac & Rocha, 1995), and can bury macroinvertebrates leading to mortality (Rutherford & Mackay, 1986). Management of turbidity in aquatic habitats is recommended to foster resilient ecosystems (Forio et al., 2023). The result of turbidity correlating higher richness and Shannon diversity should not be indicative of higher habitat quality in SWMPs as there may be other factors not measured within this study influencing this result.

Pond area and perimeter supported Shannon diversity in the model competition. Similar support for increased pond area has been noted in Holtmann et al. (2019a); they also caution that in their results this increase is related to increased presence of invasive plant species. Additionally, Hassal & Anderson (2015) find pond area to be a good predictor for biodiversity. However, the installation of larger SWMPs may compete with the economic realities of development, where larger ponds substantially increase the costs of development (U.S. Environmental Protection Agency, 2015). As it may be more economically viable to build smaller SWMPs to fit the minimum guidelines provided by design manuals, a homogenous design implementation may impact biodiversity in urban areas.

Commonly, sampling events are conducted in the spring and summer seasons. In the summer, high-temperature runoff from impervious surfaces can affect water temperature in the pond. Increasing water temperature and creating extreme temperature swings have been found to negatively impact species richness (Vannote & Sweeney, 1980). Due to the sampling occurring

in October, temperature in this study does not reflect the potential maximum temperature that may impact invertebrate survival (Bonacina et al., 2023). Macroinvertebrate sampling, depending on the season, has been shown to impact species richness, where autumn sampling events produce greater richness (Hill et al., 2016).

In relation to water temperature, conductivity is associated with differences in community composition in SWMPs and can negatively impact benthic macroinvertebrates (Perron & Pick, 2020b). Conductivity is a measure of water's ability to transmit an electric current; where an increase chloride ions from road salt contribute and influence conductivity (Grand River Conservation Authority, 2025). Salt in shallow lentic systems like SWMPs can persist for a long time, and in summer heat events, can increase in concentration due to evaporation (Evans & Frick, 2001). As SWMPs capture and detain runoff impervious surfaces, the resulting sedimentation of salts in a SWMP can be retained throughout rain events (Goldman & Horne, 1983; Wetzel, 1983). Due to our October sampling, road salt and other pollutants that would raise conductivity may have been gradually diluted by autumn rain events. Similar observations of conductivity in different aquatic systems find lower conductivity in autumn (Cockerill et al., 2017).

As summer temperature influences these stressors on macroinvertebrates, the community composition I found in October may be an indicator of the invertebrates that survived through the summer; this may show a broader temporal relation between community composition and SWMP conditions by using macroinvertebrates as bioindicators for pollution (Erasmus et al., 2021; Orozco-González & Ocasio-Torres, 2023). For a clearer understanding of how temperature and conductivity could impact macroinvertebrate communities, I recommend taking water

quality measurements of the ponds throughout the summer and autumn to better represent the temperature and conductivity extremes.

4.2 Pond Design and Land use Impact Biodiversity in Ponds

SWMP design is an important driver in supporting biodiversity in urban aquatic environments, where engineered wetlands had higher Shannon diversity and Pielou's evenness than in wet ponds. As part of their design, both wet ponds and engineered wetlands must contain a permanent pool of water throughout the year. However, the differences between the facilities may impact the community assemblages more likely to be found. Wet ponds, for instance, are often designed with deeper detention basins, whereas engineered wetlands are shallower in both their permanent detention basin and open water area (Government of Ontario, 2003). Due to the shallow nature of engineered wetlands, they often need more land to achieve their management goals. Shallow pond habitats are noted to harbour higher macroinvertebrate biodiversity compared to deeper ponds and shallow lakes where an absence of insectivorous fish in shallow ponds promoting higher macroinvertebrate diversity (Scheffer et al., 2006). Similarly, a study investigating trophic interactions suggest that juvenile fish predation limits macroinvertebrate densities and diversity (Batzer et al., 1998).

Anthropogenic transformation of land is crucial for understanding biodiversity loss within urbanized areas. Land cover, and the type of cover that surrounds the surrounding landscape are important when considering the connection between the land around these facilities and the ecosystems that support richer aquatic communities. Biodiversity loss can be attributed to changes in the surrounding land cover available for biota to collect resources and create habitat (Braat et al., 2008). Increasingly, built-up areas within urban and suburban

landscapes are fragmenting and isolating populations, leading to declines in species richness (Miller & Hobbs, 2002). Suburbs as a form of land cover are not included in the list of OBBN land cover examples, along with commercial, industrial, and agricultural lands. Within this framework, an information gap had to be addressed under the highly urbanized landscape.

Many benthic macroinvertebrates need both aquatic and terrestrial resources to be successful, making the resources adjacent to the pond important when installing a SWMP. Designing SWMPs with a significant riparian area, as well as other habitat types like planting forests at a distance to the pond may create better environments for the macroinvertebrates in the pond (Samways and Steytler, 1996; Plenzler & Michaels, 2015).

4.3 Macroinvertebrate communities in SWMP are similar to other lentic systems.

Across the lentic systems I compared to Kitchener-Waterloo's SWMPs, such as Hassall & Anderson (2015), Esmail (2022), and Hogg (2006), the community composition is similar. Particularly as it relates to SWMPs, the consistent design and implementation of these facilities in the urban-suburban landscape may homogenize aquatic ecosystems and homogenize community composition. This homogenization effect is not new within the literature as other studies have noted this phenomena in various taxa including a flattening of diatom diversity across continents (Minelgaite et al., 2020). Similarly, I found significant overlaps in community composition across different sites in Ontario. Urbanization and the homogenization of the landscape may be one key factor in describing the results of this chapter. The "Urban Homogenization Hypothesis" posits that cities and other urbanized land use changes lead to alterations in ecologies due to development practices (McKinney 2006; Groffman et al., 2014). Likewise, due to continued pressures of developments on natural wetlands, richer communities exist in natural wetlands compared to communities to developed lands (Groffman et al., 2017).

As it relates to the findings in this chapter, I found significant differences in taxa richness depending on the land cover that surrounds a SWMP. Likewise, despite engineered wetlands having higher biodiversity than wet ponds, the land cover surrounding the ponds may indicate a broader challenge for municipal planners who want to design biodiverse neighbourhoods.

If SWMPs are designed to be similar, the community composition of these ecosystems may become less even, favouring taxa that can better adapt to the urban environment. The distribution of taxa that are more tolerant in urban contexts may drive out sensitive species from the urban landscape (McKinney & Lockwood, 1999). While many ecologists argue that SWMPs may be important pieces in preserving urban biodiversity, the task of advocating for SWMPs to become high quality habitat directly challenges the infrastructure needs of municipalities.

4.4 Challenges with OBBN

This chapter incorporates components that rely on open data through municipal partners, as well as supplemental data from other sources (Esmail, 2022; Hassall & Anderson, 2015; Hogg, 2006) that are not submitted into the OBBN database. Much of the data on OBBN's database consists of streams and northern lakes within a different biogeographical realm from Southwestern Ontario. Of the available wetlands in the database, only three entries are present. Data entry into the system is dependent on the end user. Overall, there is a missed opportunity for future research due to a lack of adequate wetland reference data, and studies using OBBN in shallow lentic systems to evaluate habitat condition would benefit from more shared data collected from healthy, intact wetlands to help contextualize results from systems like SWMPs. Future research using methods other than OBBN such as Canadian Aquatic Biomonitoring Network protocol (CABIN) (Environment and Climate Change, 2017) may be an alternative if no reference data is in the OBBN database for shallow lentic ecosystem types.

5.0 Final thoughts and recommendations

Overall, stormwater management facilities such as wet ponds and engineered wetlands are an important component of blue-green infrastructure in urban areas. These pieces of infrastructure demonstrate the importance of facility type when choosing to design for biodiversity in urban areas. Community composition of macroinvertebrates sampled from SWMPs across the province was relatively similar, and the composition of wet ponds and engineered wetlands that I sampled in the Kitchener-Waterloo region formed a nested subset of that broader variation in composition. Although in the context of other published studies, the community composition of macroinvertebrates was very similar between wet ponds and engineered wetlands, pond type was the best predictor of Pielou's evenness and a reasonable predictor of Shannon diversity, with both these indices being higher in engineered wetlands and % dominants being higher in wet ponds.

The nature of SWMPs within a landscape creates a critical understanding that the aquatic and terrestrial realms of blue-green infrastructure are more vital in fostering biodiverse urban areas. Increasing biodiversity within ponds is a task that involves ensuring both aquatic and terrestrial habitats are heterogeneous and unique, providing niche opportunities for specialists in an increasingly generalist landscape. Although municipalities classify SWMPs as stormwater infrastructure, there is an opportunity to incorporate these facilities into a region's biodiversity goals.

Developers also have an opportunity to contribute to addressing biodiversity concerns by implementing more engineered wetlands over wet ponds. Connecting to nature is a key feature that many residents in neighbourhoods value and may provide community benefits, such as becoming a community gathering space (Ureta et al., 2021). While design guidelines provided by

municipalities maintain flood protections, residents often view stormwater ponds as places to connect with the environment. Socially, the implementation of engineered wetlands can provide ecosystem services while offering key points of cultural connection between a neighbourhood and urban nature. For these reasons, municipalities and the developers who build SWMPs can "innovate" when designing stormwater infrastructure with biodiversity in mind.

Chapter 4: Ponds in Perspective – Integrating Findings and Looking Ahead

1.0 Thesis Summary

This thesis set out to investigate the stormwater management facilities in Kitchener-Waterloo. With my research, I aim to inform the RISE project and its partners about macroinvertebrate biodiversity in urban and suburban SWMPs.

In the introductory chapter, I covered what a SWMP is, why SWMPs are important, and conducted a text analysis of the stormwater master plan documents for the cities of Kitchener, Waterloo, and Cambridge. I found that these documents precisely describe SWMPs as pieces of infrastructure that protect private property rather than identifying them as being natural heritage features that provide important wildlife habitat in urban and suburban areas. The findings in the text analysis reveal that municipalities in the Waterloo Region approach stormwater management ponds as utilities instead of imagining them as providing habitat within cities.

Next, I presented an extended literature review and performed a meta-analysis on papers comparing SWMPs to control ponds. I found that both SWMPs and control ponds harbour similar levels of biodiversity. This agrees with a similar recent meta-analysis carried out by Ferzoco and McCauley (2024), who compared 11 studies, 3 of which were different from the 18 I compared. They conclude that there is no difference between SWMPs and control ponds. Similarly, they also found challenges in understanding the term “control pond” in the studies. One of the challenges I faced when conducting the meta-analysis was the use of the control pond as a reference within different landscapes. Study design and landscape context across multiple studies and geographies posed a challenge in detangling if there is a significant difference in biodiversity in SWMPs versus control ponds. In terms of what factors influence biodiversity in stormwater ponds, my meta-analysis revealed a weak but not statistically significant effect of

water quality. For future research, I recommended exploring mammalian use of SWMPs as invertebrates and amphibians are highly represented in the literature.

Lastly, I presented my analysis investigating the predictors of biodiversity in stormwater management ponds, comparing wet ponds and engineered wetlands, and compared the ponds in Kitchener-Waterloo to other small lentic systems. I found a correlation between turbidity and richness in ponds, although this finding may be due to multicollinearity. Next, I found that land cover surrounding the ponds influenced richness in the pond where ponds surrounded by forest and scrubland increased richness, displaying the importance of connecting the aquatic realm to the terrestrial. As well, I found engineered wetlands have higher levels of Shannon diversity and Pielou's evenness compared to wet ponds. Additionally, I found that wet ponds tended to have a higher percentage of dominant species compared engineered wetlands. Ultimately, I found that community composition between Kitchener-Waterloo's ponds are similar to other small lentic systems in Ontario.

As SWMPs are an increasingly researched field within ecology, I would recommend that future researchers in the area of urban aquatic ecology consider what benchmark would be suitable as a reference in an urban ecosystem. Particularly for research in Ontario where OBBN methods are common, publishing and uploading results to the OBBN data repository will make new research more accessible for those interested in understanding how cities are impacting biodiversity. As there are relatively few studies that investigate local biodiversity in SWMPs, and even fewer natural reference sites in urbanized areas, considering what a benchmark pond, and having the available data to use as a reference may help to standardize methods for future research.

2.0 Future Research & Opportunities

Regarding the two data chapters, many research questions can be opportunities for future research. To start, there is a significant research gap in the use of stormwater ponds by mammals. Colleagues have encountered beavers in SWMPs; additionally, I have encountered stoats hunting waterfowl. Interactions during field research in an urban area often spark curious conversations with community members. In multiple instances, coyotes have been noted as a concern. Community members have reported coyotes as drinking and preying on waterfowl and other small animals around SWMPs. While I find macroinvertebrates critical to understanding pond biodiversity, coyotes are a major concern for community members. As urban and suburban development encroaches on coyote habitat, understanding how coyotes move in a landscape and use SWMPs can be an important area for research and community engagement.

Next, there is an opportunity for municipalities who are creating environmental and biodiversity strategies. In January 2022, the City of Kitchener developed an urban forestry strategy plan to increase the city's tree canopy coverage to 30% by 2030 (City of Kitchener, 2024). As they mention in their plan, the biodiversity of terrestrial habitats is a key issue in achieving this 30% goal; the city has identified that reaching the minimum 30% goal is crucial to ensuring connectivity and promoting biodiversity. As presented in the title of this thesis, SWMPs are systems that transition between aquatic and terrestrial habitats. Referencing the findings in Chapter 2, stormwater management ponds owned by the City of Kitchener. Ponds in landscapes with greater forested land cover than suburban land cover had higher macroinvertebrate richness; this aligns with the city's greening goal and potentially broadening biodiversity across terrestrial and aquatic assets. An example of a Canadian city that takes an integrated stormwater-biodiversity approach is the City of Vancouver. The City of Vancouver has received funding

from both provincial and federal governments to implement its “Rain City” strategic planning goals (City of Vancouver, 2025). With this strategy, the city plans to re-imagine stormwater not as a waste product but as an active resource. With over 300 projects in the process of coming online, Vancouver has directly addressed biodiversity as a part of their blue-green infrastructure. They emphasize the importance of designing and creating a inclusive stormwater system with a focus on making nature more accessible (City of Vancouver, 2025). Integration into wider park systems, as well as active systems such as multi-use trails for recreation, imagines a future for the city of Vancouver that keeps more water in its urban watershed to use as an asset for ecological and cultural well-being. The City of Kitchener’s stormwater management master plan does push for further integration between stormwater assets and ecological and cultural services like the naturalization of portions of the creeks throughout the city. While Kitchener does not currently have biodiversity as a project goal within its stormwater master plan, the naturalization of these creeks could be a step towards implementing biodiversity planning when revitalizing critical stormwater assets.

Recently, the City of Waterloo has engaged with its citizens on an updated park master plan for Waterloo Park. A defining feature of the park includes wetland meadow habitat along the banks of Laurel Creek, which flows into Silver Lake, a large stormwater facility that is the focal point of the park. Public outreach and public input for the project, as of writing this thesis, is currently open for recommendations with many comments focusing on maintaining natural heritage features of the park (City of Waterloo, 2025). The public's interest in the natural areas of Waterloo Park reflects their interest in maintaining and promoting biodiverse parks.

3.0 Significance & Concluding Remarks

Before European settlement in North America, wetlands comprised 25% of Southern Ontario's land cover; it is also in these former wetlands that most of Ontario's urban lands have developed (Lysyk, 2023). The unintended consequences of suburban development under our current approach to stormwater design present an opportunity to improve current implementation measures while addressing urgent biodiversity conservation concerns. Understanding the biodiversity of stormwater management ponds will help municipalities develop more robust blue-green design manuals, which ensure builders and developers design biodiverse neighbourhood SWMPs.

Firstly, the significance of my text analysis lies in quantifying the context of municipal planning documents, highlighting a gap in communicating biodiversity initiatives in regional cities. Secondly, the significance of my meta-analysis shows there are many similarities between SWMPs and control ponds in supporting broader urban biodiversity. Specifically, ponds surrounded by suburbs had lower levels of richness compared to facilities surrounded by more natural land cover. As well, engineered wetlands offer the co-benefits of enhanced biodiversity and improved flood mitigation compared to traditional wet ponds in urban areas.

While this project has brought forward key insights, there are significant challenges that may impact the implementation of my research. Over the past couple of years while conducting my research, the Ontario government has signalled and made sweeping changes to provincial legislation that can impact vital wetland and aquatic ecosystems in the province. Firstly, an amendment of the *Conservation Authorities Act, R.S.O. 1990*, known as *Regulation detailing new Minister's Permit and Review powers under the Conservation Authorities Act* (Government of Ontario, 2025b)will weaken conservation authorities' power when developers appeal permits.

Under this amendment, developers will no longer need licenses from a conservation authority and may build developments closer to critical wetlands. Under this amendment, developers can build closer to critical wetland habitat while increasing their development with an undetermined flood risk. Secondly, *Bill 17, Protect Ontario by Building Faster and Smarter Act, 2025* (Government of Ontario, 2025) impacts housing and infrastructure development by sidelining municipal planning documents with the goal of the legislation to build the Government's projected 1.5 million new homes. These homes, which need SWMPs to protect against floods, will continue to shape and change the urban landscape across the province, and importantly, and will significantly undercut municipalities who want to create and enforce sustainability design guides.

As ecologists, we must understand how these shifts in legislative language will impact the environments where we conduct research. While ecology and environmental advocacy are separate, I think it is important for ecologists, especially urban ecologists, to speak up and advocate for nature within our cities. We ecologists study the organisms, populations, and communities, and how biotic & abiotic factors interact within the broader ecosystem; we ecologists can mobilize this knowledge to become stewards of the urban environment. Over the past two years, I have made these stormwater ponds a significant focus in my life. I appreciate the SWMP as a feature in the urban landscape, and when biking across sites, I see the cultural and ecological value of these facilities. When one views a stormwater management pond as infrastructure, it strips the SWMP of its ecological context. To consider the SWMP as a critical piece in promoting urban aquatic habitat, we need to collectively re-signify the SWMP as a piece of infrastructure to one that is habitat.

To conclude, SWMPs are important within the urban landscape despite their complex relationships with communities, ecologists, developers, government, and benthic

macroinvertebrates (the list of stakeholders is extensive). I hope that designing for biodiversity will be beneficial for the neighbourhoods that will have access to blue-green infrastructure and the biota that inhabit the ponds. I am reminded of queer theorist José Esteban Muñoz, who relates queerness as a horizon that allows us to inspire movement toward a reality that glimpses beyond the present (Muñoz, 2009). Hope is not a naivety, but a critical transformation that creates a future where SWMPs become something more than pieces of infrastructure. I invite the readers to go outside and spend time at their local SWMP and experience the unintentional habitat this infrastructure supports.

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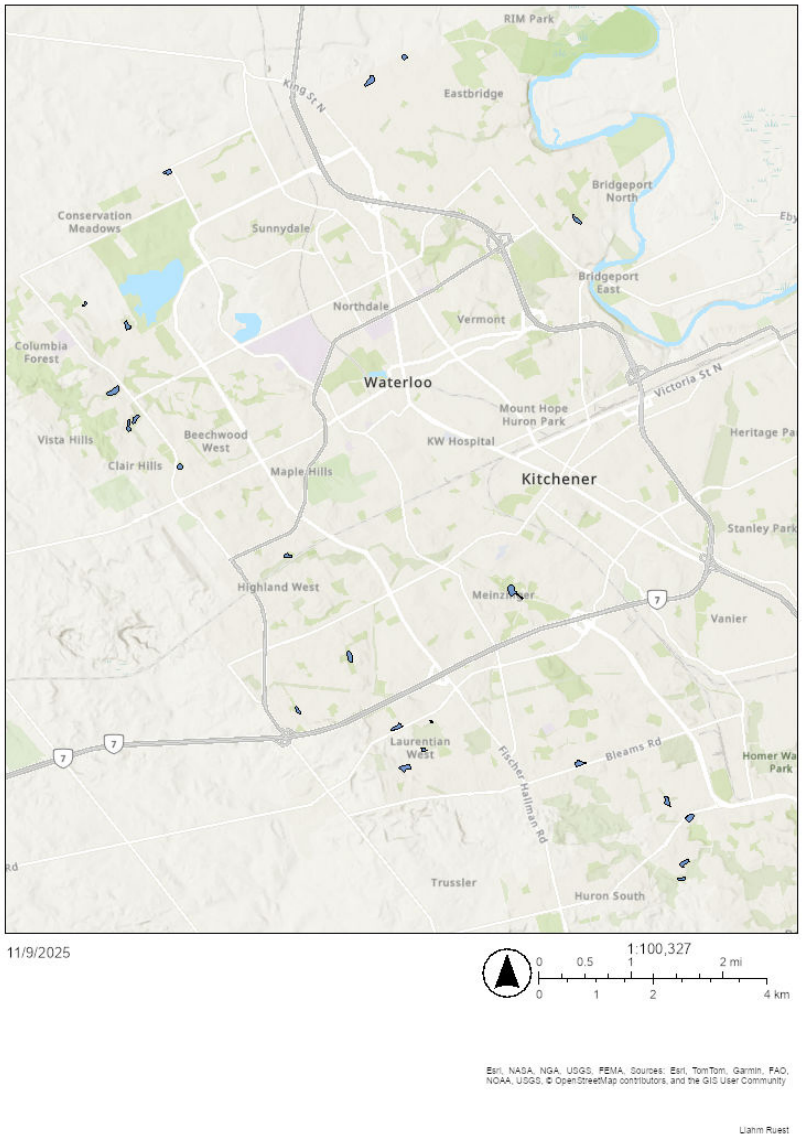
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Appendix & Supplementary Data

Appendix 1: Map of SWMP sites in Kitchener-Waterloo



Appendix 2: Table of Linear Models used in the Model competition as it relates to pond determinants against biodiversity metrics of richness, Shannon diversity, and Pielou's evenness

Model Competition Linear Models Testing Pond Parameters with Biodiversity Index									
	Richness			***H'***			***J***		
	p	SE	R^2	p	SE	R^2	p	SE	R^2
Pond Area	0.056	1.98	0.1178	0.0857	0.4031	0.0887	0.208	0.154	0.0289
Permanent Pool Volume	0.115	2.08	0.139	0.731	0.4251	-0.0787	0.663	0.158	-0.0713
Catchment Area	0.345	1.88	-0.0033217	0.208	0.3789	0.03591	0.276	0.145	137
Pond Perimeter	0.061	1.984	0.1119	0.137	0.4101	0.0566	0.345	0.156	0.345
Shape Index	0.309	2.102	0.003645	0.747	0.4307	-0.0404	0.897	0.159	-0.0446
Compactness Ratio	0.473	2.13	-0.02068	0.645	0.4296	-0.0352	0.8719	0.159	-0.0442
Fractal Dimension Index	0.862	2.15	-0.04399	0.361	0.4235	-0.00574	0.296	0.156	0.006331
Water Temp	0.949	2.153	-0.04526	0.892	0.432	-0.0446	0.962	0.159	-0.0454
DO	0.52	2.132	-0.02555	0.947	0.432	-0.0452	0.764	0.159	-0.0411
pH	0.56	2.136	-0.02911	0.592	0.429	-0.0316	0.331	0.156	-0.000454
Conductivity	0.296	2.099	0.0063	0.206	0.416	0.0294	0.266	0.155	0.013
Turbidity	**0.00247**	1.74	0.3169	0.0538	0.396	0.1205	0.234	0.154	0.0212
Chl-*a*	**0.00331**	1.762	0.2999	**0.0253**	0.384	0.1716	0.117	0.151	0.0671
PC	**0.00967**	1.843	0.234	0.097	0.405	0.08016	0.309	0.156	0.00358
Dom. Land Cover	**0.0192**	1.724	0.3292	0.274	0.409	0.06388	0.6295	0.161	-0.0635
Macrophyte Cover	0.2659	2.069	0.0345	0.317	0.418	0.01836	0.0957	0.146	0.0957
Algae Cover	0.275	2.054	0.0481	0.5346	0.429	-0.0336	0.4934	0.158	0.4934
Substrate	0.6637	2.182	-0.0737	0.6542	0.4797	-0.07616	0.5918	0.1601	-0.05209
Pond Type	0.642	2.142	-0.03499	0.0686	0.3997	0.1039	**0.0406**	0.145	0.1396

Appendix 3 (1/3): List of Linear Models of Richness, Shannon diversity, and Pielou's diversity used in AIC Model Competition.

Variable Tested	Linear Model
Pond Area	lm(Richness~`Pond Area_m2`, data=dat_1)
Pond Volume	lm(Richness~`Perm Pool_m3`, data=dat_1)
Pond Perimeter	lm(Richness~`Pond Perimeter`, data=dat_1)
Conductivity	lm(Richness~`Conductivity_us`, data=dat_1)
pH	lm(Richness~`pH`, data=dat_1)
Water Temp	lm(Richness~`Water Temp_C`, data=dat_1)
DO	lm(Richness~`Turbidity_FNU`, data=dat_1)
Macrophyte Cover	lm(Richness ~ `Macrophyte Cover`, data=dat_1)
Algae Cover	lm(Richness ~ `Algae Cover`, data=dat_1)
Dominant Land Cover	lm(Richness ~ `Dominant Land Cover Overall`, data=dat_1)
Substrate	lm(Richness ~ `Substrate`, data=dat_1)
Multivariate Model	lm(Richness ~ `Pond Area_m2`+`Perm Pool_m3`+`Pond Perimeter`+`Conductivity_us`+`pH`+ Water Temp_C`+`Turbidity_FNU`+`Macrophyte Cover`+`Algae Cover`+`Dominant Land Cover Overall`+`Substrate`, data=dat_1)

Appendix 3 continued (2/3): List of Linear Models of Richness, Shannon diversity, and Pielou's diversity used in AIC Model Competition.

Variable Tested	Linear Model
Pond Area	lm(Pielou~`Pond Area_m2`, data=dat_1)
Pond Volume	lm(Pielou~`Perm Pool_m3`, data=dat_1)
Pond Perimeter	lm(Pielou~`Pond Perimeter`, data=dat_1)
Conductivity	lm(Pielou~`Conductivity_us`, data=dat_1)
pH	lm(Pielou~`pH`, data=dat_1)
Water Temp	lm(Pielou~`Water Temp_C`, data=dat_1)
DO	lm(Pielou~`Turbidity_FNU`, data=dat_1)
Macrophyte Cover	lm(Pielou ~ `Macrophyte Cover`, data=dat_1)
Algae Cover	lm(Pielou ~ `Algae Cover`, data=dat_1)
Dominant Land Cover	lm(Pielou ~ `Dominant Land Cover Overall`, data=dat_1)
Substrate	lm(Pielou ~ `Substrate`, data=dat_1)
Multivariate Model	lm(Pielou ~ `Pond Area_m2`+`Perm Pool_m3`+`Pond Perimeter`+`Conductivity_us`+`pH`+ Water Temp_C`+`Turbidity_FNU`+`Macrophyte Cover`+`Algae Cover`+`Dominant Land Cover Overall`+`Substrate`, data=dat_1)

Appendix 3 continued (3/3): List of Linear Models of Richness, Shannon diversity, and Pielou's diversity used in AIC Model Competition.

Variable Tested	Linear Model
Pond Area	lm(Shannon~`Pond Area_m2`, data=dat_1)
Pond Volume	lm(Shannon~`Perm Pool_m3`, data=dat_1)
Pond Perimeter	lm(Shannon~`Pond Perimeter`, data=dat_1)
Conductivity	lm(Shannon~`Conductivity_us`, data=dat_1)
pH	lm(Shannon~`pH`, data=dat_1)
Water Temp	lm(Shannon~`Water Temp_C`, data=dat_1)
DO	lm(Shannon~`Turbidity_FNU`, data=dat_1)
Macrophyte Cover	lm(Shannon ~ `Macrophyte Cover`, data=dat_1)
Algae Cover	lm(Shannon ~ `Algae Cover`, data=dat_1)
Dominant Land Cover	lm(Shannon ~ `Dominant Land Cover Overall`, data=dat_1)
Substrate	lm(Shannon ~ `Substrate`, data=dat_1)
Multivariate Model	lm(Shannon ~ `Pond Area_m2`+`Perm Pool_m3`+`Pond Perimeter`+`Conductivity_us`+`pH`+ Water Temp_C`+`Turbidity_FNU`+`Macrophyte Cover`+`Algae Cover`+`Dominant Land Cover Overall`+`Substrate`, data=dat_1)

Appendix 4: Welch's t-test Table Comparing Wet Ponds to Engineered Wetlands Expanded to Include Max and Min Values

	Wet Pond				**Engineered Wetland**							
	Mean	**SE**	**Min**	**Max**	**Mean**	**SE**	**Min**	**Max**	**t**	**p**	**df**	**Sig.**
Pond Area (m^2)	5295.250	1269.130	1579.000	23416.000	5503.250	1824.350	334.000	16561.000	-0.094	0.927	13.896	ns
Pond Perimeter (m)	358.566	41.343	161.651	895.226	397.812	77.482	79.185	799.860	0.121	0.910	3.597	ns
Permanent Pool Volume (m^3)	2886.200	451.739	390.000	5303.000	2702.000	1450.596	432.000	6925.000	-1.304	0.275	3.346	ns
Shape Index	1.462	0.063	1.087	1.964	1.618	0.085	1.222	1.964	-1.630	0.144	7.576	ns
Compactness Index	0.041	0.004	0.021	0.068	0.033	0.004	0.021	0.055	1.848	0.093	10.436	ns
Fractal Dimension Index	1.392	0.012	1.325	1.494	1.432	0.016	1.371	1.505	-1.011	0.339	8.628	ns
Catchment Area (HA)	33.330	4.253	17.800	70.100	23.468	5.887	2.500	50.660	1.068	0.313	9.017	ns
Water Temp (ºC)	11.550	0.568	7.550	15.500	10.156	0.581	8.000	12.200	1.716	0.103	18.772	ns
DO (mg/L)	11.015	0.868	5.795	17.950	9.011	0.722	5.045	11.270	1.417	0.173	18.665	ns
pH	7.681	0.183	6.855	9.335	7.514	0.202	6.380	8.160	0.579	0.570	16.185	ns
Conductivity (µs/cm)	860.111	144.753	282.000	2268.500	658.556	67.617	399.450	964.500	0.479	0.637	21.891	ns
Turbidity (FNU)	11.271	2.776	0.075	39.000	14.948	4.672	1.995	41.750	0.772	0.452	14.633	ns
PC (µg/L)	1.143	0.215	0.135	3.100	1.398	0.260	0.490	2.460	-0.968	0.346	17.309	ns
Chl-*a* (µg/L)	15.968	3.663	1.495	56.200	19.988	4.986	4.515	51.235	-1.161	0.261	18.116	ns

Appendix 5: Key Metrics and other Definitions of Measurements

Key OBBN Metrics	
%EPT	total percentage of Ephemeroptera at a site
%diptera	total percentage of flies and other dipterans including Chironomidae
%insects	total percentage of insects including Odonata, Coleoptera, Hemiptera, and other insects
%gastropoda	total percentage of snails and other gastropods at a site
%worms	percent total of Oligochaeta, Turbellaria, and Hirudinea (worms, flatworms, and leeches)
%chironomidae	total percentage of blood worm, no-seeums, and other midge larvae
%odonata	total percent of dragonfly and damselfly larvae in pond
%AmiIsopod	total percentage of scuds and aquatic isopods
%hemiptera	total percentage of true bugs such as diving beetles
%predators	total percentage of predatory larvae such as odonatan, hemiptera, etc
%scrapers	total percentage of algae grazers and scrapers in a pond
%gatherers	total percentage of organisms that feed from sediment, water, and other detritus
%filterers	total percentage of organisms that draw their algae from the water column
%tolerant	Count of the number of unique taxa considered to be tolerant to pollution. Sums and divides by site abundance of individuals with a tolerance value ≥ 6
%intolerant	Count of the number of unique taxa considered to be intolerant to pollution. Sums and divides by site abundance of individuals with a tolerance value <6
%dominant	Calculates the % of the most dominant taxa
HBI Index	This index uses tolerance values for each taxa, and abundance of those taxa.
H'	Shannon-Weiner Diversity represents the proportion of different species in a population. Higher values indicate higher biodiversity.
J	Pielou's Evenness represents the spread of abundance and evenness across a site, uses H' in the calculation. Ranges from 0-1 where 1= perfect evenness
Richness	total number of unique identifiable taxa at the lowest taxonomic resolution identified
Pond Metrics	
Shape Index	How the shape compares to a perfect square or circle.
Compactness Ratio	How closely the shape resembles a circle (the most compact form
Fractal Dimension Index	The complexity of a shape's boundary.
Water Metrics	Measured with YSI EXO Sonde
Water Temp	Water temperature in degrees Celsius.
pH	Measure of acidity or alkalinity (scale 0–14)
DO	Oxygen dissolved in water (milligrams per litre).
Conductivity	Electrical conductivity (microsiemens/cm). Indicates total dissolved ions (salts, nutrients, pollutants). Higher values can mean urban runoff, road salt, or pollution.
Turbidity_	Measures water clarity. High turbidity often means sediment, algae, or organic matter, which can block light and smother habitats.
PC_	A pigment found in cyanobacteria (blue-green algae), measured in micrograms per litre. Often used as an indicator of cyanobacterial abundance and potential harmful algal blooms.
Chla_	Chlorophyll-a concentration (μg/L). A proxy for total algal biomass. Higher levels often mean nutrient enrichment (eutrophication) and a broad primary producer as it relates to trophic level.

Appendix 6: Figshare links to supplementary data

Chapter 1: https://doi.org/10.6084/m9.figshare.30906791 – R code for the text analysis

Chapter 2: https://doi.org/10.6084/m9.figshare.30906770 – R code for Meta-Analysis & Excel file with all retrieved papers

Chapter 3: https://doi.org/10.6084/m9.figshare.30906923 – R code & dataset for analysis